Grand Opening Event
Athens, 24-26 Jan 2023

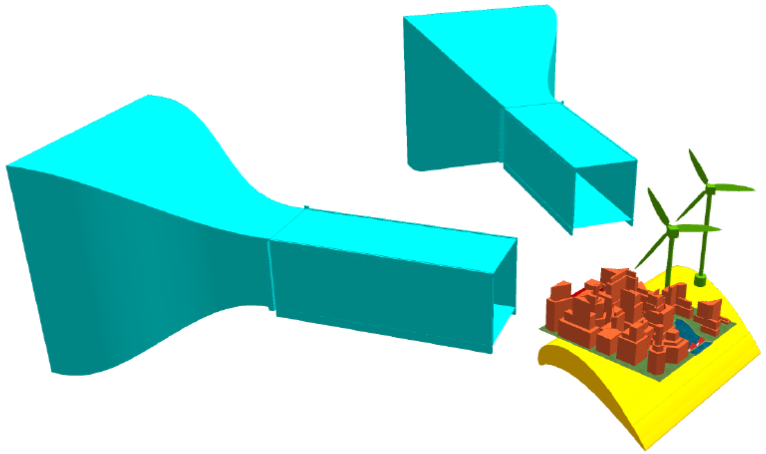
TWEET-IE

Twin Wind tunnels for Energy and the EnvironmenT - Innovations and Excellence

From planar PIV to 3D-LPT

Dr. Andrea Sciacchitano

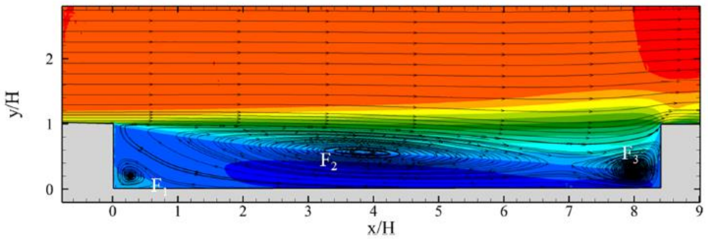
a.sciacchitano@tudelft.nl



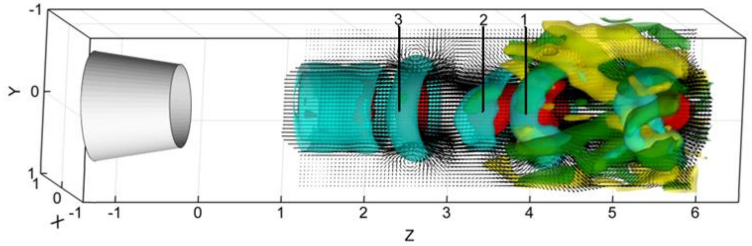
TU Delft

Content

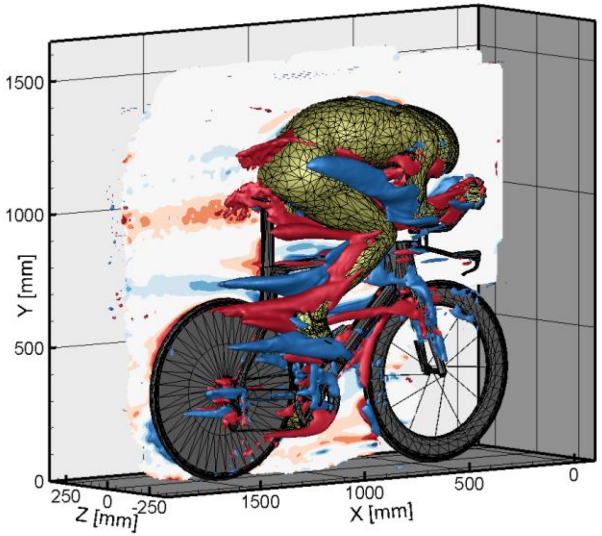
- 2D Particle Image Velocimetry



- 3D Particle Image Velocimetry and Lagrangian Particle Tracking



- Large-scale PIV



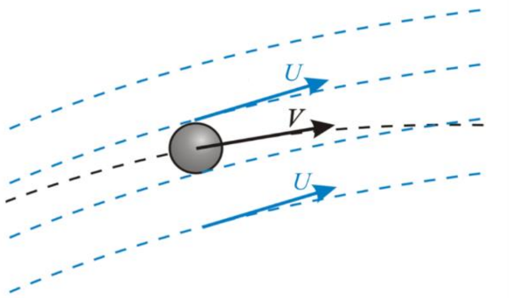
2D PIV
Working principle

- Measurement technique to determine the flow velocity
- Small particles inserted into the flow and carried by the fluid
- The particles are illuminated by a laser
- Couples of images are recorded by a camera
- The images are processed to determine the particles displacement
- The displacement is divided by the pulse separation time to extract the flow velocity

2D PIV
Key components

1) Tracer particles:

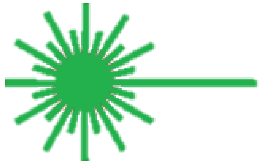
- They must follow the flow
- They should be visible



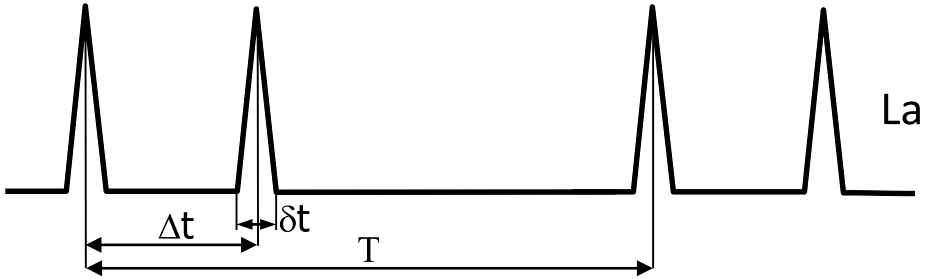
$$\underbrace{V - U}_{\text{Slip velocity}} = -\frac{d_p^2}{18}\frac{(\rho_p - \rho_f)}{\mu}\frac{dV}{dt}$$

Material (in air)	d_p [µm]	Density [kg/m³]
DEHS	1-3	10^3
Glycol-water	1-3	10^3
Vegetable oil	1-3	10^3
TiO_2	0.2 – 0.5	$1 - 4 \times 10^3$

2) Illumination:

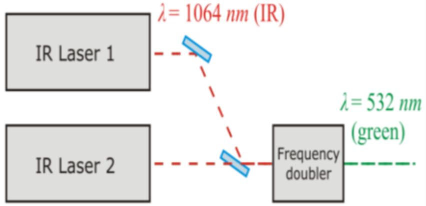


- Should provide enough light
- Particles imaged as dots and not as streaks
→pulsed light needed (LASERS)



Laser pulses

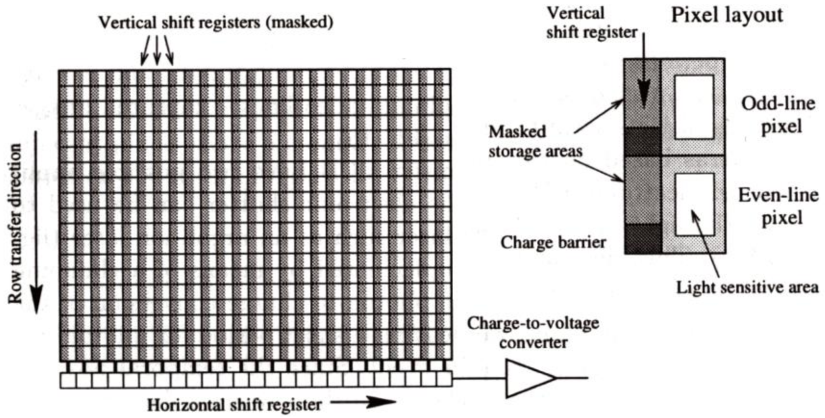
Type	Wavelength [nm]	Power or pulse energy	Repetition rate [Hz]
Argon ion	514, 488	10 ÷ 30 W	CW
Nd:YAG	532	20 ÷ 500 mJ	10 ÷ 30
Nd:YLF	526	10 ÷ 30 mJ	1,000 ÷ 10,000

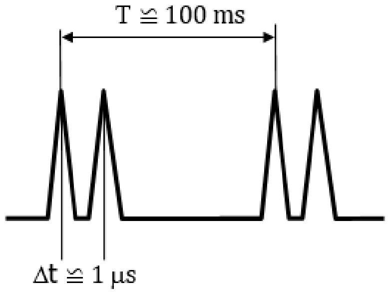


2D PIV
Key components

3) Imaging

- Use of CCD or CMOS cameras
- Couples of images are acquired



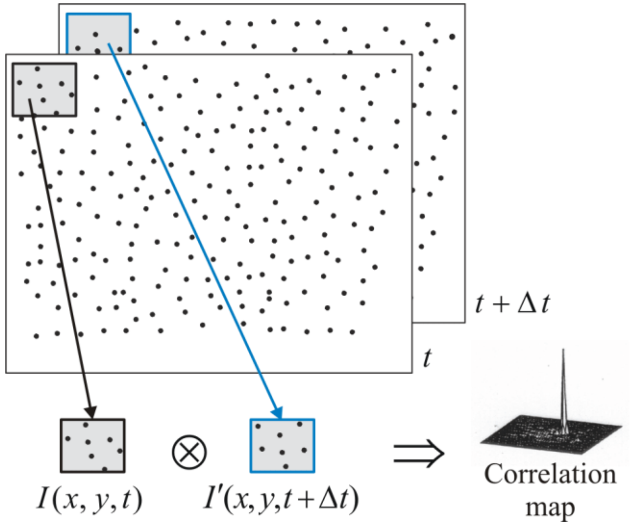


- Pixel size: 5-20 μm
- Resolution: 1-25 MPx

4) Processing:

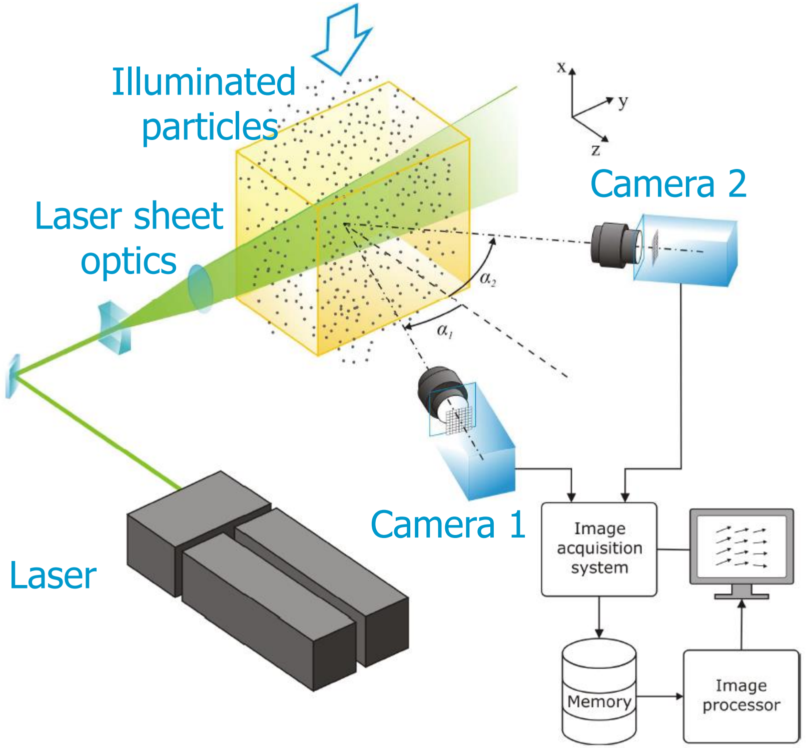
- Images divided into interrogation windows (e.g. 16x16 or 32x32 pixels)
- Cross-correlation analysis in each interrogation window
- The position of the correlation peaks indicates the avg particle displacement in the window
- Divide by Magnification factor and Δt to get velocity

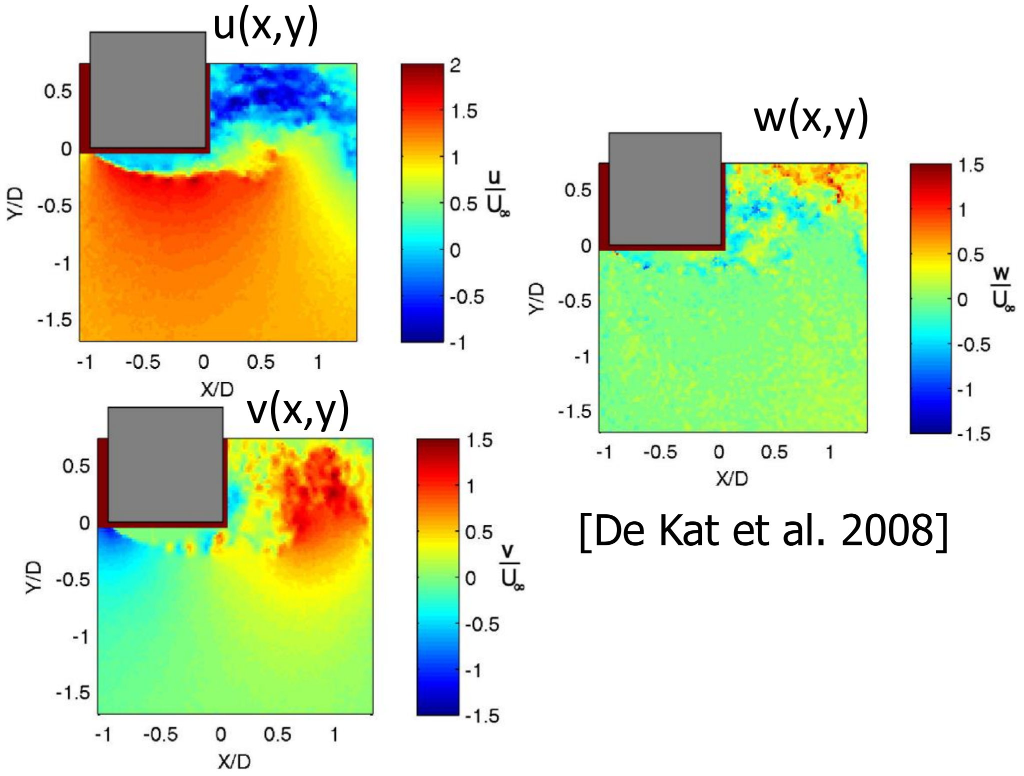
$$\phi(m,n) = \frac{\sum_{i,j=1}^{I,J} I(i,j)\cdot I'(i+m,j+n)}{\sqrt{stdev(I)\cdot stdev(I')}}$$



Stereoscopic PIV
2D-3C measurements

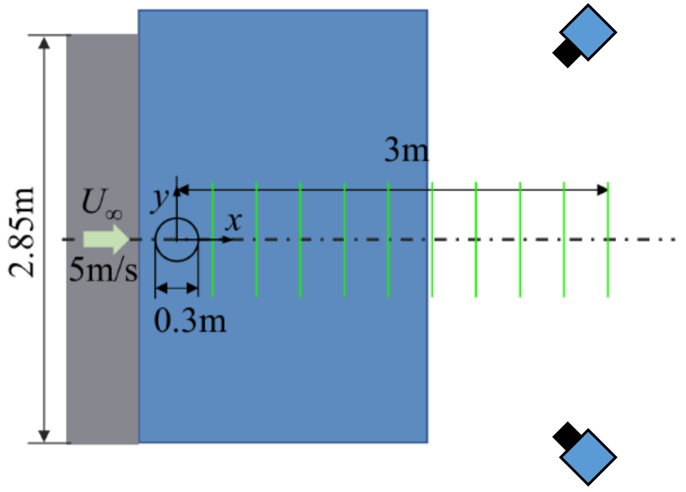
- 2 cameras
- Output: u(x,y), v(x,y) and w(x,y): 3 velocity components in a 2D domain

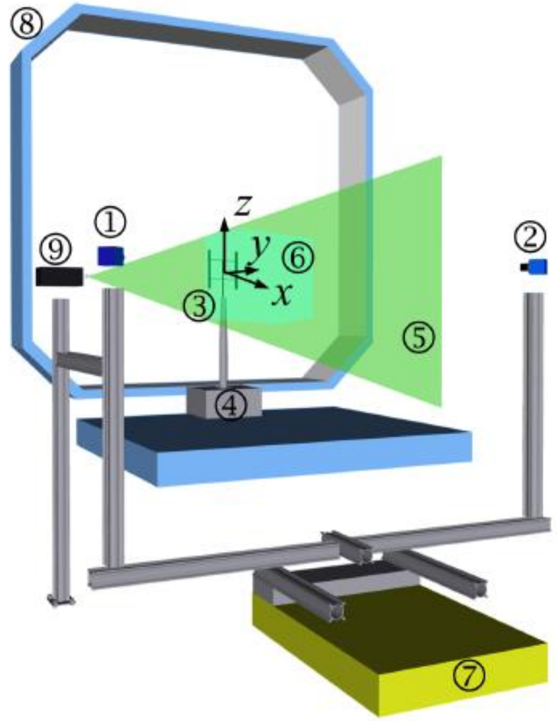


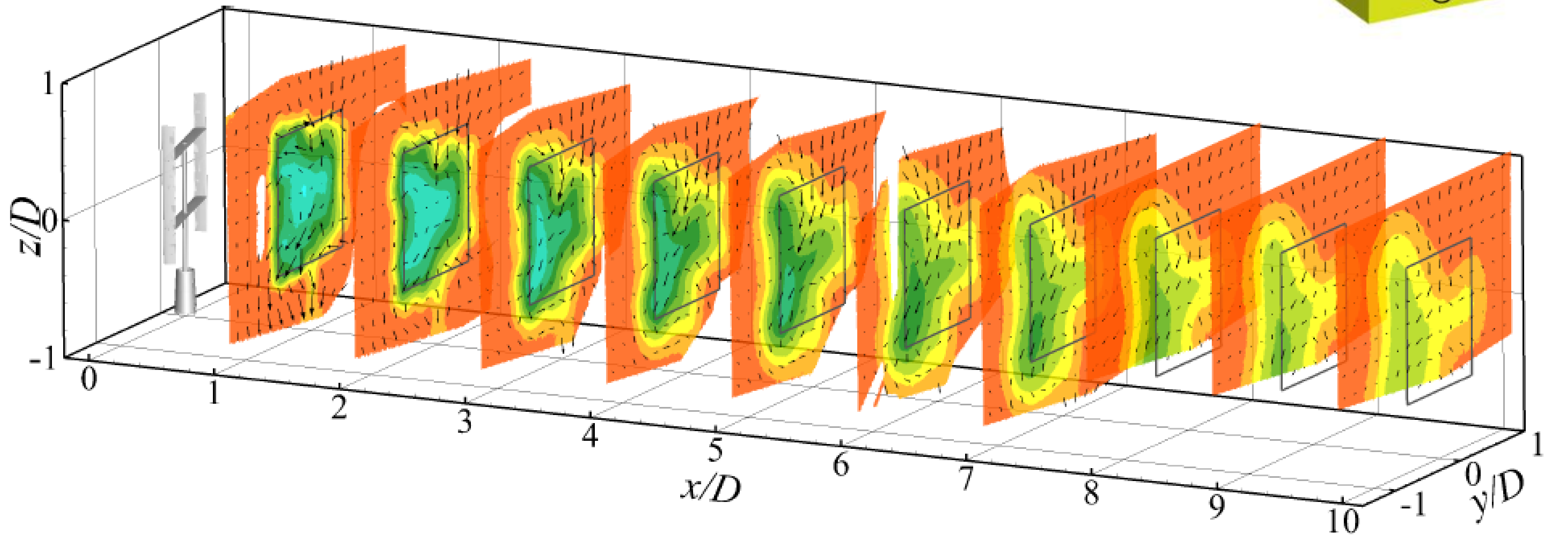


[De Kat et al. 2008]

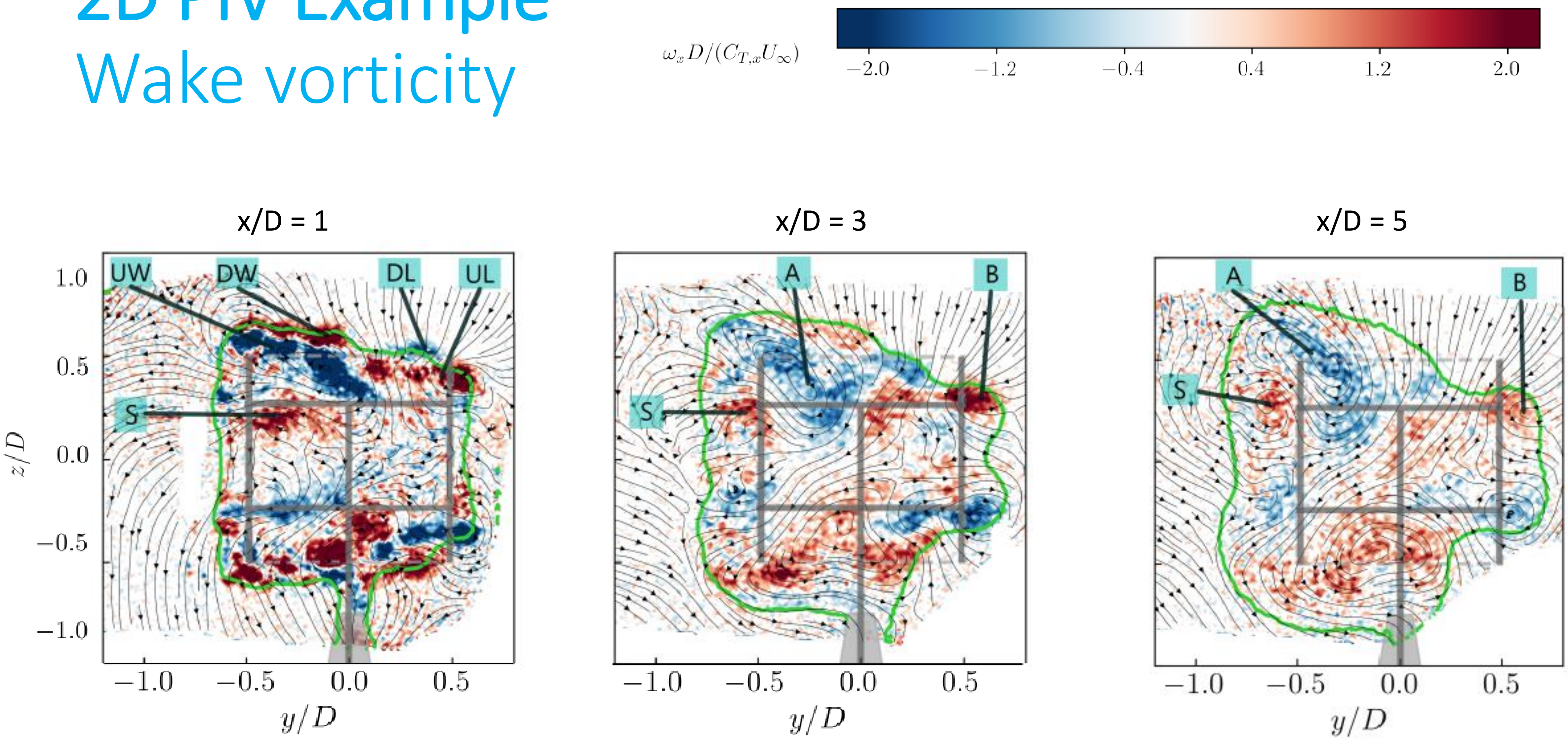
2D PIV Example
VAWT wake



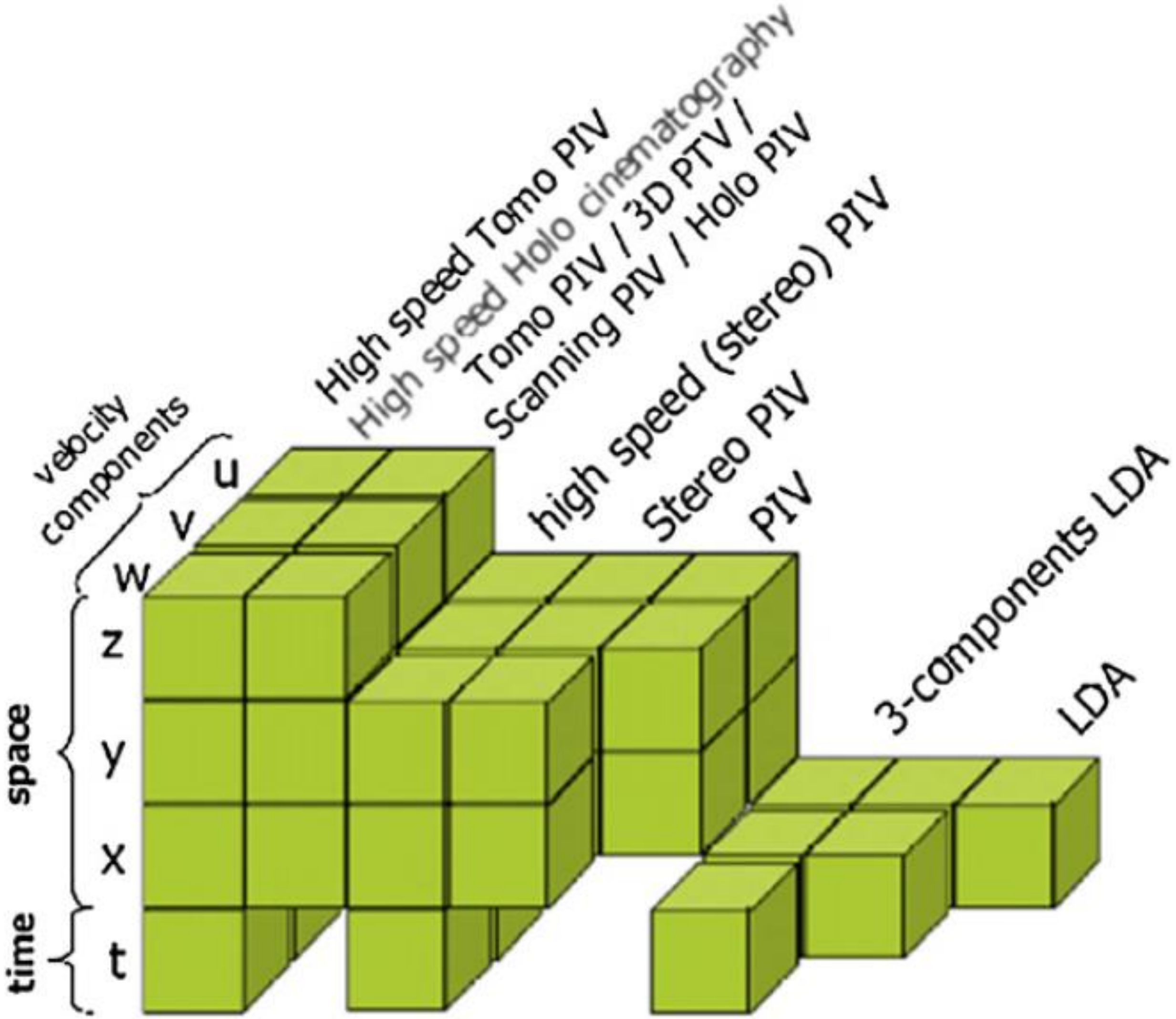




2D PIV Example
Wake vorticity



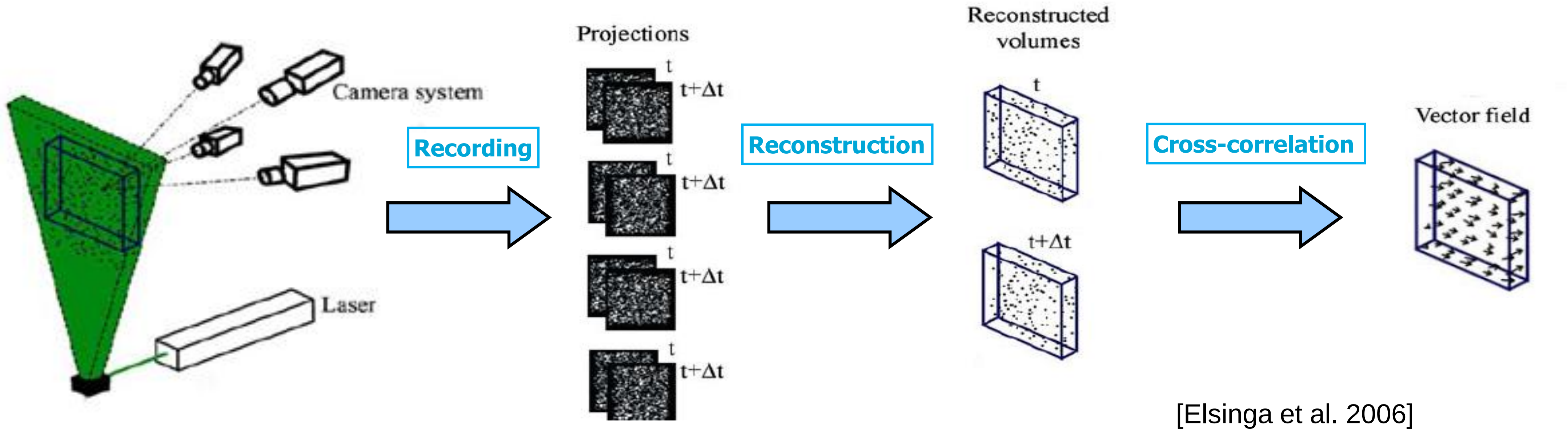
Measurement domain and components



[Scarano 2012]

- Planar PIV: 2D-2C
- Stereo PIV: 2D-3C
- Tomo-PIV: 3D-3C

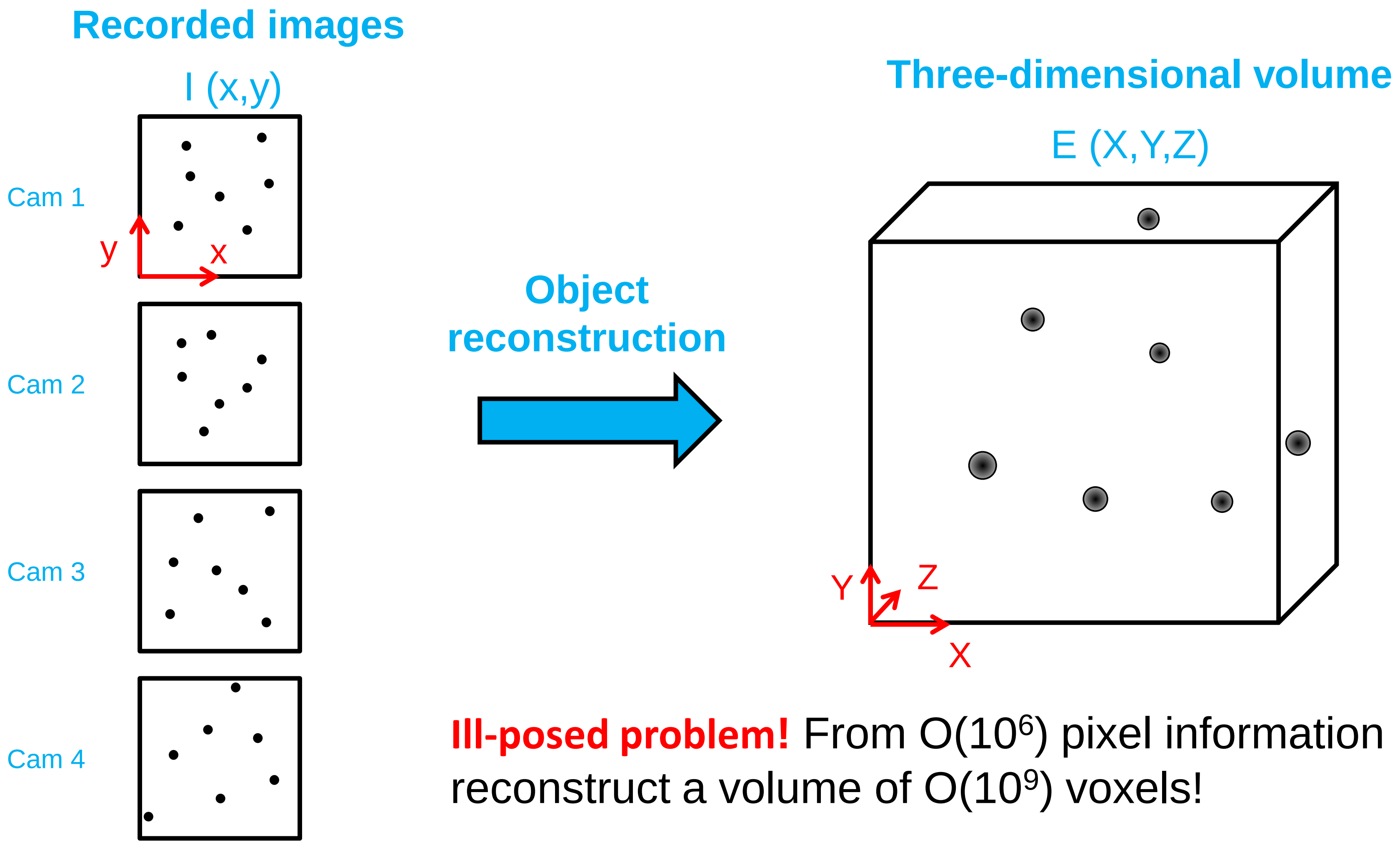
Tomographic PIV
Working principle



[Elsinga et al. 2006]

- Particles illuminated in a volume
- Multiple cameras (3-4) record images
- Reconstruction of 3D distribution of tracers particles
- Output: 3 velocity components in a 3D domain

Object Reconstruction
From 2D images to 3D particles distribution



Ill-posed problem! From $O(10^6)$ pixel information I need to reconstruct a volume of $O(10^9)$ voxels!

Object Reconstruction
Solution of the inversed problem

Intensity in physical space

Voxel location in physical space

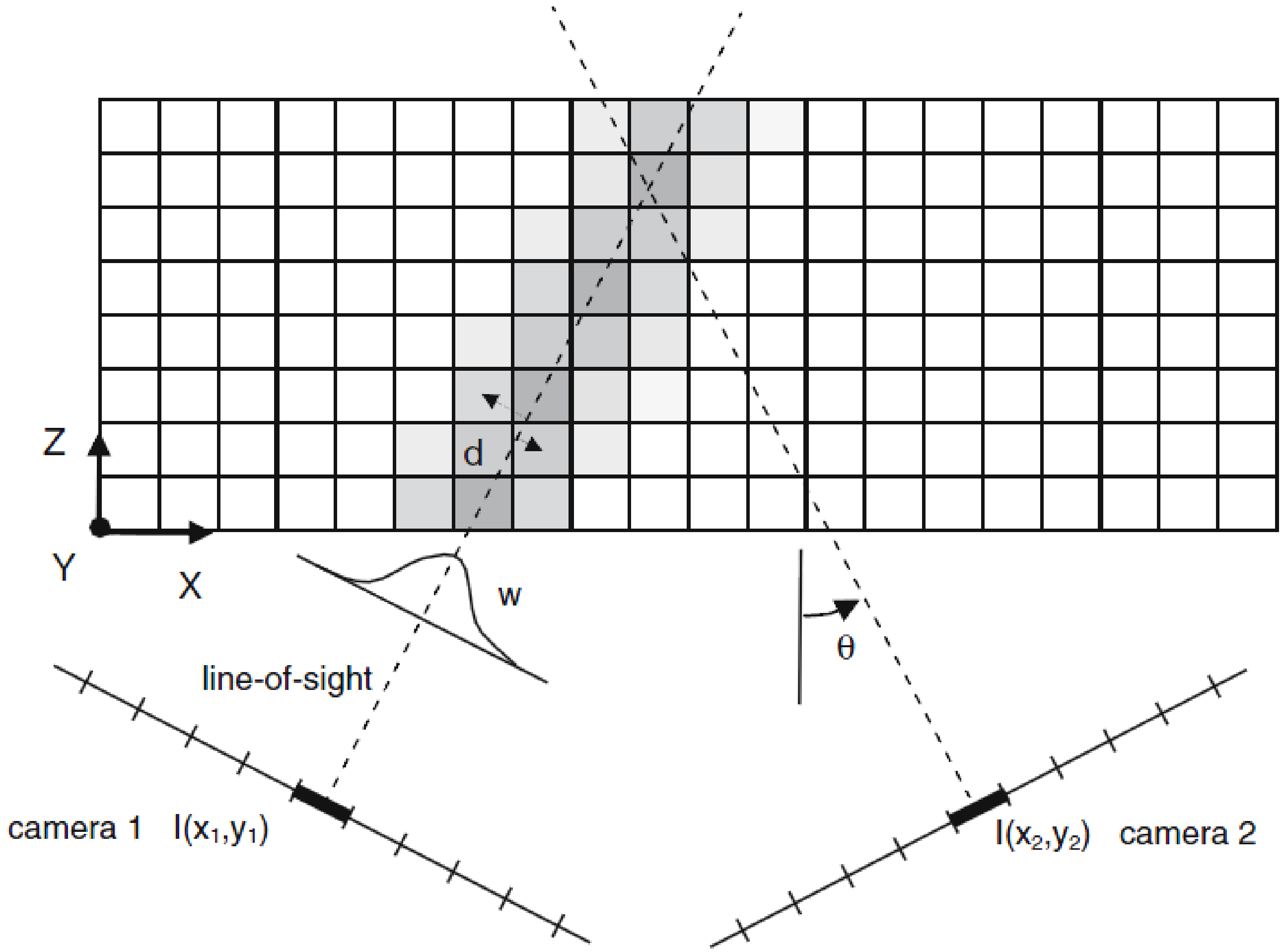
Pixel intensity

$$\sum_{j\in N_i} w_{i,j} E\left(X_j, Y_j, Z_j\right) = I\left(x_i, y_i\right)$$

Pixel location

Number of voxels contributing to $I(x_i,y_i)$

Weighting function

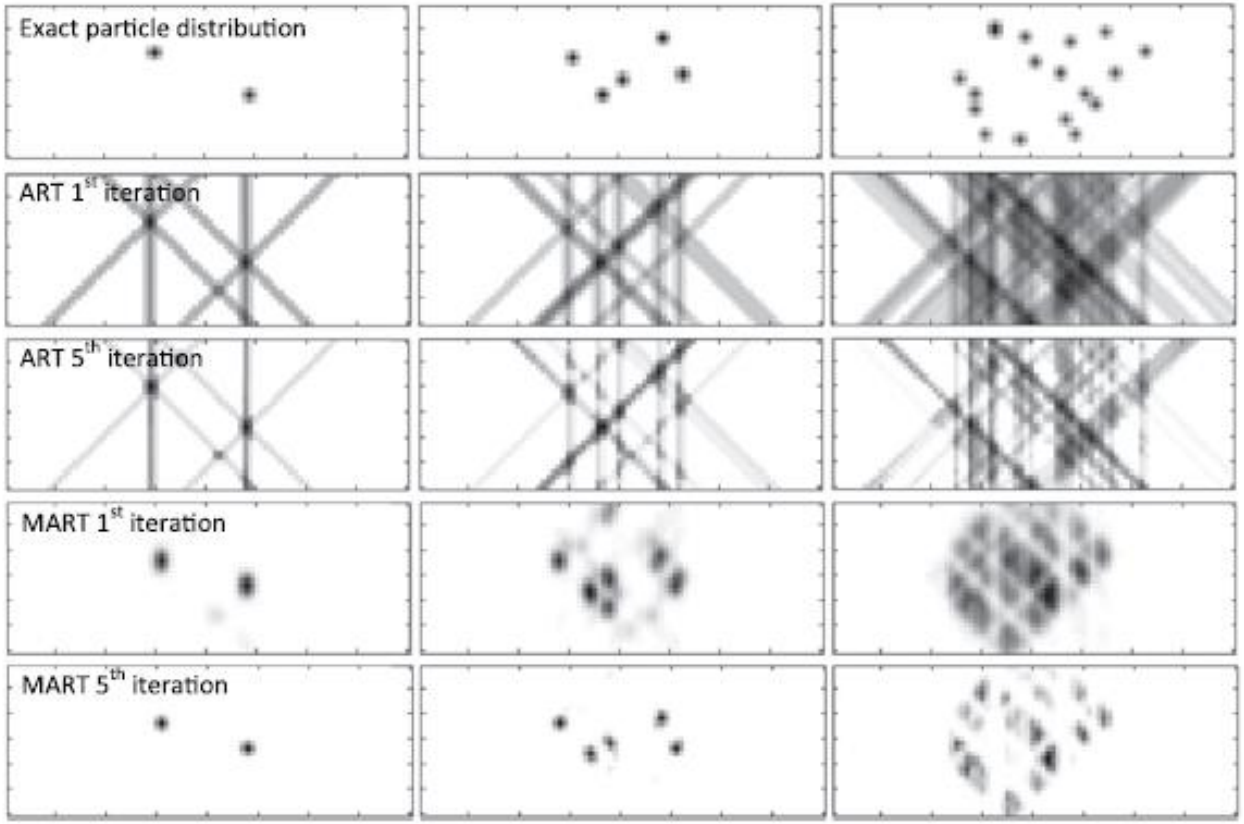


Reconstruction Algorithms

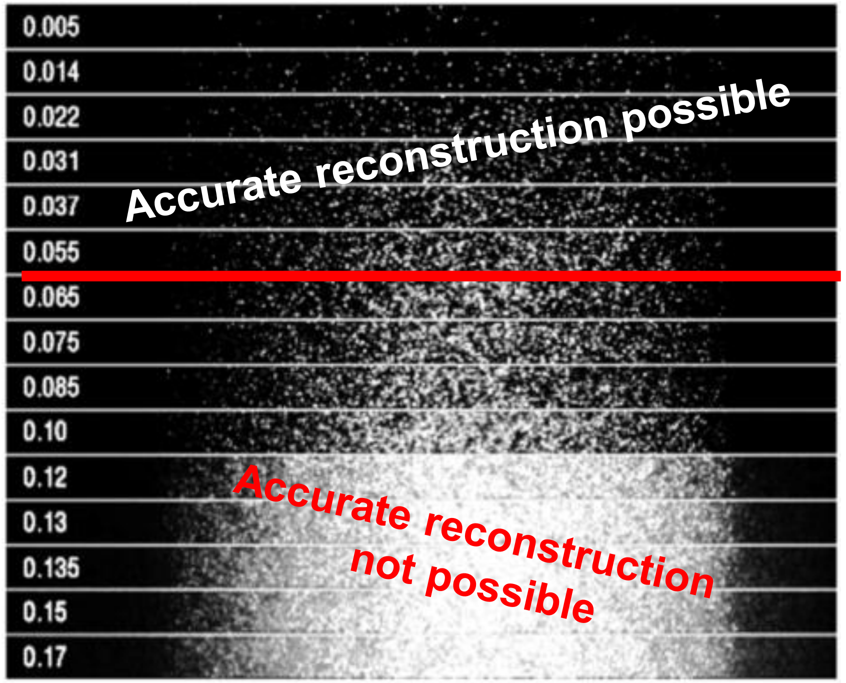
$$\text{ART}: \quad E_{k+1}(X_j,Y_j,Z_j) = E_k(X_j,Y_j,Z_j) + \mu W_{i,j} \frac{I(x_i,y_i) - \sum_{i=1}^{N} W_{j,i} E_k(X_j,Y_j,Z_j)}{\sum_{i=1}^{N} W_{j,i}}$$

$$\text{MART}: \quad E_{k+1}(X_j,Y_j,Z_j) = E_k(X_j,Y_j,Z_j) \cdot \left(\frac{I(x_i,y_i)}{\sum_{i=1}^{N} W_{j,i} E_k(X_j,Y_j,Z_j)} \right)^{\mu W_{i,j}}$$

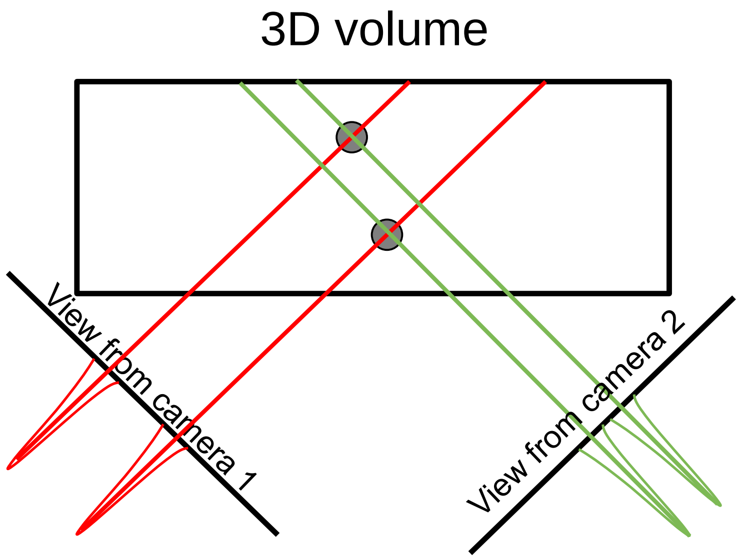
- ART (Algebraic Reconstruction Technique)
- MART (Multiplicative Algebraic Reconstruction Technique)
- MLOS (Multiplicative Line-Of-Sight)



Images with varying seeding density
(# of particles per pixel)

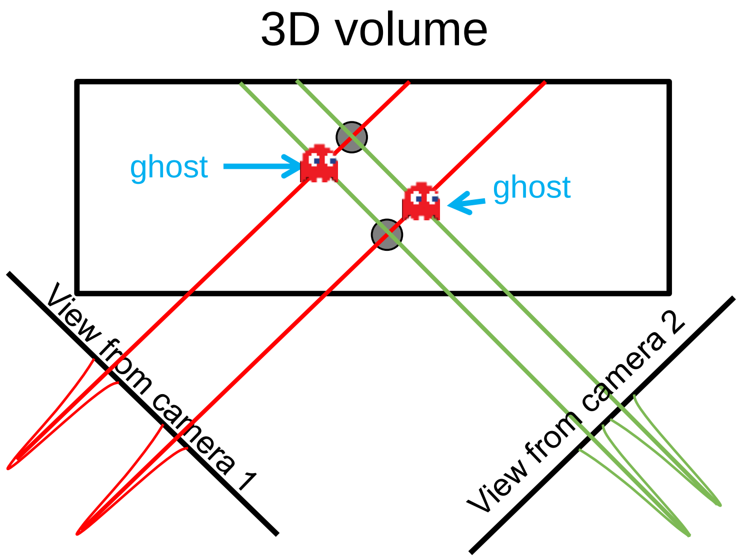


Object Reconstruction
Ghost particles

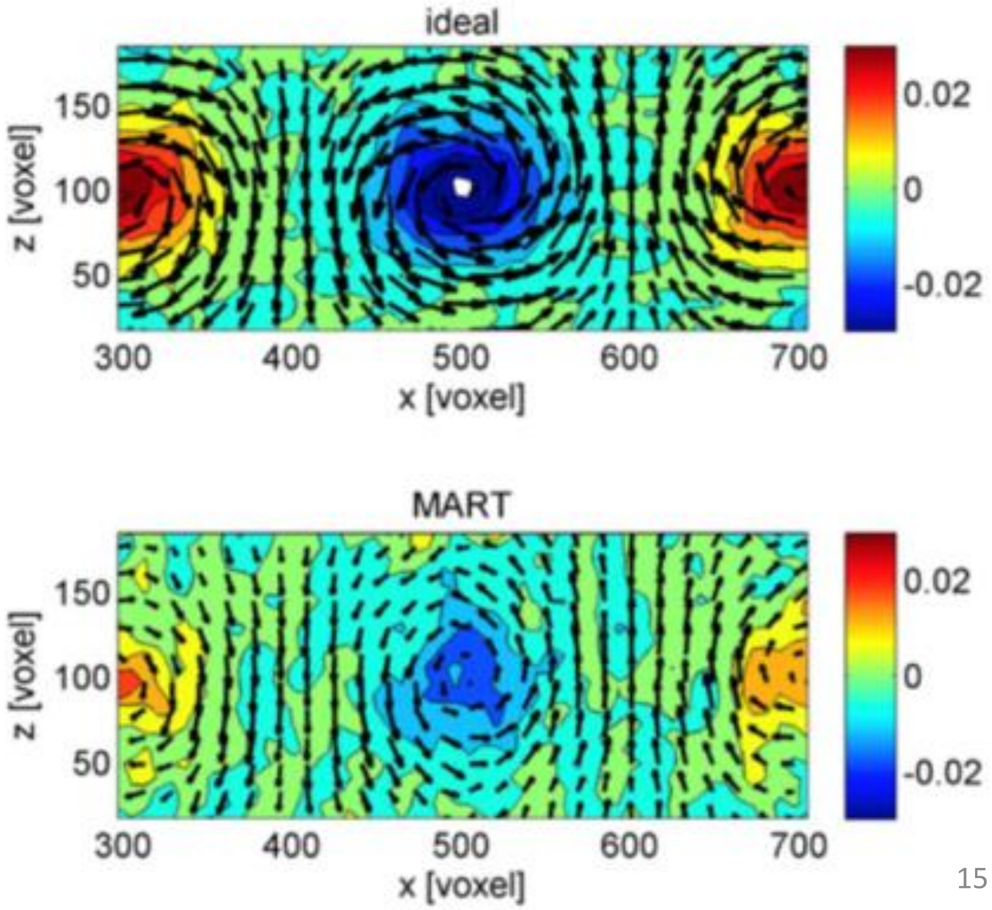


Object Reconstruction
Ghost particles

- Regarded as “reconstruction noise”, but not random (Elsinga et al., EiF 2011)
- Dominate the signal at high source density



Ghost particles affect velocity gradient estimates



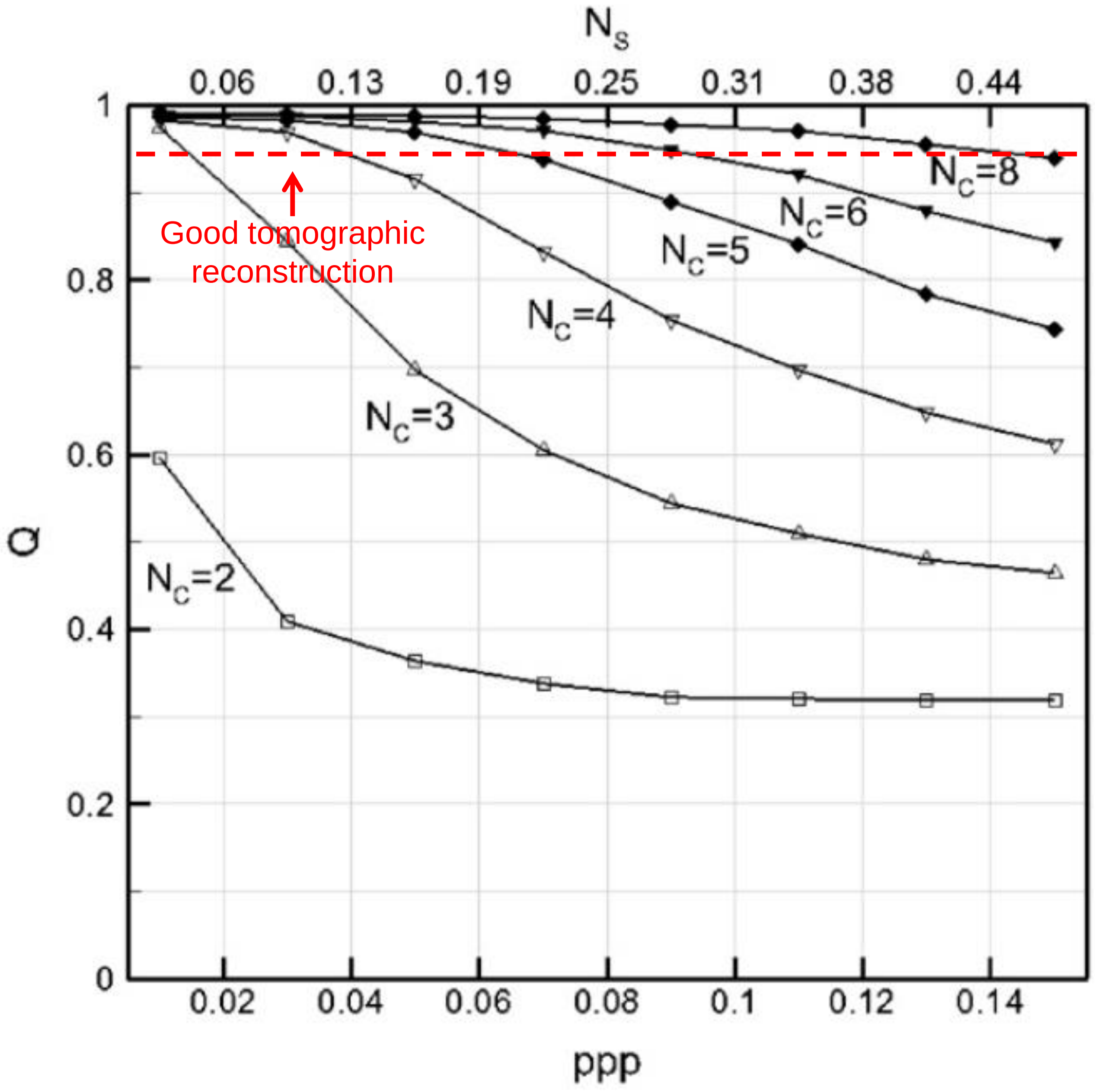
Object Reconstruction
Reconstruction Quality

Reconstructed intensity

Exact intensity

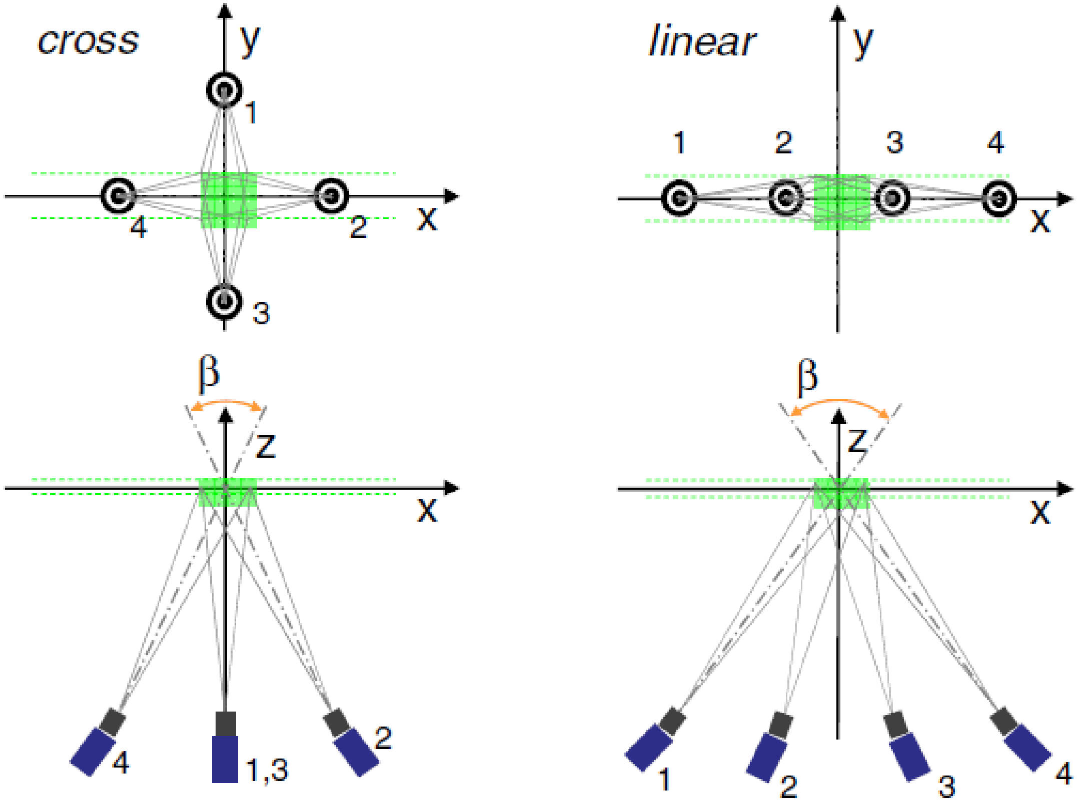
$$Q = \frac{\sum_{X,Y,Z} E_1(X,Y,Z) \cdot E_0(X,Y,Z)}{\sqrt{\sum_{X,Y,Z} E_1^2(X,Y,Z) \cdot \sum_{X,Y,Z} E_0^2(X,Y,Z)}}$$

- Reconstruction quality Q decreases with increasing seeding density ppp
- Reconstruction quality Q increases when increasing number of cameras



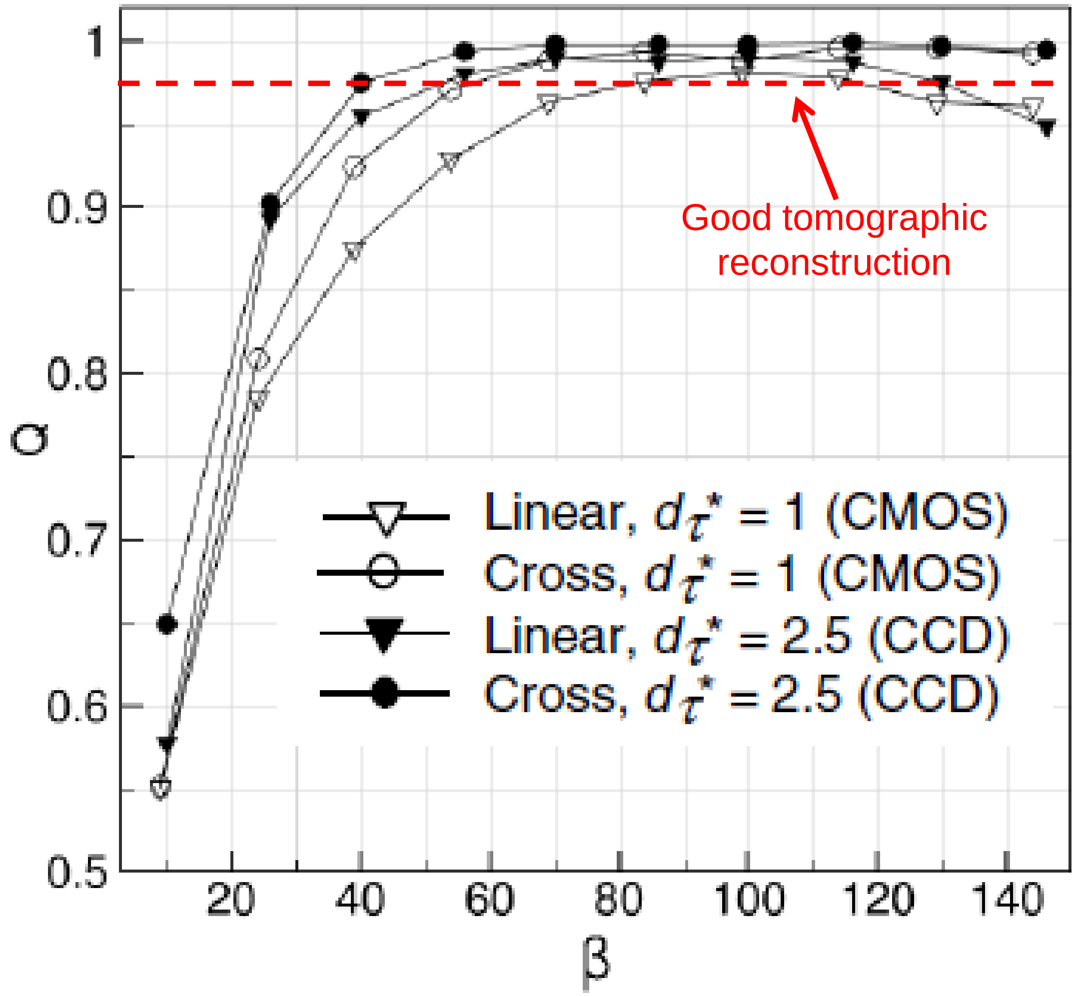
Tomographic Imaging
Cameras configurations

Configurations



Scarano [2013]

Reconstruction quality Q



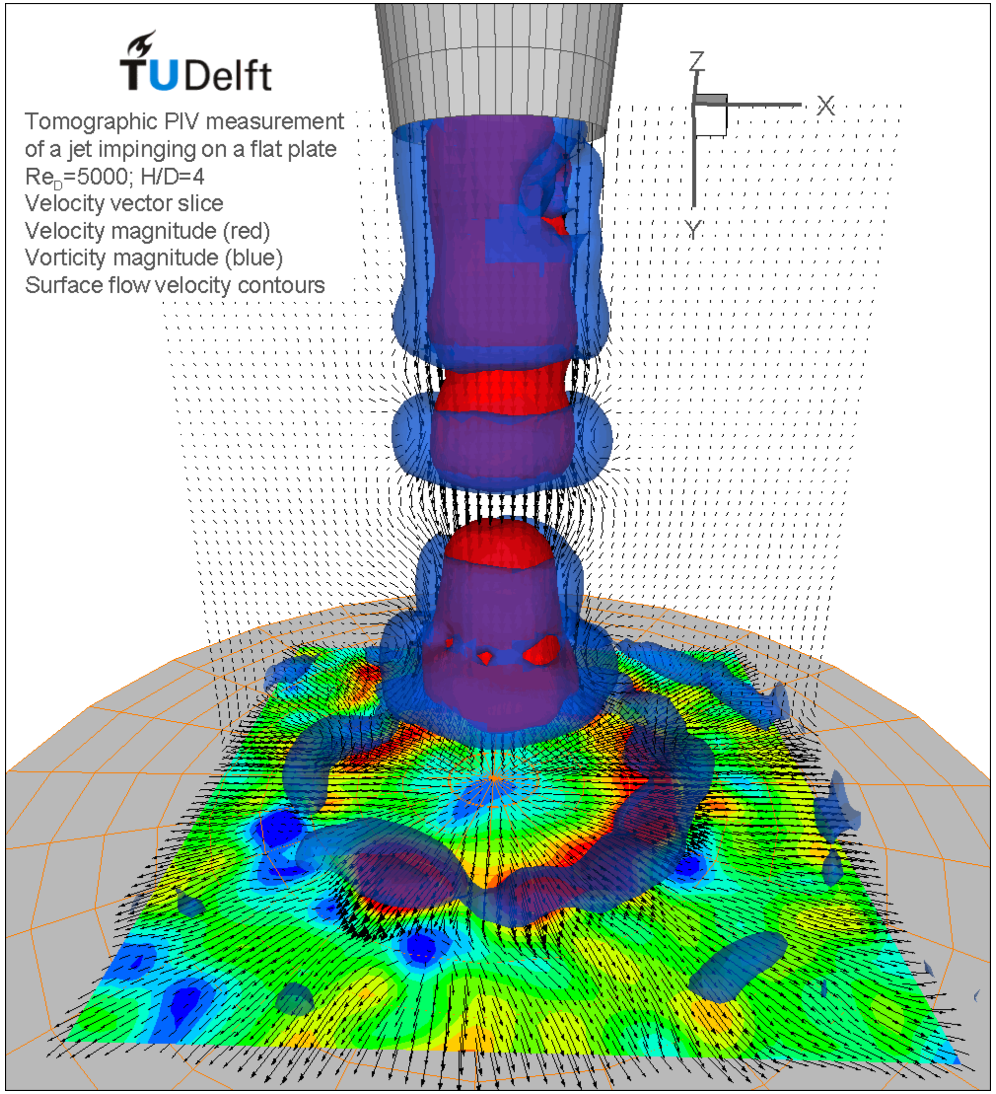
Tomographic angle among the cameras

Motion Analysis

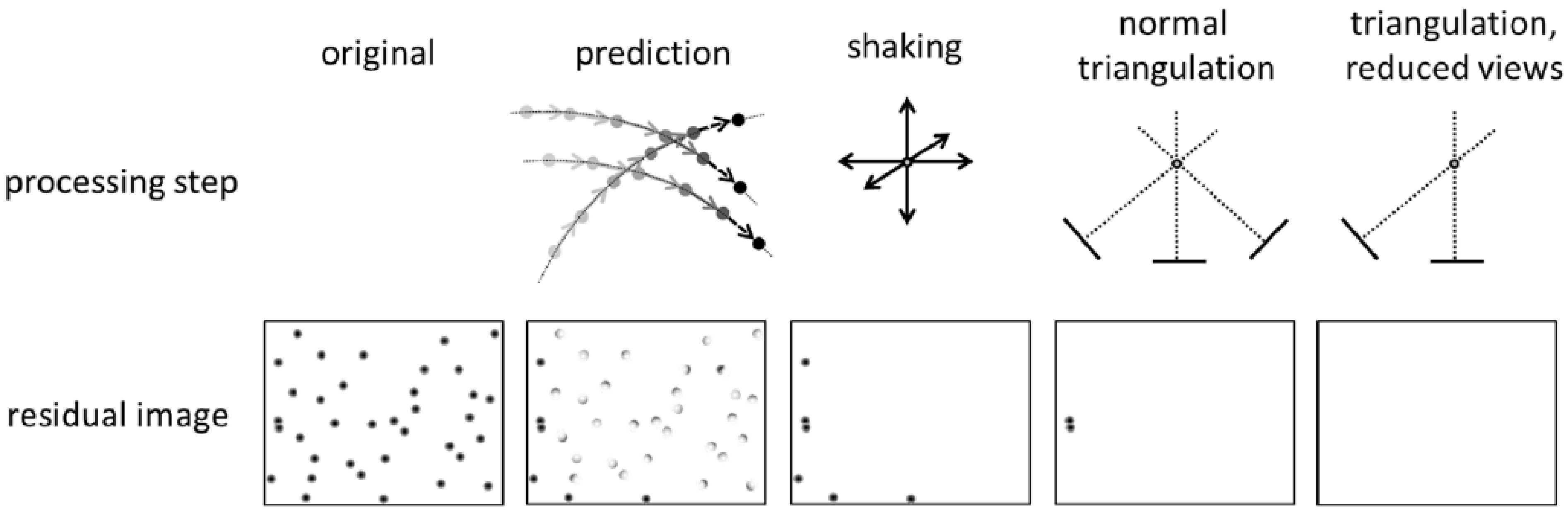
Similar procedure to 2D PIV:

- Divide the volumes at times *t* and *t*+*Δt* into interrogation volumes
- Cross-correlation between the interrogation volumes
- Location of the maximum in the correlation space
- Computation of the velocity: $\mathbf{V} = \Delta\mathbf{x} / (M \cdot \Delta t)$

$$R(l,m,n) = \frac{\sum_{i,j,k=1}^{I,J,K} E(i,j,k,t) \cdot E(i-l, j-m, k-n, t+\Delta t)}{\sqrt{\sum E(t)^2 \cdot \sum E(t+\Delta t)^2}}$$



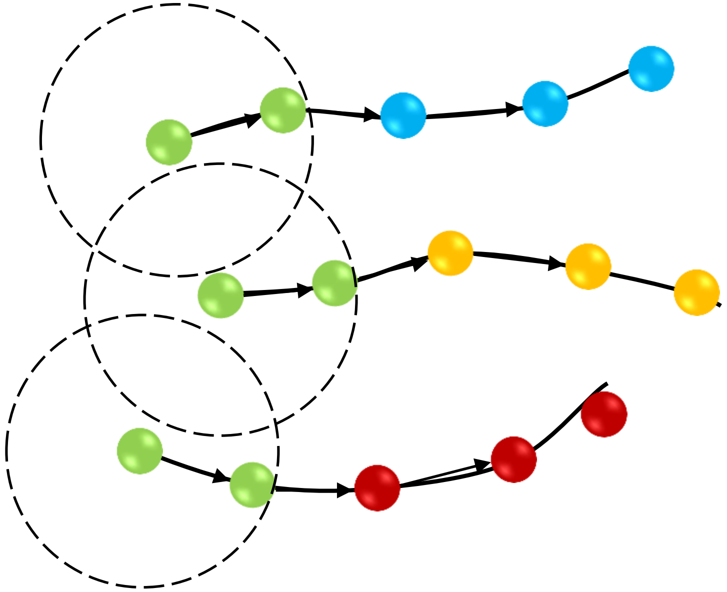
From Tomo-PIV to Lagrangian Particle Tracking
Shake-The-Box algorithm



Schanz et al. (2016)

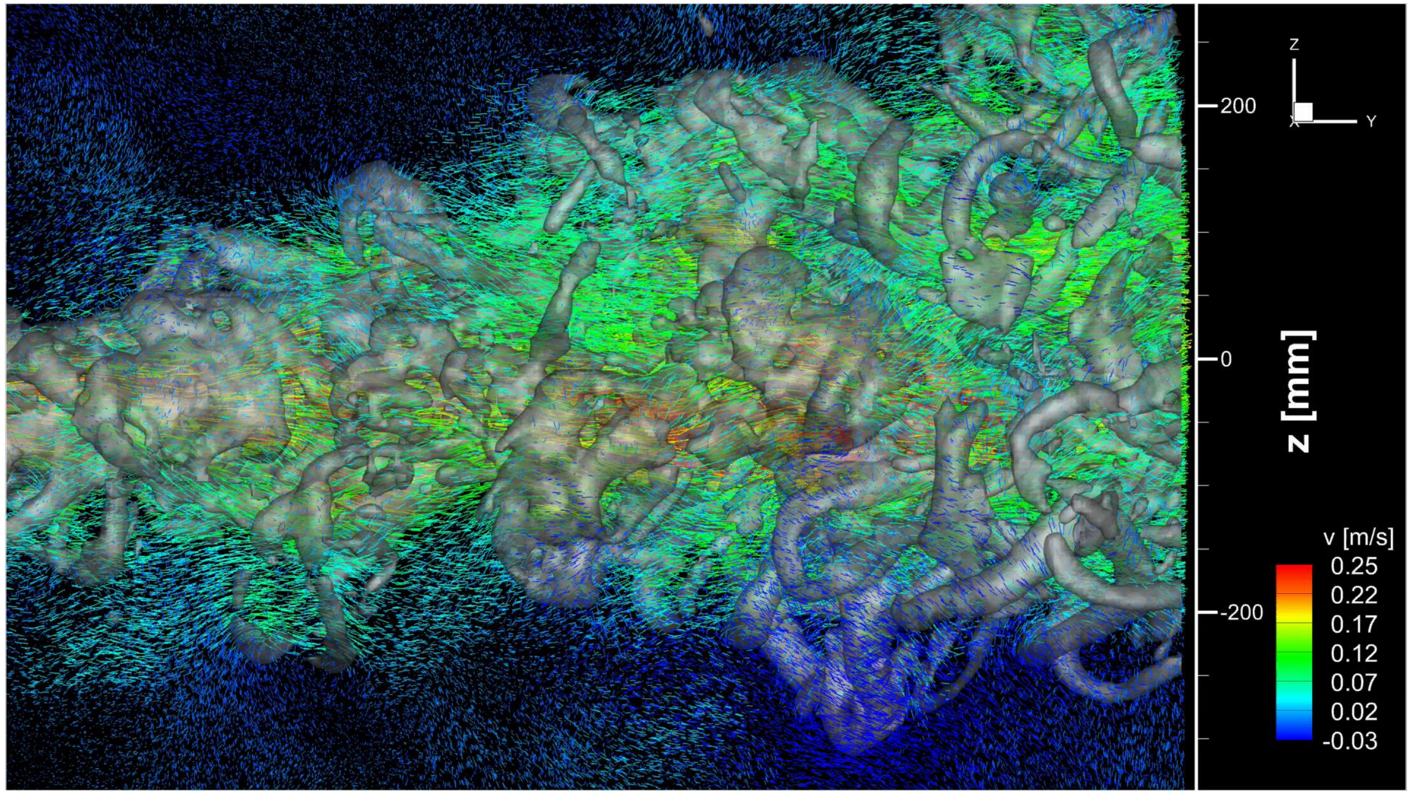
- Efficient approach for particles triangulation and tracking
- Problem of ghost particles significantly reduced
- Velocity and acceleration information retrieved along a track

Shake the Box
Lagrangian Particle Tracking at high particle image densities



t1

Schanz et al. (2016)

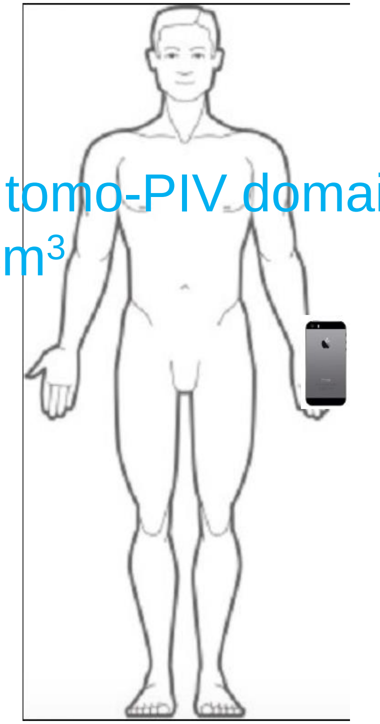


- Efficient approach for particles triangulation and tracking
- Problem of ghost particles significantly reduced
- Velocity and acceleration information retrieved along a track

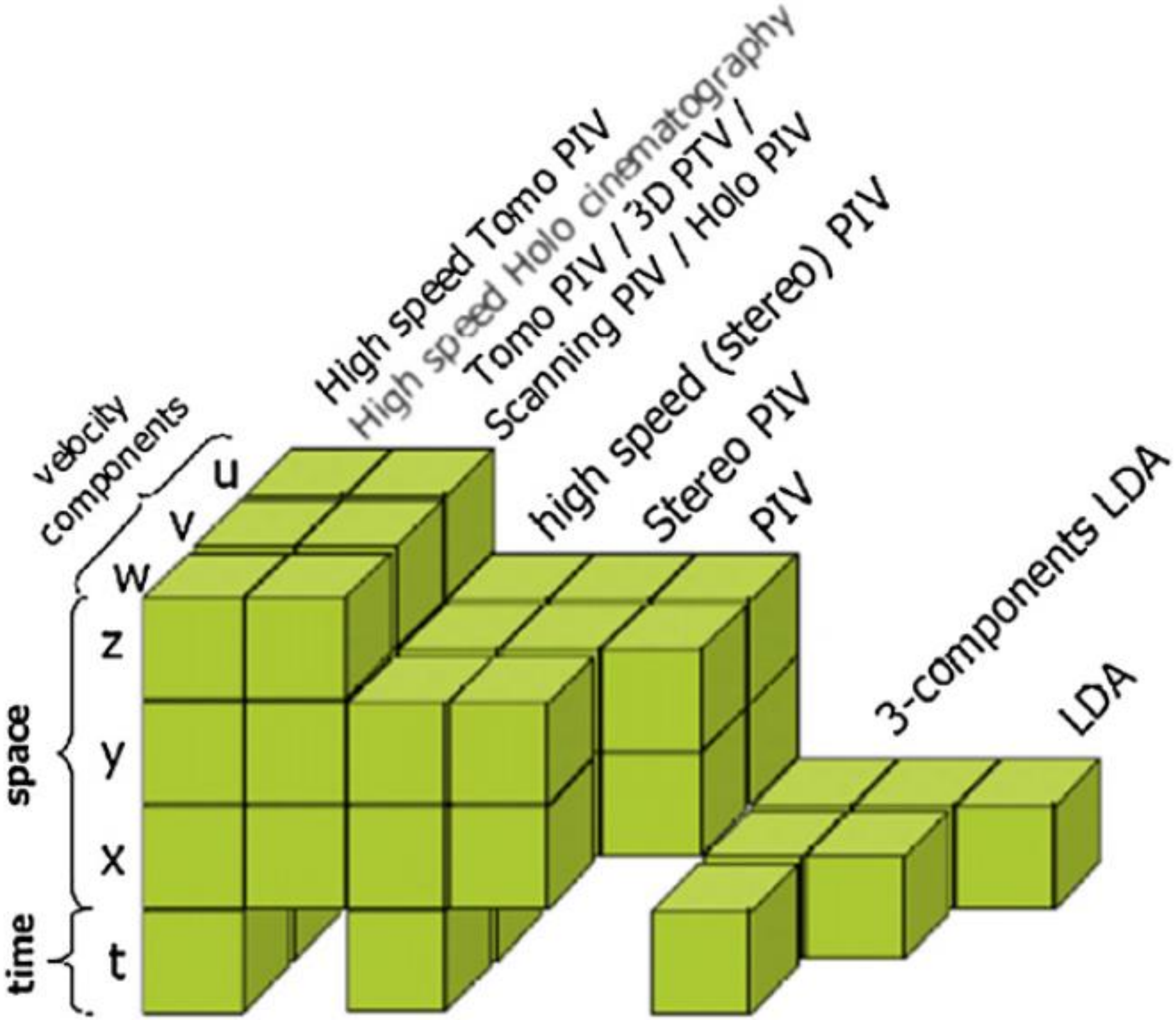
DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

Measurement domain and components

Desired volume:
O 1 m^3



Typical tomo-PIV domain:
25-50 cm^3

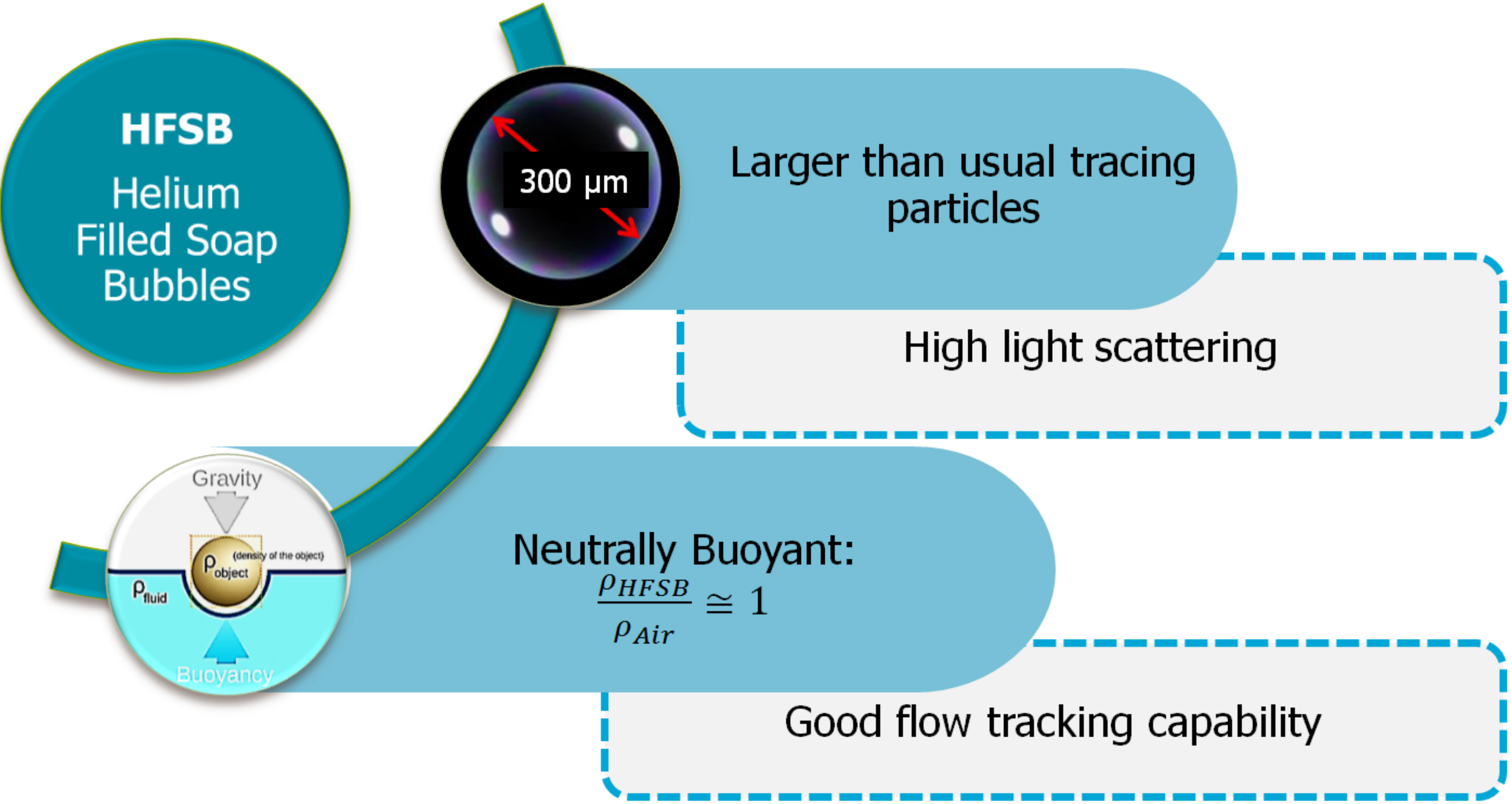


[Scarano 2012]

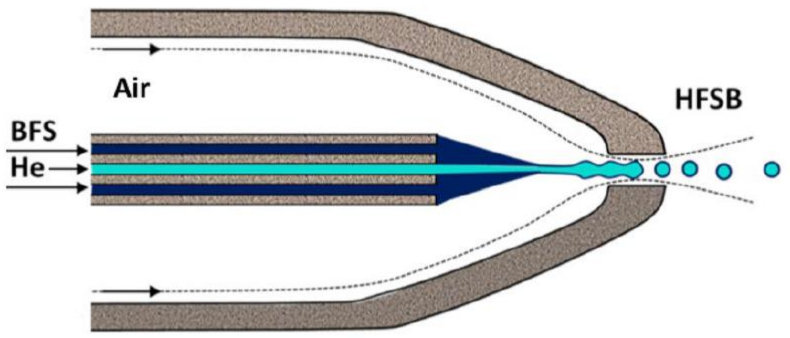
Large-scale PIV

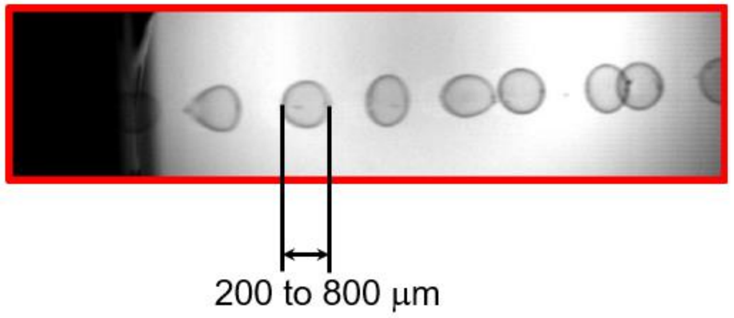
How to achieve measurement volumes O(1 m^3)]?

Helium-filled soap bubbles (HFSB) as flow tracers!



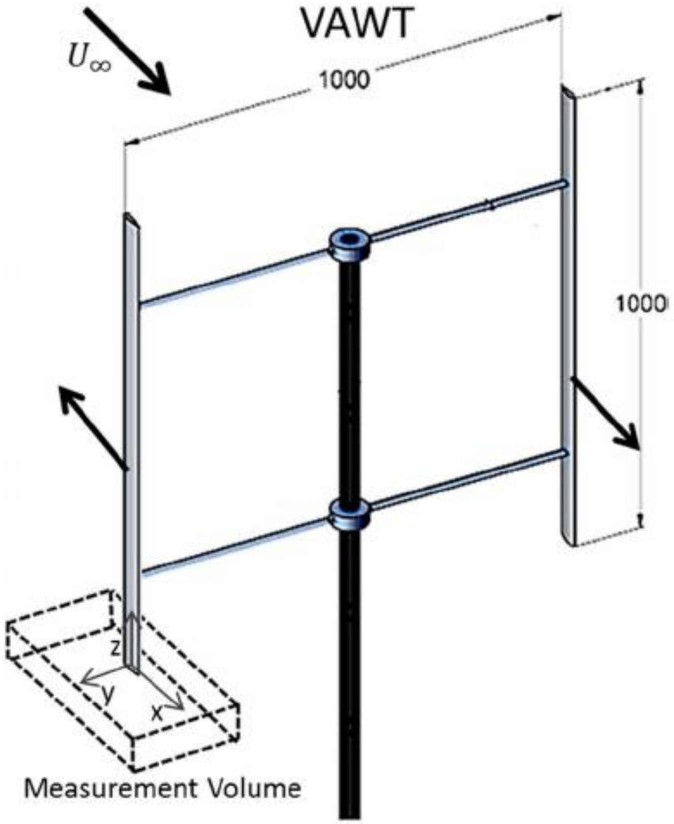
Bubble generator

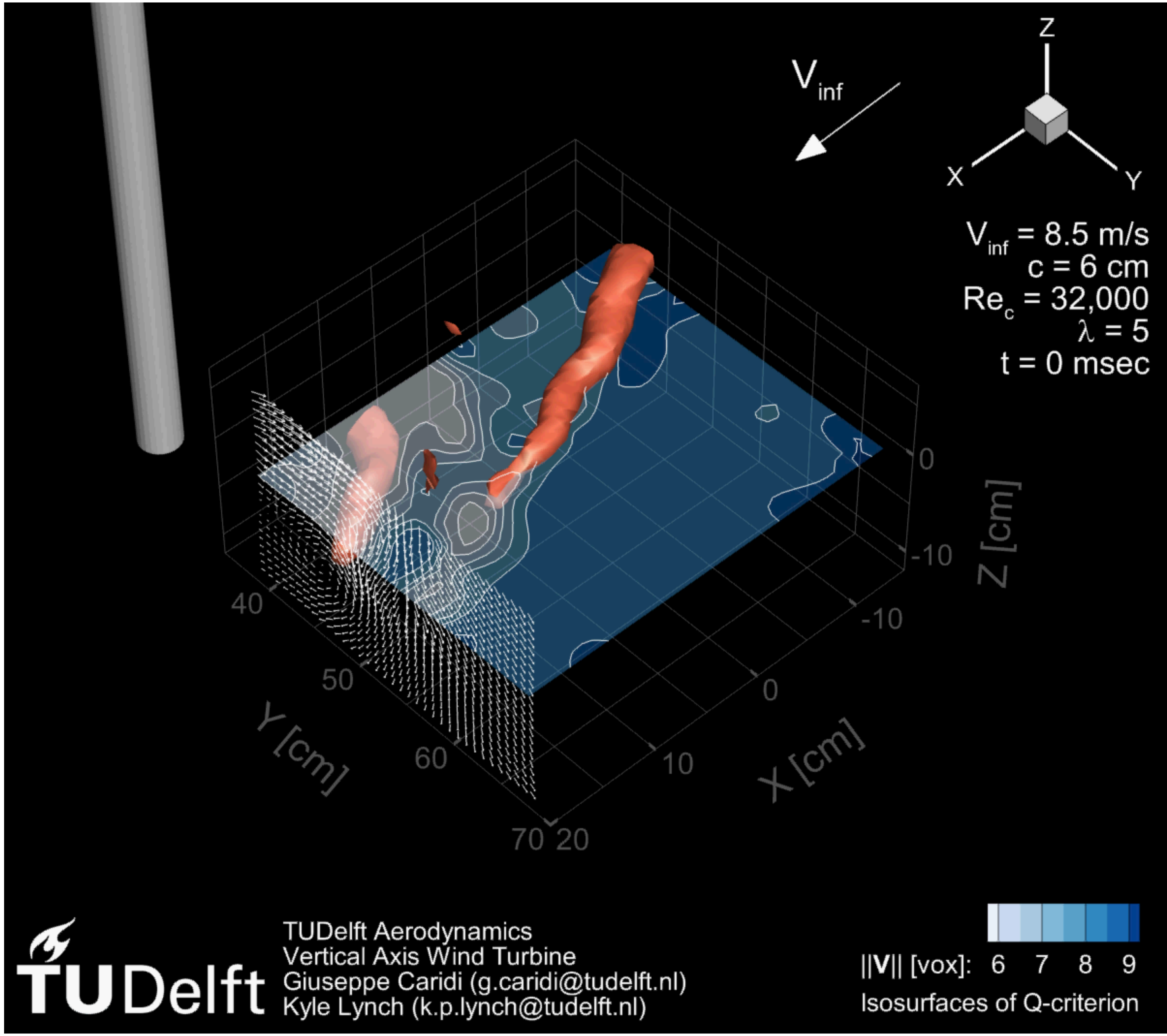




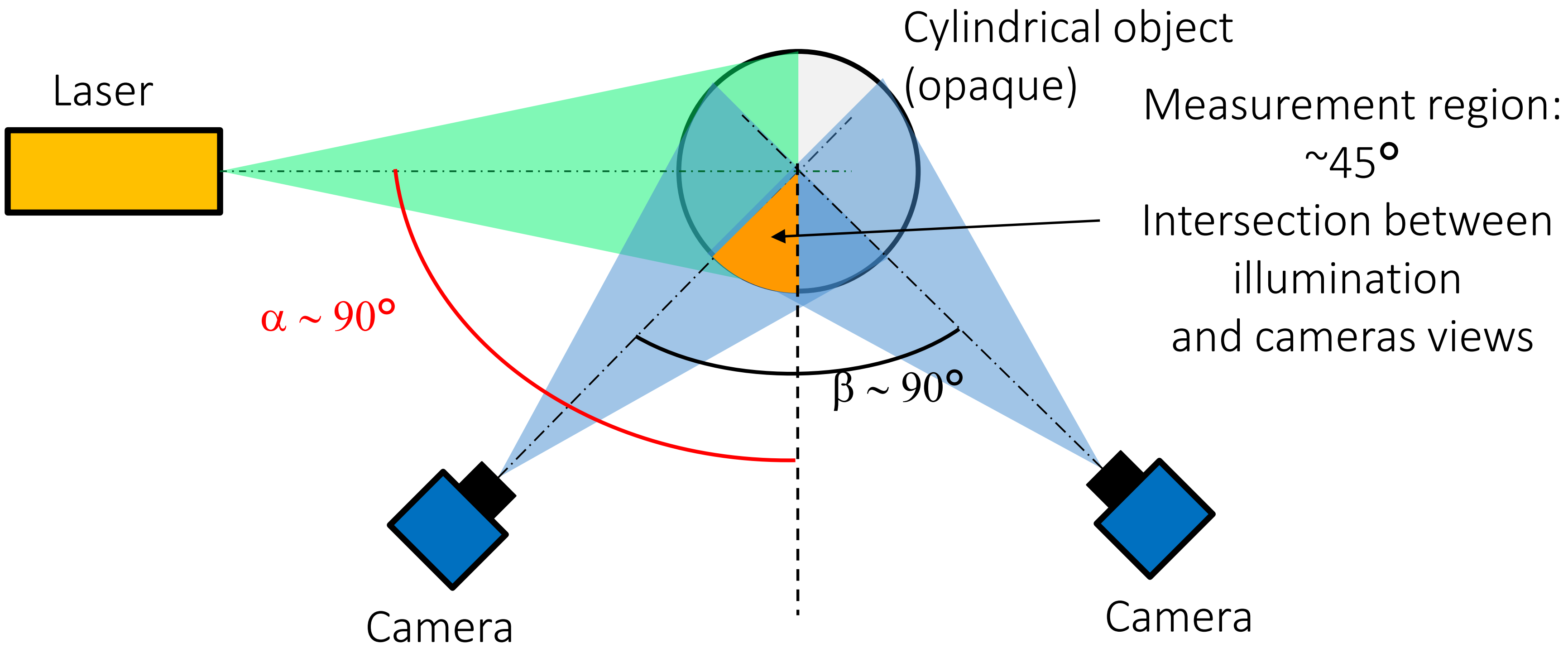
- Larger diameter by factor O(100) than standard particles
- Increased light scattering by factor 10^4-10^5
- Production rate: ~50,000 bubbles/s

Large-scale PIV
Application to VAWT





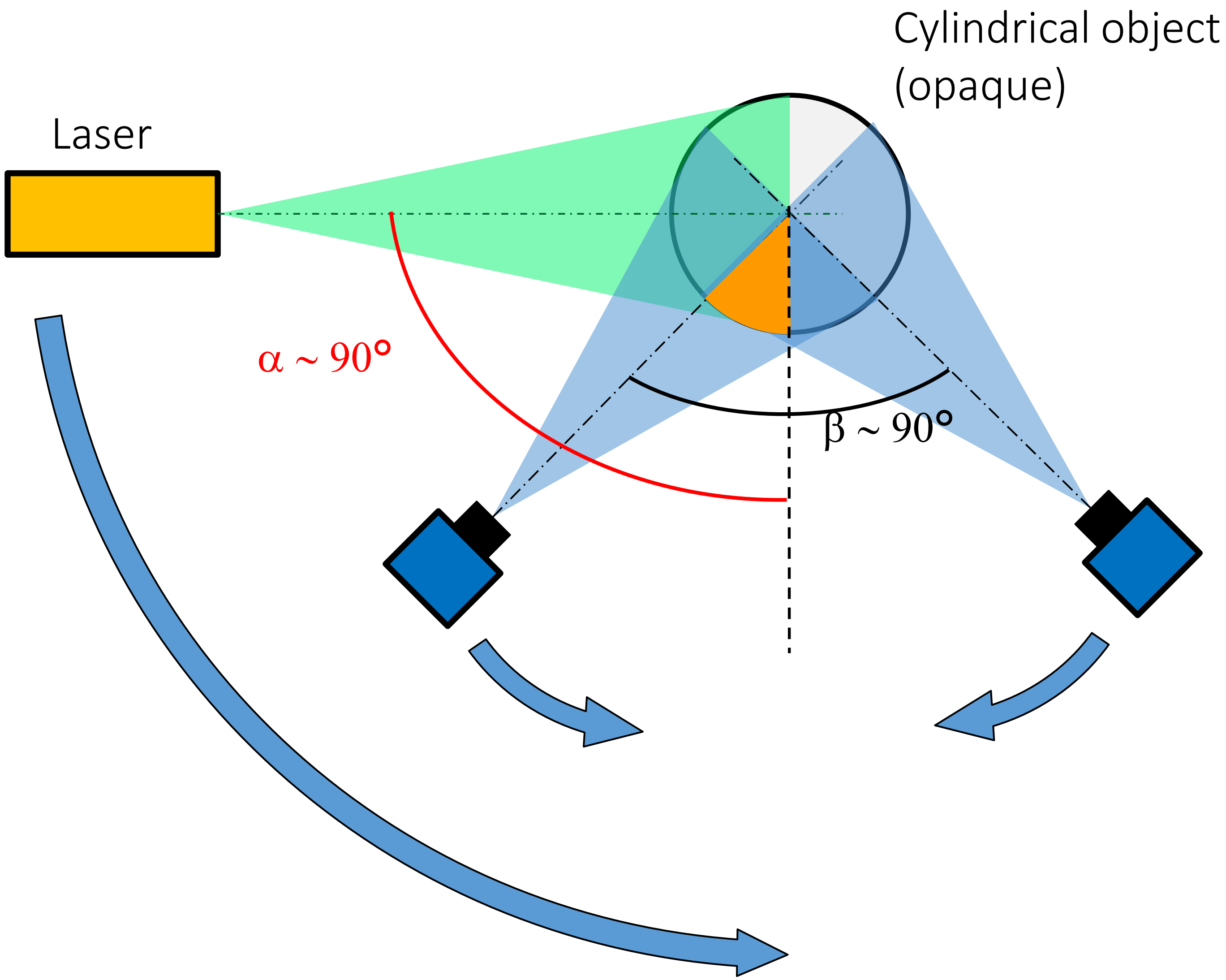
With standard tomo-PIV arrangement the measurement domain is still limited…



→360°/45° = 8 measurements needed to cover the entire surface around the cylinder

If one setup takes half a day, four days of setup required!!

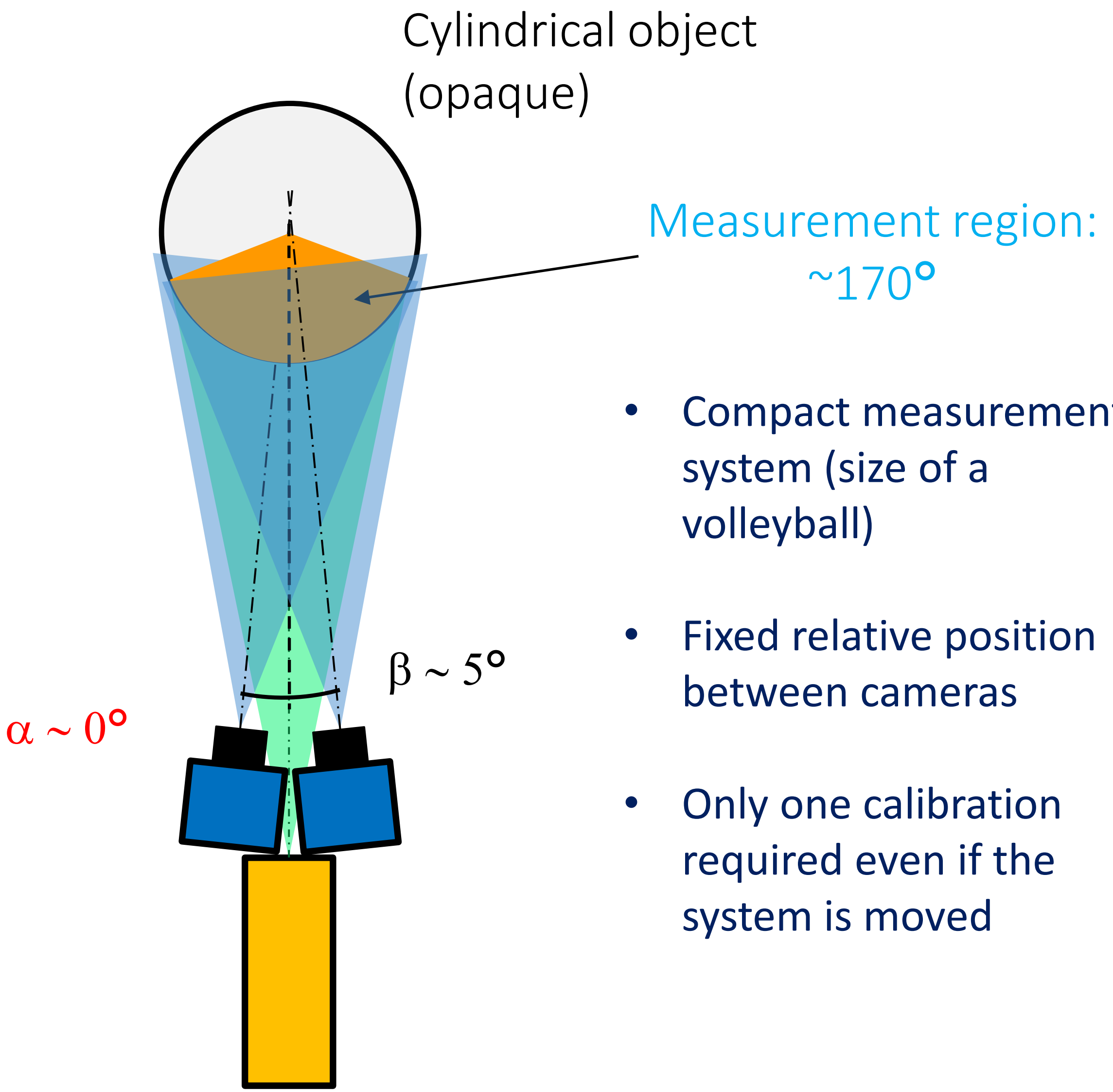
Can we make the system more versatile?



Can we make the system more versatile?

Coaxial Volumetric Velocimetry (CVV)
(Schneiders et al. 2018)

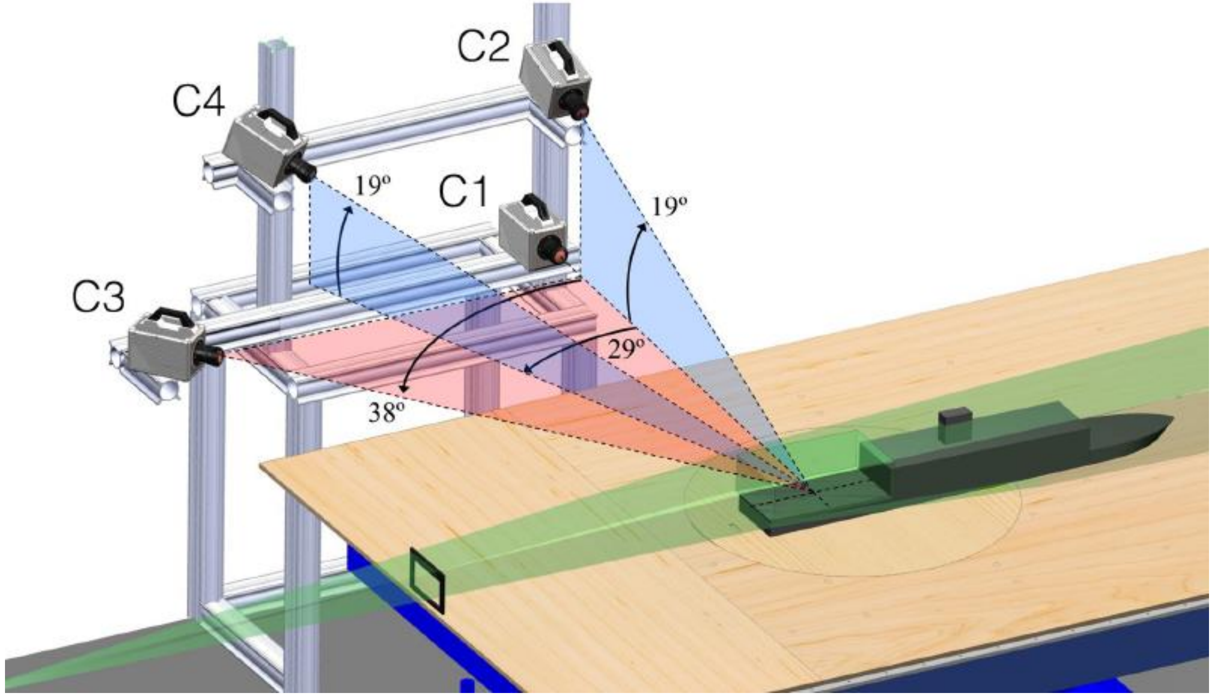
- Coaxial arrangement between illumination and imaging (α~0°)
- Low tomographic aperture (β~5°)



- Compact measurement system (size of a volleyball)
- Fixed relative position between cameras
- Only one calibration required even if the system is moved

Coaxial velocimeter VS standard tomo-PIV

Conventional tomographic PIV system

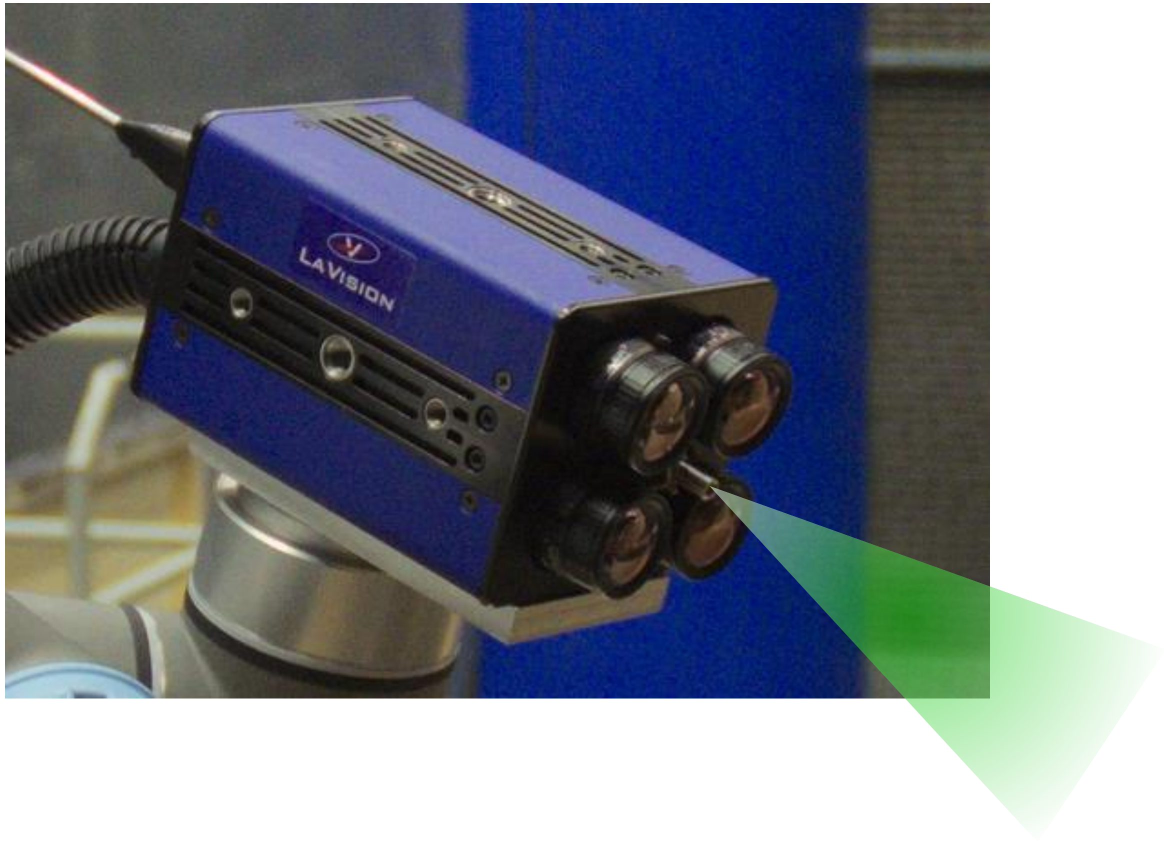


- Large aperture
- Calibration procedure
- Instantaneous 3D velocity field

CVV system

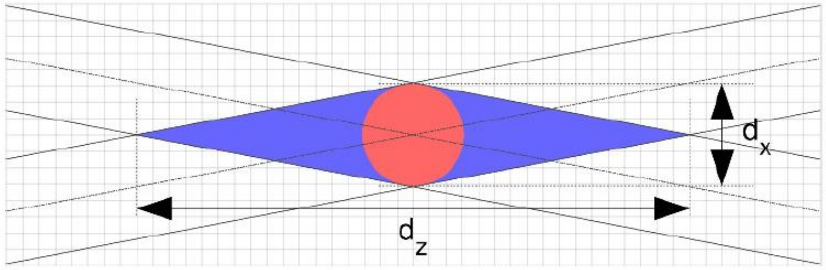
- Small aperture + laser optic fiber
- No calibration
- Ensemble-averaged 3D velocity

Challenges of the CVV system



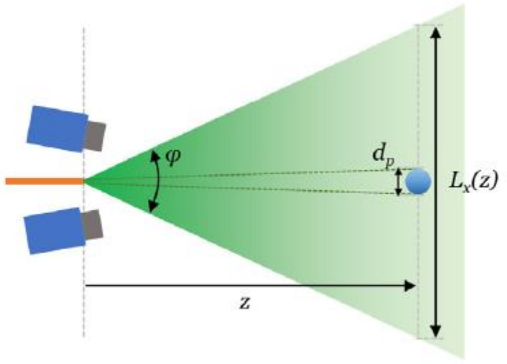
1. Measurement accuracy

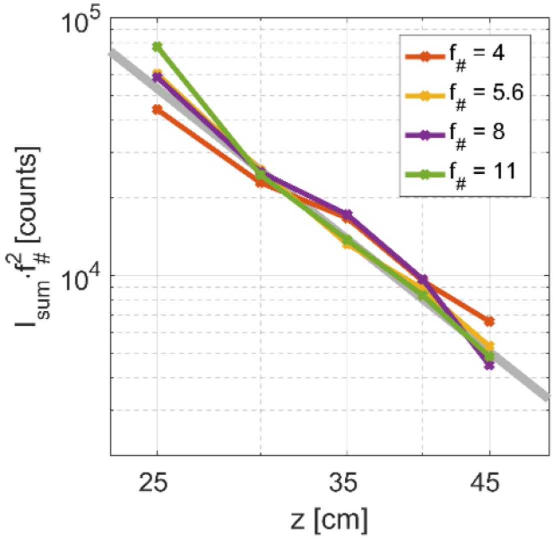
Low tomographic aperture ~5 deg → time-resolved measurements needed



2. Depth of the measurement domain

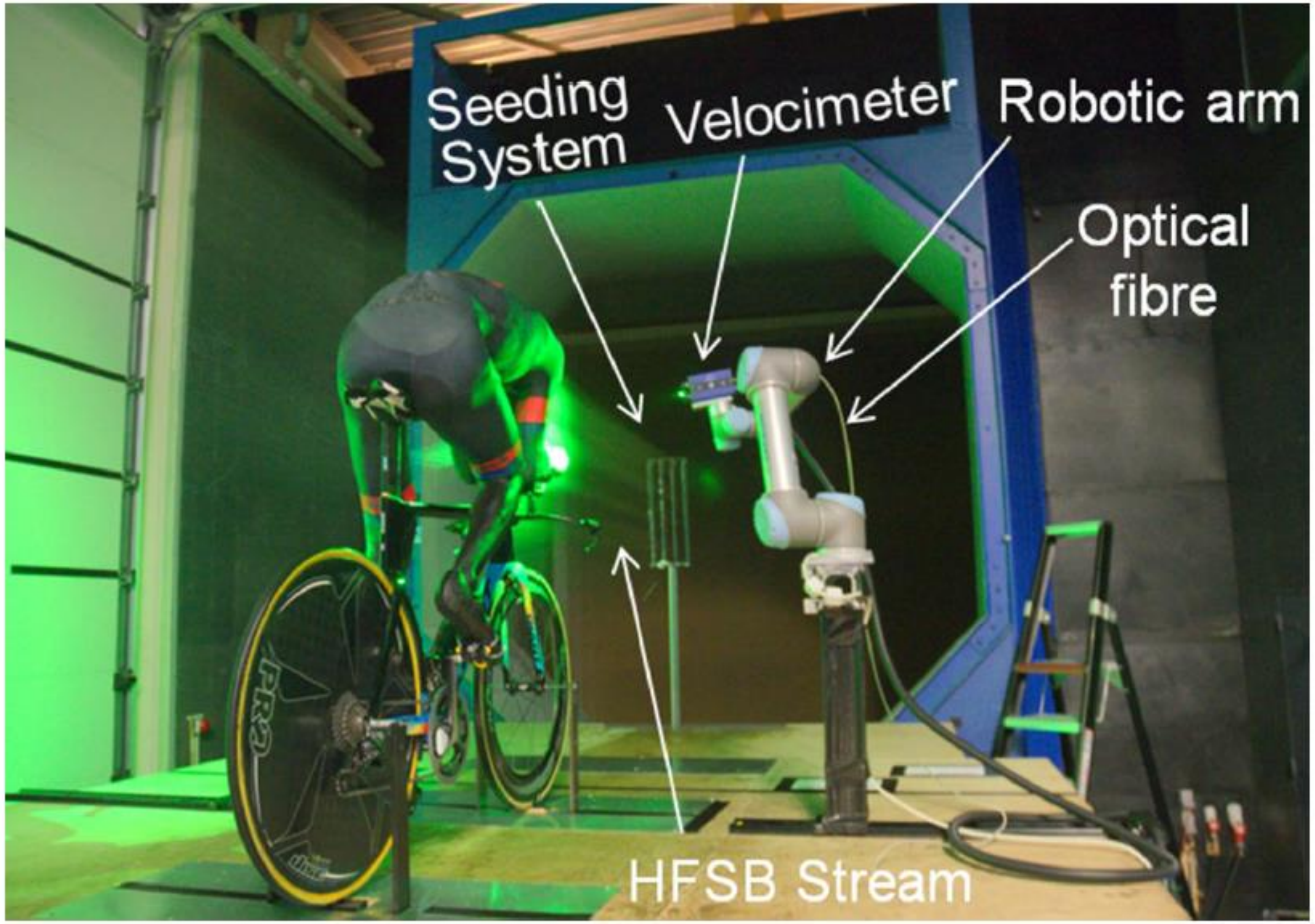
The intensity received by the sensor drops with z^{-4}





Flow around full-scale cyclist

Setup of the experiment

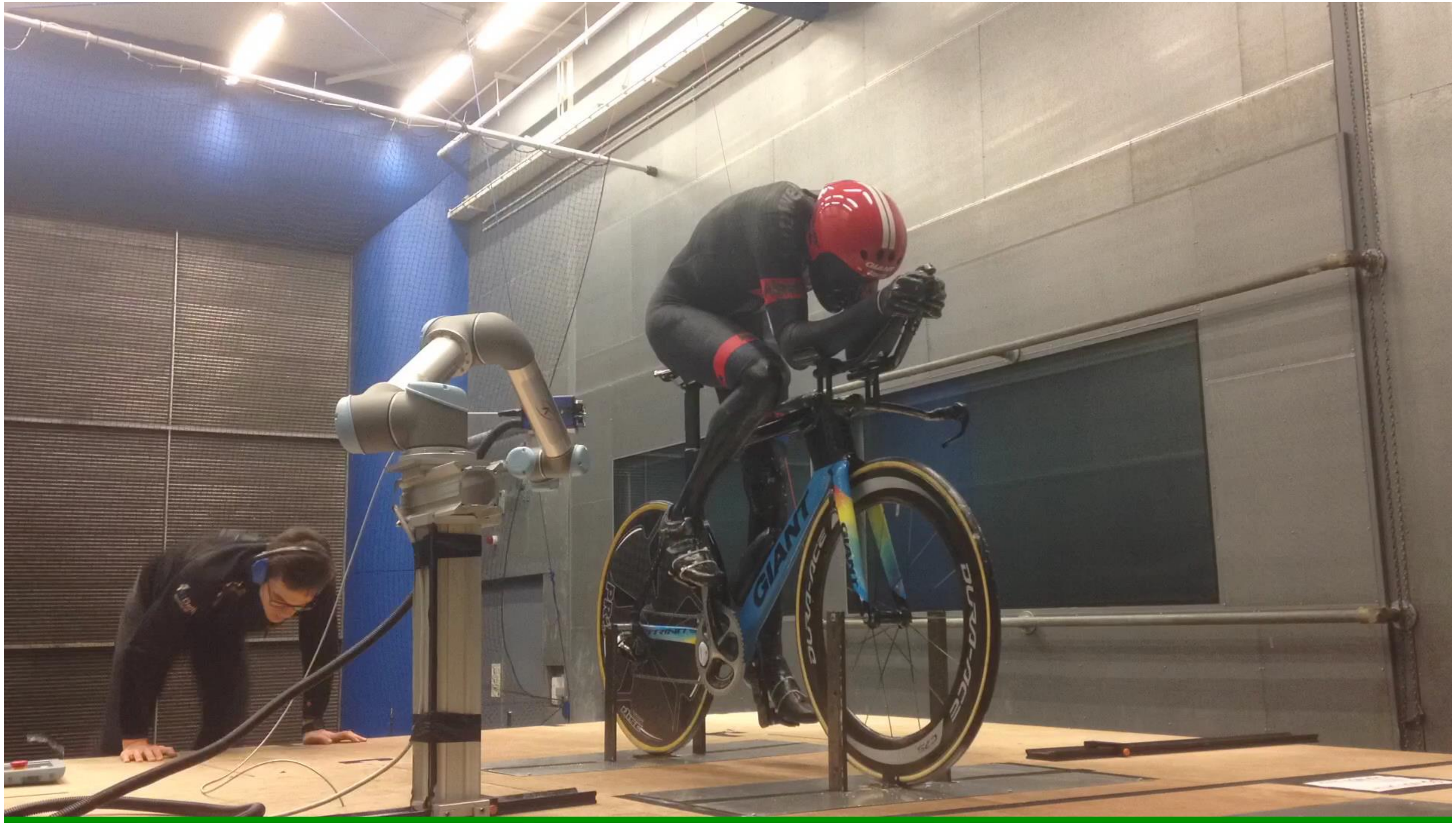


Jux et al. 2018, Exp Fluids

- TU Delft Open Jet Facility: 2.85x2.85 m^2
- Full-scale cyclist model
- V_∞ = 14 m/s
- Re = 5.5×10^5
- Measurement domain >2 m^3:
-     $2\times1.6\times0.7$ m^3
-     achieved with ~400 cones

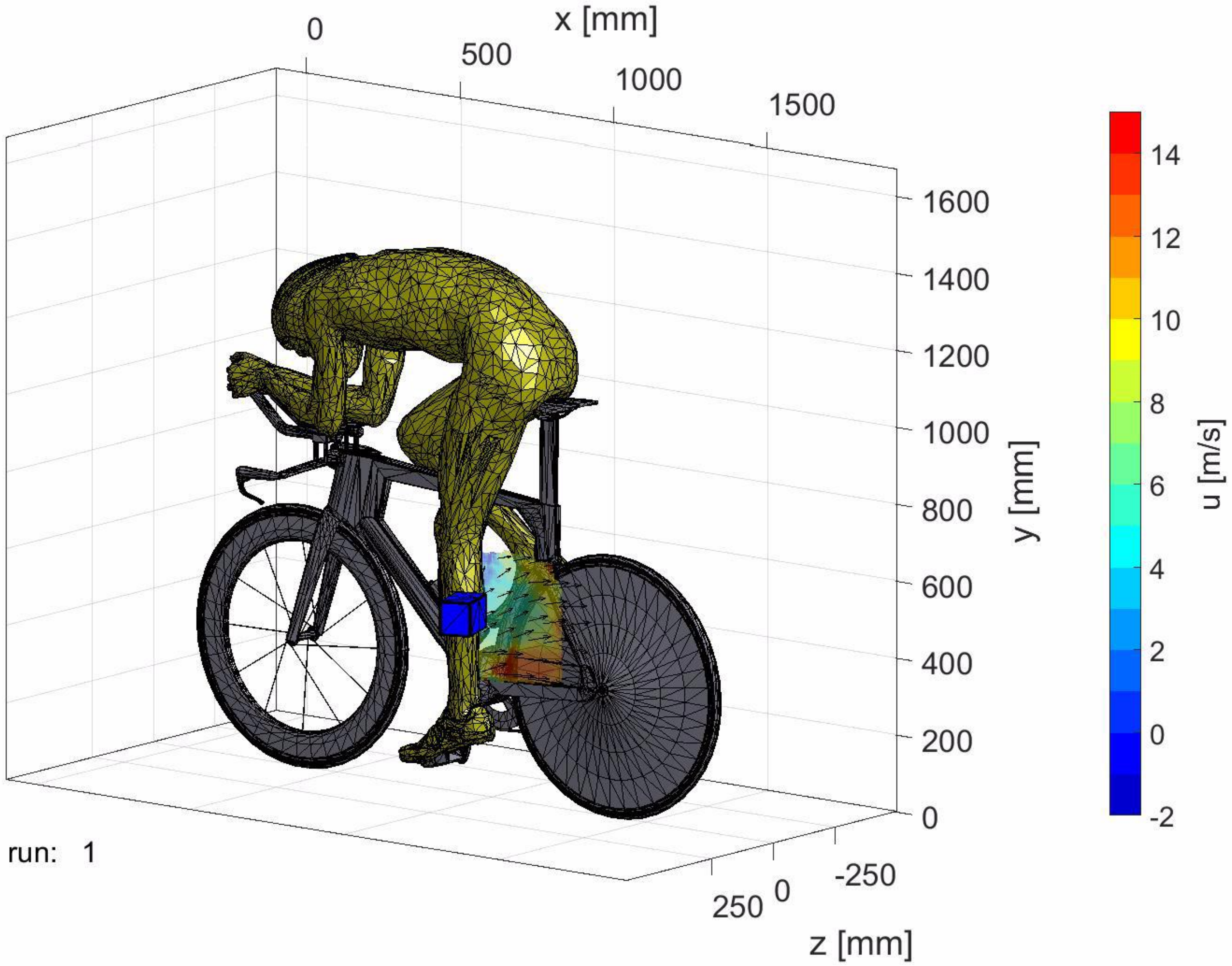
Flow around full-scale cyclist

Robot operation



Flow around full-scale cyclist

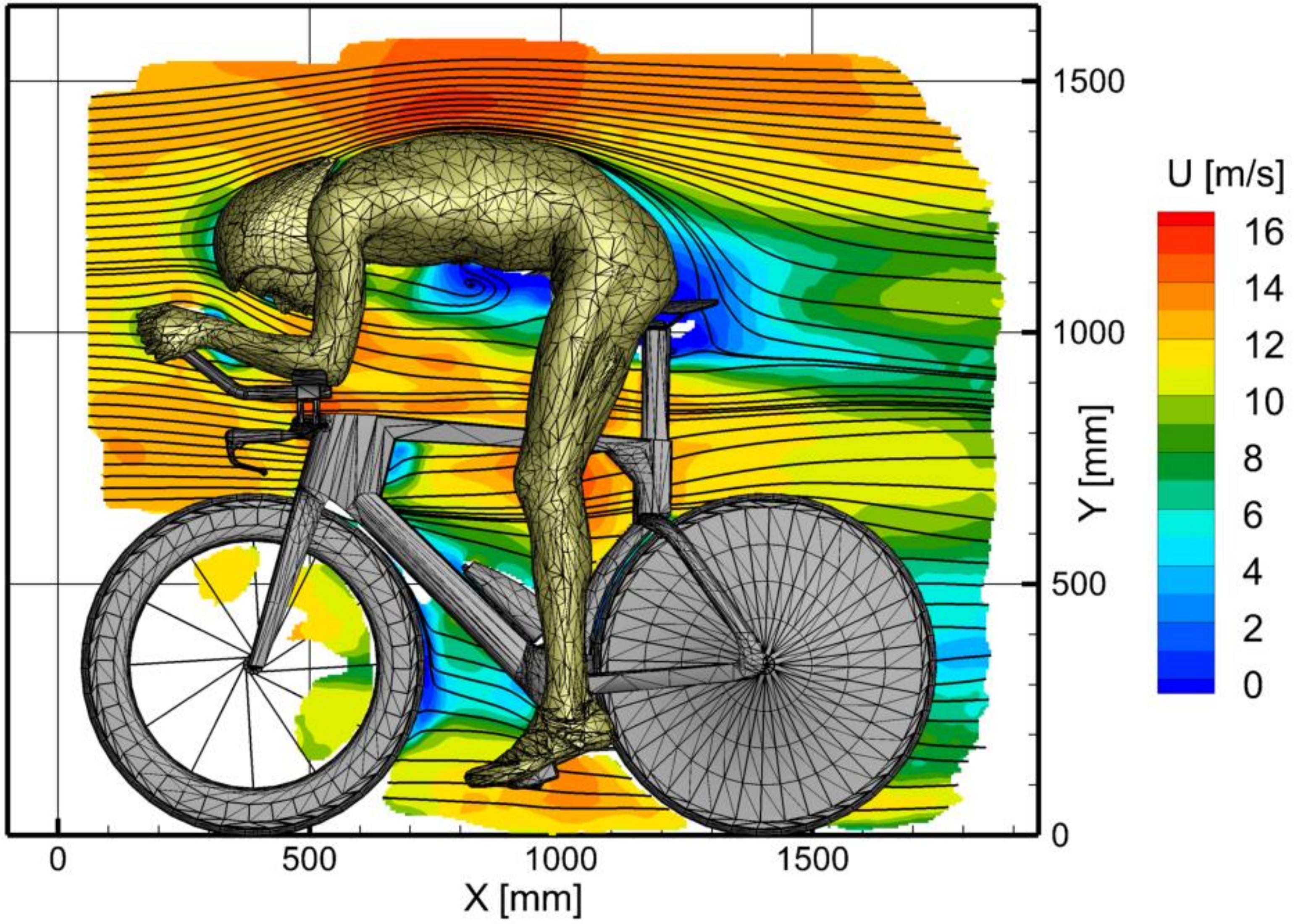
Velocity field reconstruction



Jux et al. 2018, Exp Fluids

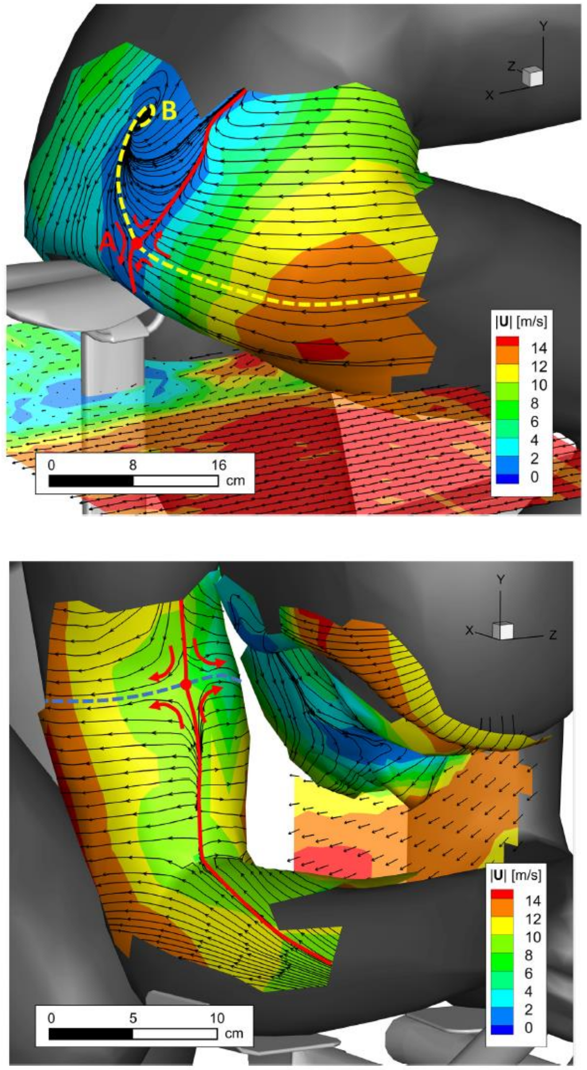
Flow around full-scale cyclist

Velocity field results



Jux et al. 2018, Exp Fluids

Skin Friction Lines



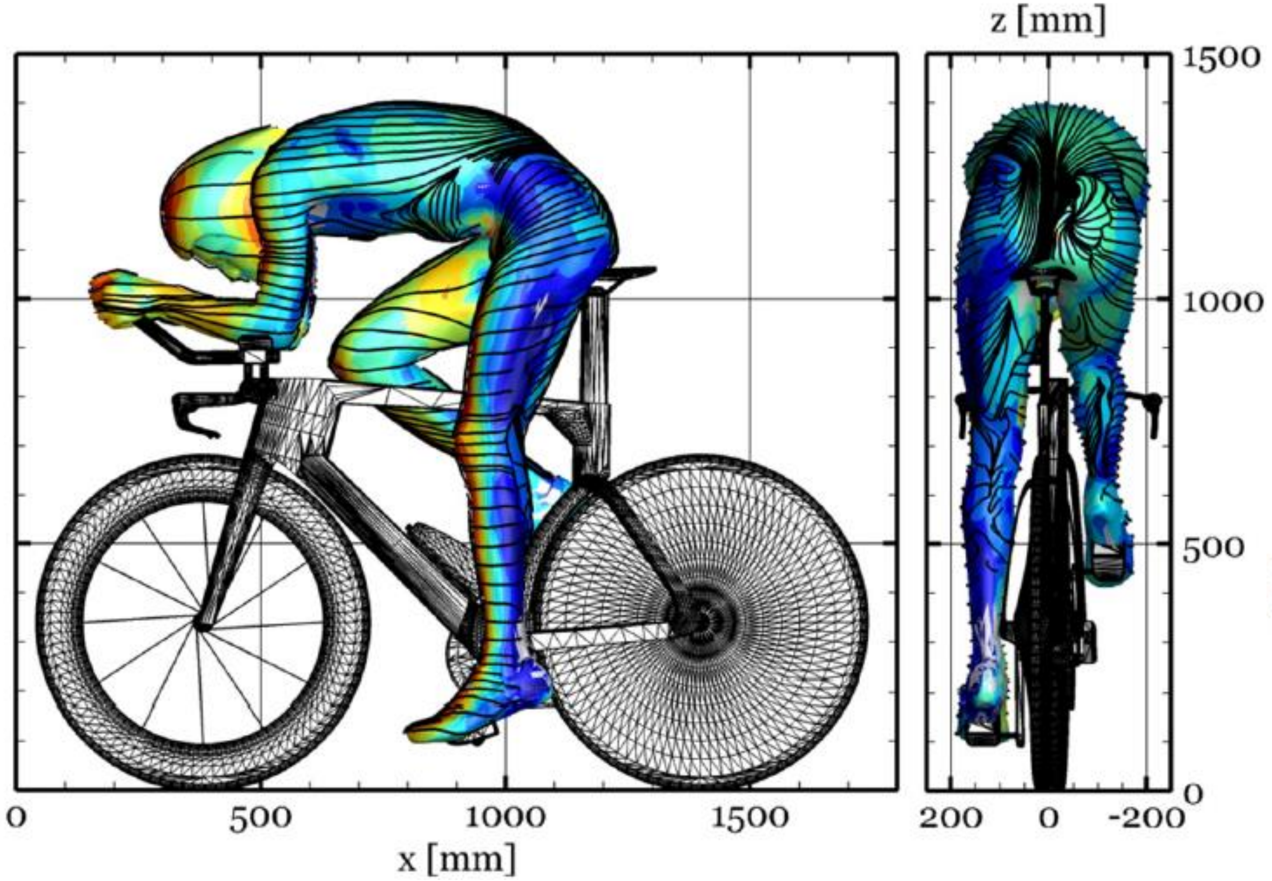
Schneiders et al. 2018, Meas Sci Technol

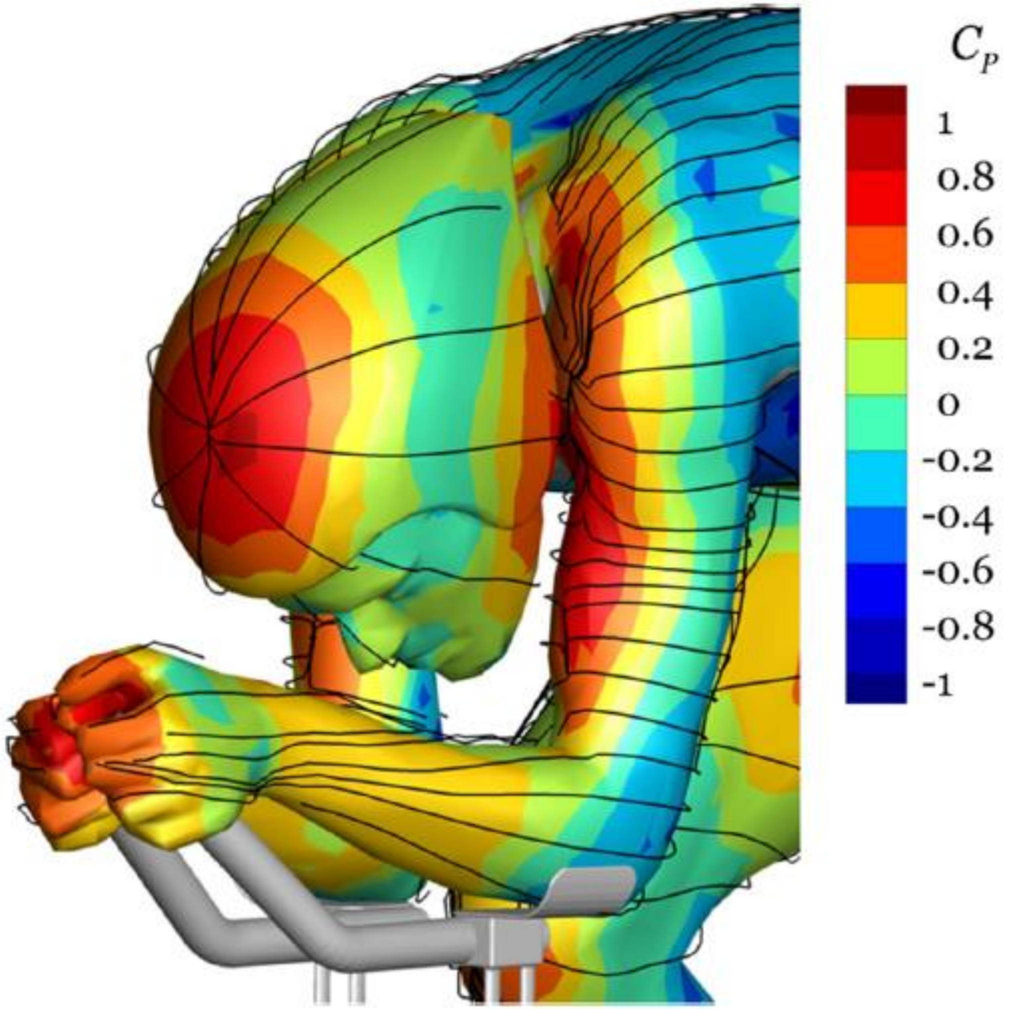
Flow around full-scale cyclist

Pressure field results

Reynolds-averaged Navier-Stokes equations:

$$\nabla\bar{p} = -\rho(\bar{u}\cdot\nabla)\bar{u} - \rho\nabla\cdot\overline{u'u'} + \cancel{\mu\nabla^2\bar{u}}$$





Jux et al. 2020, Meas Sci Technol

Conclusions

- **PIV** provides accurate velocity information in planes
- Three-dimensional flow measurements possible by using more cameras (**Tomographic PIV**)
- **Lagrangian Particle Tracking** via Shake-the-Box algorithm valid alternative for efficient 3D flow measurements
- **Helium-filled soap bubbles (HFSB)** tracers needed for measurements in volumes up to O m^3
- **Robotic PIV** for versatile 3D flow measurements in large volumes
- **3D pressure field** reconstruction via integration of pressure gradient from Navier-Stokes equations

Thank you for your attention

Questions?

TU Delft