Micro Resolution Particle Image Velocimetry and Application to Slip Flow

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Micro-PIV vs. Standard PIV

- Micro-PIV
  - Volume Illuminates the test section
  - Measurement Plane is defined by the depth of focus of the lens
- Standard PIV
  - Light Sheet Illumination
  - Measurement Plane is defined by the light sheet used to illuminate the particles.

Standard Light Sheet Illumination

(taken from Schaffer, 5,333,044)

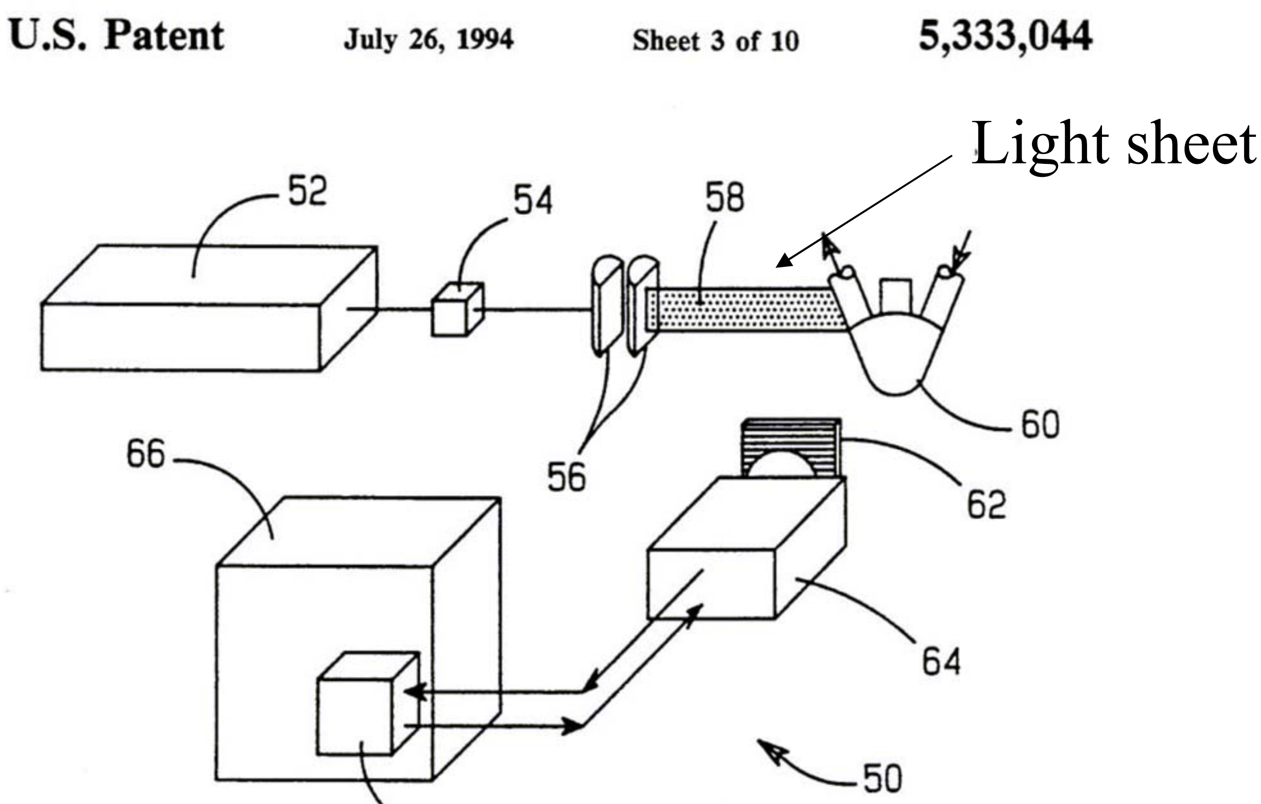
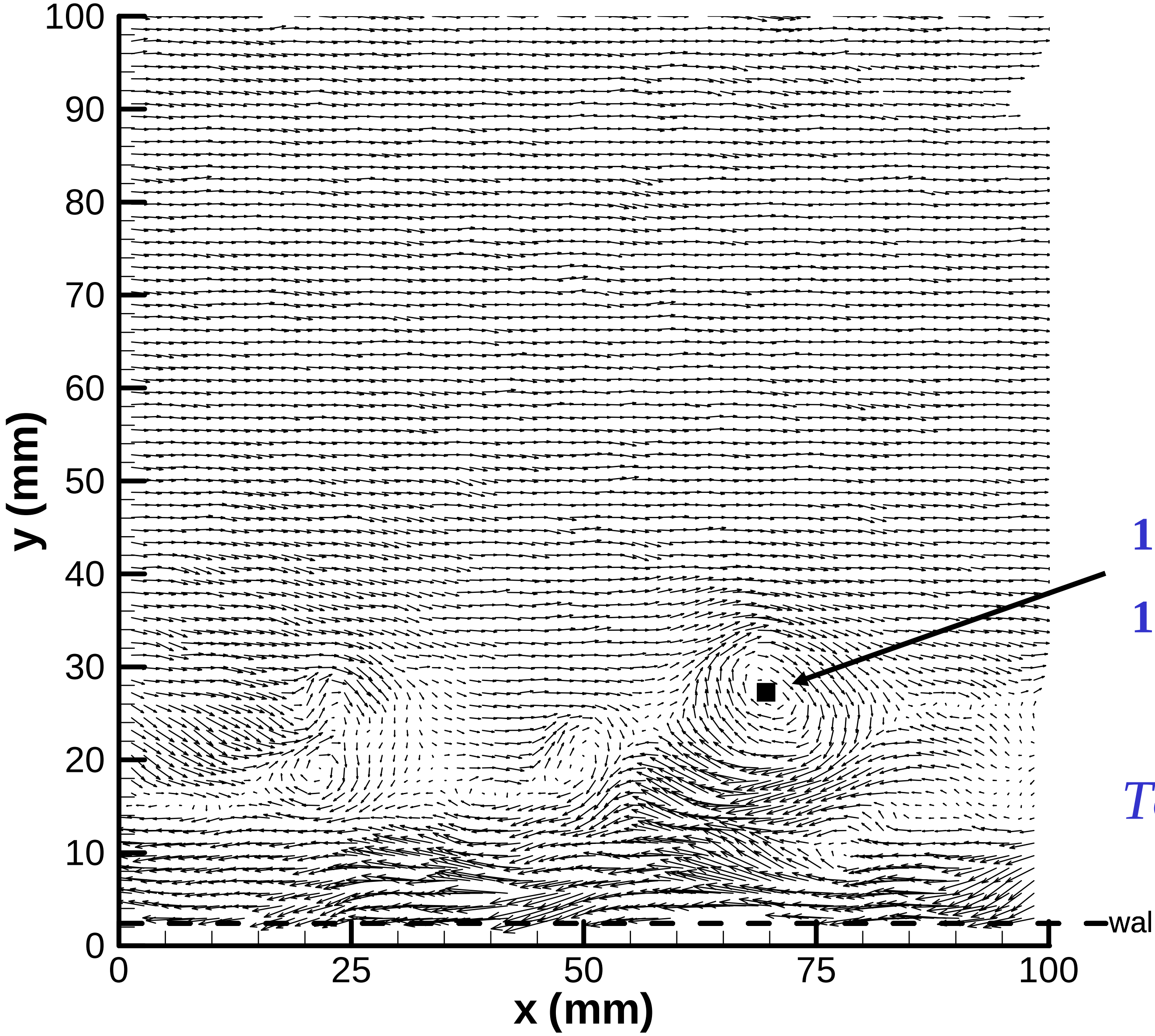


FIG. 3

High Resolution PIV – Turbulent Flow

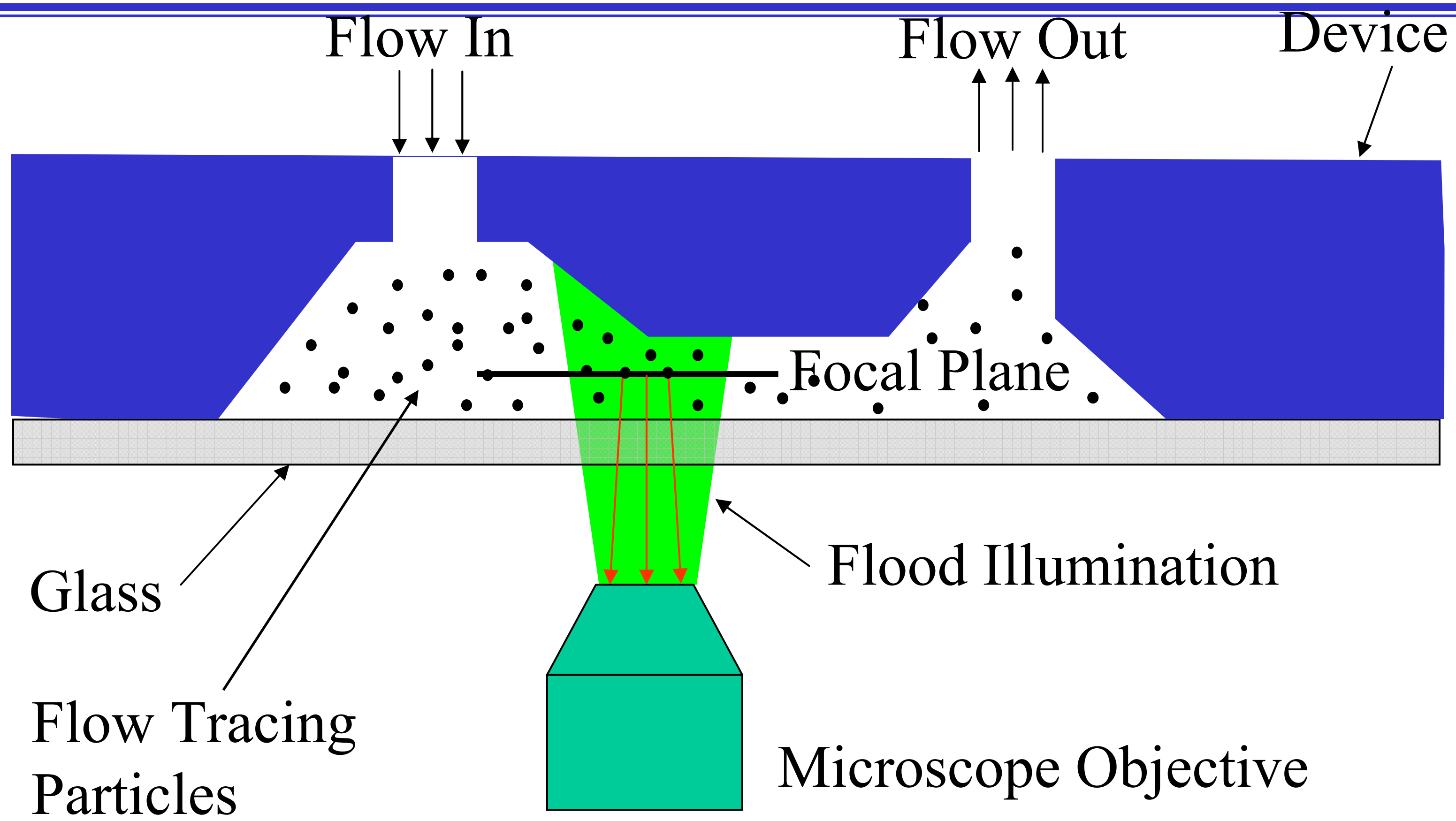


1500 × 1500 μm

10 MEMS Devices

Tompkins (2000)

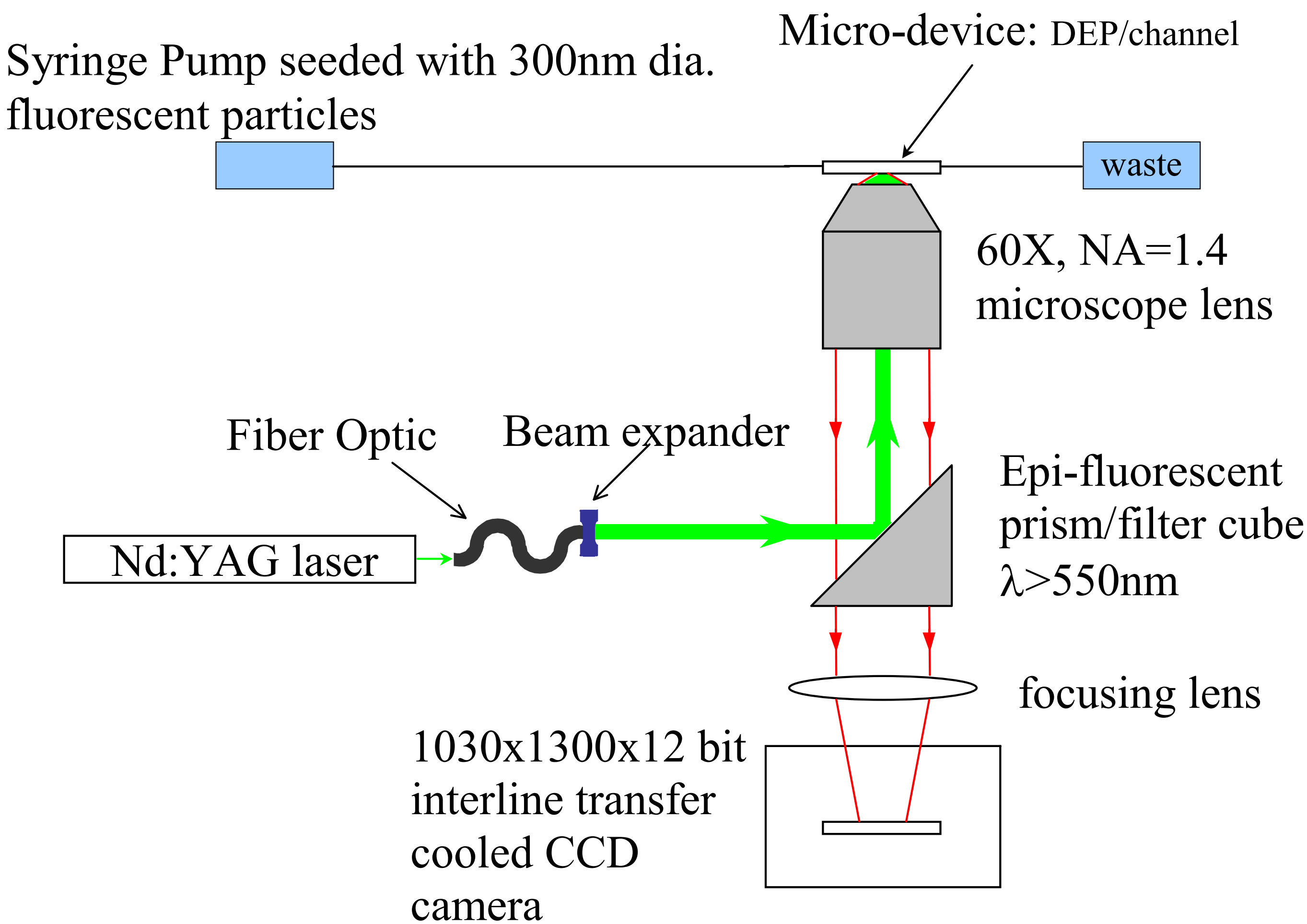
Micro-PIV Schematic



US Patent No. 6,653,651

(Meinhart, Santiago, Wereley, Adrian)

Micro-PIV
(Epi-fluorescence illumination)

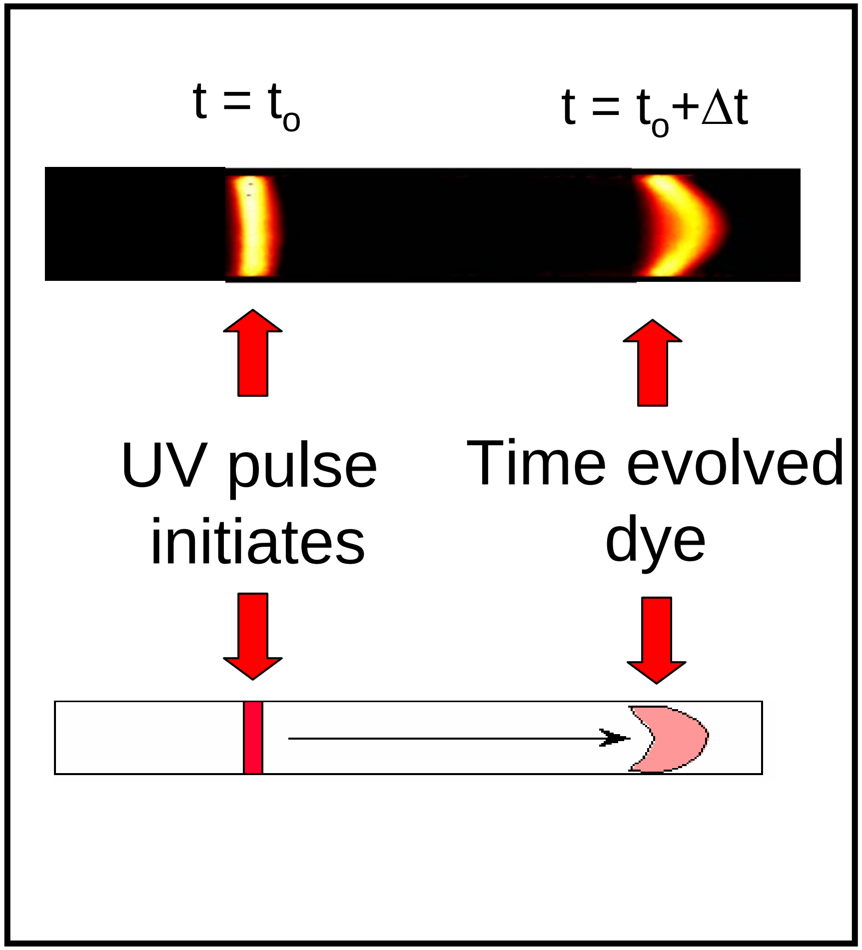


Micro-PIV vs. Caged Fluorescence

- Micro-PIV
  - Uses discrete images of discrete particles
  - Image Processing by Correlation or Particle Tracking
- Caged Fluorescence
  - Caged Fluorescent Dye is place in the fluid (Scalar)
  - Image Processing by inverting Scalar Equation

$$\frac{\partial C}{\partial t} + \left(u \cdot \nabla \right) C = D \nabla^2 C$$

Caged-Fluorescence Imaging

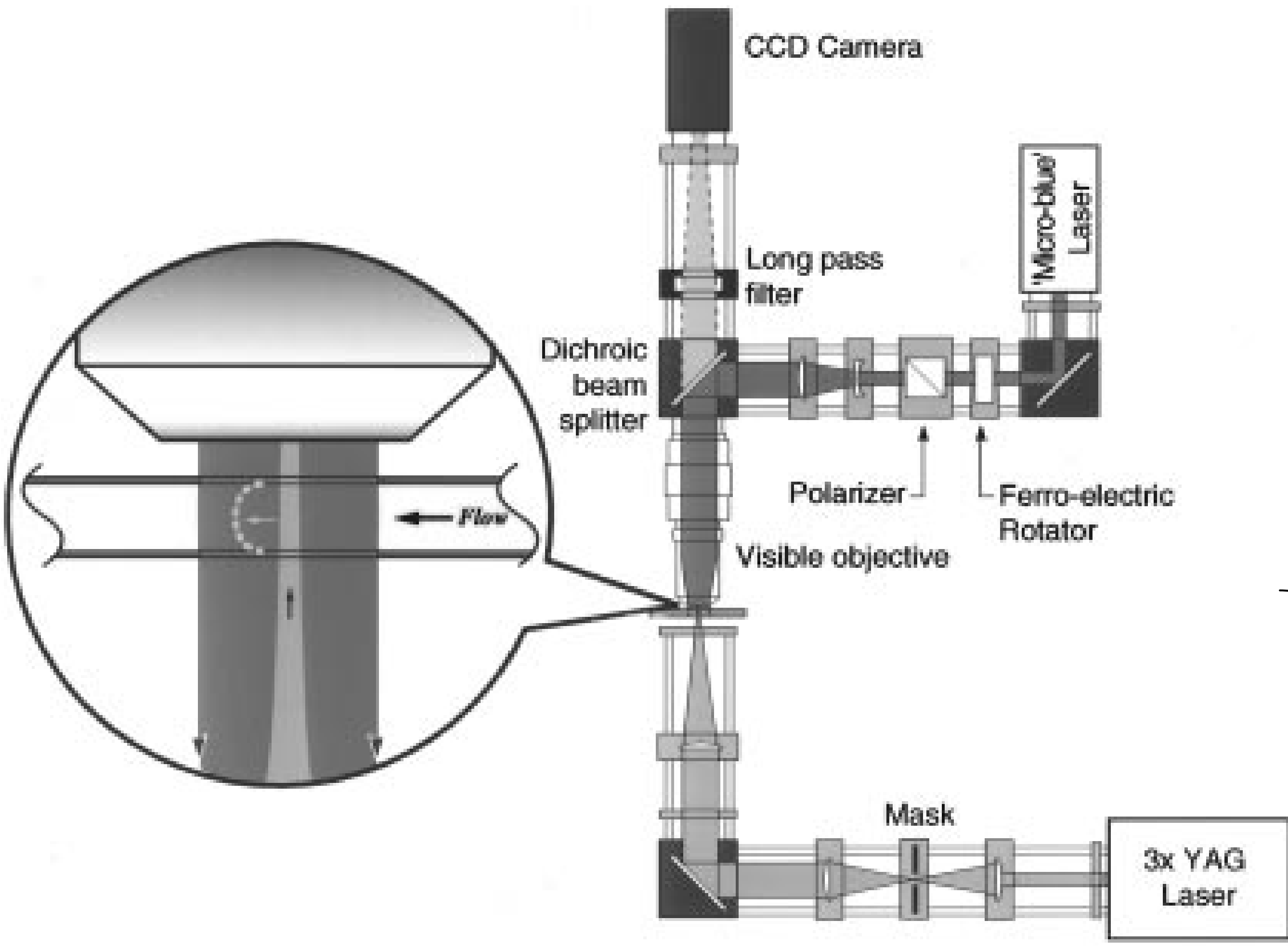


- Dual Interrogation Scheme
  - dye is uncaged by UV laser beam (355nm)
  - fluorescence is then excited by argon ion laser (488nm)
- Time line is *optically injected* in flow

Herr et al., 10th Int. Conf. Solid-State Sensors and Actuators, 1999.

Caged-fluorescence: apparatus

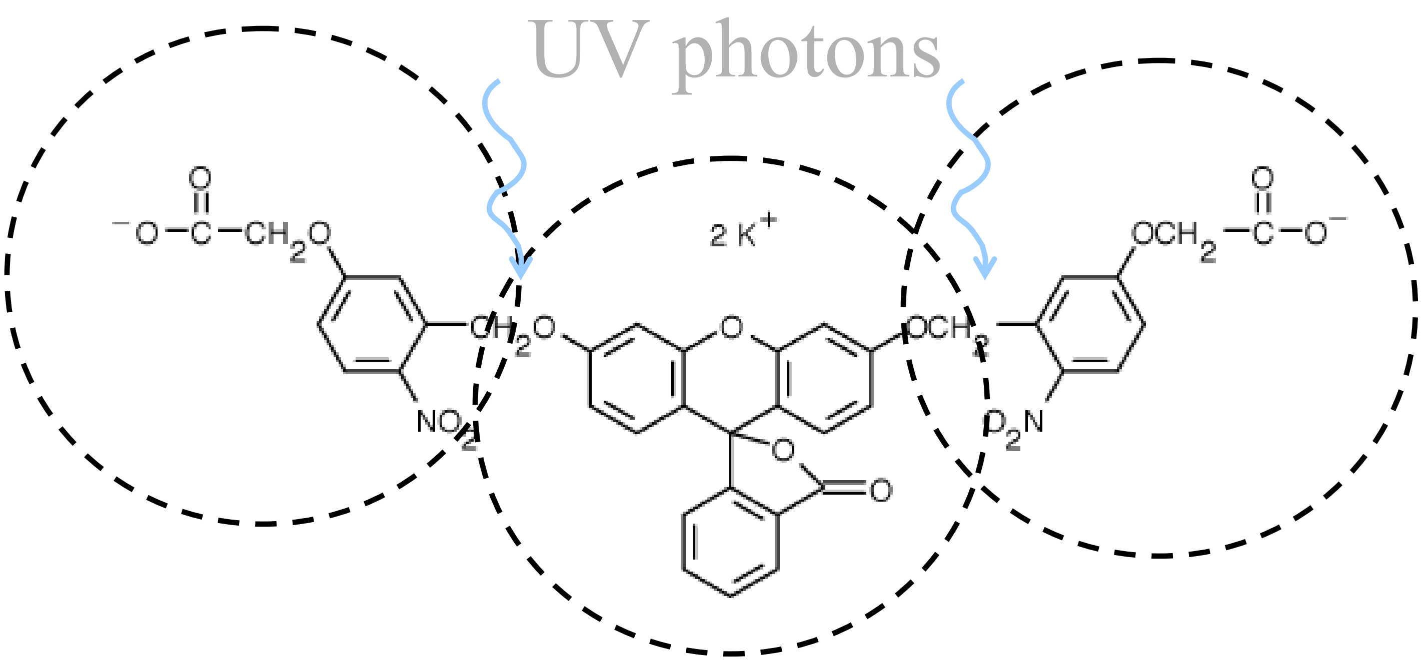
taken from Paul et al. (1998)



Equipment required beyond micro-PIV

Caged-fluorescence: overview

- "Caged" dyes (caging groups prevent fluorescence)
- Caging group(s) can be removed with UV light
- Uncaged dye is fluorescent



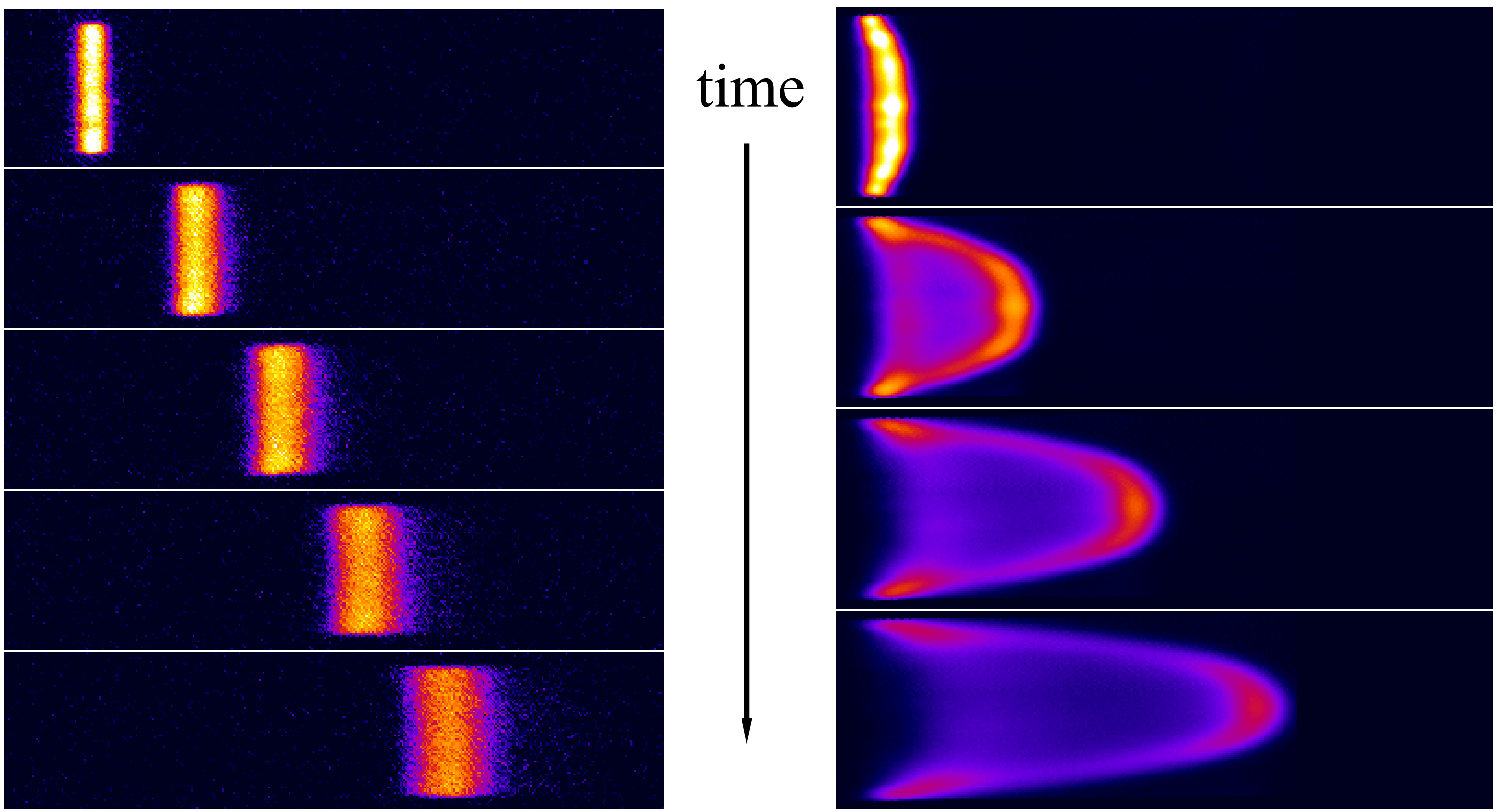
Molecular Probes Inc., Eugene, Oregon

Caged-fluorescence: imaging

(from Santiago Stanford)

Electrokinetic flow
200 µm wide x 9 µm deep

Pressure-driven flow
250 µm wide x 70 µm deep

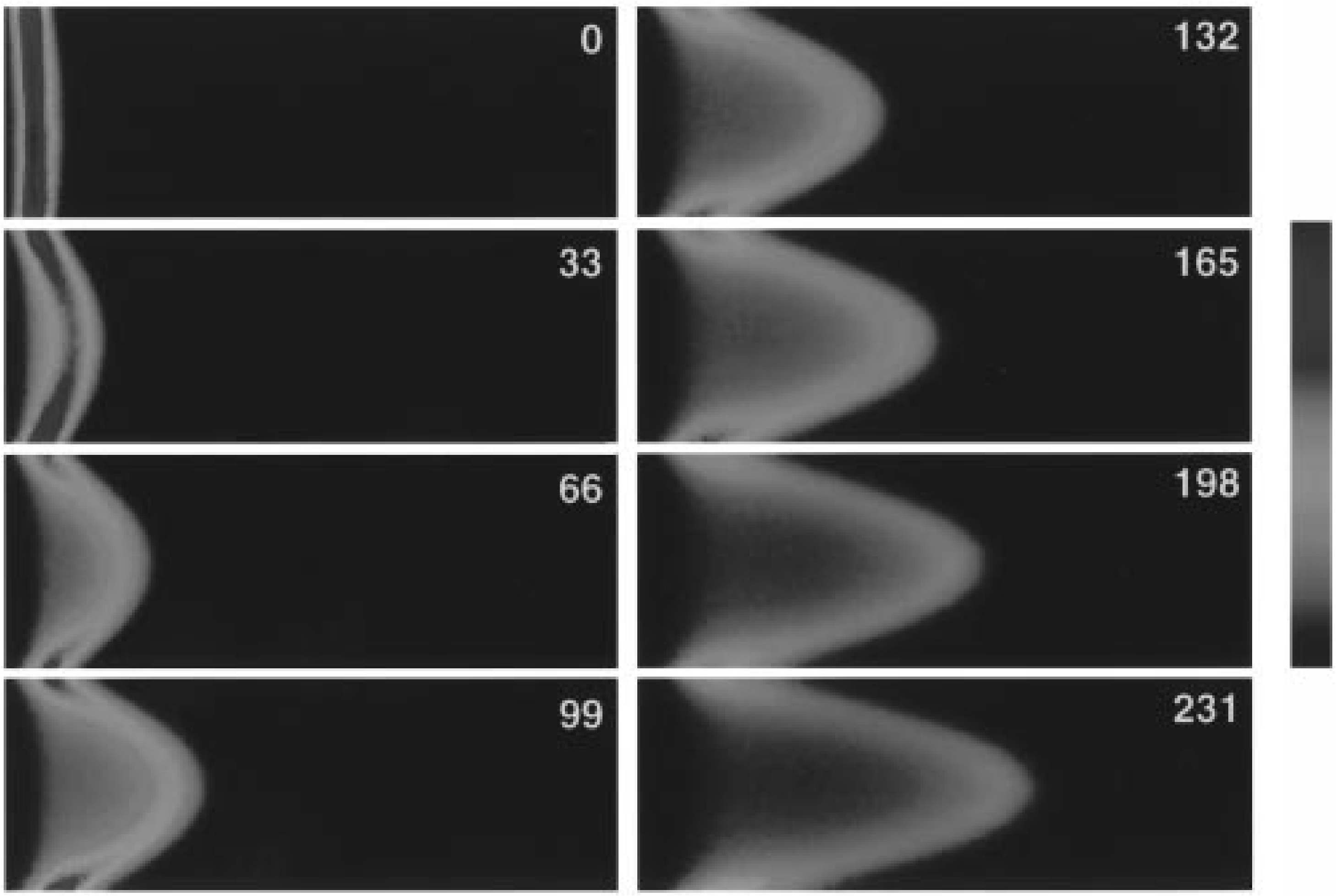


plug-like

parabolic

Caged-fluorescent Images taken

from Paul et al. (1998)



Velocity data of microchannel flow

Paul et al. (1998)

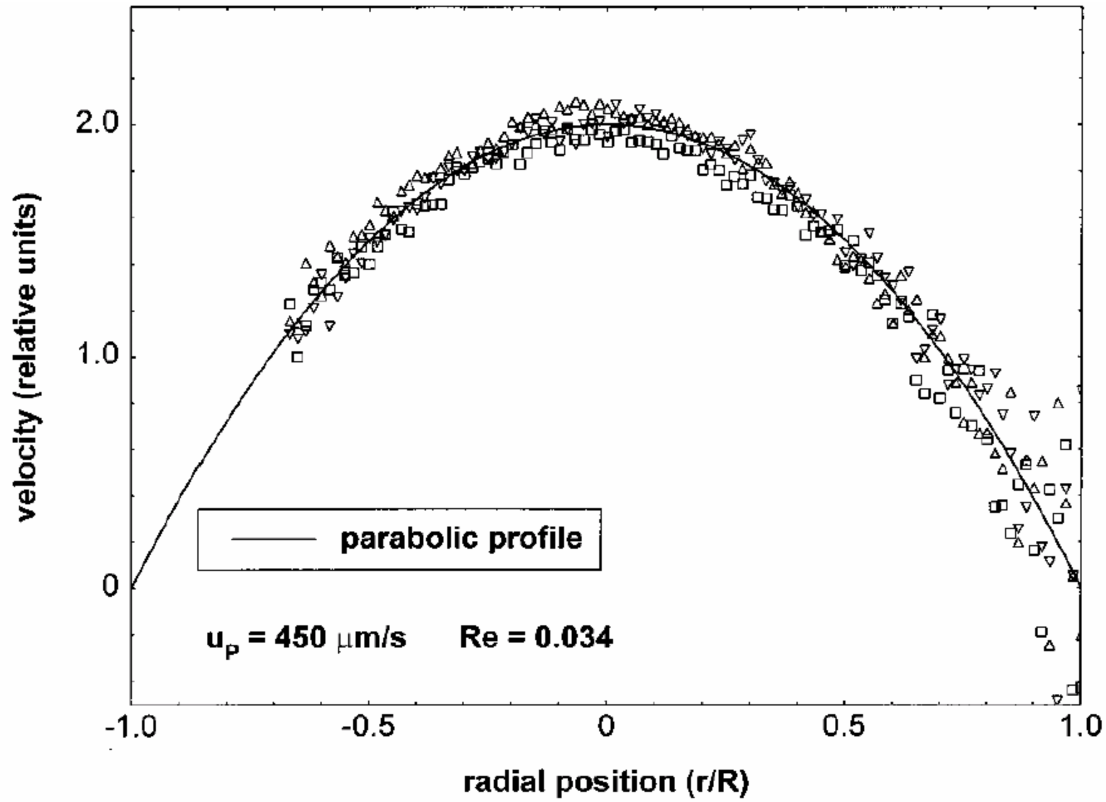
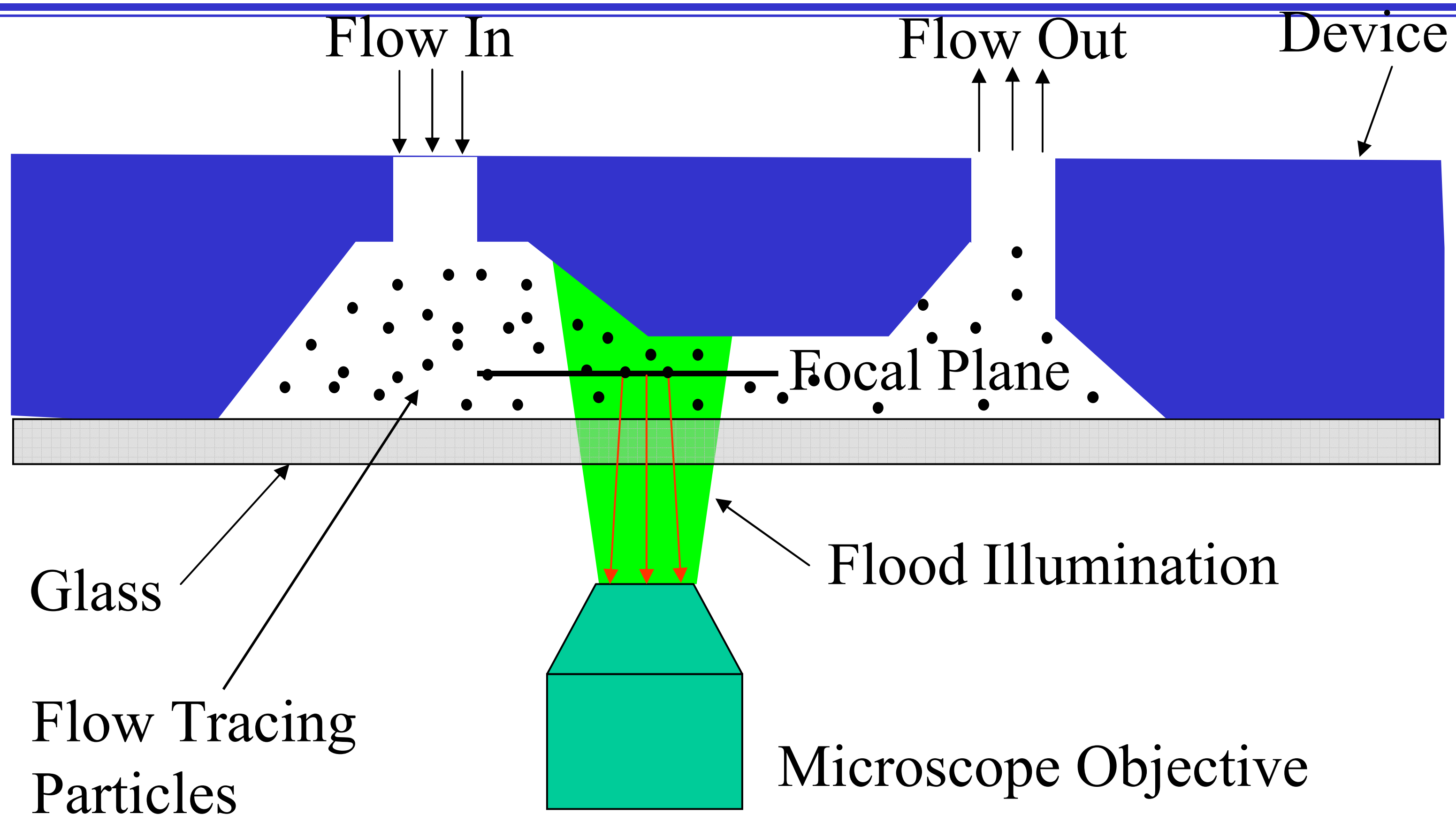


Figure 4. Three SIV velocity profiles (points) recovered from three image pairs for pressure-driven flow in a 75 μm i.d. open capillary. A parabolic profile (line) is also shown for comparison. Velocity data were not recovered for $-1 < r/R < -0.5$ due to poor signal-to-noise in the data.

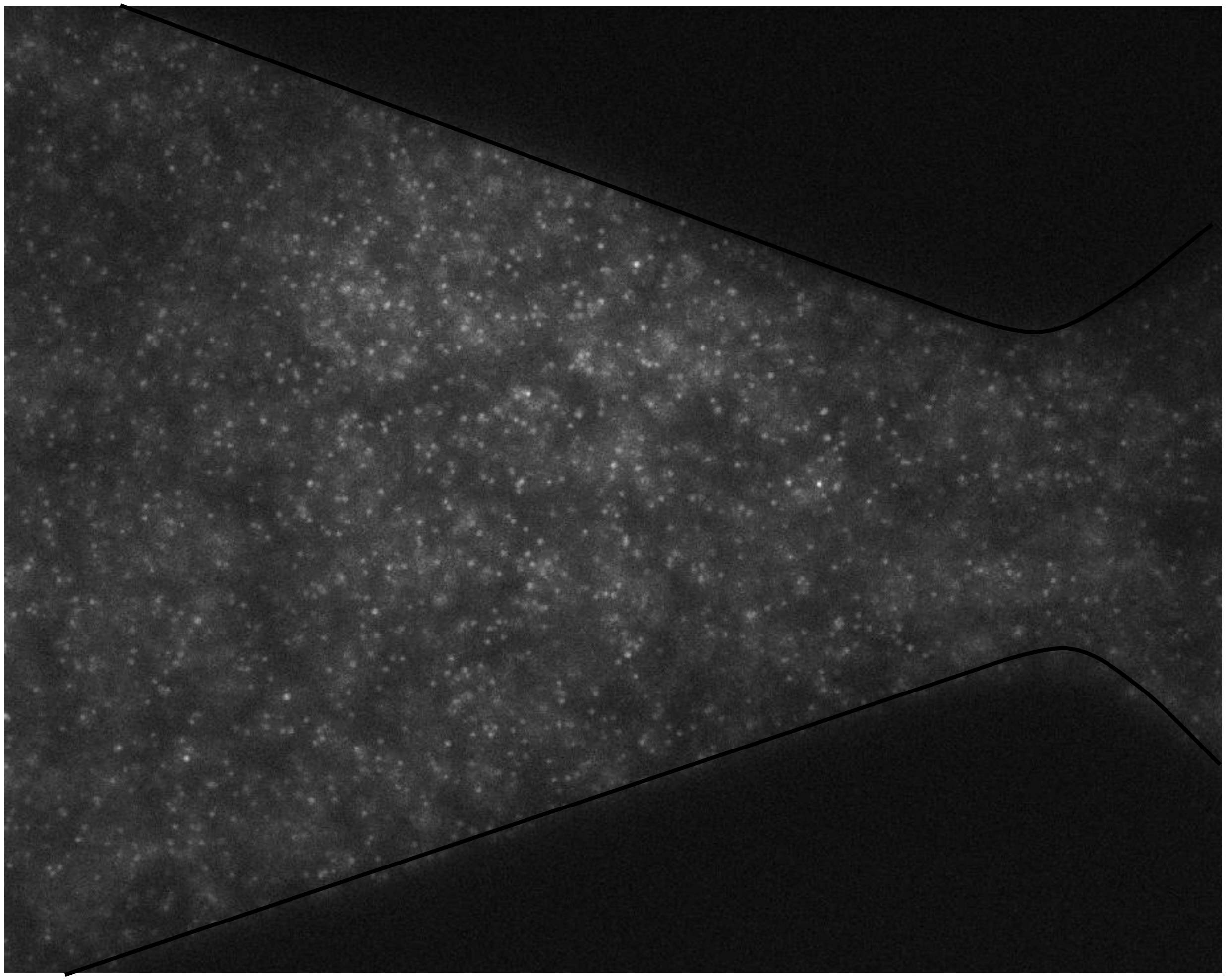
Micro-PIV Schematic



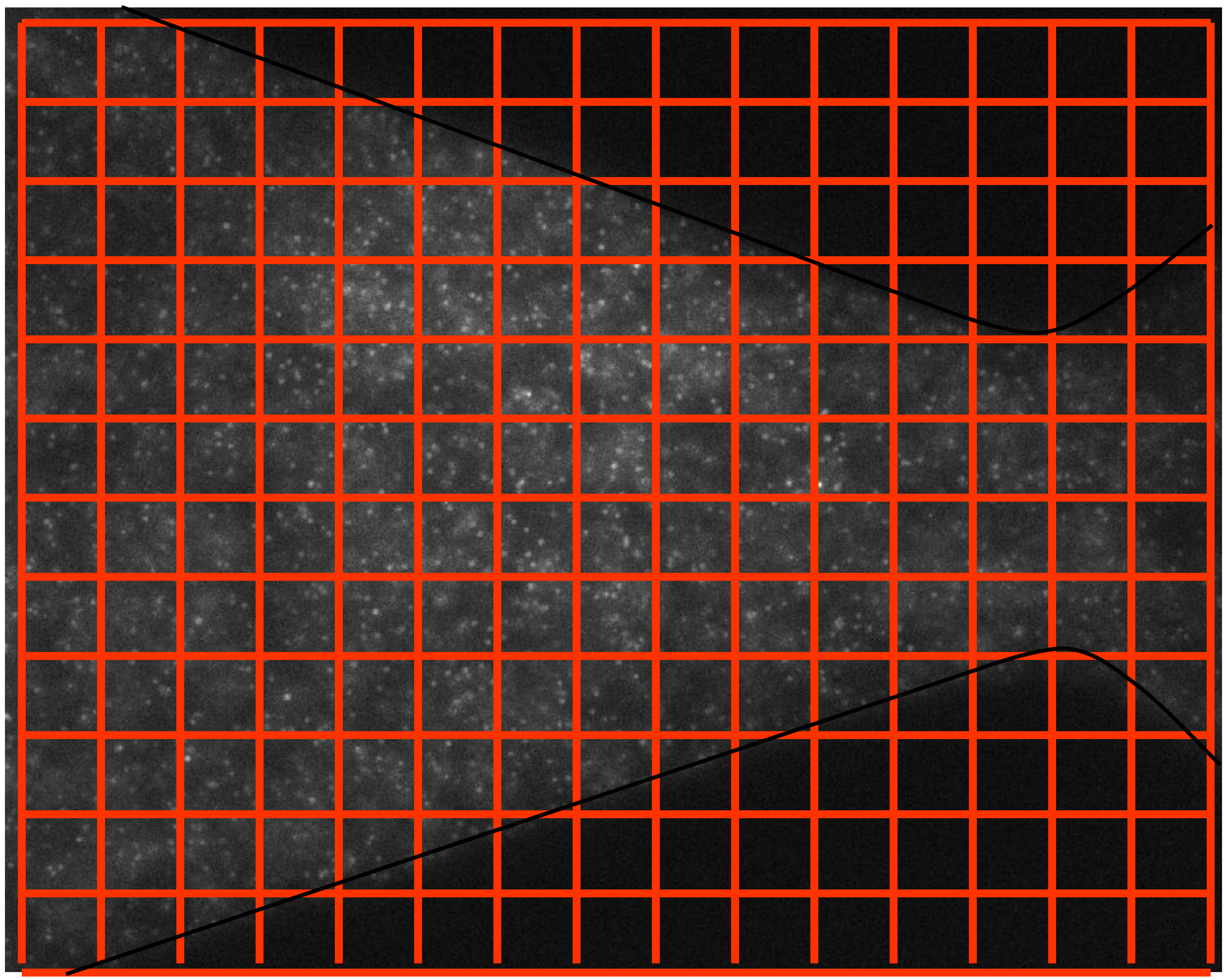
US Patent No. 6,653,651

(Meinhart, Santiago, Wereley, Adrian)

Typical Micro-PIV Image

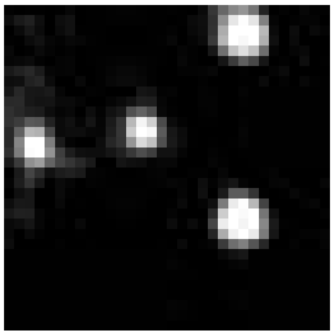


Typical Micro-PIV Image



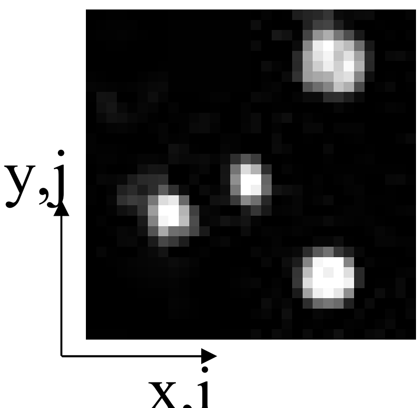
Cross-Correlat PIV

Interrogation Region #1



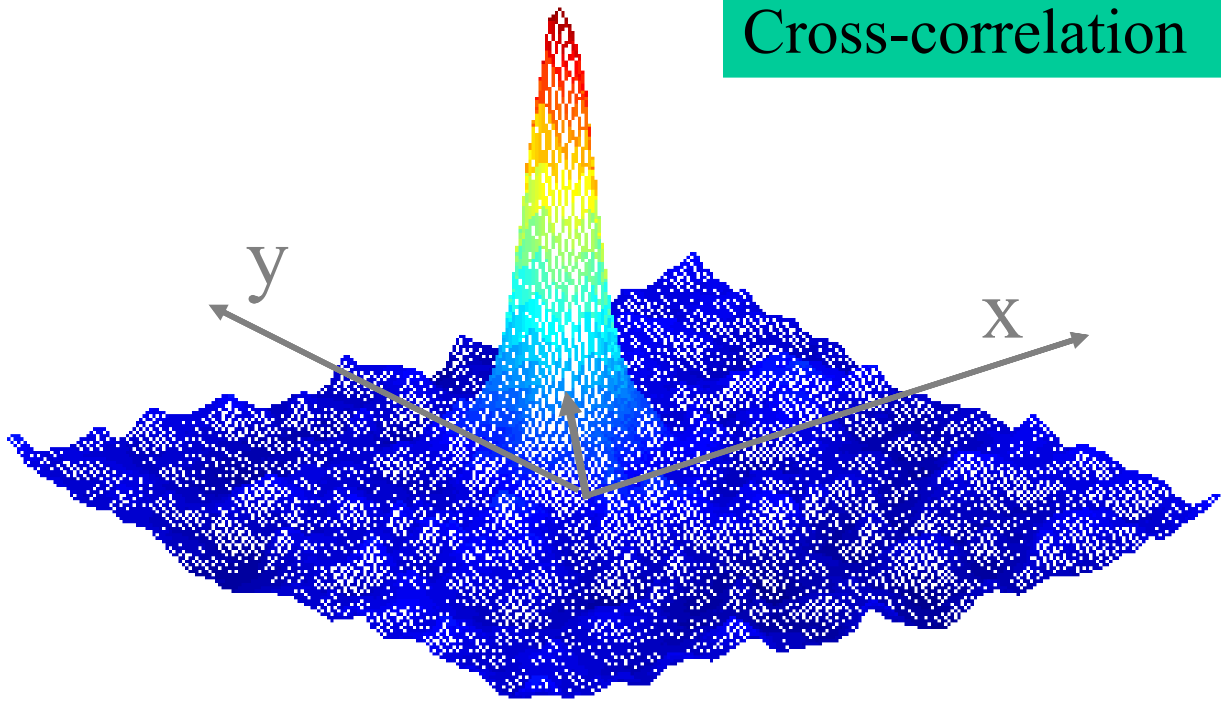
$f_k(i,j)$

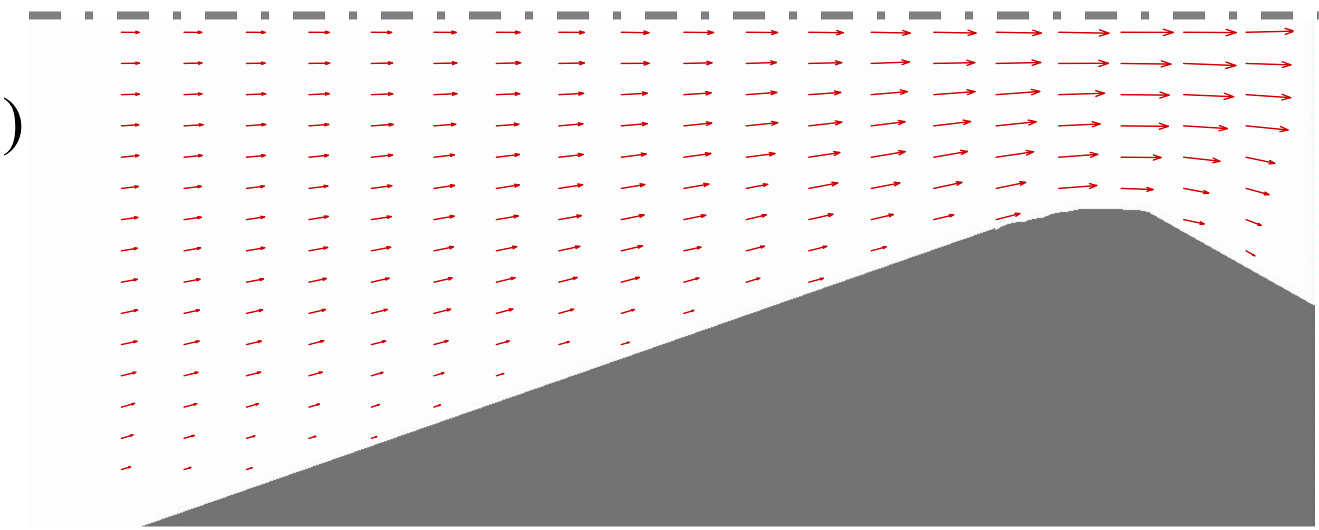
Interrogation Region #2



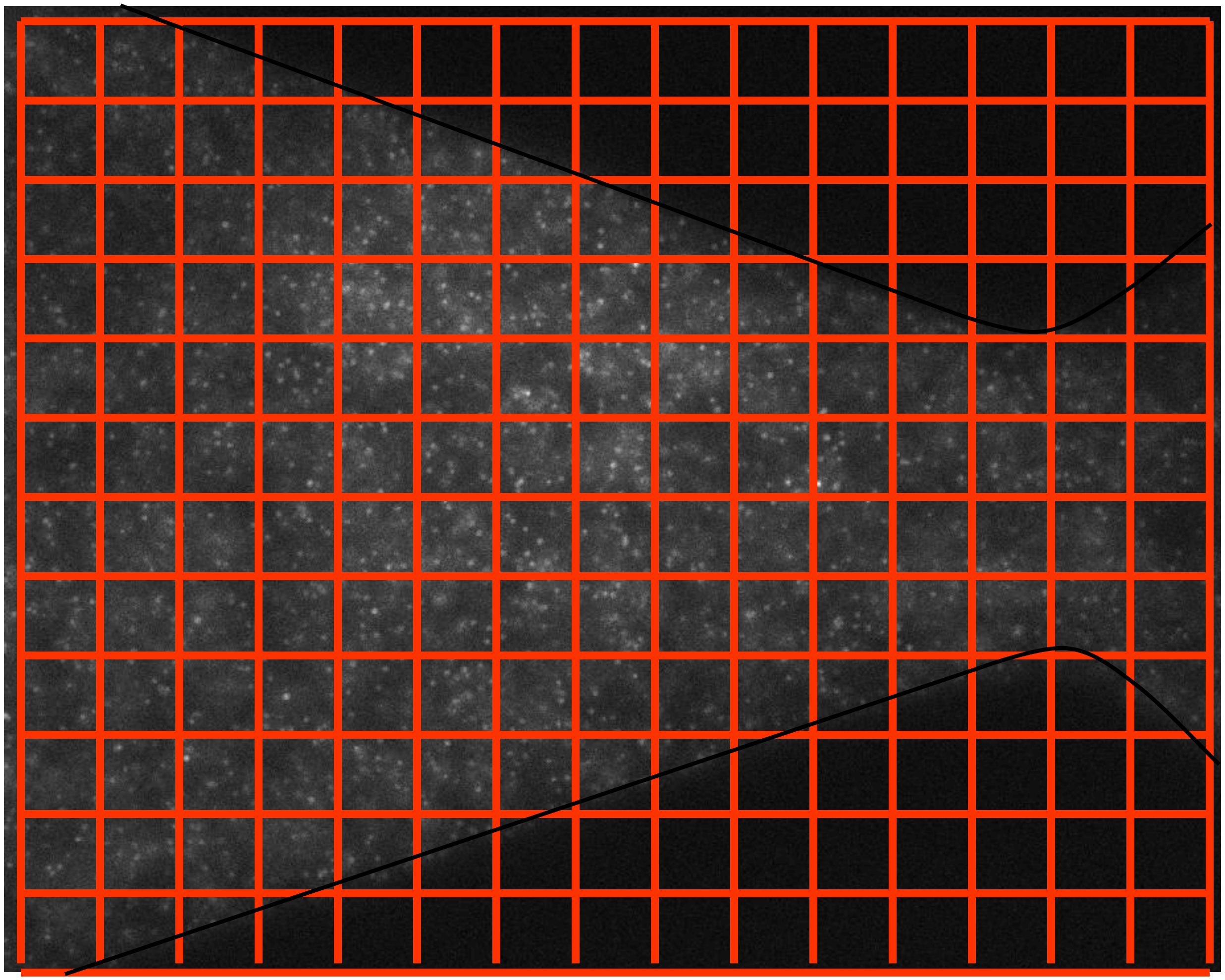
$g_k(i,j)$

Cross-correlation



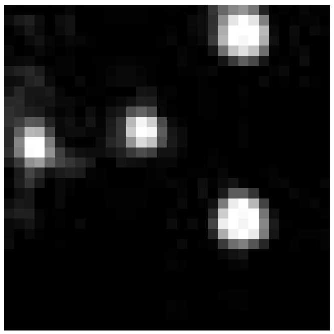


Typical Micro-PIV Image



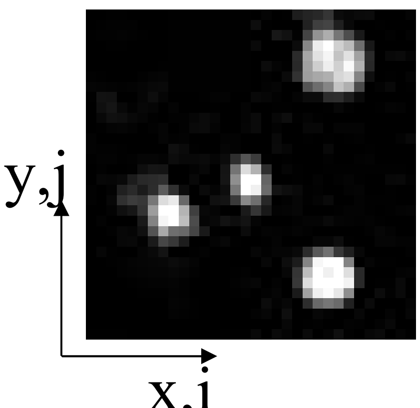
Cross-Correlat

Interrogation Region #1



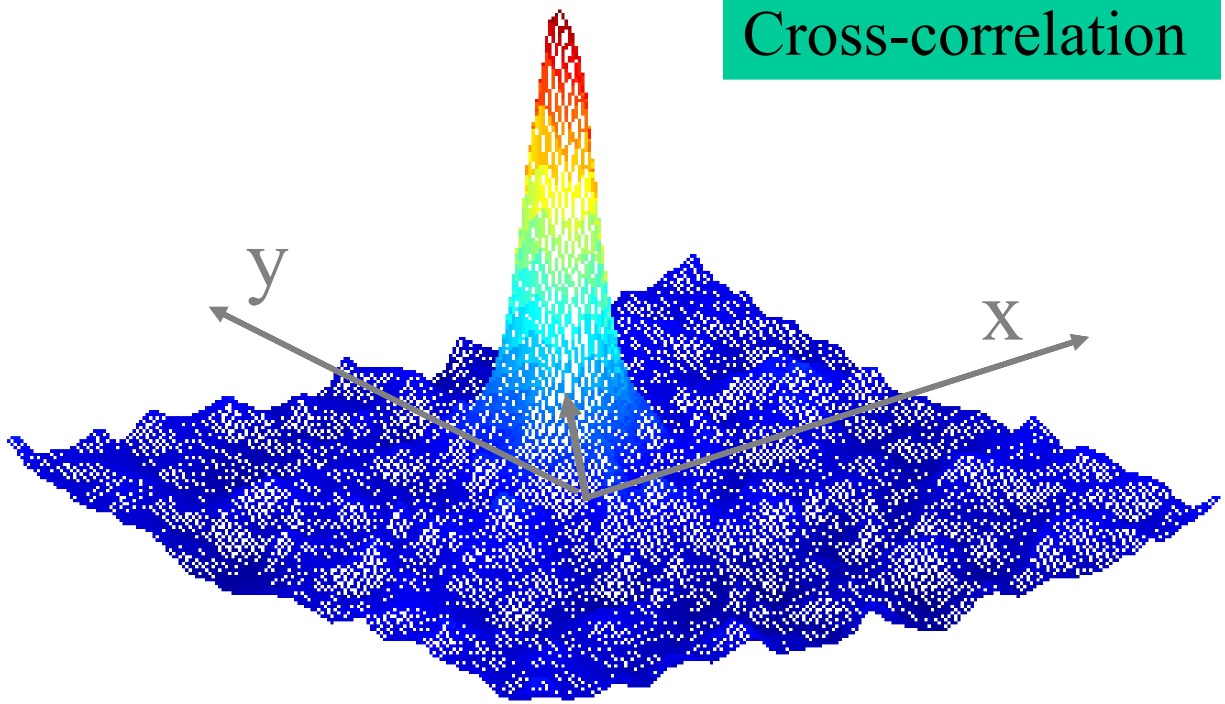
$f_k(i,j)$

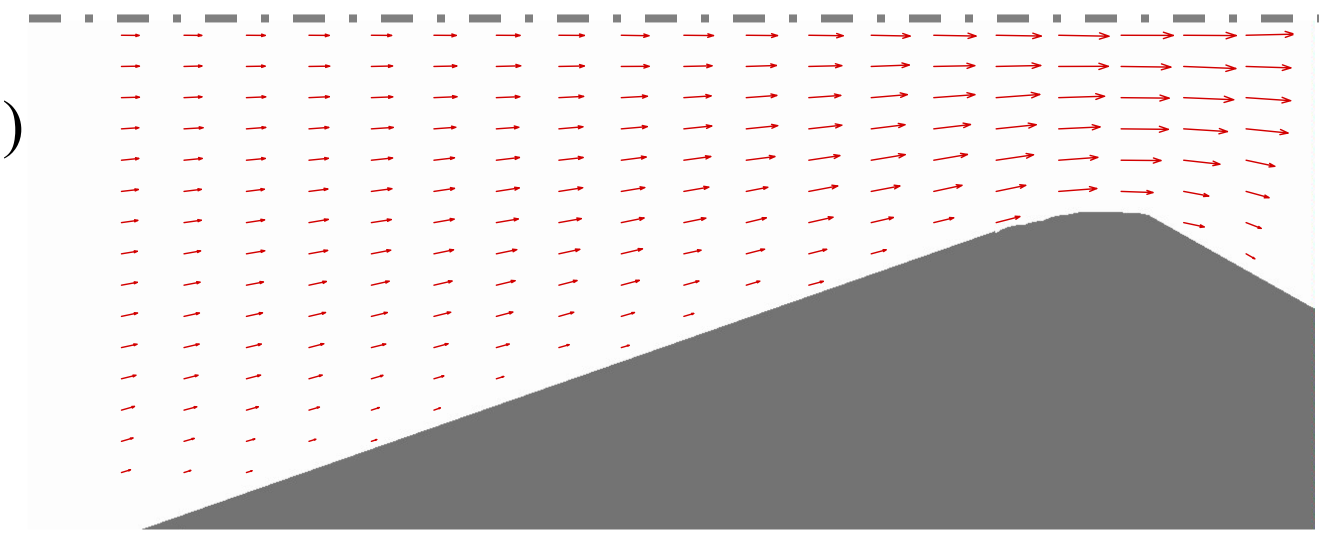
Interrogation Region #2



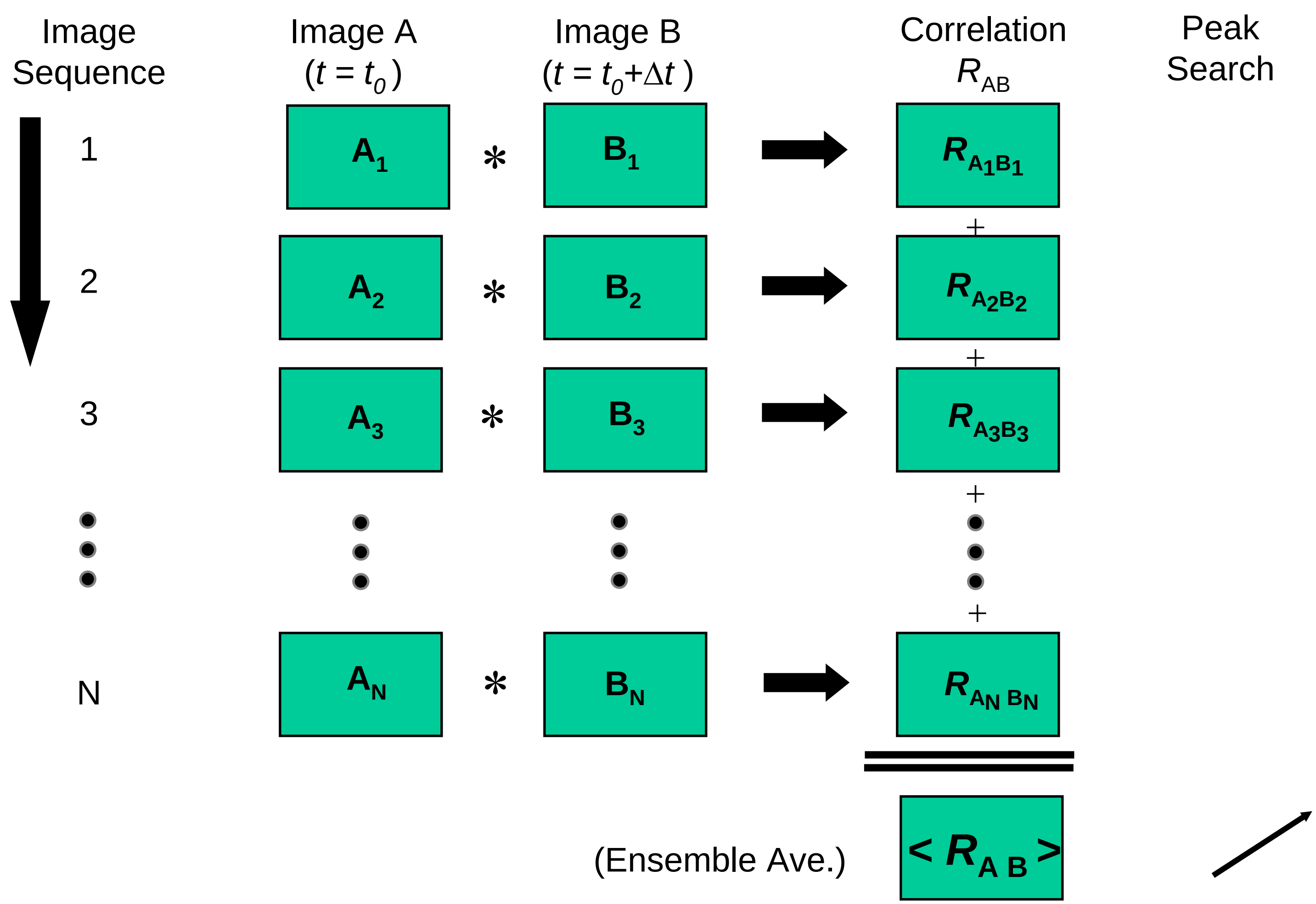
$g_k(i,j)$

Cross-correlation

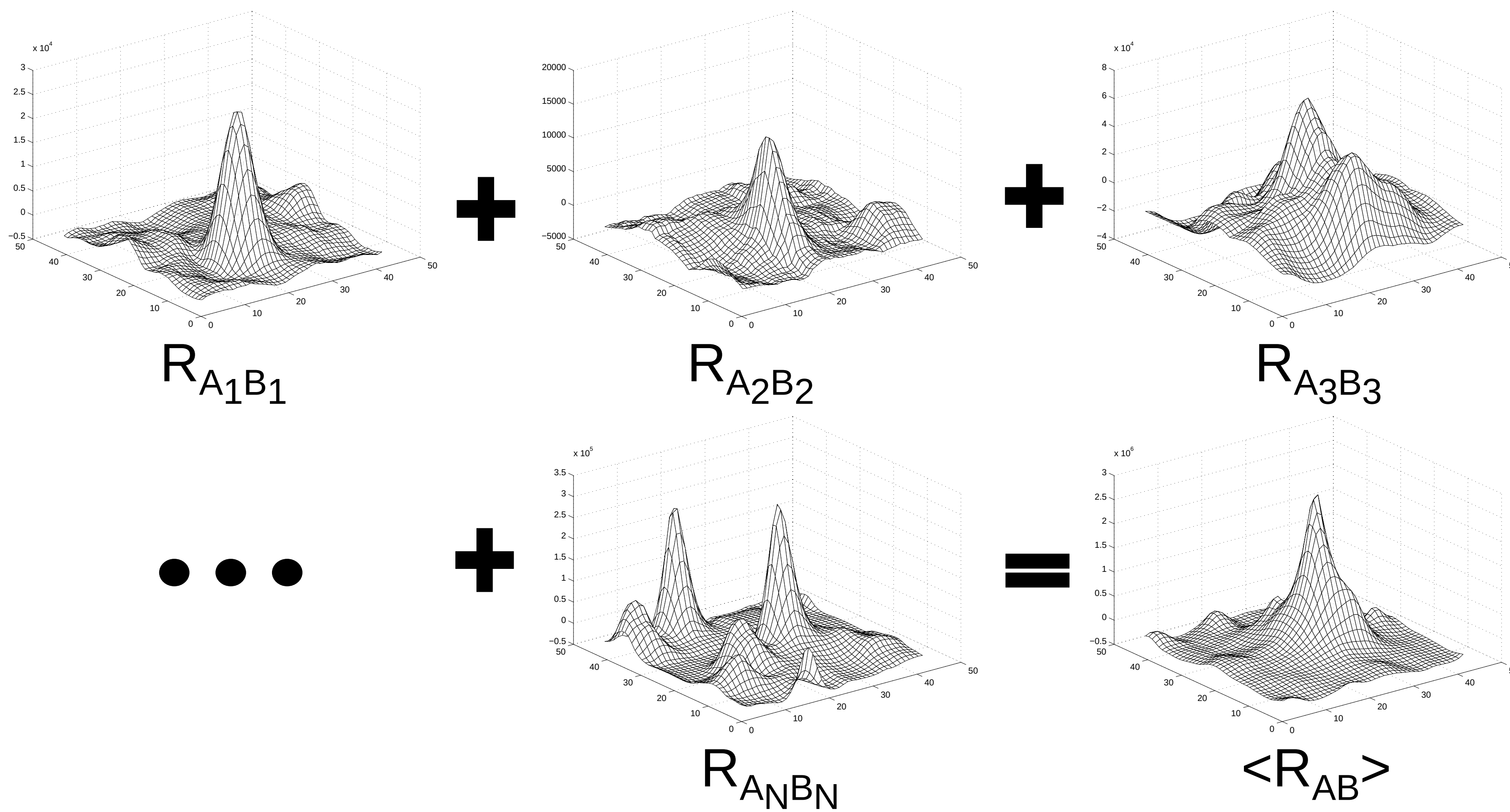




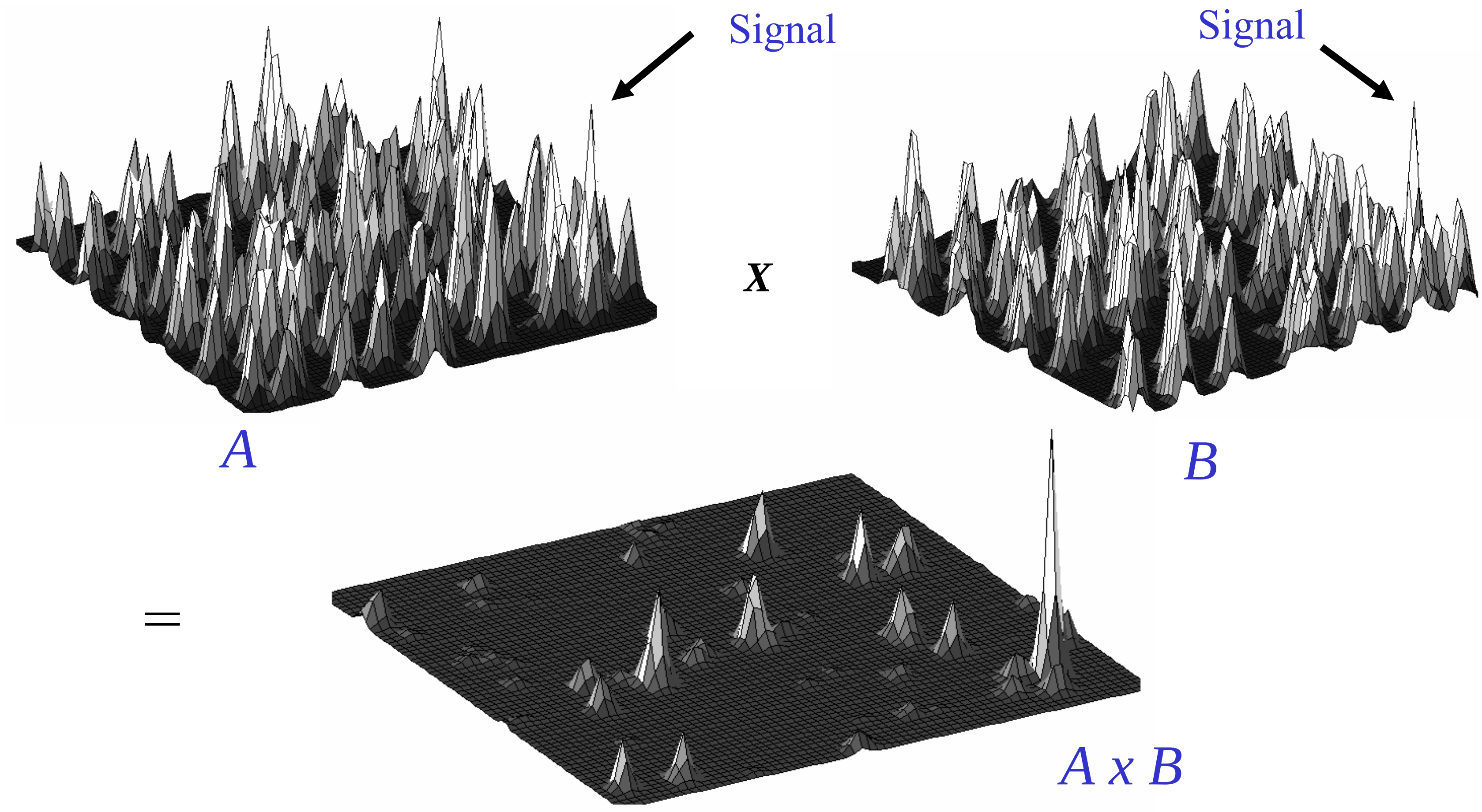
Average Correlation Algorithm



Arithmetic Average Correlation



Geometric Average Correlation



If signal is present – geometric average can pull it out of the noise

Combination of Geometric & Arithmetic Averaging

n - number of additions
m - number of multiplications

$n \; x \; m$ matrix of correlation functions

$N = n \; x \; m$ total number

$$
\begin{aligned}
\bar{R} = & \left(R_{11} + R_{12} + R_{13} + \cdots + R_{1n}\right) \\
& \times\left(R_{21} + R_{22} + R_{23} + \cdots + R_{2n}\right) \\
& \times\left(R_{31} + R_{32} + R_{33} + \cdots + R_{3n}\right) \\
& \quad \vdots \qquad \vdots \qquad \vdots \qquad\qquad \vdots \\
& \times\left(R_{m1} + R_{m2} + R_{m3} + \cdots + R_{mn}\right)
\end{aligned}
$$

What is the optimum combination of *n* & *m*?

Optimal Number for Signal

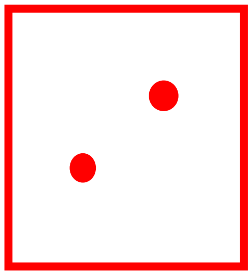
$$\bar{R} = \left(R_{11} + R_{12} + R_{13} + \cdots + R_{1n}\right)$$
$$\times\left(R_{21} + R_{22} + R_{23} + \cdots + R_{2n}\right)$$
$$\times\left(R_{31} + R_{32} + R_{33} + \cdots + R_{3n}\right)$$
$$\vdots \qquad \vdots \qquad \vdots \qquad\qquad \vdots$$
$$\times\left(R_{m1} + R_{m2} + R_{m3} + \cdots + R_{mn}\right)$$

Number of signal terms $\sim n^m$

Highest signal obtained $n = 2, 3$

$m = N/n$

Optimal Number for Reliability



C – Concentration of particles (μm^{-3})

V – Volume of interrogation region

$$P(k) = \frac{(CV)^k}{k!} e^{-CV}$$

Probability of finding k particles in V
(Poisson Distribution)

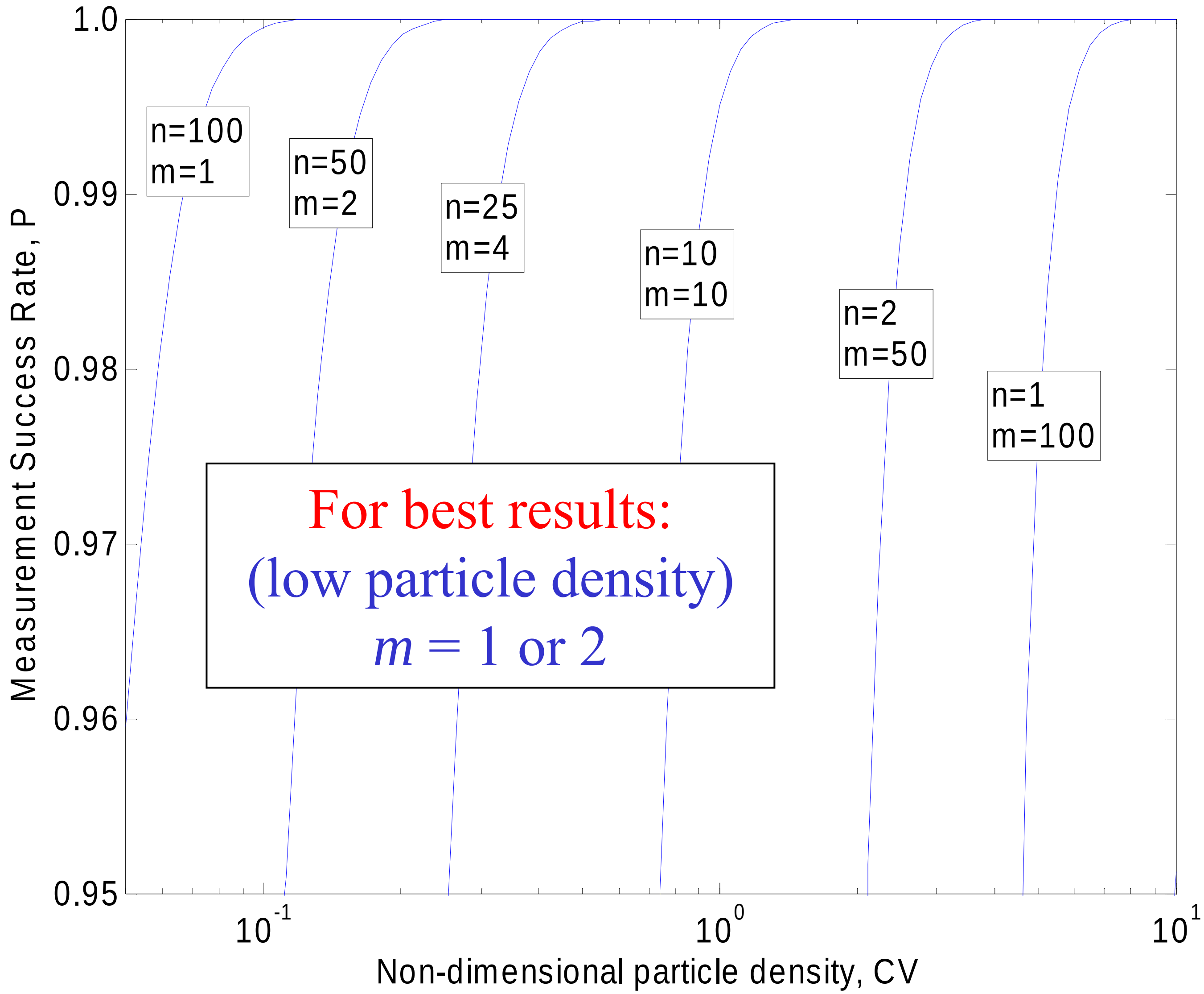
$$P_n(k \geq 2) = 1 - (1 + nCV) e^{-nCV}$$

Probability of finding *2* particles by adding n correlations

$$P_n^m(k \geq 2) = \left[1 - (1 + nCV) e^{-nCV}\right]^m$$

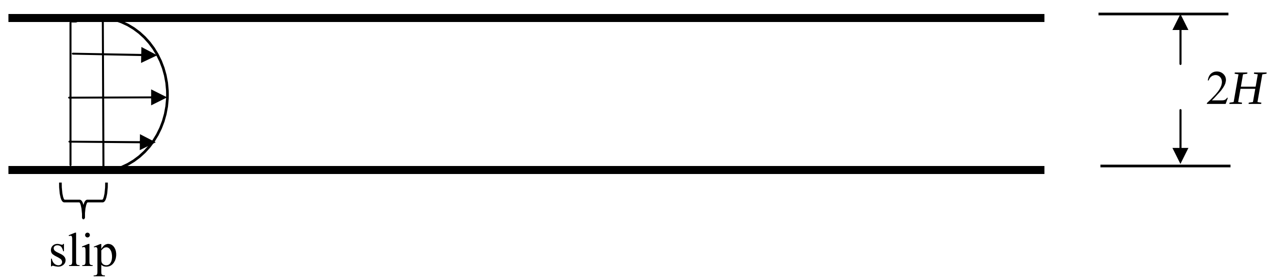
Probability of finding *2* particles by adding n correlations in m multiplicative groups

Probability of Reliable Measurement vs. Particle Density (N = 100)



Slip Flow Boundary Condition

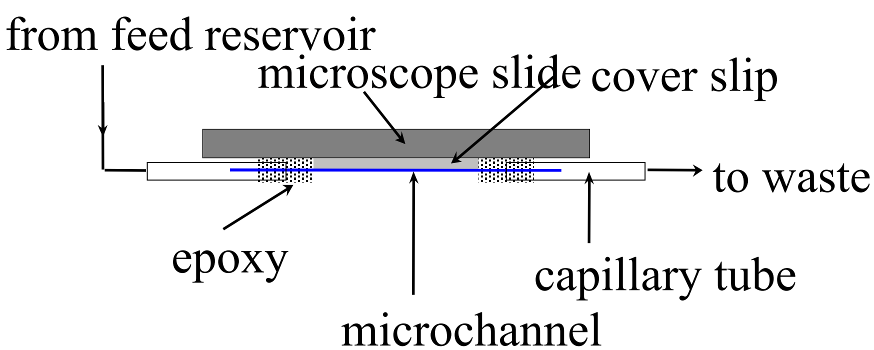
- Navier's hypothesis (1832): $v_x = \beta\,(dv_x/dy)$
- For Stokes flow between two infinite plates

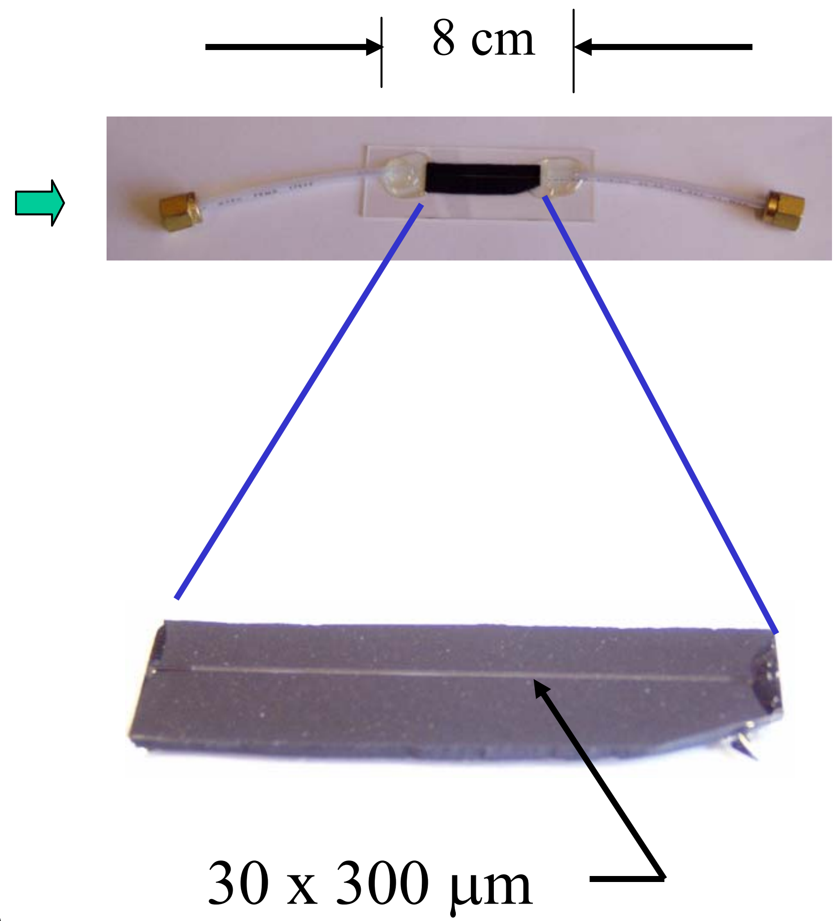


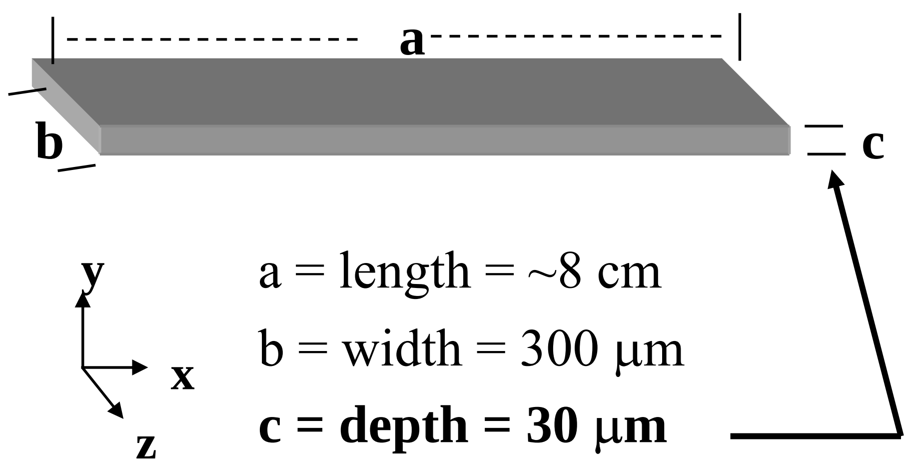
$$v_x(y) = \frac{H^2}{2\mu}\left(-\frac{dp}{dx}\right)\left[1-\left(\frac{y}{H}\right)^2+\frac{2\beta}{H}\right]$$

no-slip (under $1-\left(\frac{y}{H}\right)^2$)

Extruded Glass Microchannel







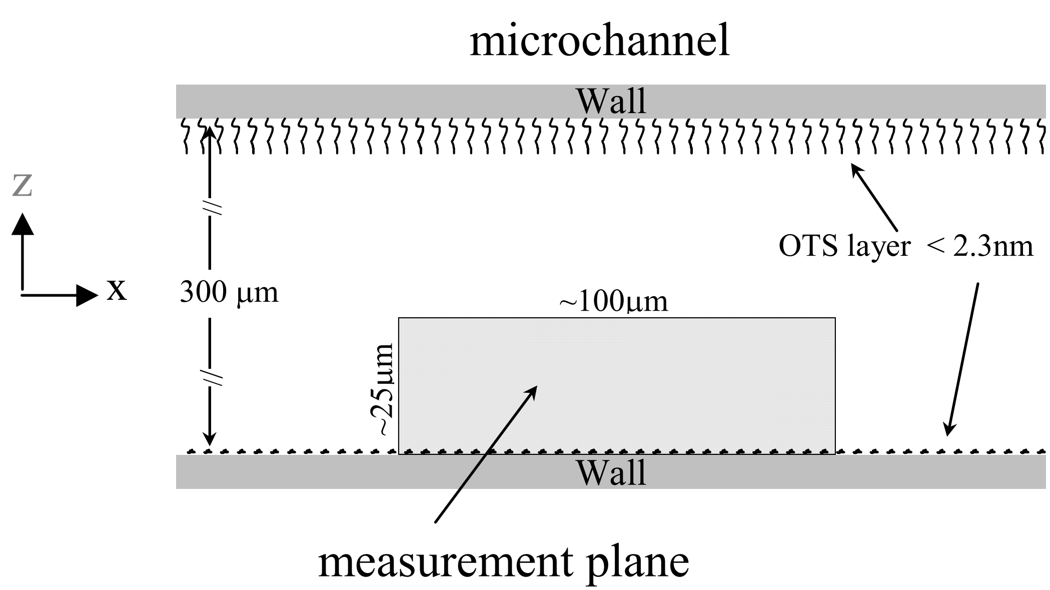
a = length = ~8 cm

b = width = 300 µm

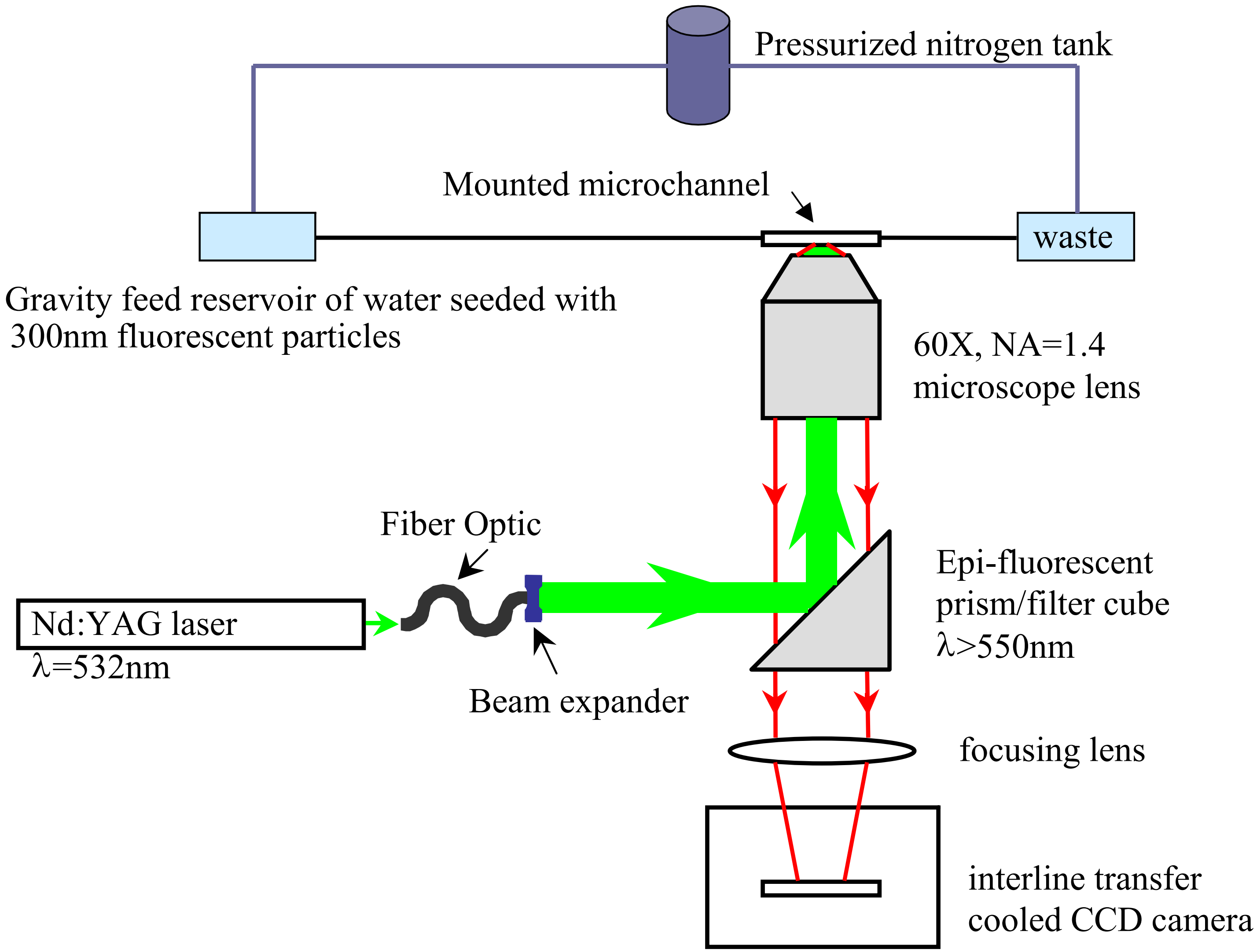
c = depth = 30 µm

Channel Types

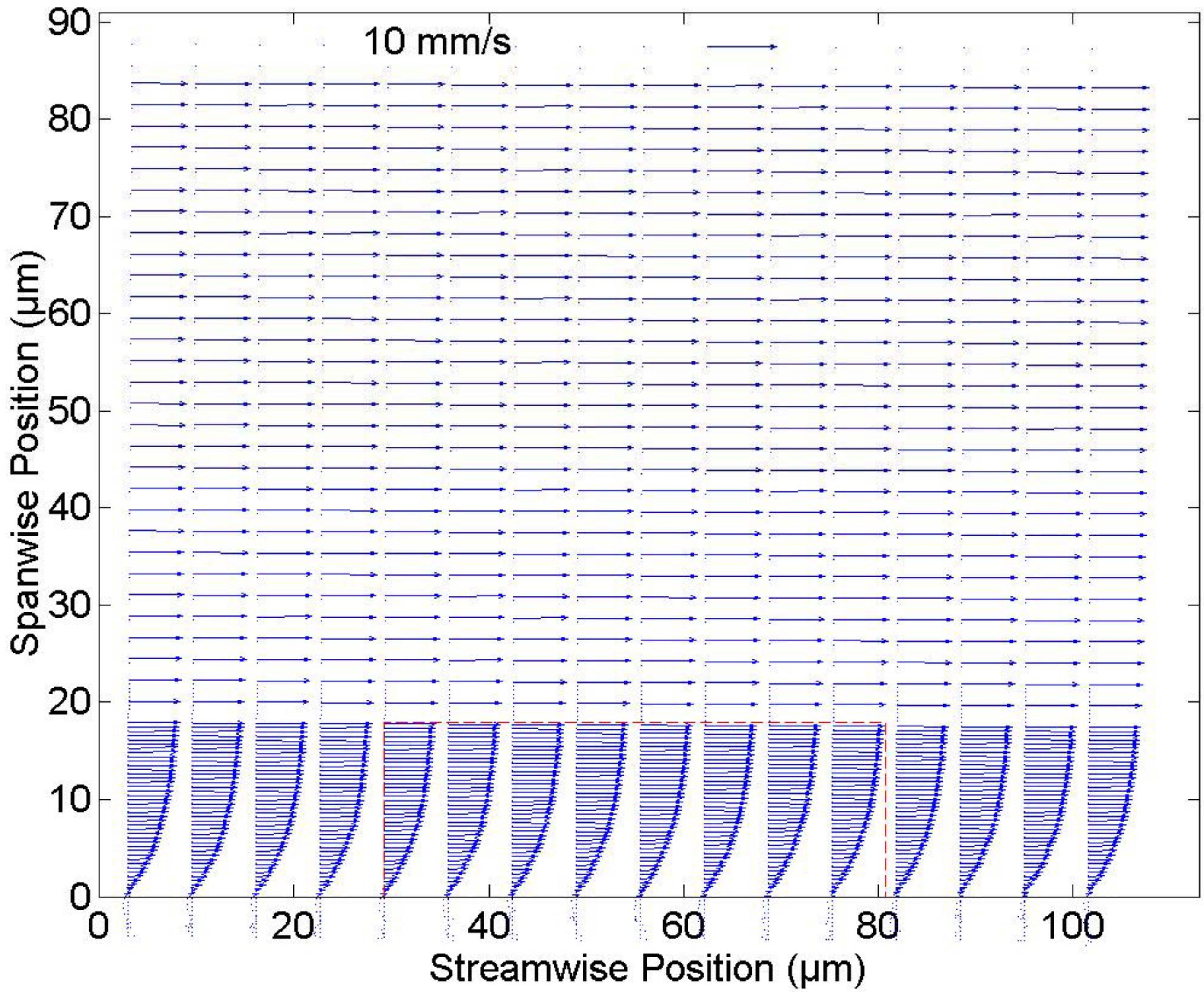
- Hydrophilic
  - Untreated glass
- Hydrophobic
  - Coated with octadecyltrichlorosilane (OTS)



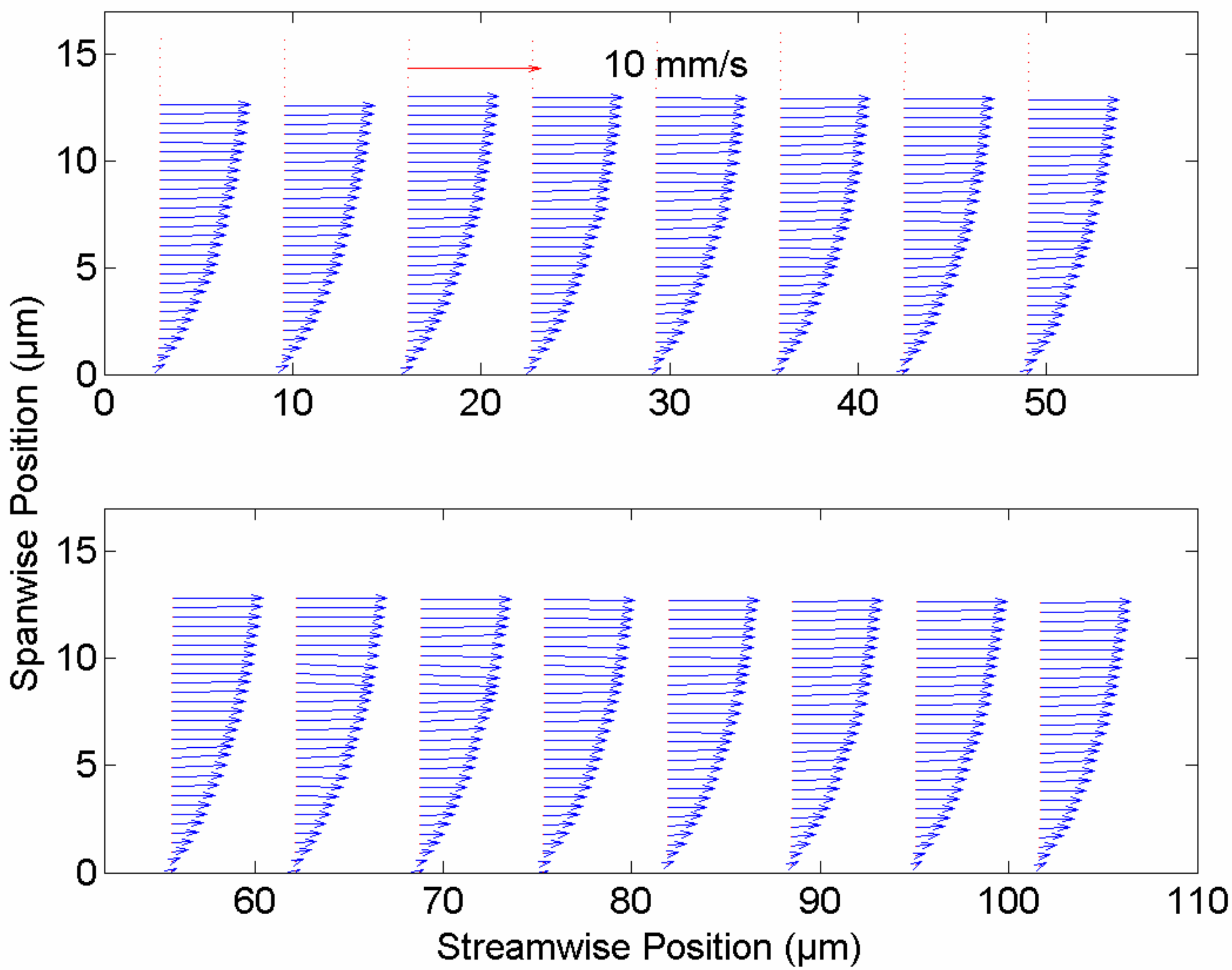
Experimental Apparatus



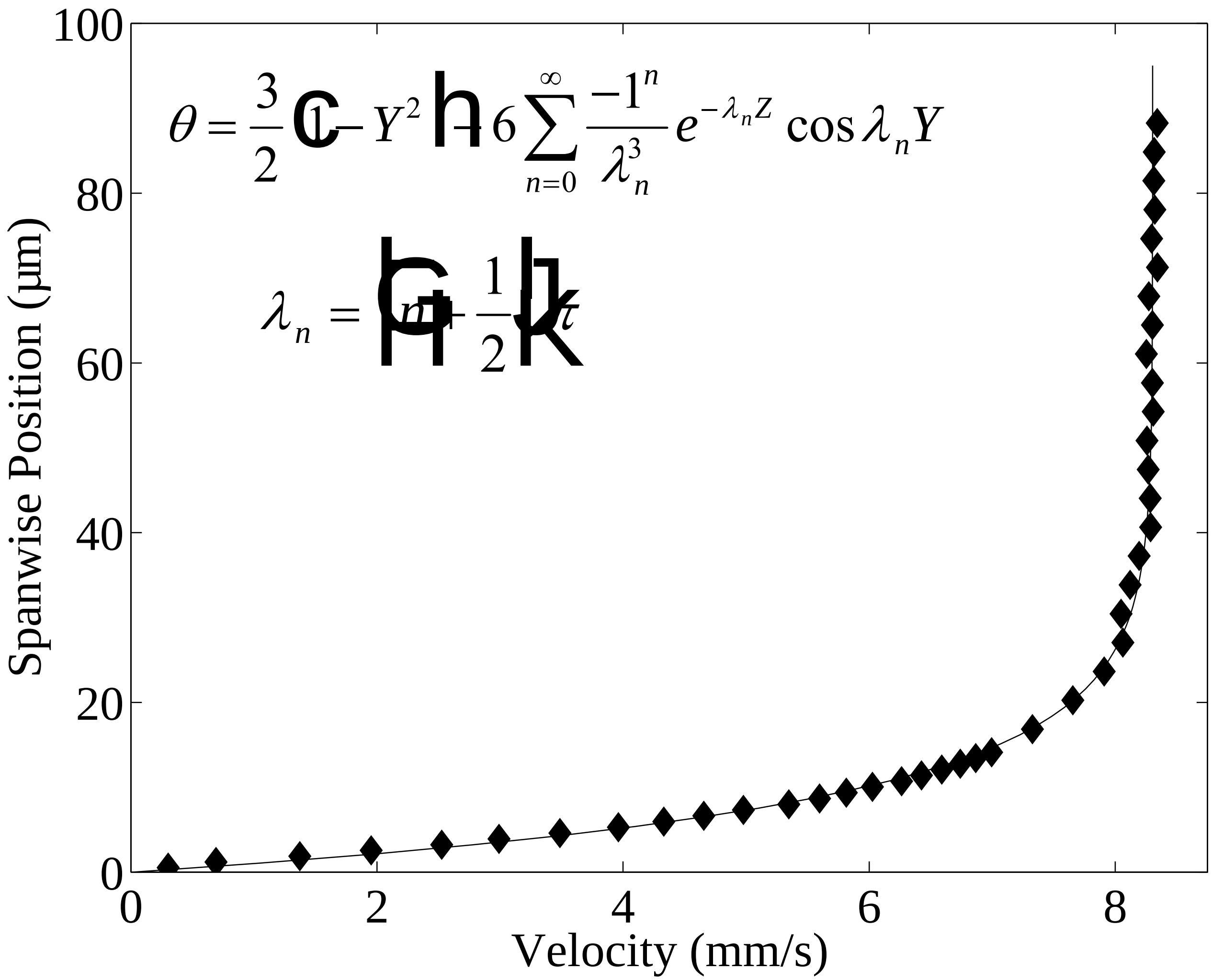
30 x 300μm Channel Flow (Hydrophilic Surface)



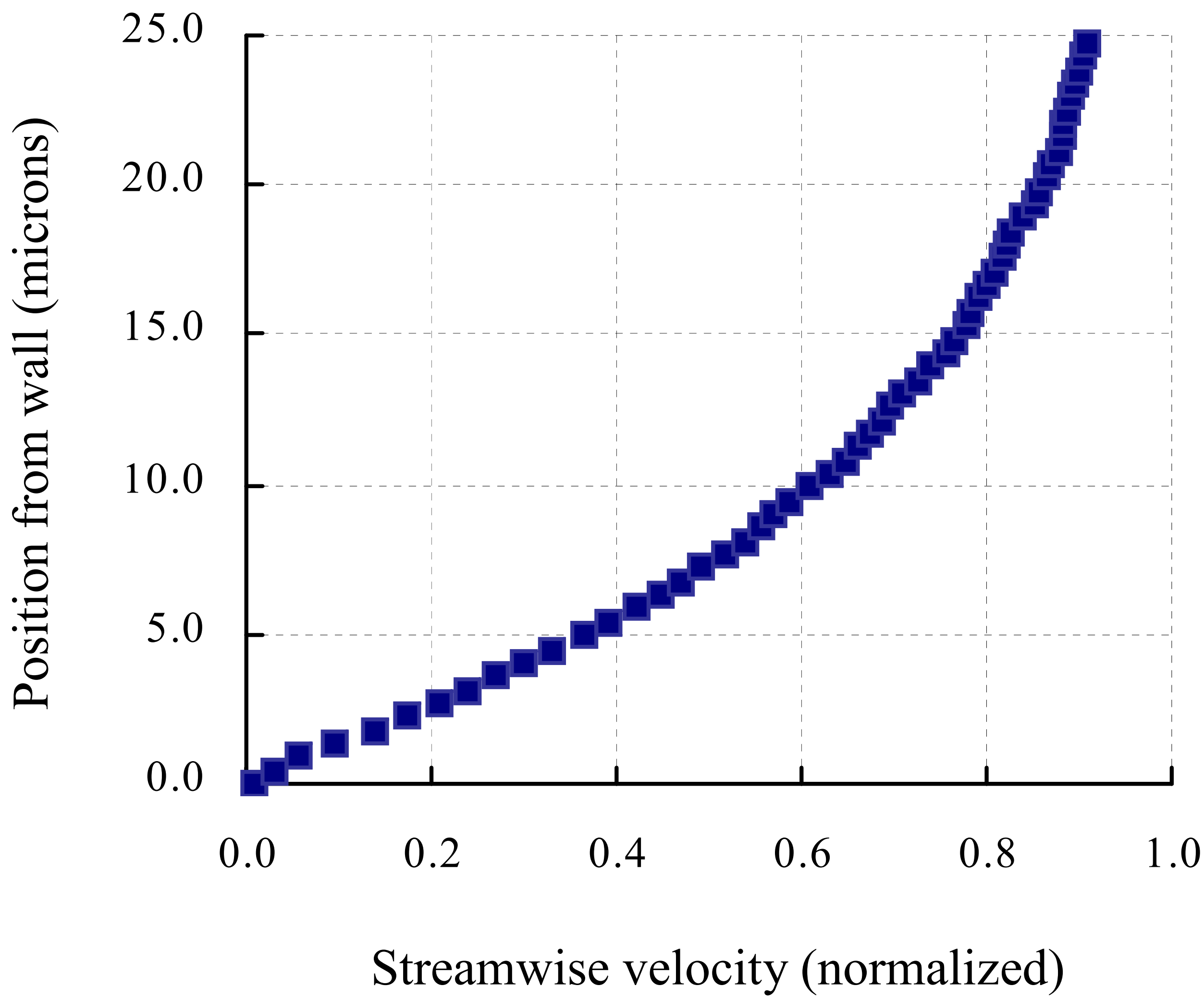
Hydrophilic Velocity Fields



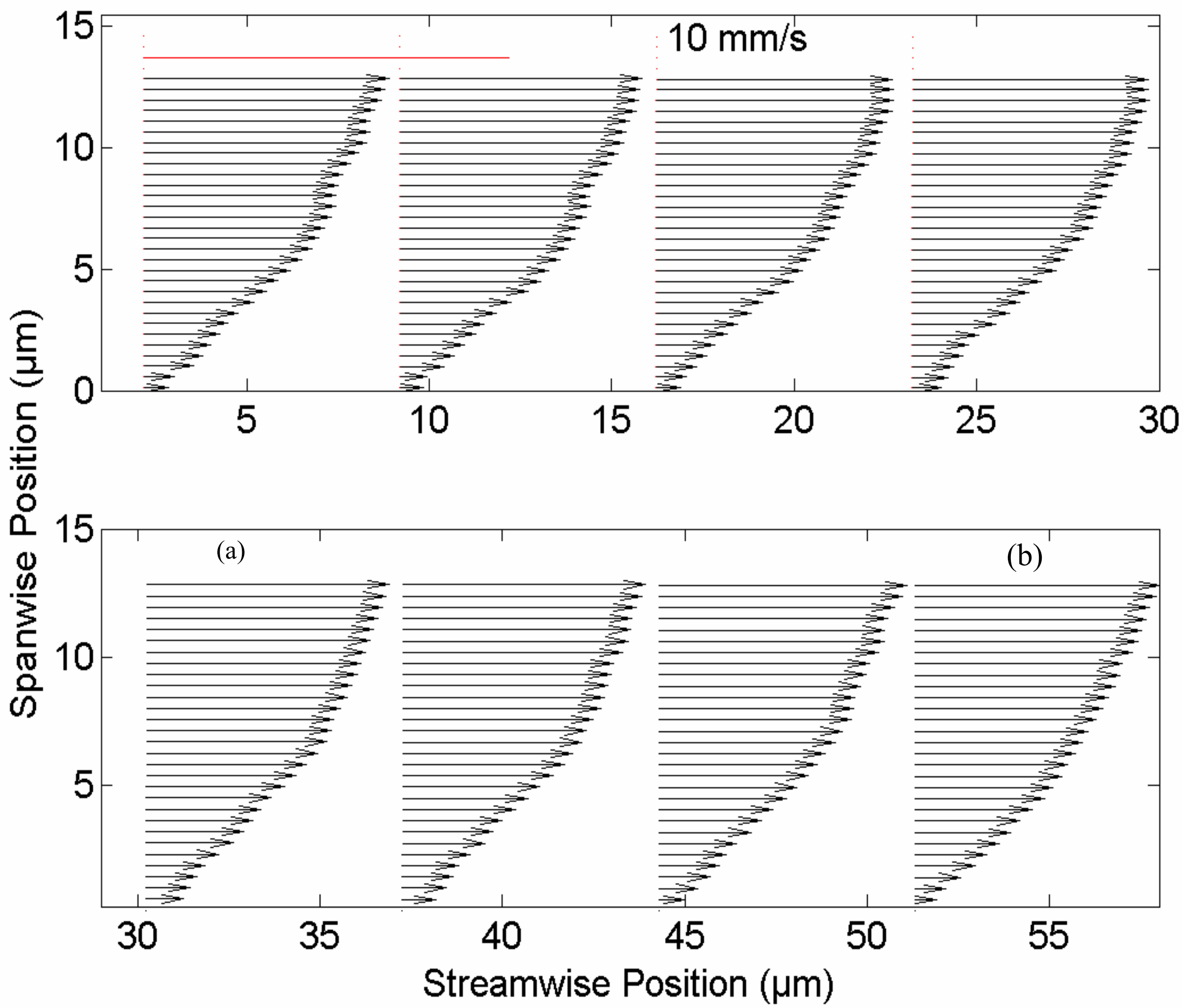
Analytical solution to Stokes Equation with No-Slip Boundary Condition



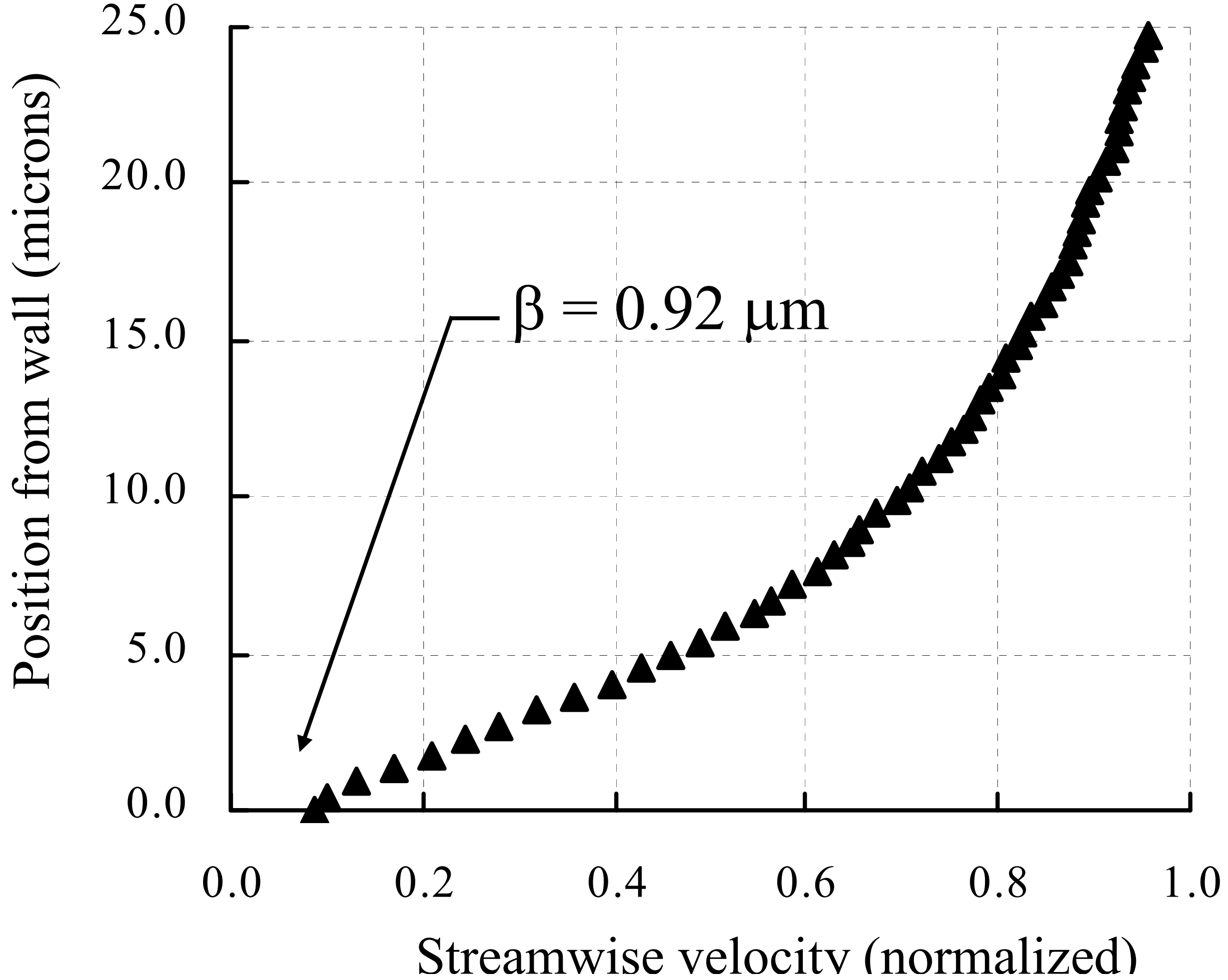
Velocity Profile for a Hydrophilic Microchannel (no-slip)



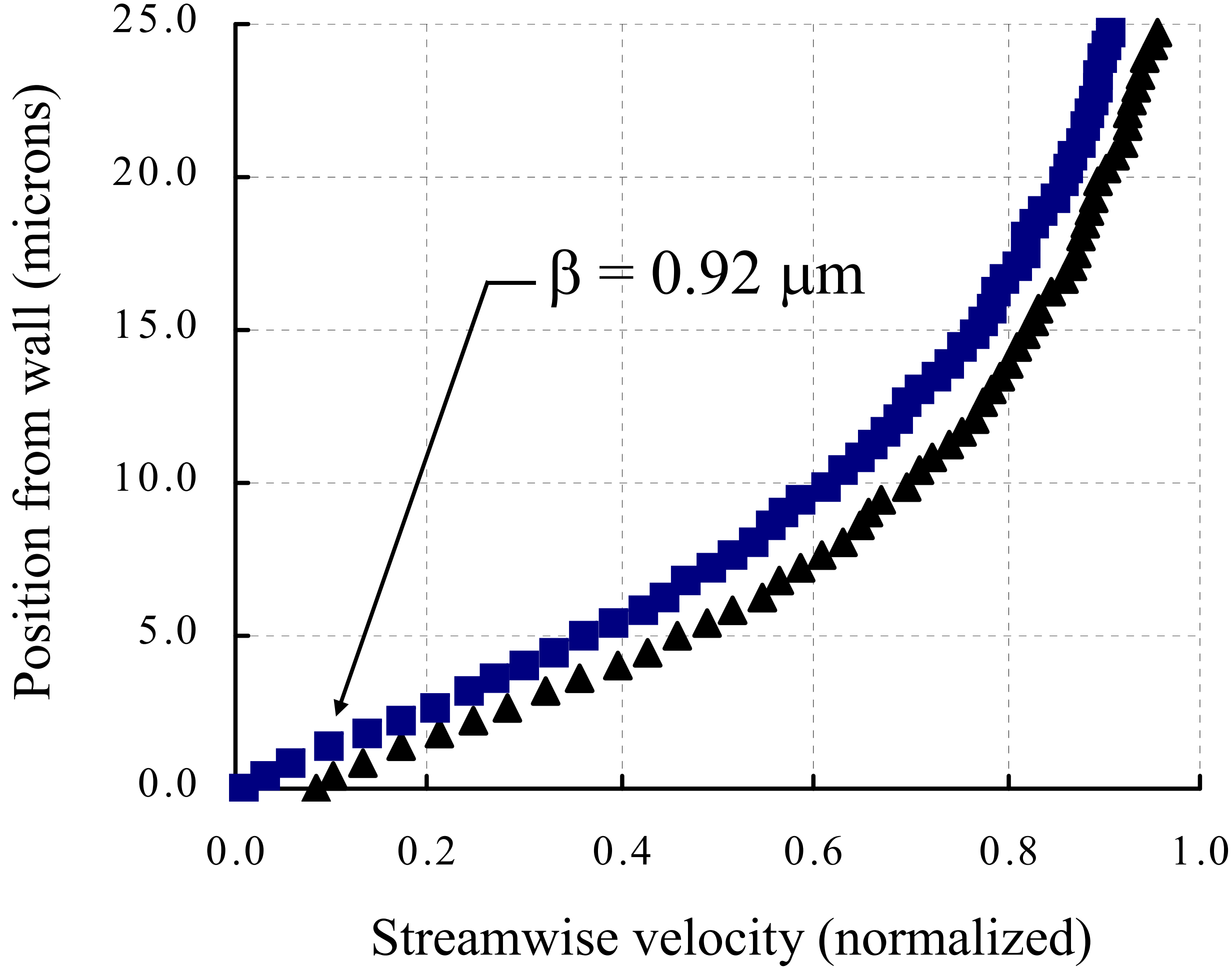
Hydrophobic Velocity Fields

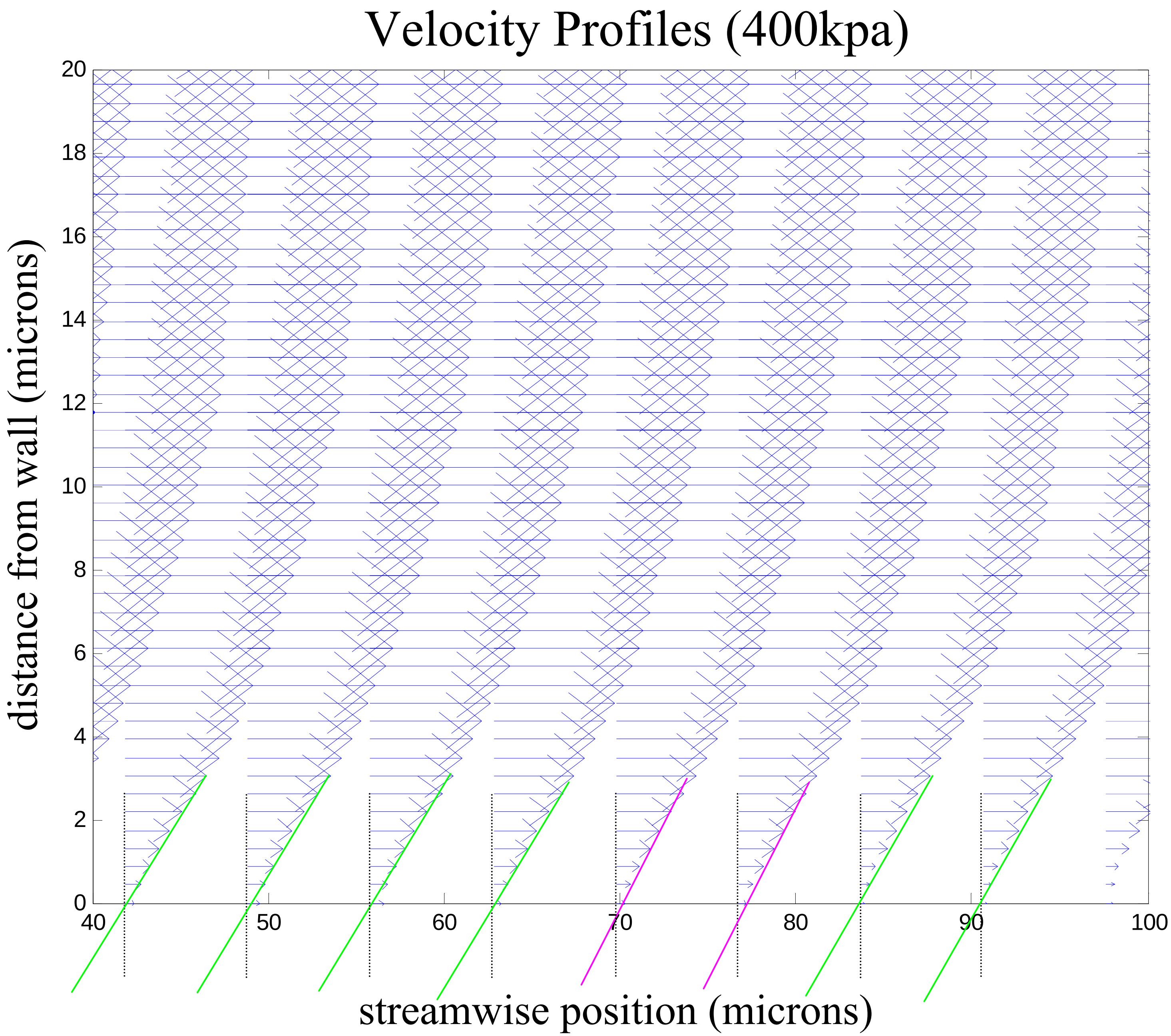


Velocity Profile in a Hydrophobic Microchannel (slip)



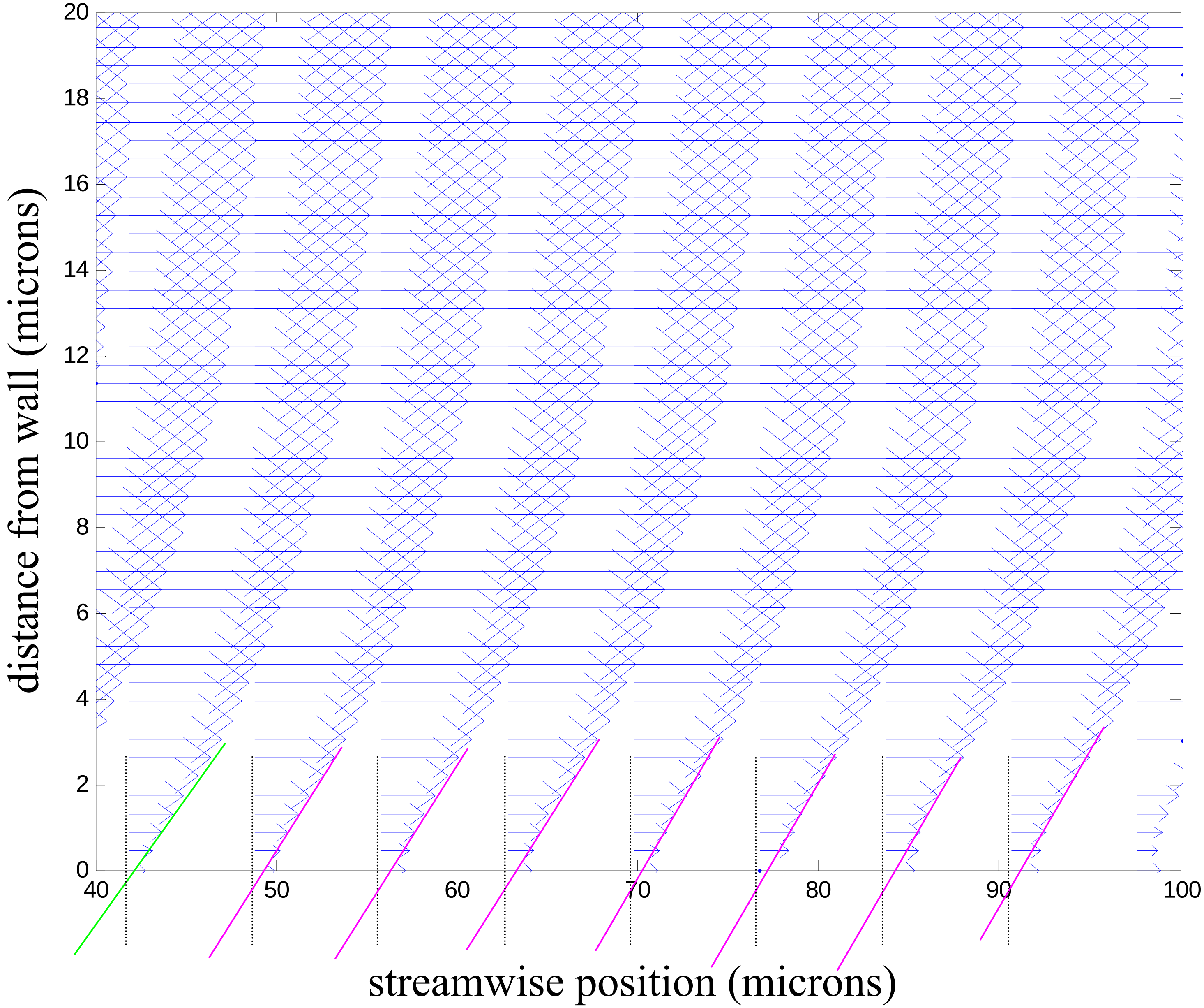
Profile Comparison

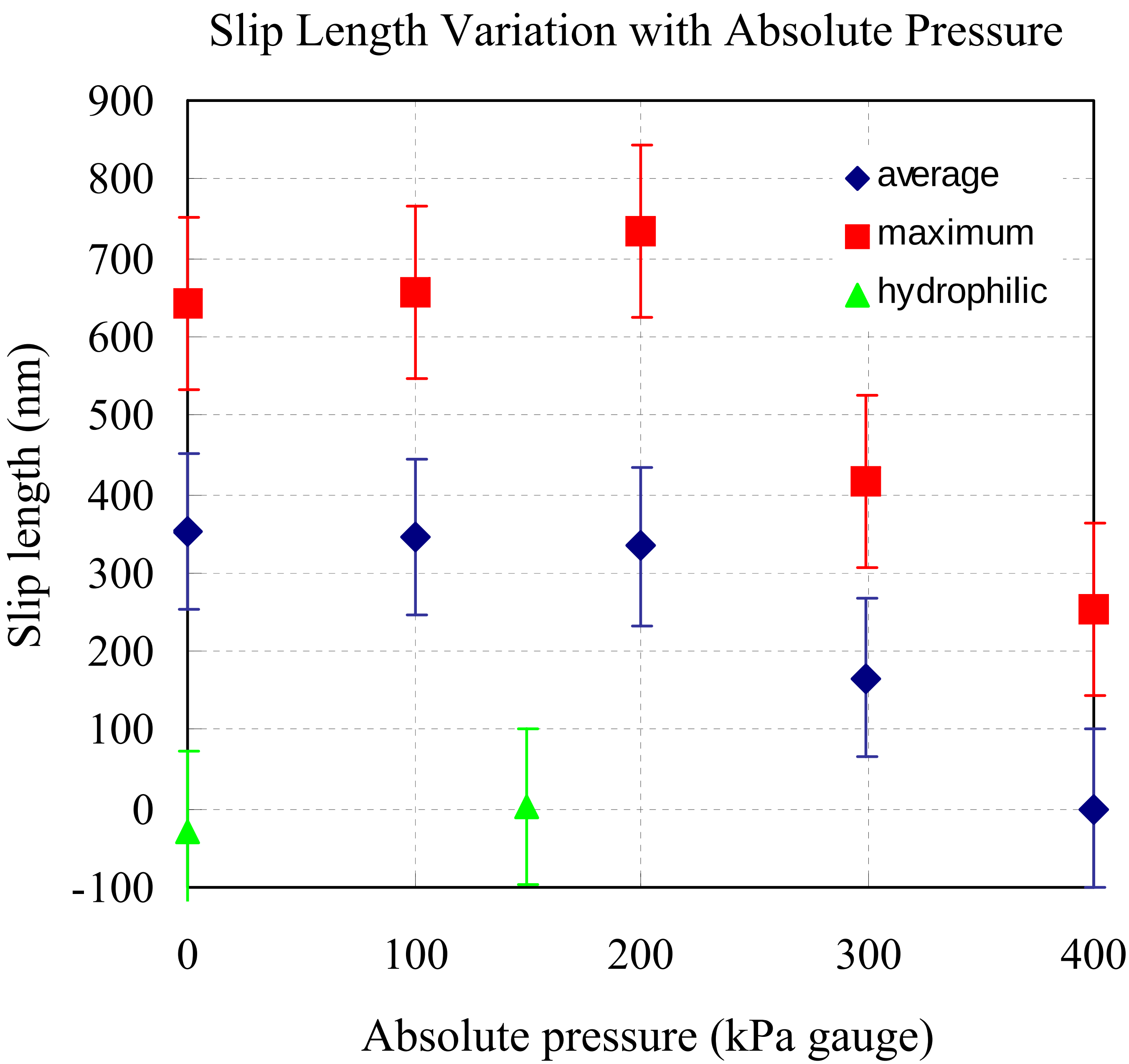




Velocity Profiles (400kpa)
distance from wall (microns)
streamwise position (microns)
0
2
4
6
8
10
12
14
16
18
20
40
50
60
70
80
90
100

Velocity Profiles (100kpa)



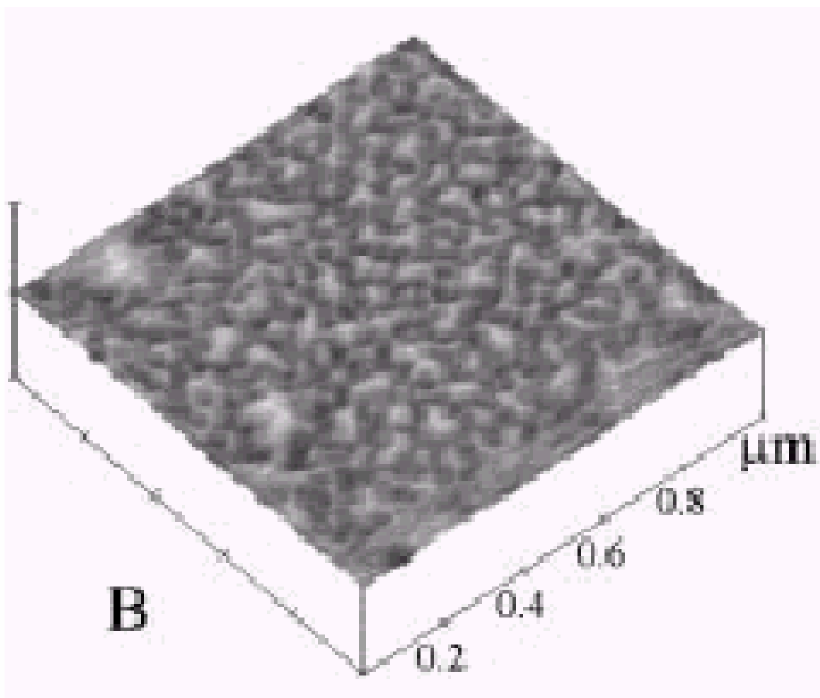


Slip Length Variation with Absolute Pressure
Slip length (nm)
900
800
700
600
500
400
300
200
100
0
-100
average
maximum
hydrophilic
0
100
200
300
400
Absolute pressure (kPa gauge)

Observation of Nano-bubbles

- Effects of soluble gasses

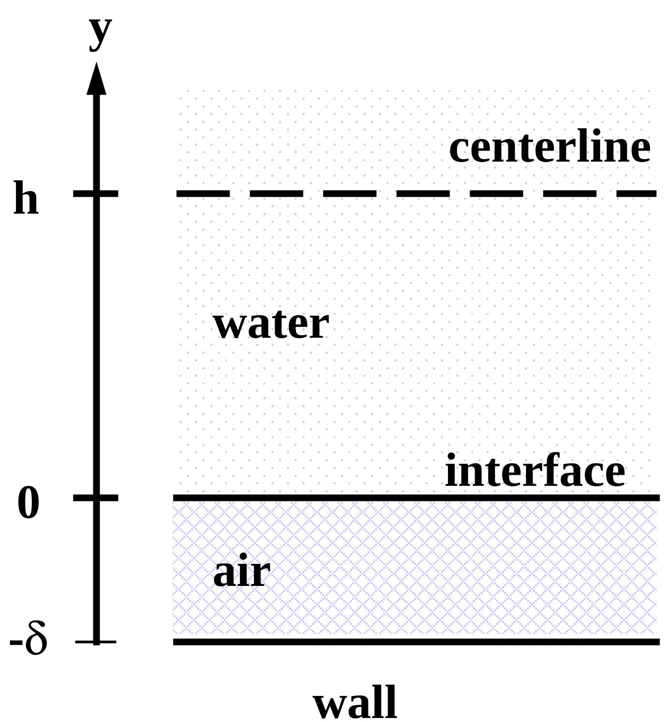
Image of a hydrophobic glass surface (Tyrrell & Attard, 2001)



- hydrophobic surface acts as a nucleation site
- complete coverage
- pancake bubbles ~30 nm high

1-D Air Gap Model

Estimation of Nano-bubble/air gap height



Water velocity result:

$$u_w = \frac{1}{2\mu_w}\left(\frac{dP}{dx}\right)_w \left[y^2 - 2hy - 2\frac{\mu_w}{\mu_a}h\delta - \frac{\mu_w}{\mu_a}\delta^2 \right],$$

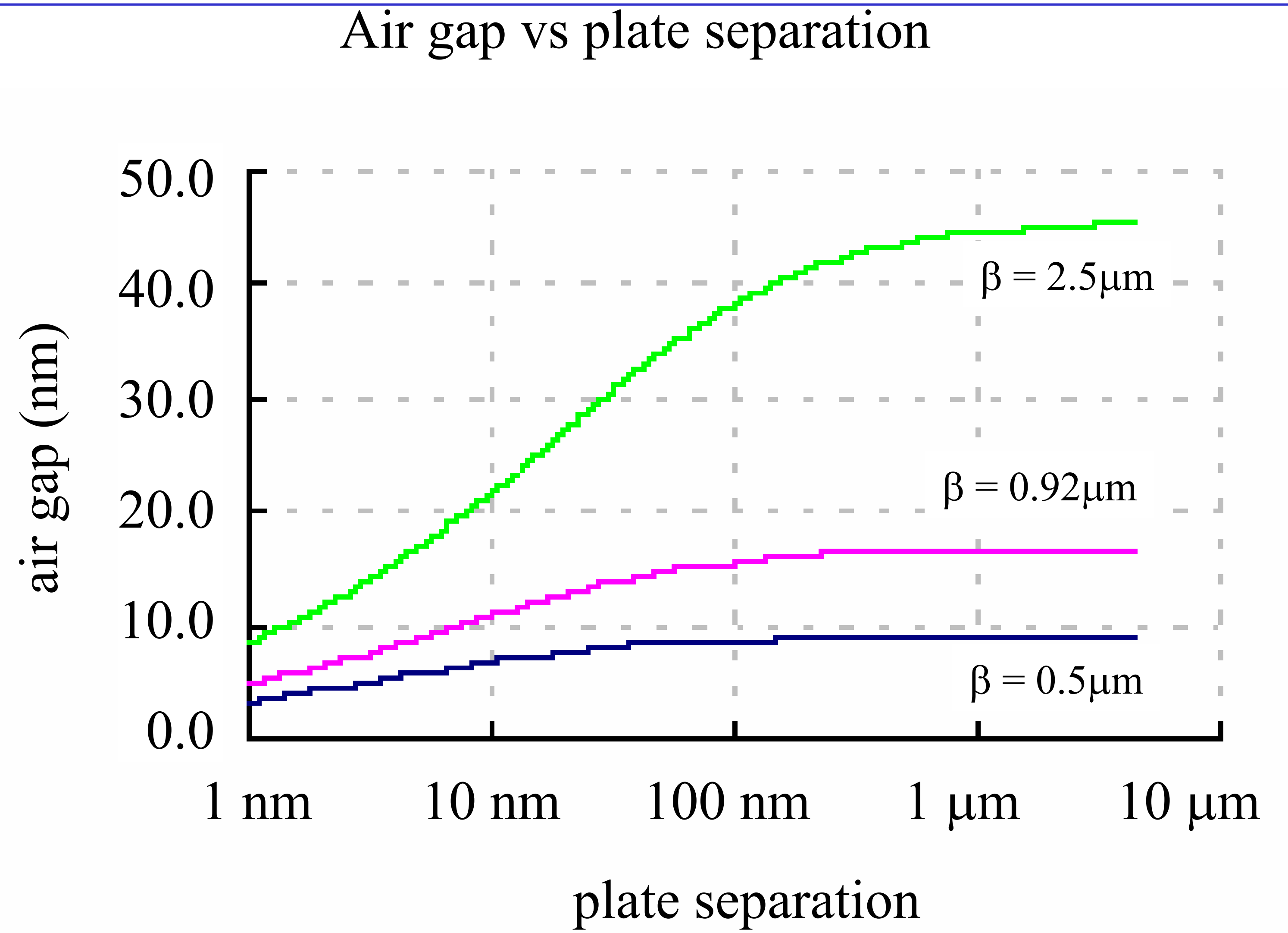
Interface:

$$y = 0 \quad u_w = \beta \frac{\partial u_w}{\partial y}$$

Bubble height equation:

$$\frac{\delta^2}{2} + h\delta - \frac{\mu_a}{\mu_w}\beta h = 0$$

1-D Air Gap Model



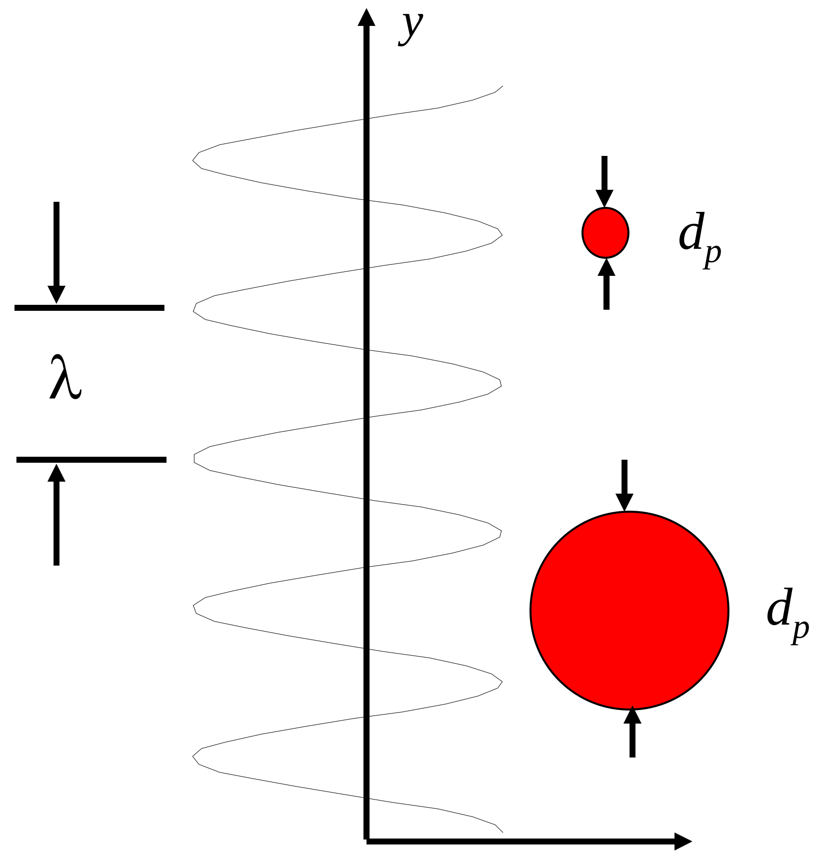
Particle Size Can Limit Spatial Resolution

Particles must be smaller enough:

1. Track the desired flow features !!!

Particles must be large enough

1. Dampen Brownian motion
2. Visible above background



$$u = u_0 \cos\left(\frac{2\pi y}{\lambda}\right)$$

Quantum NanoSpheres (new type of tracer for micro-PIV)

- Create particles for high spatial resolution
  - **Resolution cannot be smaller than particle size**
  - Brownian motion can create noise
  - d_p ~ 50 nm range
  - Bright fluorescent signal

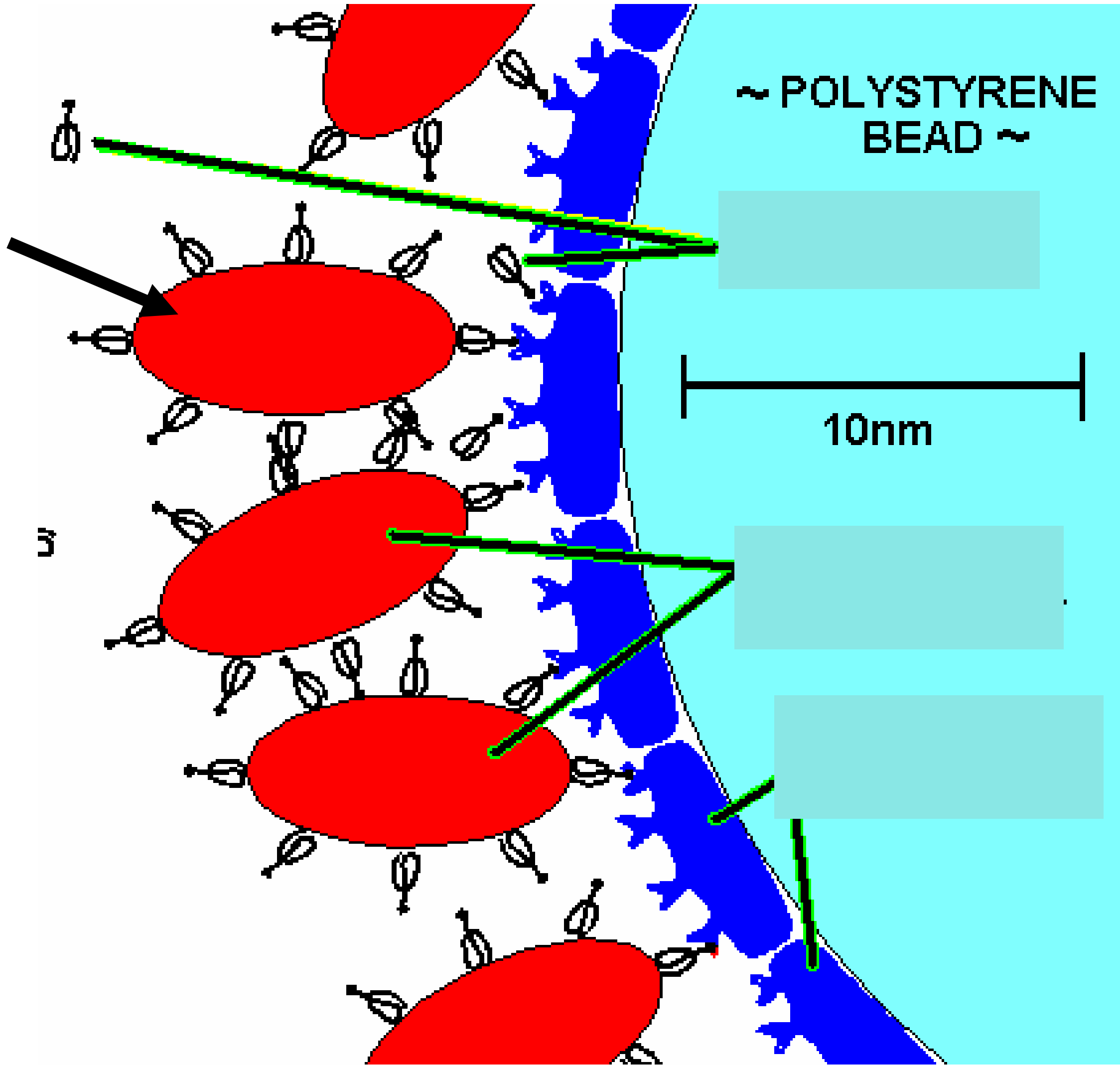
d_p= 390 nm

$$D = \frac{\kappa_B T}{3\pi\mu\, d_p}$$

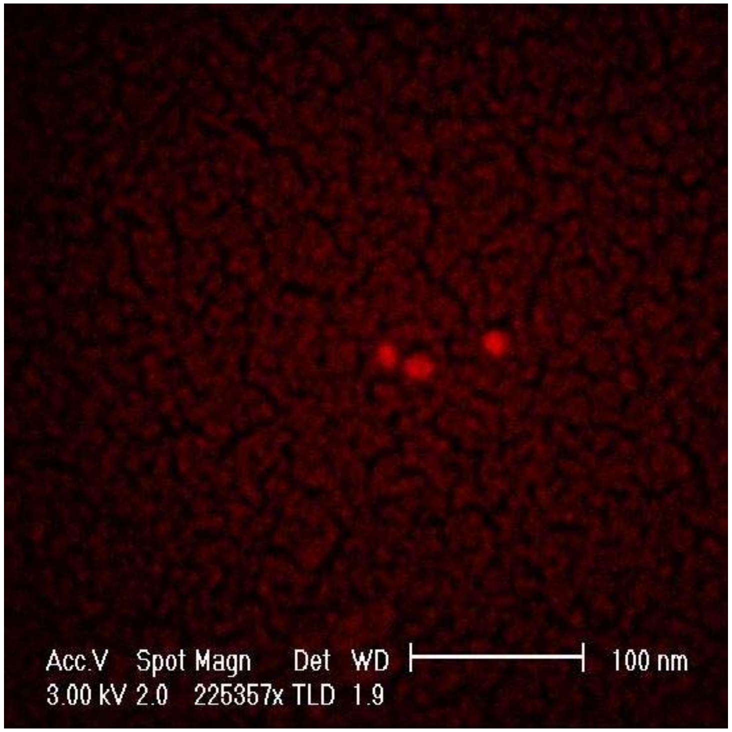
- Strategy
  - Use high fluorescent QD's
  - Attach to polystyrene beads – reduce diffusion

Quantum NanoSpheres

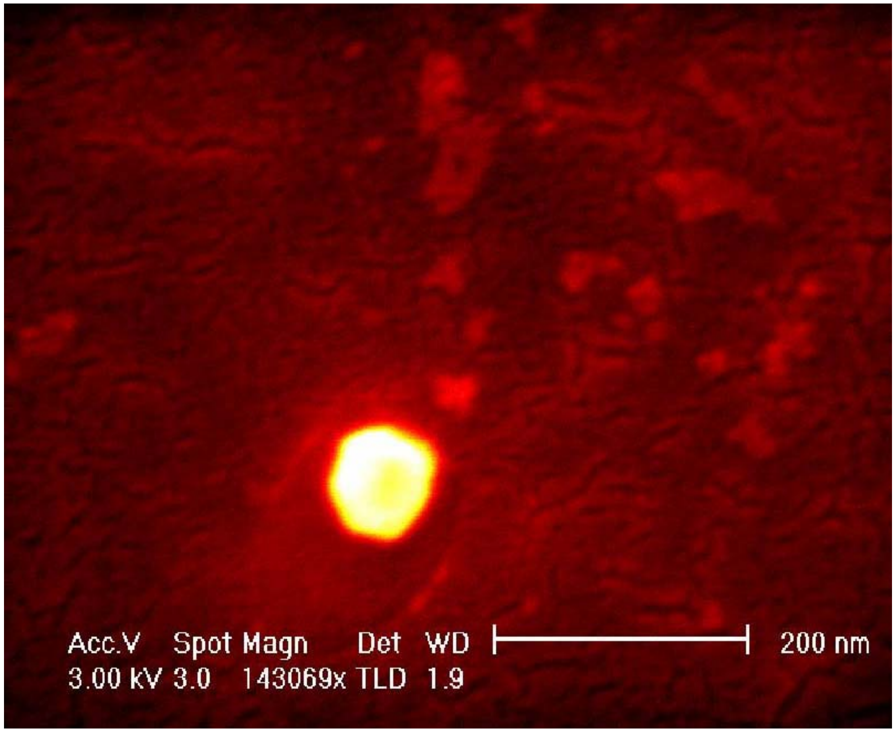
Quantum Dots



Quantum NanoSpheres ($d_p \sim 70$ nm)

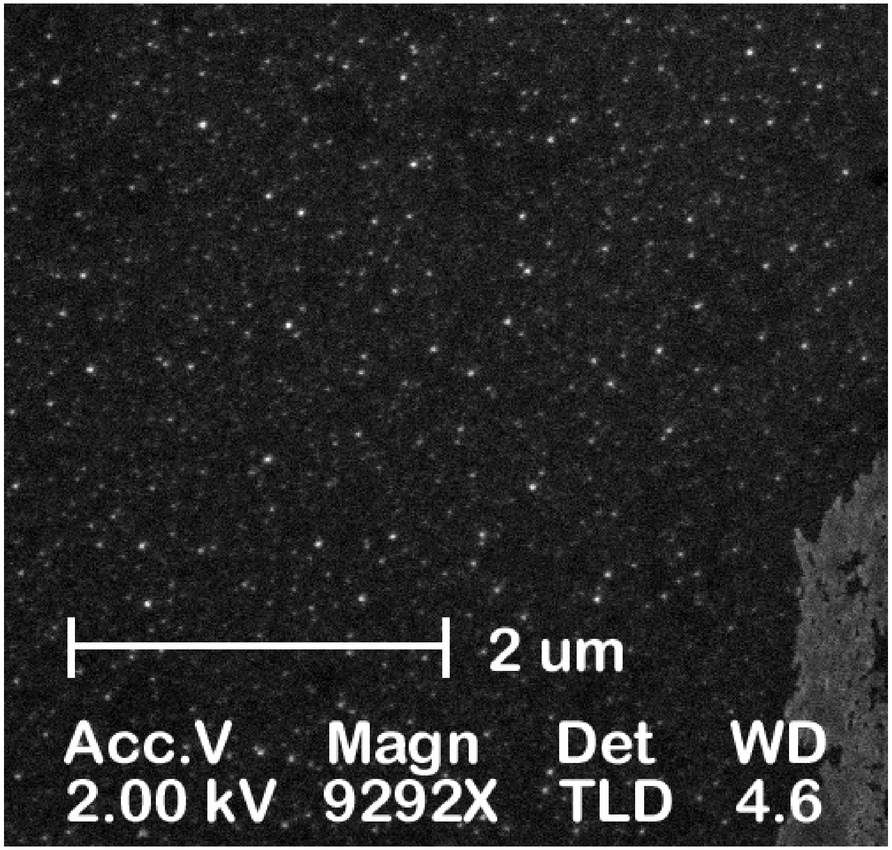


Individual Quantum Dots - SEM

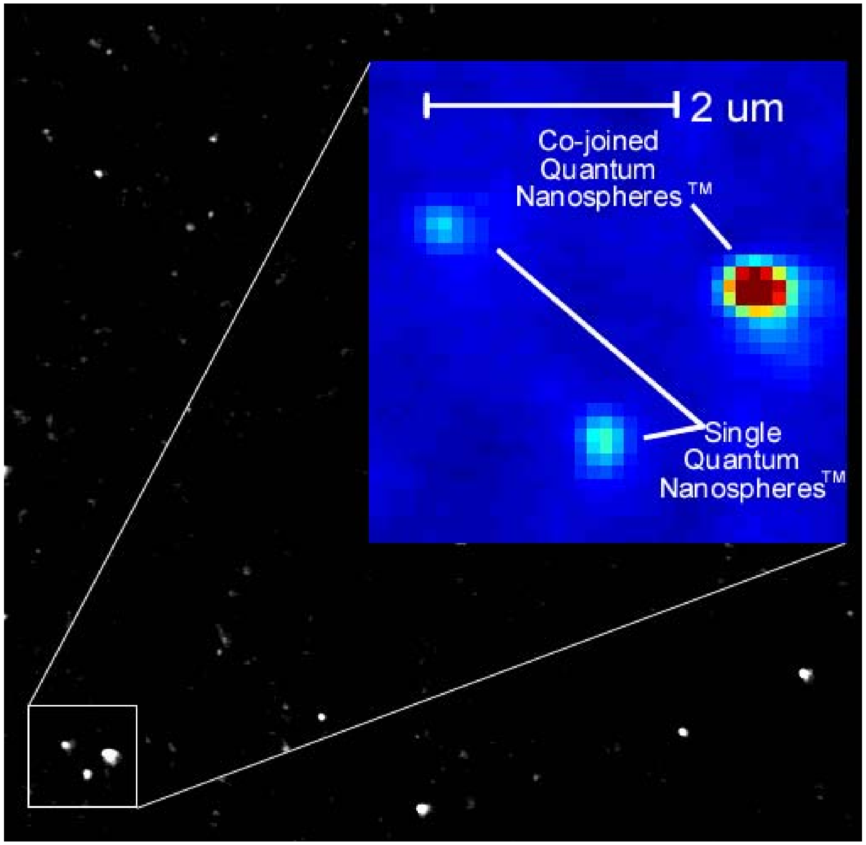


Quantum NanoSphere - SEM

Quantum NanoSpheres (d_p ~ 70 nm)

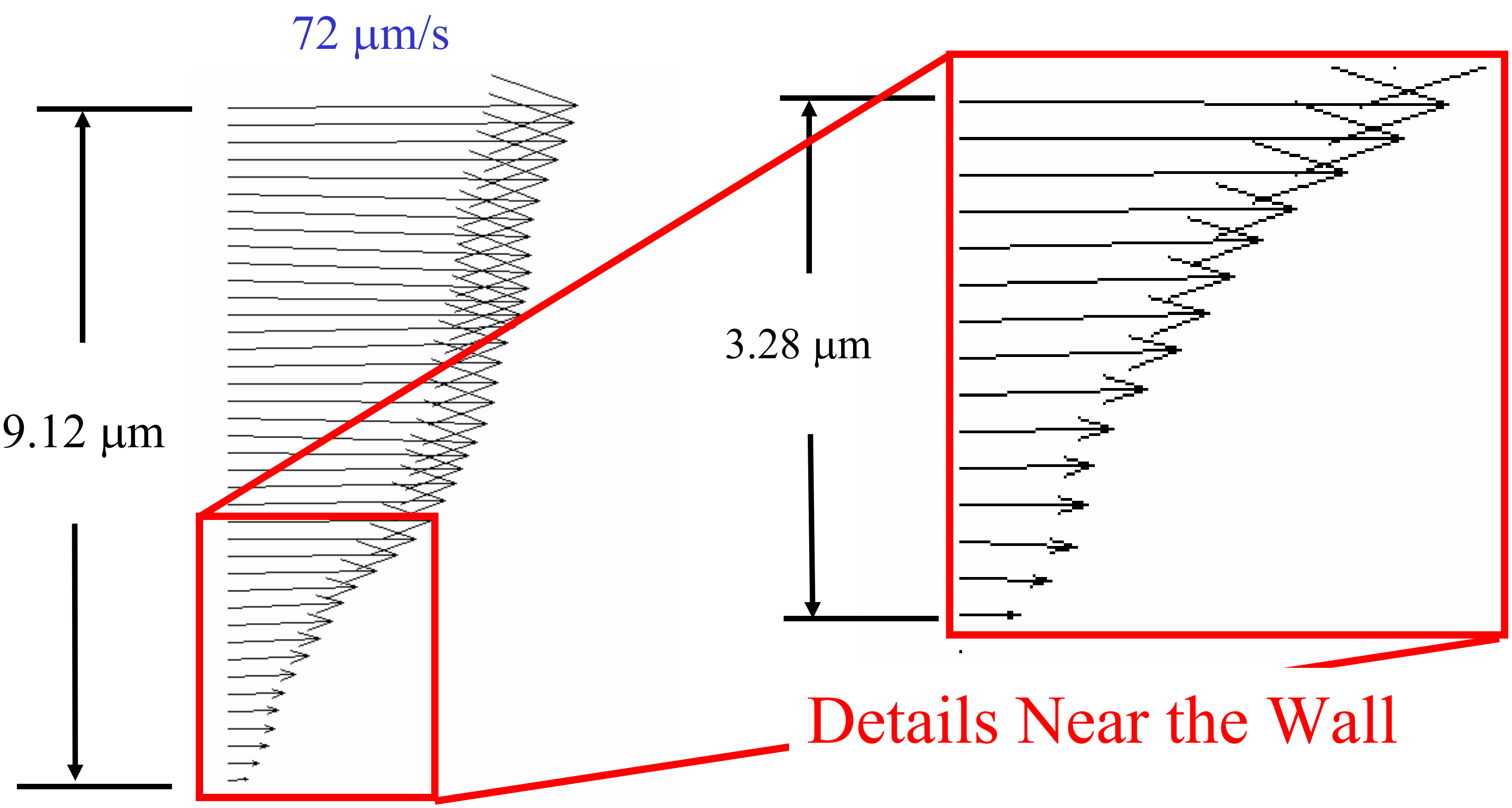


Immmobilized QN's - SEM



QN's in Solution – Optical

Velocity Profile – measured using QN's



Interrogation Spot **468 nm**

With 50% overlap, vector spacing **234 nm**

Conclusions (Correlation Theory)

- Geometric averaging of correlation functions
  - Dramatically improves signal to noise
  - Signal peak is limited by the lowest quality correlation
  - Requires moderating seeding density
- Arithmetic averaging of correlation functions
  - More robust than geometric averaging
  - Increases the effective particle density
  - $m = 1$ or 2 is most likely optimal (particle density)

Conclusions (Slip Flow)

- Measured fluid slip of OTS surfaces
  - $\beta = 0.4 - 0.92\ \mu m$

- Slip from nano-bubbles at surface?
  - 1-D air gap models predicts 18 nm bubbles/air gap
  - consistent with measured bubble height

- Slip length decreases with increasing absolute pressure

Conclusions (Quantum Nanospheres)

- **PIV cannot resolve flow structures smaller than the particle size !!!!!!**
- Developed a technique to create new type of particle
  - $d_p \sim 70$ nm
  - Bright fluorescence (no photo bleaching)
- Spatial resolution ~ 470 nm
  - **(vector spacing ~ 235 nm with 50% overlap)**
- **With single pixel interrogation**
  - **Spatial resolution ~ 65 nm (vector spacing ~ 32 nm)**

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