Particle Image Velocimetry

Romain MONCHAUX

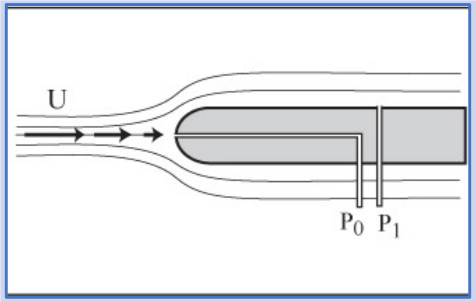
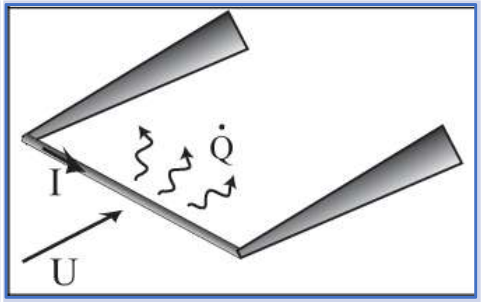
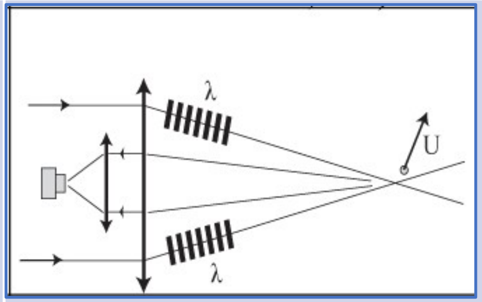
romain.monchaux@ensta.fr

Laboratoire de Mécanique et de ses Interfaces

Unité de Mécanique, ENSTA

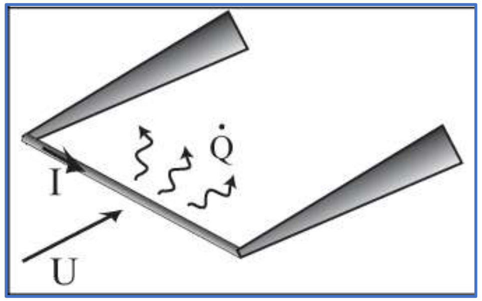
Institut Polytechnique de Paris

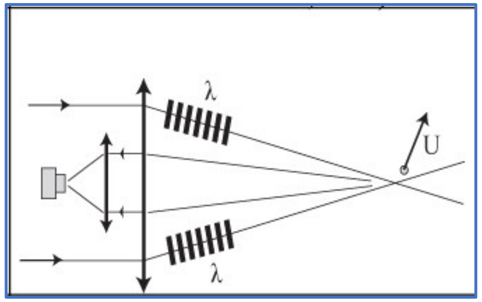
Why PIV ?

	Pitot Tube	Hot Wire Anemometry	Laser Doppler Anemometry
Sketch			
Principle	Two pressure measurements: static and dynamics Bernoulli	Measure of dissipated Joule power in a wire	Interferometric measurement of a Doppler shift on scattering particle
Pros	Easy to use Cheap (1 k€) Suited for time average	Very high time and space resolution Suited for fluctuation measurements Easy to use Medium price (10 k€)	Non intrusive High time and space resolution Suited for fluctuations Suited for several components
Cons	Highly intrusive Very poor time & space resolution	Intrusive, fragile Non linear calibration Sensitive to temperature	Non regular sampling High price (50-100 k€) Seeding required Difficult settings

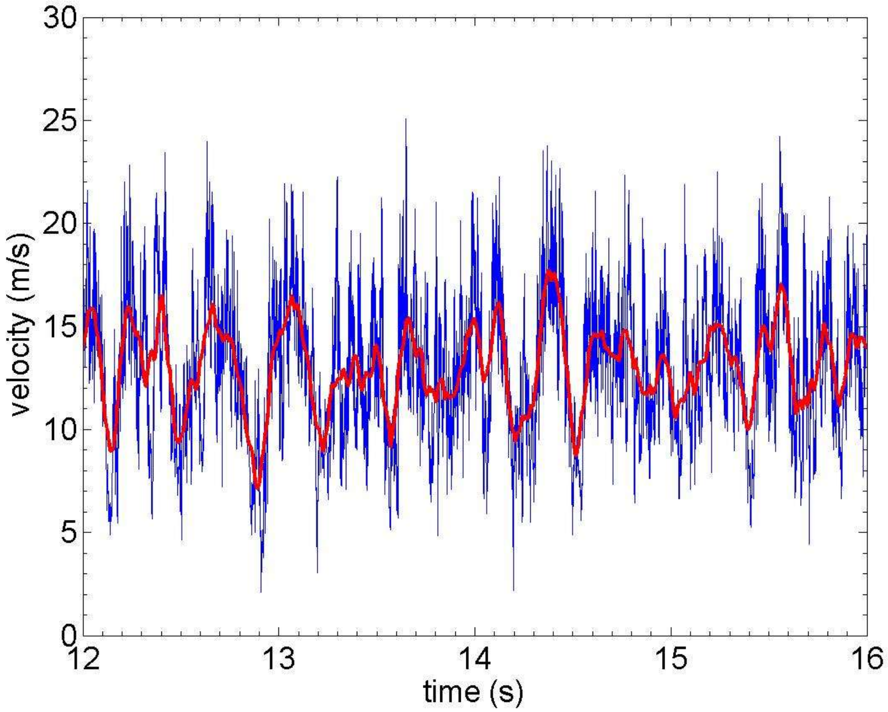
Why PIV ?

Hot-Wire





Laser Doppler Anemometry

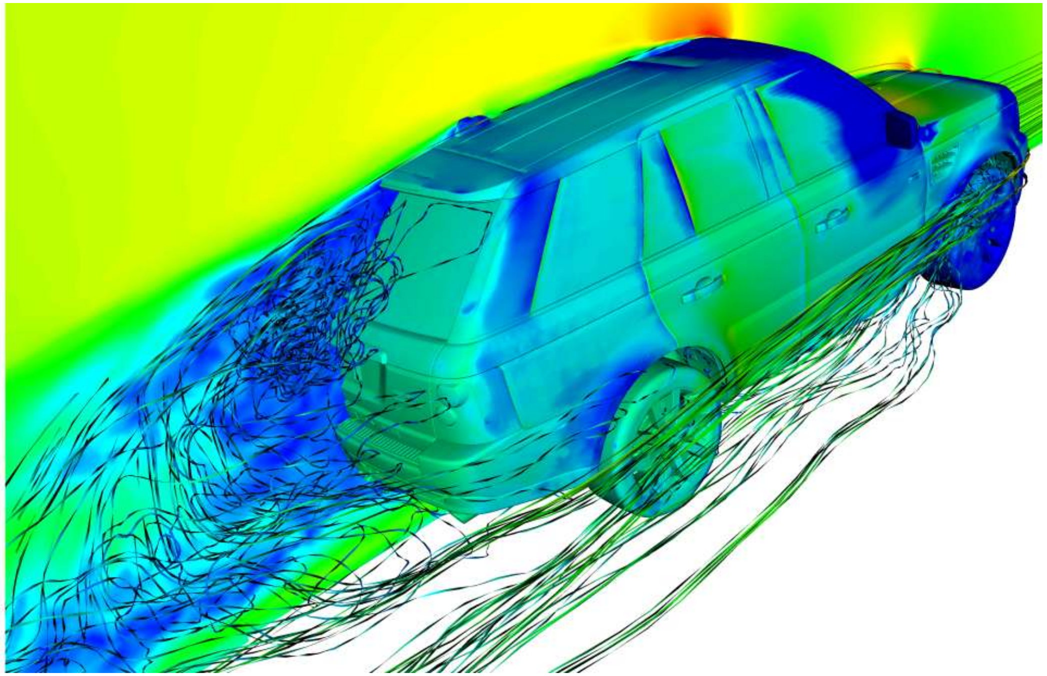


1D time resolved signals

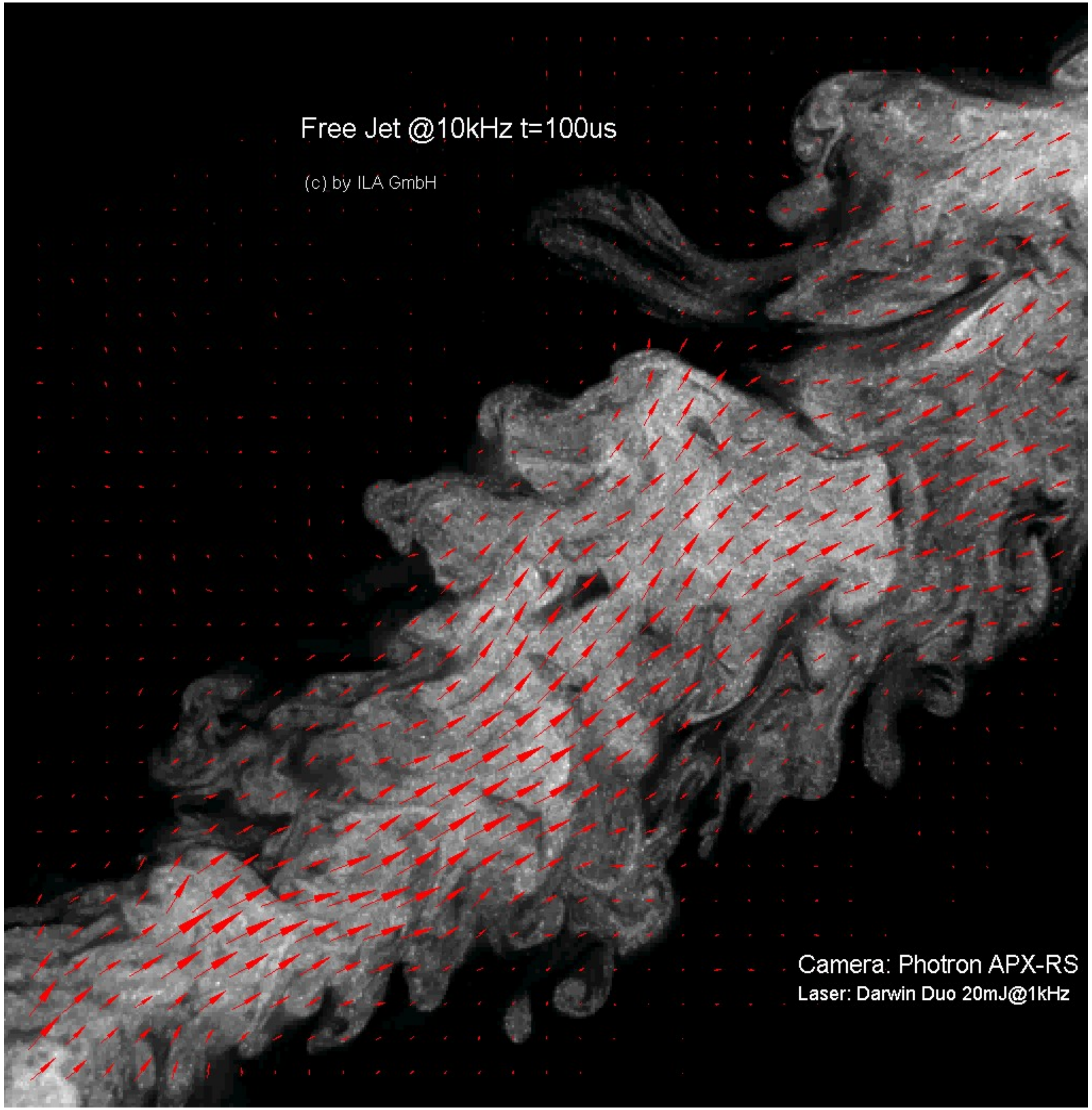
Why PIV ?

Resolved numerical simulations
expensive in time

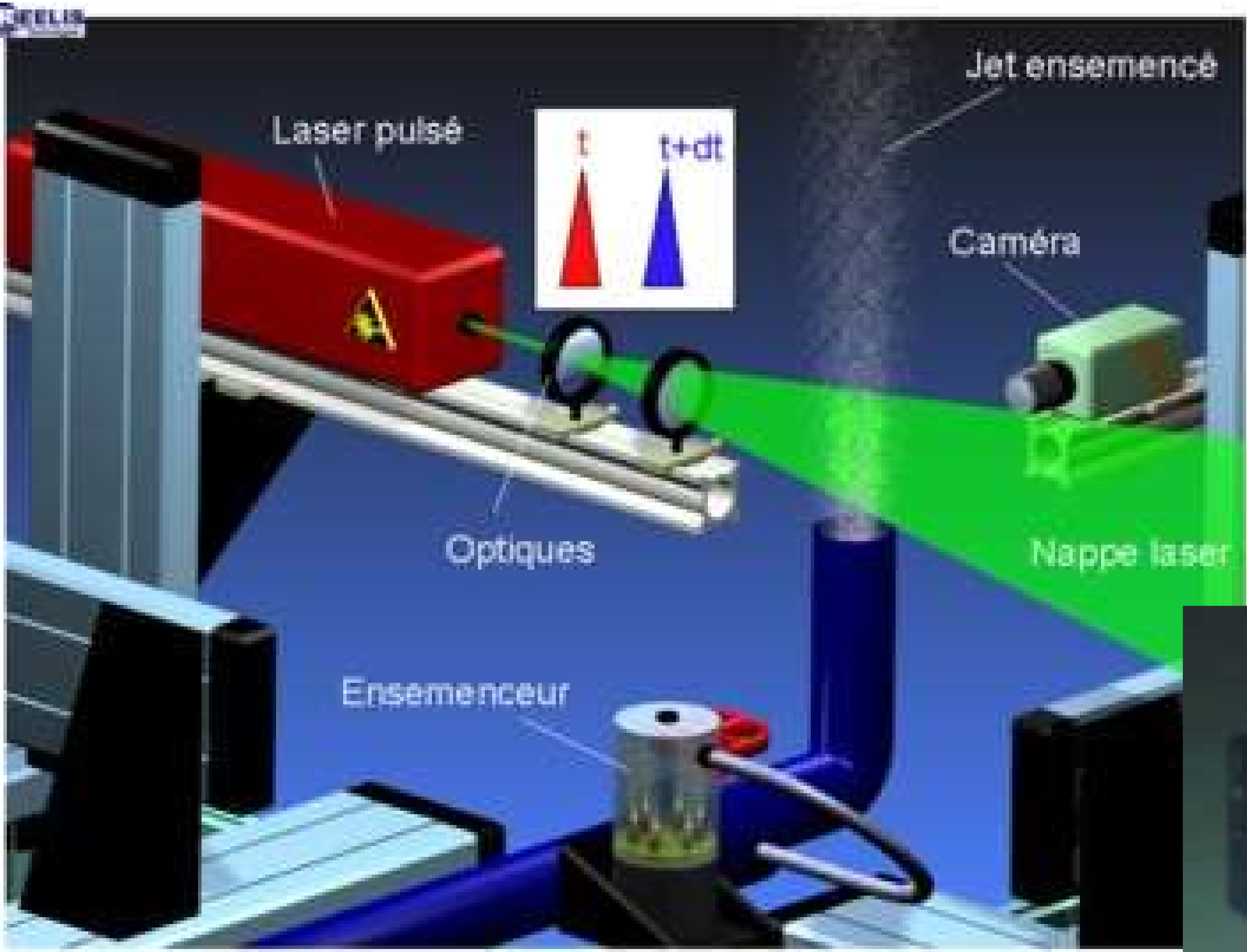
Experiment: more or less cheap



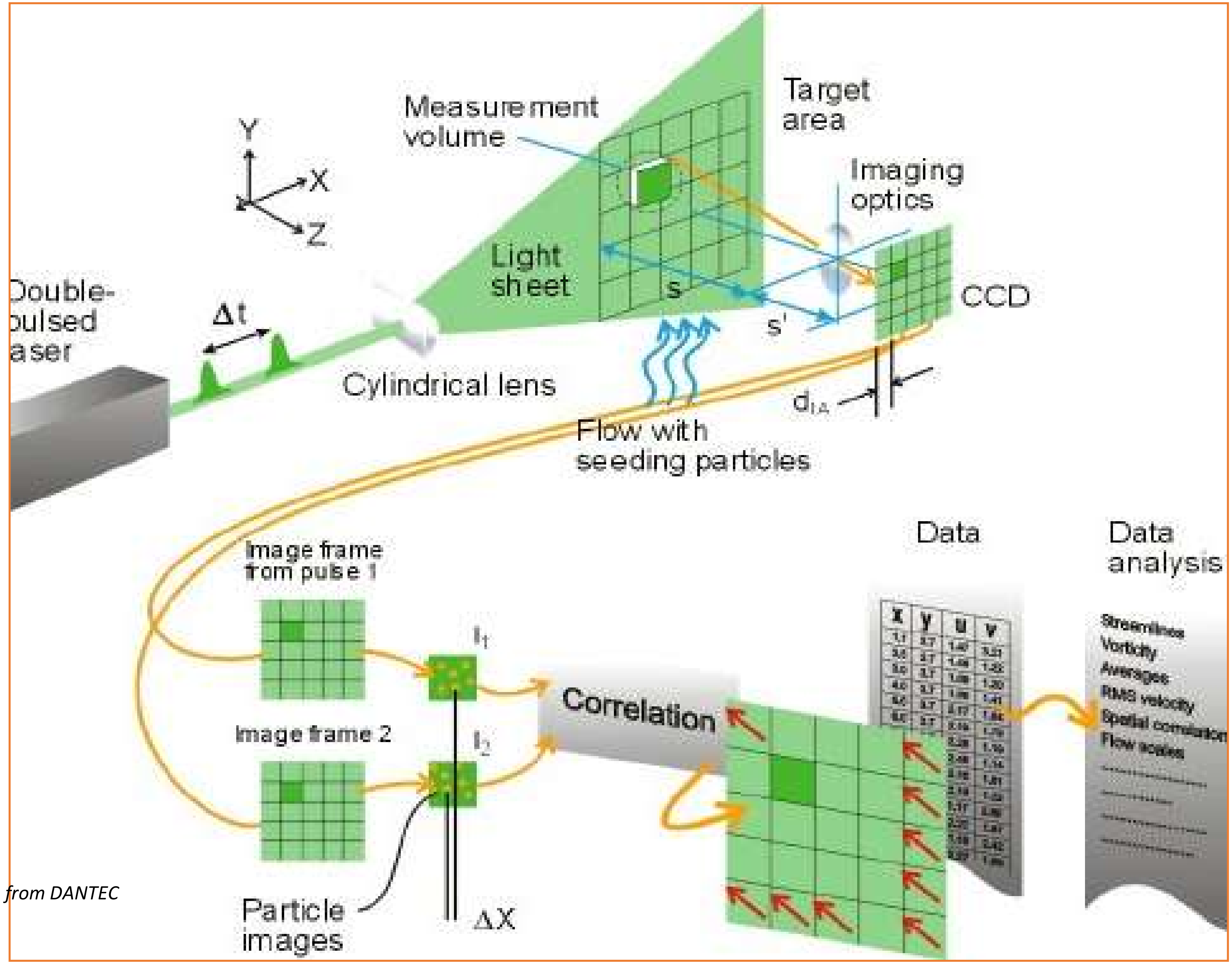
Why PIV ?


Free Jet @10kHz t=100us
(c) by ILA GmbH
Camera: Photron APX-RS
Laser: Darwin Duo 20mJ@1kHz

Particles Image Velocimetry: principles

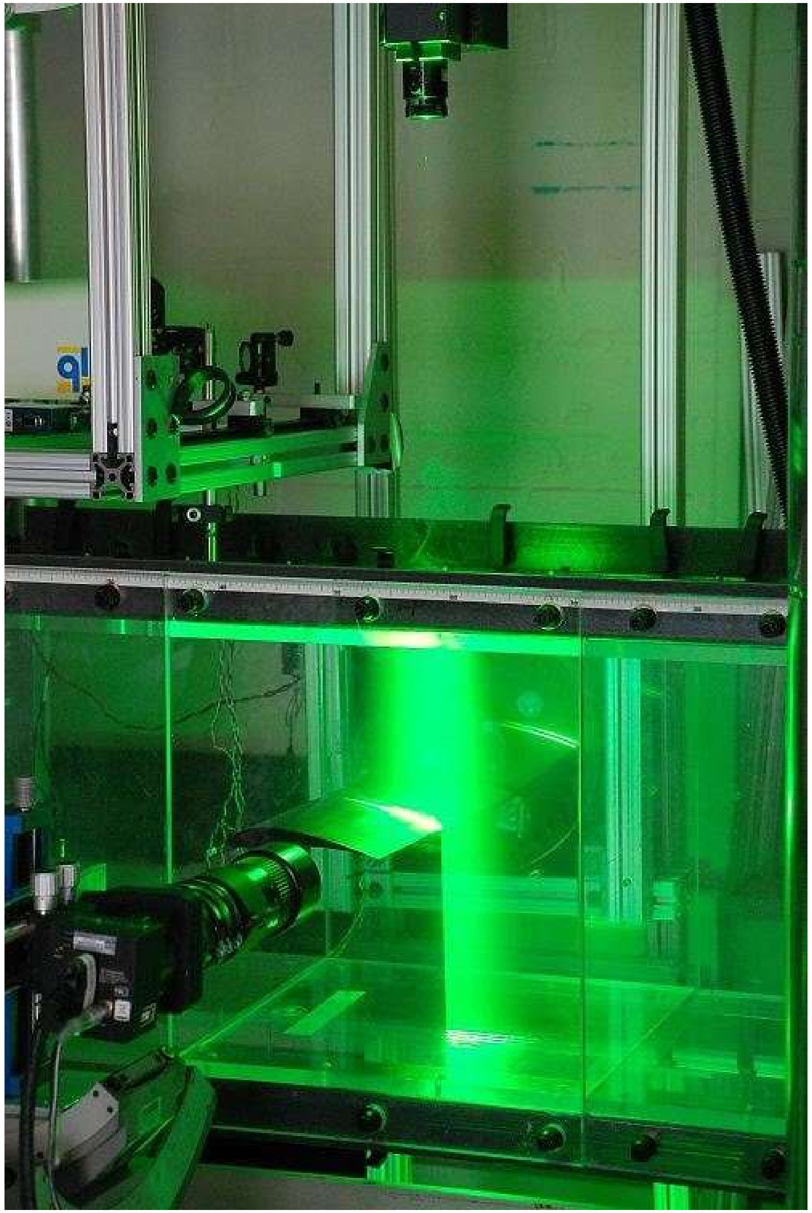


Particles Image Velocimetry: principles

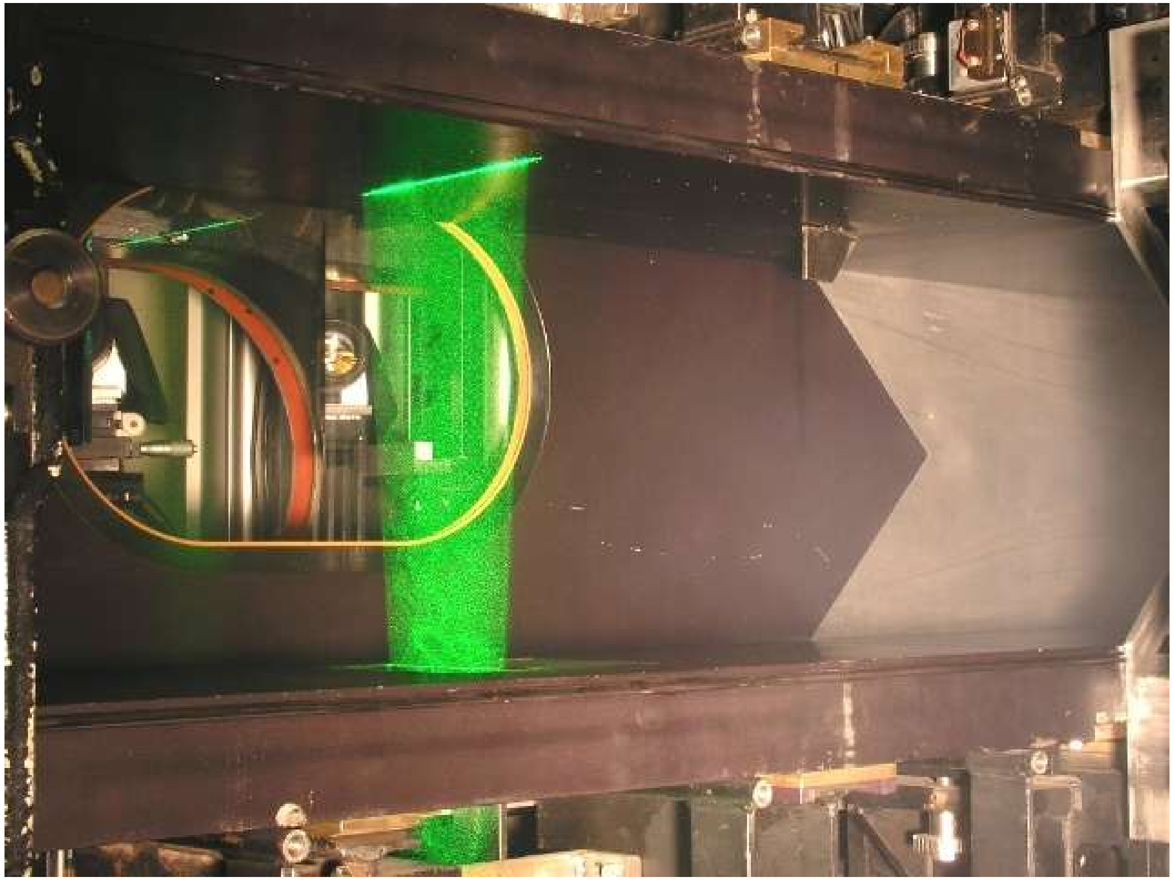


from DANTEC

Particles Image Velocimetry: example

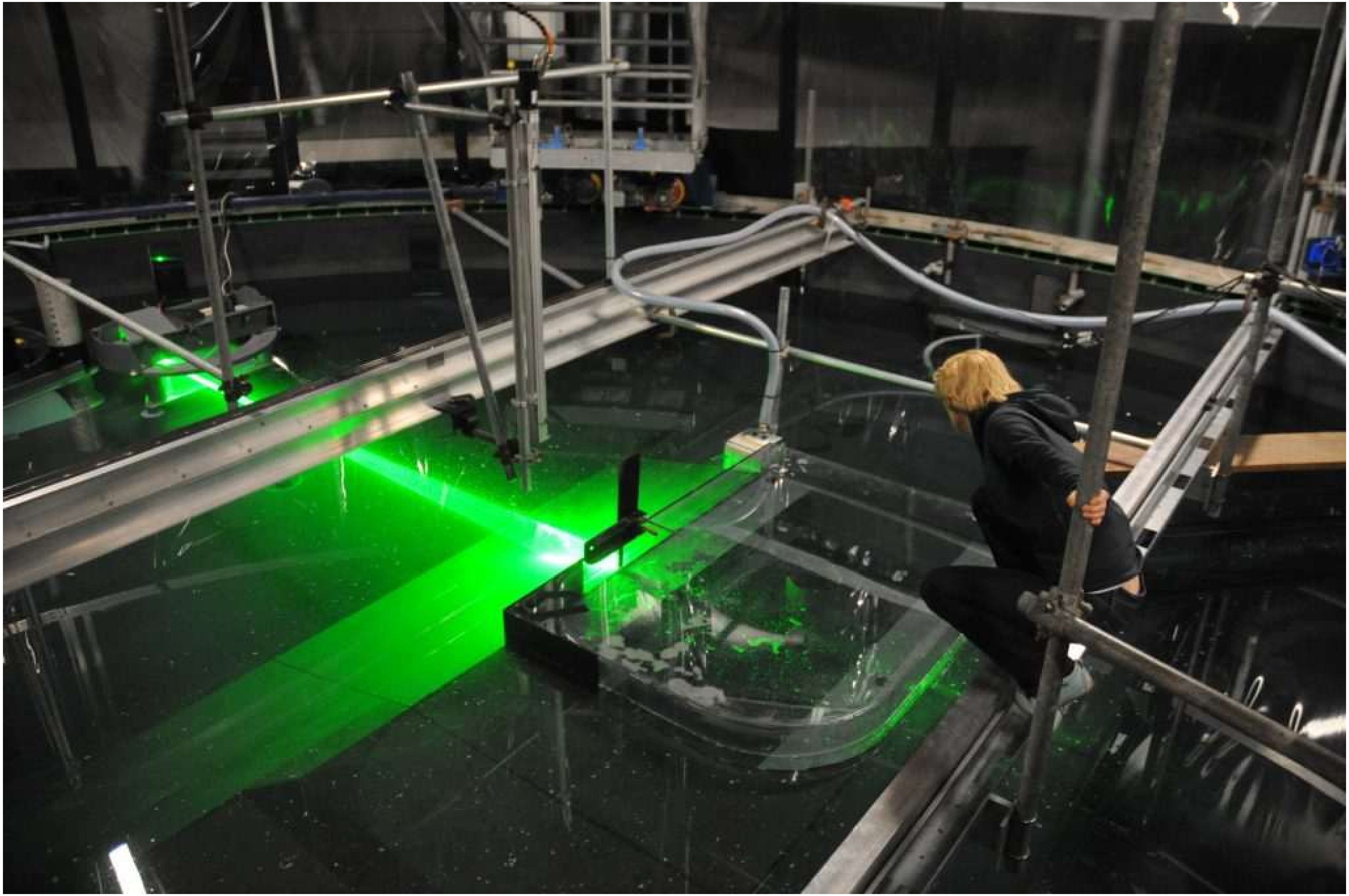


Wind-tunnel



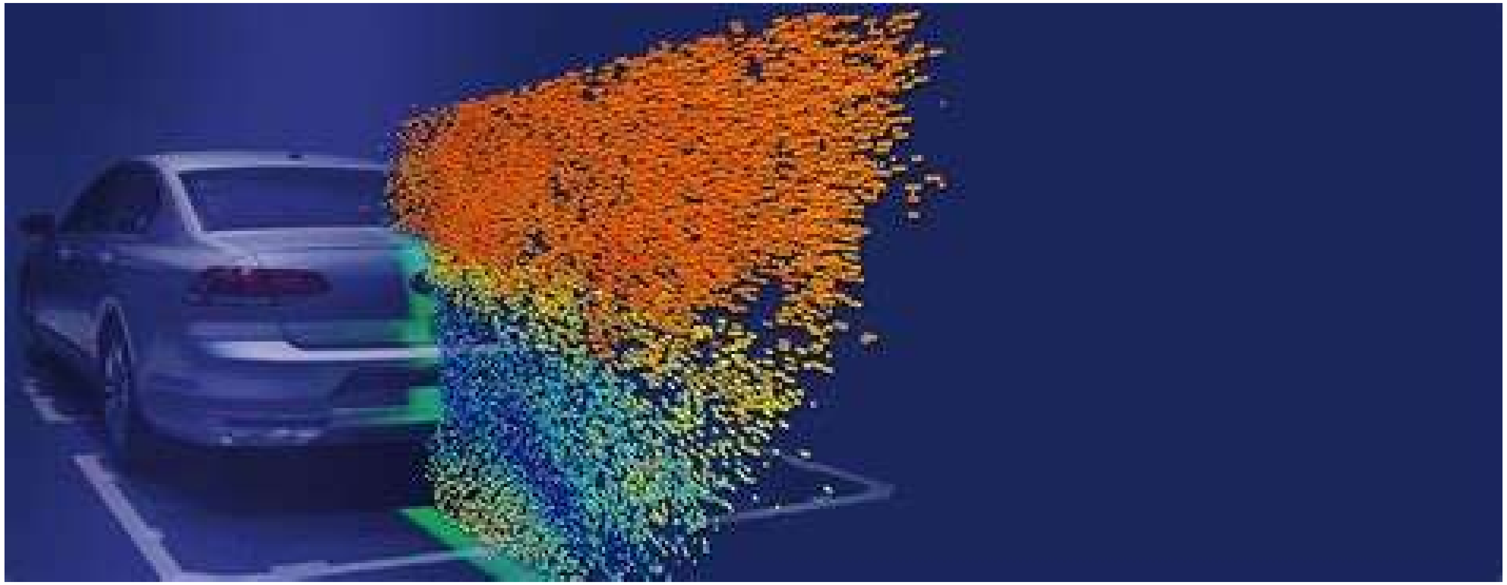
Water channel

Particles Image Velocimetry: example

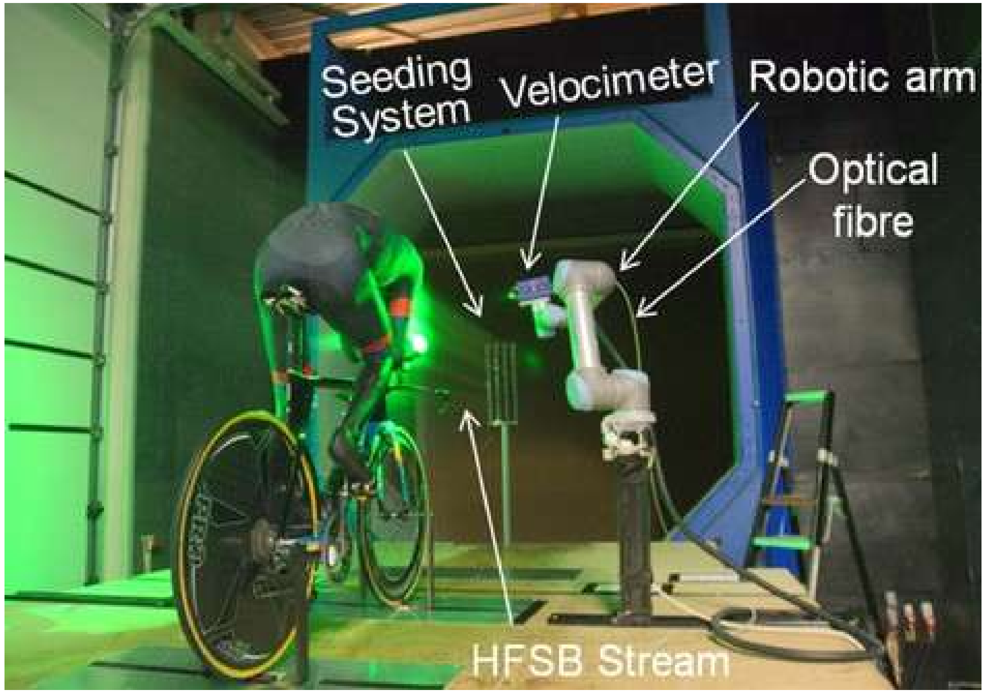


Coriolis platform

Particles Image Velocimetry: example

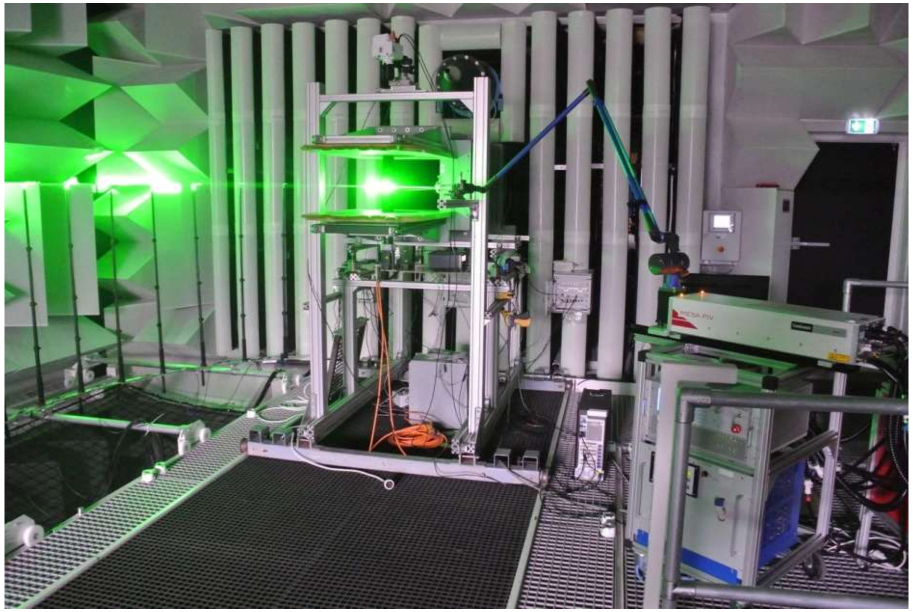


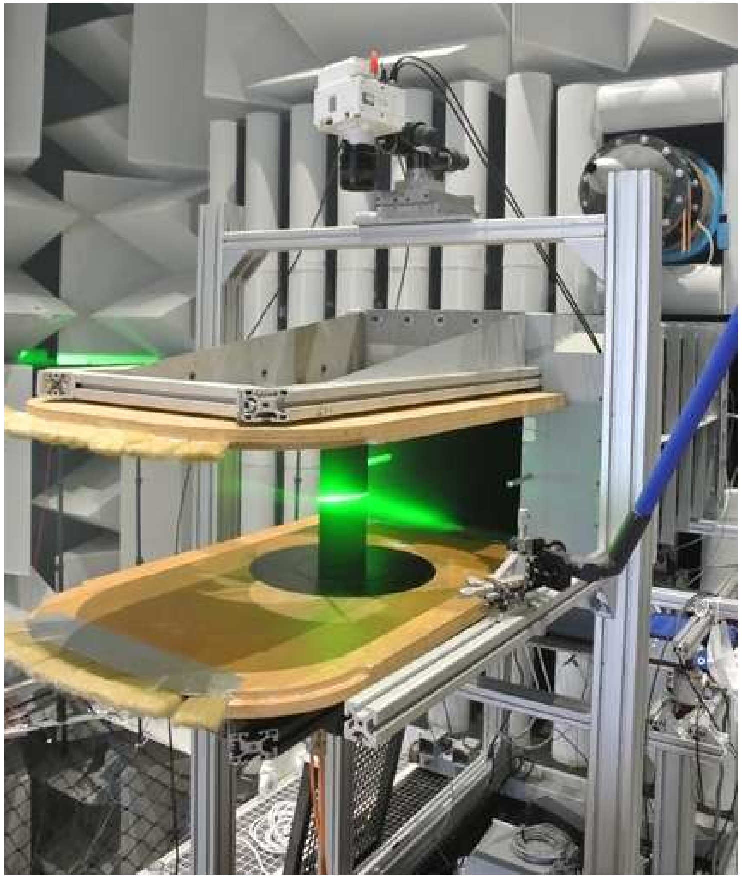
Lavision website

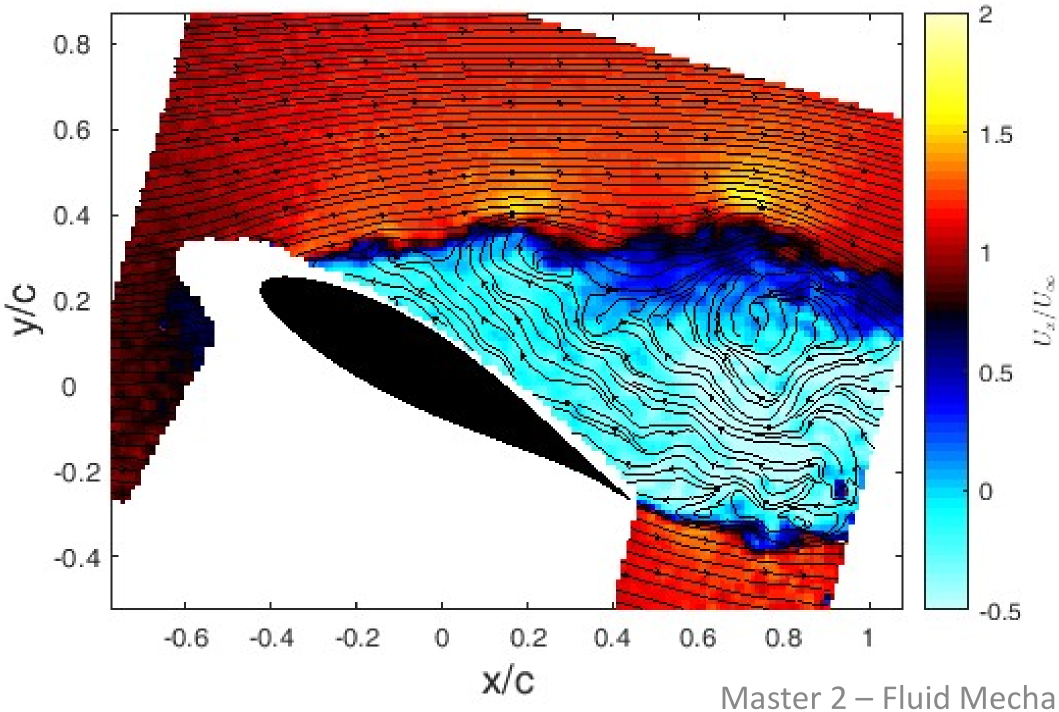


Sciacchitano et al. *Experiments in Fluids*, 2018

Particles Image Velocimetry: example





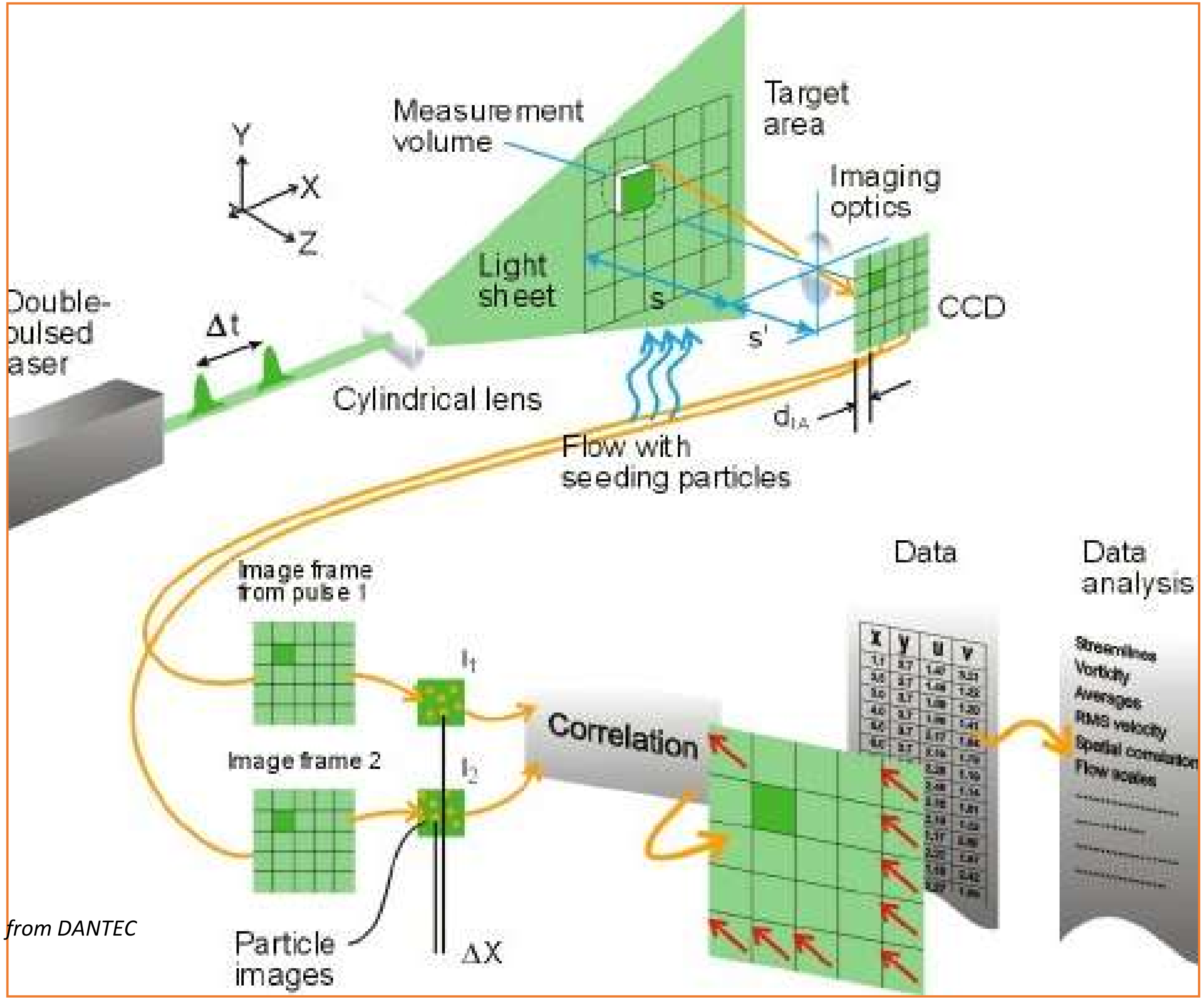


Airfoil in a wind-tunnel
Collaboration ENSTA-LMFA
PhD Lisa Sicard

PIV material:
- Seeding particles
- 1 light sheet
- 1 or 2 cameras
- 1 good computer

PIV input:
- Pair of images

PIV output:
- 2D velocity fields



from DANTEC

Particles Image Velocimetry: outlines

1. Introduction

2. Equipment:

- Tracers
- Light sheet
- Cameras
- Synchronisation

3. Software and algorithms:

- Correlation
- Advanced algorithms
- Bias
- Post-processing
- Analysis

4. A step forward

- Stereoscopic PIV
- 3D PIV
- Multiphysic PIV

Tracers

Reduced inertia:

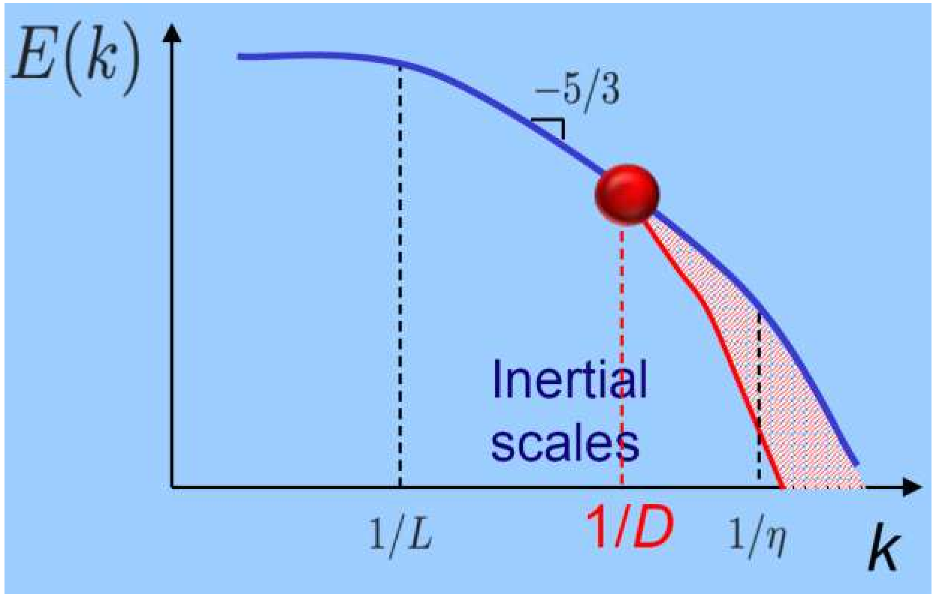
- Neutrally buoyant
- As small as possible

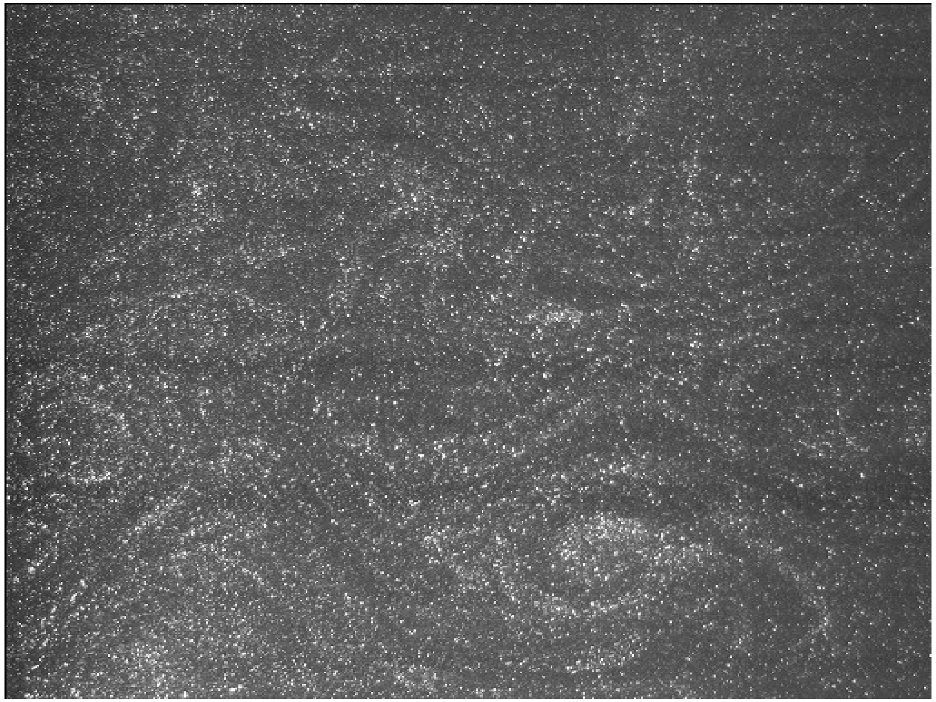
High visibility:

- Good light scatering
- Large enough

Spherical shape

Air vs water





Tracers

A PIV guy's cupboard:

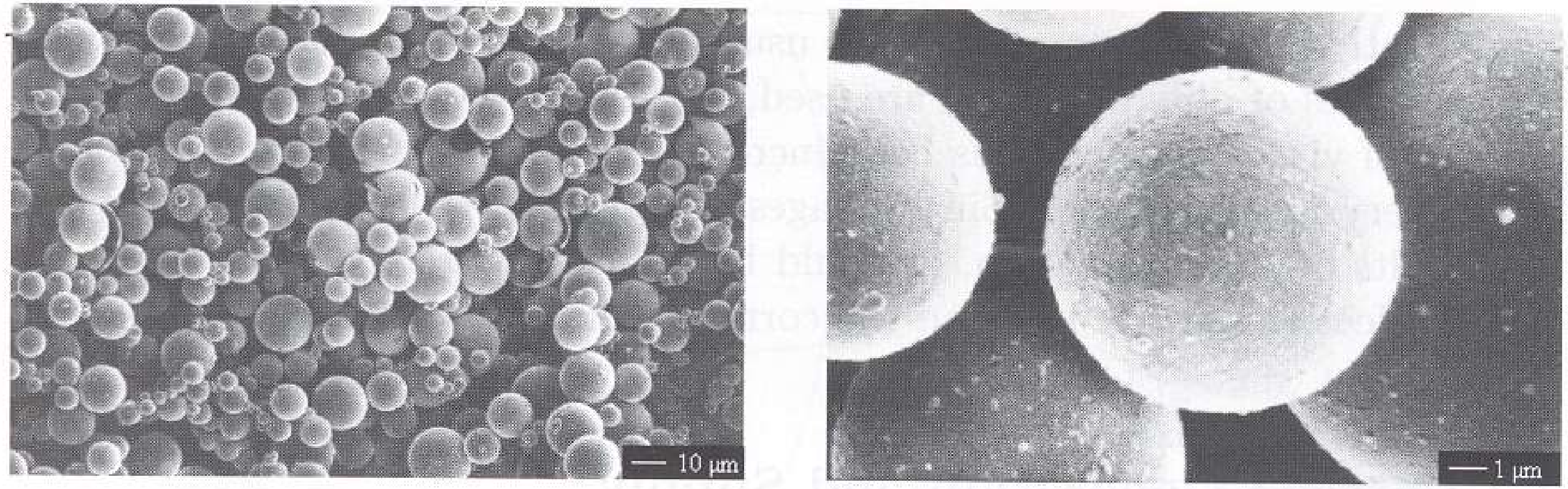


Fig. 2.8. Micrographs of silver coated hollow glass spheres: ×500 and ×5000.

Tracers

Aerosol generator

Helium-filled soap bubble generator

Tracers

Water seeding

	Diameter	Relative Density	Response time
Hollow glass spheres	10 µm	1.05	0.5 µs
Aluminium powder	3 µm	2.7	0.9 µs

Air seeding

	Diameter	Relative Density	Response time
Oil dropplets	1 µm	920	0.3 µs
SiO_2 beads	0.8 µm	2600	5 µs
Inflated bubbles	300 µm	1	0.3 µs

Tracers

Scatering patterns

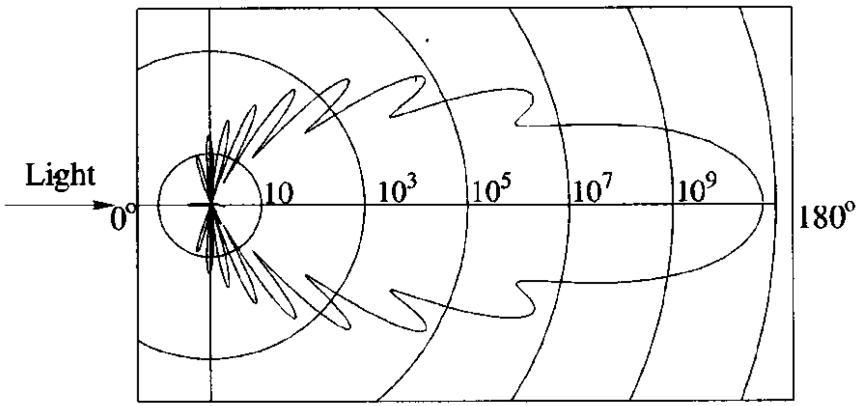


Fig. 2.5. Light scattering by a 1 μm glass particle in water.

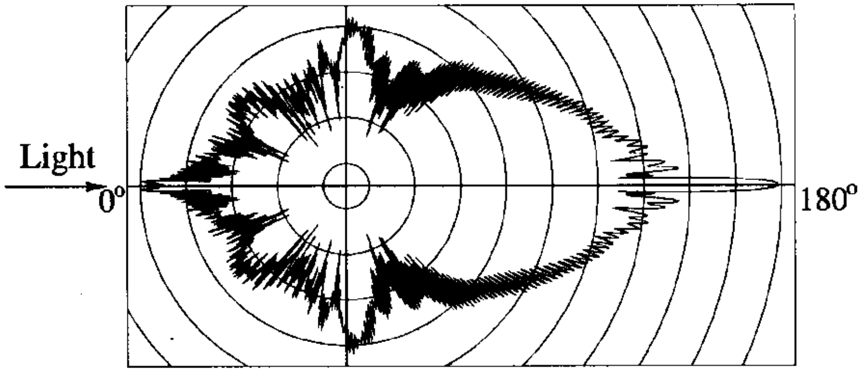


Fig. 2.6. Light scattering by a 10 μm glass particle in water.

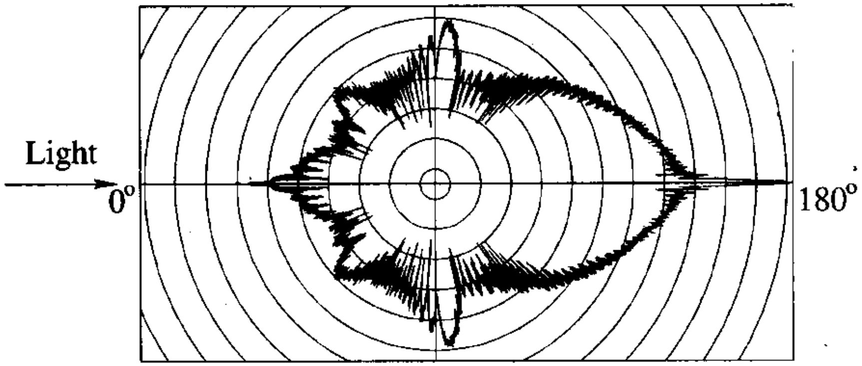


Fig. 2.7. Light scattering by a 30 μm glass particle in water.

Light source

Led panel
Typical power : 0.1 – 5 W (1-10 keuros)

Continuous Lasers
Typical power : 0.5 – 5 W (5-50 keuros)
(1 W correspond to 30 mJ per pulse at 30Hz)

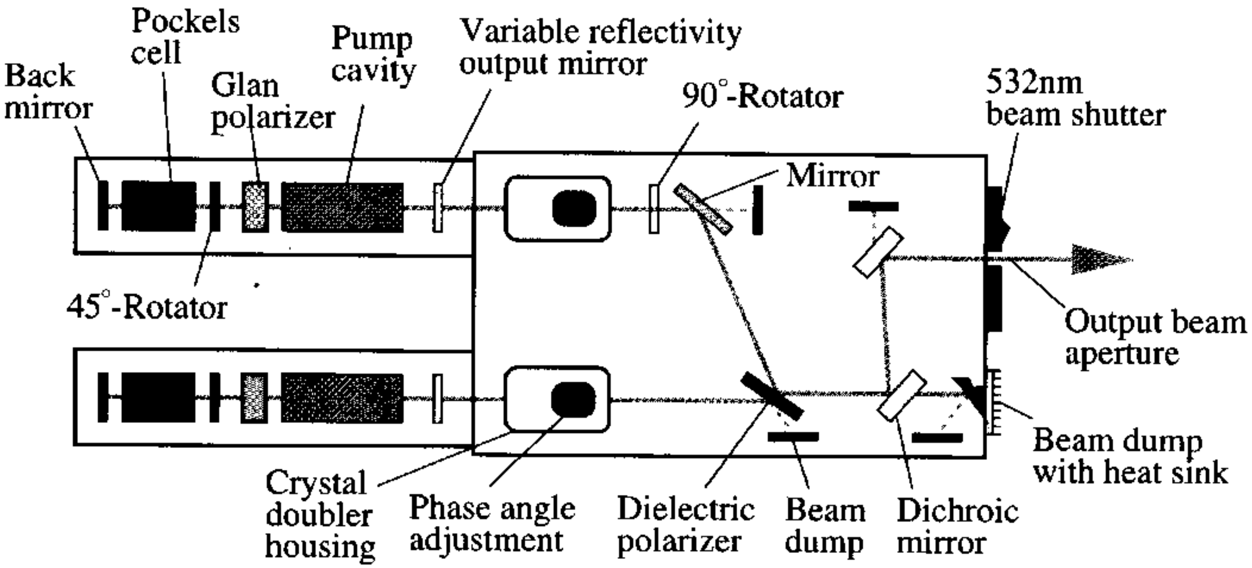
Pulsed Lasers
Pulse duration: 10 – 100 ns
Energy per pulse :
- in water : 10 – 100 mJ (20-30 keuros)
- in air : 50 – 500 mJ (80-100 keuros)

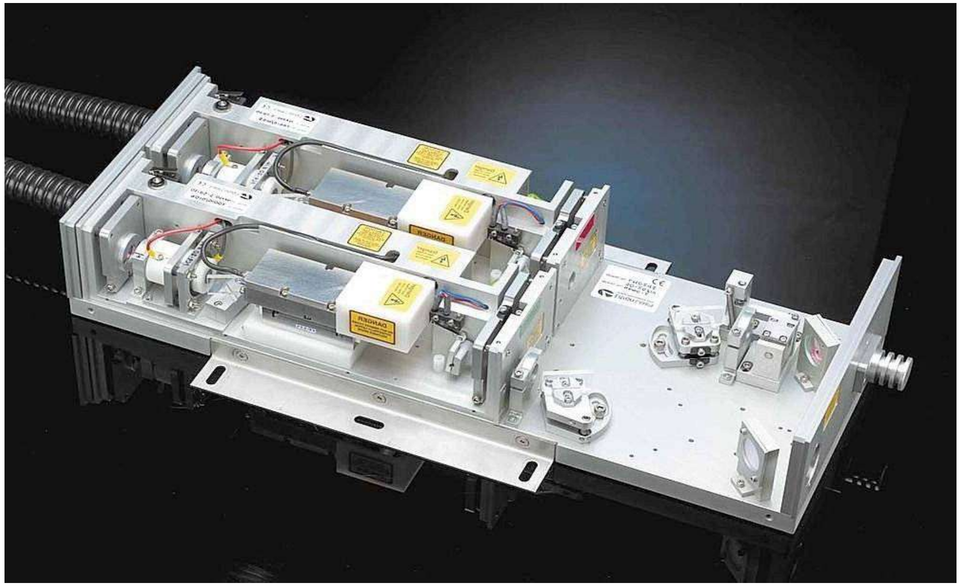
Rate:
- Lower range (10-30 Hz)
- Higher range (1-10 kHz)

MINILITE™ PIV SPECIFICATIONS

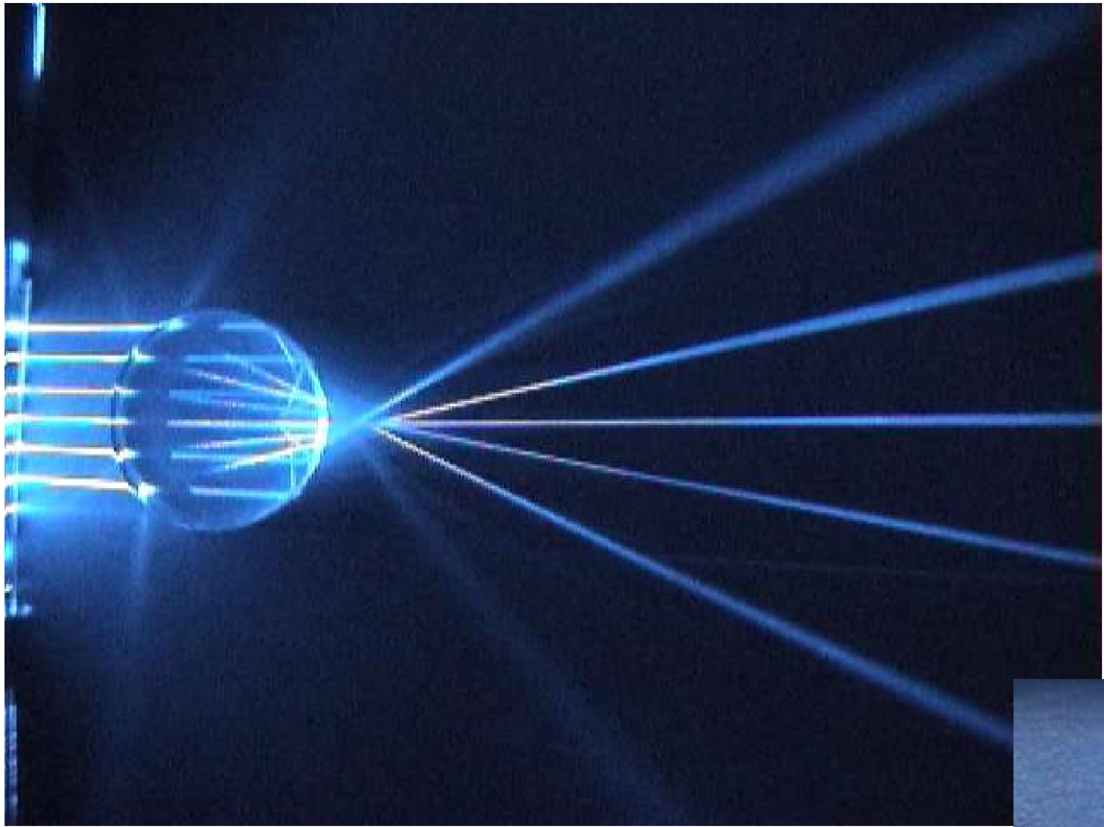
DESCRIPTION	MINILITE™ PIV
Repetition Rate (Hz)	1-15
Energy (mJ)	
1064 nm	50
532 nm	25
Pulsewidth[1] (nsec)	
1064 nm	4-6
532 nm	3-5
Divergence [2] (mrad)	< 3
Jitter [3] (±ns)	0.5
Energy Stability [4] (±%)	
1064 nm	2; 0.7
532 nm	3; 1.0
Beam Spatial Profile (fit to Gaussian) [5]	
Near Field (<1 M)	0.70
Far Field (∞)	0.95

Double cavity pulsed Laser

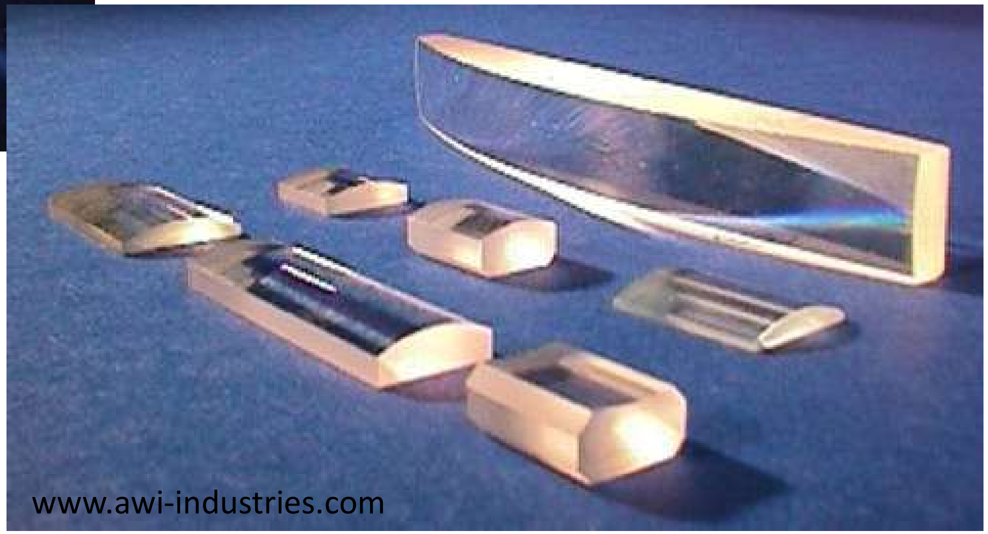




Light source

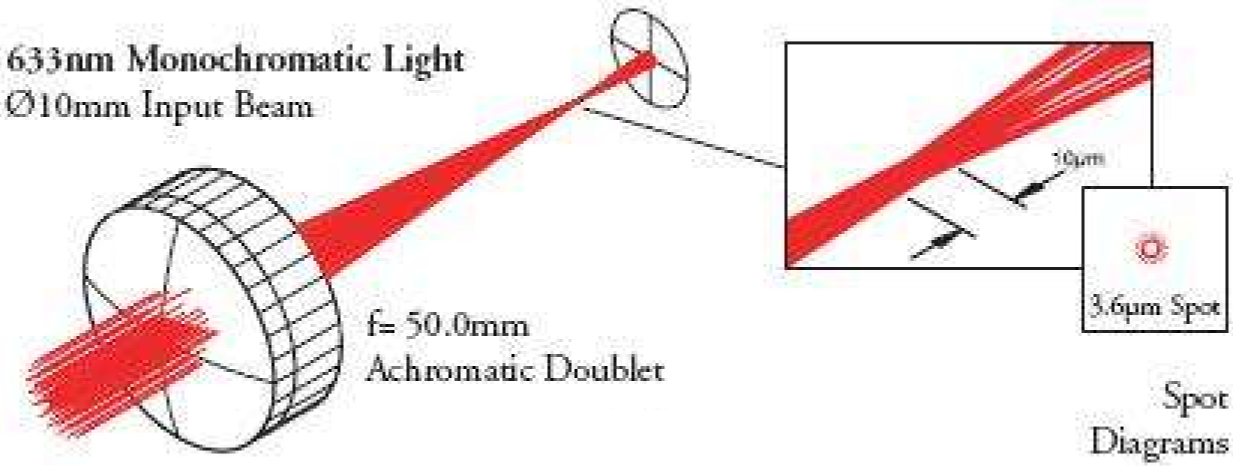


Refraction from a cylindrical lense



Light source

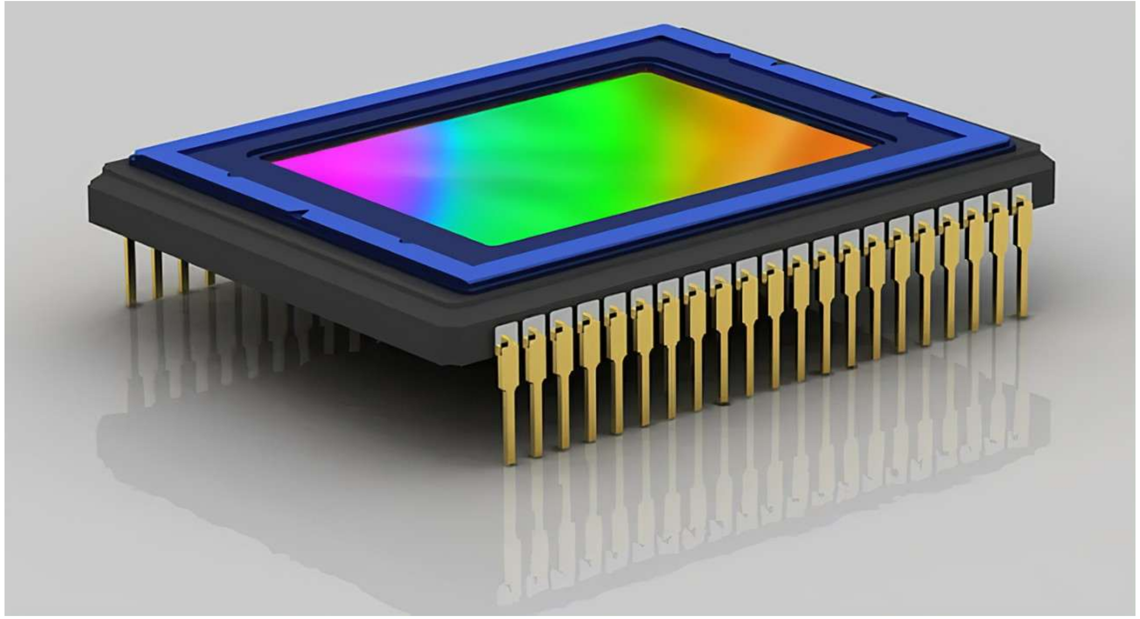
Thickness setting

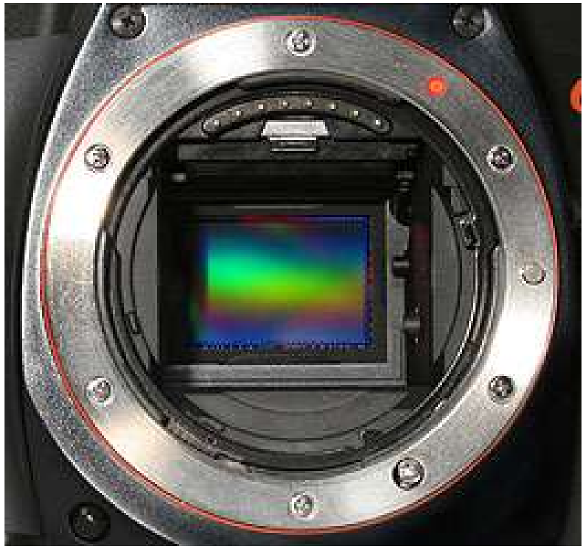


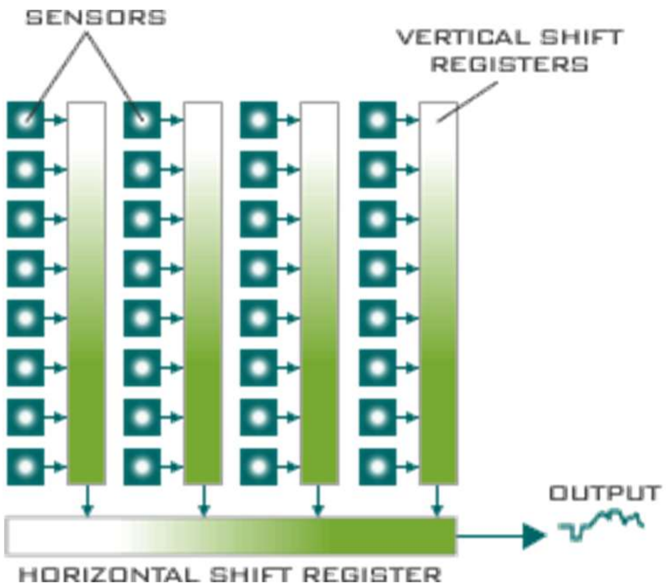

Dantec


Oxford laser

Cameras







Resolutions :
1000 x 1000 to 5000 x 4000

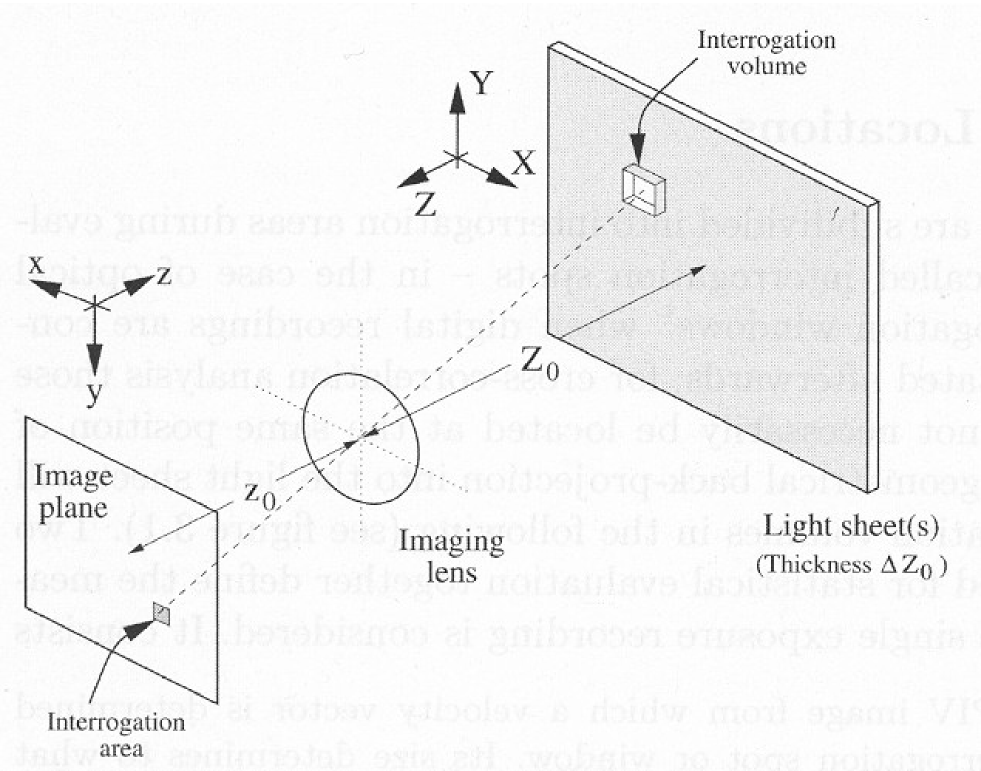
Cameras

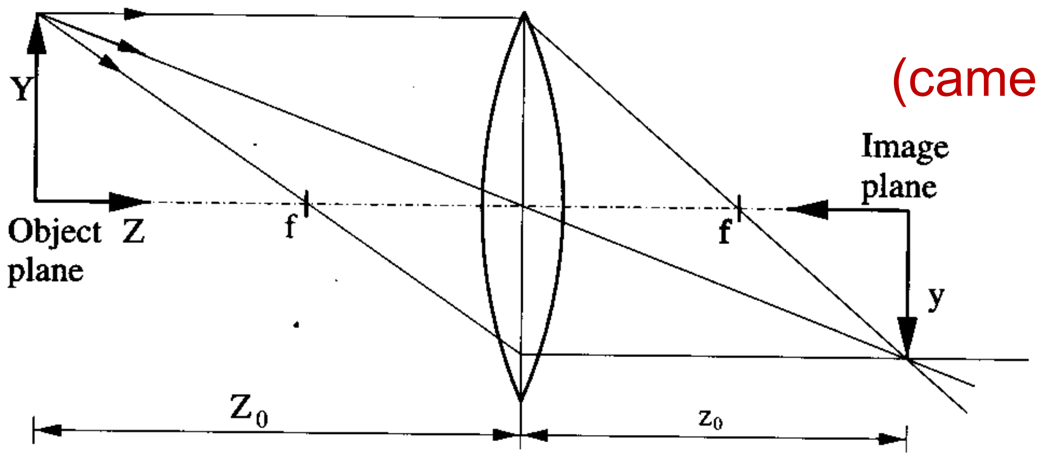
	Standard cameras	Double-frame cameras	Fast cameras (internal RAM or RAID)
Sensor	CCD 10 – 12 bits (1024 à 4096 n.g.)	CCD 12 – 14 bits (4096 à 16384 n.g.)	CMOS 12 or 16 bits sCMOS
Resolution	1000^2 2000^2 20 - 100 Hz	1000^2 2000^2 2x4 à 2x30 Hz	1000^2 2000^2 0.5 à 10 kHz
Price	0.5-1 k€	5 – 20 k€	60-180 k€

Cameras

Welcome to the photography world !

Images





(camera)

Magnification:

$M = y / Y$

= image/object (< 1)

Images

Projection error

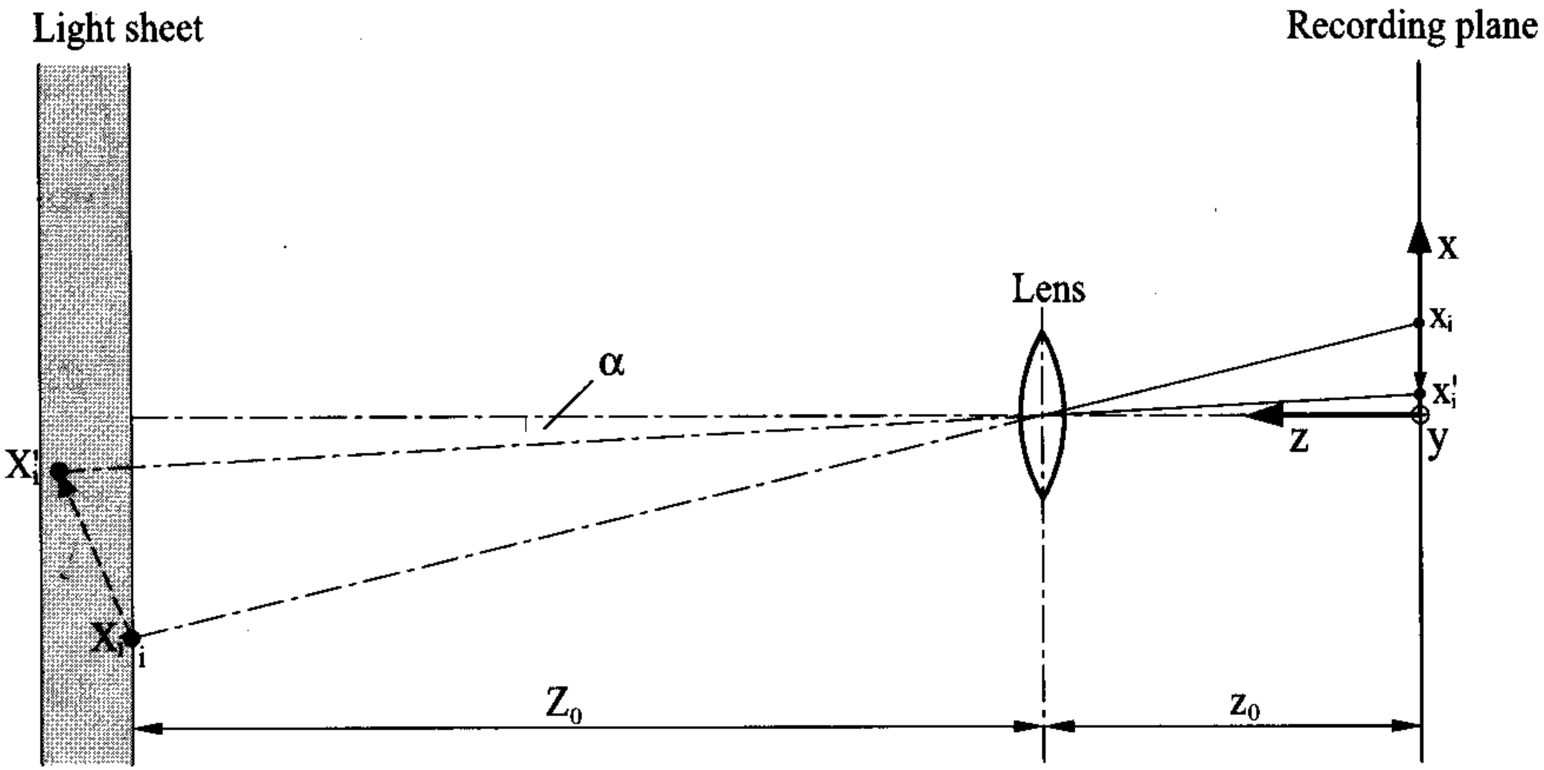
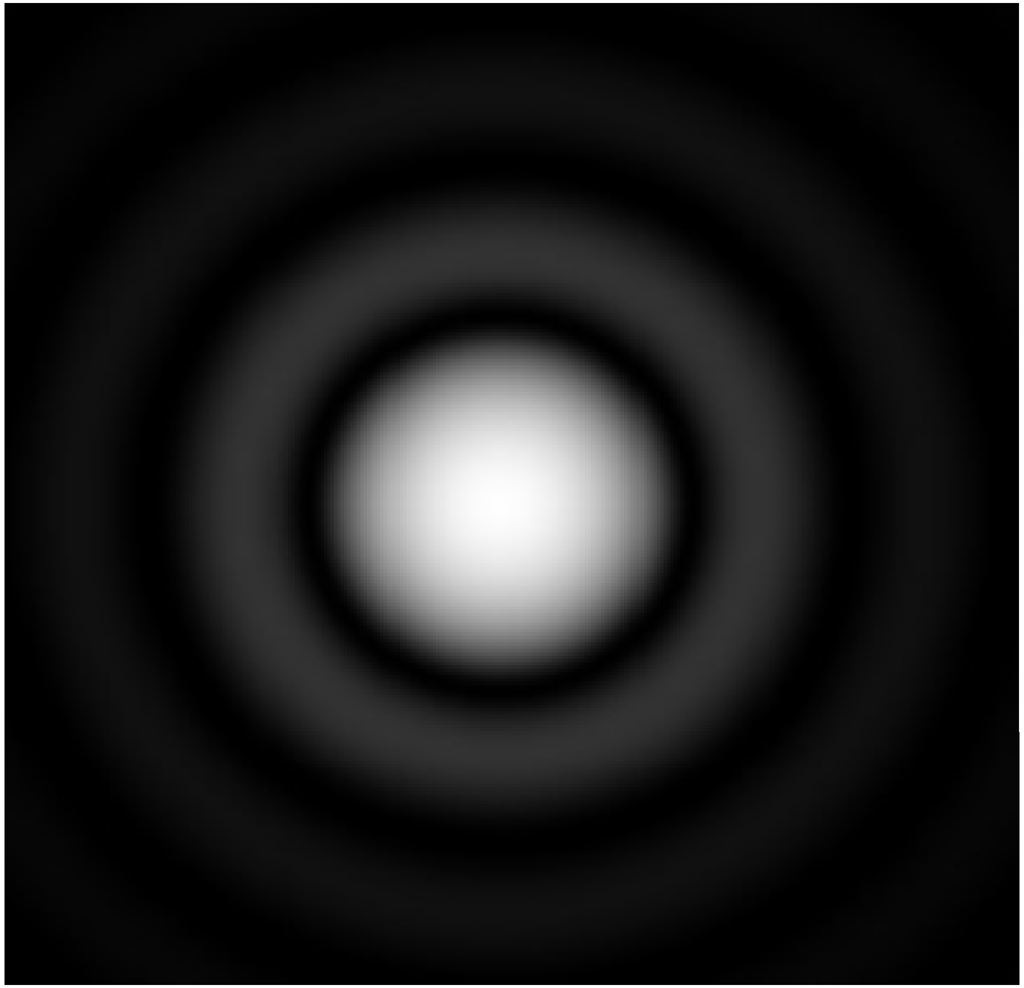
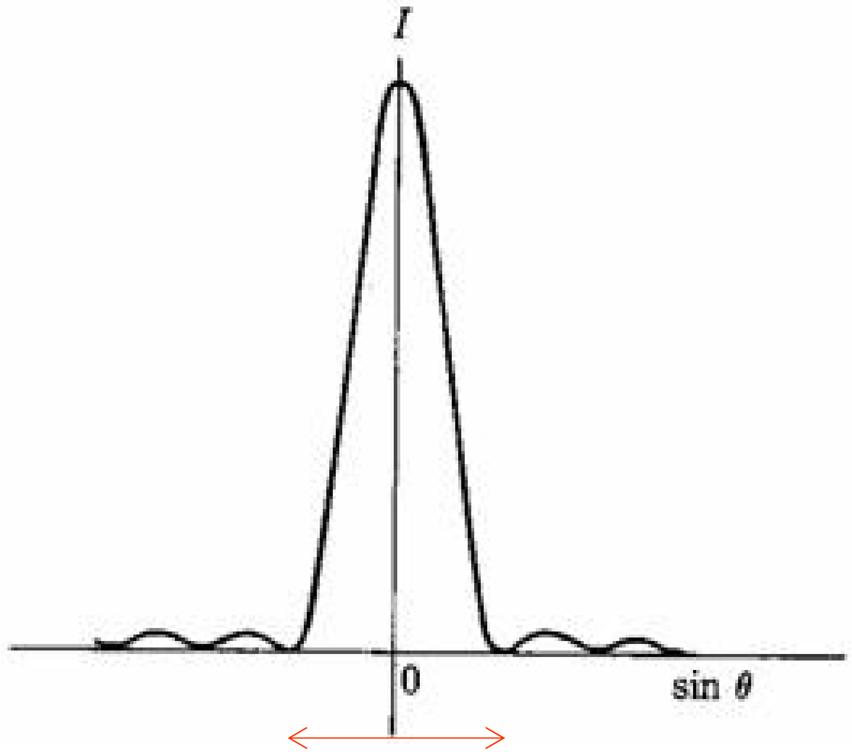


Fig. 2.37. Imaging of a particle within the light sheet on the recording plane.

Images

Diffraction limit: Airy disc





2.44 λ/D

λ:light wave length
D: camera aperture

→ Limit the separation power

Images: field of view and field depth

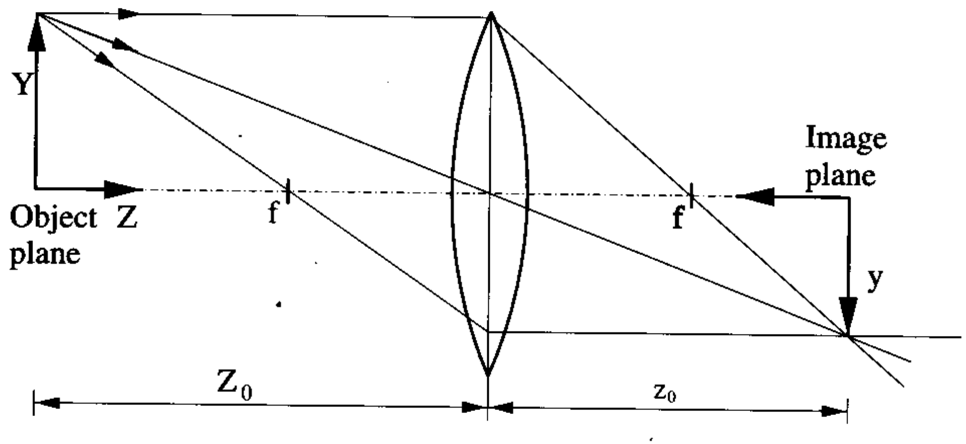
Aperture = f/1.4. DOF=0.8 cm

Aperture = f/4.0. DOF=2.2 cm

Aperture = f/22. DOF=12.4 cm

Calibration target

Matching real world coordinates and picture coordinates

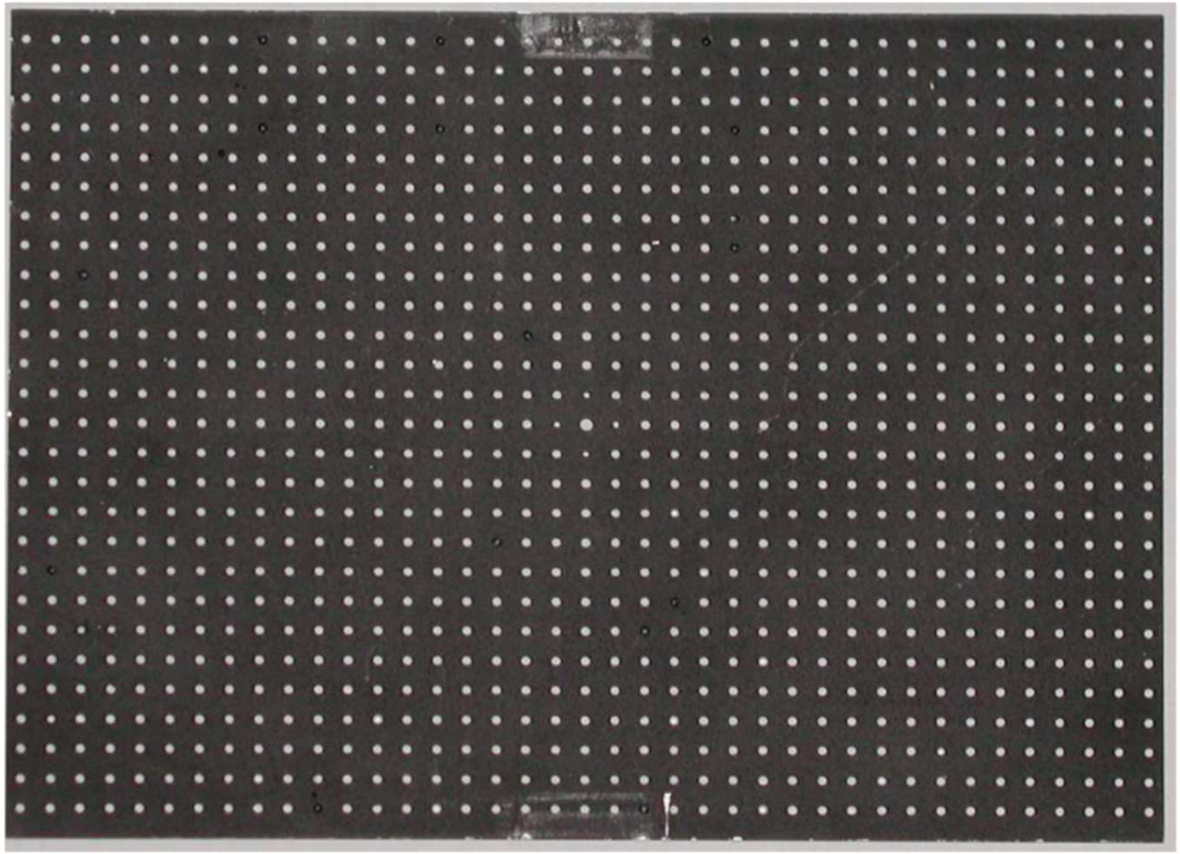


Scale factor

Image distorsion

Calibration target

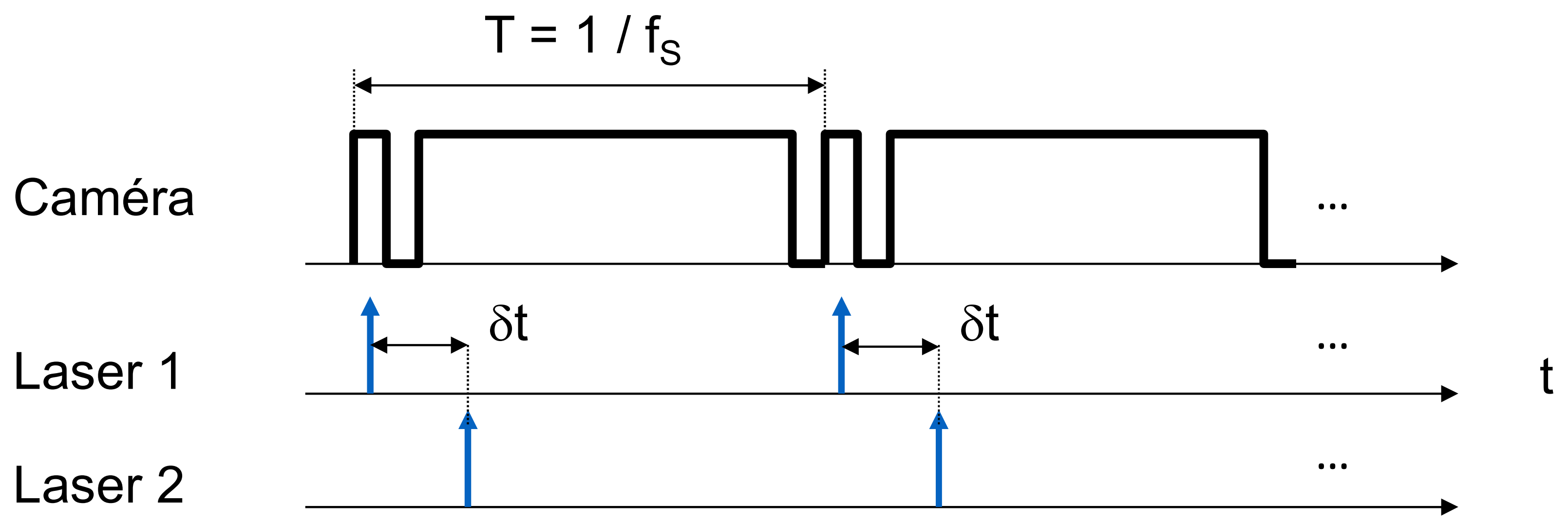
Matching real world coordinates and picture coordinates



Different mappings:

- Physical
- Linear
- Non linear

Synchronisation



Standard PIV time-line

δt: time between pulses
T: time between velocity fields

Commercial Softwares

Acquisition system + image processing

Free Softwares

Acquisition system + image processing

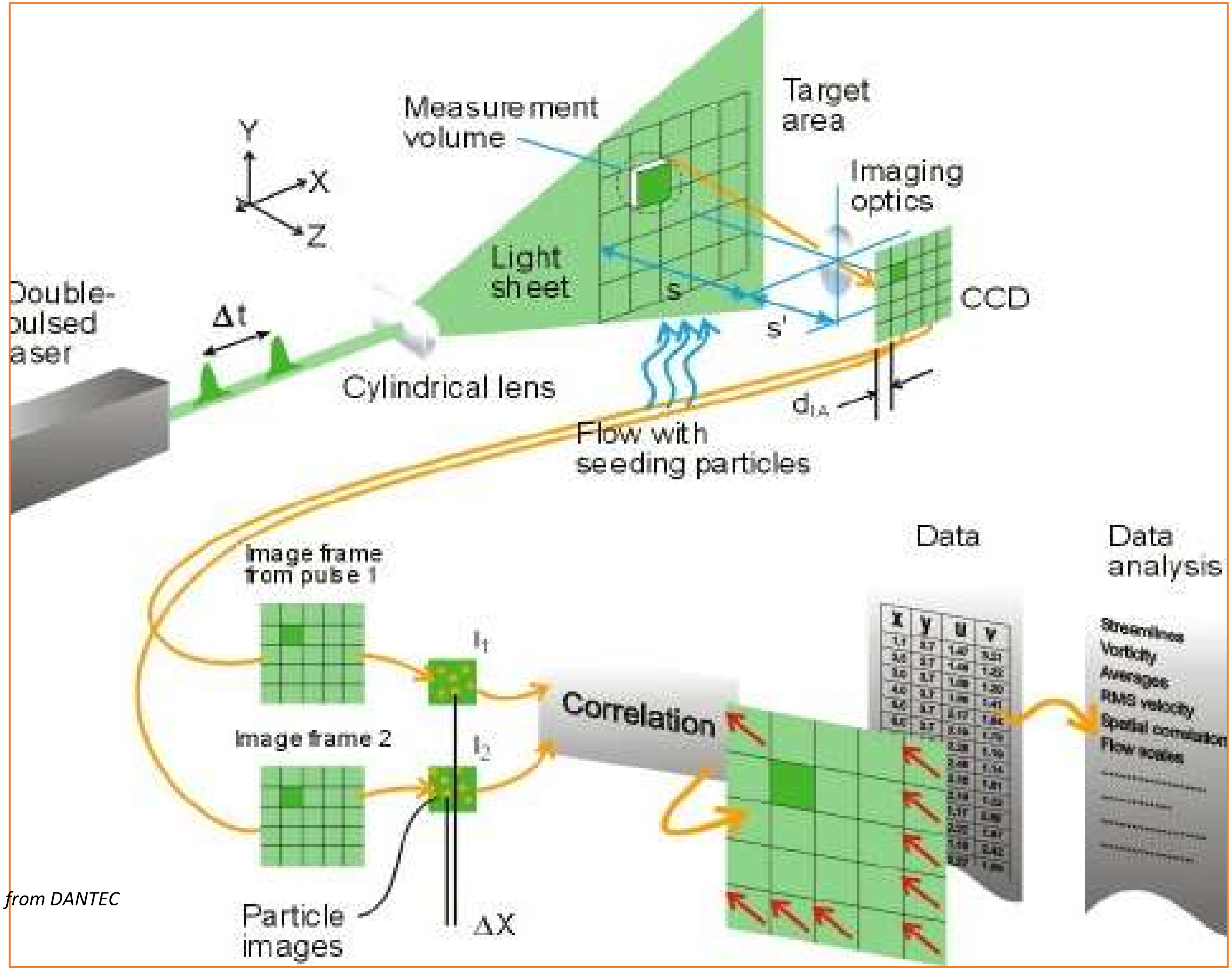
Image processing only

Other in-house acquisition system

Particles Image Velocimetry: outlines

1. Introduction
2. Equipment:
   - Tracers
   - Light sheet
   - Cameras
   - Synchronisation
3. **Software and algorithms:**
   - **Correlation**
   - **Advanced algortithms**
   - **Bias**
   - **Post-processing**
   - **Analysis**
4. A step forward
   - Stereoscopic PIV
   - 3D PIV
   - Multiphysic PIV

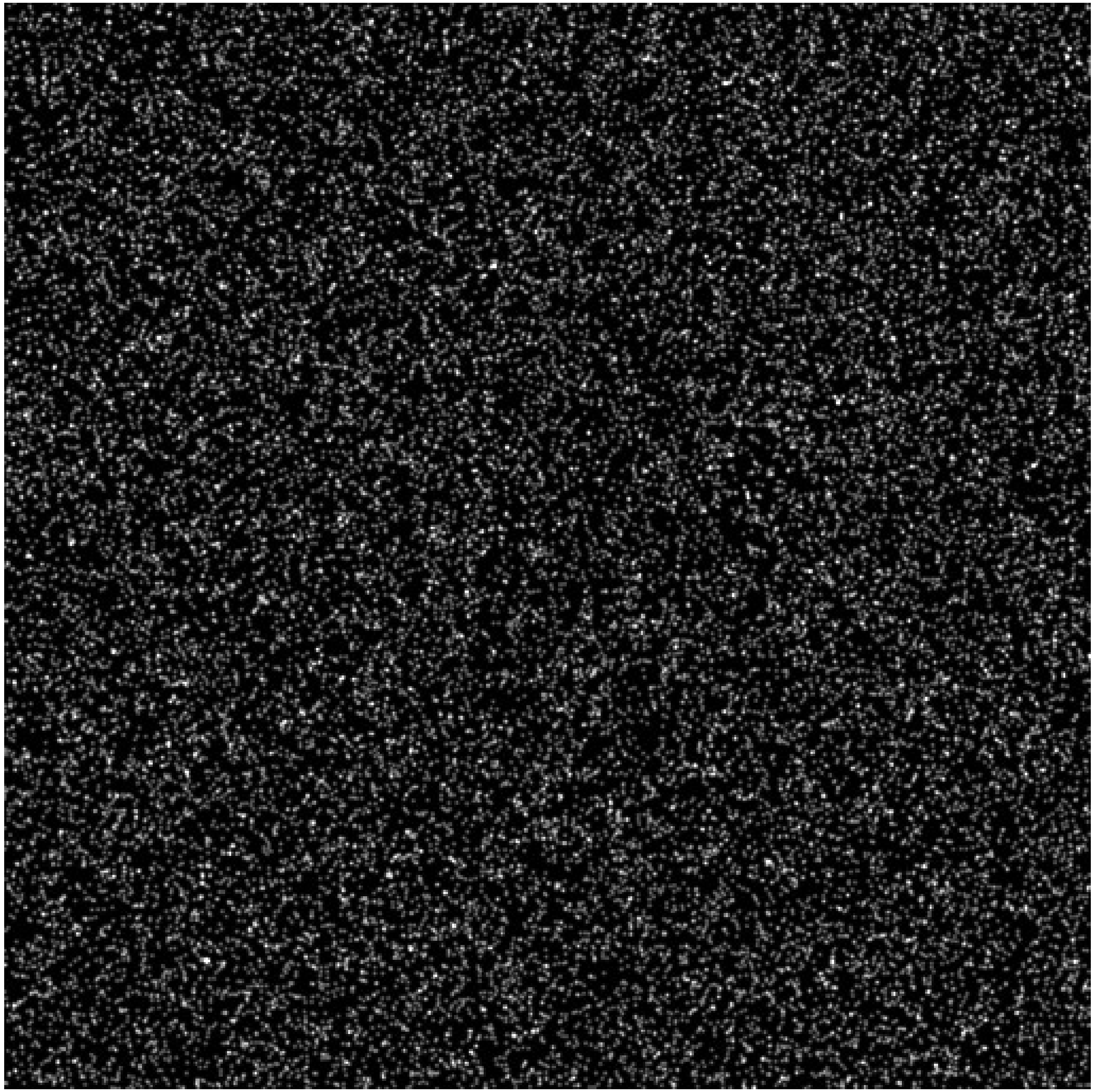
Particles Image Velocimetry: principles



from DANTEC

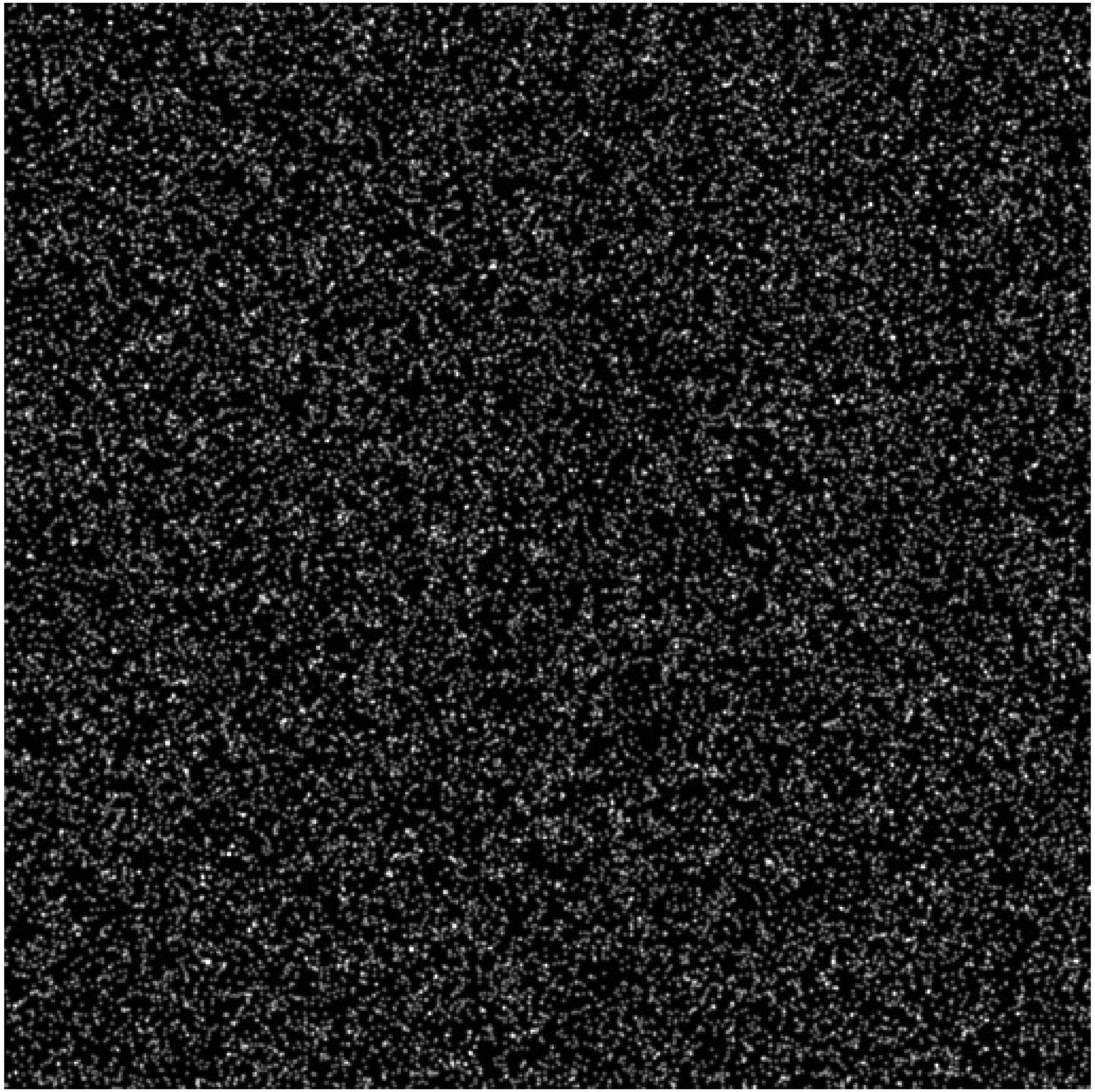
Particles Image Velocimetry: correlation

Image t=0



Particles Image Velocimetry: correlation

Image t=dt

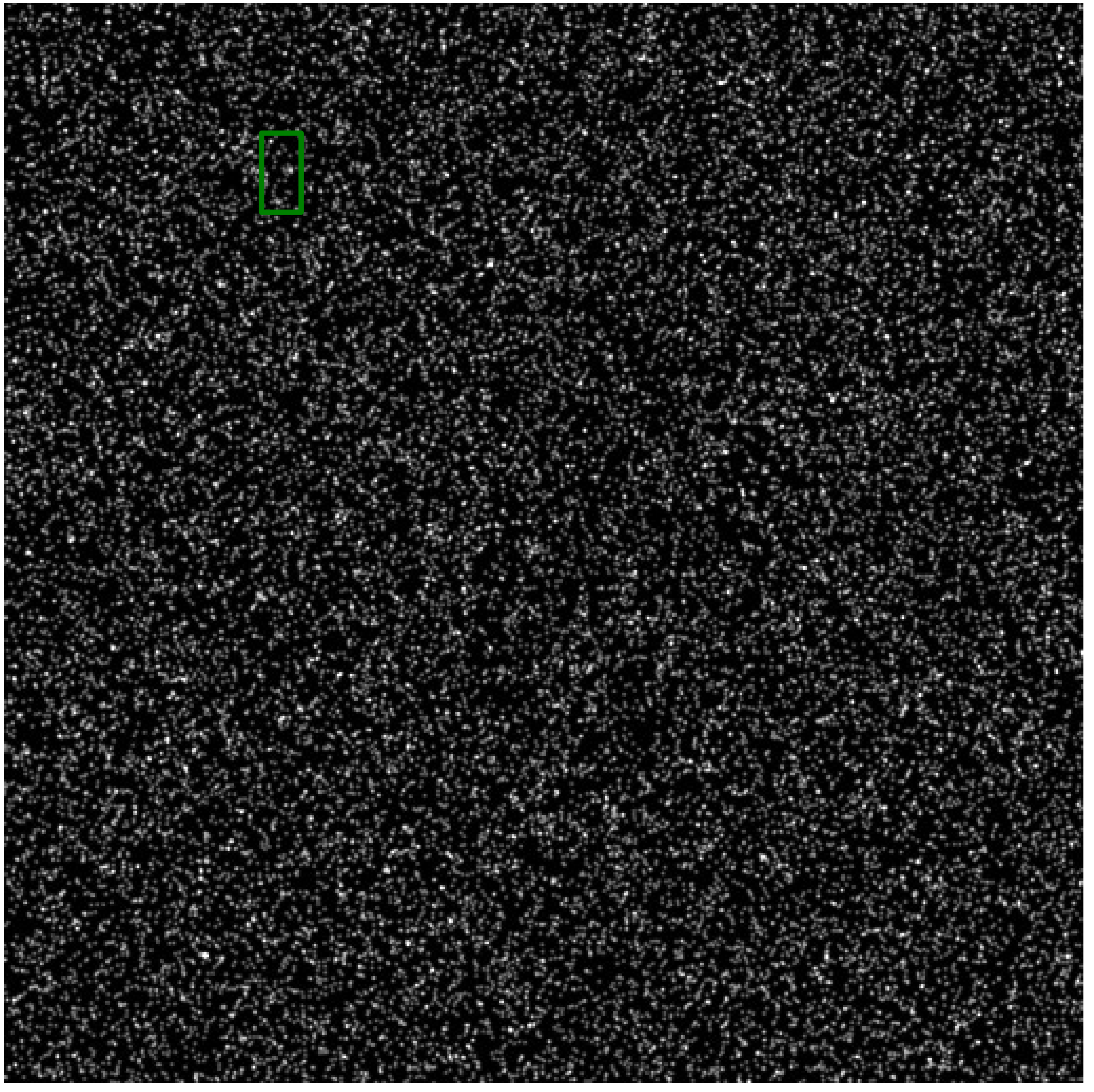


Particles Image Velocimetry: correlation

Image t=0

Particle pattern

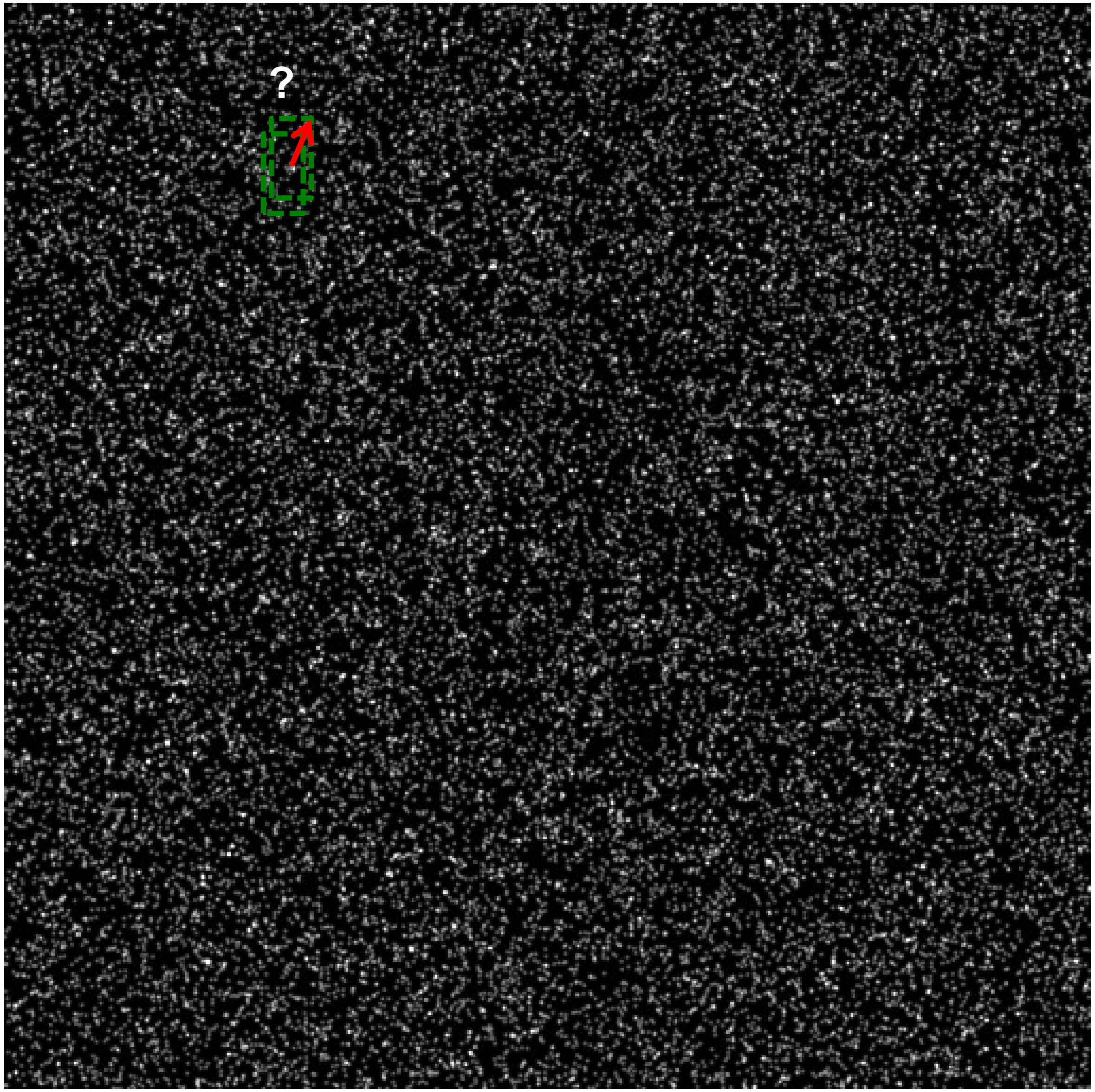
Interrogation Window



Particles Image Velocimetry: correlation

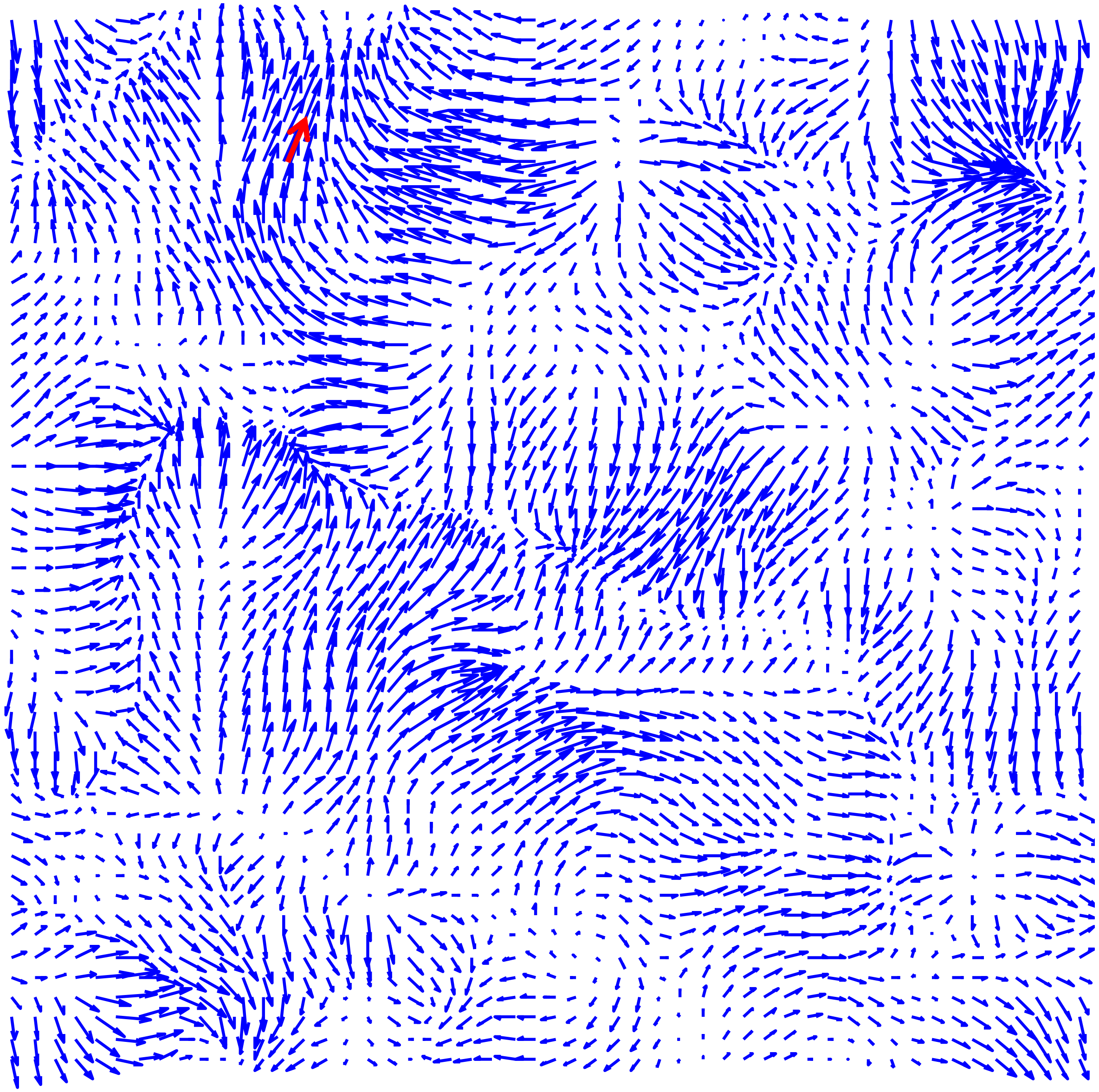
Image t=dt

Image cross-correlation



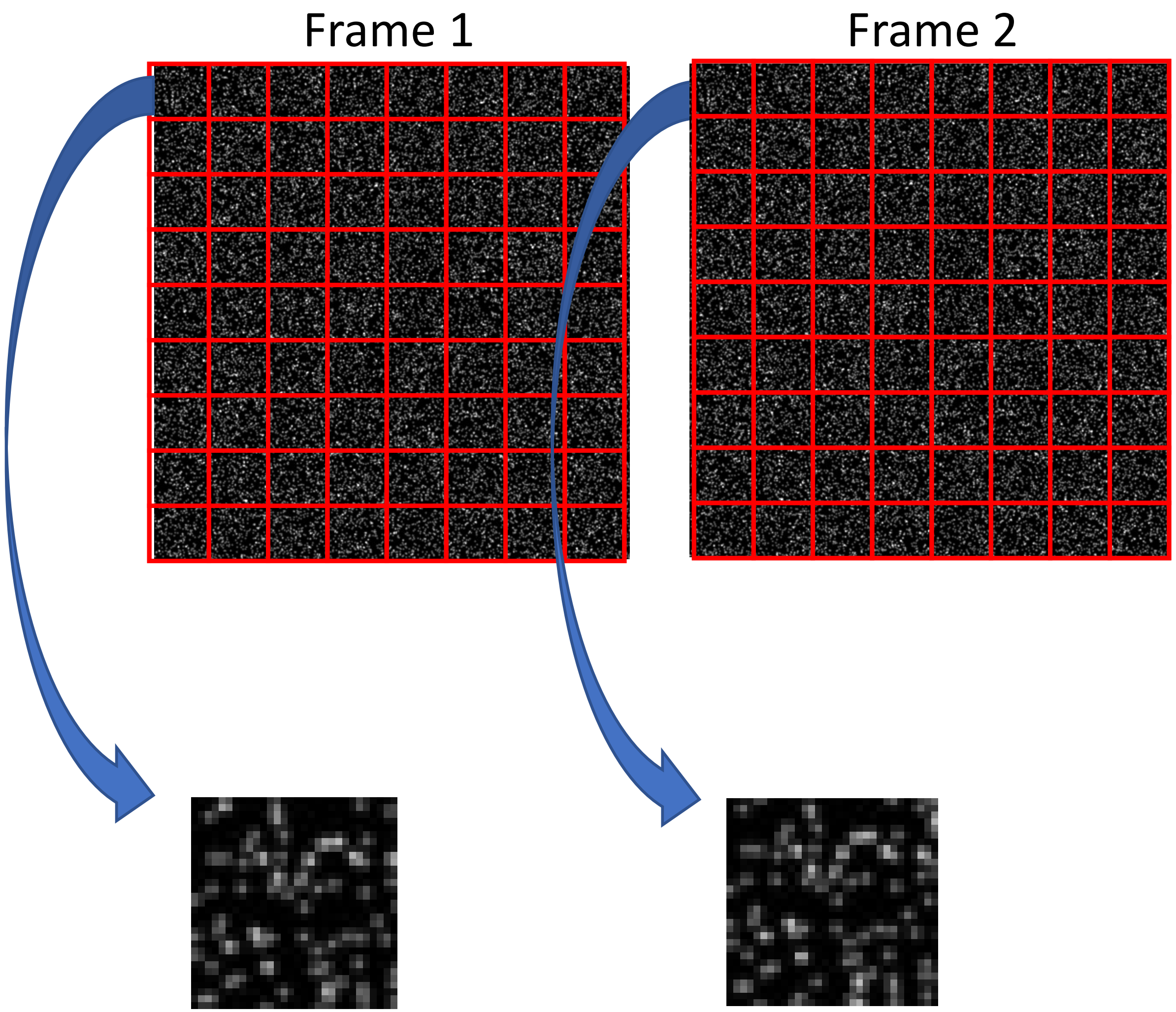
Particles Image Velocimetry: correlation

2D velocity field



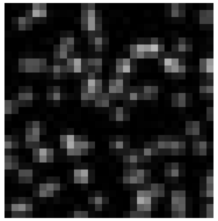
- High spatial resolution
- Time resolved

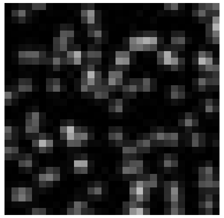
Particles Image Velocimetry: algorithms



$$C_{ff}(\Delta x, \Delta y) = \iint f(x,y) f(x - \Delta x, y - \Delta y) dx dy$$

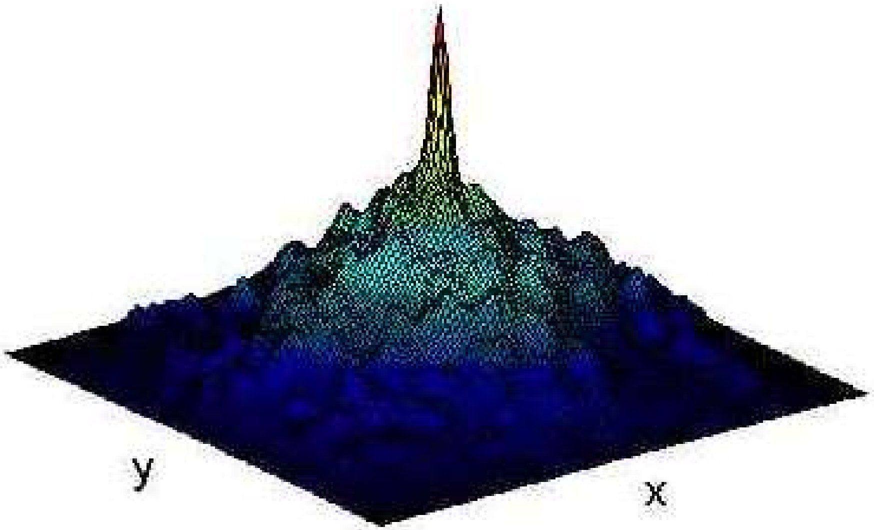
Particles Image Velocimetry: algorithms



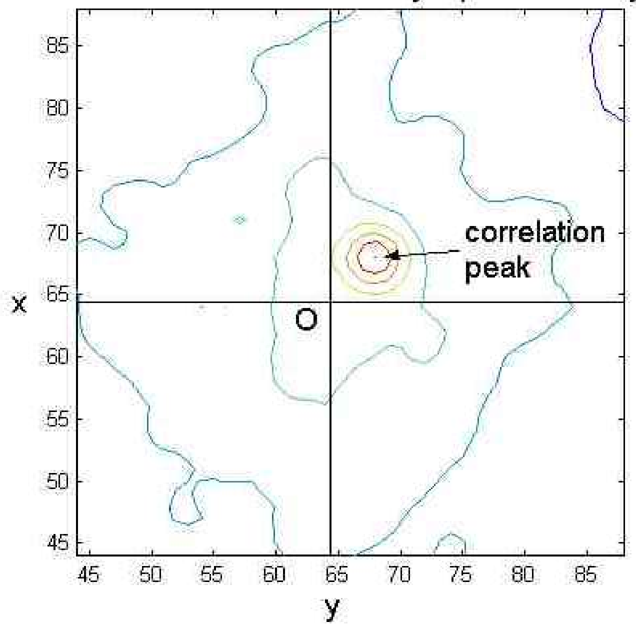


$$C_{ff}(\Delta x, \Delta y) = \iint f(x,y) f(x-\Delta x, y-\Delta y) dx dy$$

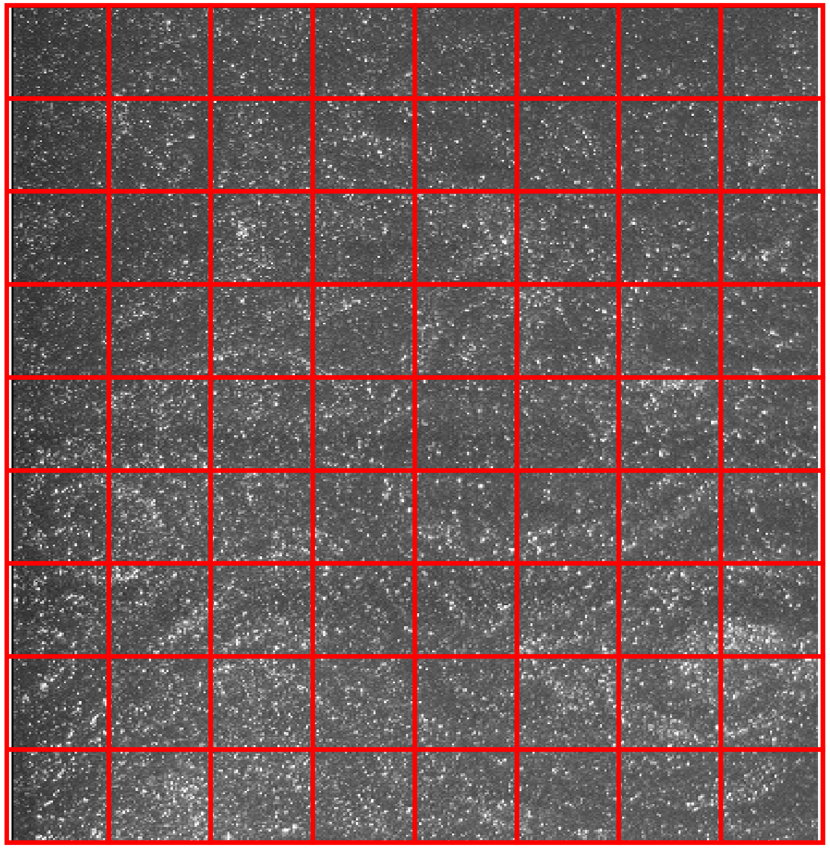
3D view of the correlation function



Correlation Peak Shifted by 4 pixels in x & y



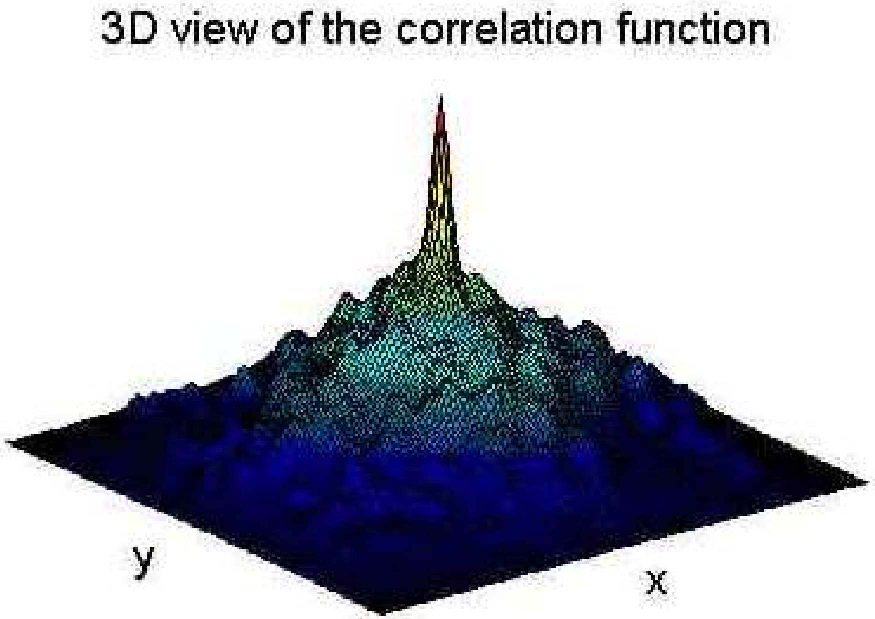
Basic correlation: resolution



Grid resolution

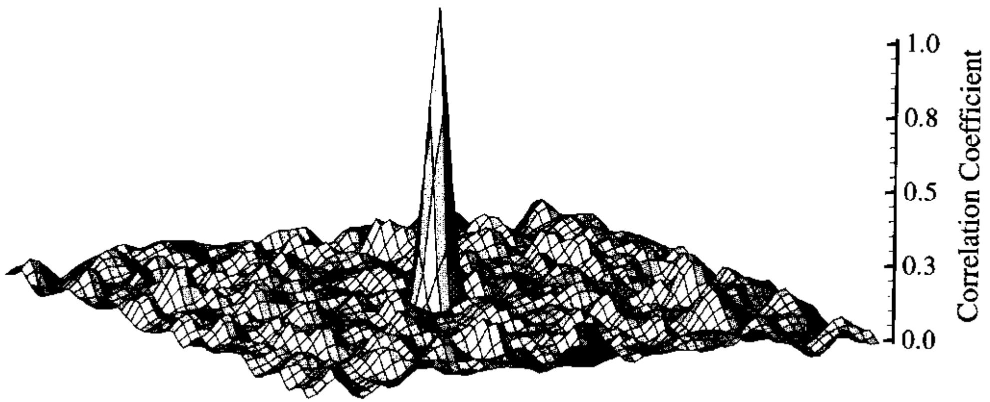
- PIV map on N_x x N_y boxes
- Typical box sizes : 16x16, 32x32, 64x64 pixel^2
- Typical pixel size: 0.1 mm to 1 mm
- Overlaping : typically 50%

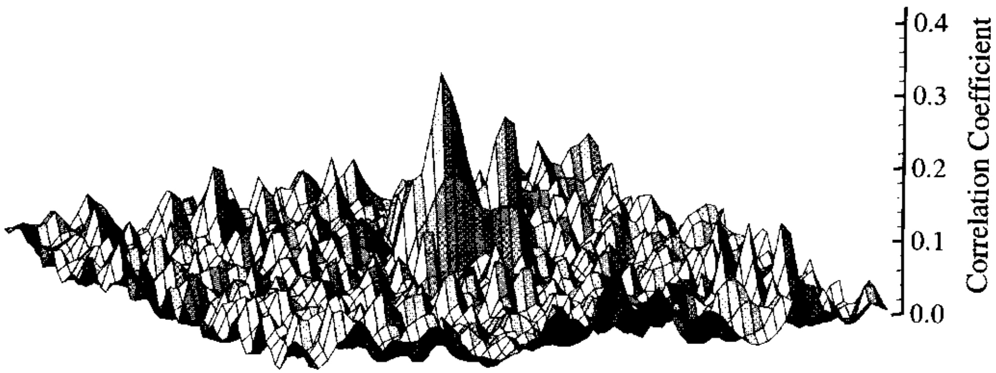
Resolution and error



Precision

- Peak location accuracy
- Peak detection quality
- Validation





Particle size on images

Actual particle size
Particle brigthness
Sensor pixel size
Focus

Pixel locking

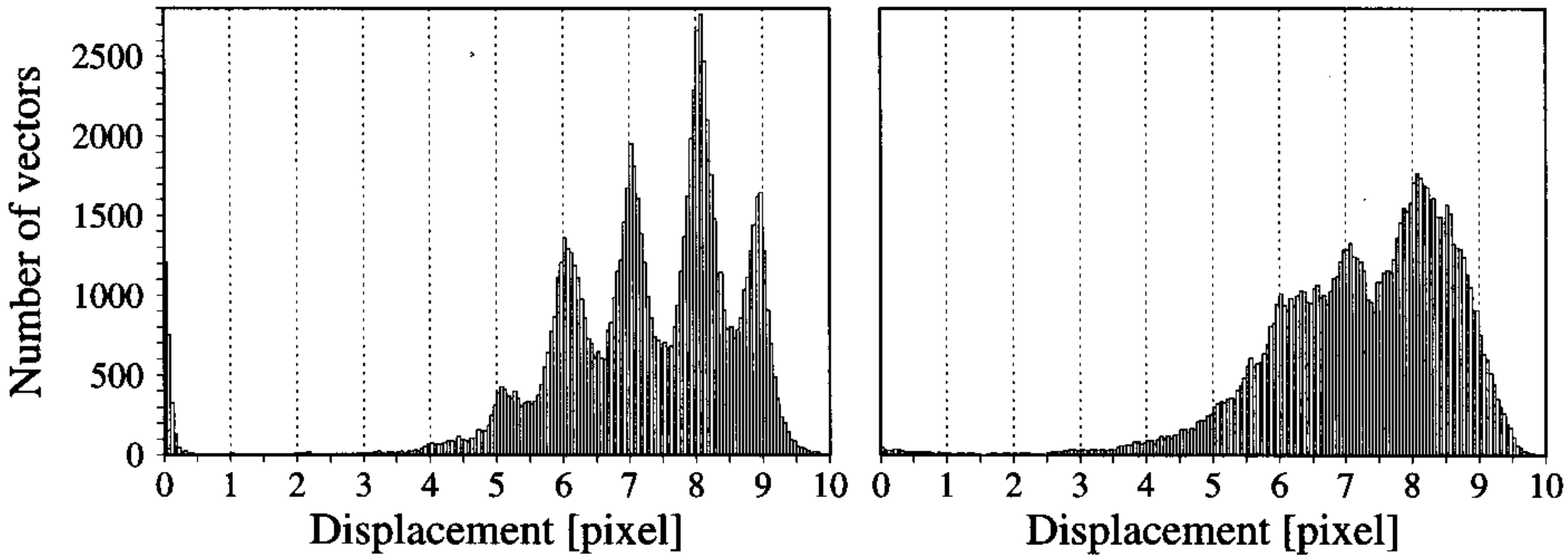
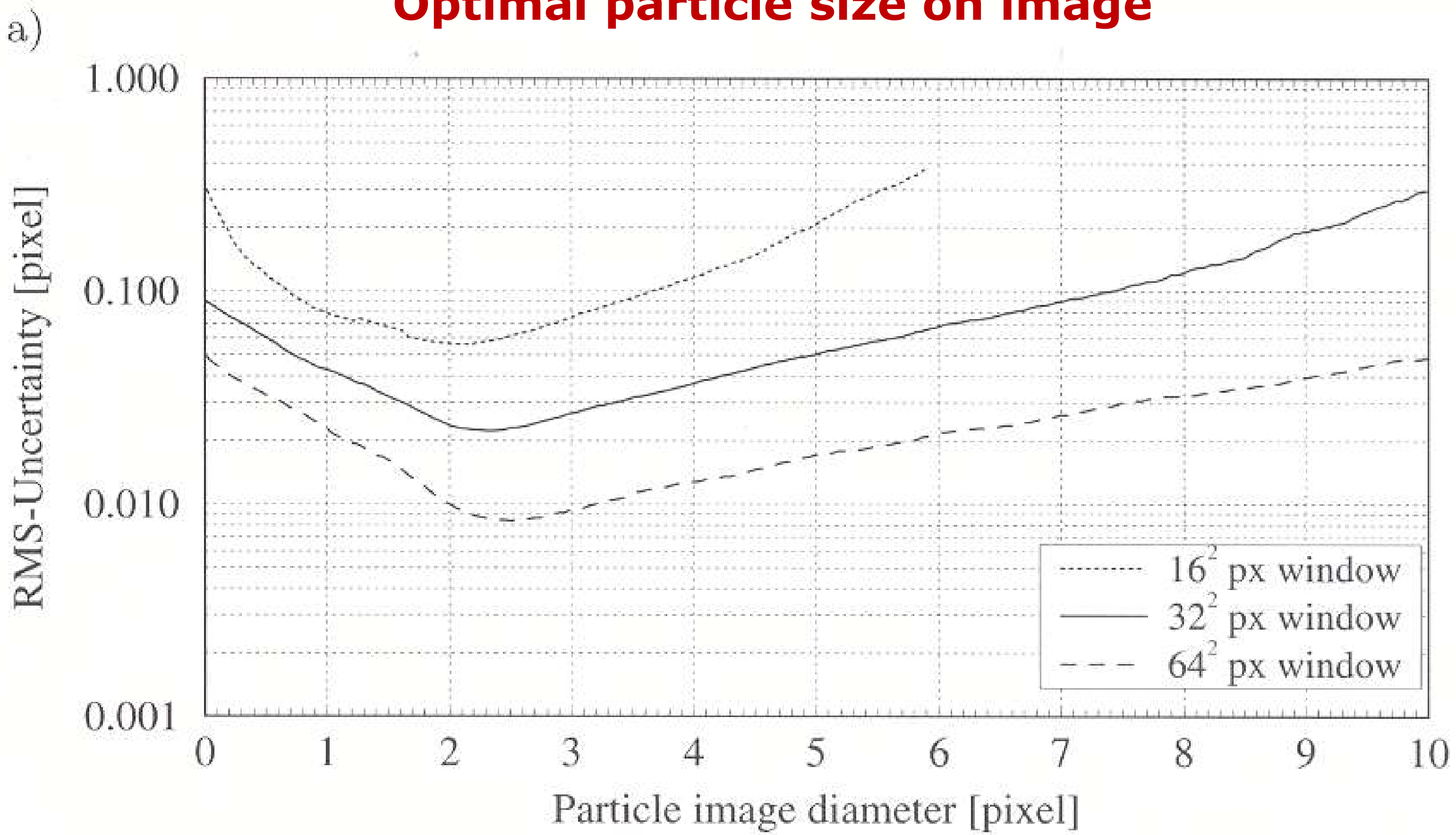


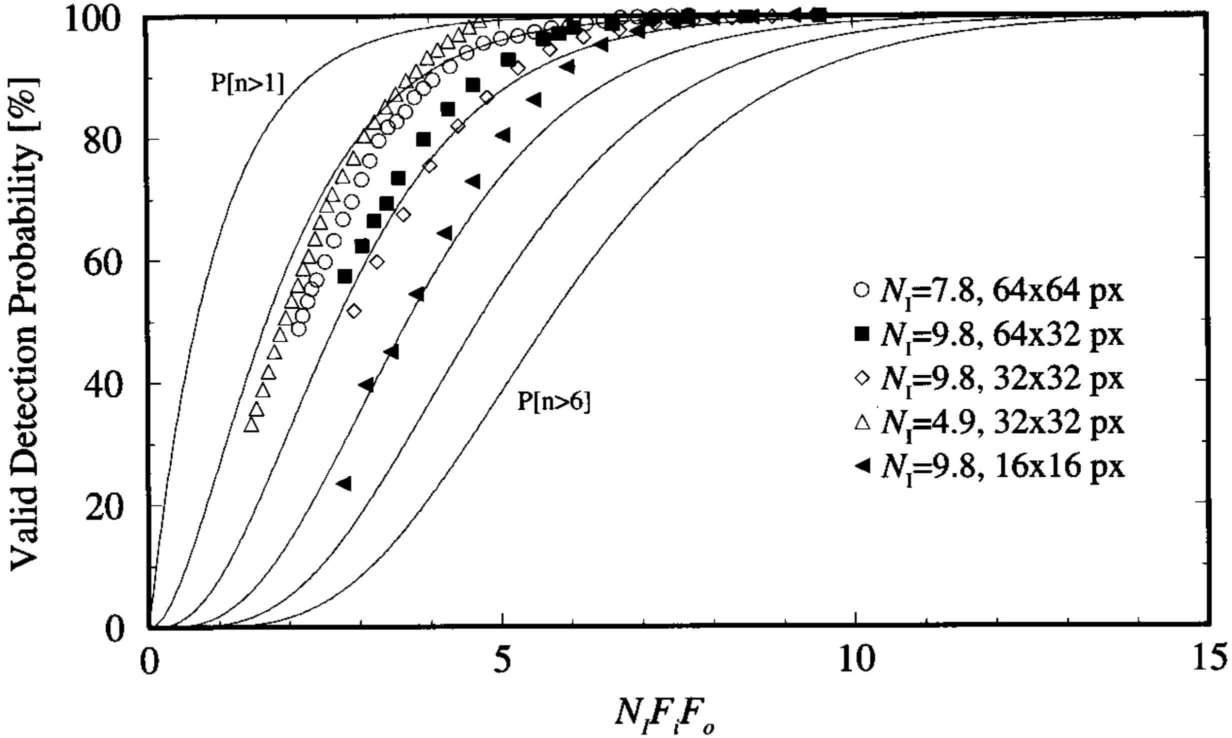
Fig. 5.34. Histograms of actual PIV displacement data obtained from a 10-image sequence of a turbulent boundary layer illustrating the "peak locking" associated with insufficient particle image size (left). Image pre-processing can reduce this effect (right). Histogram bin-width = 0.05 pixel.

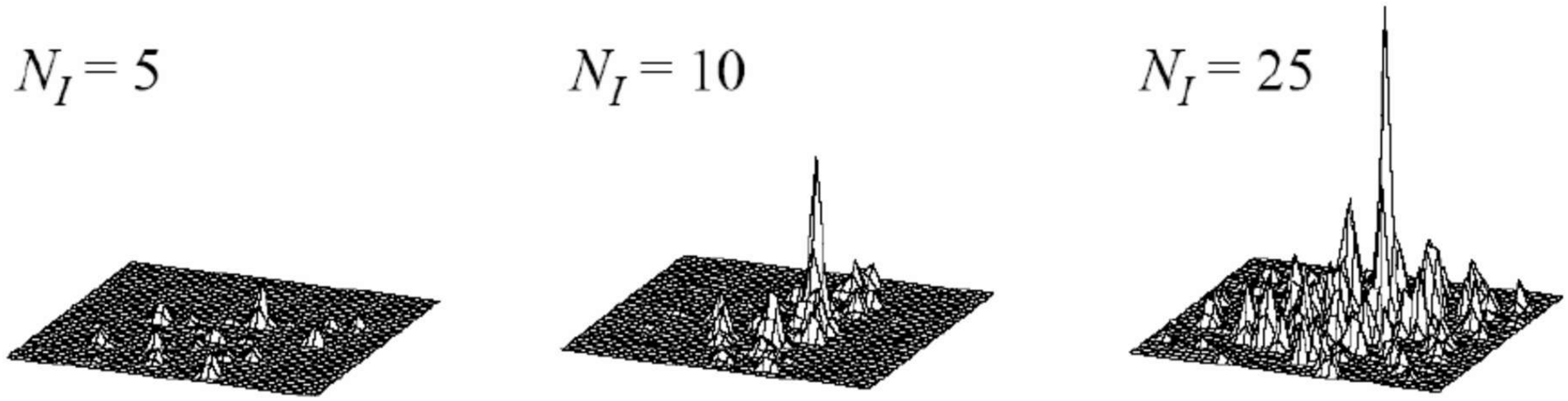
Particle size on images

Optimal particle size on image



Minimal density in particle





Setting the parameters: compromises

Time between pulses

In plane displacement => resolution

Out of plane displacement => lost particles

Tracer density / Number of particles per box

Detectability

Correlation relevance

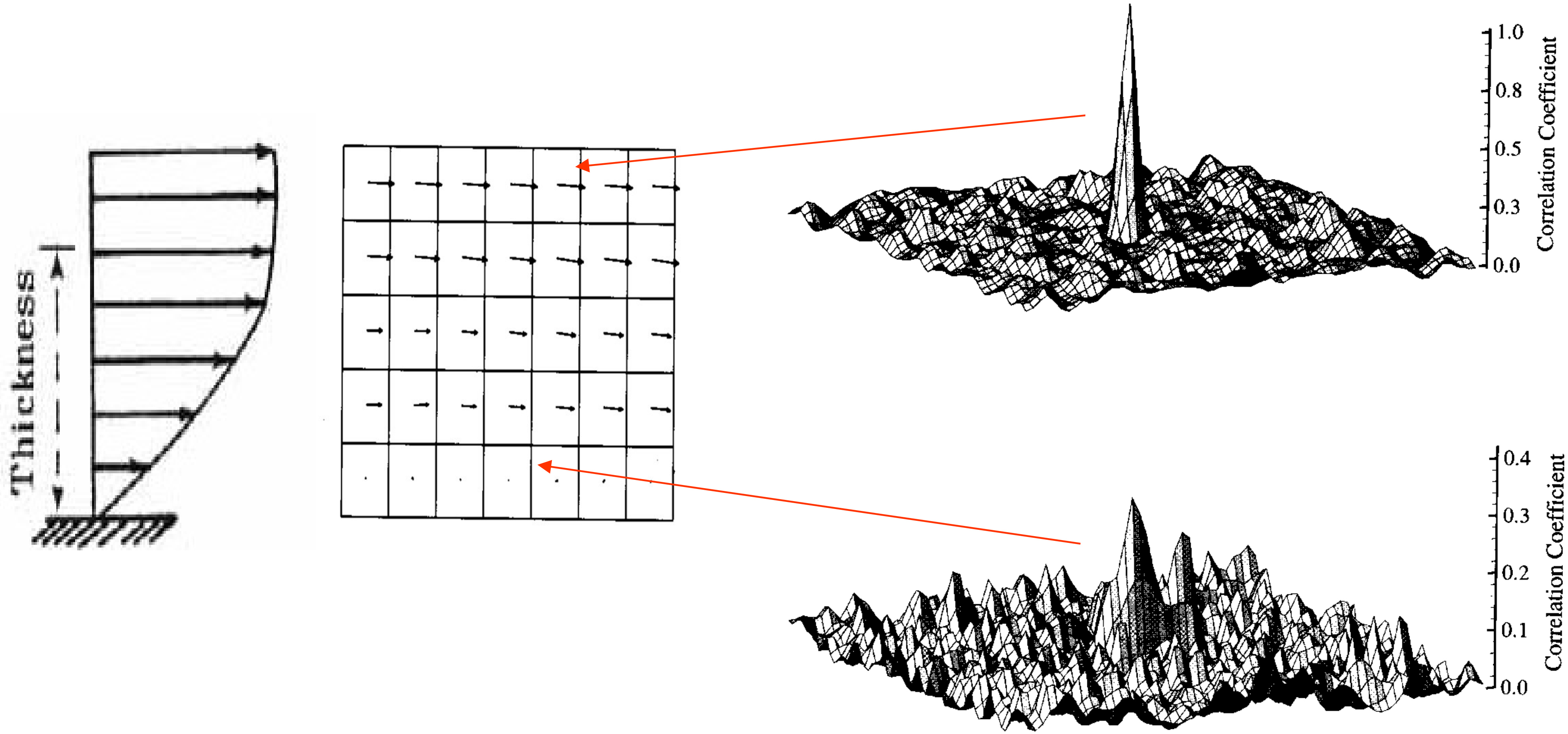
Particle size on images

Detectability

Pixel locking

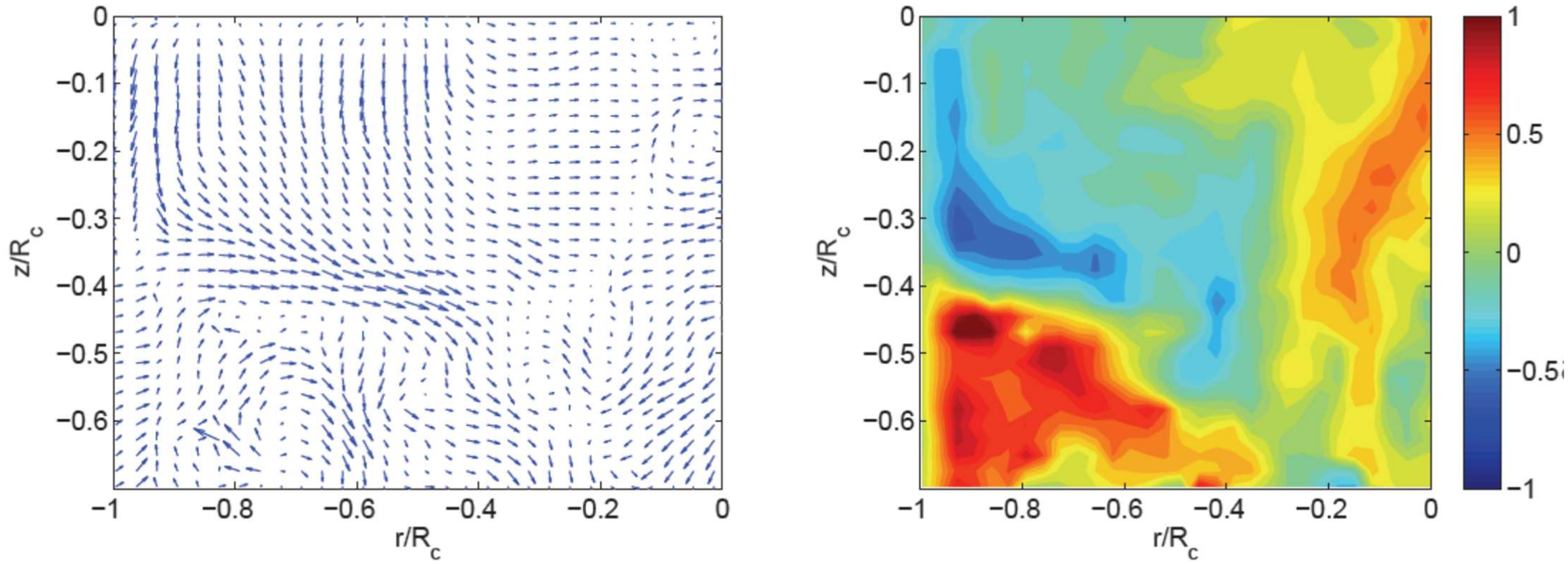
Optimal size

Strong gradients and resolution



⟹ Toward multi-pass PIV

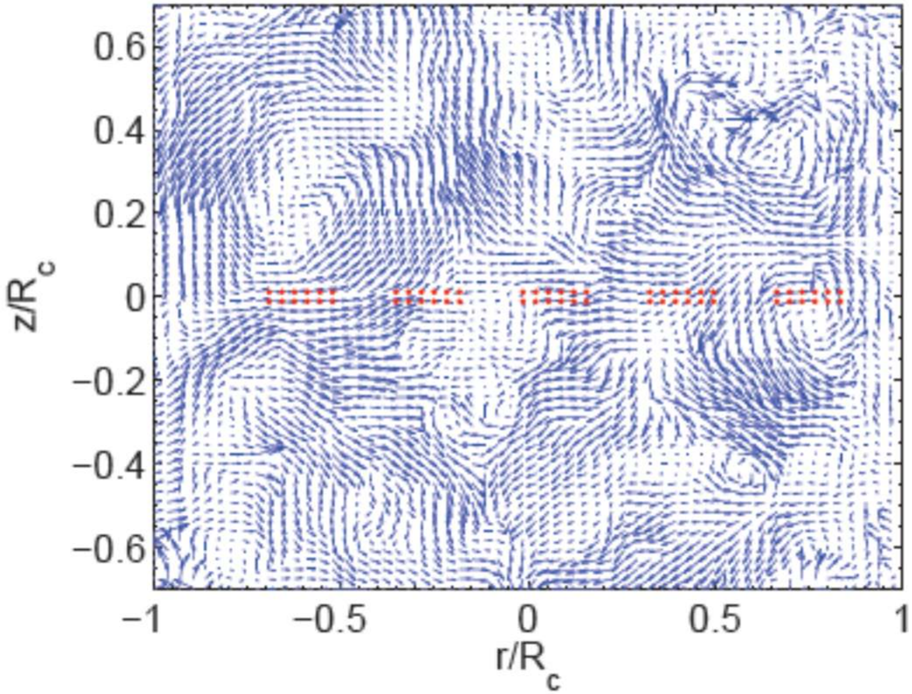
Post-processing



Typical velocity fields:

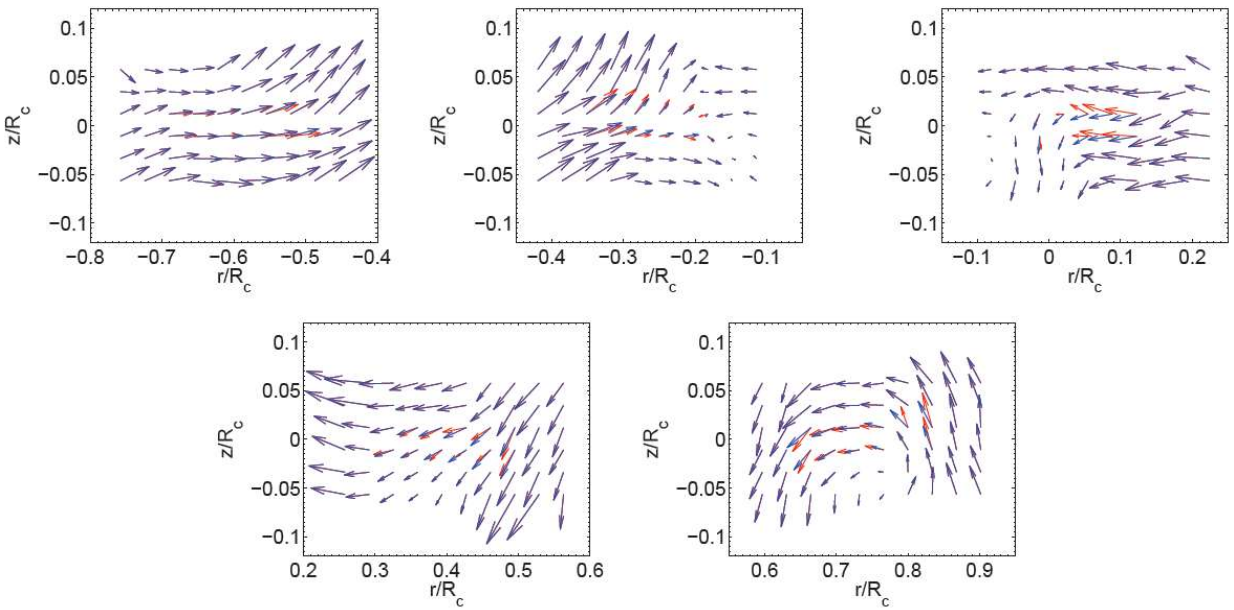
- Possible spurious vectors
- Checking resolution of gradients
- First step before statistical/Fourier analysis

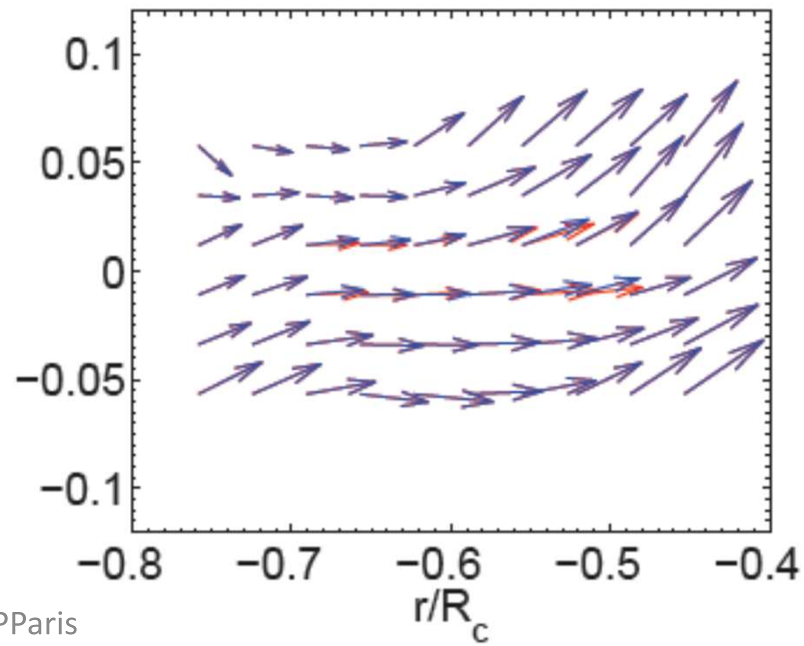
Post-processing



Removing spurious vectors:

- Isolating them:
  - Absolute thresholds
  - Local thresholds
- Replacing them:
  - Moving average





Post-processing

Median filter

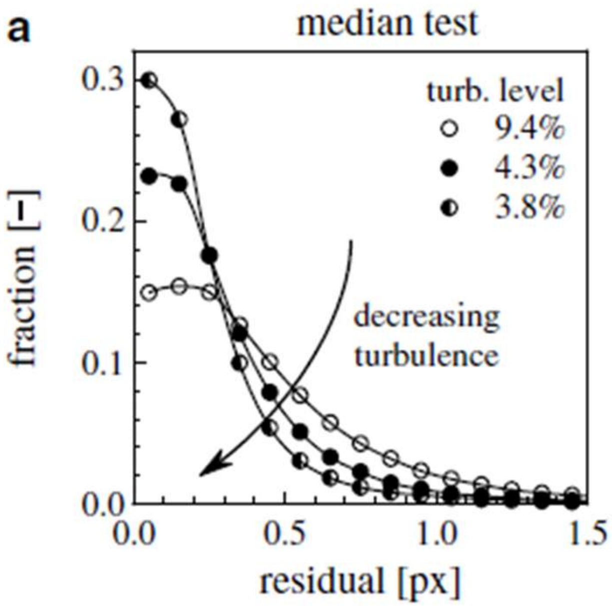
Residual depend on turbulence level

Experiments in Fluids (2005) 39: 1096–1100
DOI 10.1007/s00348-005-0016-6

LETTER

Jerry Westerweel · Fulvio Scarano

Universal outlier detection for PIV data

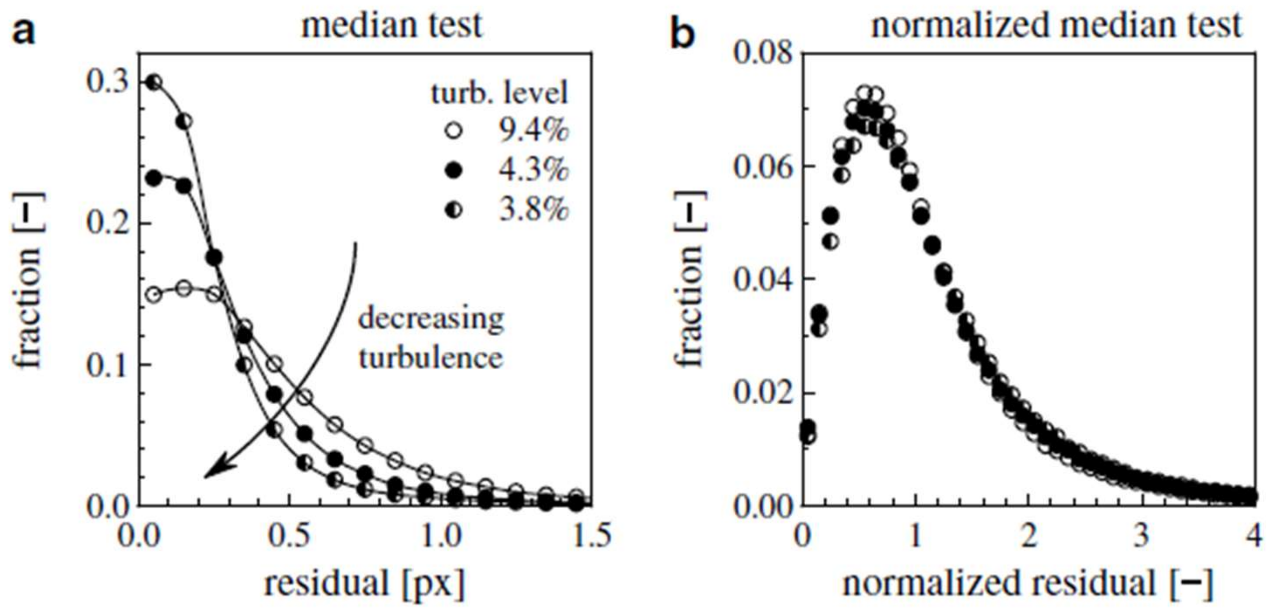


Post-processing

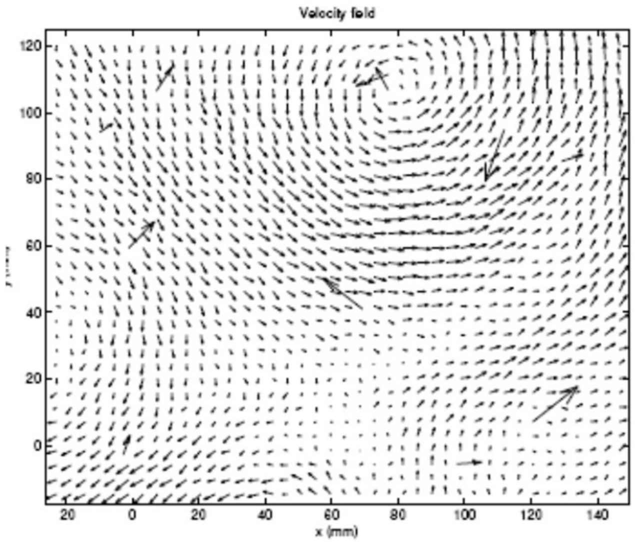
Universal outlier detection:
- median filter
- local normalization
- residual is independent of flow conditions

A residual r_i, defined as: $r_i = |U_i - U_m|$ (Westerweel 1994), is determined for each vector $\{U_i \mid i = 1,\ldots,8\}$, and the median r_m of $\{r_1, r_2, \ldots, r_8\}$ is used to normalize the residual of U_0:

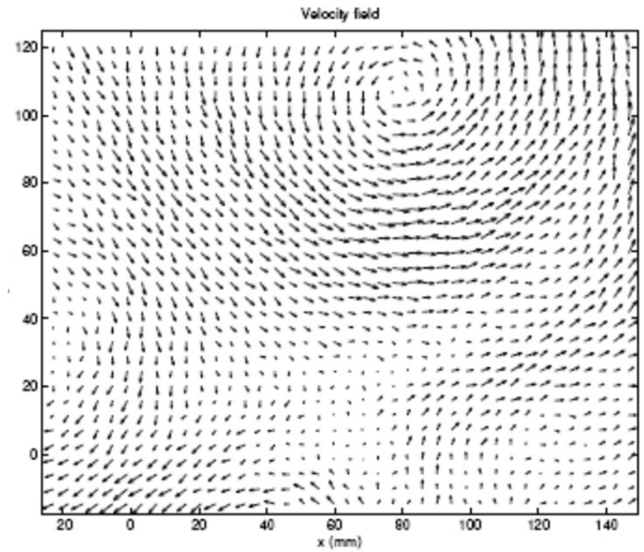
$$r'_0 = \frac{|U_0 - U_m|}{r_m}, \qquad r^*_0 = \frac{|U_0 - U_m|}{r_m + \varepsilon}, \tag{1}$$



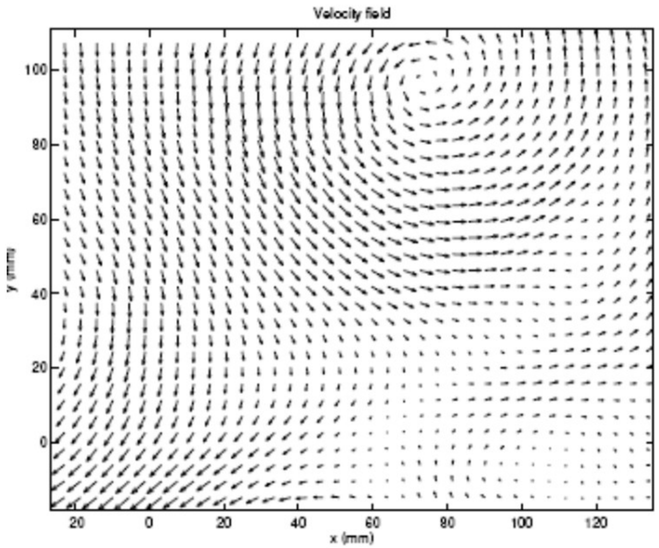
Post-processing



Removing/replacing spurious vectors



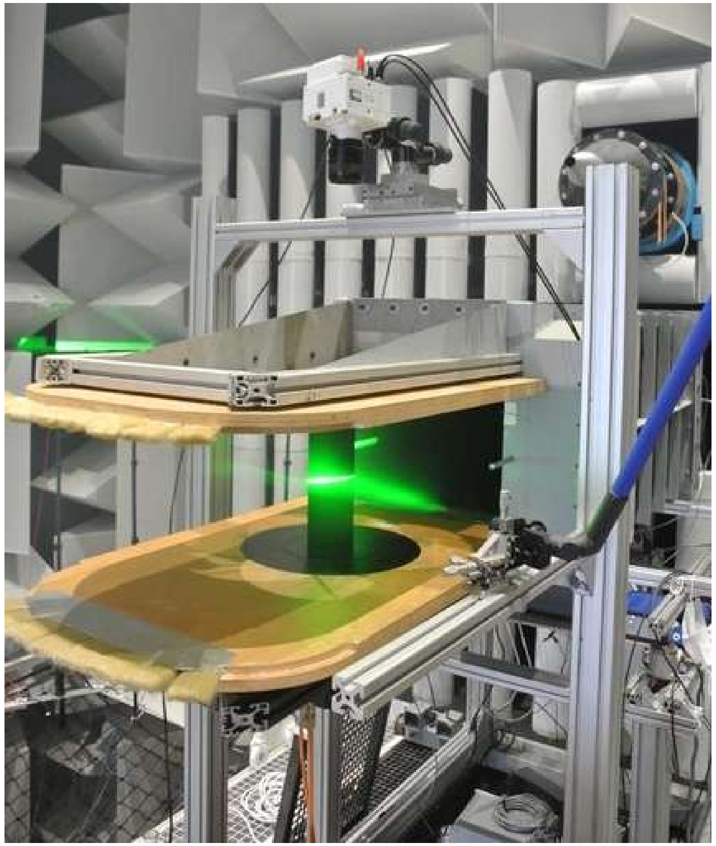
Smoothing

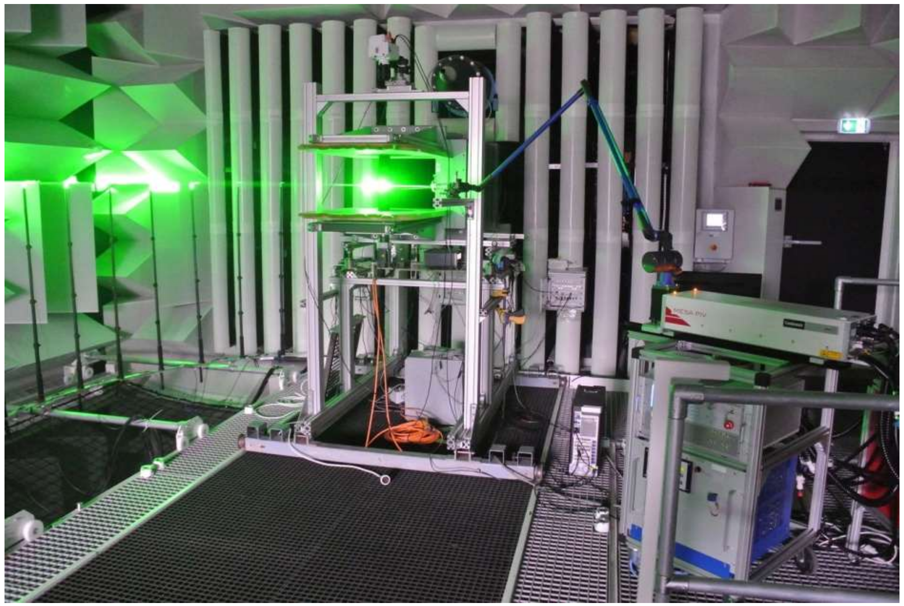


Caution with smoothing !

Time-resolved PIV

	Fast cameras (internal RAM or RAID)
Sensor	CMOS 12 or 16 bits sCMOS
Resolution	1000^2 to 4000^2 0.5 à 10 kHz
Price	20-380 k€



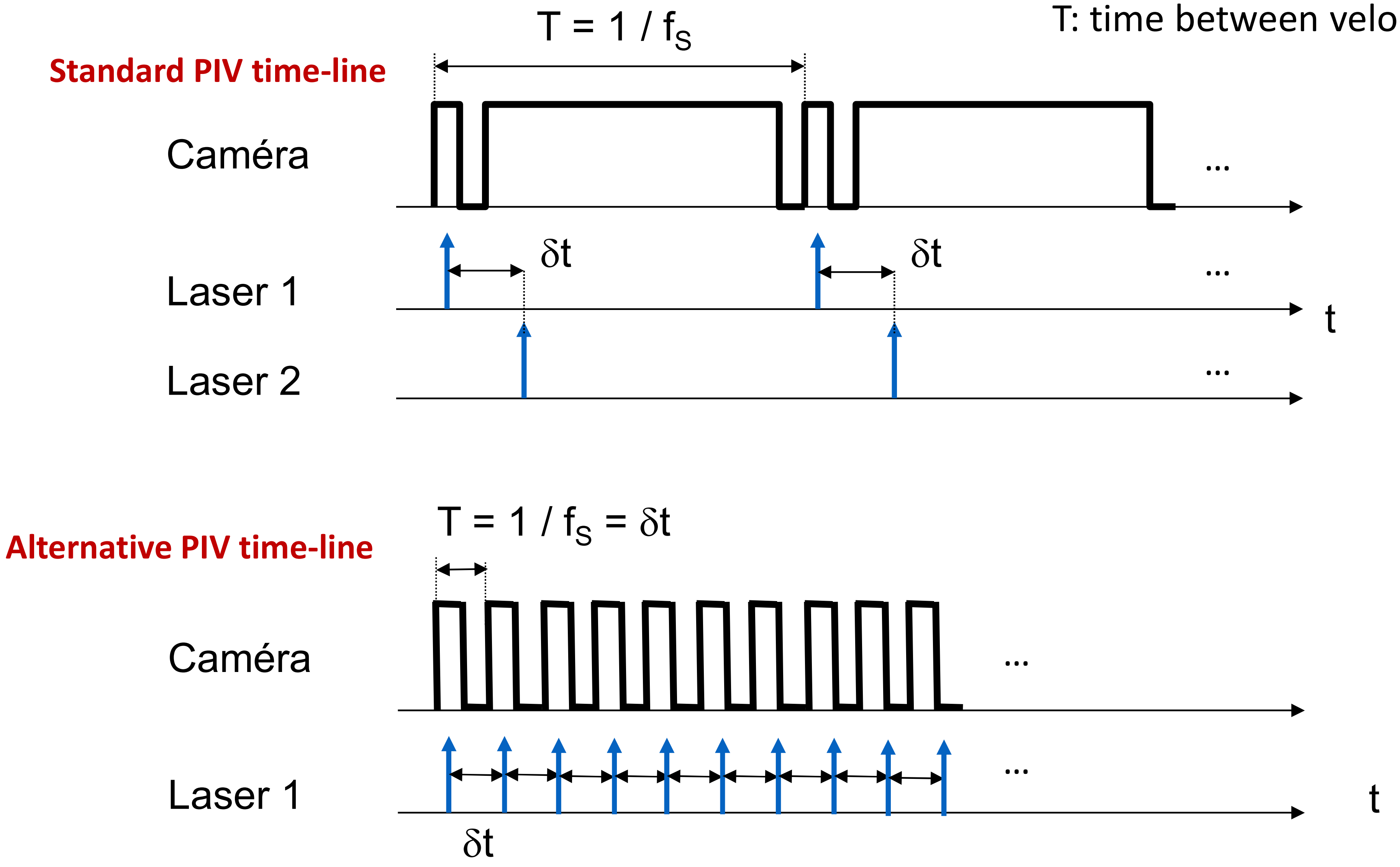


Continuous or high repetition rate light sources

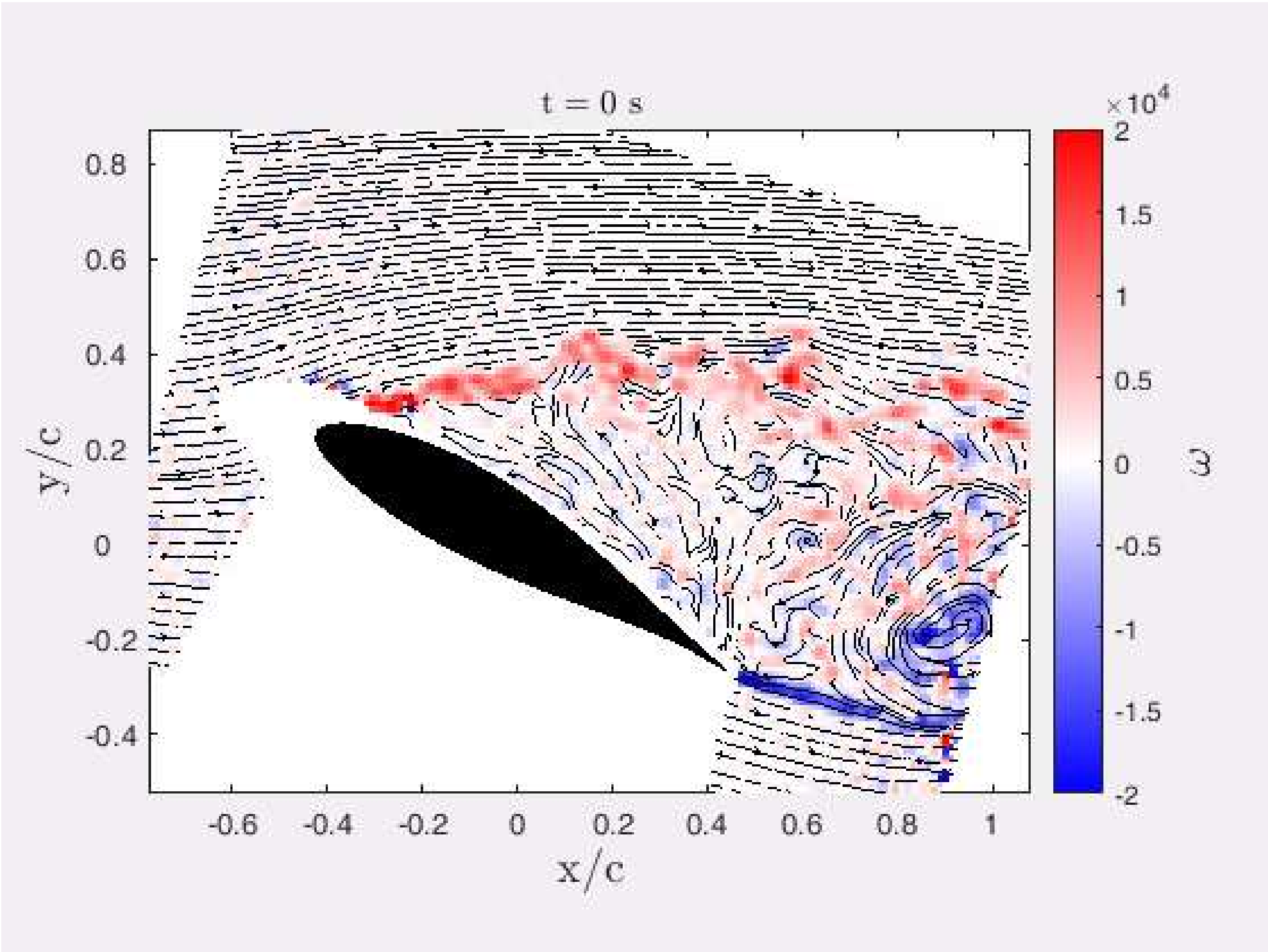
Time-resolved PIV

δt: time between pulses

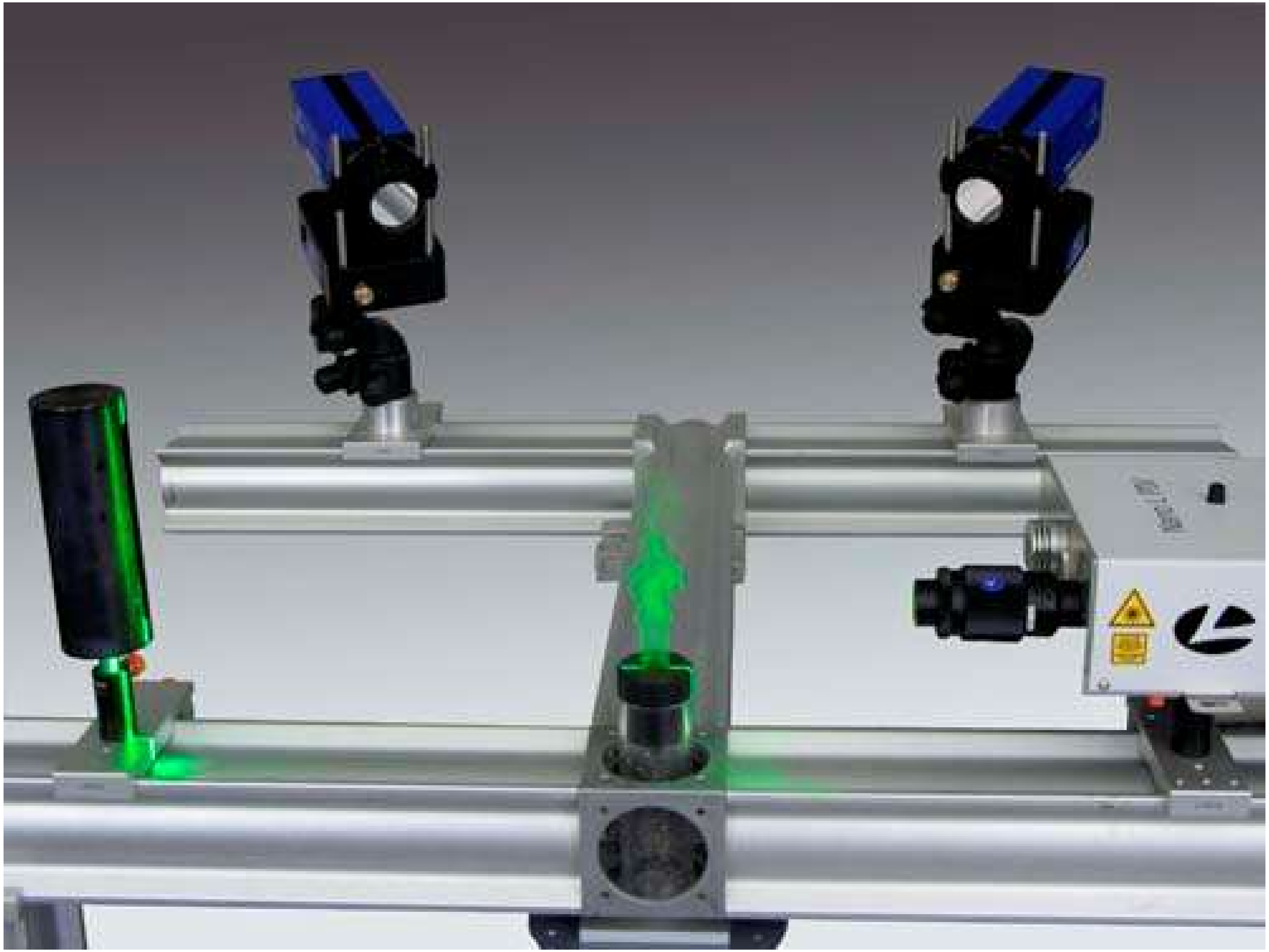
T: time between velocity fields



Time-resolved PIV



Stereoscopic PIV



Stereoscopic PIV principle

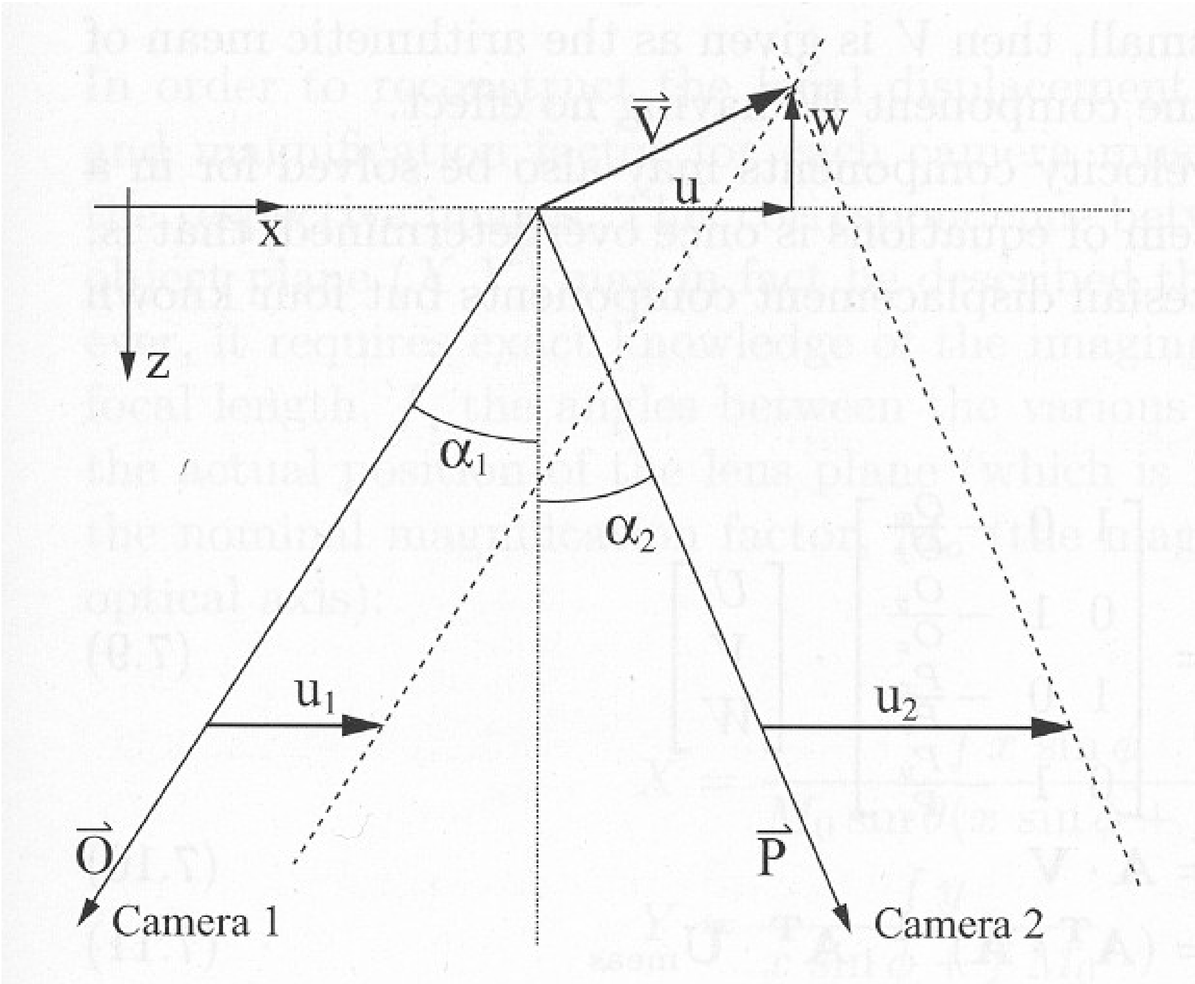
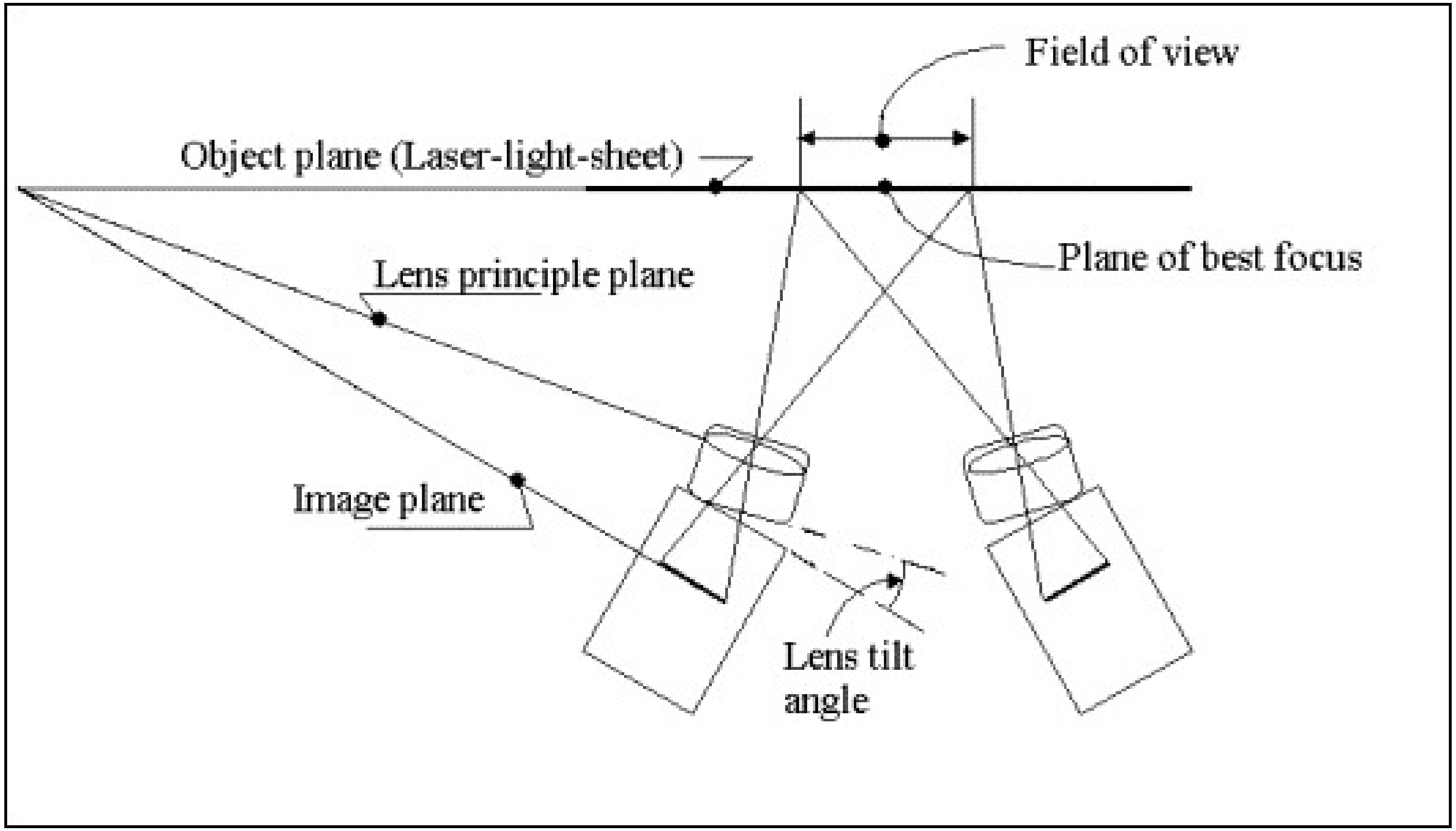
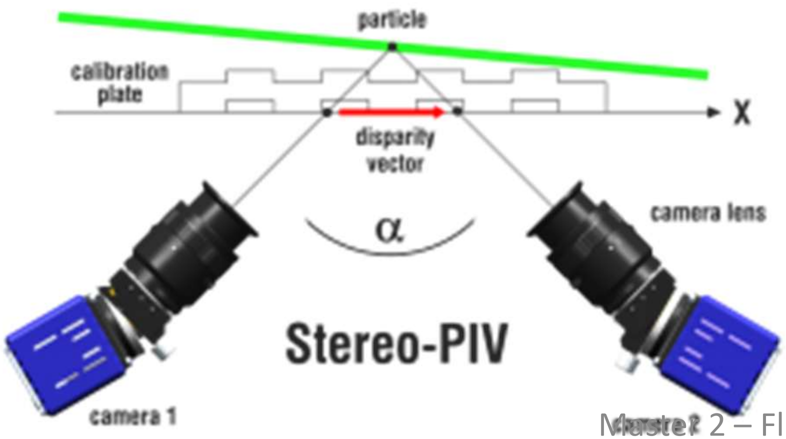


Fig. 7.2. Stereo viewing geometry in the XZ-plane.

Stereoscopic PIV Sheimpflung condition



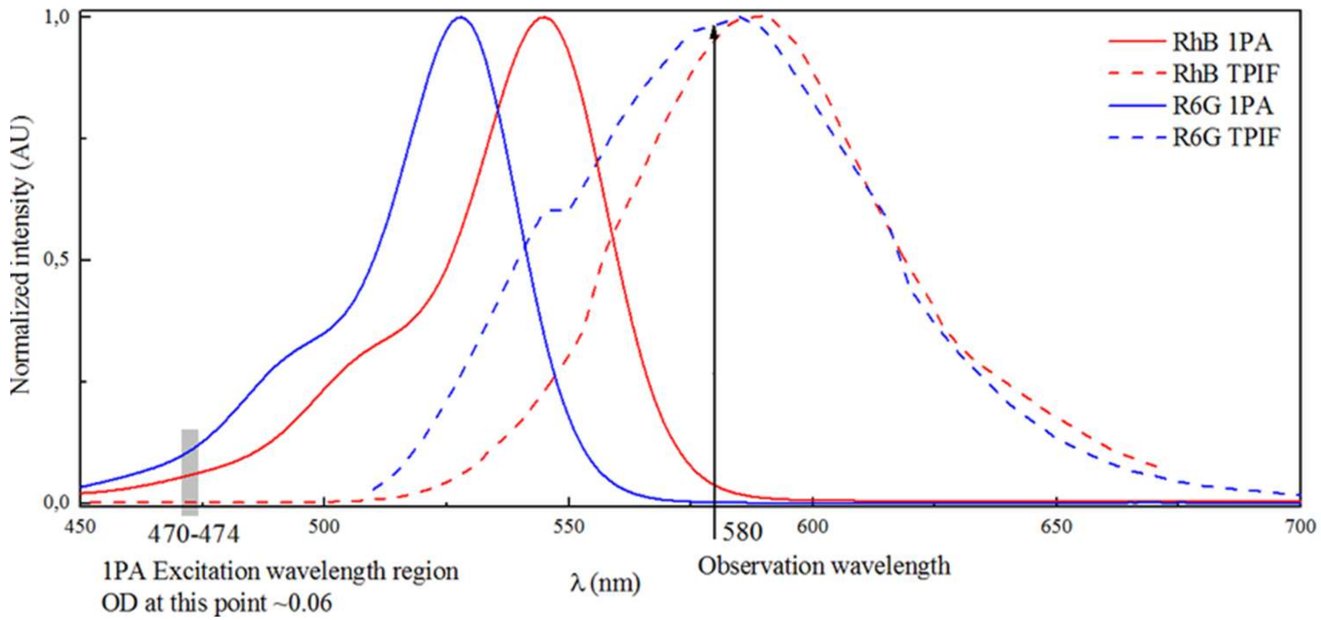


Stereoscopic PIV multiplane calibration

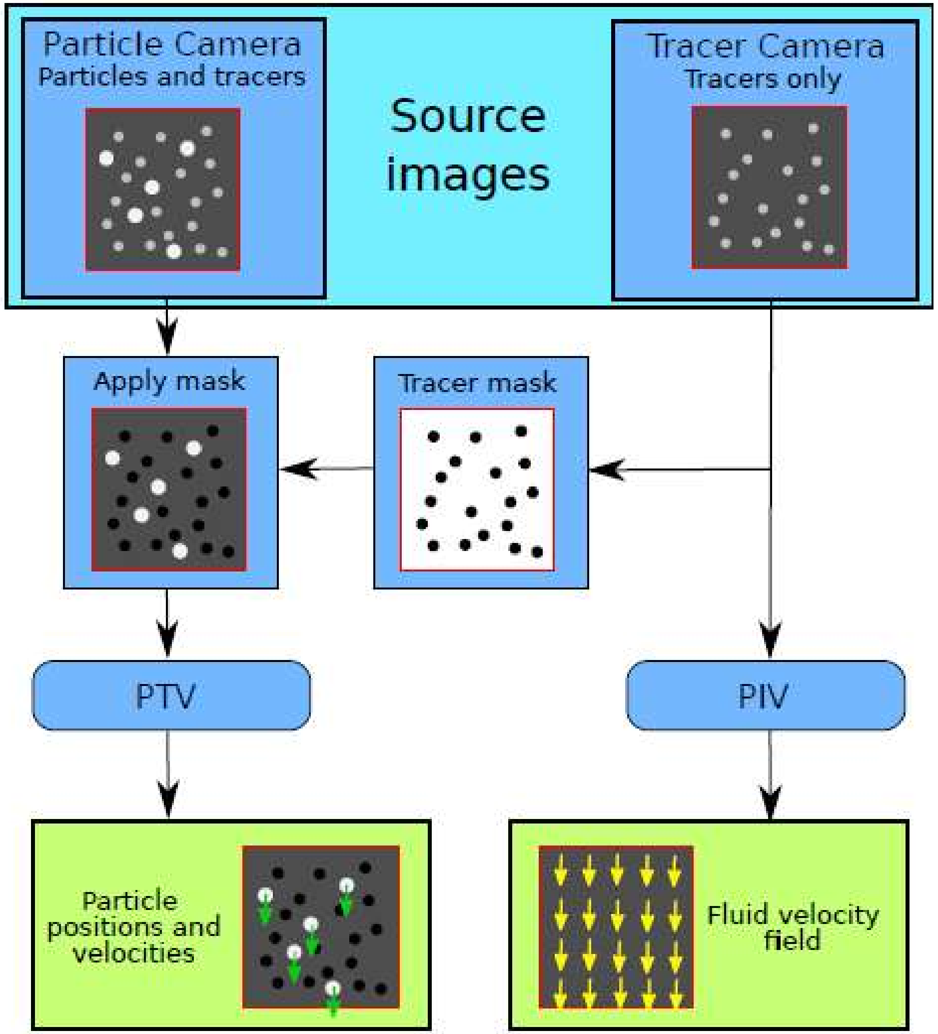
Even used for 2D-2C PIV

Multiphysics PIV

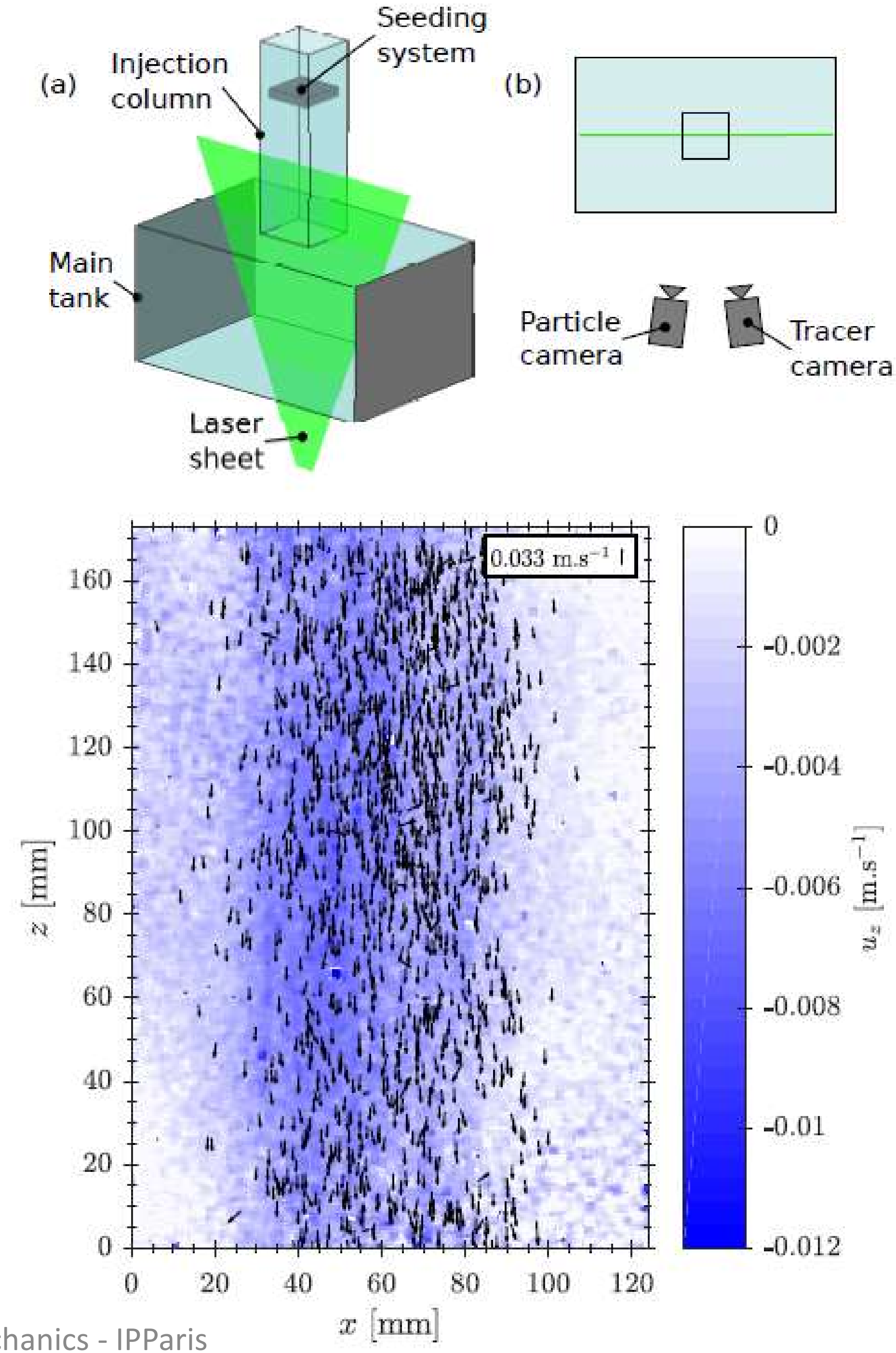
- Temperature and velocity
- Multiphase measurements:
  - particles and fluid velocities
  - multifluids



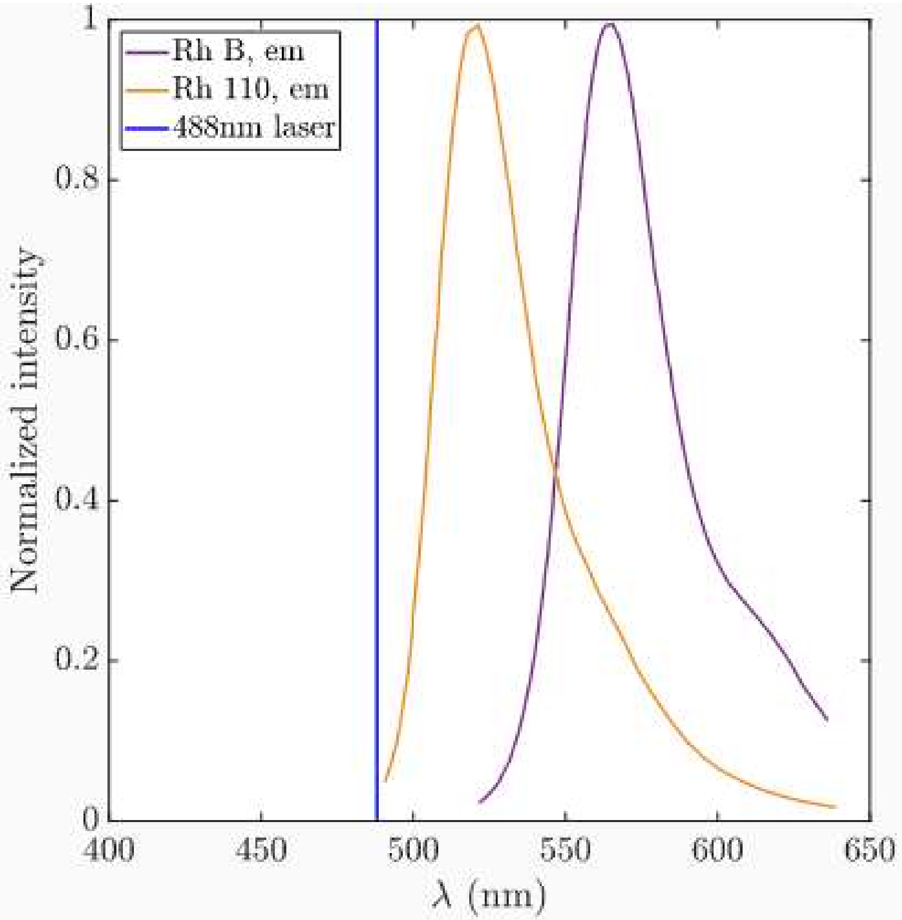
Particles and fluid velocities at ENSTA



De Souza, Zurner and Monchaux, Exp. In Fluids, 2021



Temperature and velocity at ENS Lyon



Emission spectra

2-colors, 2-dyes: Rhodamine B & 110

Laser λ=488 nm

$I_B = f(I, c_B, T), I_{110} = f(I, c_{110})$

I: incident light

c: concentration

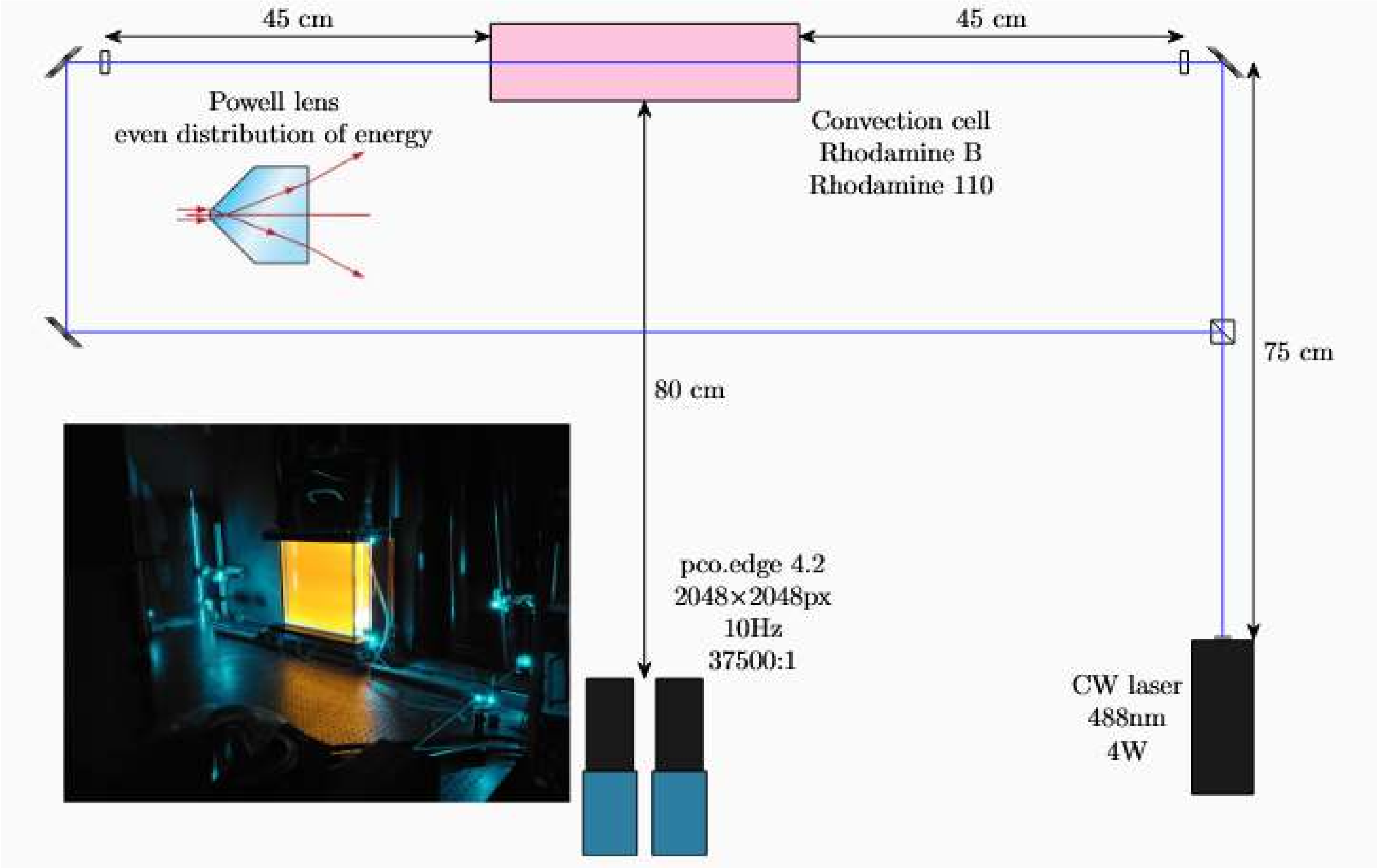
T: temperature

$\frac{I_B}{I_{110}} = f(T)$ depends only on T

Sakakibara, J., Adrian, R. J., 2004

Laser Induced Fluorescence

Temperature and velocity at ENS Lyon



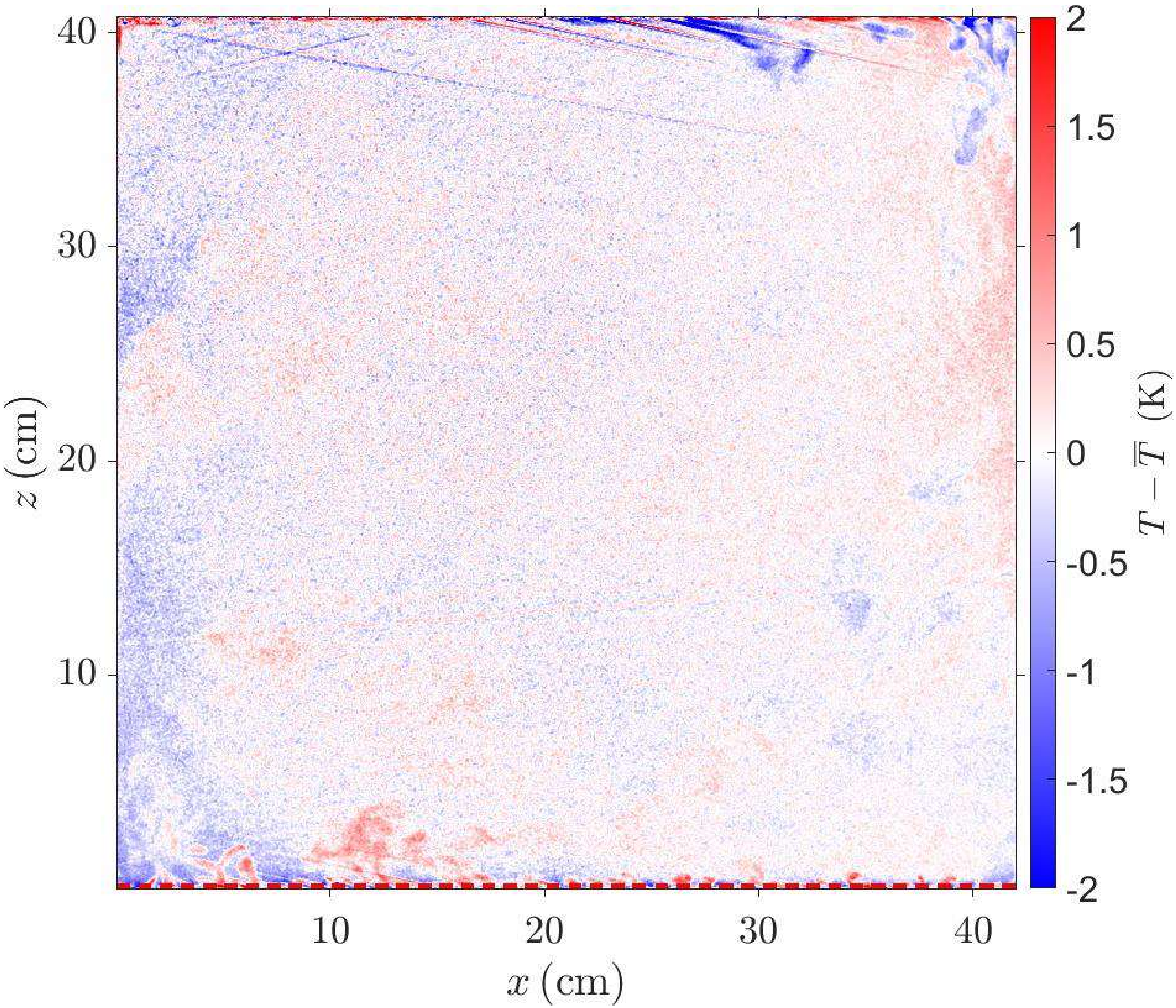
2 cameras with optical filters

4W 488 nm laser

Laser sheet from both sides of the cell, reduces light absorption

Laser Induced Fluorescence

Temperature and velocity at ENS Lyon

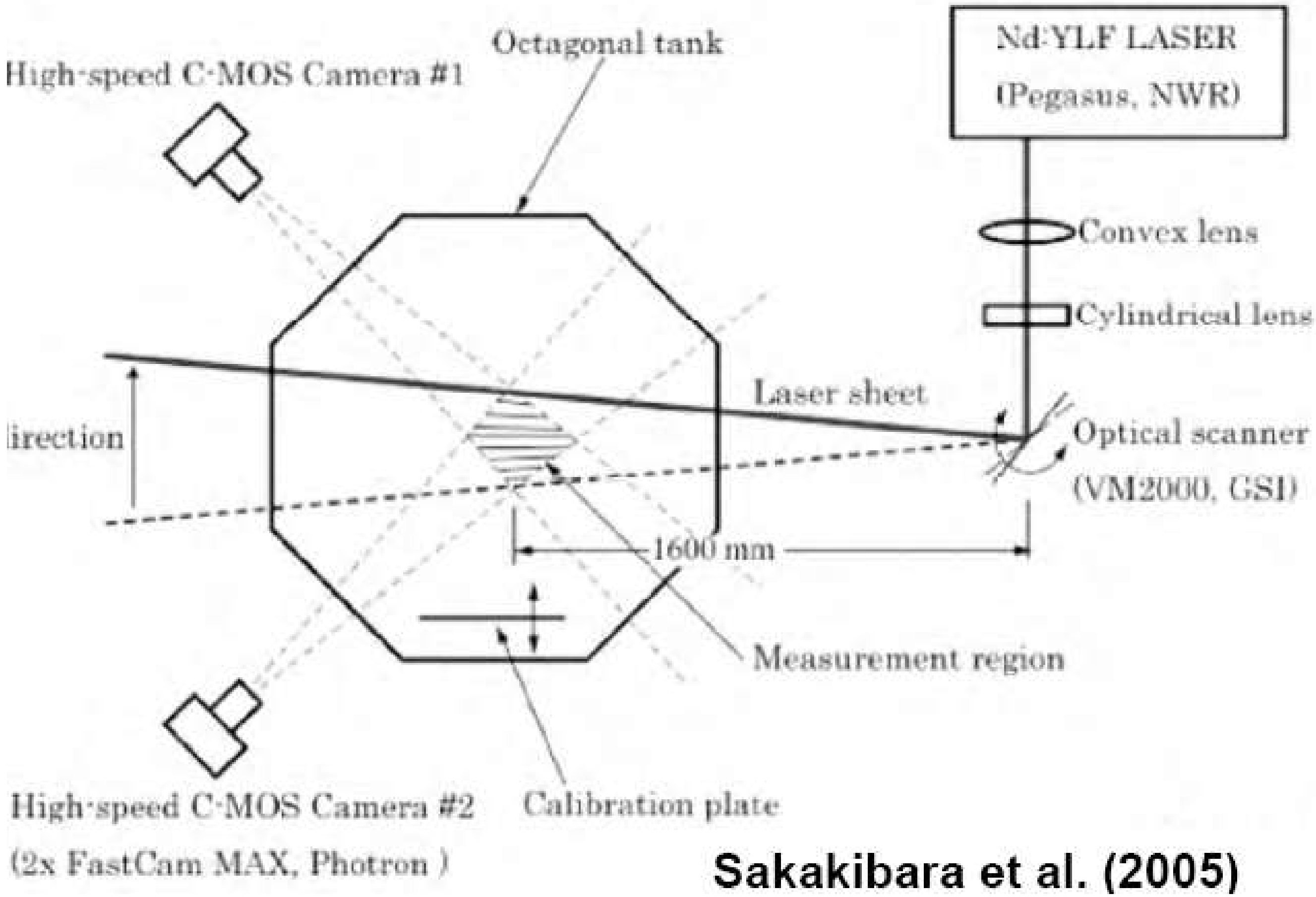


Rayleigh-Bénard Convection

Temperature field

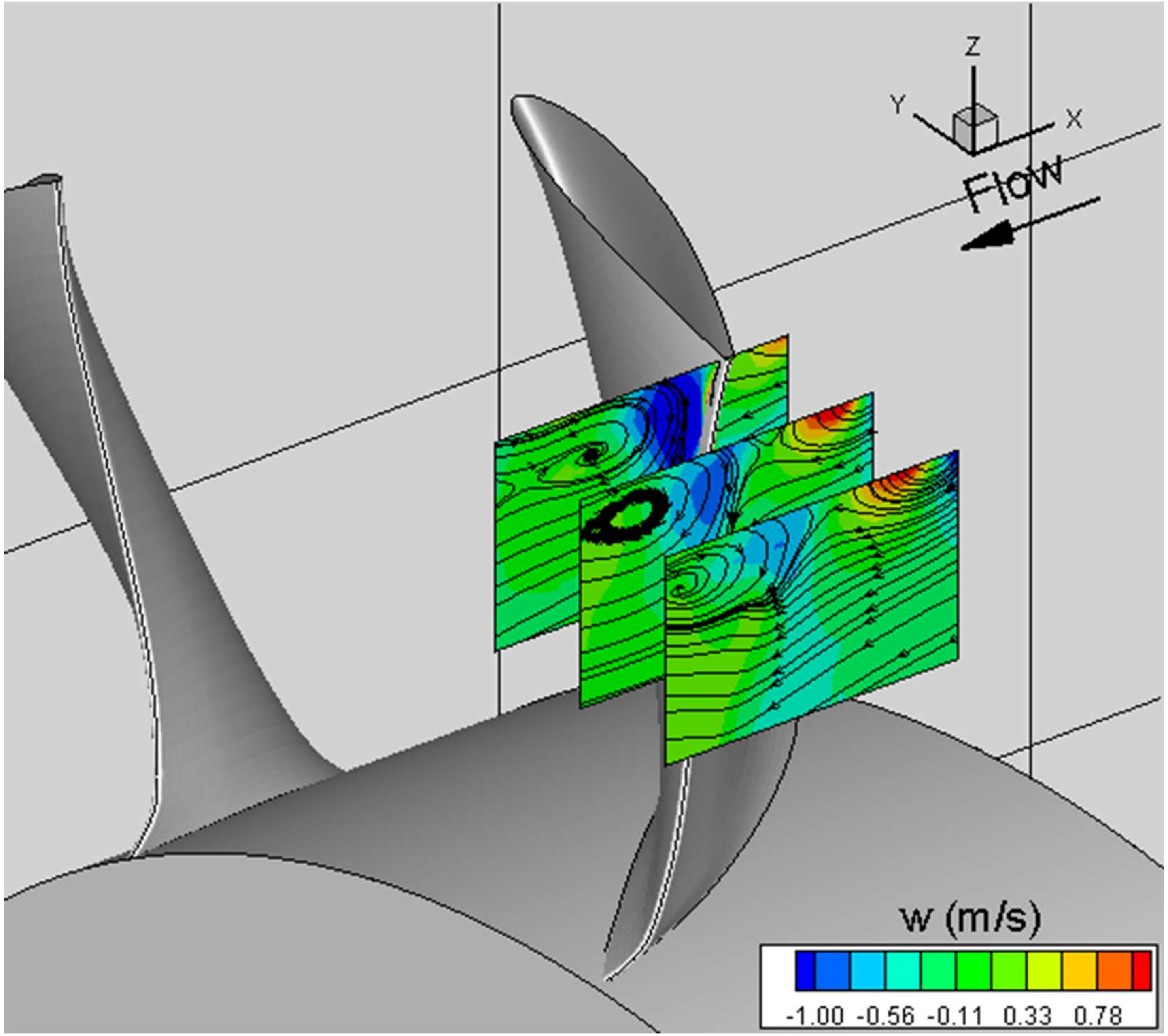
Toupoint et al. submitted

Tomographic / 3D PIV



Sakakibara et al. (2005)

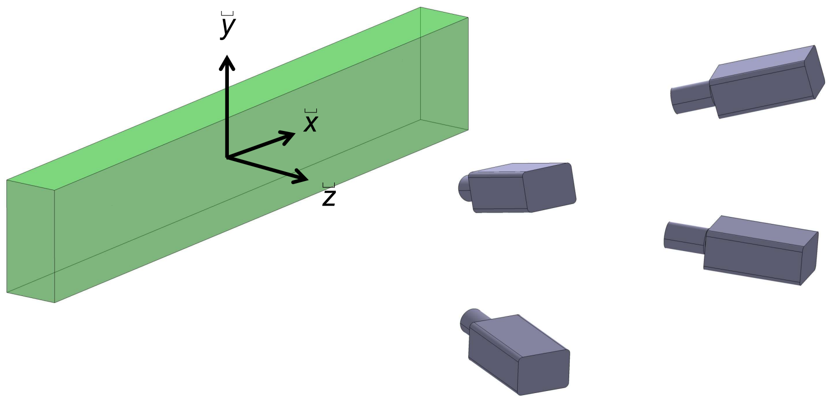
Tomographic / 3D PIV



Tomographic / 3D PIV

Ultimate goal: measure velocity and pressure: (**u**,p)

⟹ Time and space resolved 3D measurement

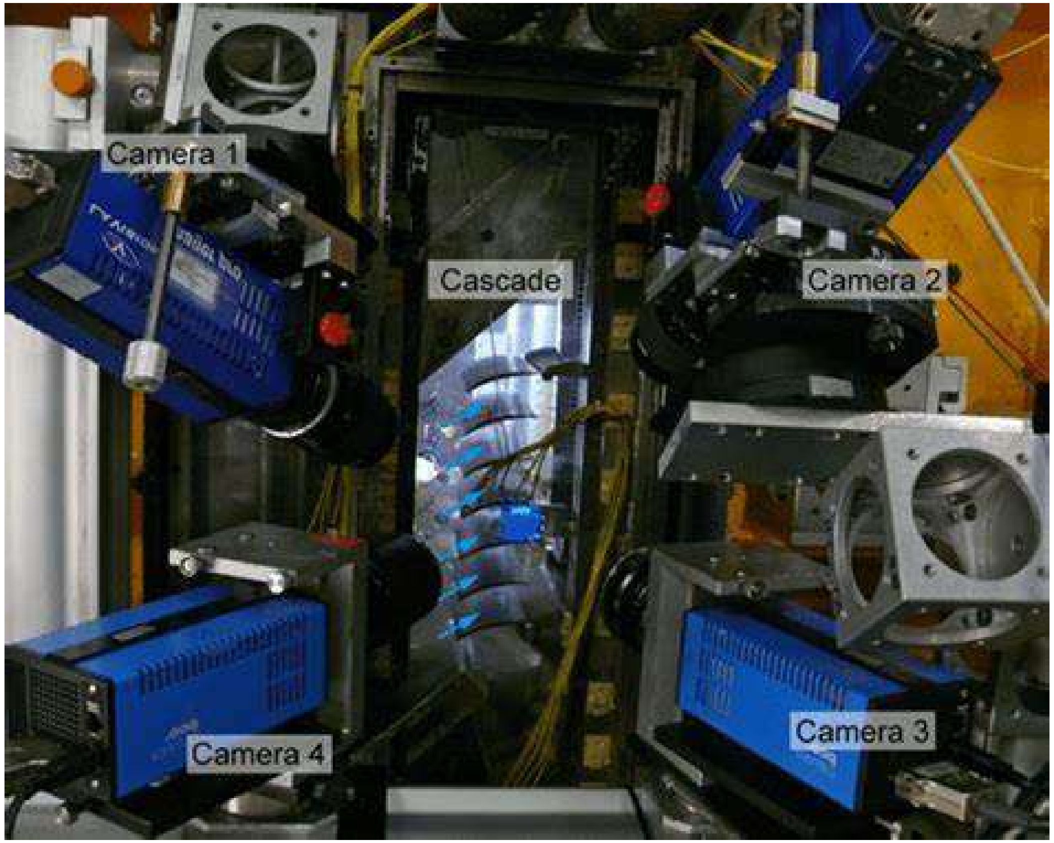


- Seeded flow
- Volumique lighting
- Optical system:

  4 to 6 cameras

How to reconstruct u ? p ?

Particles Image Velocimetry: tomograpphic / 3D PTV



4 to 8 cameras

3D calibration

Very high computation costs

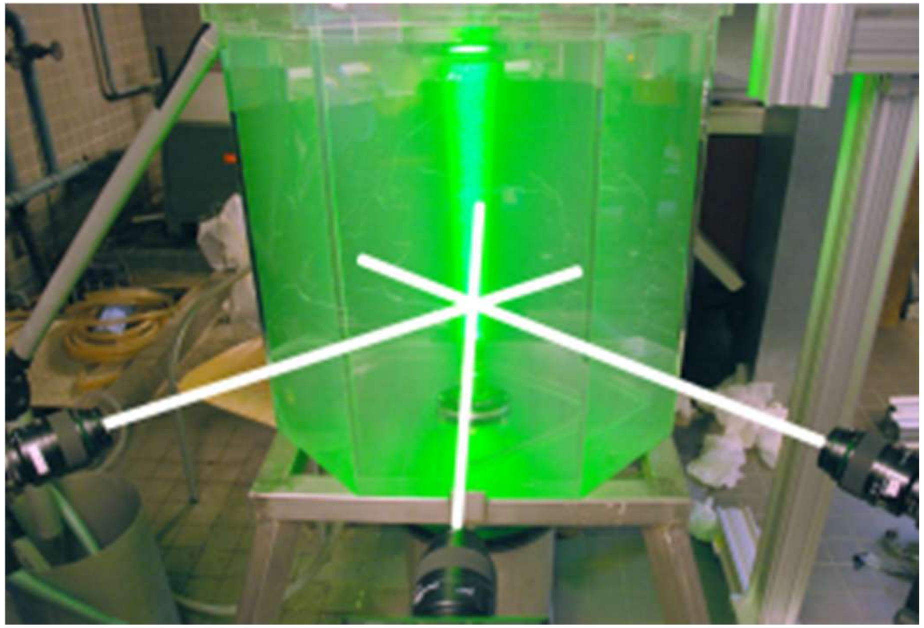
Particles Image Velocimetry: beyond the standards

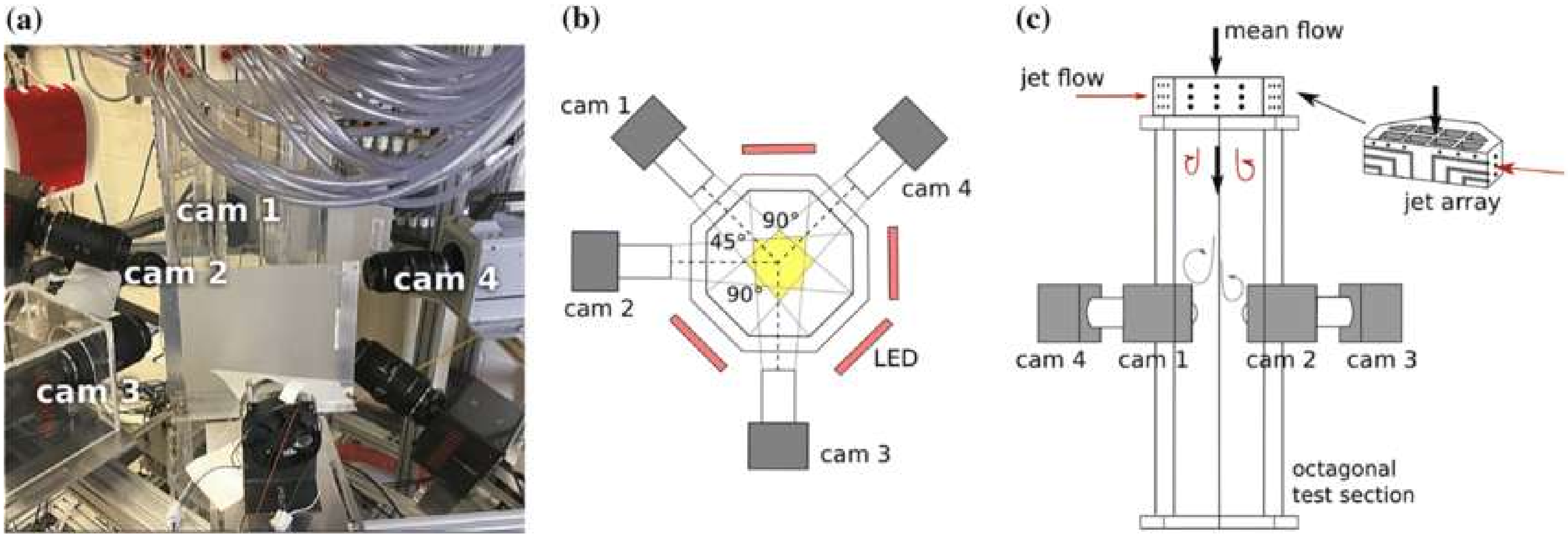
4D Particle Tracking Velocimetry

Lagrangian statistics
Eulerian statistics are possible

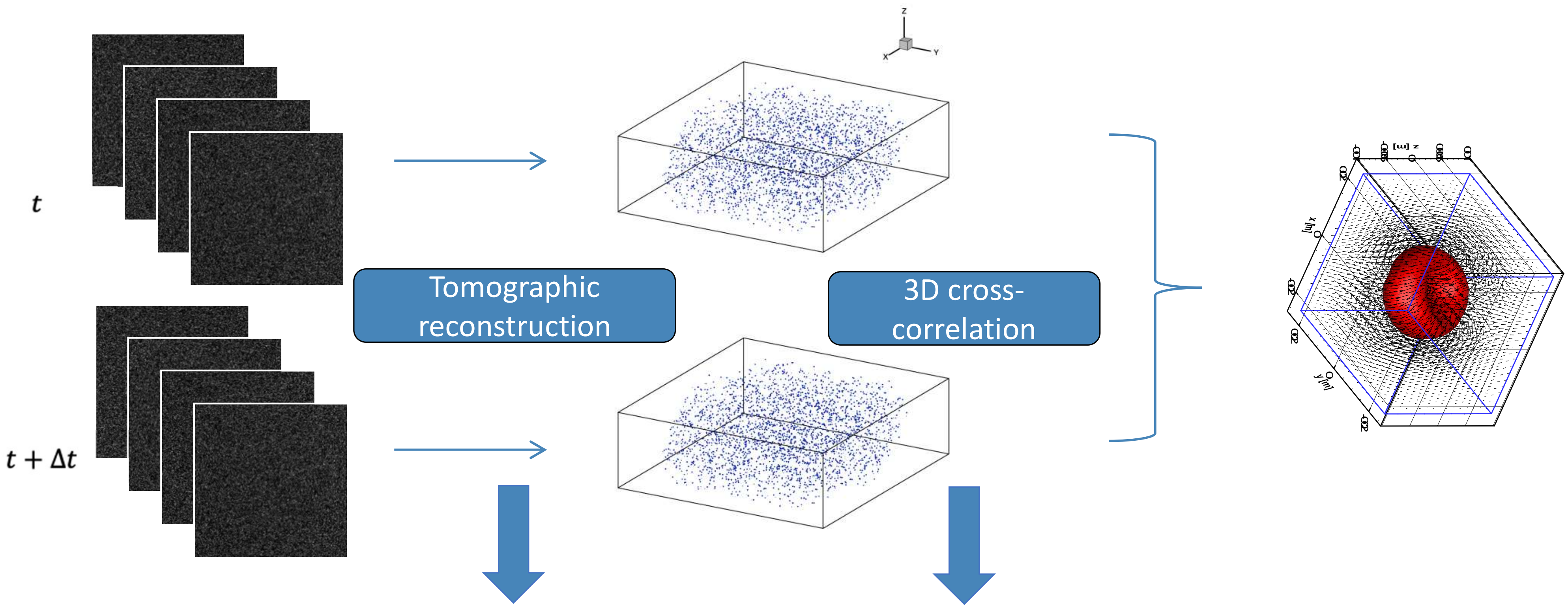
Material

- Extended light source
    - Laser
    - Led panel
- 3 to 8 fast cameras





Tomographic reconstruction & movement estimation

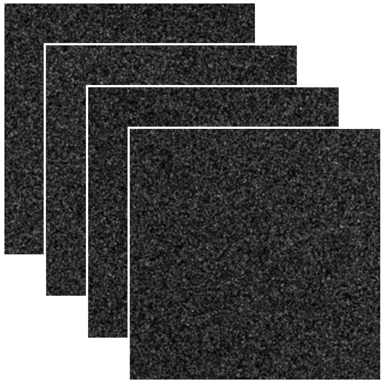


Under-determined problem
The denser the harder

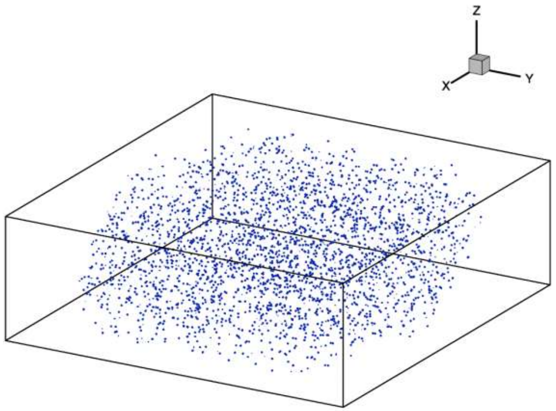
Spatial filtering as in 2D

Reconstruction model

Projections



Volume



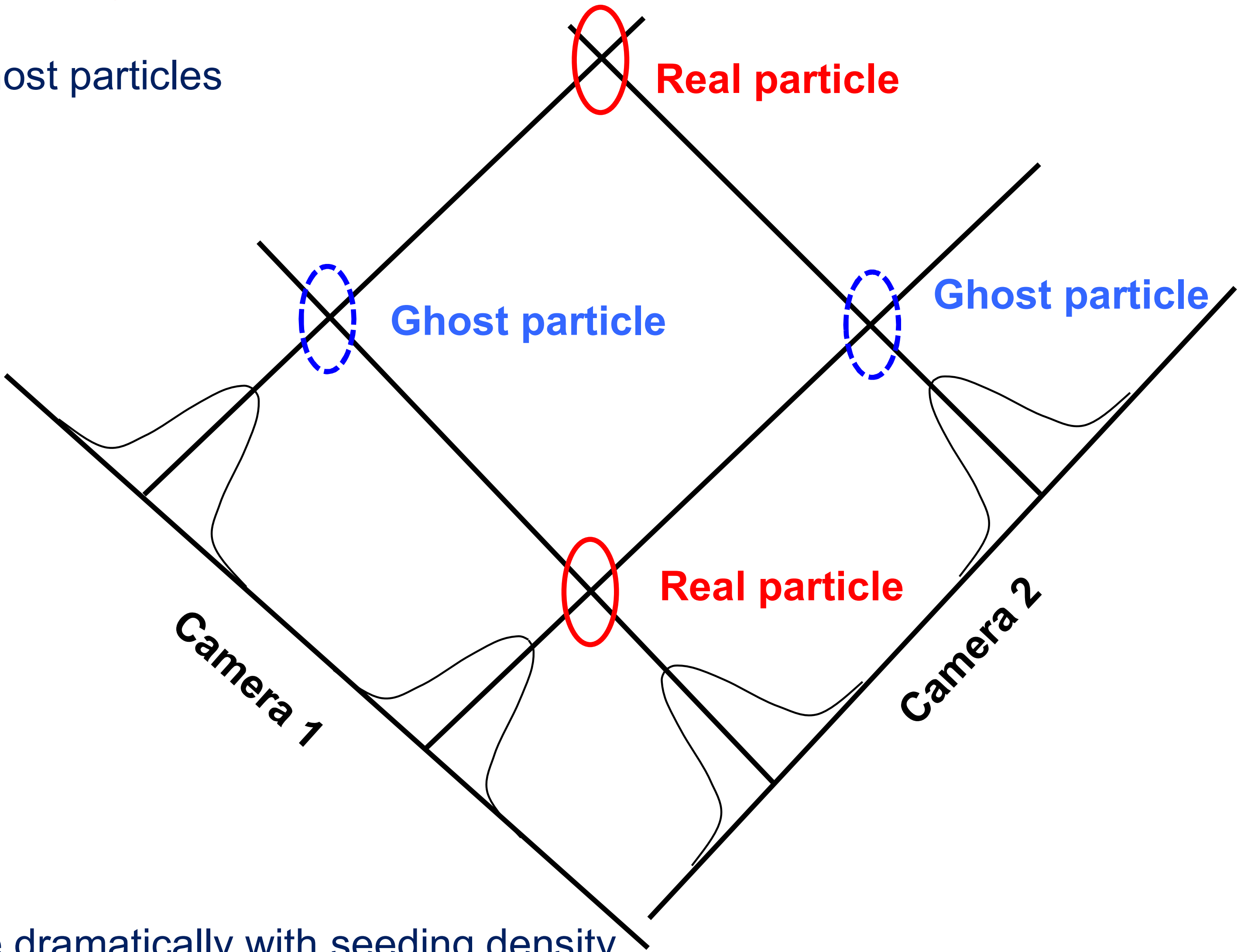
Array of **N** ***pixels***

Discretization : array of **M** **voxels**

Linear tomographic **model**

Reconstruction model

Main issue : ghost particles

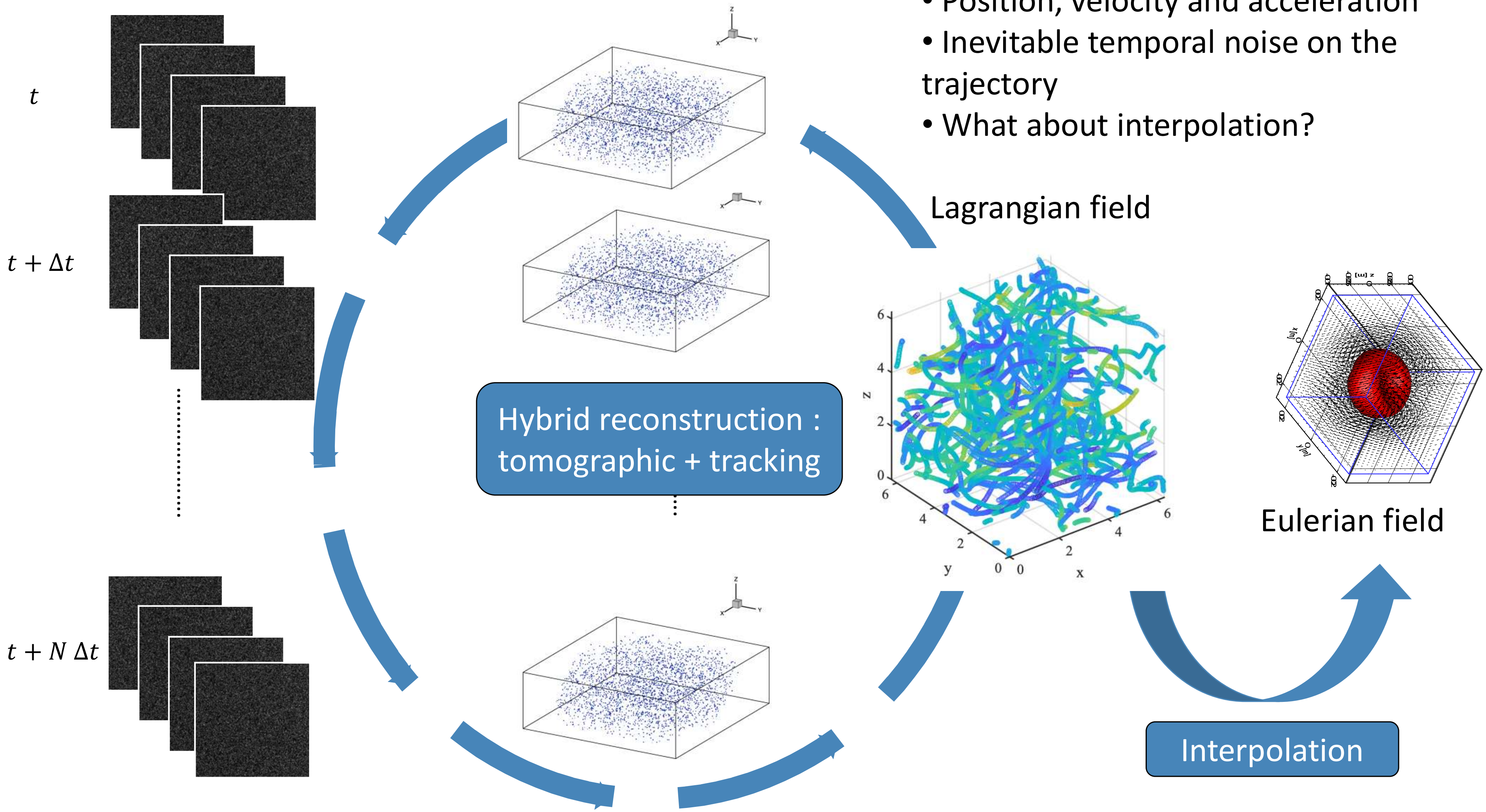


Ghost particles increase dramatically with seeding density
Ghosts act as noise that deteriorates correlation
Spatial resolution needs high seeding density

⟹ **Compromises again**

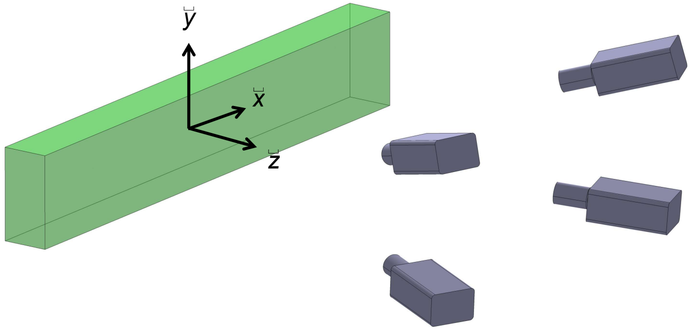
Principles

- Reconstruction with noise elimination
- Higher particle density in principle
- Position, velocity and acceleration
- Inevitable temporal noise on the trajectory
- What about interpolation?



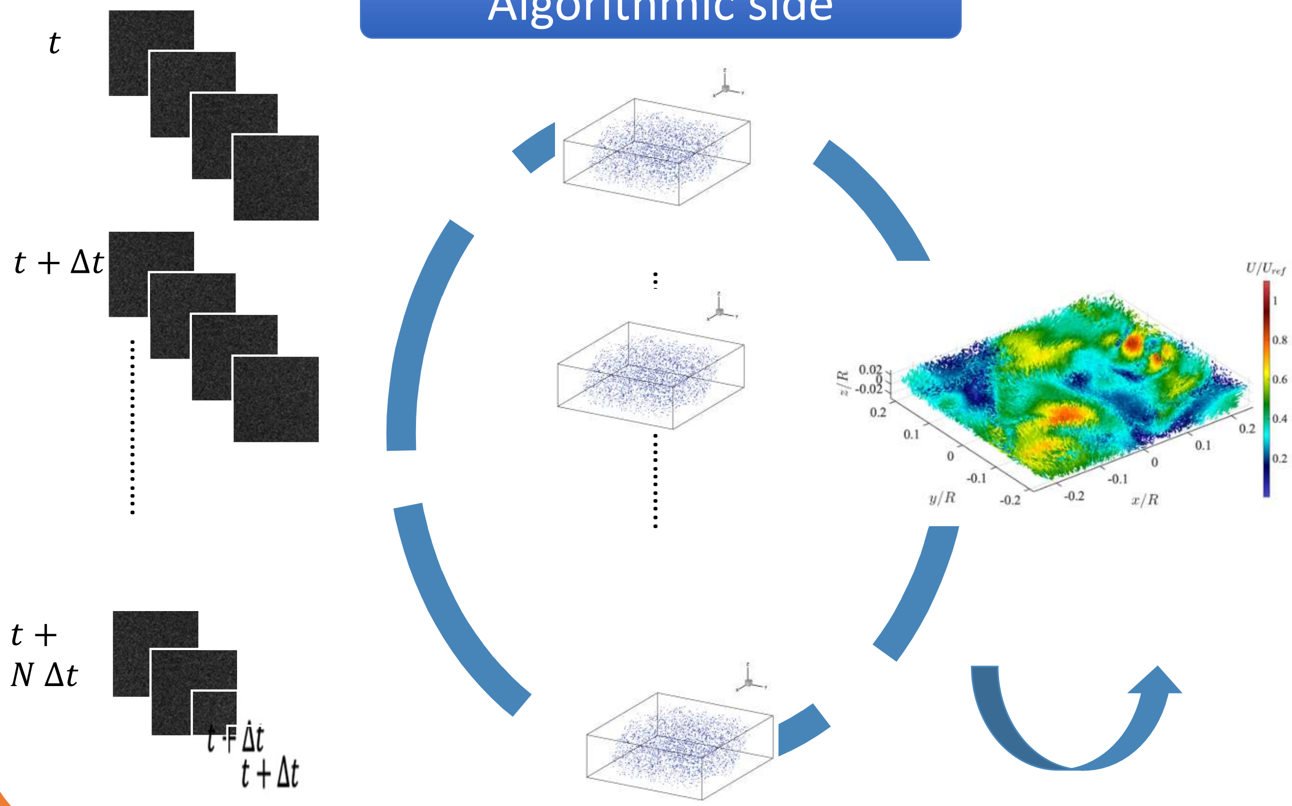
Optical metrology for 3D measurement of velocity field

Experimental side

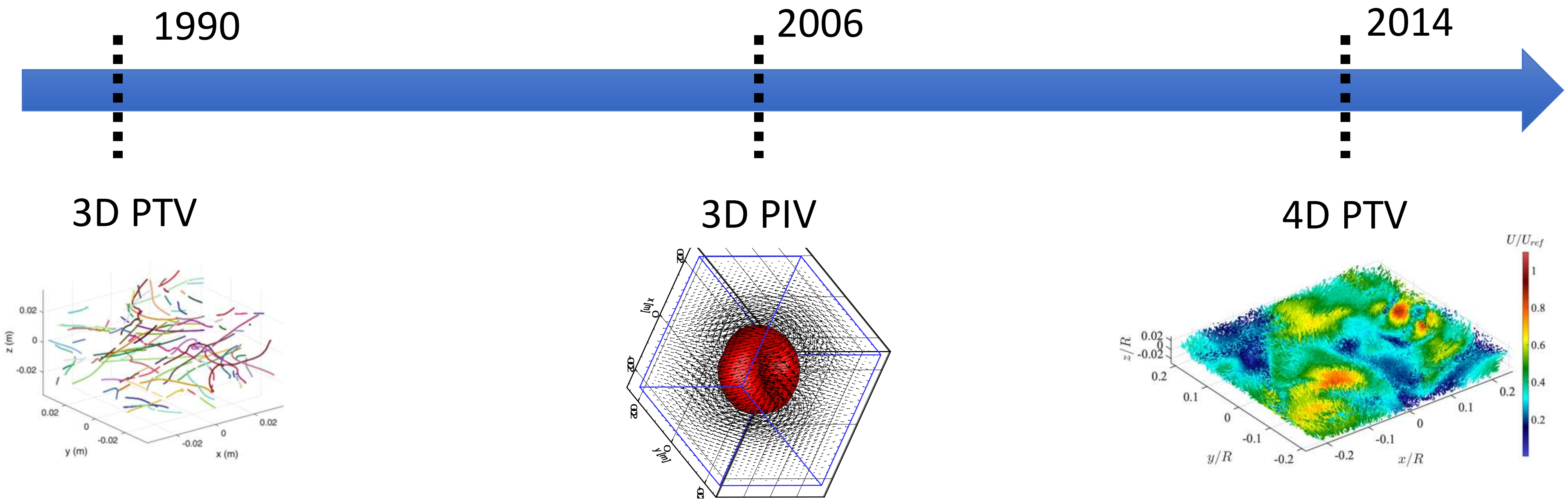


- *Seeded flow*
- *Volumic lighting*
- *Optical systems (4 cameras)*

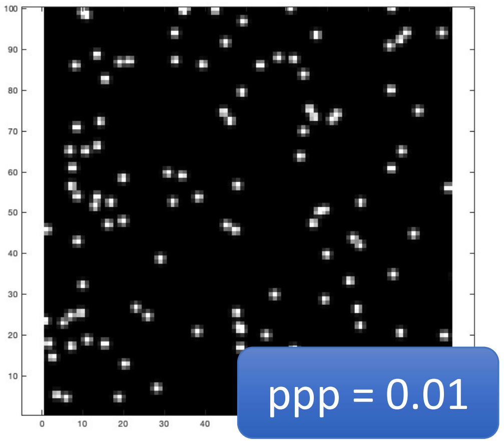
Algorithmic side

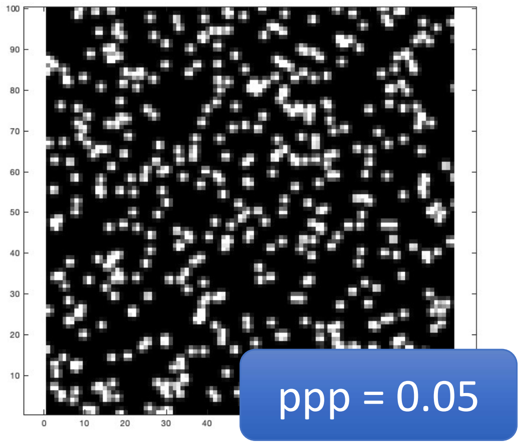


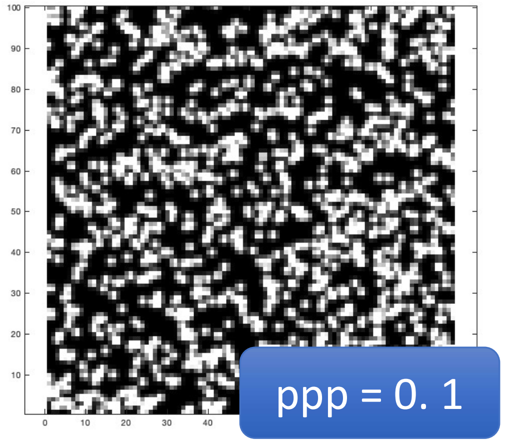
Evolution of PIV / PTV



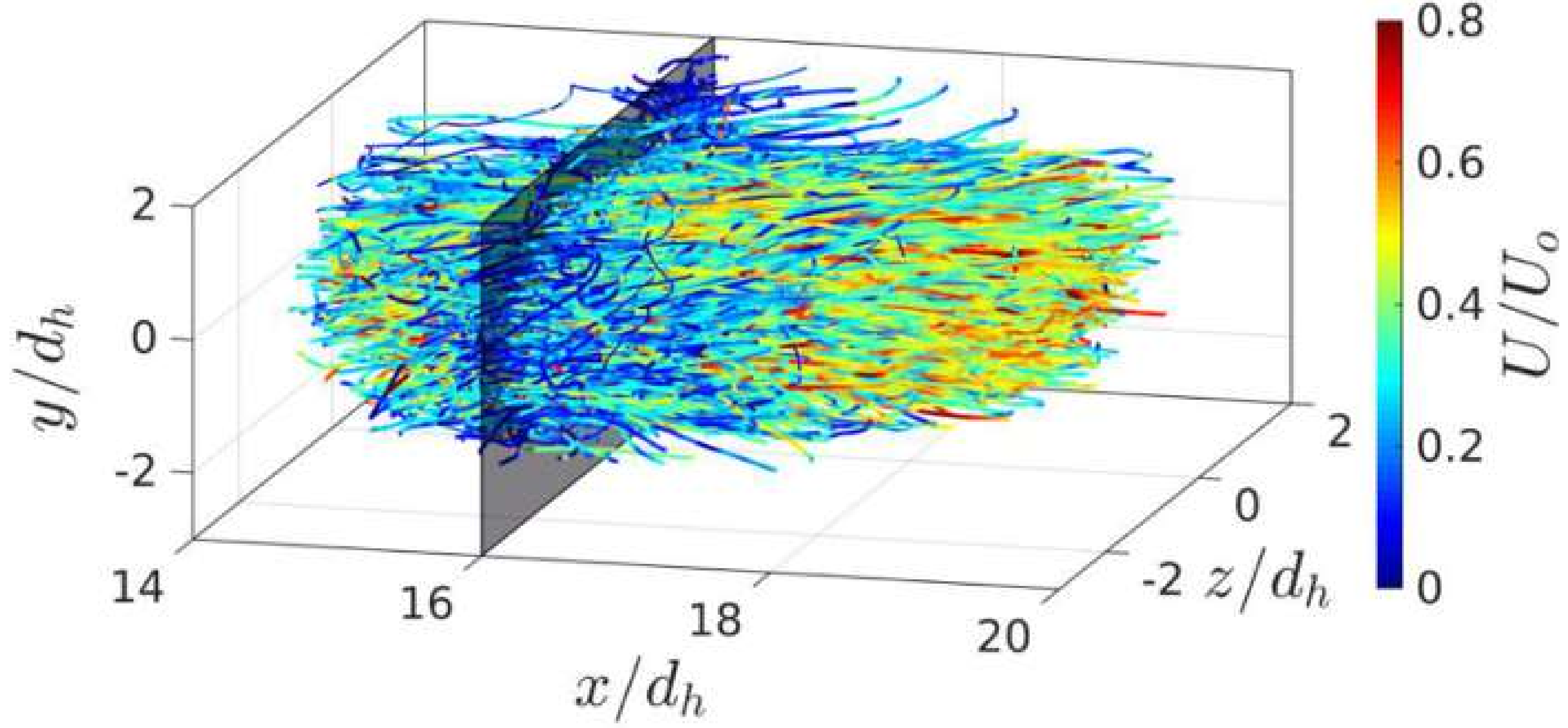
Particle Image density : particle per pixels [ppp]





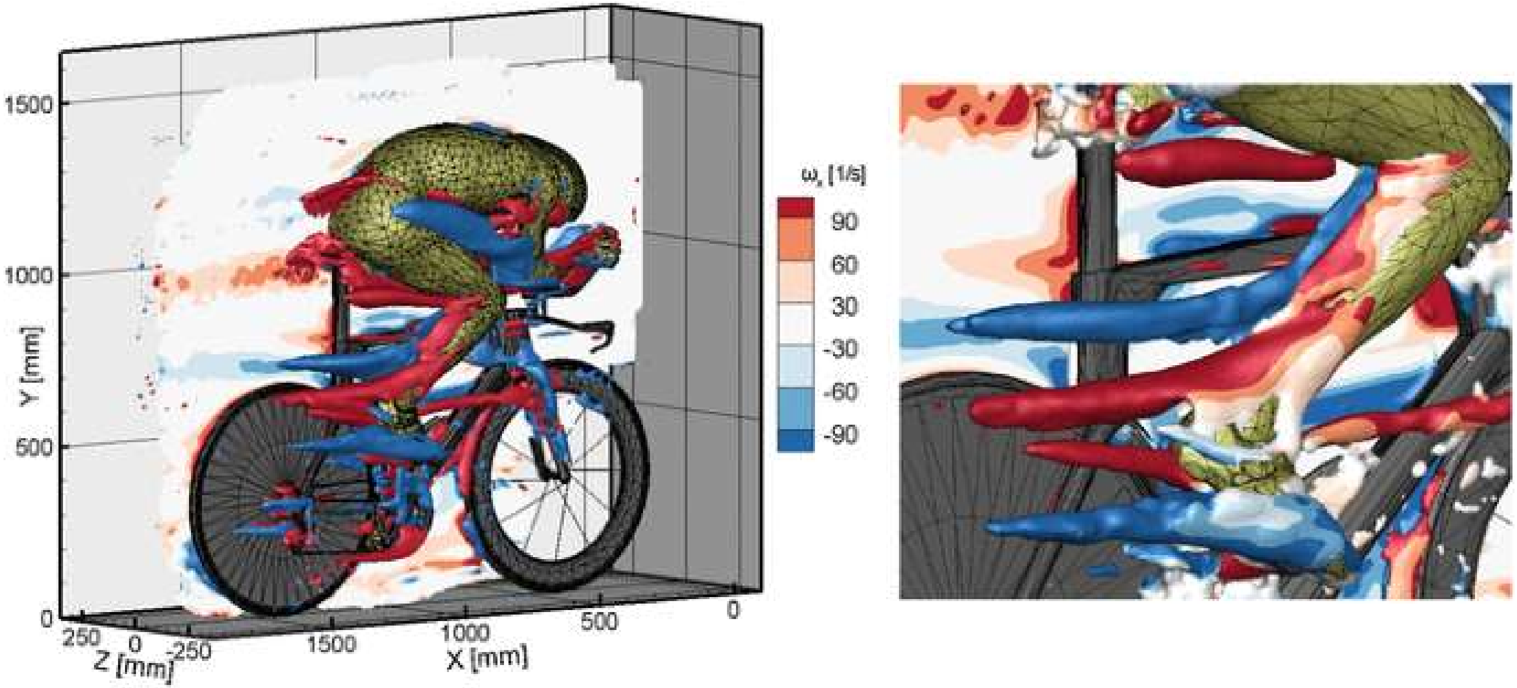


4D Particle Tracking Velocimetry



Up to 100 000 simultaneous tracks

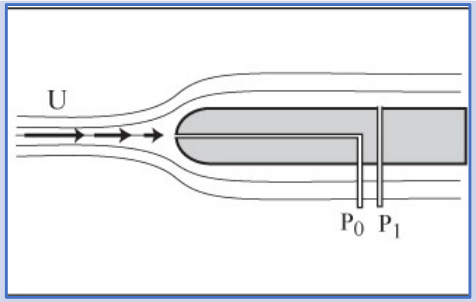
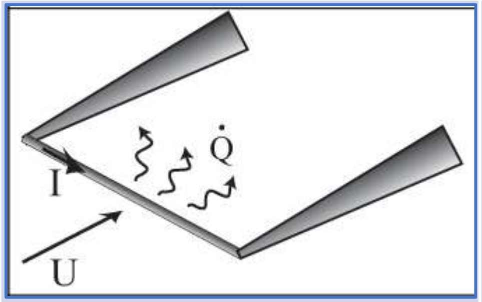
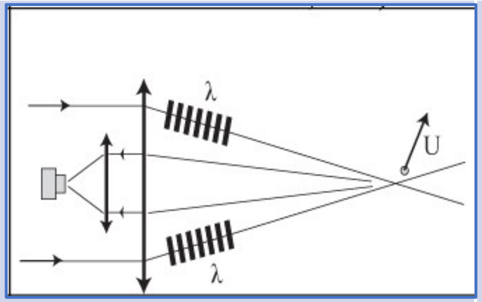
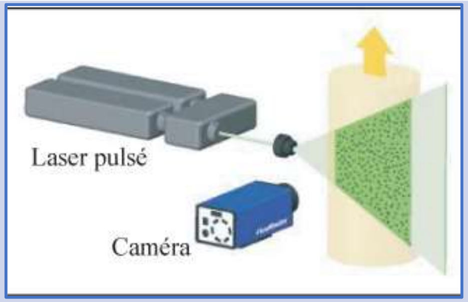
3D PIV



(a) (b)

Sciacchitano et al. *Experiments in Fluids*, 2018

Velocity measurements

	Pitot Tube	Hot Wire Anemometry	Laser Doppler Anemometry	Particle Image Velocimetry
Sketch				
Principle	Two pressure measurements: static and dynamics Bernoulli	Measure of dissipated Joule power in a wire	Interferometric measurement of a Doppler shift on scattering particle	Pattern displacement between two images (correlation)
Pros	Easy to use Cheap (1 k€) Suited for time average	Very high time and space resolution Suited for fluctuation measurements Easy to use Medium price (10 k€)	Non intrusive High time and space resolution Suited for fluctuations Suited for several components	Non intrusive 2D measurements 2 or 3 components
Cons	Highly intrusive Very poor time & space resolution	Intrusive, fragile Non linear calibration Sensitive to temperature	Non regular sampling High price (50-100 k€) Seeding required Difficult settings	Poor time resolution High price (100 k€) Seeding required