Particle Image Velocimetry

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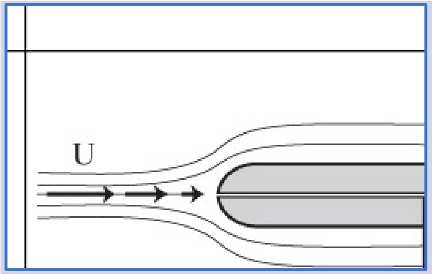
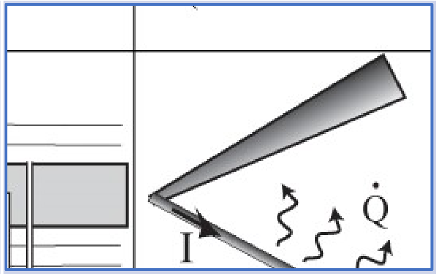
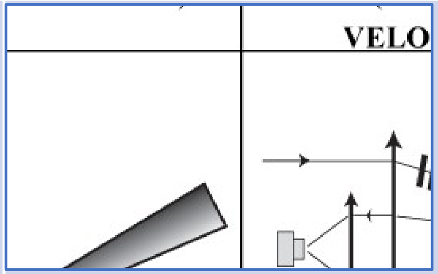
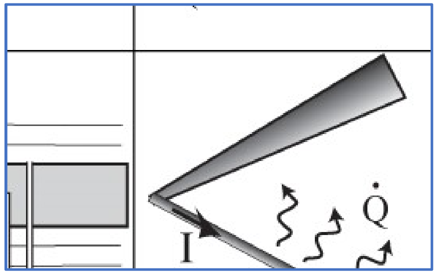
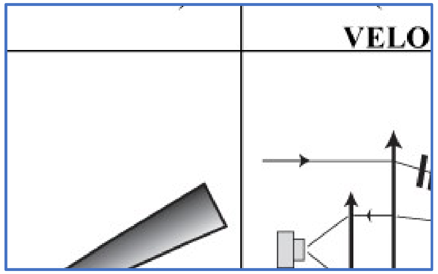
Why PIV ?

	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

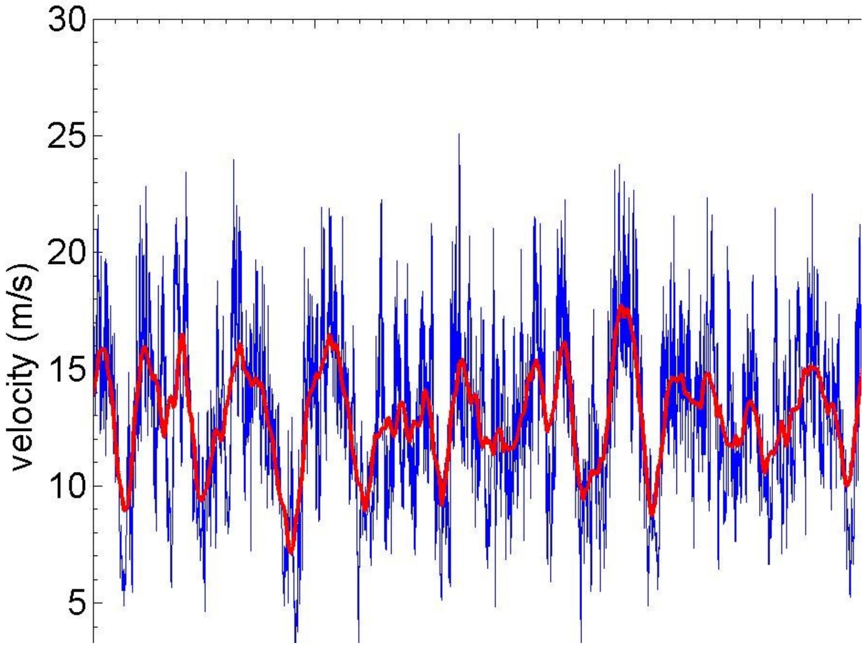
Why PIV ?

Hot-Wire





Laser Doppler Anemometry

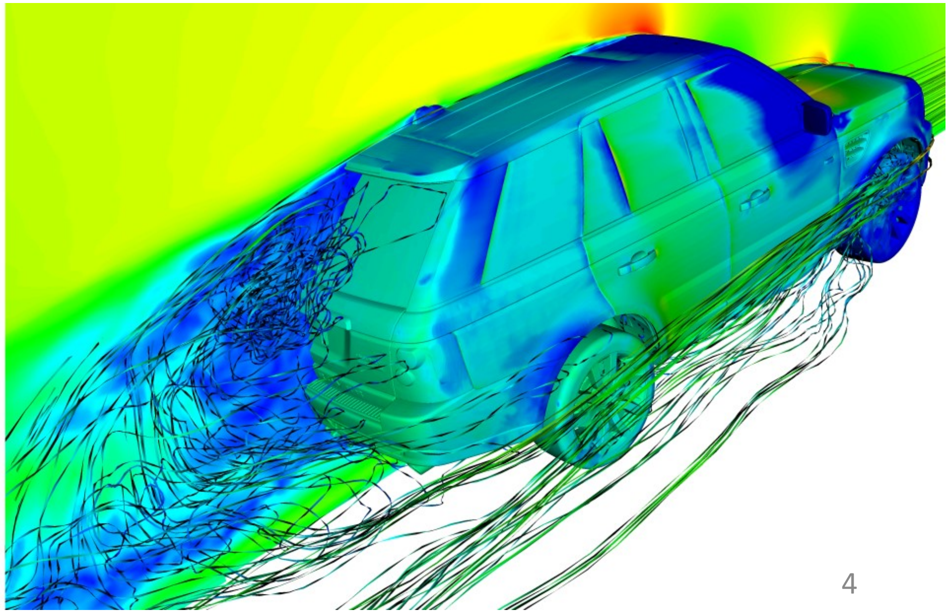


1D time resolved signals

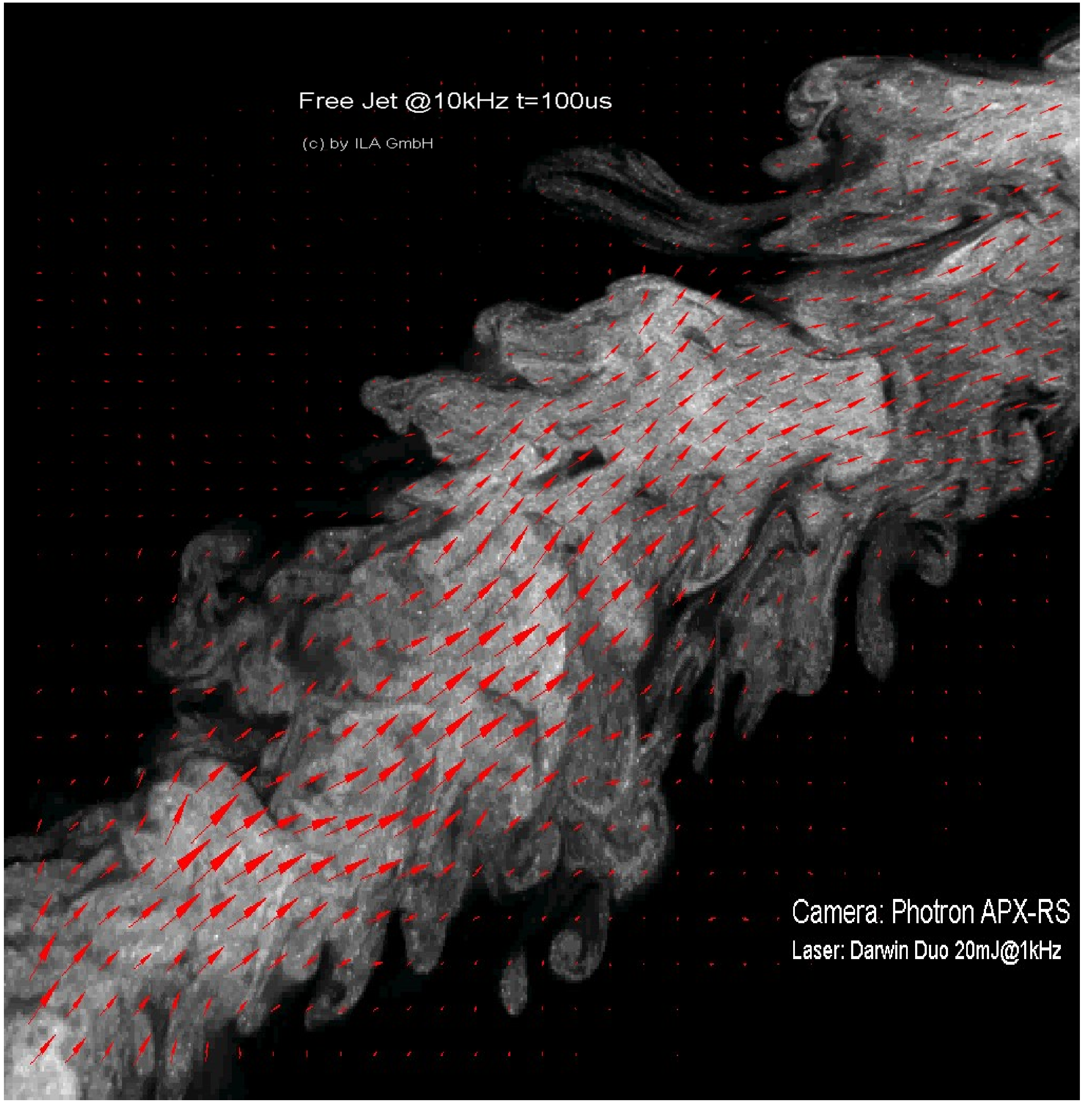
Why PIV ?

Experiment: more or less cheap

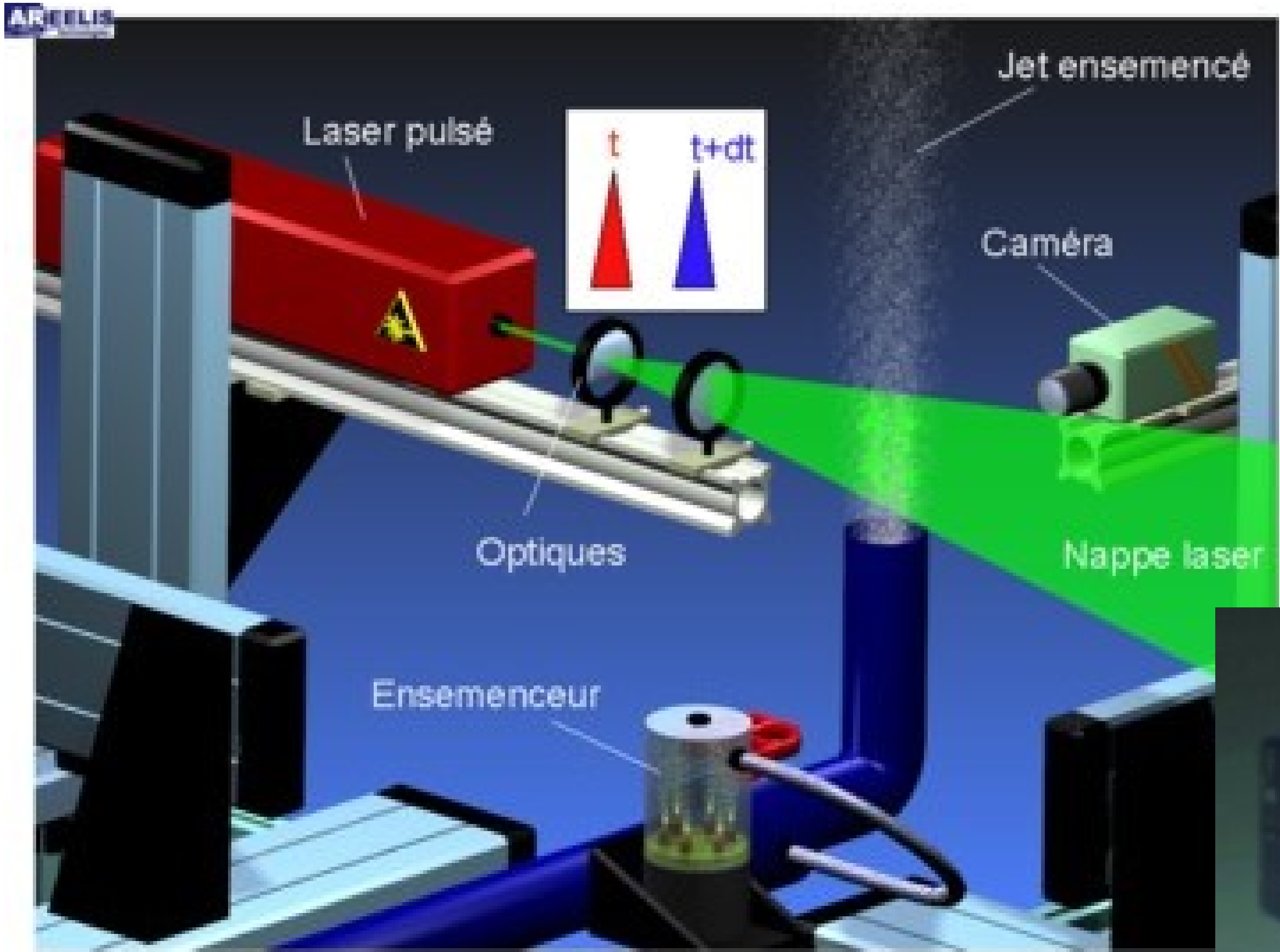
Resolved numerical simulations
expensive in time



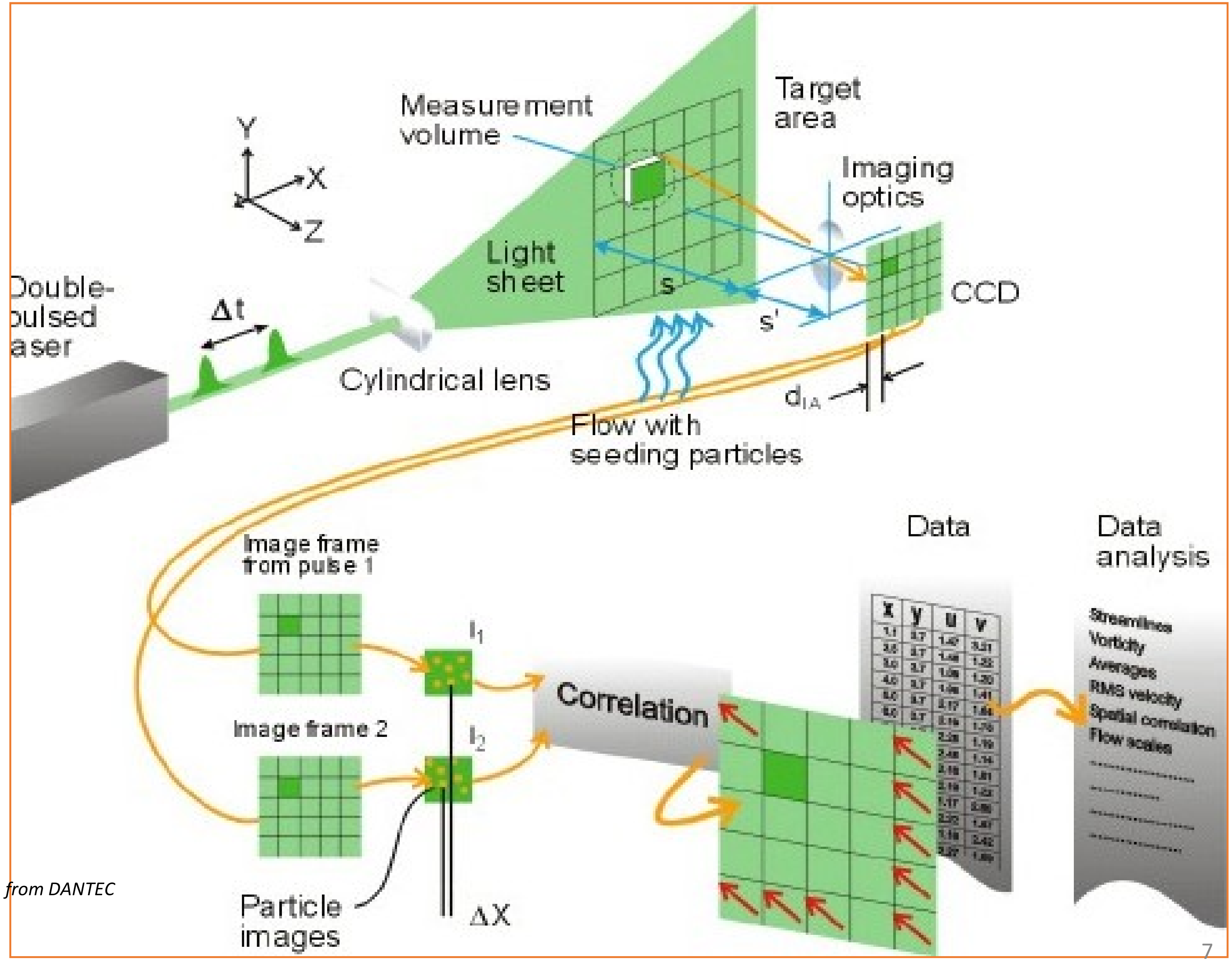
Why PIV ?


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

Particles Image Velocimetry: principles

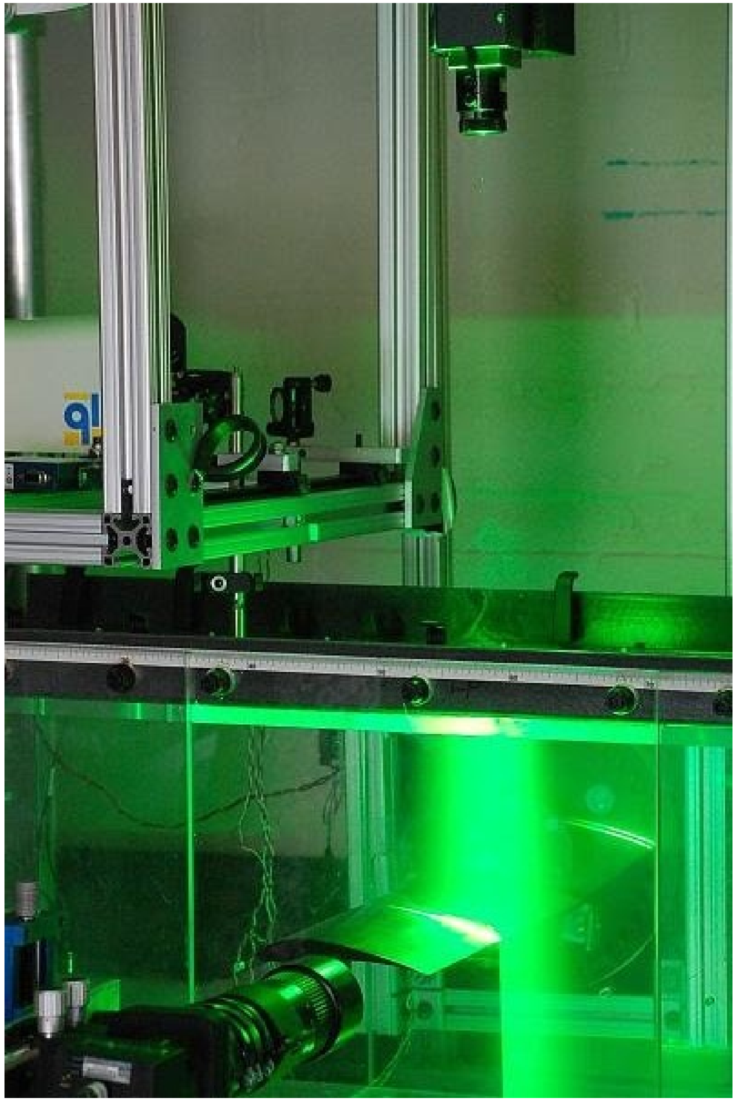


Particles Image Velocimetry: principles

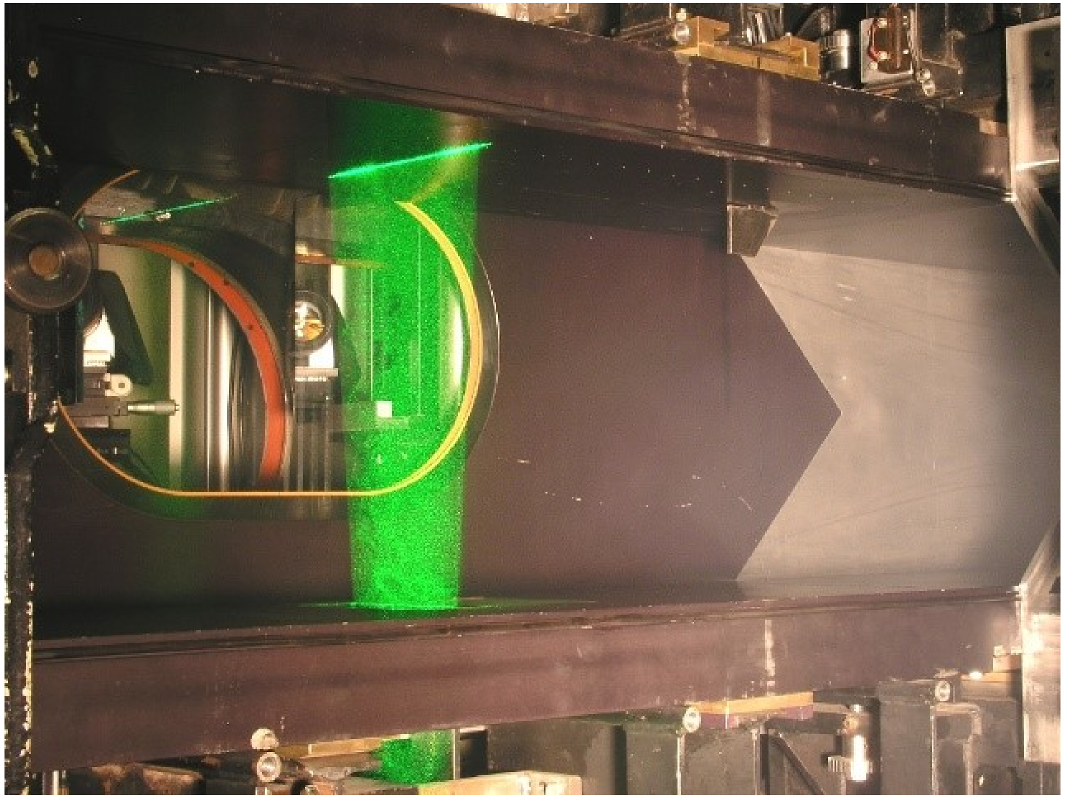


from DANTEC

Particles Image Velocimetry: example

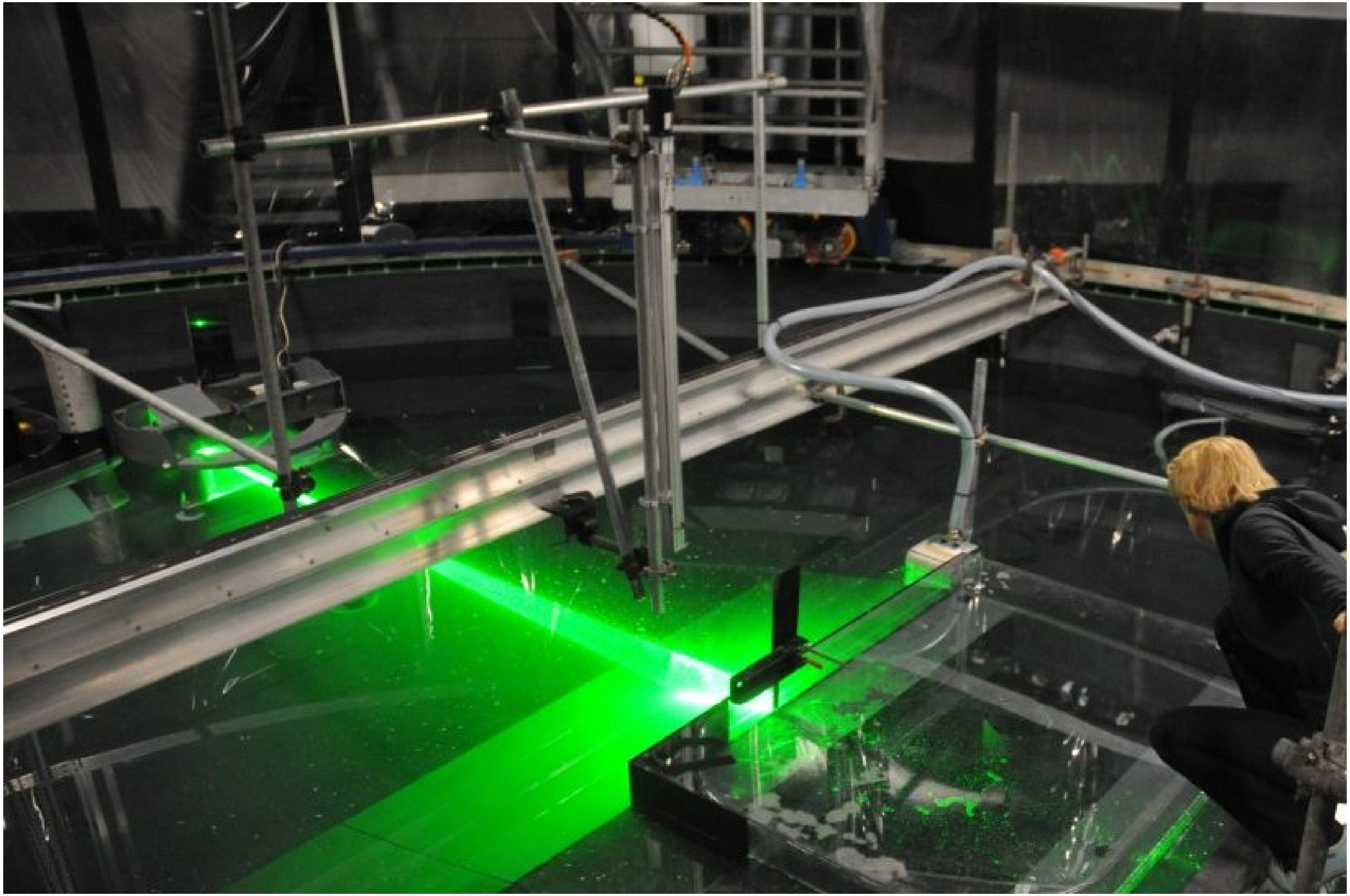


Wind-tunnel



Water channel

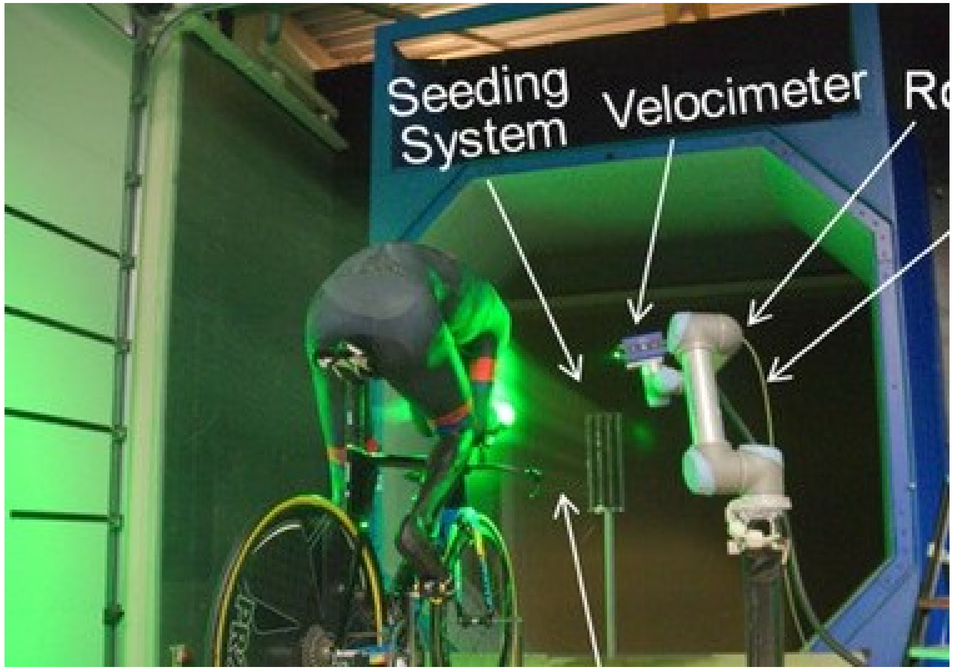
Particles Image Velocimetry: example



Coriolis platform

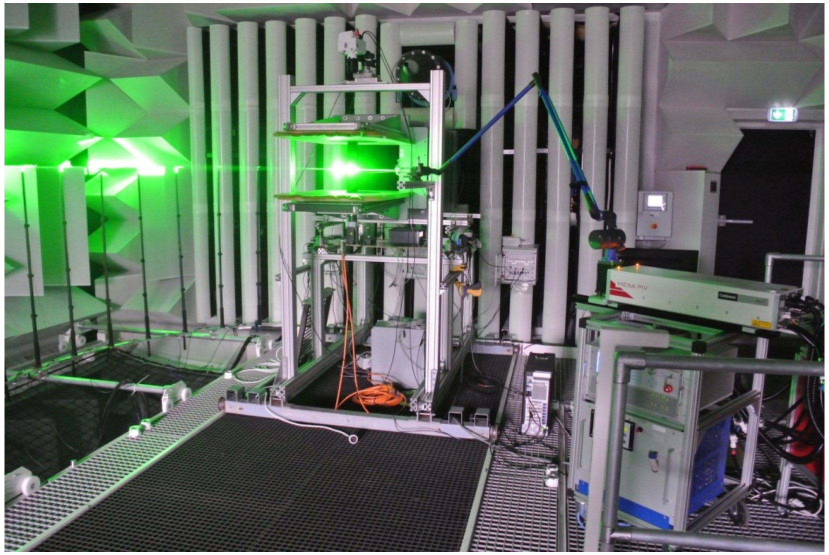
Particles Image Velocimetry: example

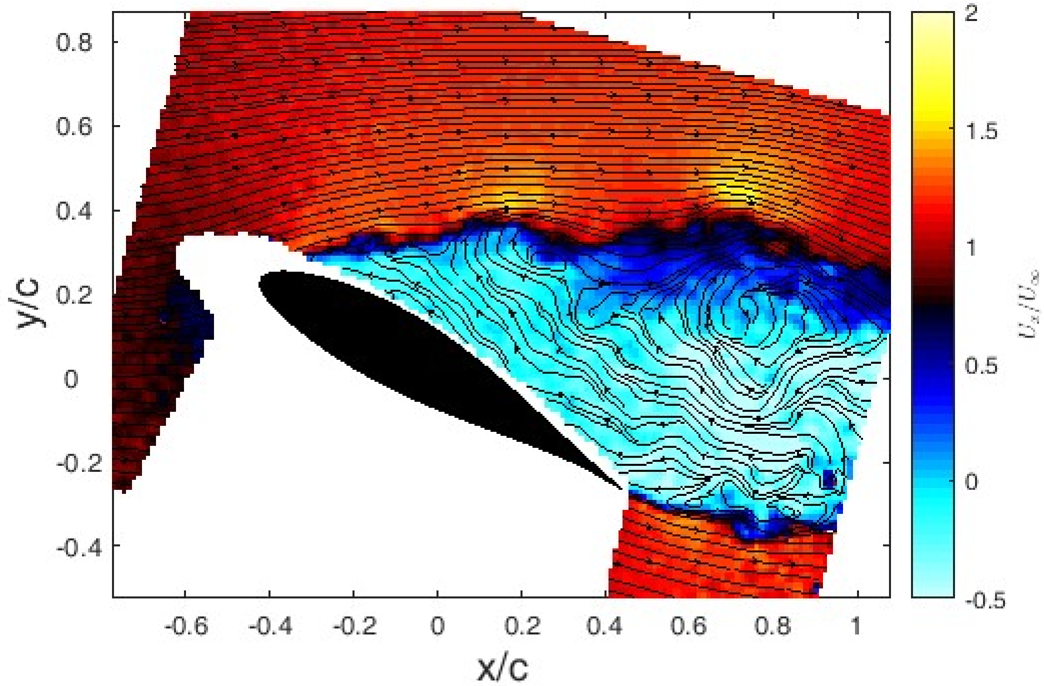
Lavision website

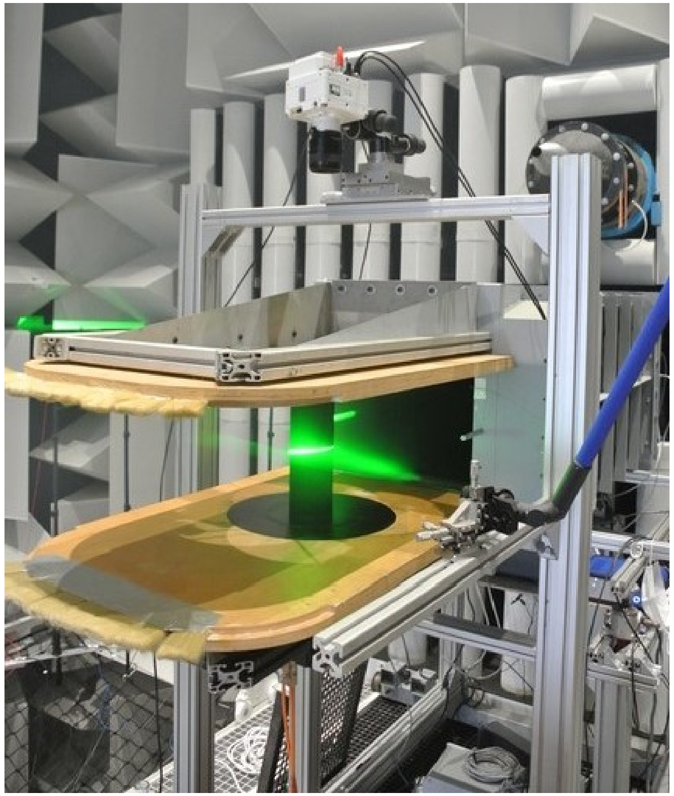


Sciacchitano et al. *Experiments in Fluids*, 2018

Particles Image Velocimetry: example





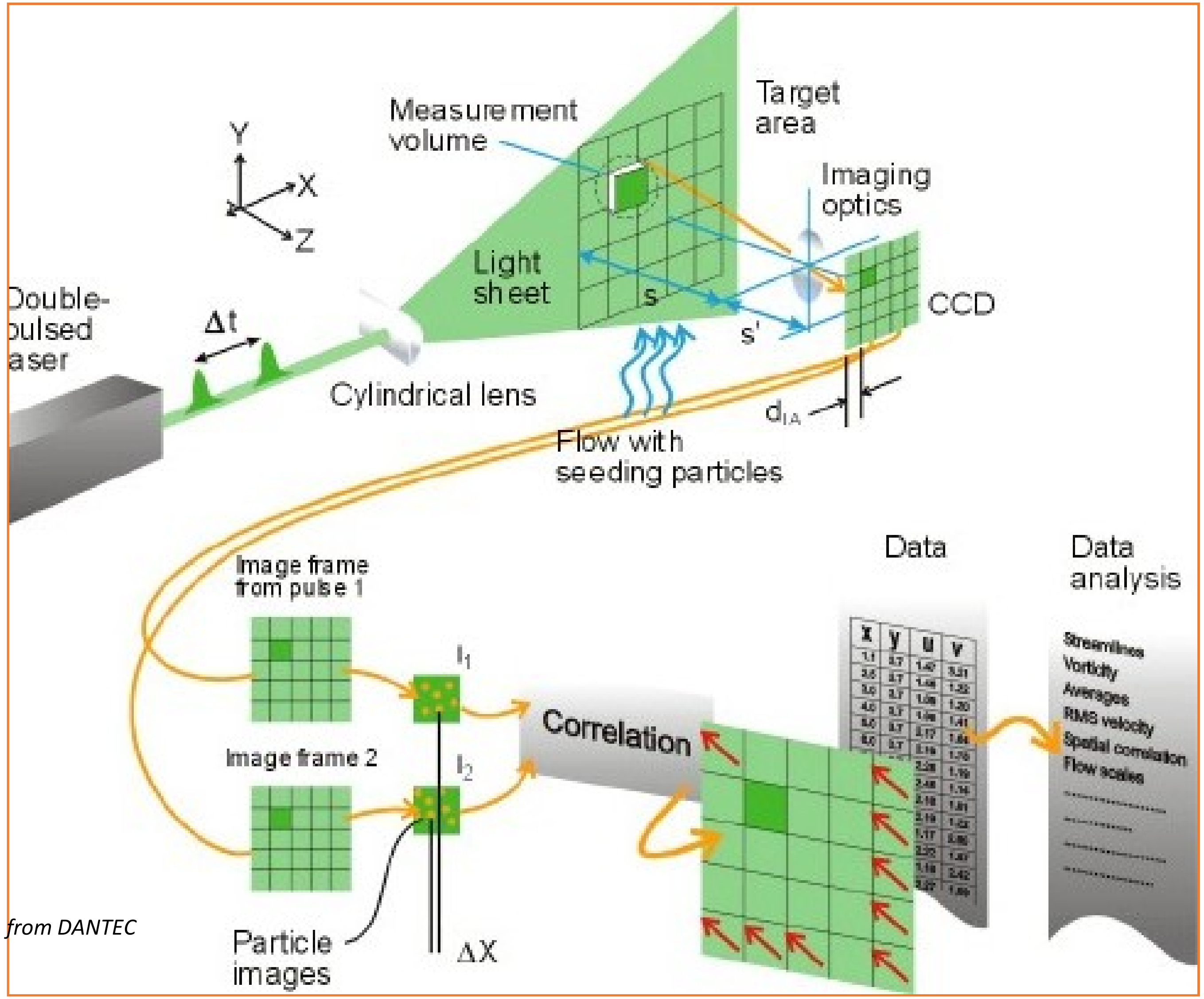


Airfoil in a wind-tunnel
Collaboration ENSTA-LMFA
PhD Lisa Sicard

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

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:

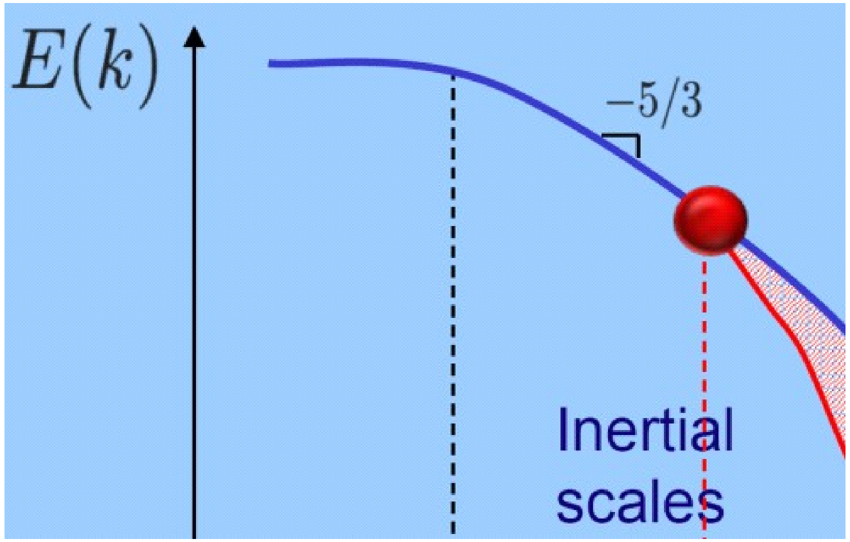
- Neutrally buoyant
- As small as possible

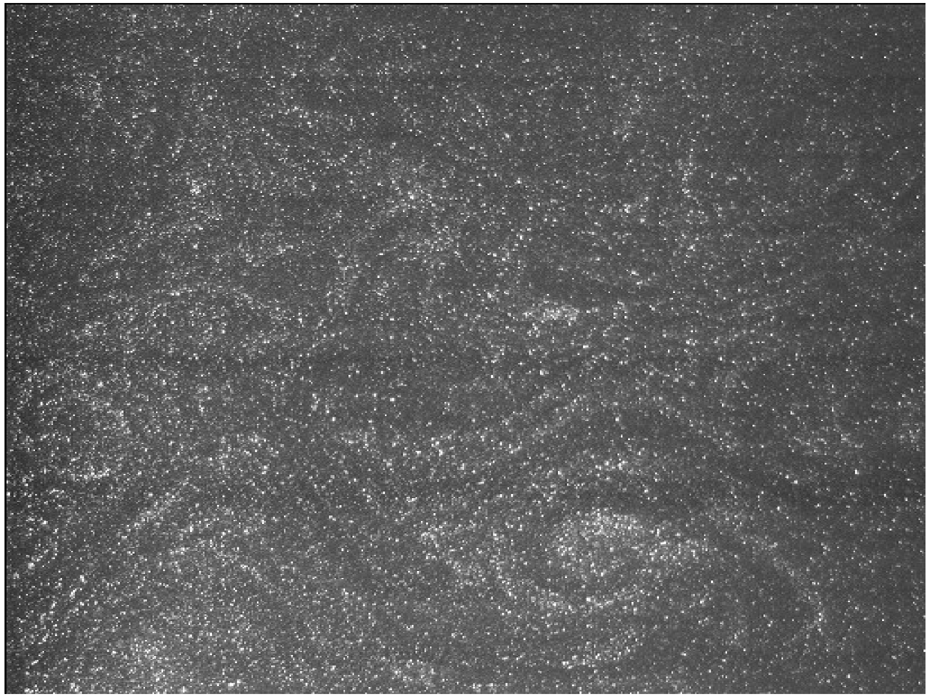
High visibility:

- Good light scatering
- Large enough

Spherical shape

Air vs water





Tracers

A PIV guy's cupboard:

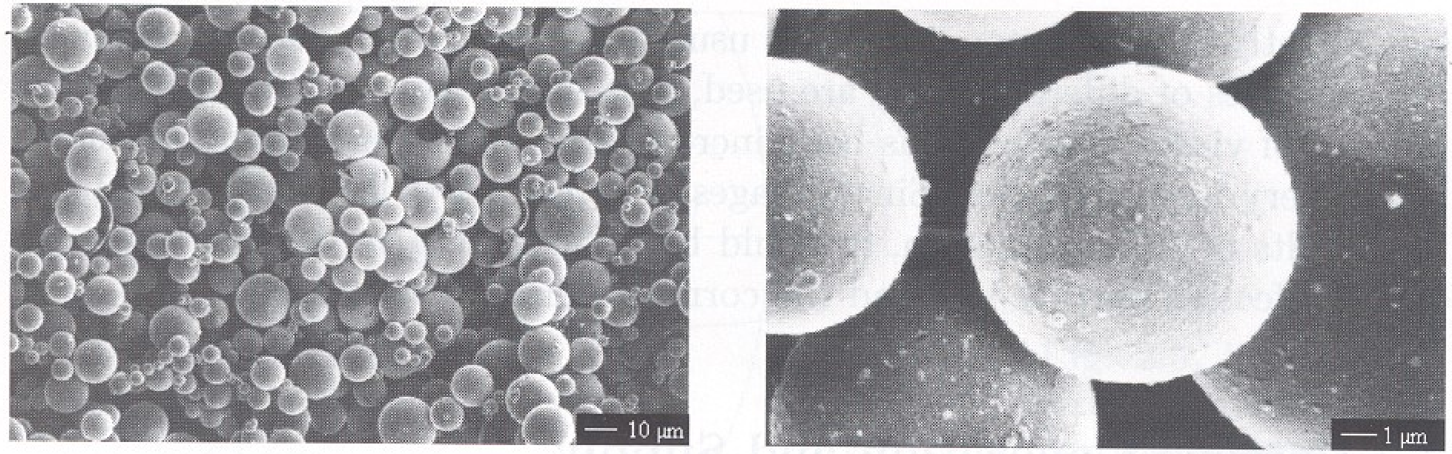


Fig. 2.8. Micrographs of silver coated hollow glass spheres: ×500 and ×5000.

Tracers

Aerosol generator

Helium-filled soap bubble generator

Tracers

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

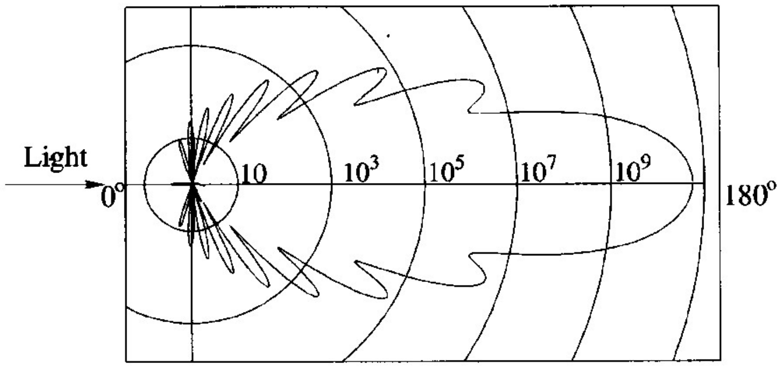


Fig. 2.5. Light scattering by a 1 μm glass particle in water.

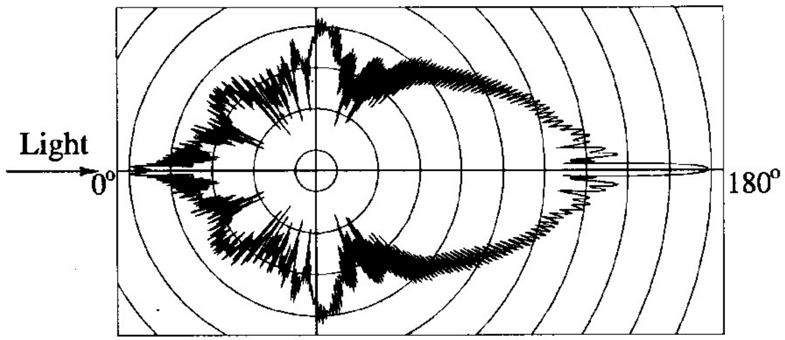


Fig. 2.6. Light scattering by a 10 μm glass particle in water.

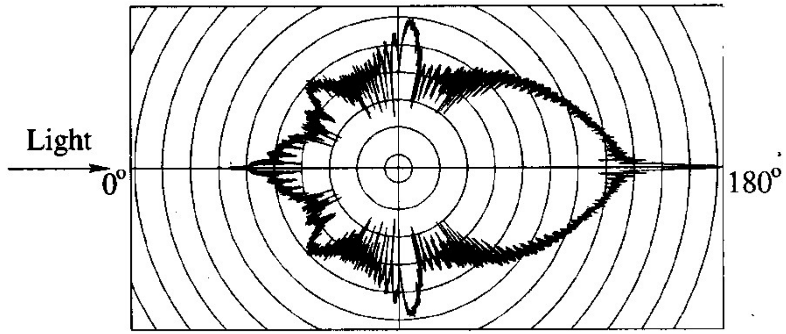


Fig. 2.7. Light scattering by a 30 μm glass particle in water.

Light source

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

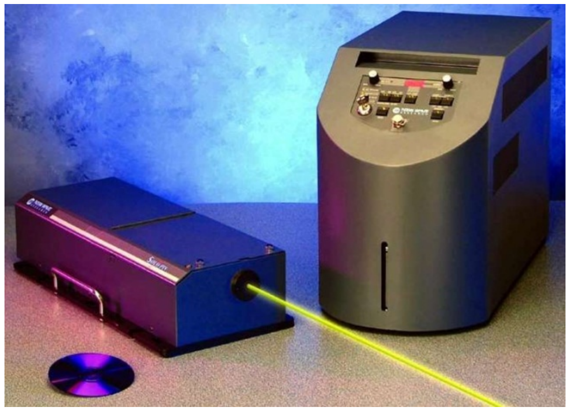
Continuous Lasers
Typical power : 0.5 – 5 W (5-50 keuros)
(1 W correspond to 30 mJ per pulse at 30Hz)

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)

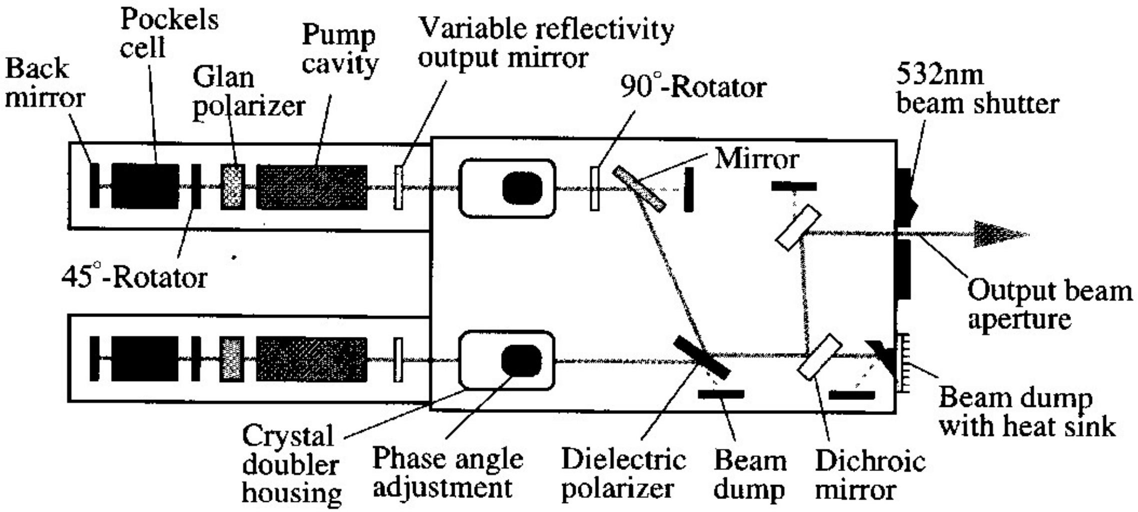
Rate:
- Lower range (10-30 Hz)
- Higher range (1-10 kHz)

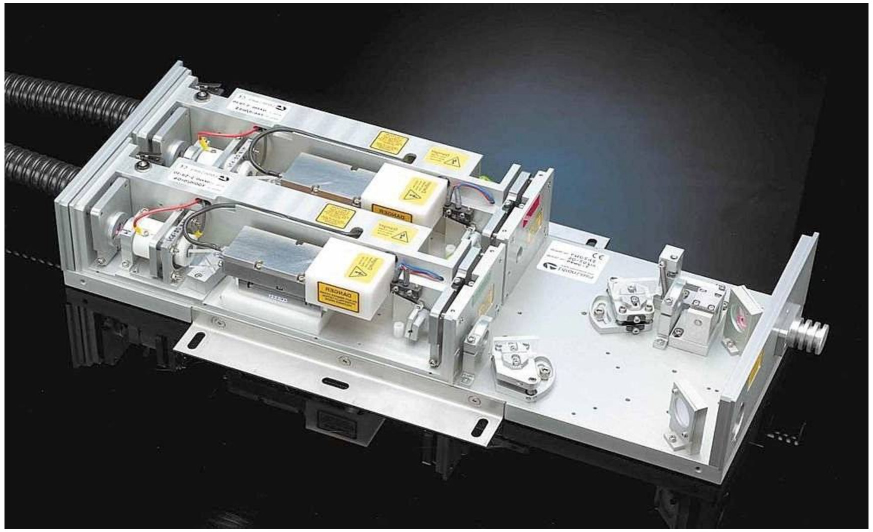
MINILITE™ PIV SPECIFICATIONS

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

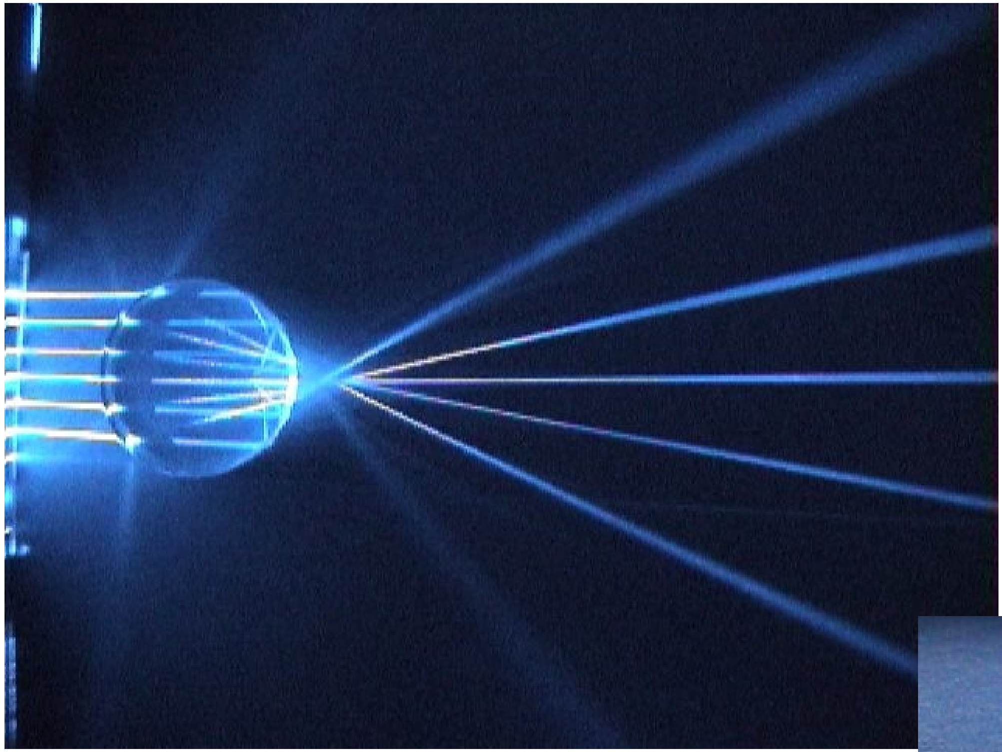


Double cavity pulsed Laser

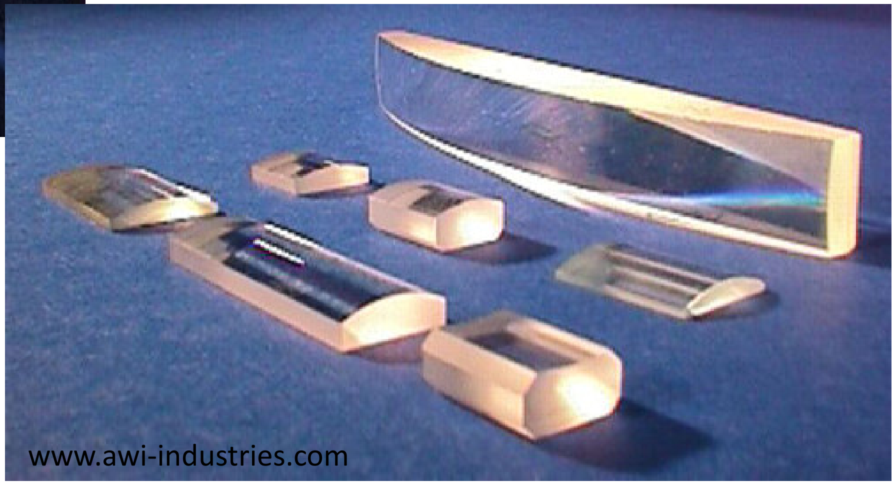




Light source

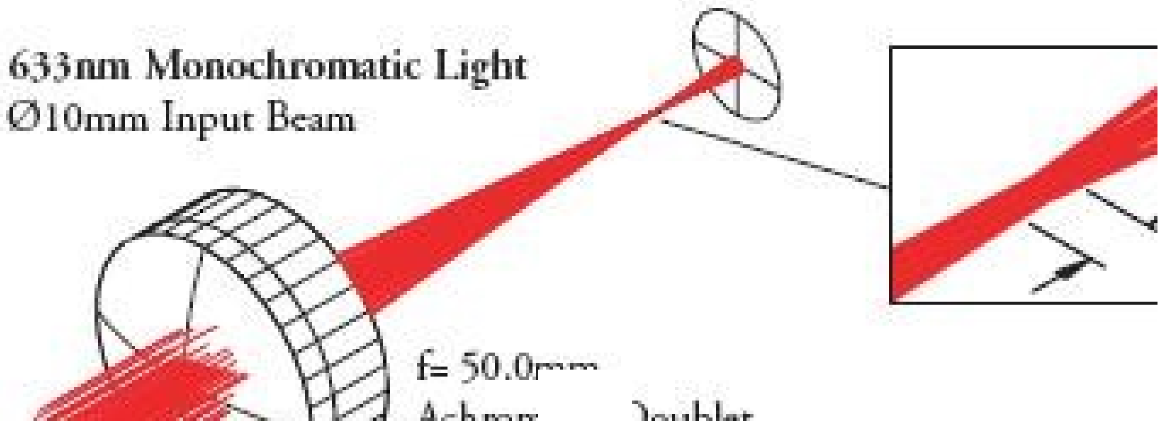


Refraction from a cylindrical lense



Light source

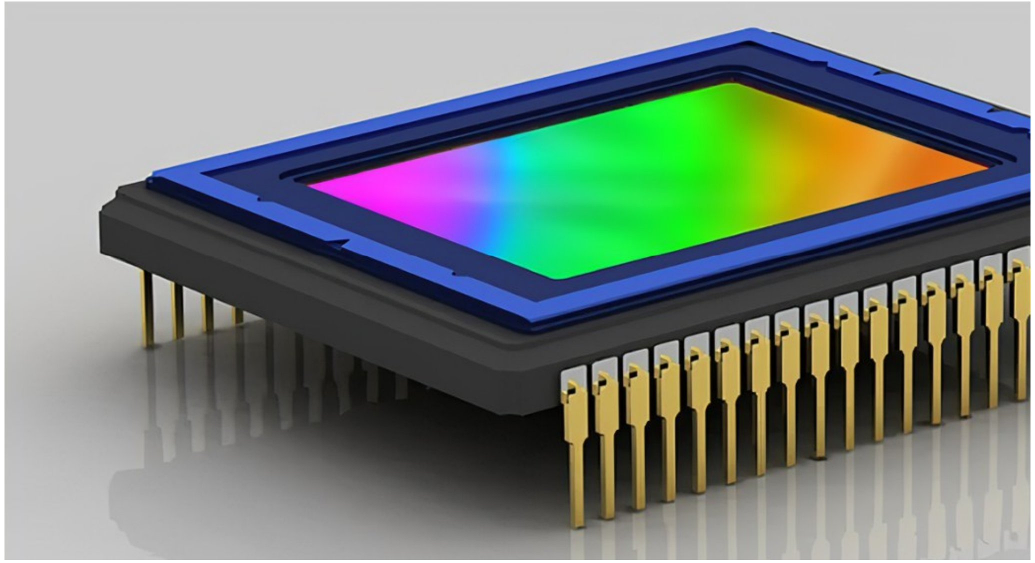
Thickness setting

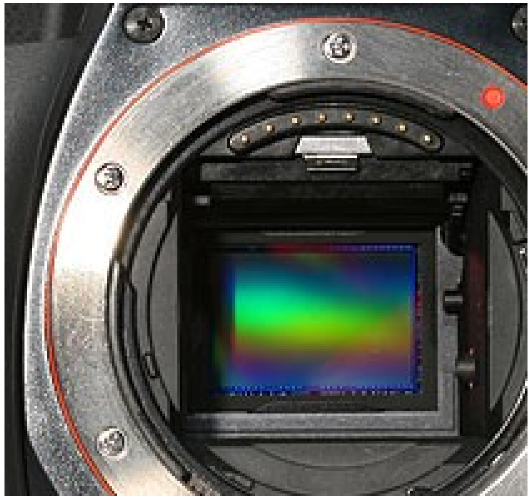


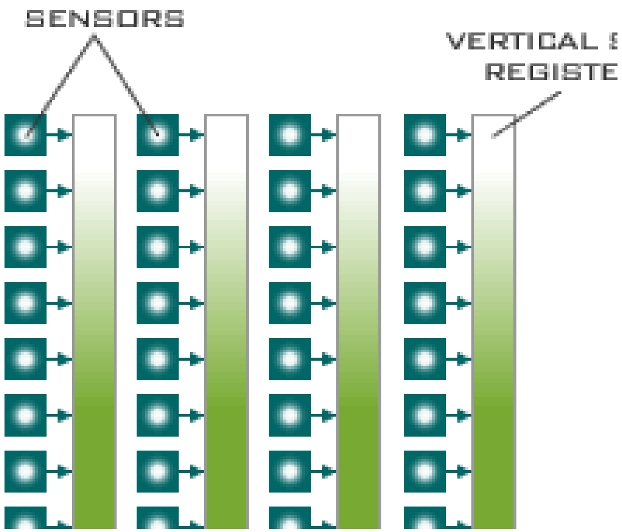
Dantec

Oxford laser

Cameras







Resolutions :
1000 x 1000 to 5000 x 4000

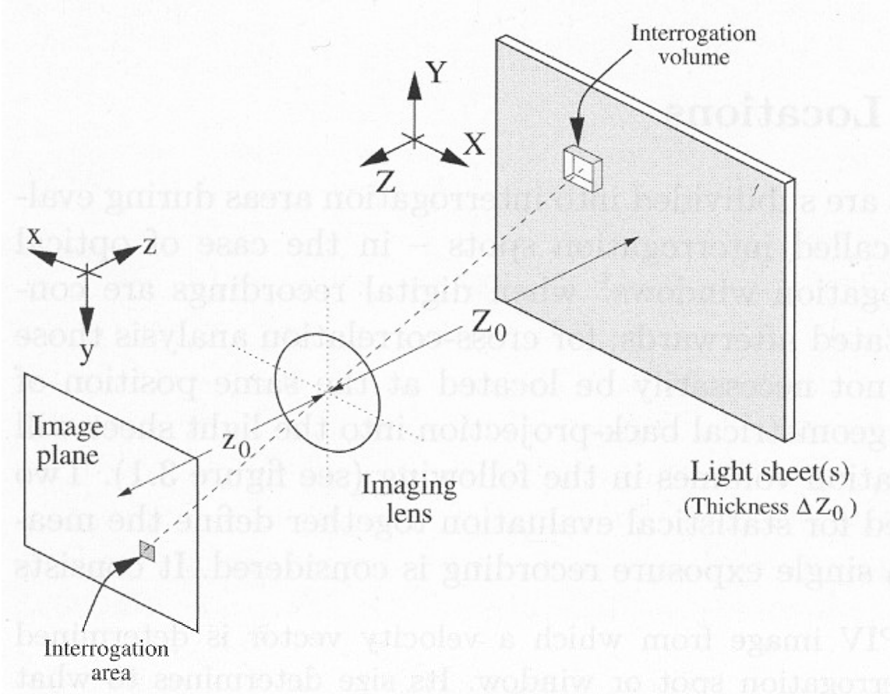
Cameras

	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€

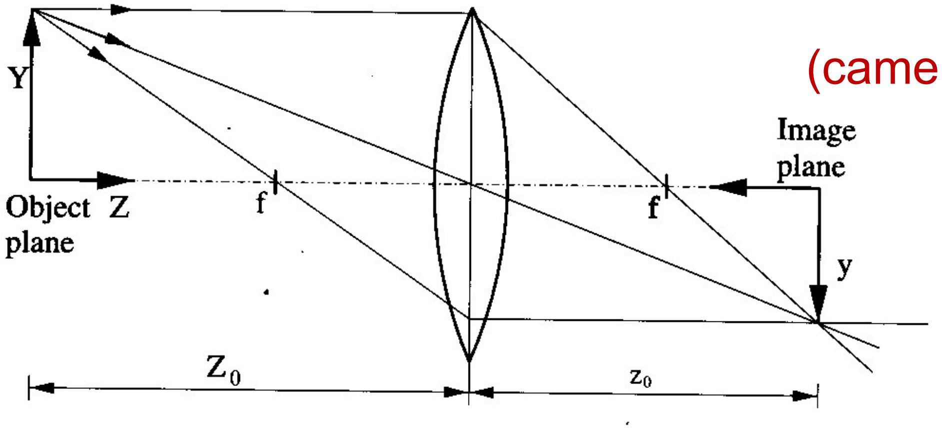
Cameras

Welcome to the photography world !

Images



Magnification:
M = y / Y
= image/object (< 1)



(camera)

Images

Projection error

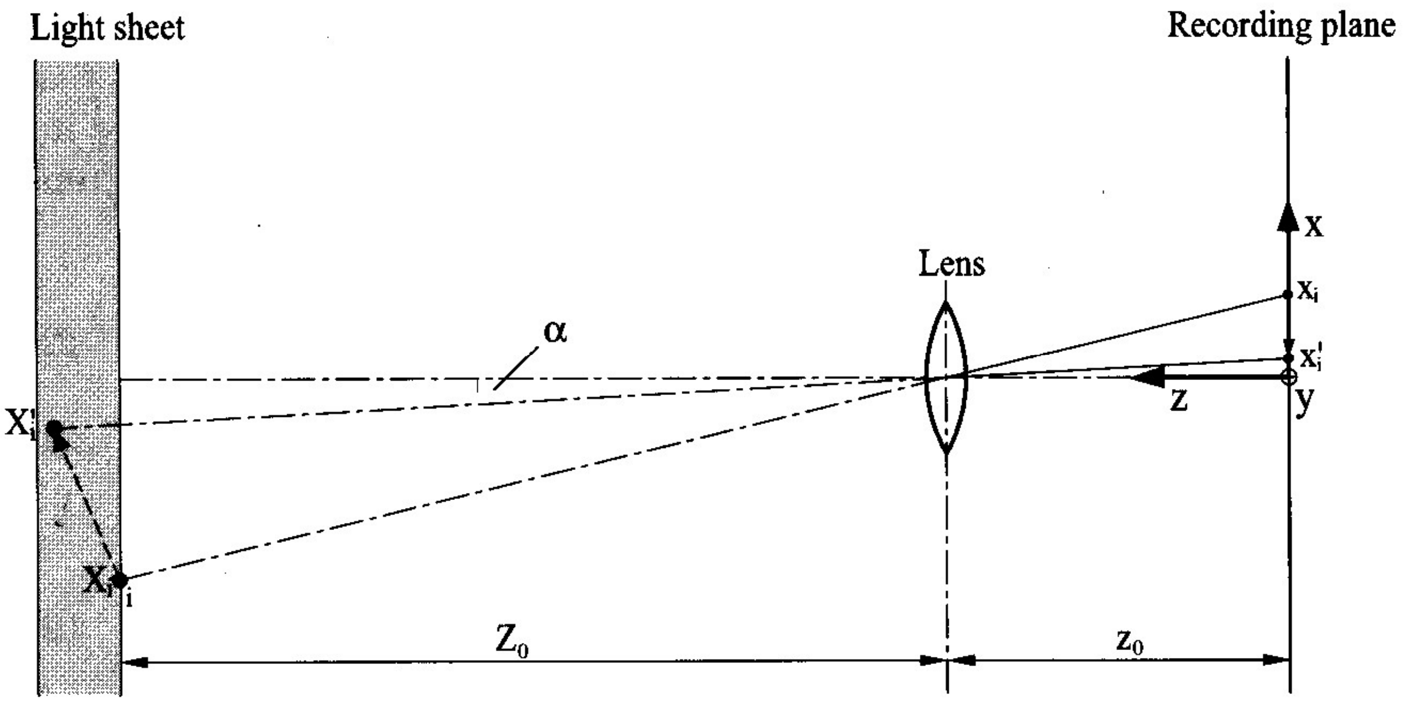
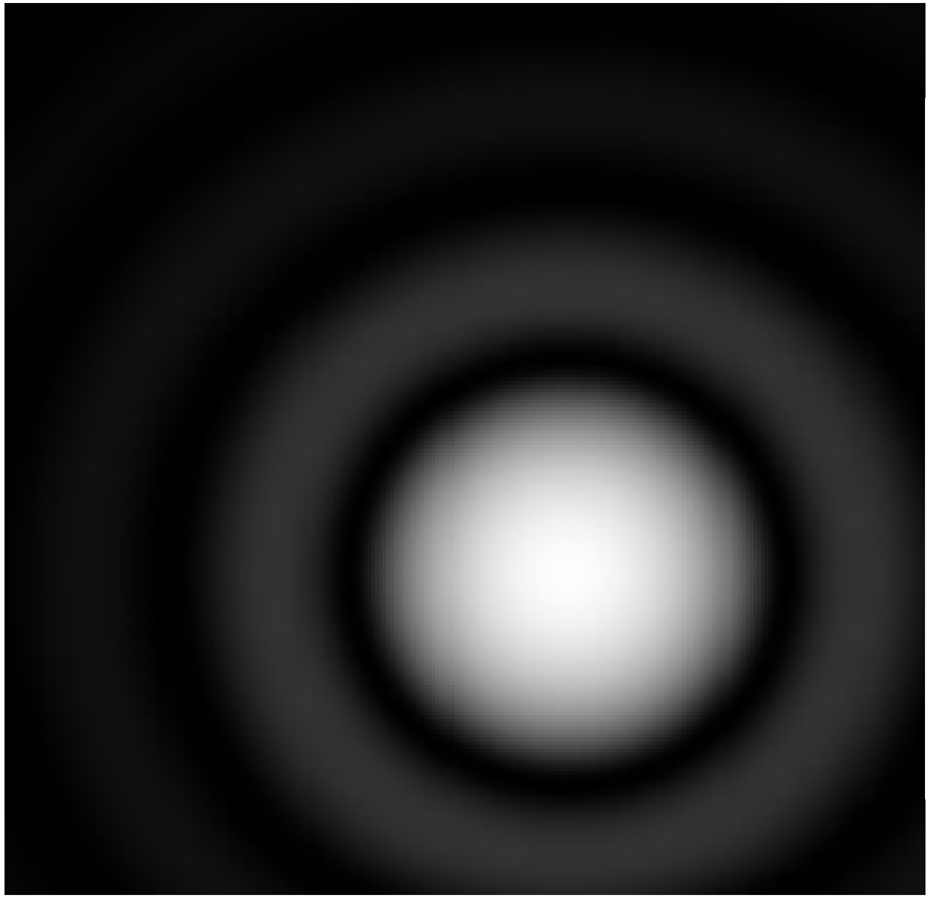
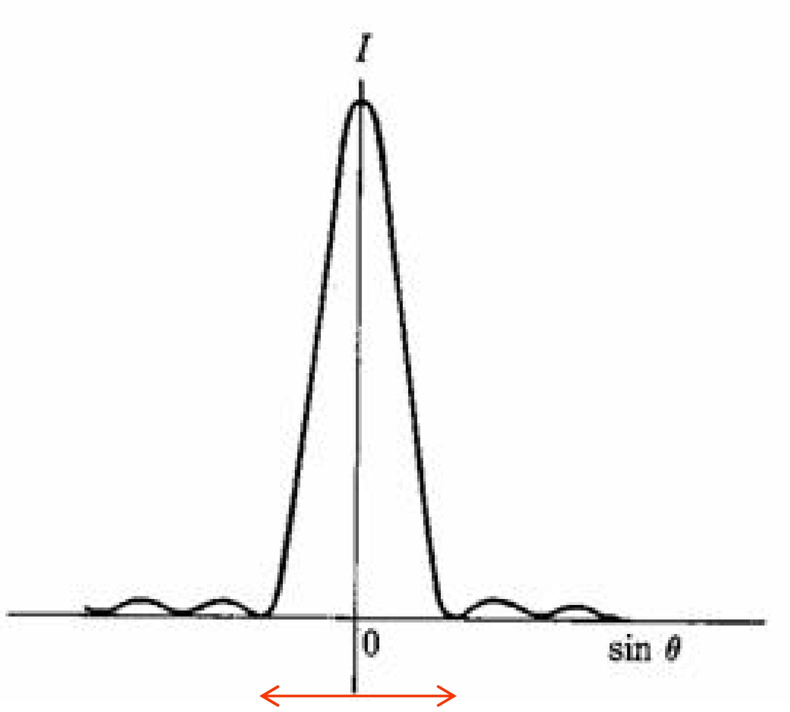


Fig. 2.37. Imaging of a particle within the light sheet on the recording plane.

Images

Diffraction limit: Airy disc





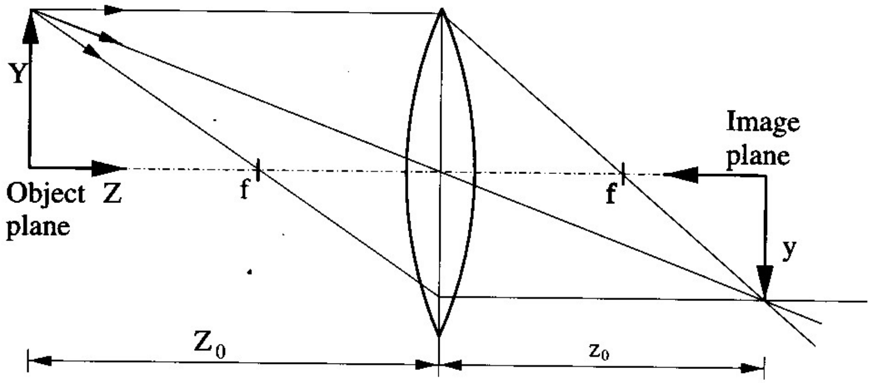
2.44 λ/D

λ:light wave length
D: camera aperture

Images: field of view and field depth

Calibration target

Matching real world coordinates and picture coordinates

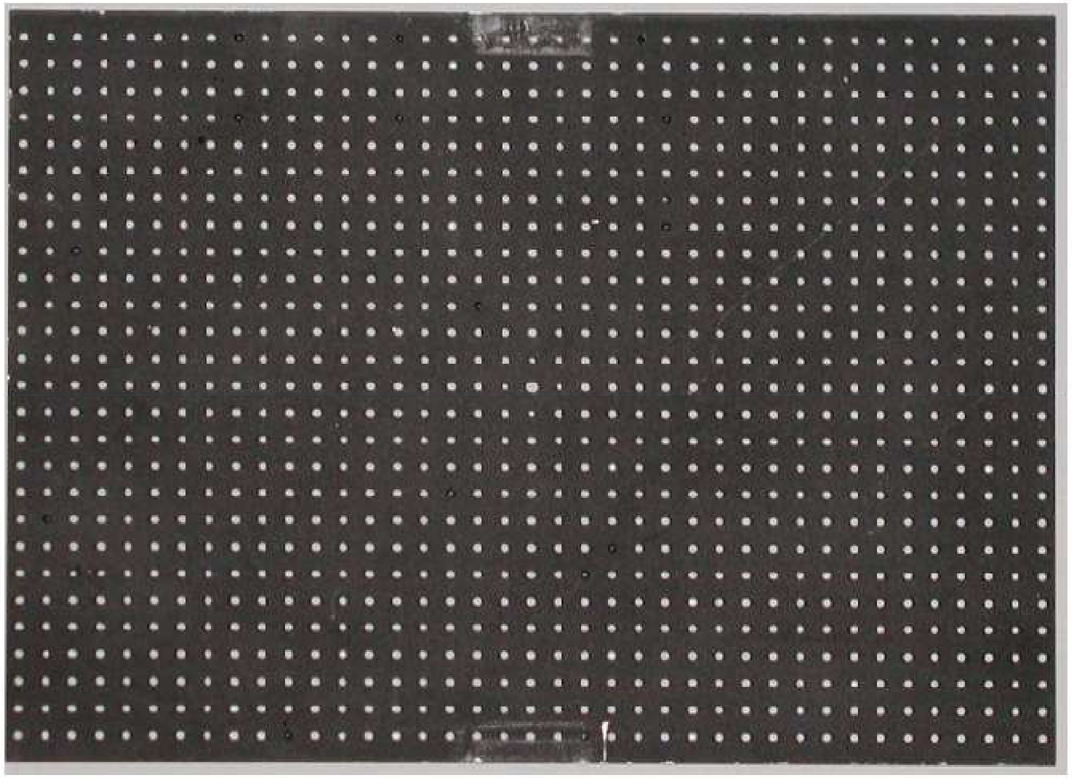


Scale factor

Image distorsion

Calibration target

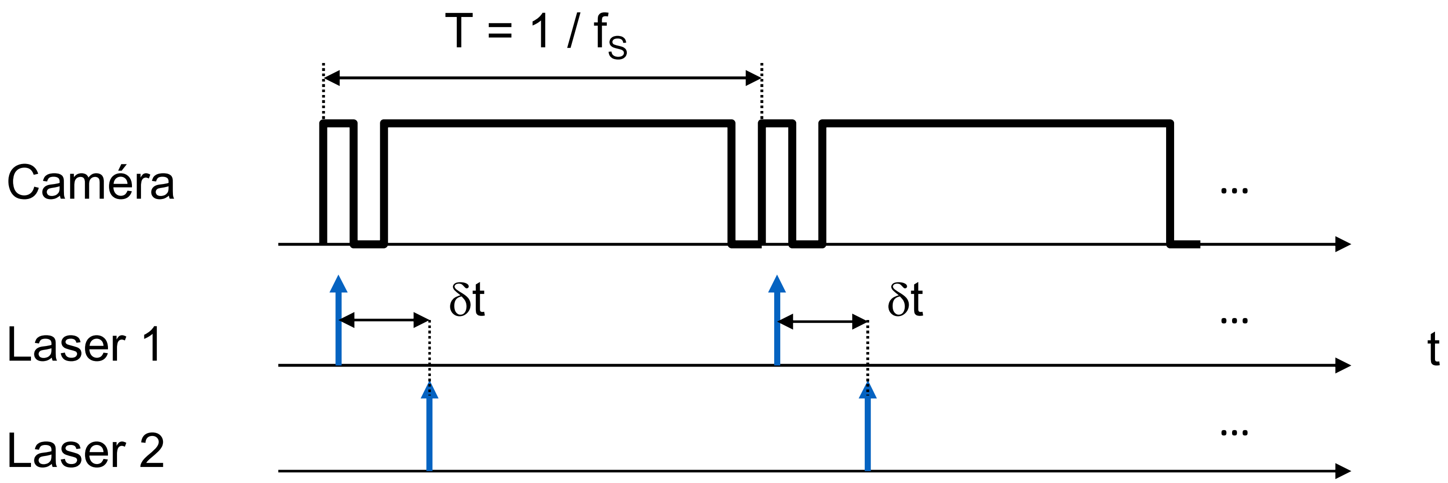
Matching real world coordinates and picture coordinates



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

Image processing only

In-house acquisition system

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   - **Bias**
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   - 3D PIV
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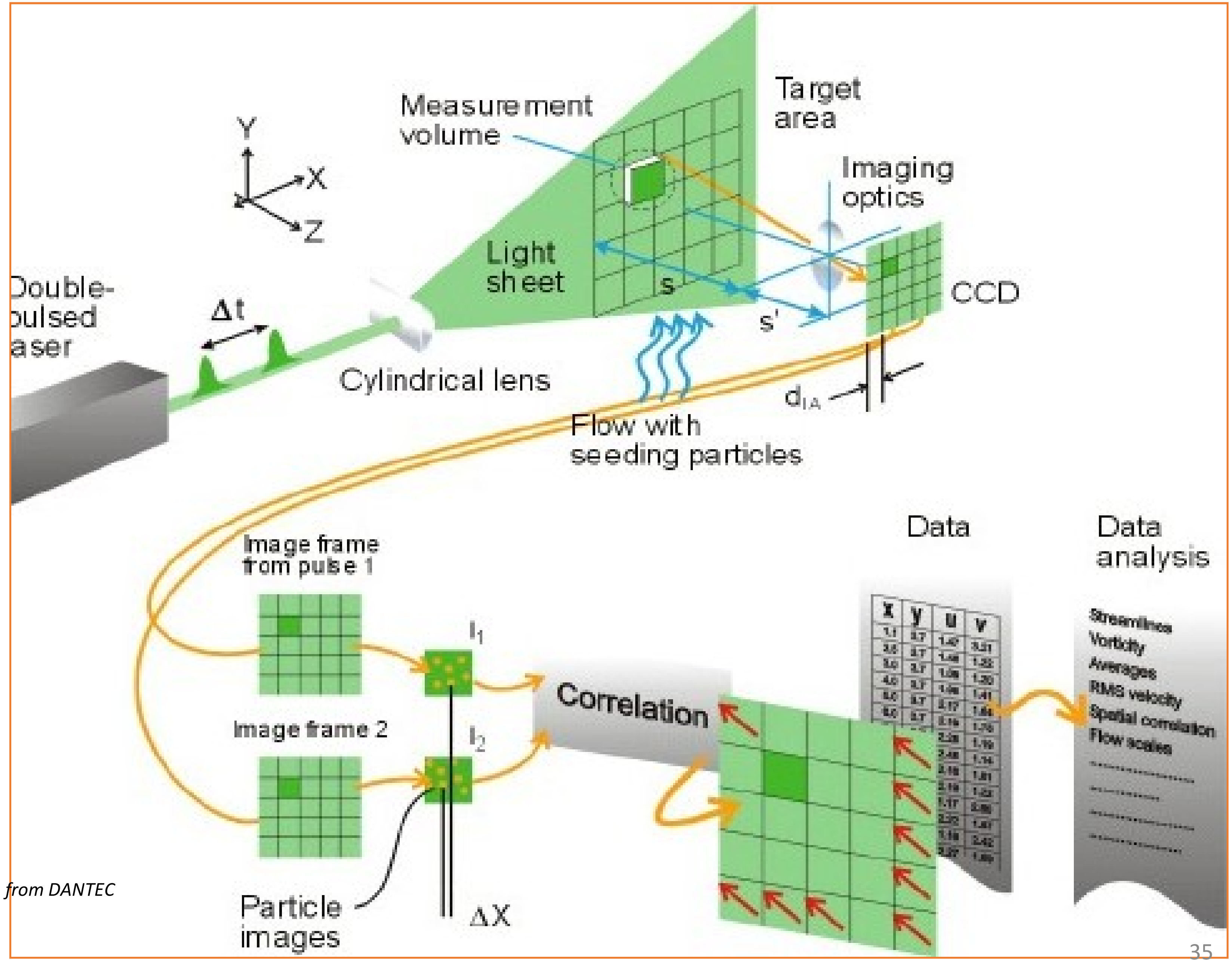
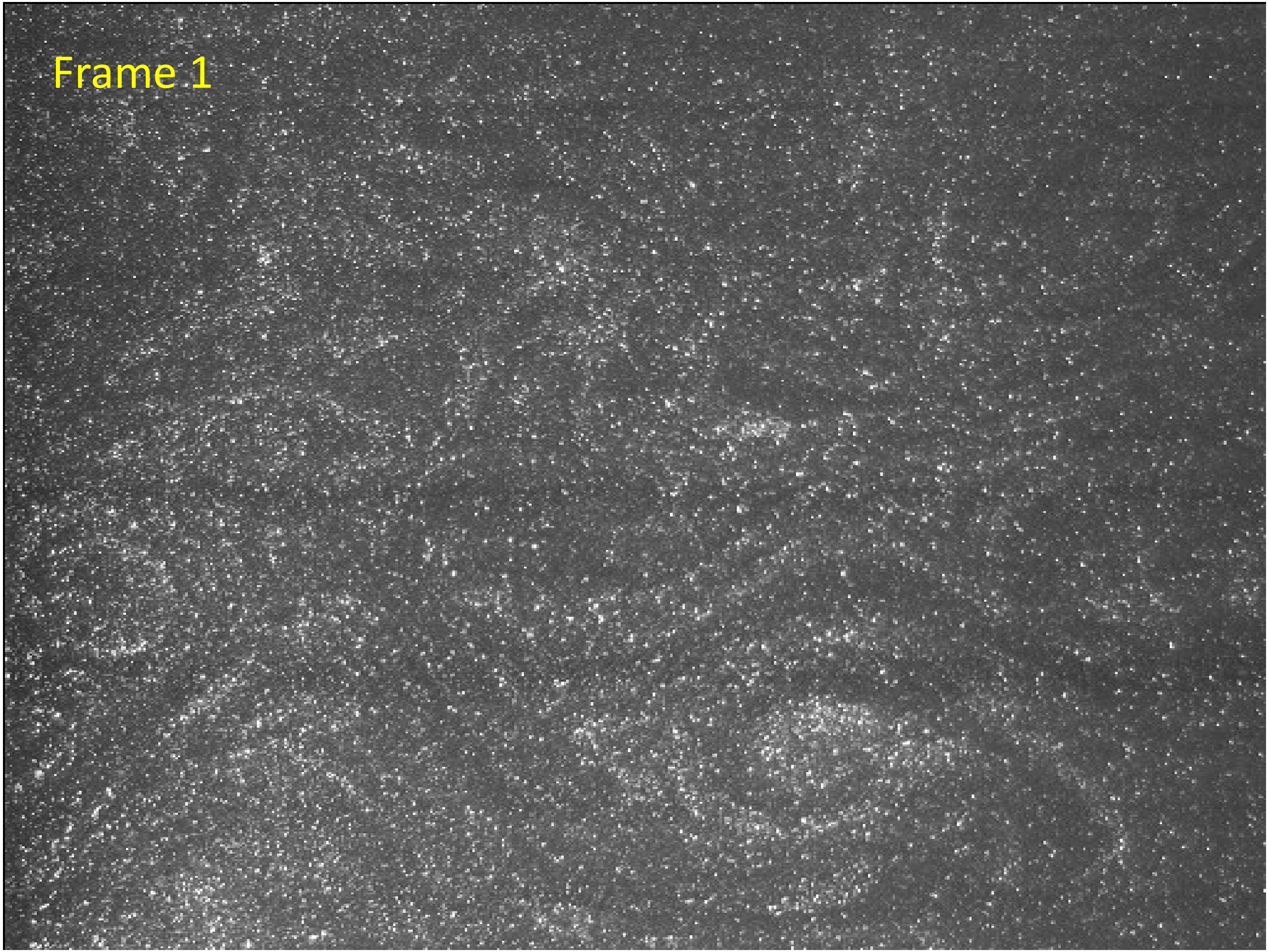
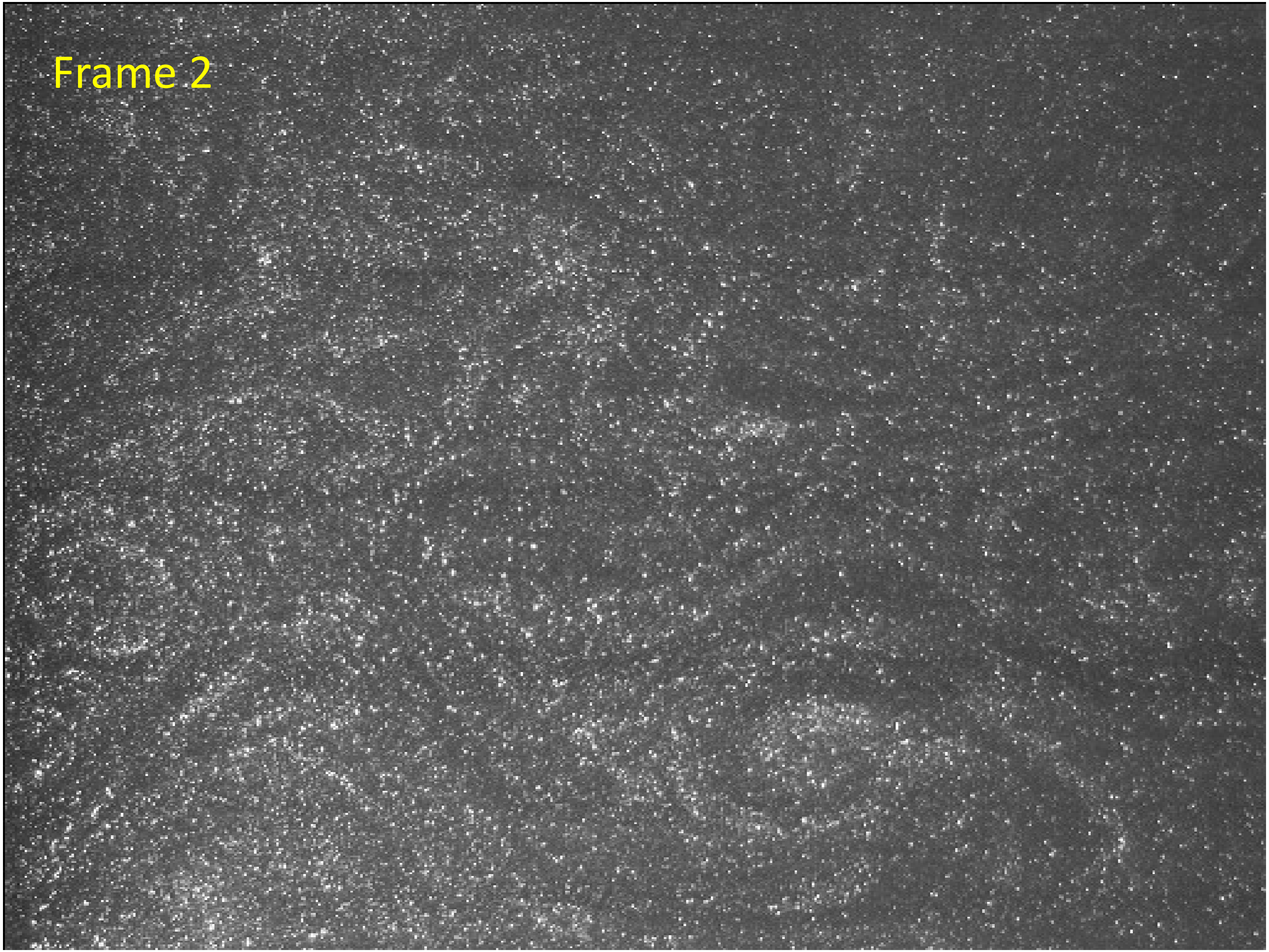
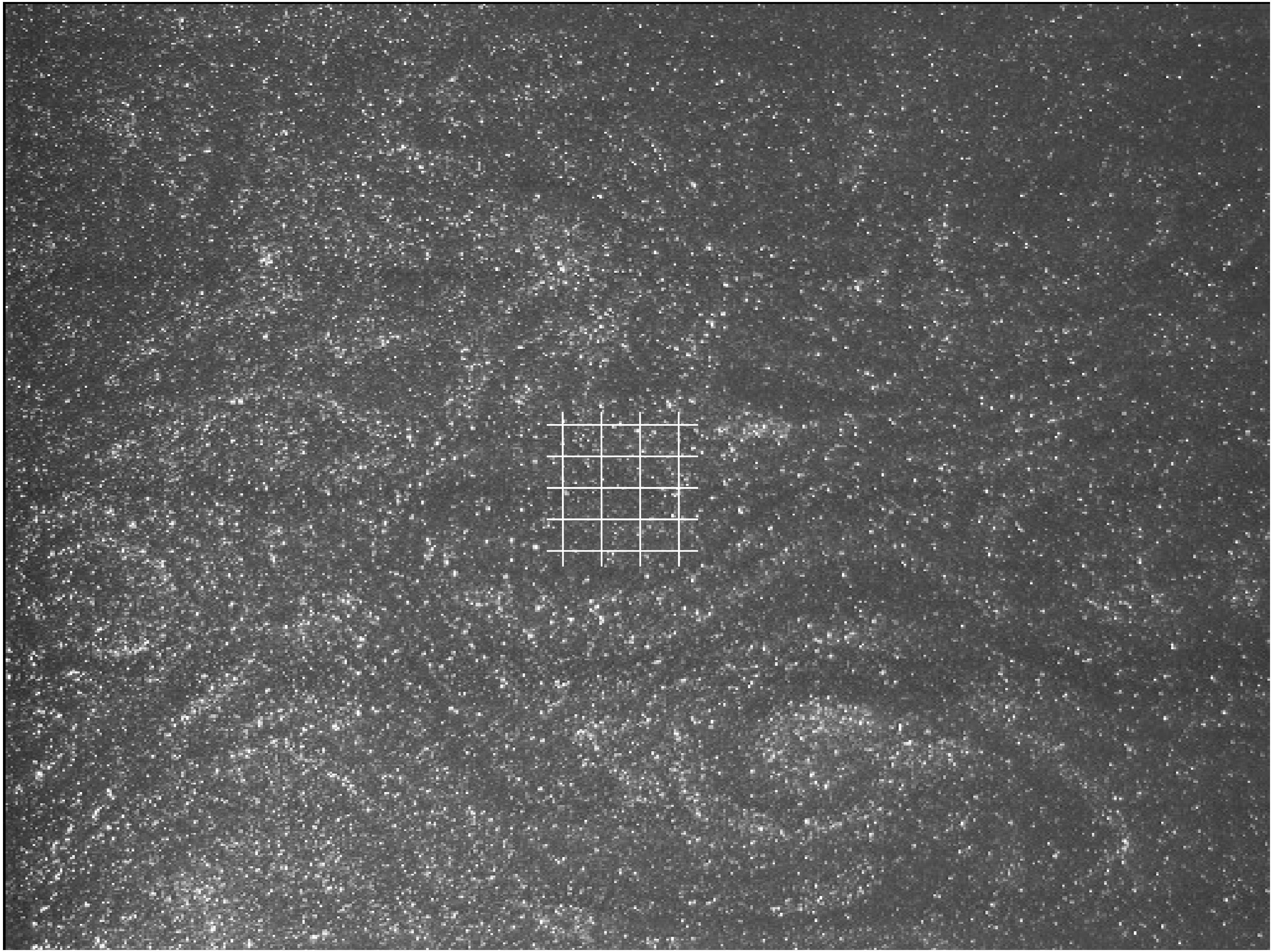
Particles Image Velocimetry: principles

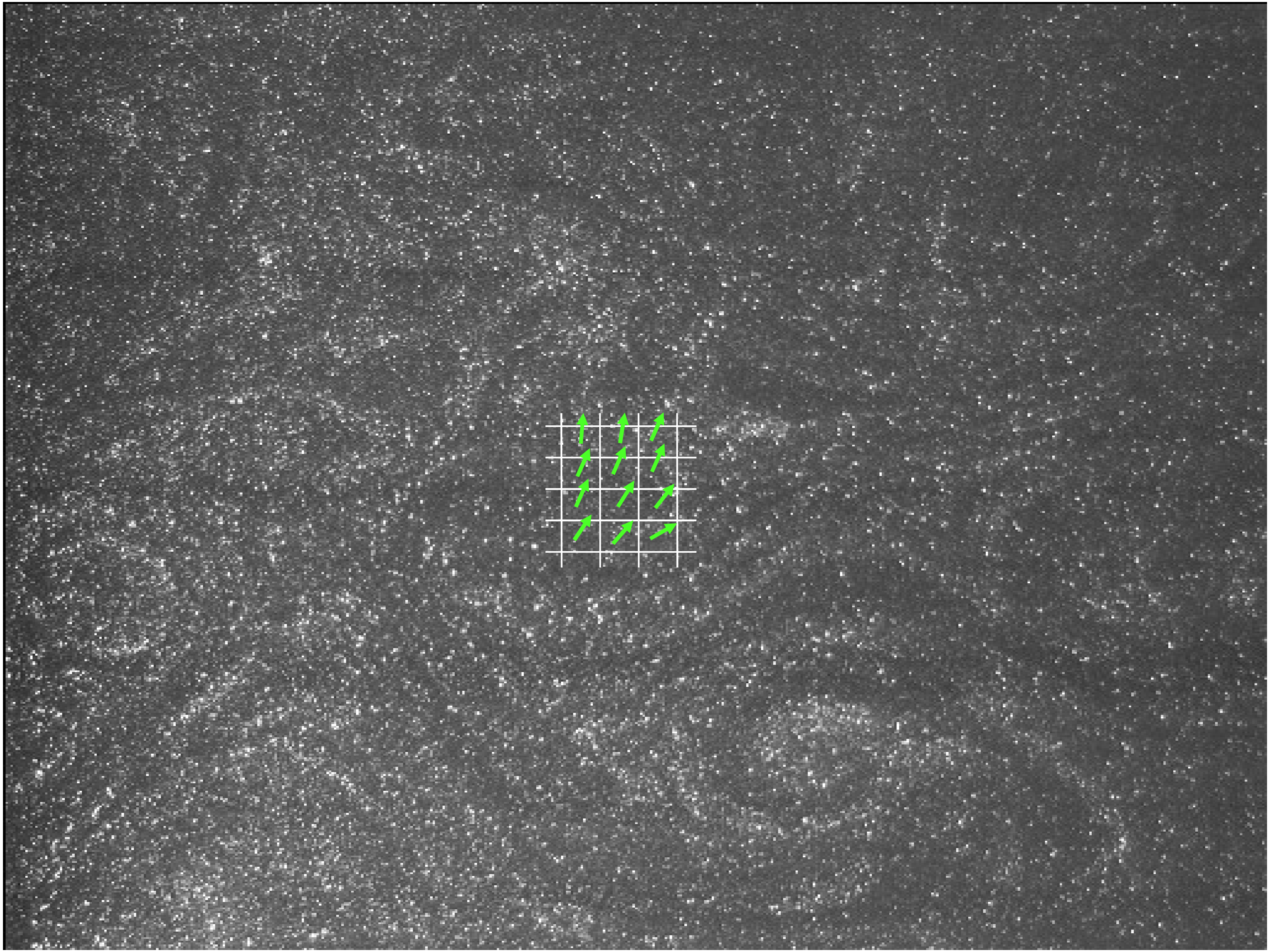


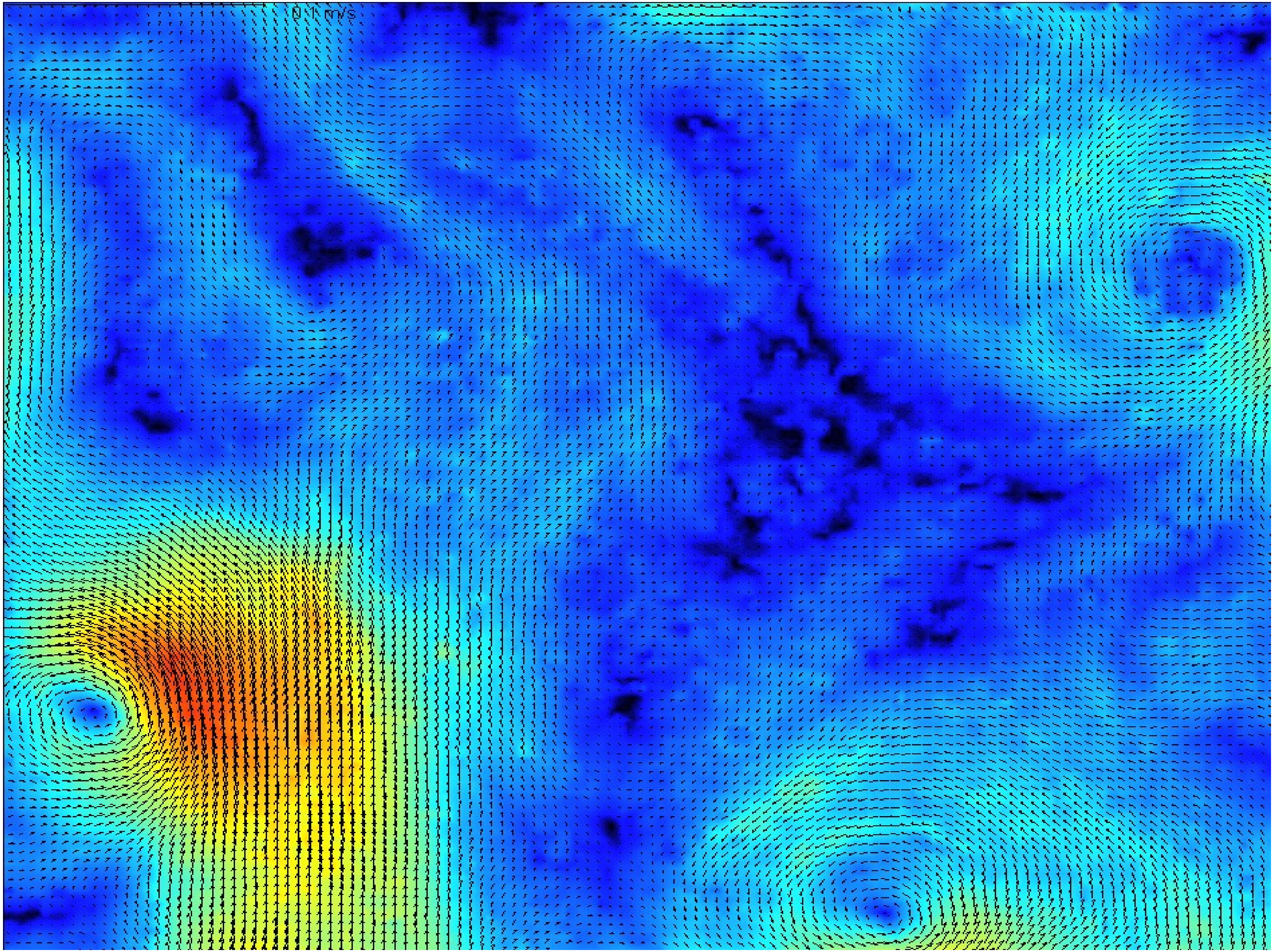
from DANTEC

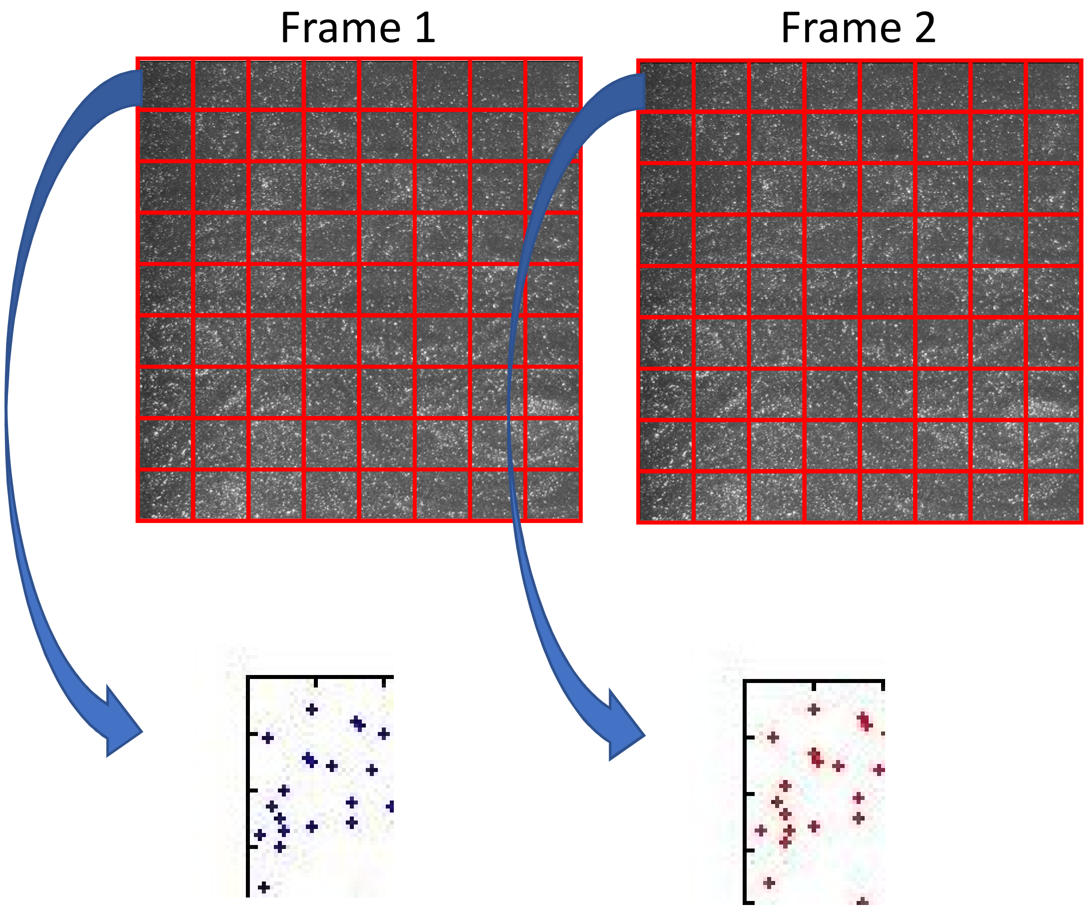

Frame 1

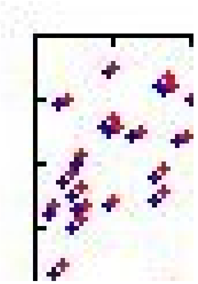

Frame 2






0.1 m/s

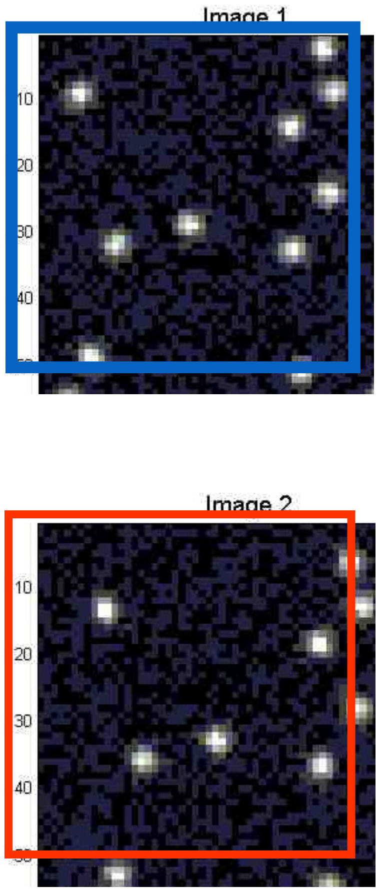


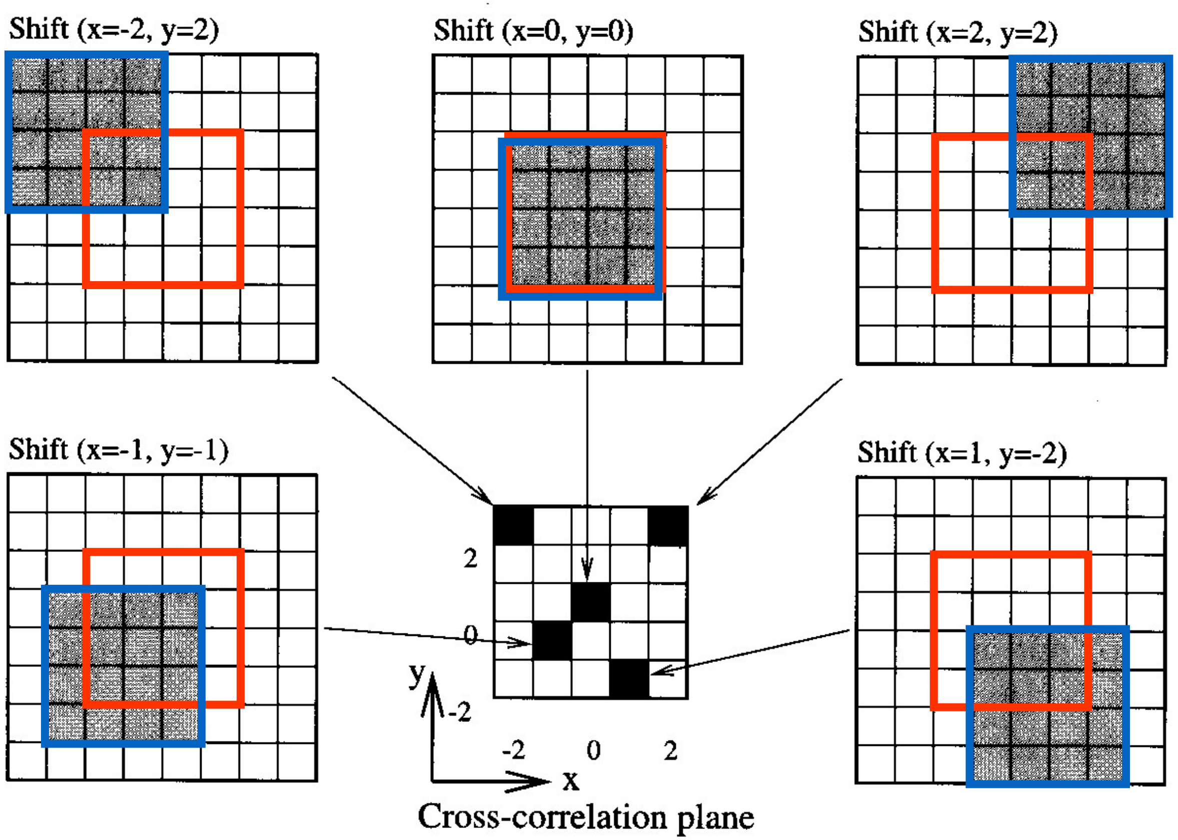


$$C_{ff}(\Delta x, \Delta y) = \iint f(x,y) f(x - \Delta x, y -$$

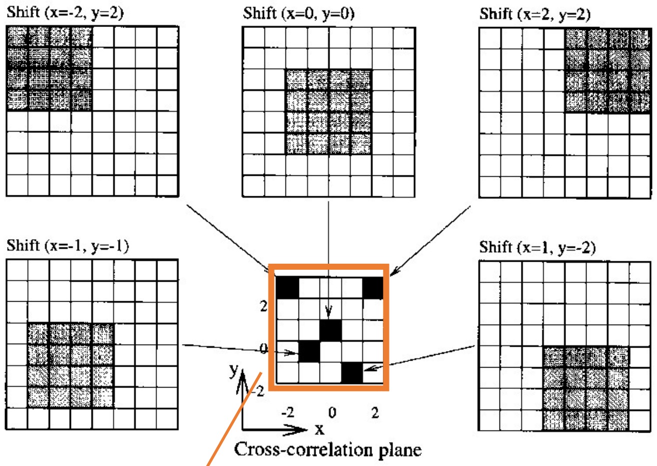
$$C_{ff}(\Delta x) = \int_{-\infty}^{+\infty} f(x) f(x -$$

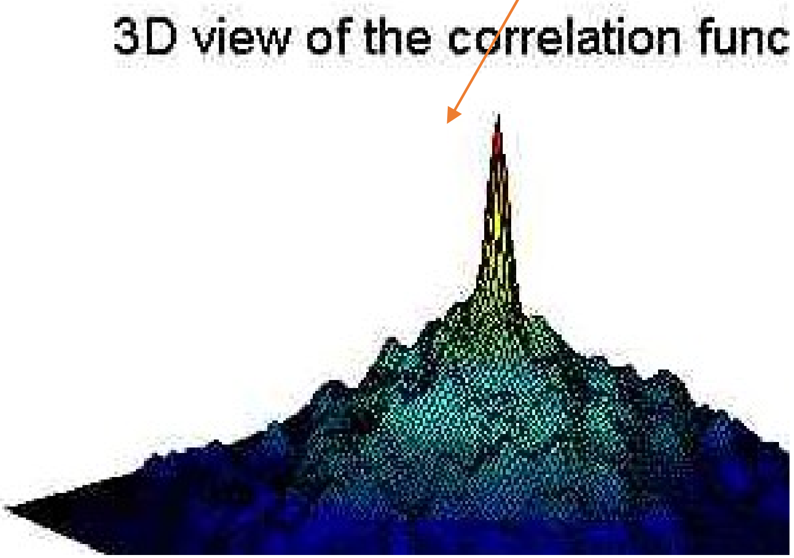
Particles Image Velocimetry: algorithms

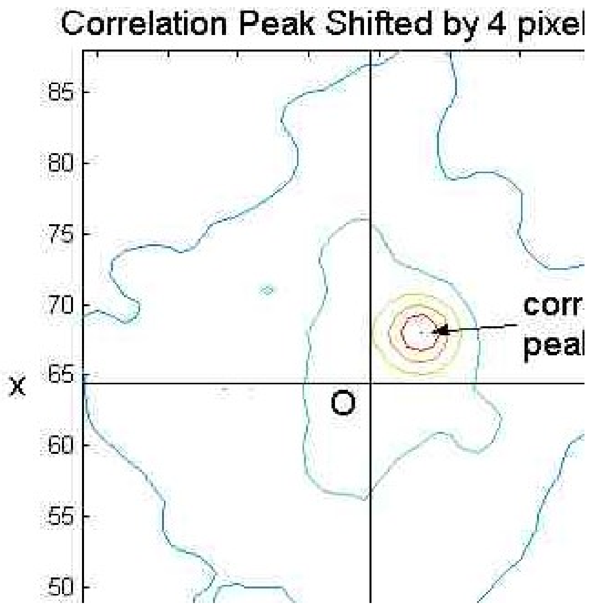




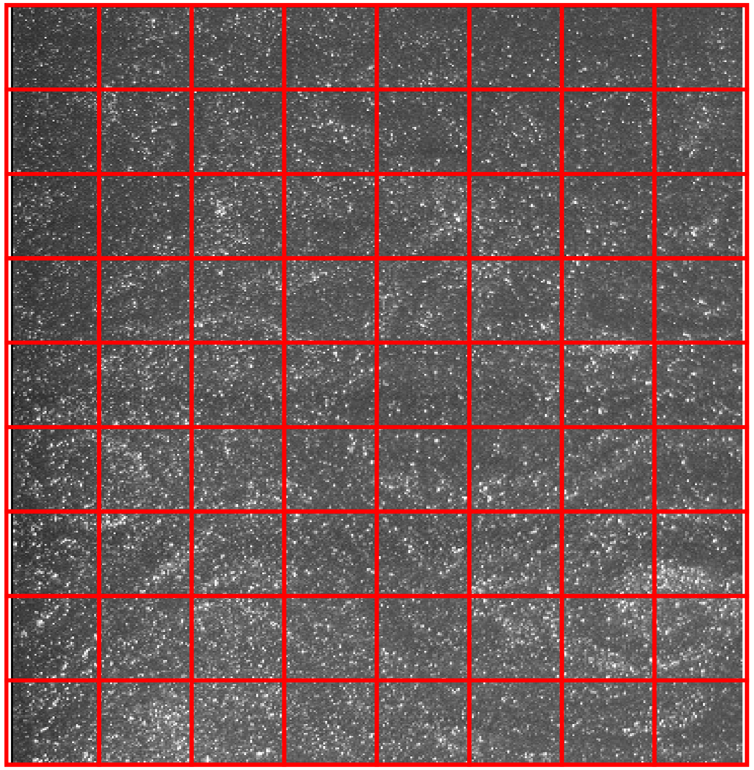
$$C_{ff}(\Delta x, \Delta y) = \iint f(x,y) f(x - \Delta x, y -$$


Shift (x=-2, y=2)
Shift (x=0, y=0)
Shift (x=2, y=2)
Shift (x=-1, y=-1)
Shift (x=1, y=-2)
2
0
-2
-2
0
2
y
x
Cross-correlation plane


3D view of the correlation func


Correlation Peak Shifted by 4 pixel
85
80
75
70
65
60
55
50
x
O
corr
peal

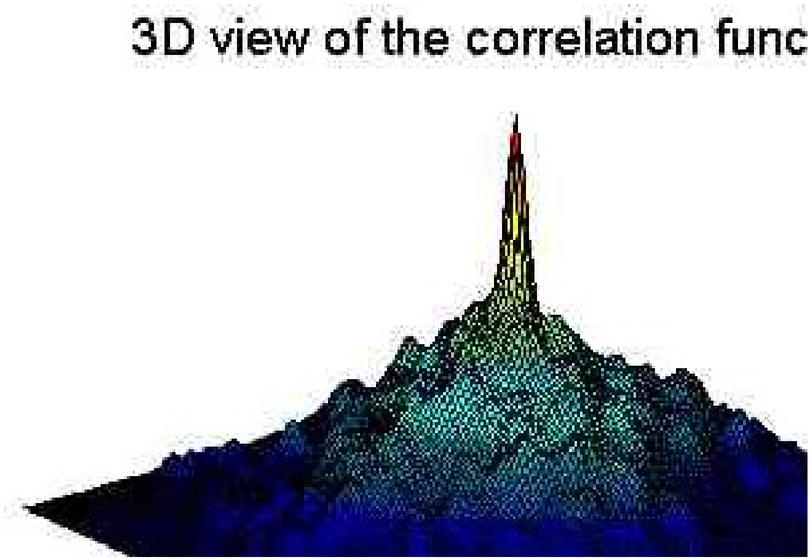
Basic correlation: resolution



Grid resolution

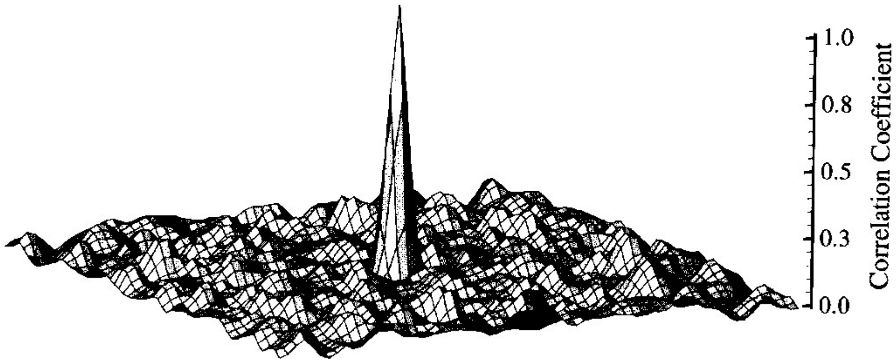
- PIV map on N_x x N_y boxes
- Typical box sizes : 16x16, 32x32, 64x64 pixel²
- Typical pixel size: 0.1 mm to 1 mm
- Overlaping : typically 50%

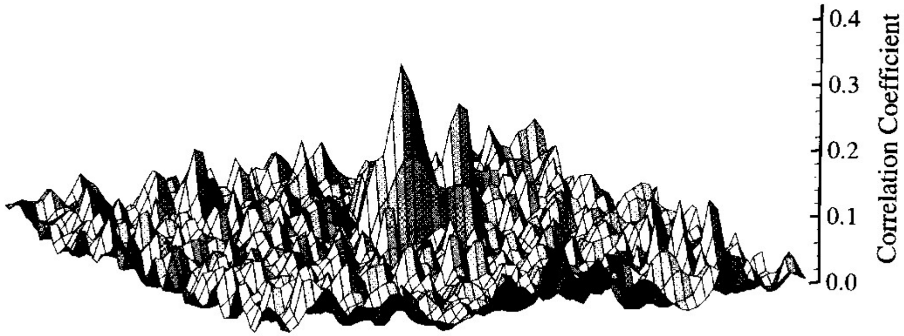
Resolution and error



Precision

- Peak location accuracy
- Peak detection quality
- Validation





Particle size on images

Actual particle size
Particle brigthness
Sensor pixel size
Focus

Pixel locking

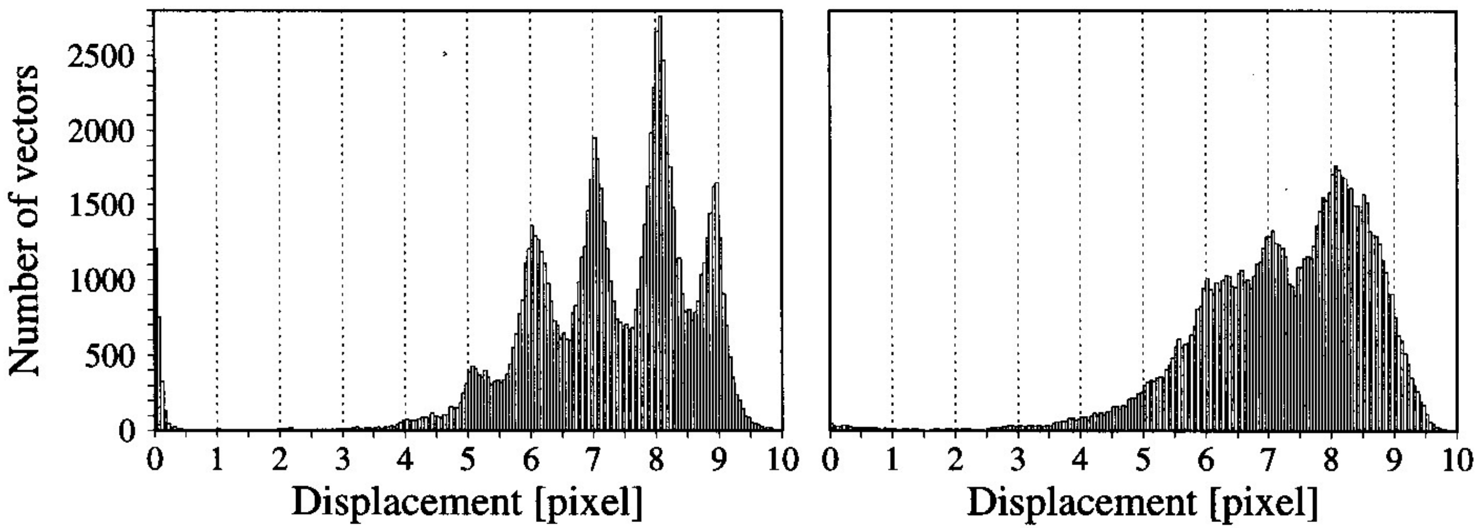
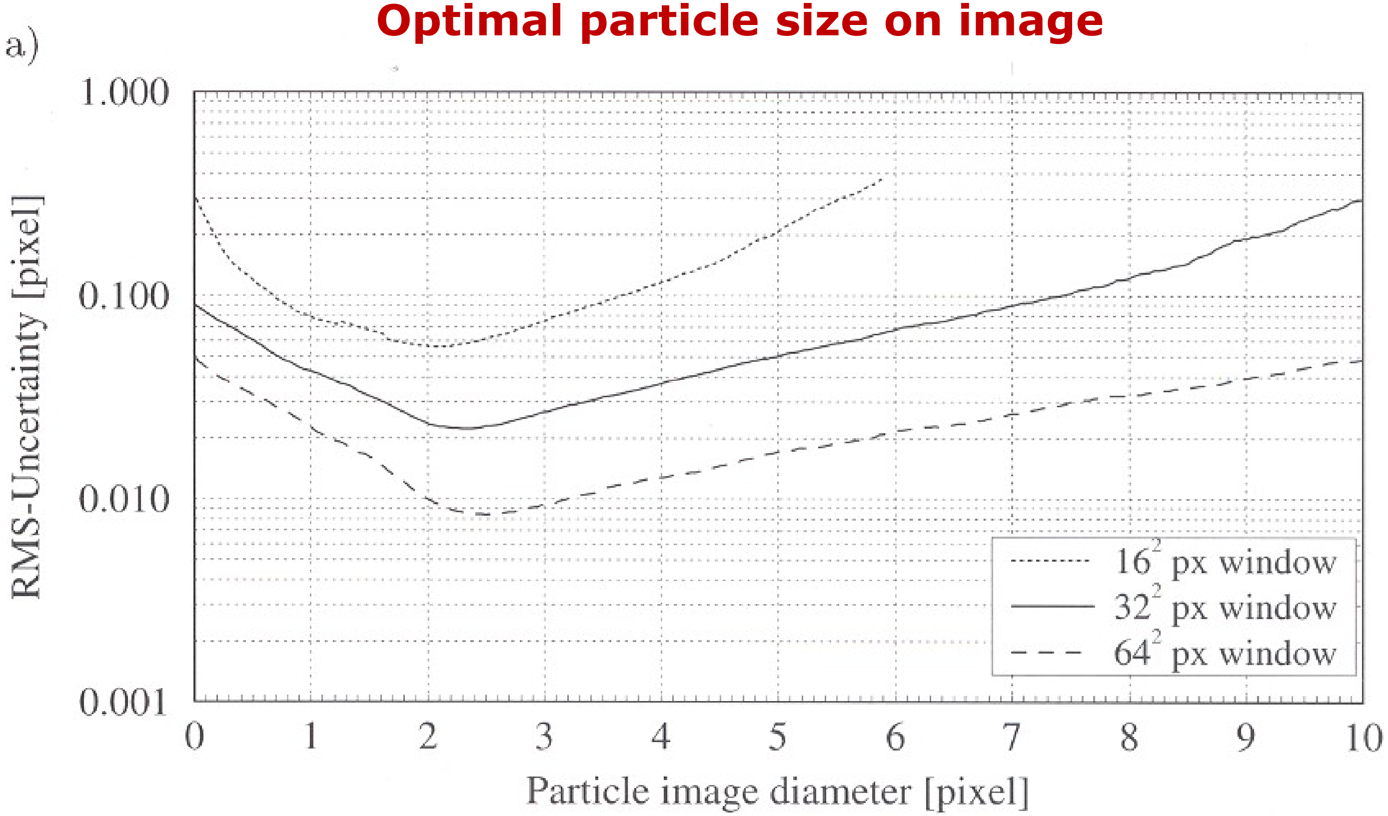


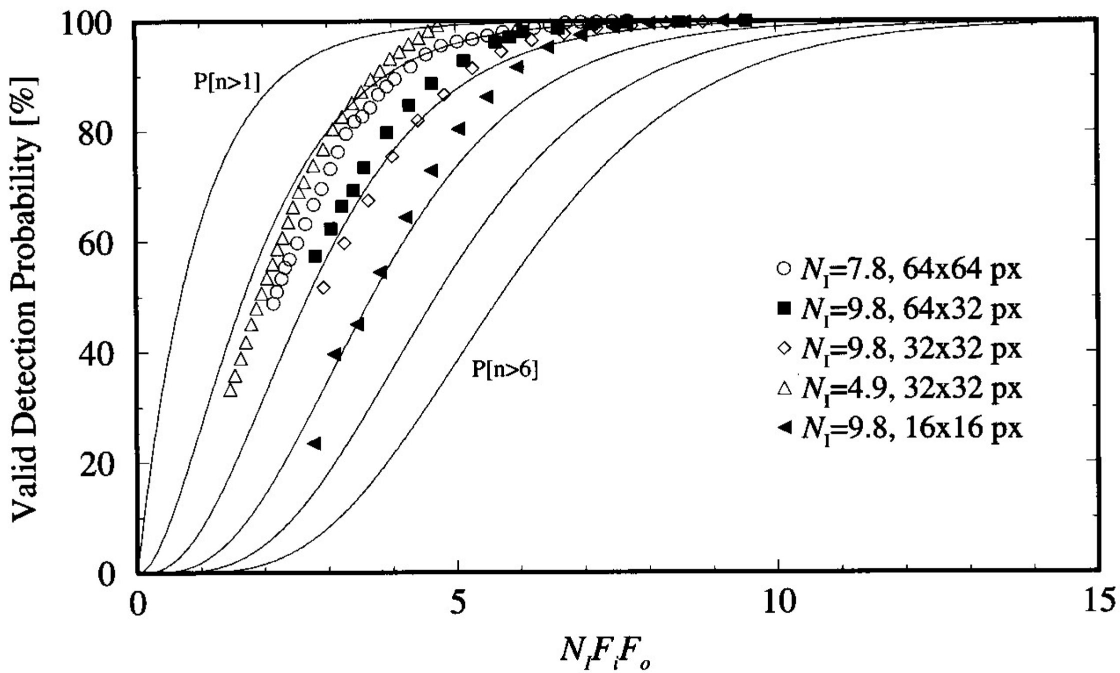
Fig. 5.34. Histograms of actual PIV displacement data obtained from a 10-image sequence of a turbulent boundary layer illustrating the "peak locking" associated with insufficient particle image size (left). Image pre-processing can reduce this effect (right). Histogram bin-width = 0.05 pixel.

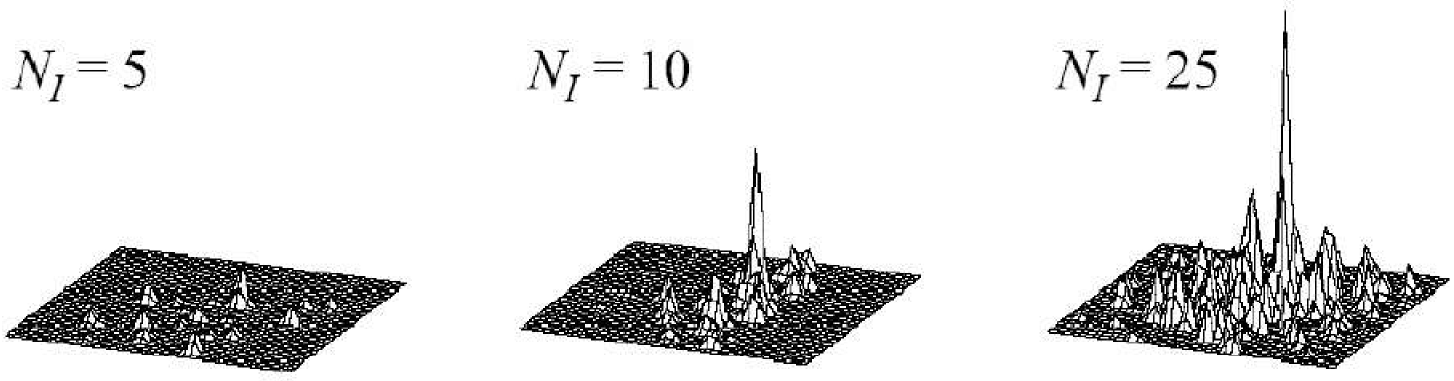
Particle size on images

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

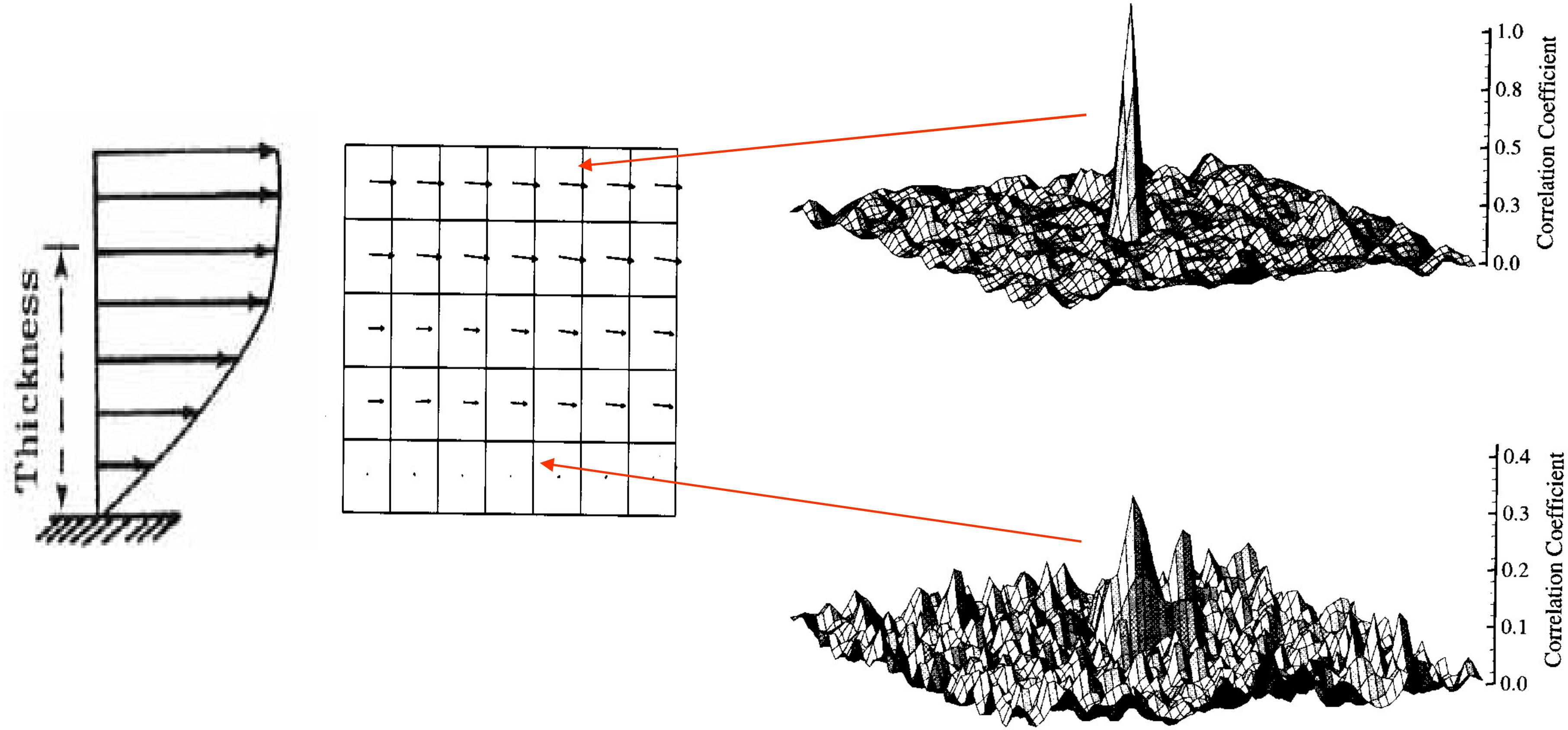
Particle size on images

Detectability

Pixel locking

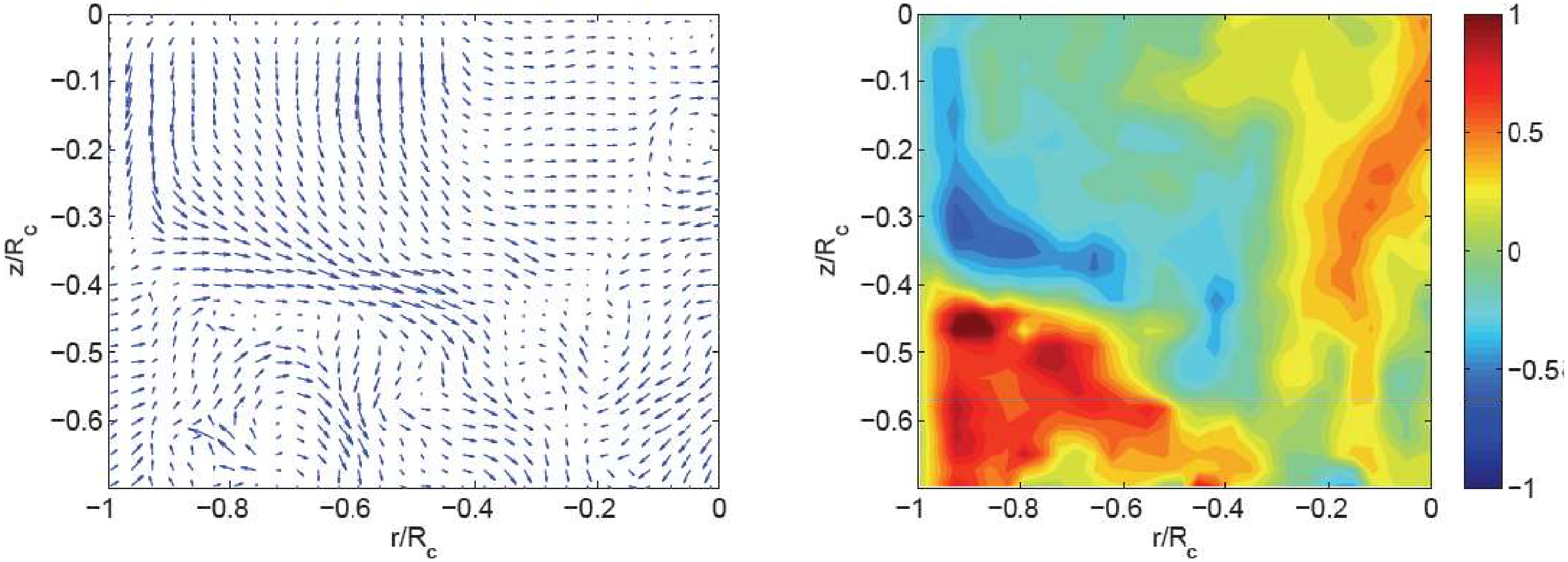
Optimal size

Strong gradients and resolution



⟹ Toward multi-pass PIV

Post-processing



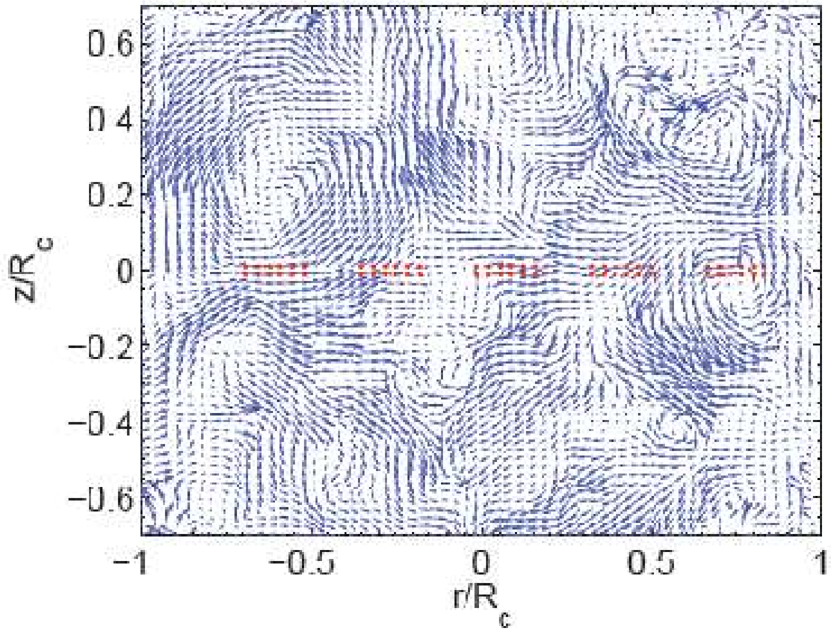
Typical velocity fields:

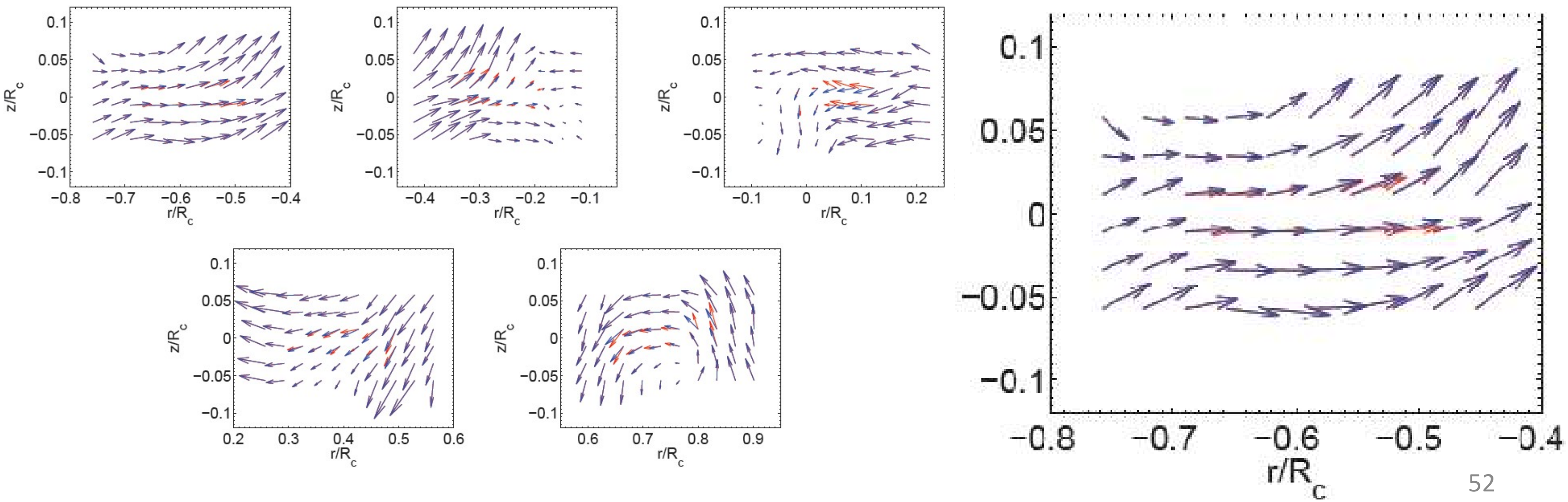
- Possible spurious vectors
- Checking resolution of gradients
- First step before statistical/Fourier analysis

Post-processing

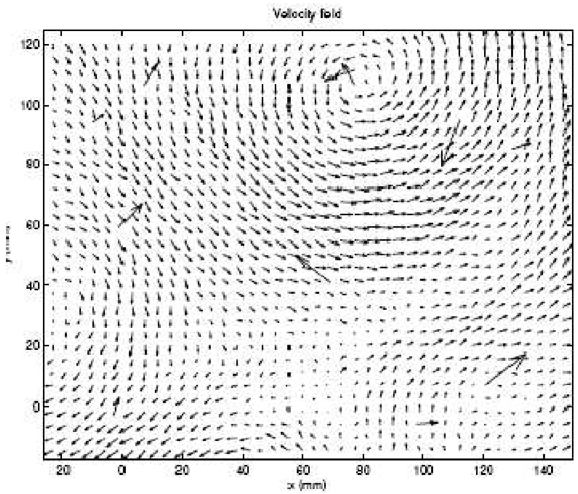
Removing spurious vectors:

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

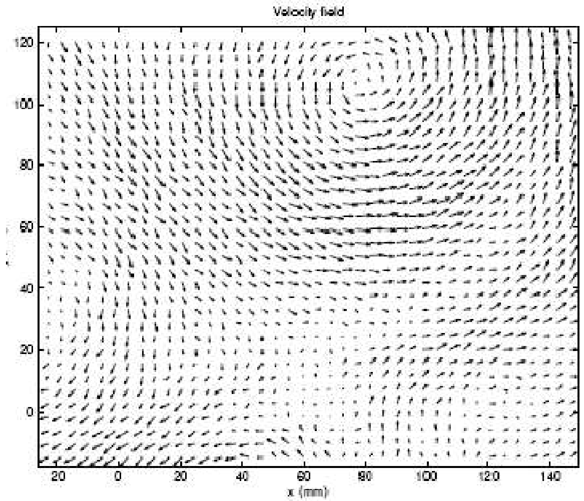




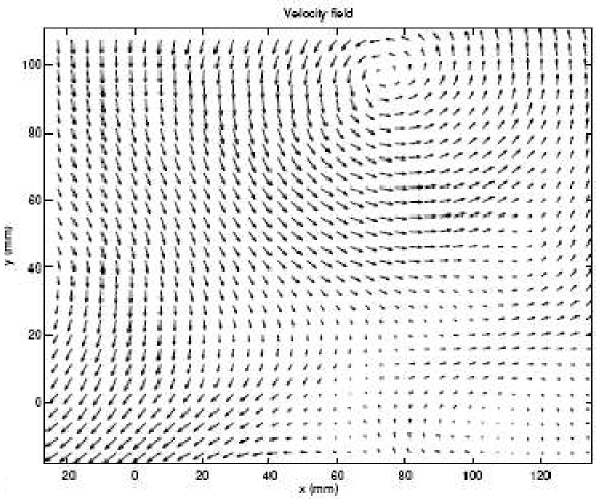
Post-processing



Removing/replacing spurious vectors



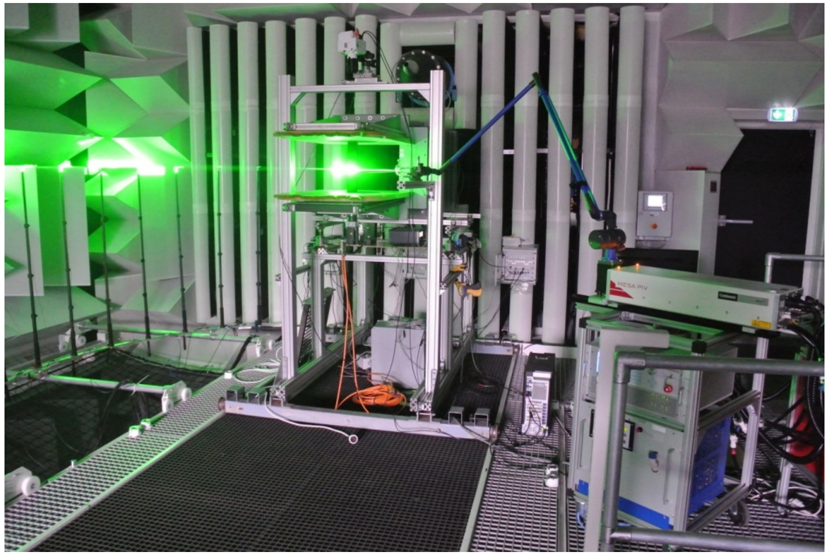
Smoothing

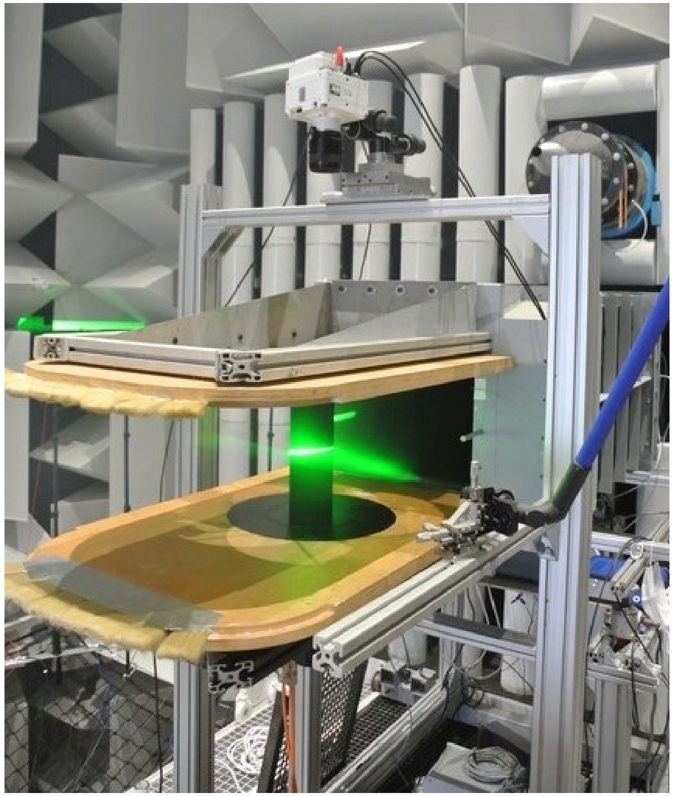


Caution with smoothing !

Time-resolved PIV

	Fast cameras (internal RAM or RAID)
Sensor	CMOS 12 or 16 bits sCMOS
Resolution	1000^2 to 2000^2 0.5 à 10 kHz
Price	20-180 k€

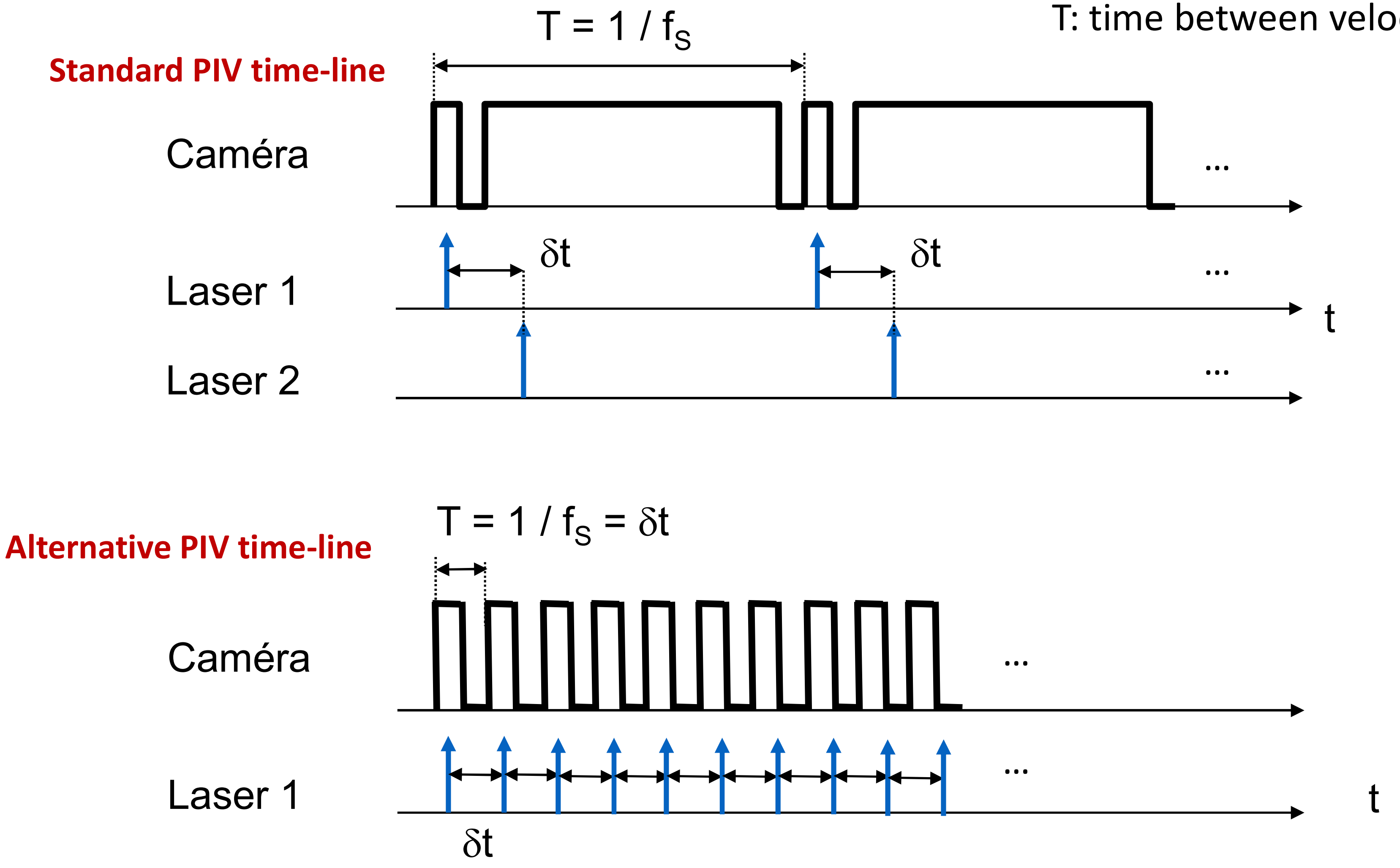




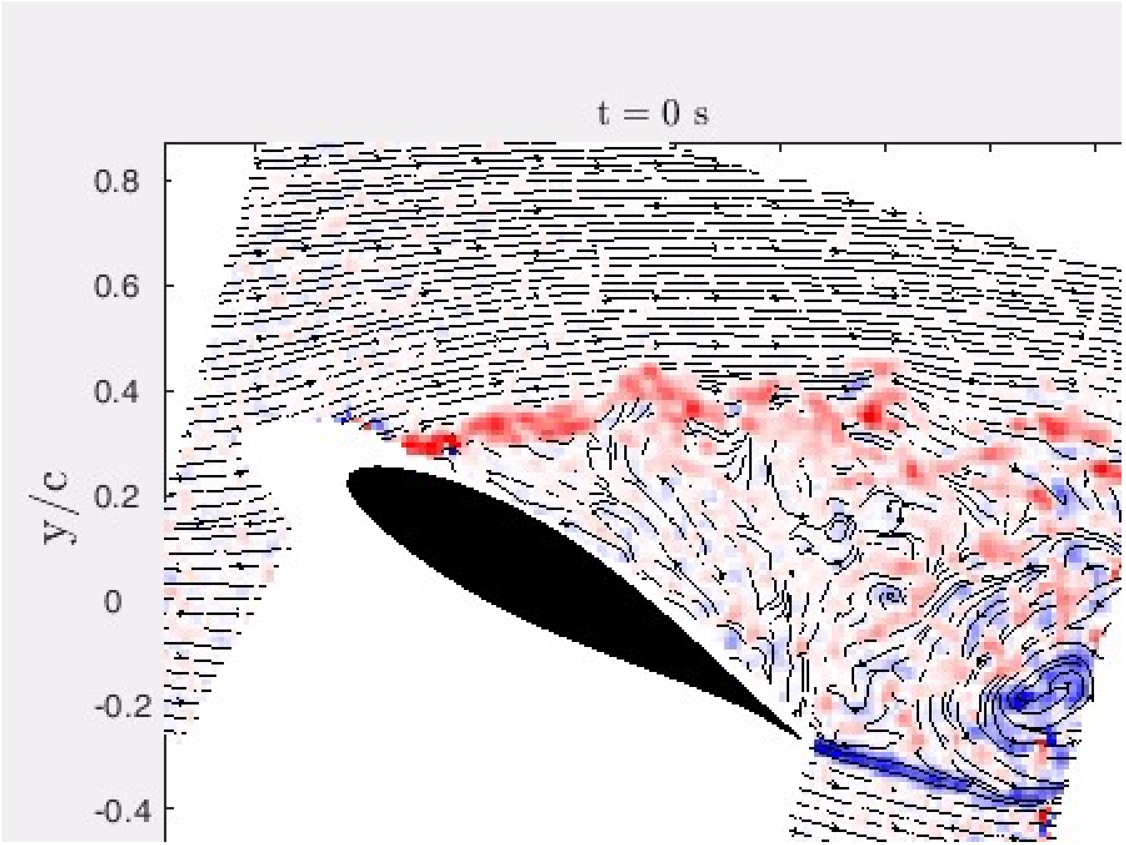
Continuous or high repetition rate light sources

Time-resolved PIV

δt: time between pulses
T: time between velocity fields



Time-resolved PIV



Stereoscopic PIV

Stereoscopic PIV principle

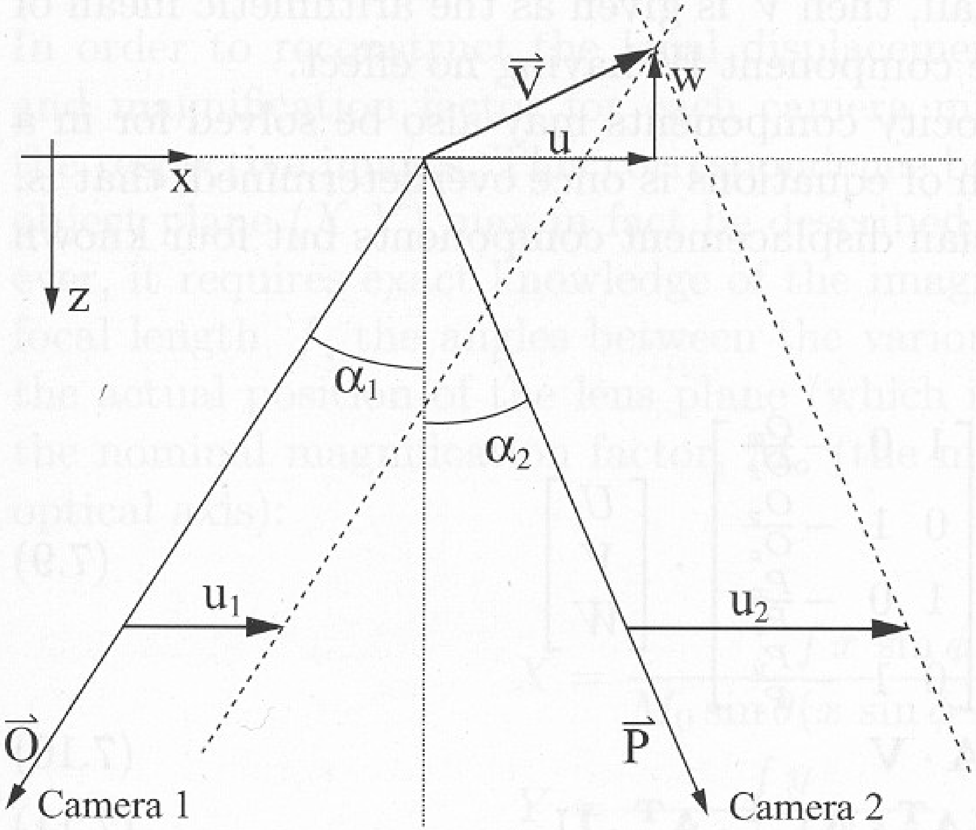
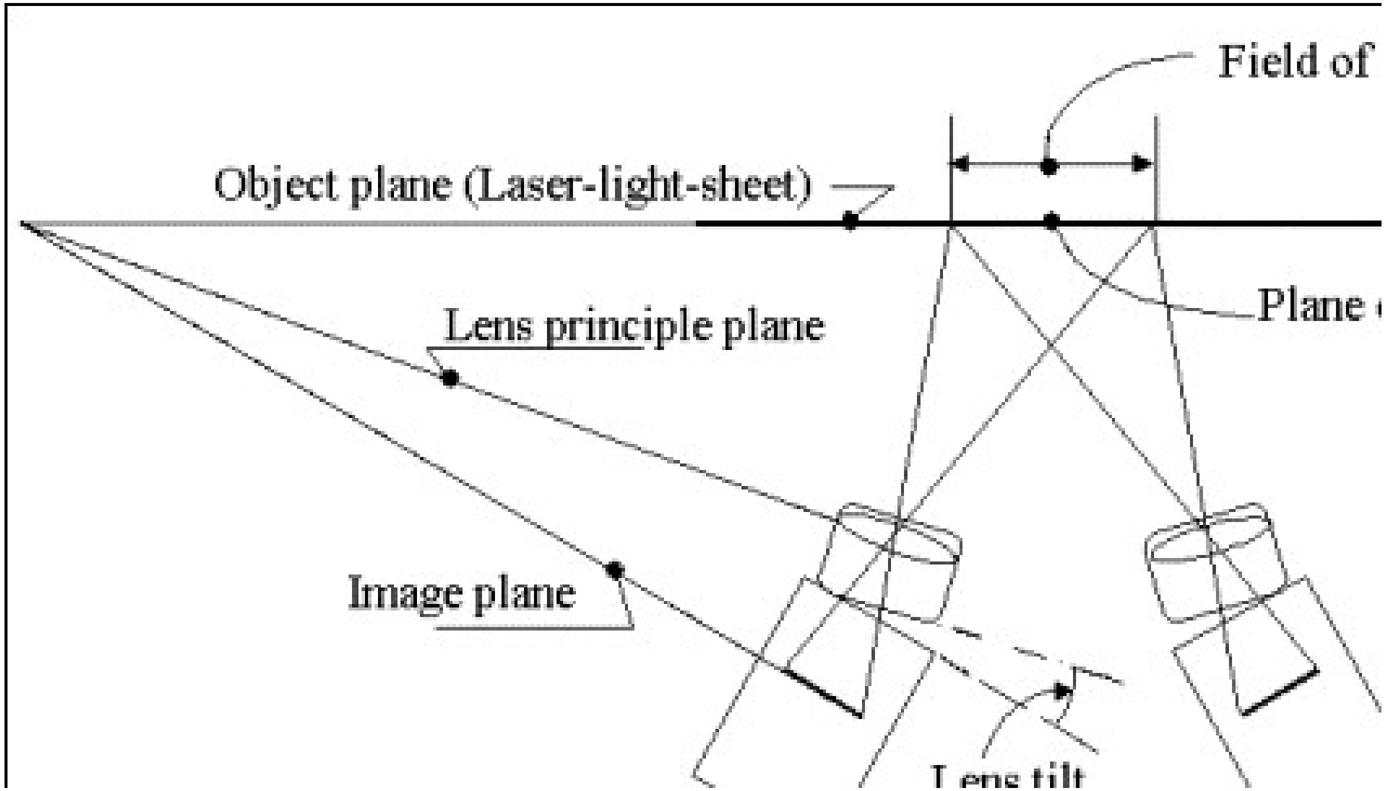
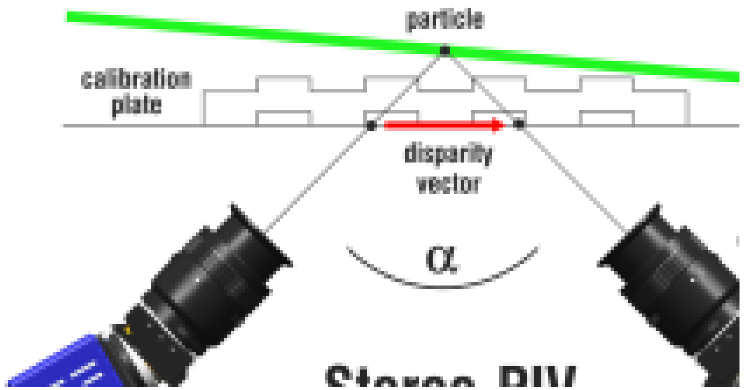


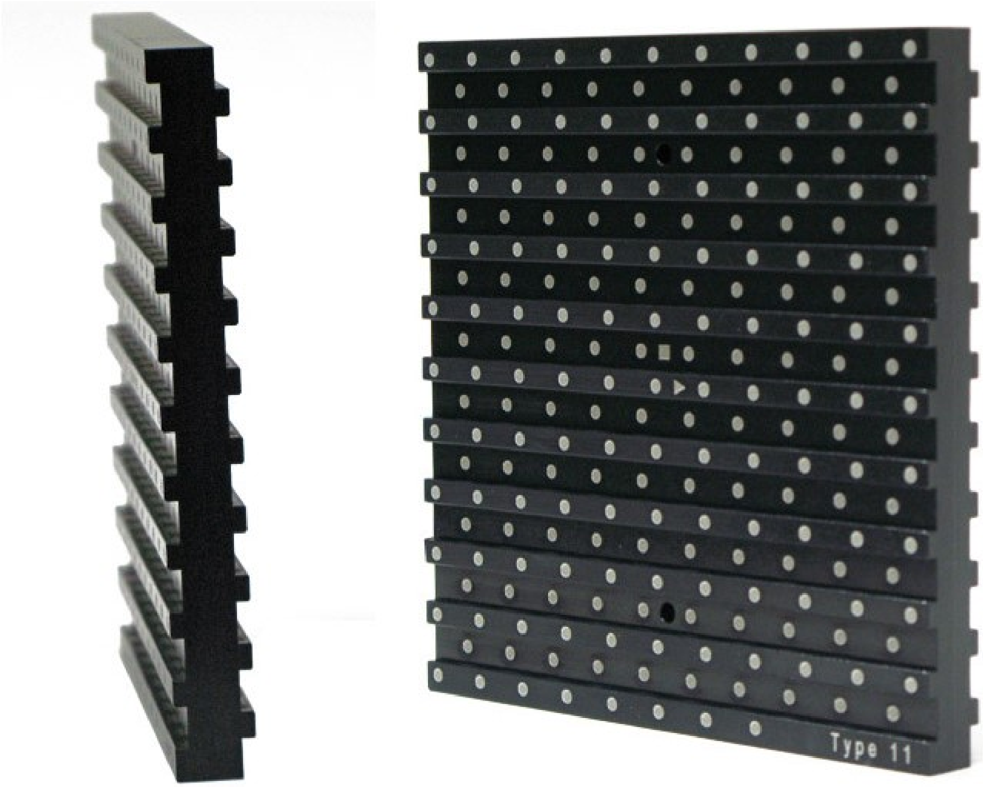
Fig. 7.2. Stereo viewing geometry in the XZ-plane.

Stereoscopic PIV Sheimpflung condition



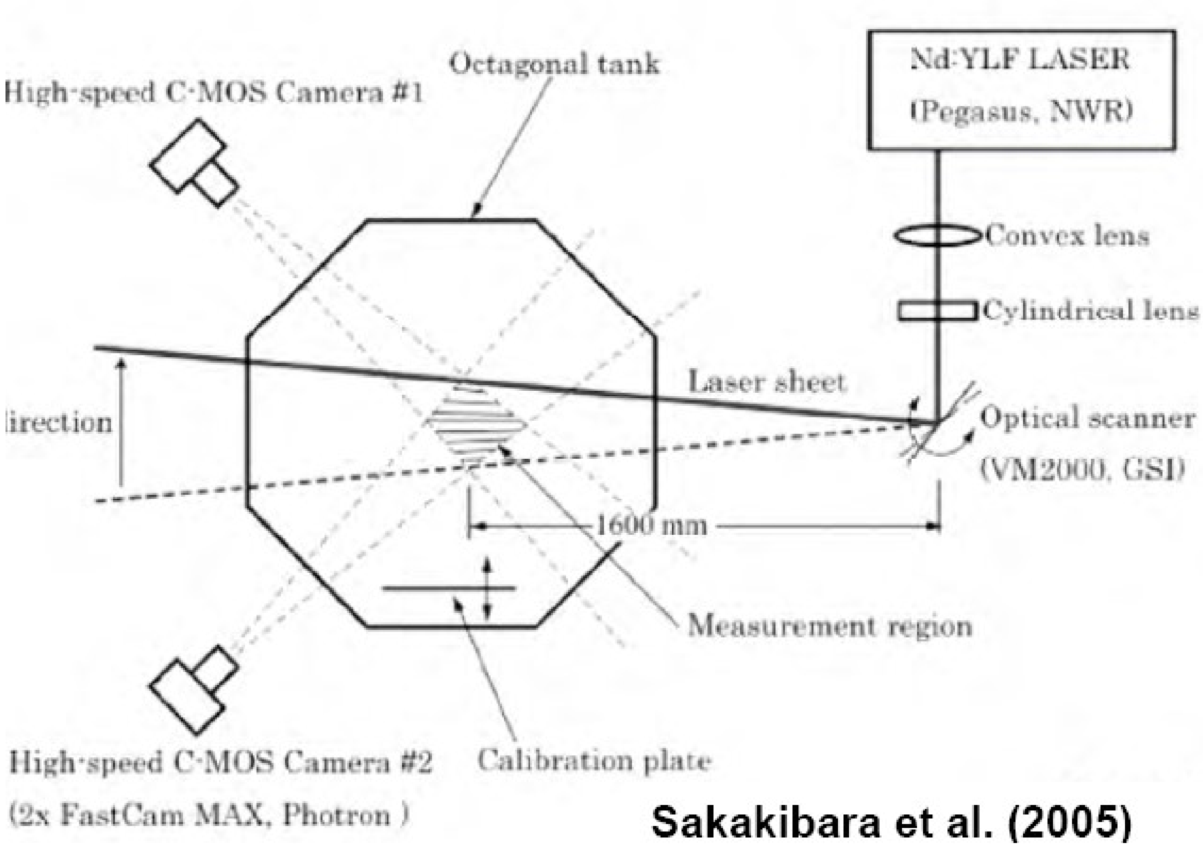


Stereoscopic PIV multiplane calibration



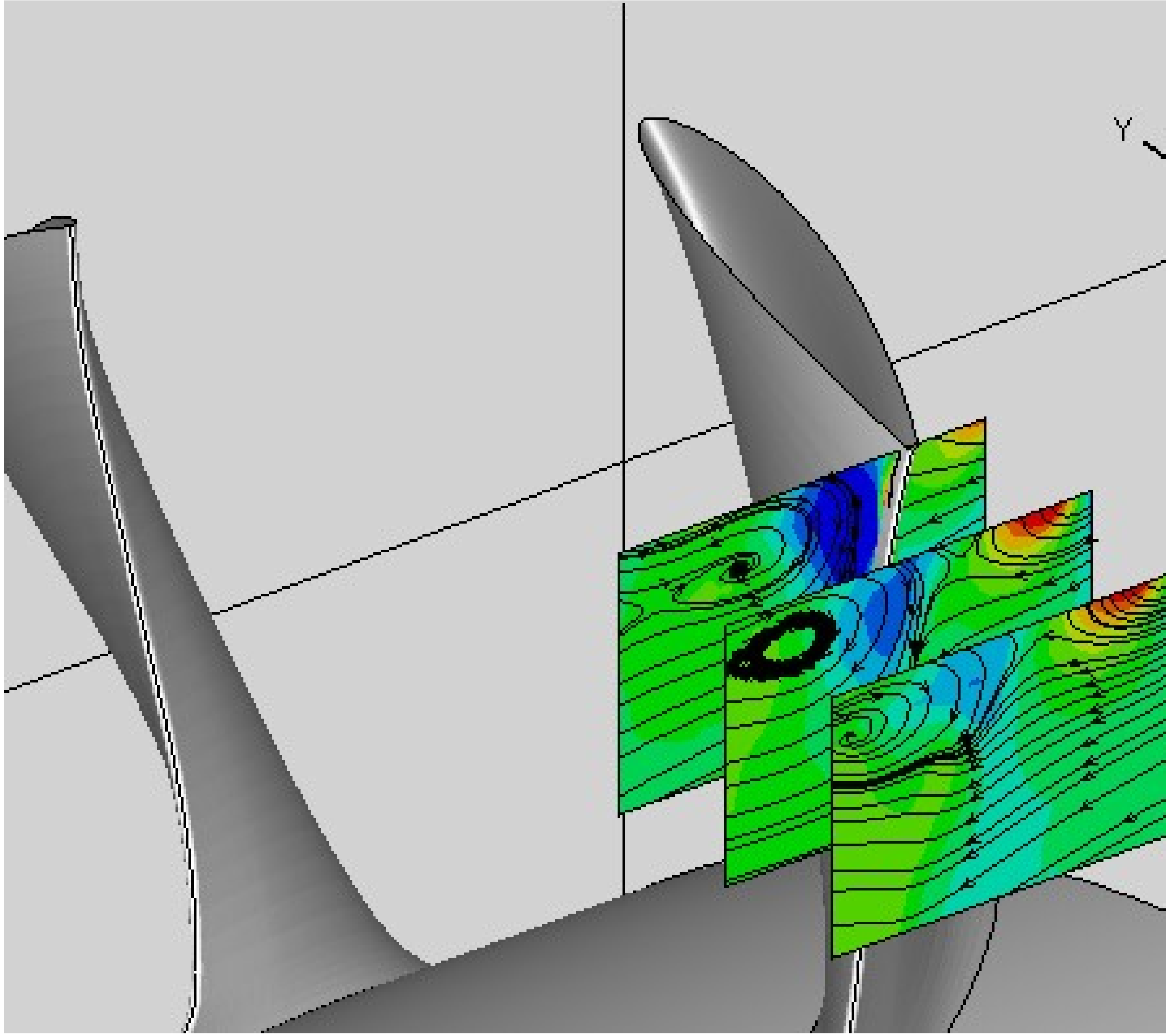
Even used for 2D-2C PIV

Tomographic / 3D PIV



Sakakibara et al. (2005)

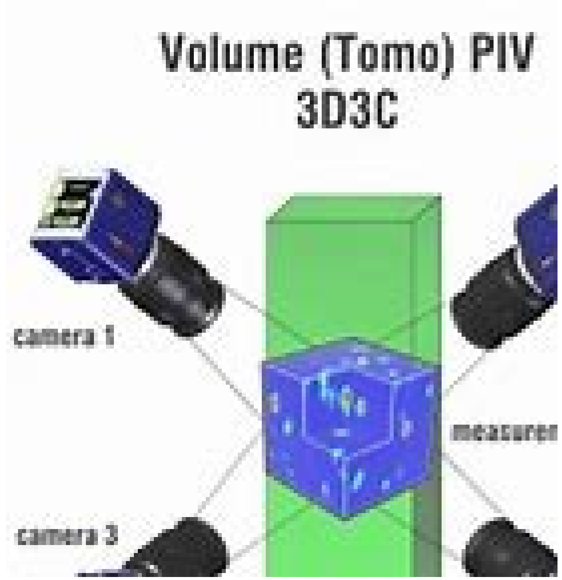
Tomographic / 3D PIV



Tomographic / 3D PIV

4 to 8 cameras

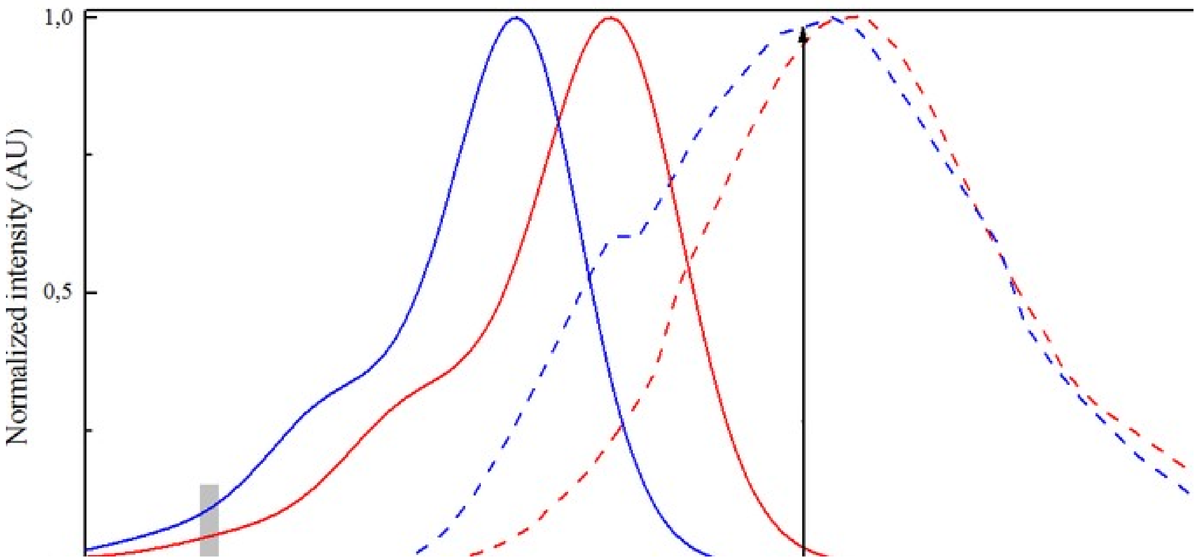
Very high computation costs



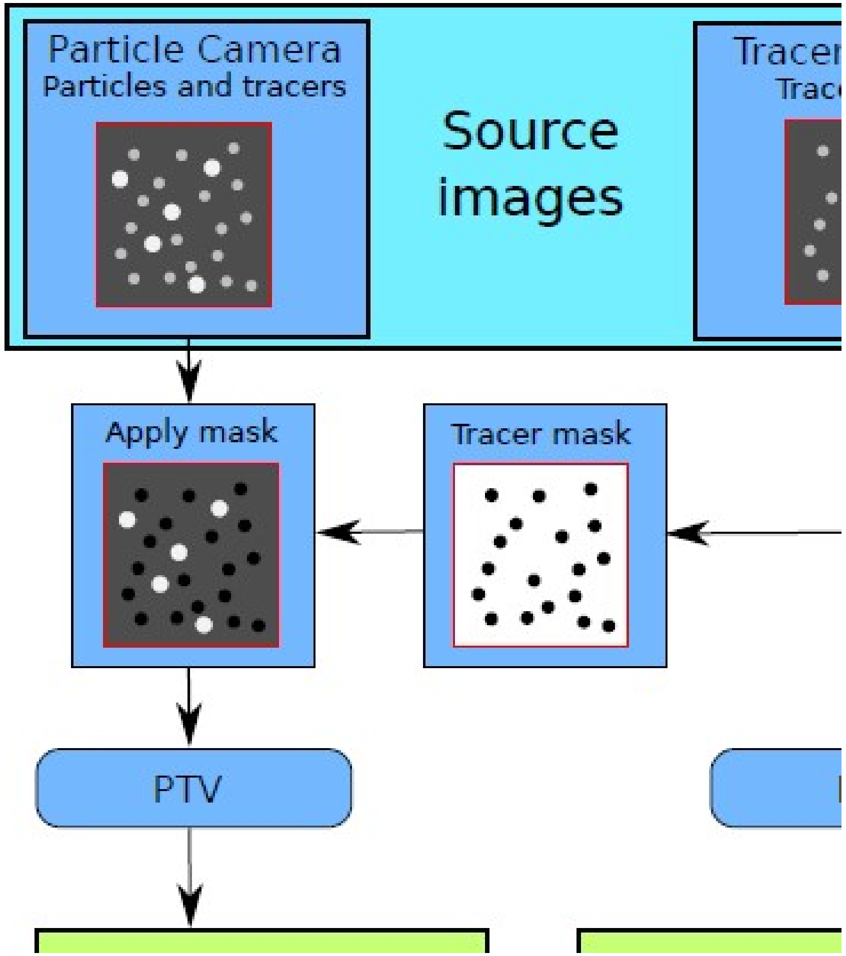
3D calibration

Multiphysics PIV

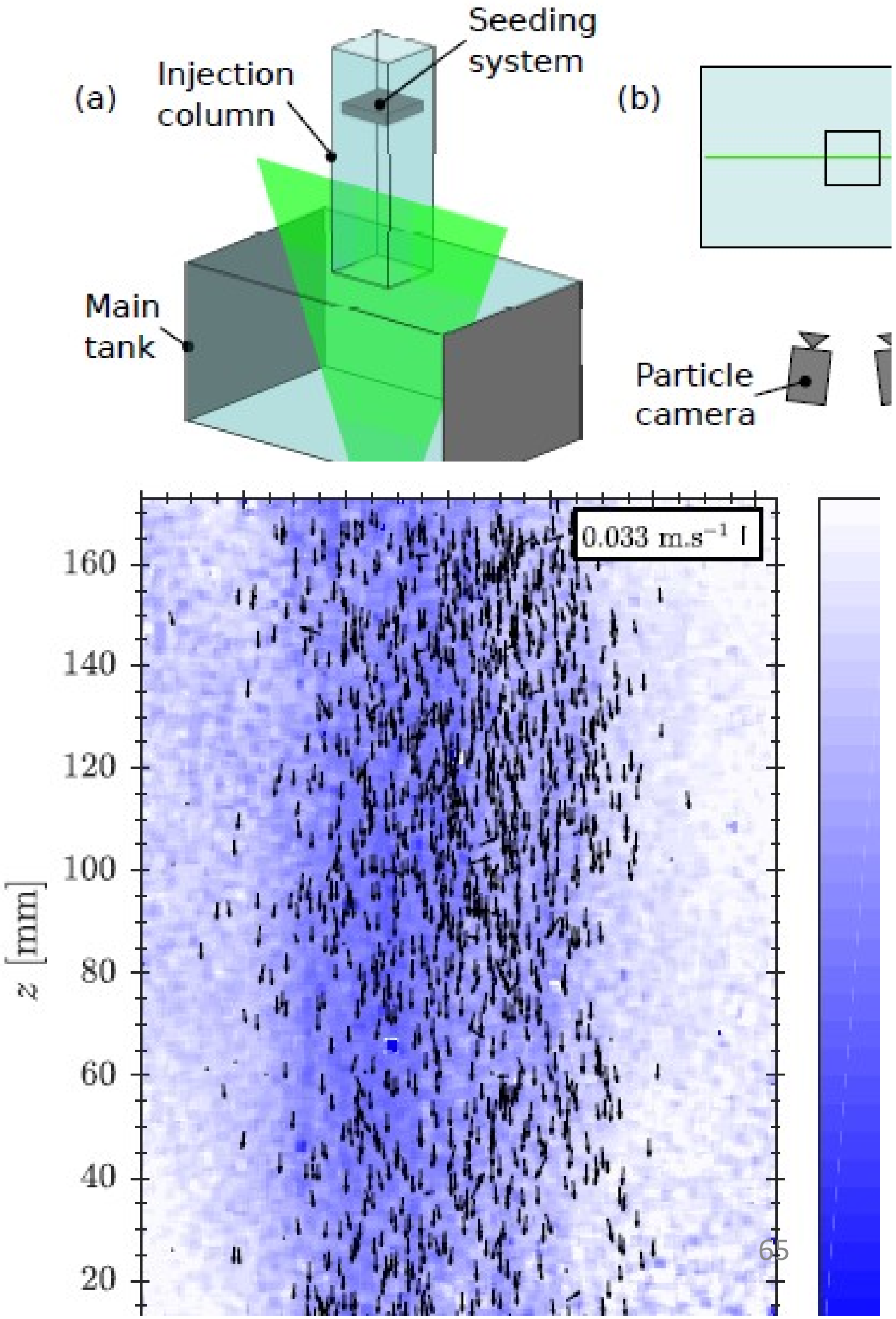
- Temperature and velocity
- Multiphase measurements:
  - particles and fluid velocities
  - multifluids



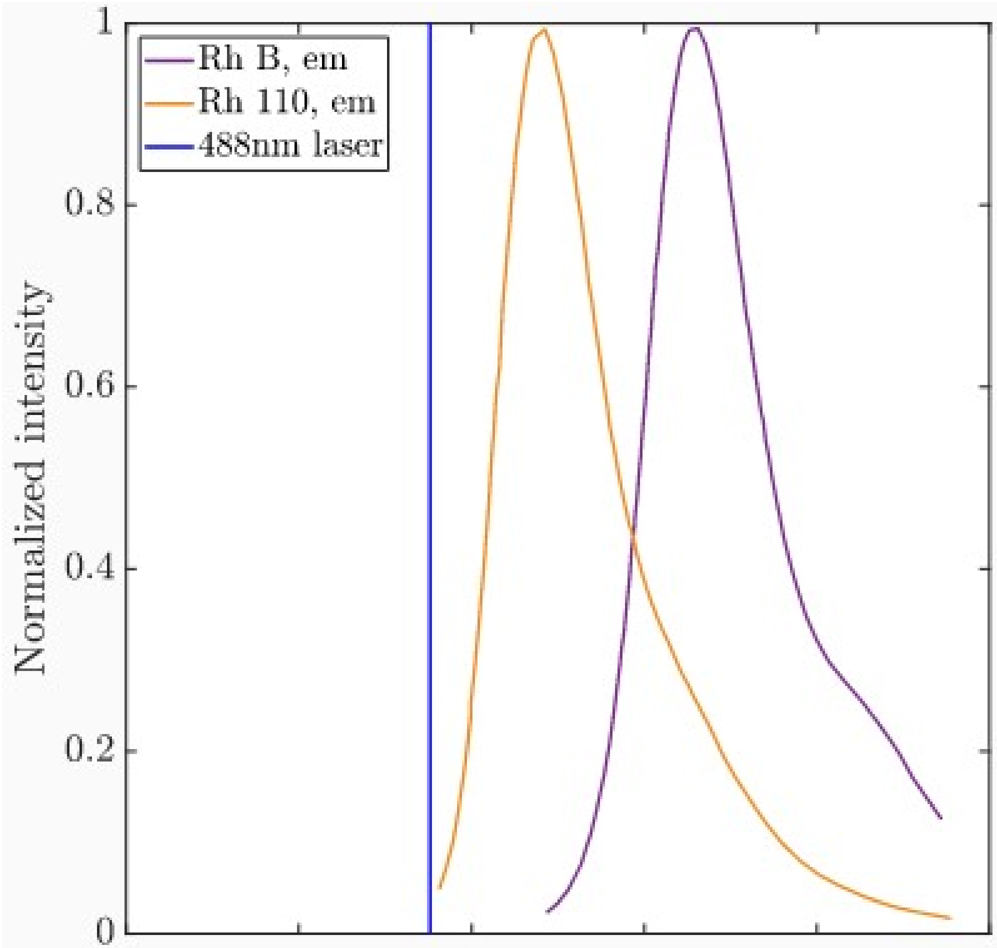
Particles and fluid velocities at ENSTA



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



Temperature and velocity at ENS Lyon



2-colors, 2-dyes: Rhod

Laser λ=488 nm

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

I: incident light

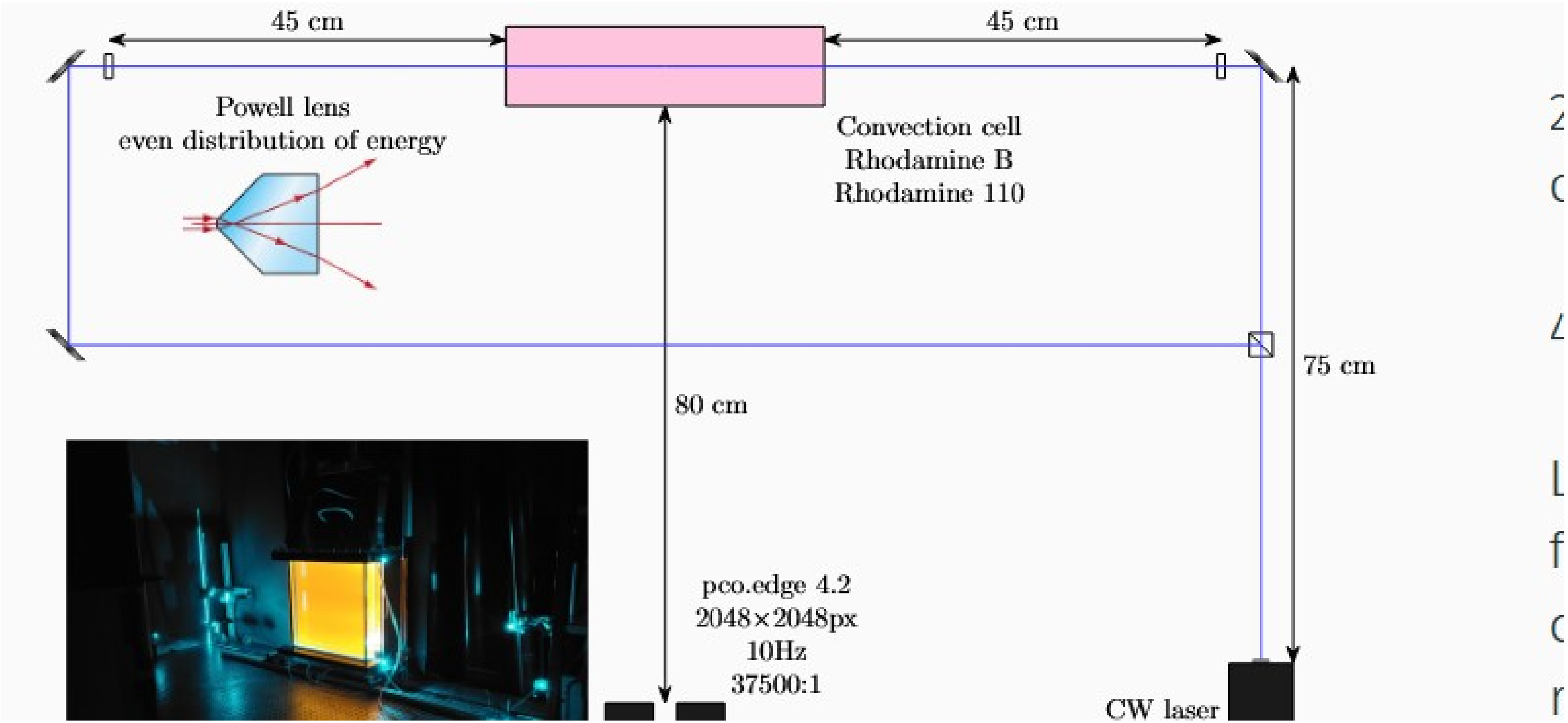
c: concentration

T: temperature

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

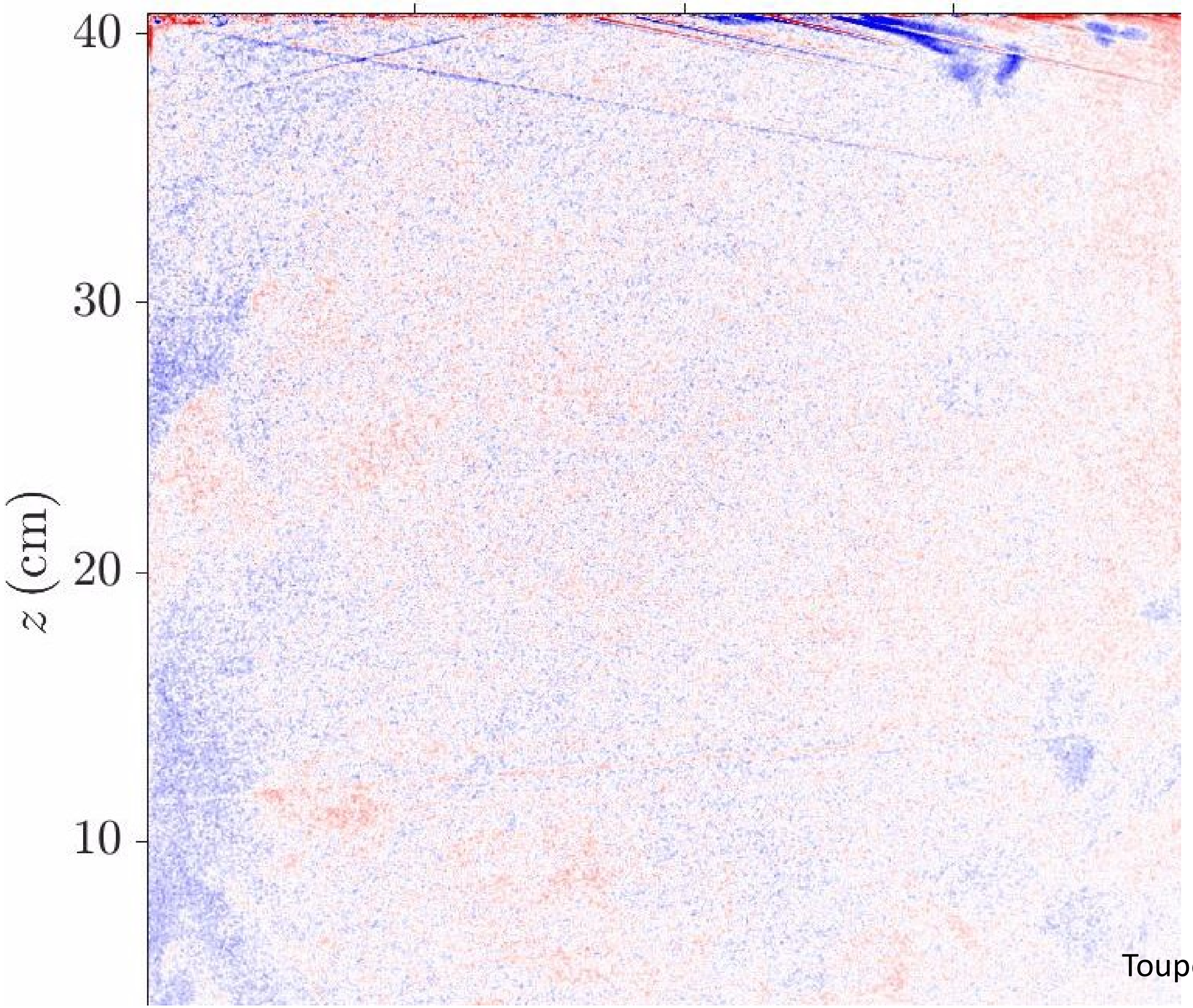
Laser Induced Fluorescence

Temperature and velocity at ENS Lyon



Laser Induced Fluorescence

Temperature and velocity at ENS Lyon



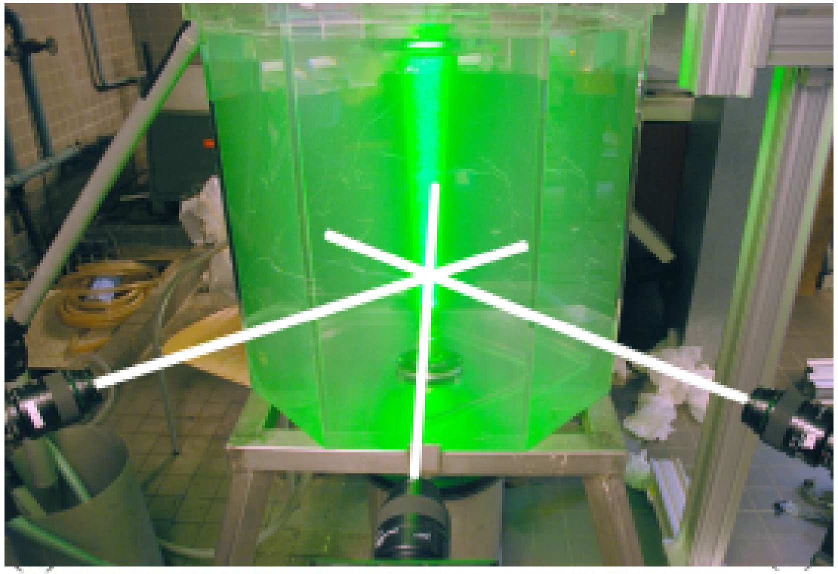
Rayleigh-Bénard Convection

Temperature field

Toupoint et al. submitted

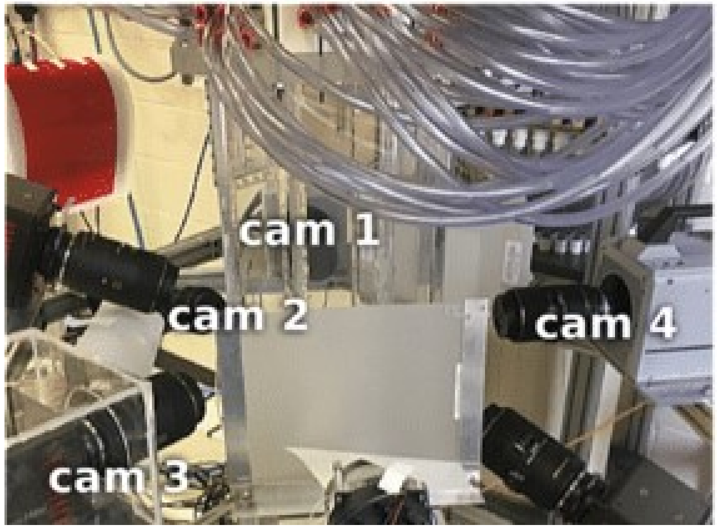
4D Particle Tracking Velocimetry

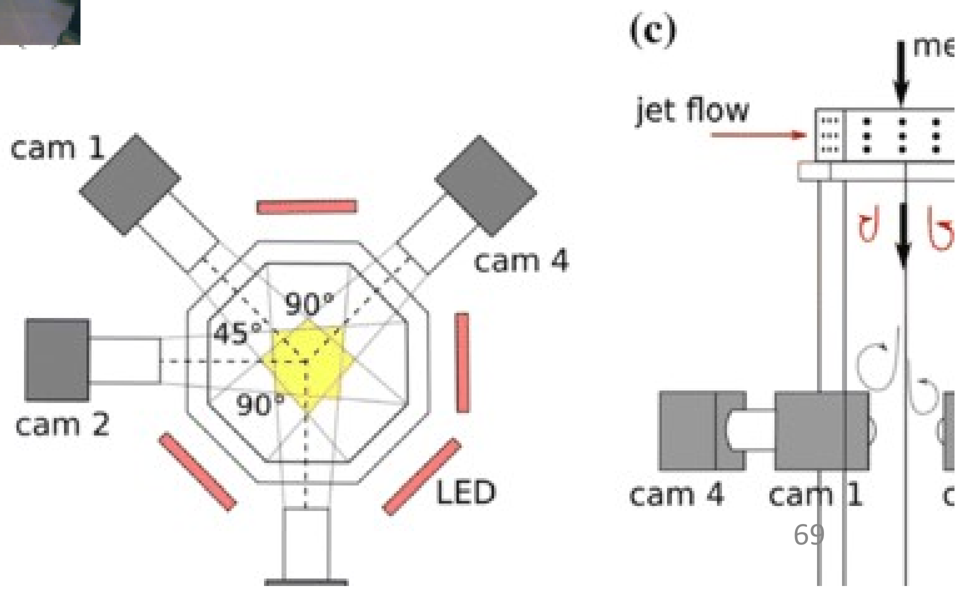
Lagrangian statistics
Eulerian statistics are possible



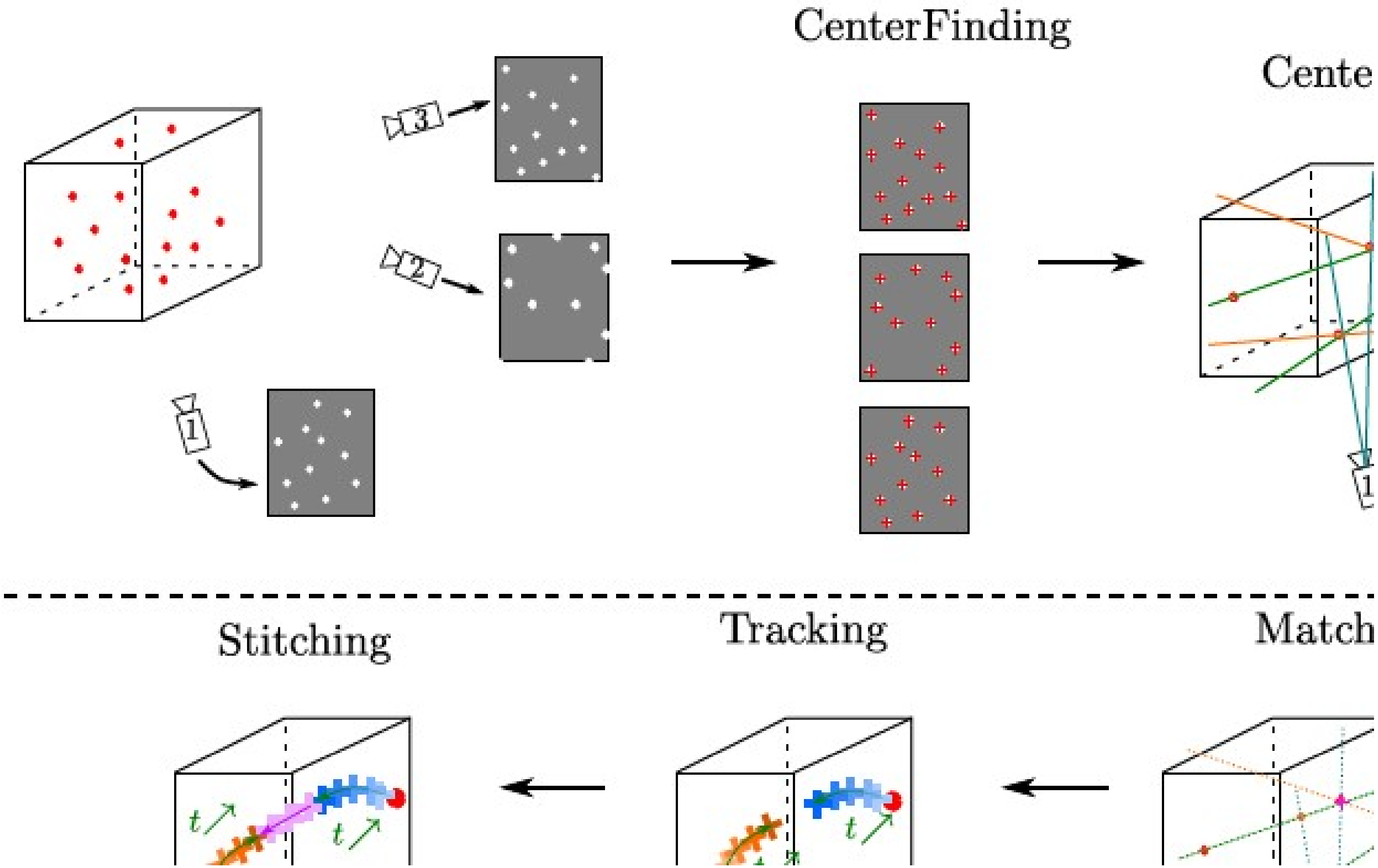
Material

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

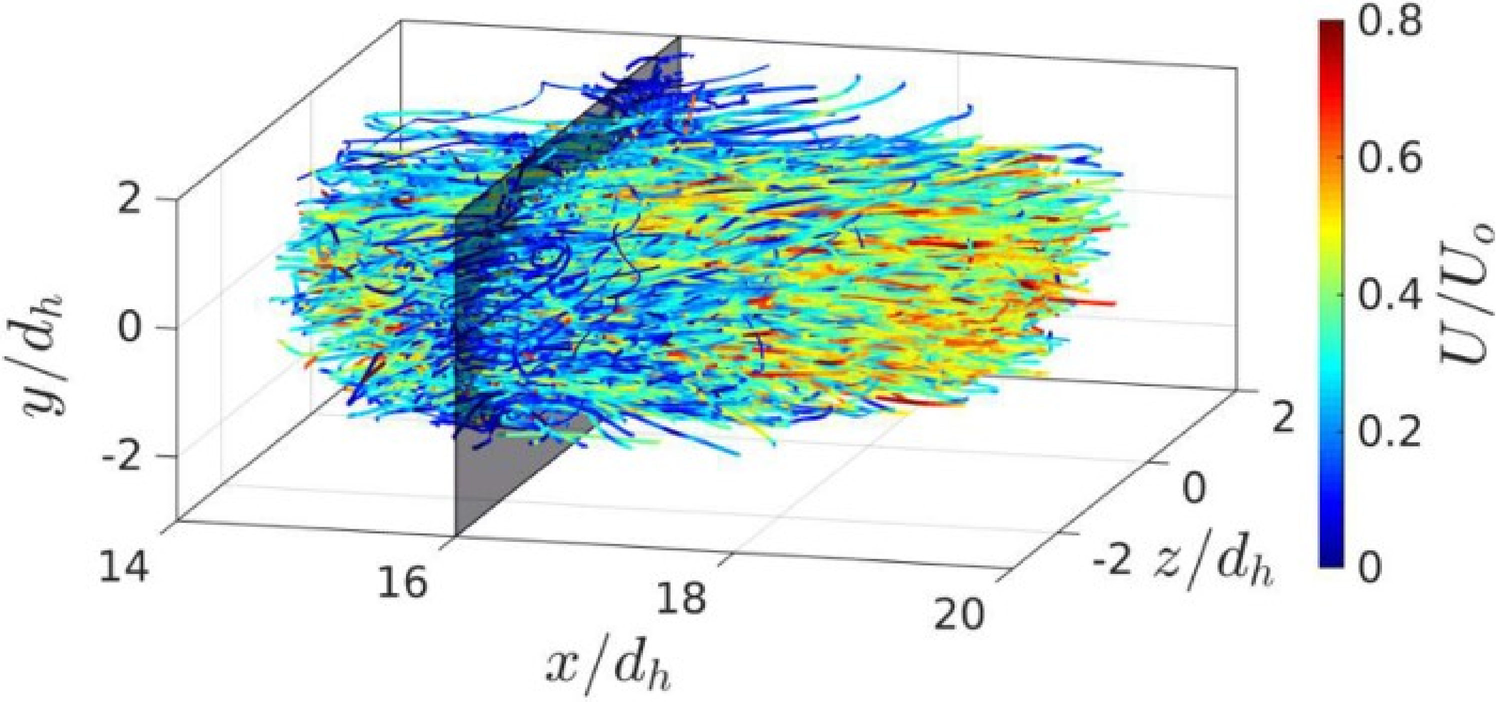




4D Particle Tracking Velocimetry

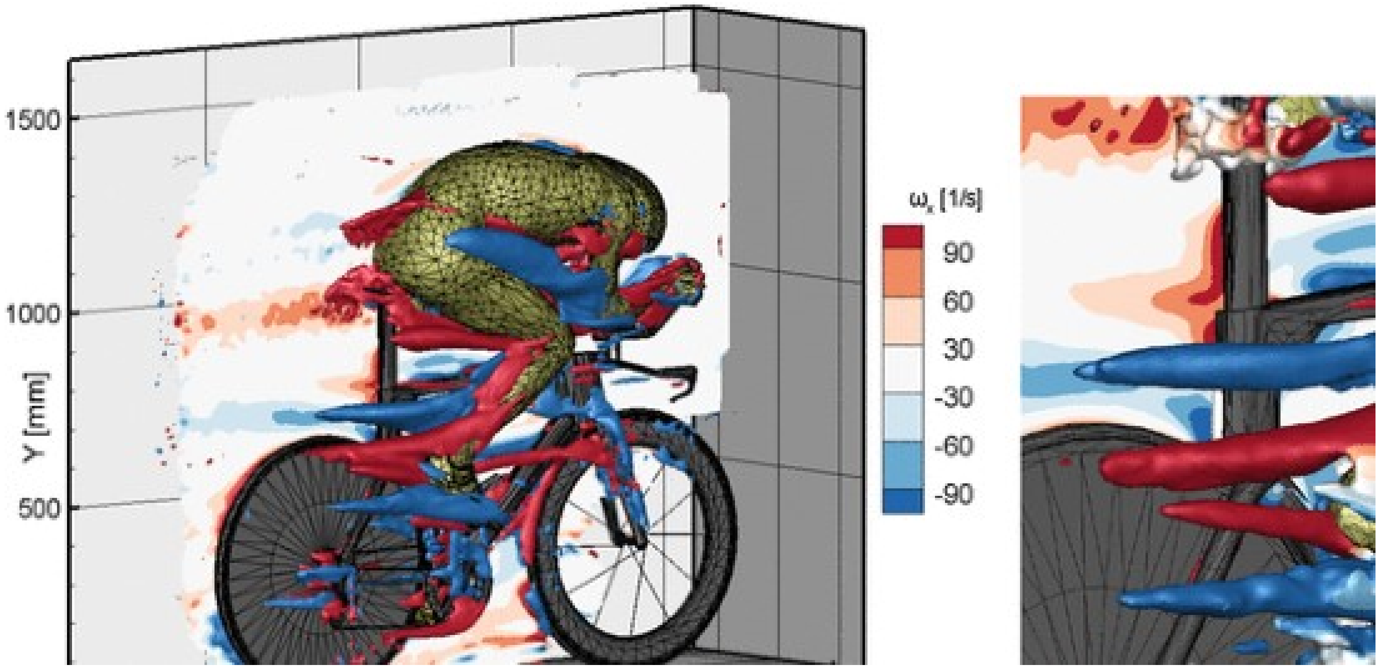


4D Particle Tracking Velocimetry



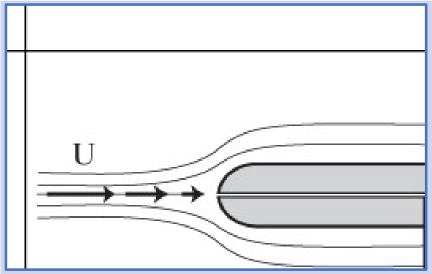
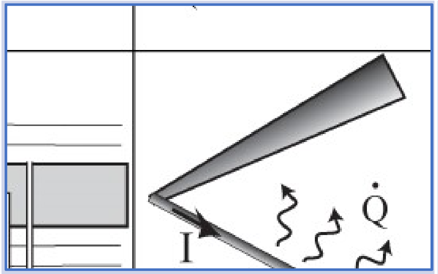
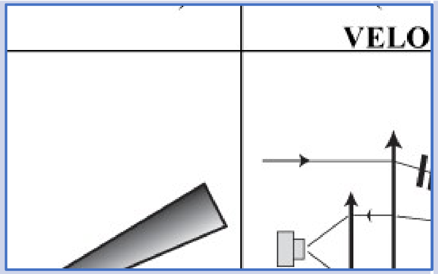
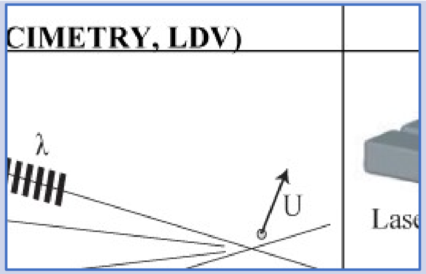
Up to 100 000 simultaneous tracks

3D PIV



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