3D-PTV and Lagrangian measurements in a wind tunnel

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Outline

- What is the three-dimensional particle tracking velocimetry
- What is the main contribution to turbulence research
- What are the limitations and possible solutions
- The (only) working solution example - Ron Shnapp

The take-home message

- You can do it and you better do it
- Real-time image analysis on a dedicated hardware is a key for long-recording, high-speed 3D-PTV
- Paradigms about 3D-PTV changes from in-lab table-top experiments to wind tunnel and field experiments
- You can readily get data sets of millions of tracer trajectories like the one recorded in a canopy flow model in an environmental wind tunnel, providing Lagrangian velocity and acceleration distributions in an urban canopy flow model

Details are in the pre-print "Real-time extension ..." by Shnapp et al. arXiv:1806.04975

Let’s follow the Lagrangian path

“Marianthe” invited people inside turbulent forms to experience them as if they were a particle borne along in the flow. Athena Tacha (1985), “Nautilus” by Philip Ball

Basic steps

Image acquisition by a multi camera arrangement

↓

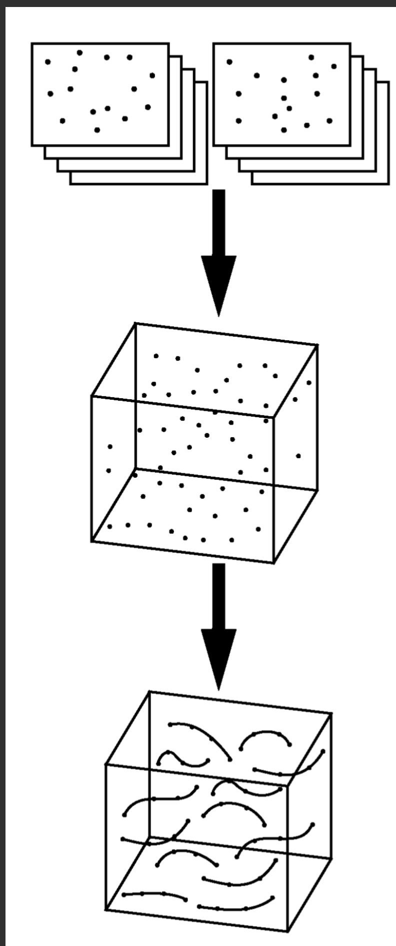
Particle detection

↓

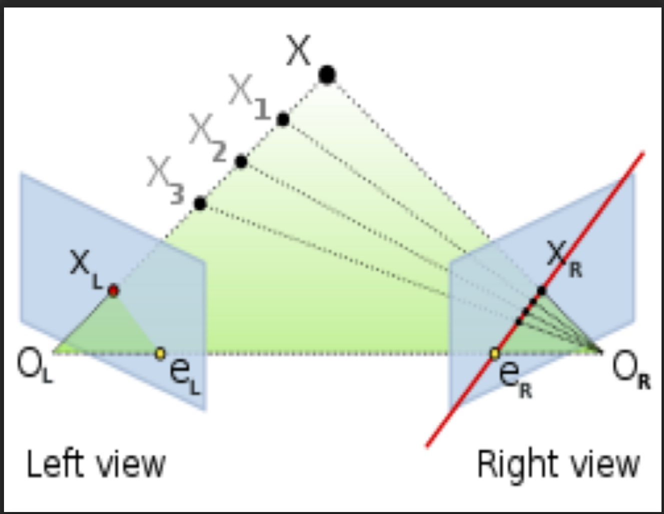
Establishment of stereoscopic correspondence

↓

Particle tracking in 3D space



Epipolar geometry



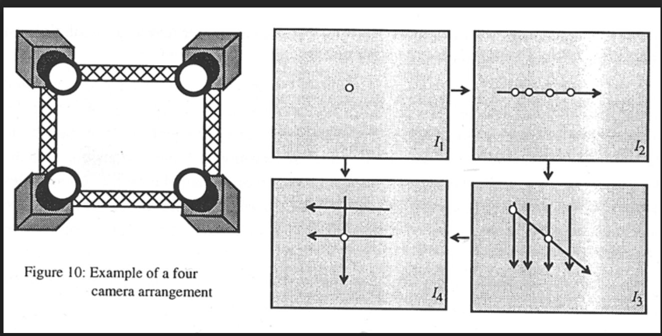
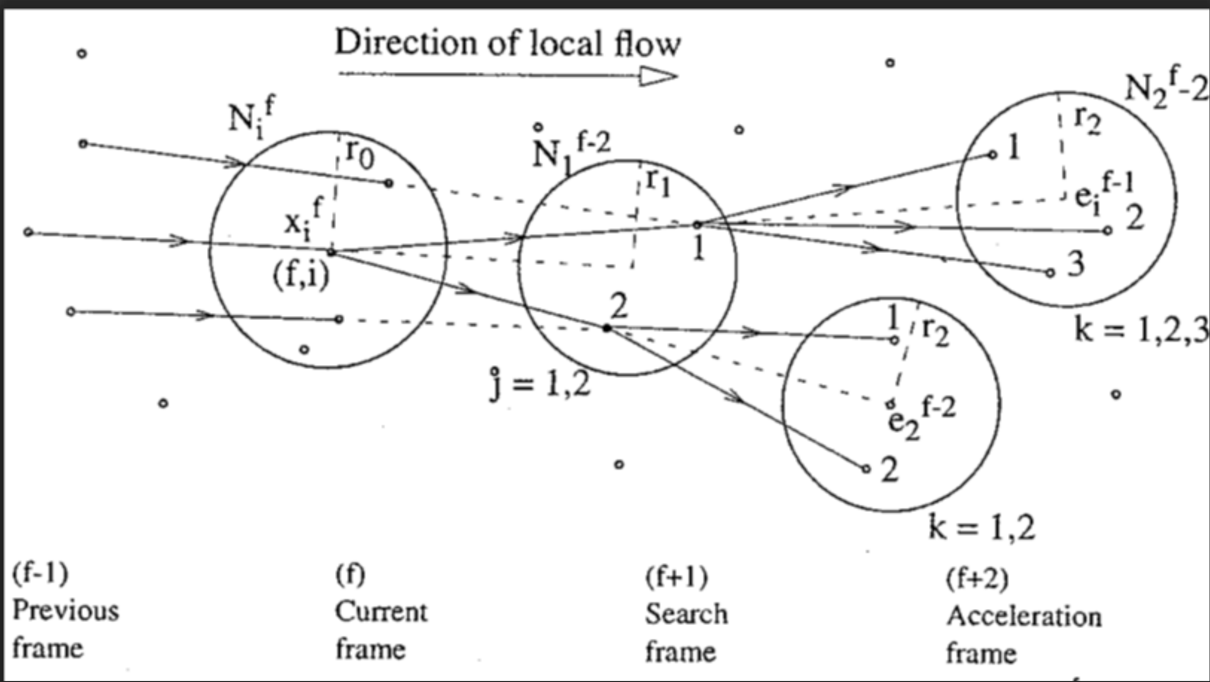


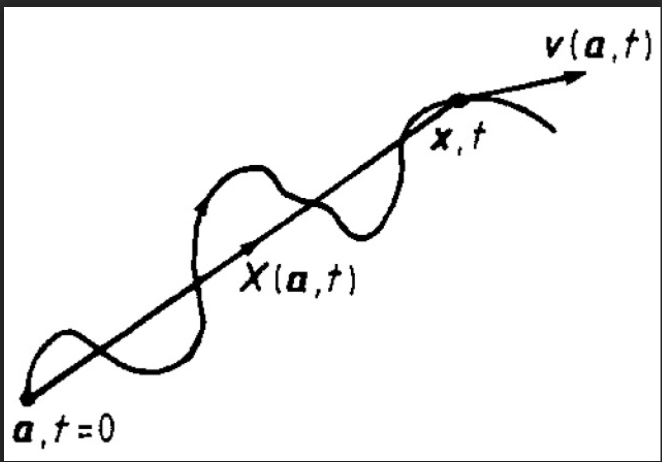
Figure 10: Example of a four camera arrangement

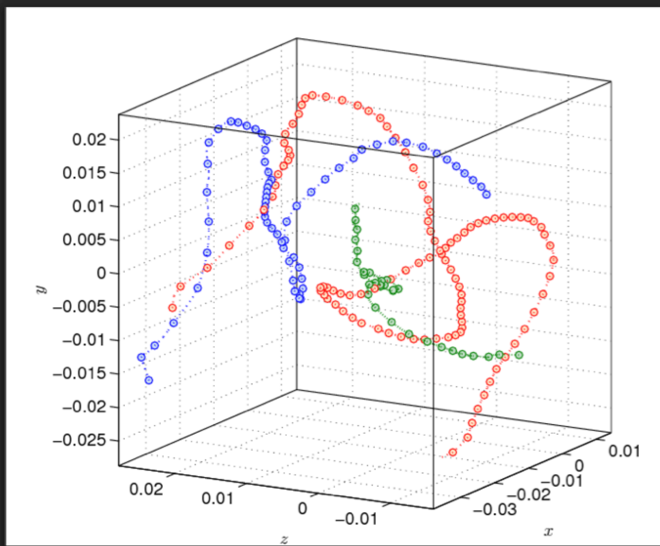
Tracking



Direction of local flow
N_i^f
r_0
x_i^f
(f,i)
N_1^{f-2}
r_1
1
2
j = 1,2
N_2^{f-2}
r_2
1
e_i^{f-1}
2
3
k = 1,2,3
1
r_2
e_2^{f-2}
2
k = 1,2
(f-1)
Previous
frame
(f)
Current
frame
(f+1)
Search
frame
(f+2)
Acceleration
frame

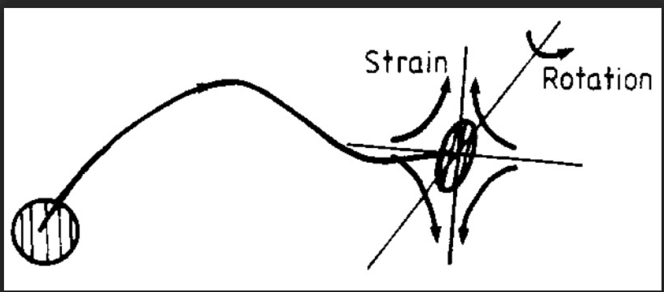
The immediate result is a Lagrangian trajectory

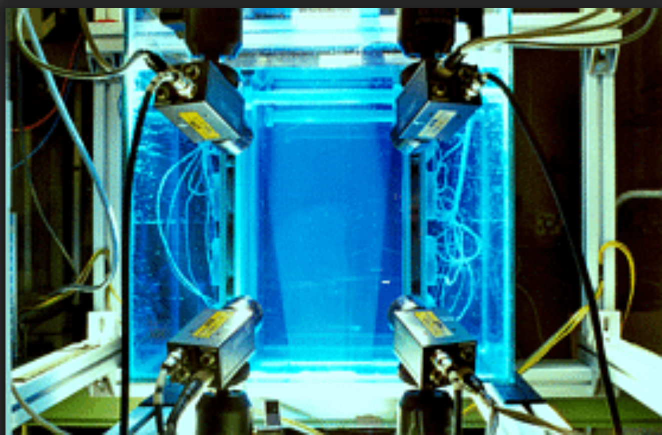




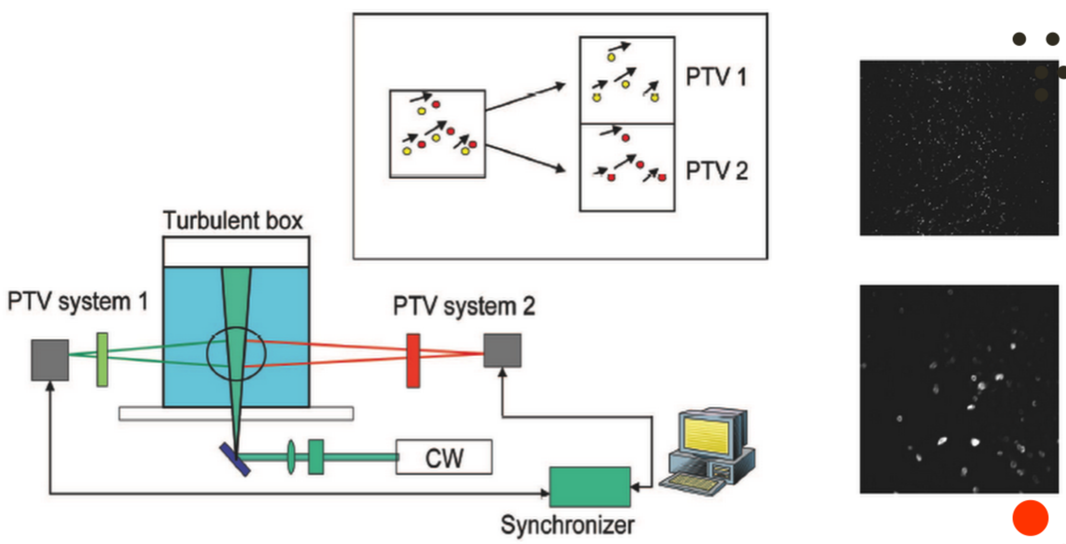
3D-PTV main focus is turbulence

Which means we need the full gradient tensor along the particle trajectories: $\partial u_i / \partial x_j$ in space and time



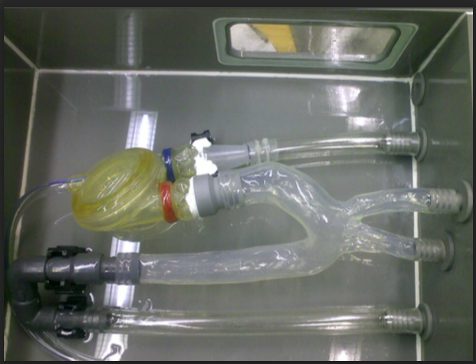


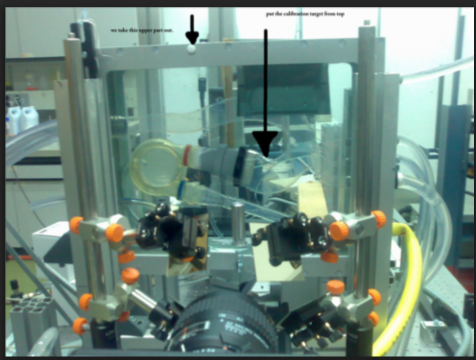
It had other applications, e.g. inertial clustering



Nd:YLF laser 527 nm, Silica Gel with Rhodamine B particles (orange fluorescence, Excitation/Emission = 560/584 nm)

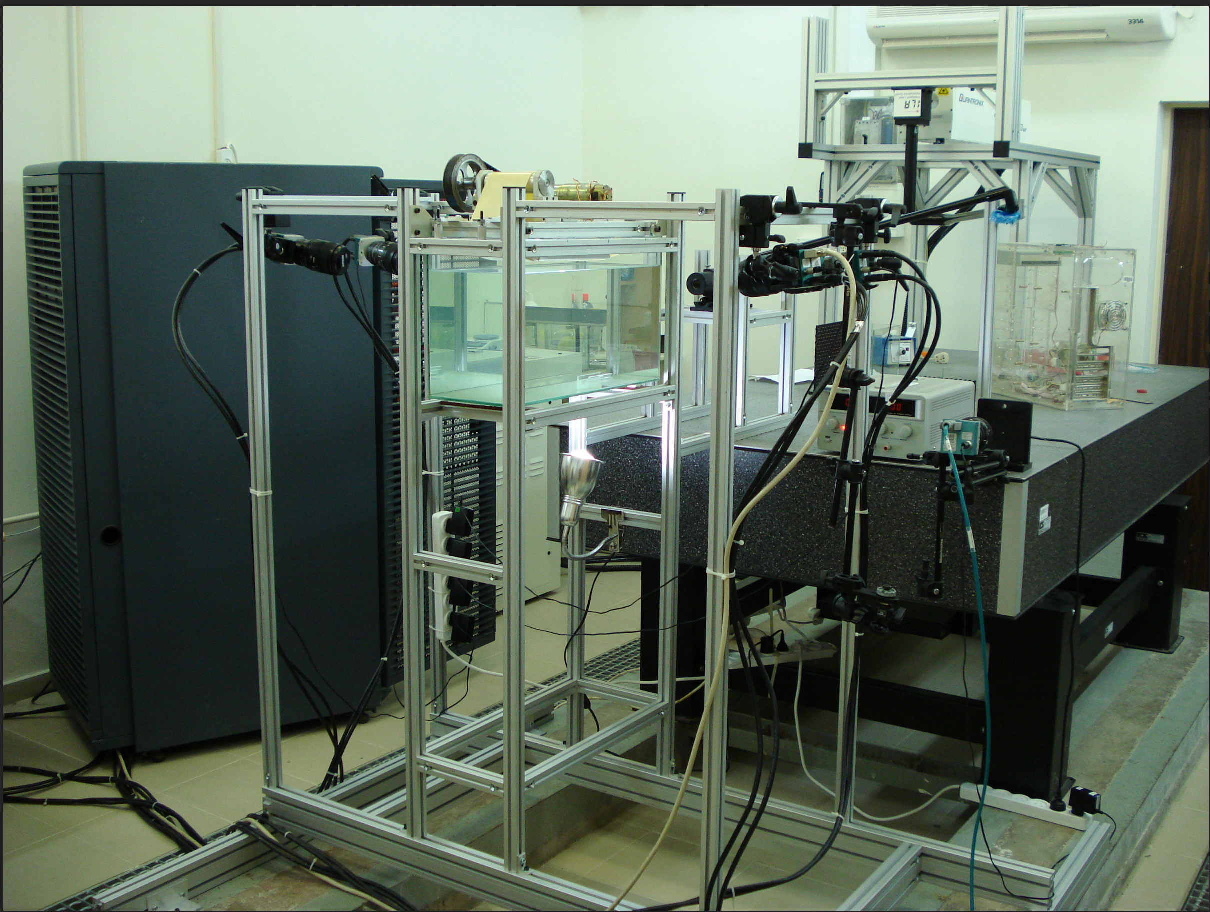
MRI + 3D-PTV




we take this upper part out.
put the calibration target from top

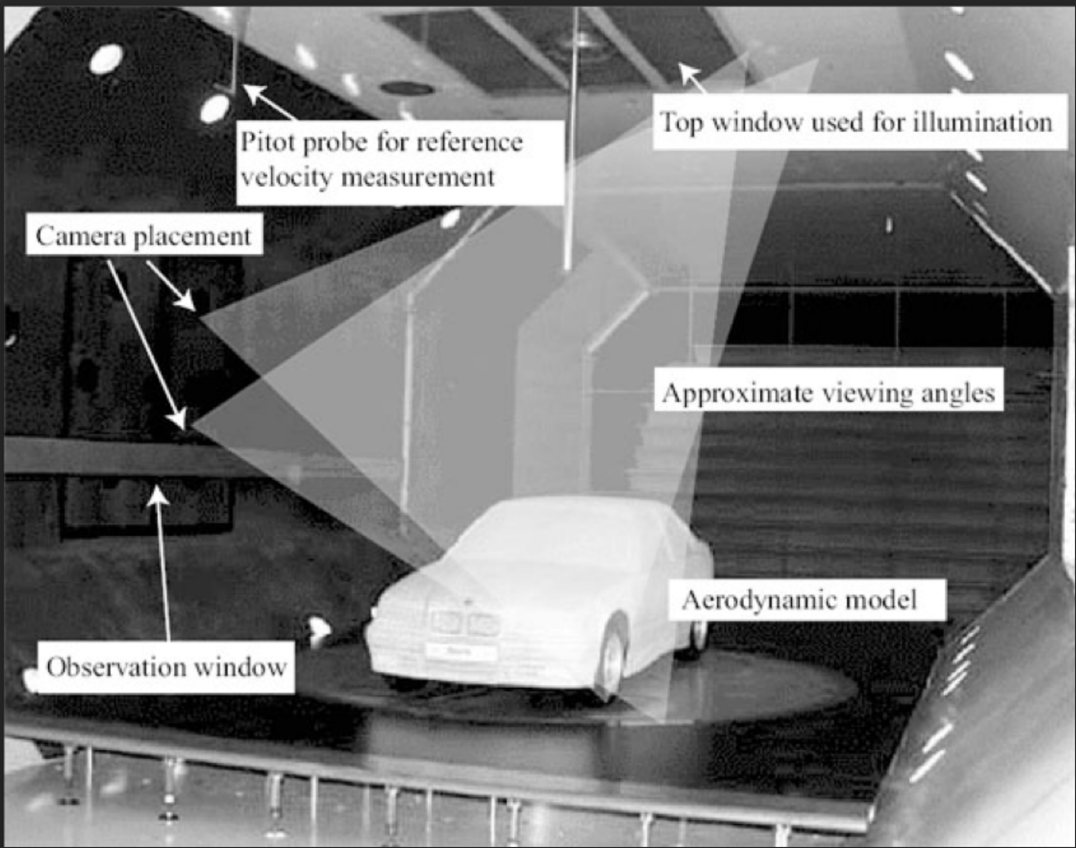

MAGNETOM Trio

3D PTV is typically a lab system



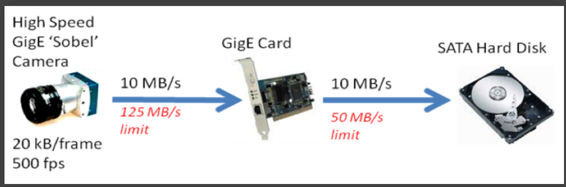
The main bottleneck is also heavy

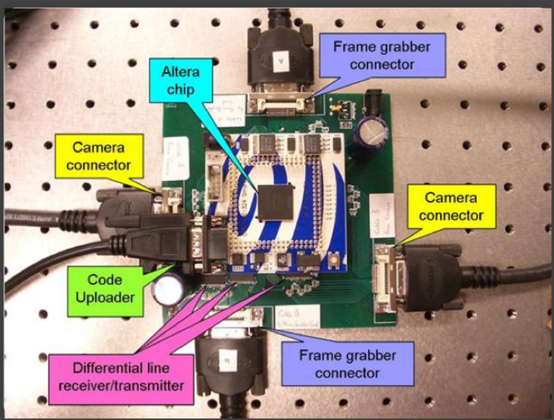
We had a dream: 3D-PTV for large scale systems



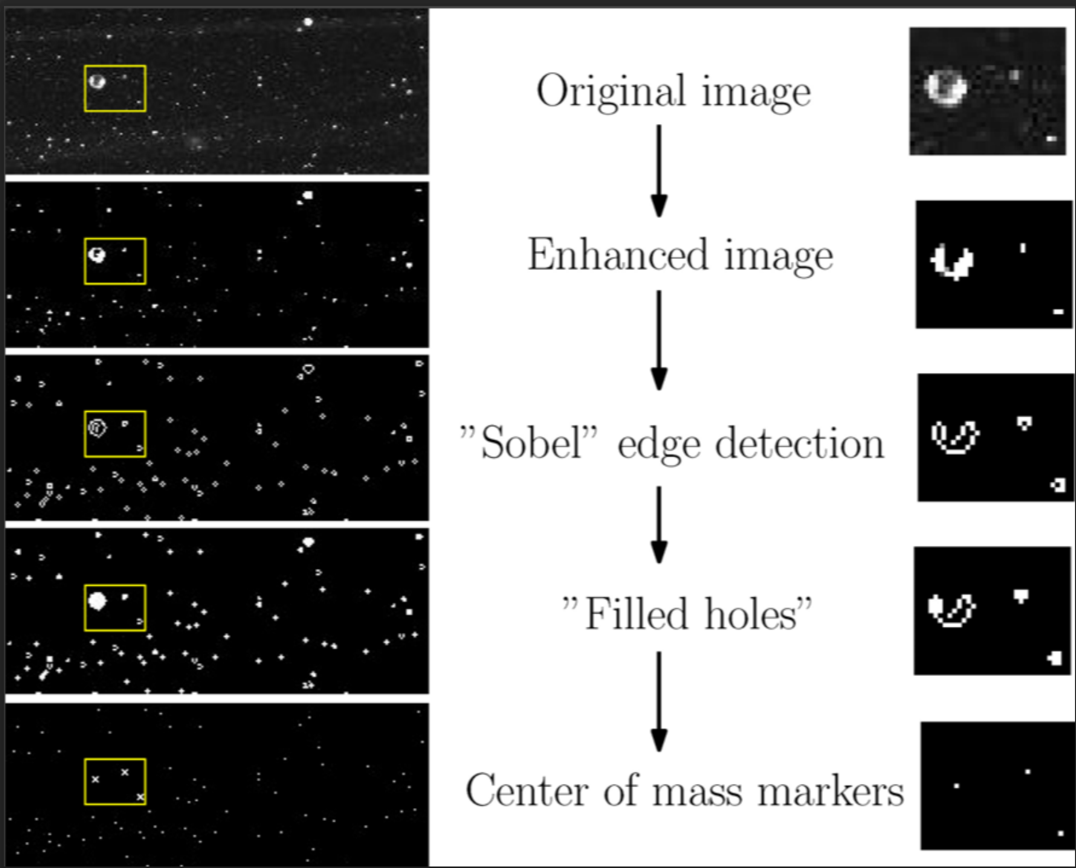
Need to eliminate the transfer rate bottleneck

from compression to on-camera processing





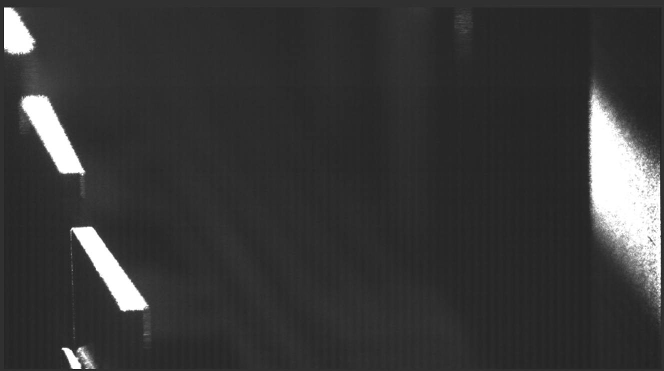
Sobel edge detection based algorithm

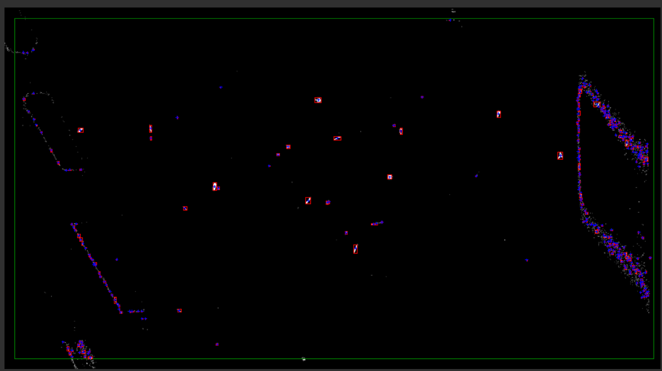


Works very well for lab experiments

Raw image - binarized image - blobs marked on the original image.

Real life is not like this





Raw 3D-PTV image the wind tunnel experiments: Background -¿ binary image after background subtraction, and detection using a local adaptive filter

We had to develop the know-how

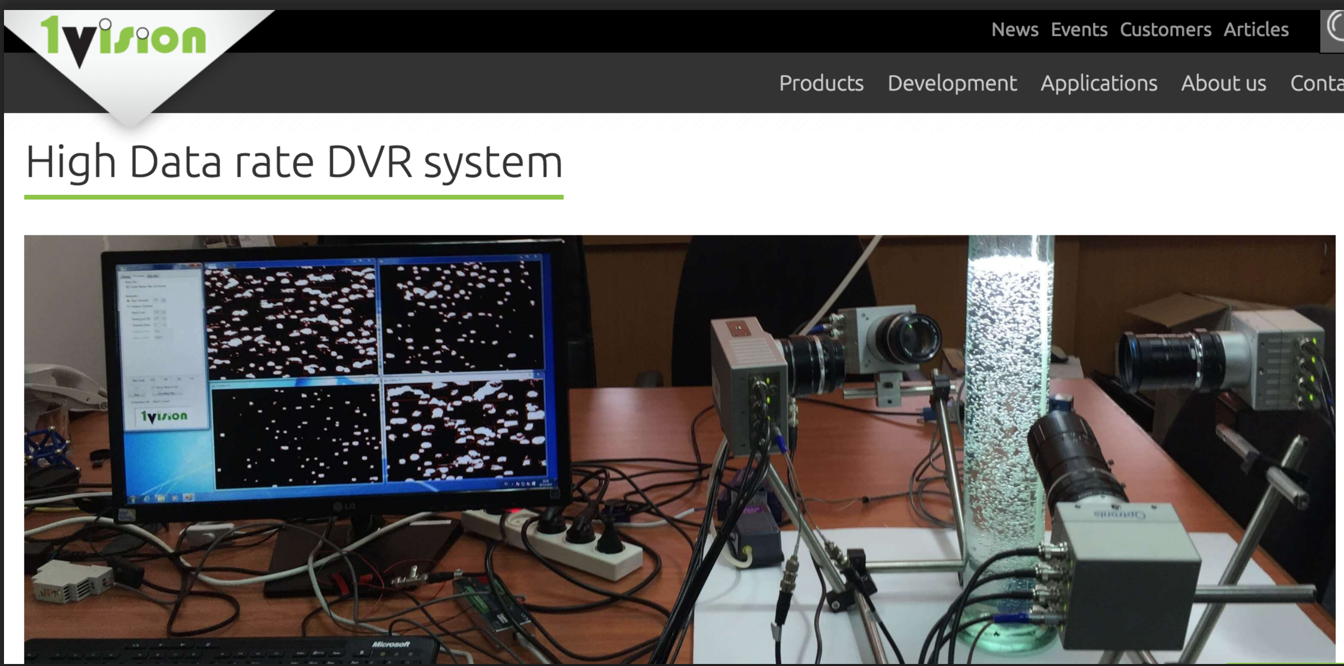
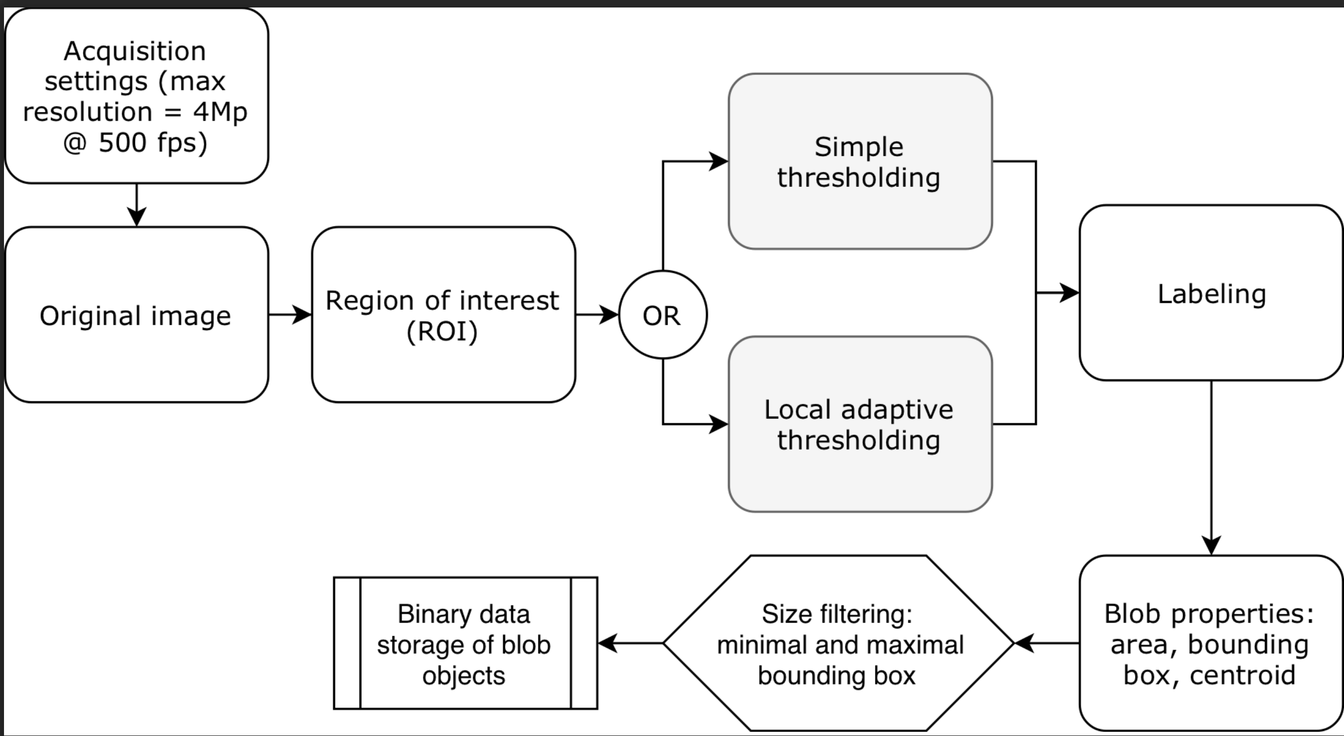
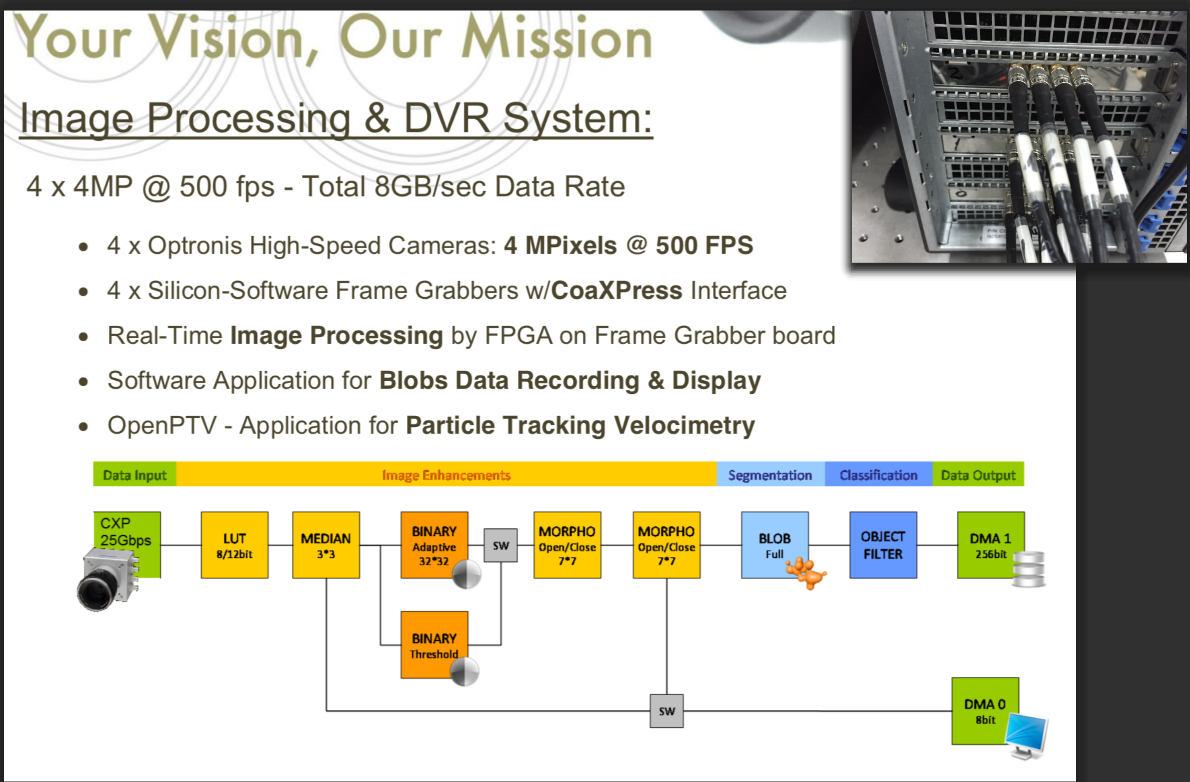


Image processing algorithm on FPGA



And its implementation on a dedicated hardware

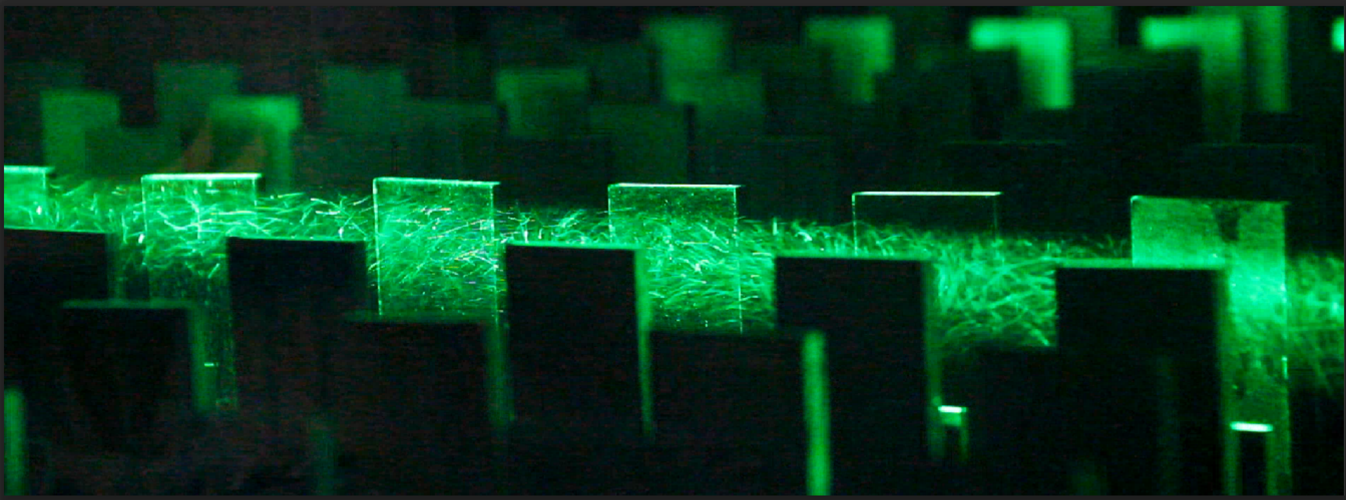


And now we are ready for the Environmental Wind Tunnel

Open source software suite, all on Github

- OpenPTV open source particle tracking velocimetry library, ‘liboptv‘, ANSI C
- PyPTV GUI for *liboptv* in Python
- FlowTracks - trajectories database management (see Meller and Liberzon 2016)
- BlobRecorder - proprietary hardware/customized software (see Shnapp et al. arxiv)

Thank you for your attention



Lagrangian Investigation of Canopy Flow Turbulence - Pair Dispersion

Ron Shnapp [1]

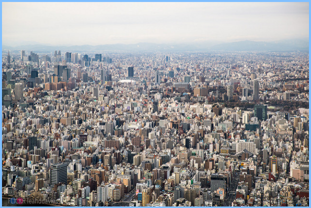
Yardena Bohbot-Raviv[2], Eyal Fattal[2], Alex Liberzon[1]

[1]Tel Aviv University, [2]IIBR

Canopy Flows

Flow in the surface layer -

- Air flow in urban regions
- Air flow in forests
- Air flow in fields

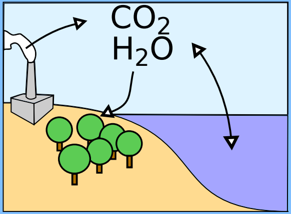


Images: Hansueli Krapf @ Wikipedia, Leah Davies @ Flickr, and M. J. Richardson, Wikipedia

Canopy Flows

Determine dispersion, mixing and surface fluxes, e.g. -

- Air quality in urban regions
- H_2O and CO_2 exchange
- Pollen transport



Images: Carol Clark @ esciencecommons.blogspot, Seth Anderson @ Flickr

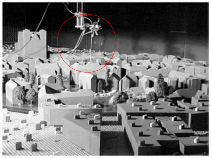
Atmospheric Surface-Layer

- The bottom part of the ABL
- **Direct interaction** with the terrain

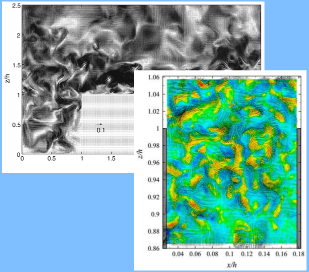
Very Intense Turbulence!

Eulerian Measurements

Stefan Arndt,
University of Melbourne



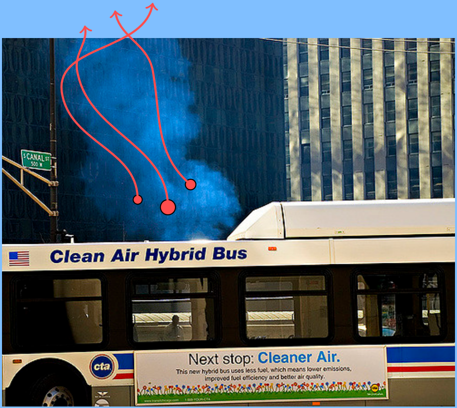
Kastner-Klein & Rotach (2003)



Coceal et al. (2006)
Zhu, van Hout & Katz (2007)

The *Lagrangian* Description

Specify fluid properties on the positions of fluid tracer particles.



$$\vec{x}(t)$$

$$\vec{v}(t, x(t))$$

Natural in dispersion problems

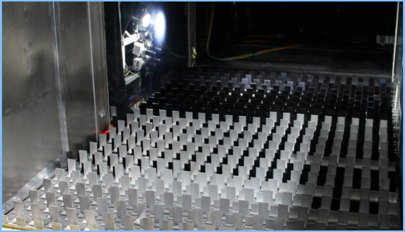
Lagrangian stochastic models

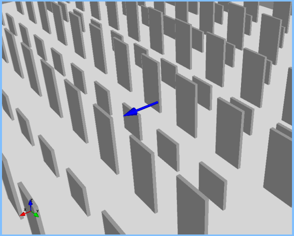
image sources: Seth Anderson @ Flickr

Experimental Data in Canopies is Very Sparse

Methods

Wind Tunnel Model



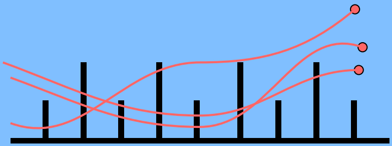


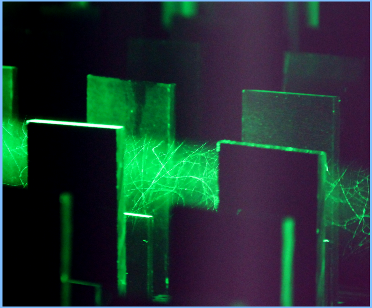
- IIBR env. wind-tunnel
- $H = 100$ & 50mm
- $U_\infty = 2.5$ & 4m/s
- $Re_\infty = 16$ & 26×10^3

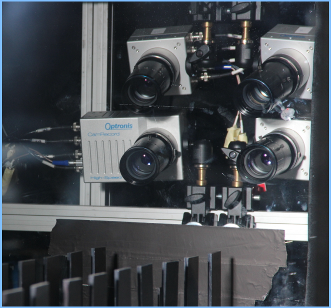
3D-PTV

Lagrangian Data through openPTV -

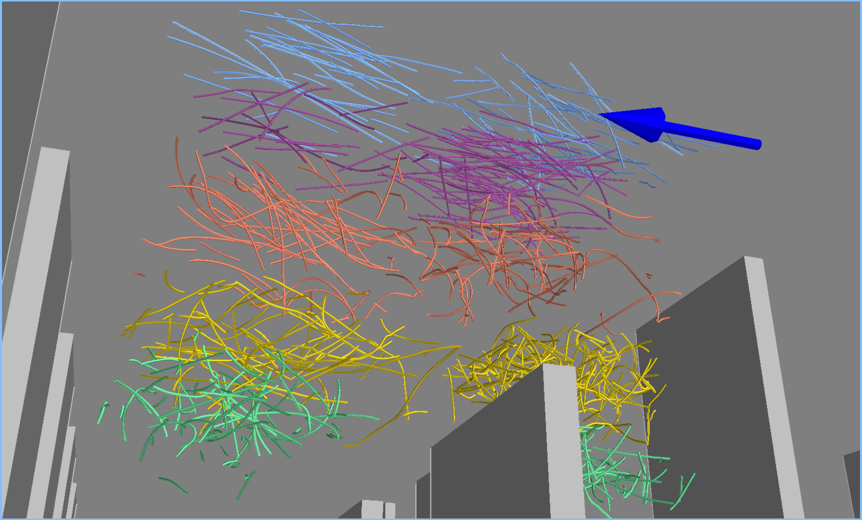
- Detection (at 500 & 1000 Hz)
- Positioning
- Tracking in 3D







3D-PTV - trajectory dataset



$\sim 6 \times 10^6$ trajectories in and above the canopy layer

3D-PTV - trajectory dataset

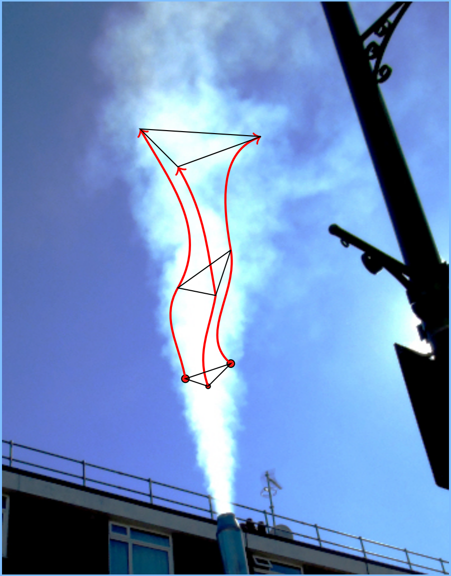
go to - https://youtu.be/NMPCWiWUqrY

Results

Pair Dispersion

Pair Dispersion

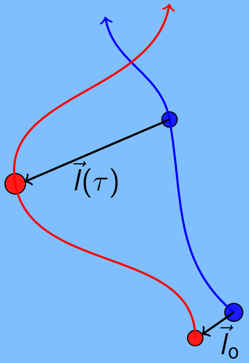
Lagrangian particles as a collective



Pair Dispersion

Consider a **pair** of Lagrangian particles:

- Distance between the pair $r(t) = |\vec{l}(t)|$
- The initial separation $r_0 \equiv r(t_0)$
- The time elapsed $\tau = t - t_0$

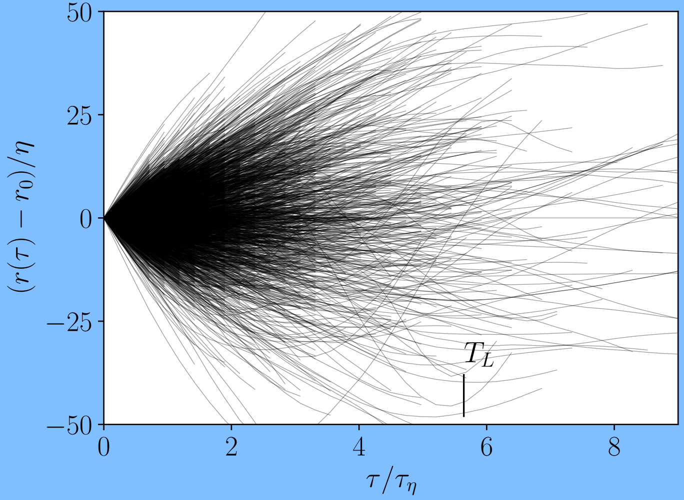


We focus on the change in separation distance

$$r(\tau) - r_0$$

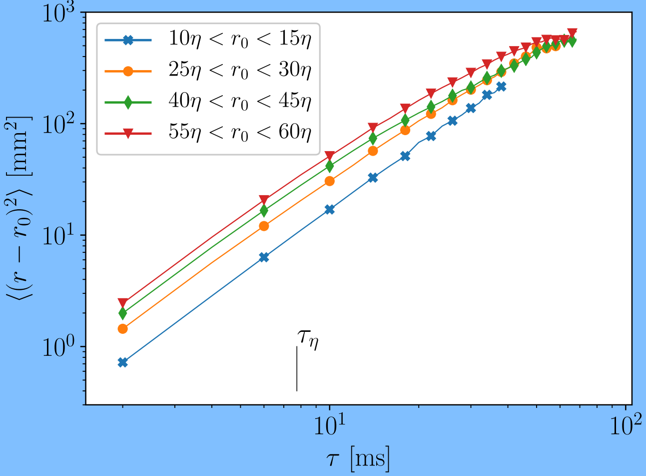
Pair Dispersion

At sub-volume inside the canopy ($\langle z \rangle \approx 0.75H$);
($\sim 0.2 \times 0.5 \times 0.5\ H^3$)



Pair Dispersion

Examine the variance as time progresses



dependence on

- r_o
- τ

Pair Dispersion

Very short times - A Ballistic Regime

$$r(\tau) = r_0 + v_0\tau + \mathcal{O}(\tau^2) \quad \Rightarrow \quad \boxed{\frac{\langle (r - r_0)^2 \rangle}{S_2(r_0)\,\tau_b^2} = \left(\frac{\tau}{\tau_b}\right)^2}$$

$$\tau_b = \left(\frac{r_0^2}{\epsilon}\right)^{1/3}$$

Here $v_0 \equiv \frac{dr}{d\tau}|_0$, $S_2(r_0)$ is the Eulerian second order structure function, and ϵ is the mean rate of dissipation.

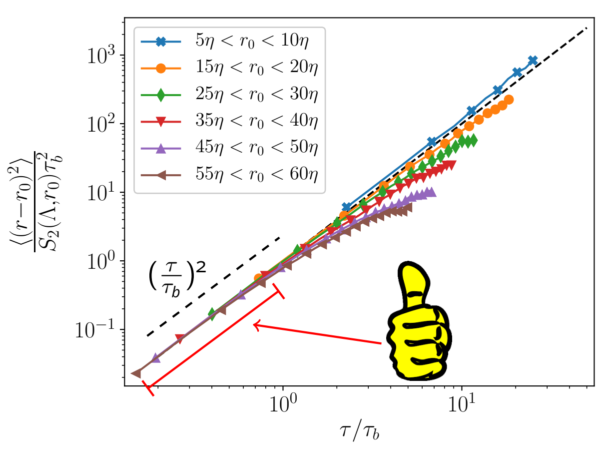
* see the *Ballistic Cascade* phenomenology by Bourgoin (2015).

Pair Dispersion

A Ballistic Regime

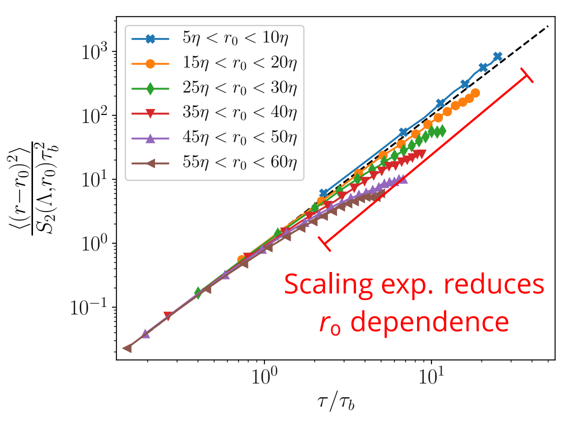
$$\frac{\langle (r - r_0)^2 \rangle}{S_2(r_0)\,\tau_b^2} = \left(\frac{\tau}{\tau_b}\right)^2$$

Agreement at short times!



Pair Dispersion

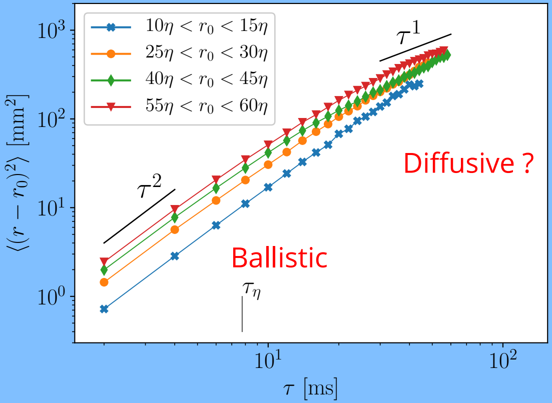
At Longer times



Pairs at different r_0 depart the Ballistic Regime at different τ_b

Pair Dispersion

At Longer times



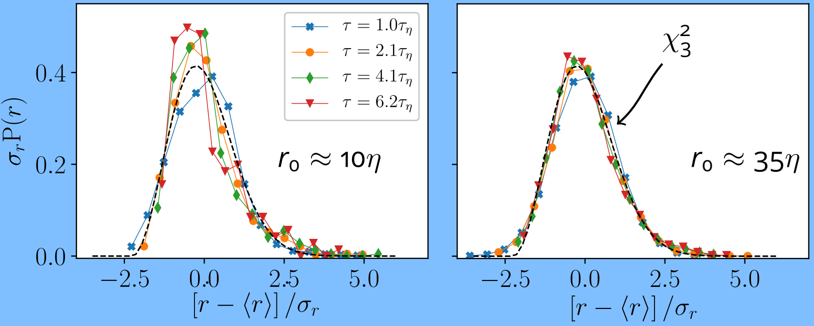
- Approach to an asymptotic $\propto \tau^1$
- Diffusive separation ?
- Suggests a decorrelation of particle velocities

Pair Dispersion

At Longer times

If pair velocities are uncorrelated then - $l_i = x_i^{(1)} - x_i^{(2)} \sim N(\mu, \sigma)$, and therefore* -

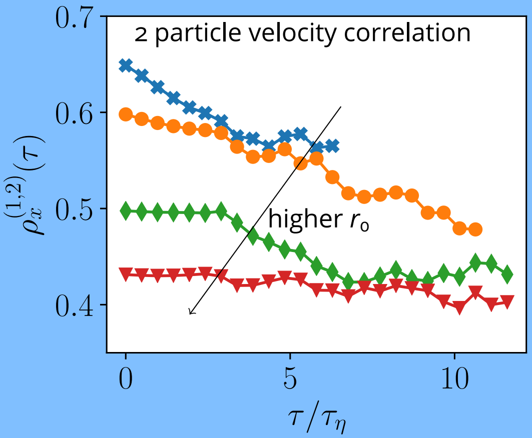
$$r^2 \sim \chi_3^2$$



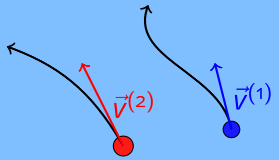
* P. K. Yeung, Physics of Fluids (1994)

Pair Dispersion

At Longer times



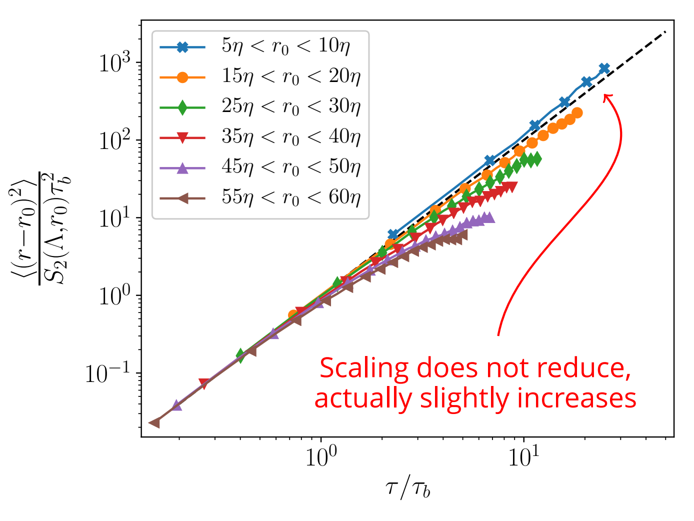
- Decorrelation depend on r_0.



Pairs with **Lagre** r_0 **are uncorrelated** $\Rightarrow$ Diffusive Separation

Pair Dispersion

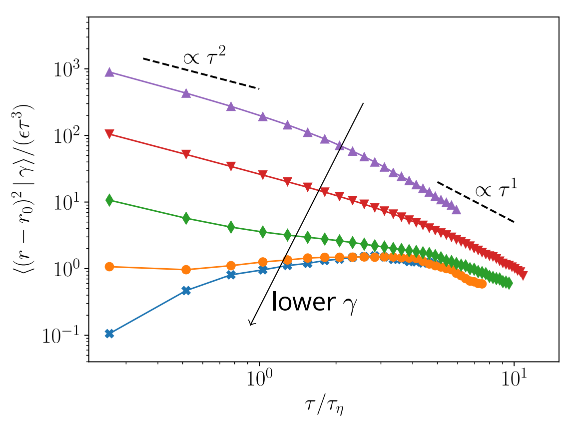
At Longer times & small r_o



Pair Dispersion

At Longer times & small r_0

Instead of r_0 we suggest* $\gamma = \frac{v_0^2}{(\epsilon r_0)^{2/3}}$



For small γ, pairs follow the scaling of the Richardson Obukhov law

$$\langle (r - r_0)^2 \rangle \propto \epsilon \tau^3$$

* Shnapp & Liberzon, PRL (2018)

Conclusions

Conclusions

Pair dispersion:

1. Large r_0: Ballistic $\rightarrow$ Diffusive
   loss of correlation at some length scale
2. Small r_0: Ballistic $\rightarrow$ Super-Diffusive
   ISR scaling + Lagranigan intermittency

I did not discuss: Anisotropy, Inhomogeneity, Large scales

* Shnapp et al. (2019) [arXiv:1806.04975]

* Shnapp and Liberzon; PRL (2018)

Conclusions

I would like to thank

1. The organizers of NCTRV
2. Prof. Alex Liberzon, Dr. Yardena Bohbot-Raviv and Dr. Eyal Fattal
3. Tel Aviv University, school of mechanical engineering
4. PAZY foundation
5. And...

Thank You!