# Grain-scale measurements of particle-fluid interaction in marine and aeolian sediment transport

**Ken Kiger**
**Department of Mechanical Engineering**
**University of Maryland**

KITP Workshop: Fluid Mediated Particle Transport in Geophysical Flows
October 3, 2013

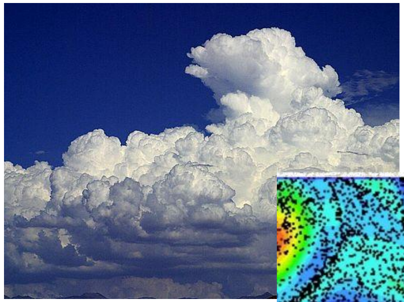
Work supported by the NSF and AFSOR

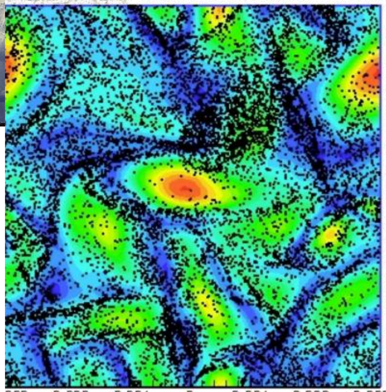
# Measurement of dispersed two-phase flows

- **Physics of collective fluid/particle coupling poorly understood**
  - What are the effective sediment turbulence characteristics?
  - Is purely stochastic description adequate?
  - How do anisotropic flow structures influence net coupling?

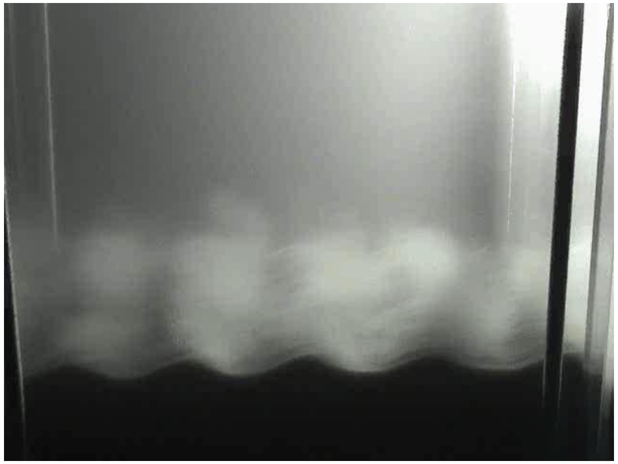
- **Primary variables of interest:**
  - Velocity of suspending fluid
  - Velocity of particulates (sediment)
  - Concentration of particulates
  - Size distribution

- **Goals**
  - Simultaneous measurement of fluid and dispersed phase motion
    - *Quantify fluid motion responsible for turbulent suspension of particles*
    - *Quantify nature of flow modification and particle/turbulence interaction*



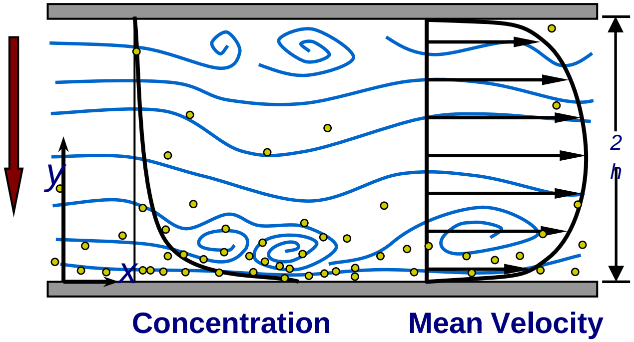


M. Garcia, http://www.cerfacs.fr/cfd/FIGURES/IMAGES/vort_stokes2-MG.jpg

# Overview

- **Two-fluid framework and closure**
- **Experimental techniques**
- **Prototypical flow: fully developed channel flow**
  - Solid-liquid suspension




- **Complex applied flow: rotorcraft downwash**
  - Solid-gas suspension

# Problem Framework: Two-Fluid Equations

- **Apply averaging operator to mass and momentum equations**
  - Drew (1983), Simonin (1991)
    - *Phase indicator function*

$$\chi_k(x_i,t)=\begin{cases}1 \text{ if } x_i \text{ inside phase } k\\ 0 \text{ if } x_i \text{ outside phase } k\end{cases}$$

$$\frac{\partial \chi_k}{\partial t}+u_{I,j}\frac{\partial \chi_k}{\partial x_j}=0$$

- *Averaging operator*

$$\alpha_k=\langle \chi_k \rangle, \text{ volume fraction} \qquad \alpha_k G_{k,ij}=\langle \chi_k g_{ij} \rangle \qquad g'_{ij}=g_{ij}-G_{2,ij}$$

- Assume no inter-phase mass flux, incompressible carrier phase
  - *Mass*

$$\frac{\partial}{\partial t}(\alpha_k\rho_k)+\frac{\partial}{\partial x_j}(\alpha_k\rho_k U_{k,j})=0$$

$$\tau_{k,ij}=\text{averaged viscous stress tensor in phase } k$$

$$I_{k,i}=\text{Mean interphase momentum transport (less mean pressure contribution)}$$

- *Momentum*

$$\alpha_k\rho_k\left(\frac{\partial U_{k,i}}{\partial t}+U_{k,j}\frac{\partial U_{k,i}}{\partial x_j}\right)=-\alpha_k\frac{\partial P_1}{\partial x_i}+\alpha_k\rho_k g_i+\frac{\partial}{\partial x_j}(\alpha_k\tau_{k,ij})-\frac{\partial}{\partial x_j}\left(\alpha_k\rho_k\langle u'_i u'_j\rangle_k\right)+I_{k,i}$$

# Two-Fluid Equations (cont)

- **Interphase momentum transport**
  - Dilute flow: no particle-particle interactions
  - For large particle/fluid density ratios, quasi-steady viscous drag is by far the dominant term
    - *For small density ratios, additional force terms can be relevant*
      - Added mass, Pressure term, Bassett history term etc.
  - For sediment, $\rho_2/\rho_1 \sim 2.5 > 1$ ($k$ =1 for fluid, $k$ =2 for dispersed phase)
    - *Drag still first order effect, but other terms will likely also contribute*

$$I_{2,i} = -I_{1,i} = -\alpha_k \left\langle \rho_1 \frac{3}{4} \frac{C_D}{d} \left|\mathbf{v}_r\right| \mathbf{v}_{r,i} \right\rangle_2$$

$$\mathbf{v}_{r,i} = u_{2,i} - u_{1,i} \qquad C_D = \frac{24\left[1 + 0.15\,\mathrm{Re}_p^{0.687}\right]}{\mathrm{Re}_p} \qquad \mathrm{Re}_p = \frac{\rho_1 \left|\mathbf{v}_r\right| d}{\mu_1}$$

# Closure requirements

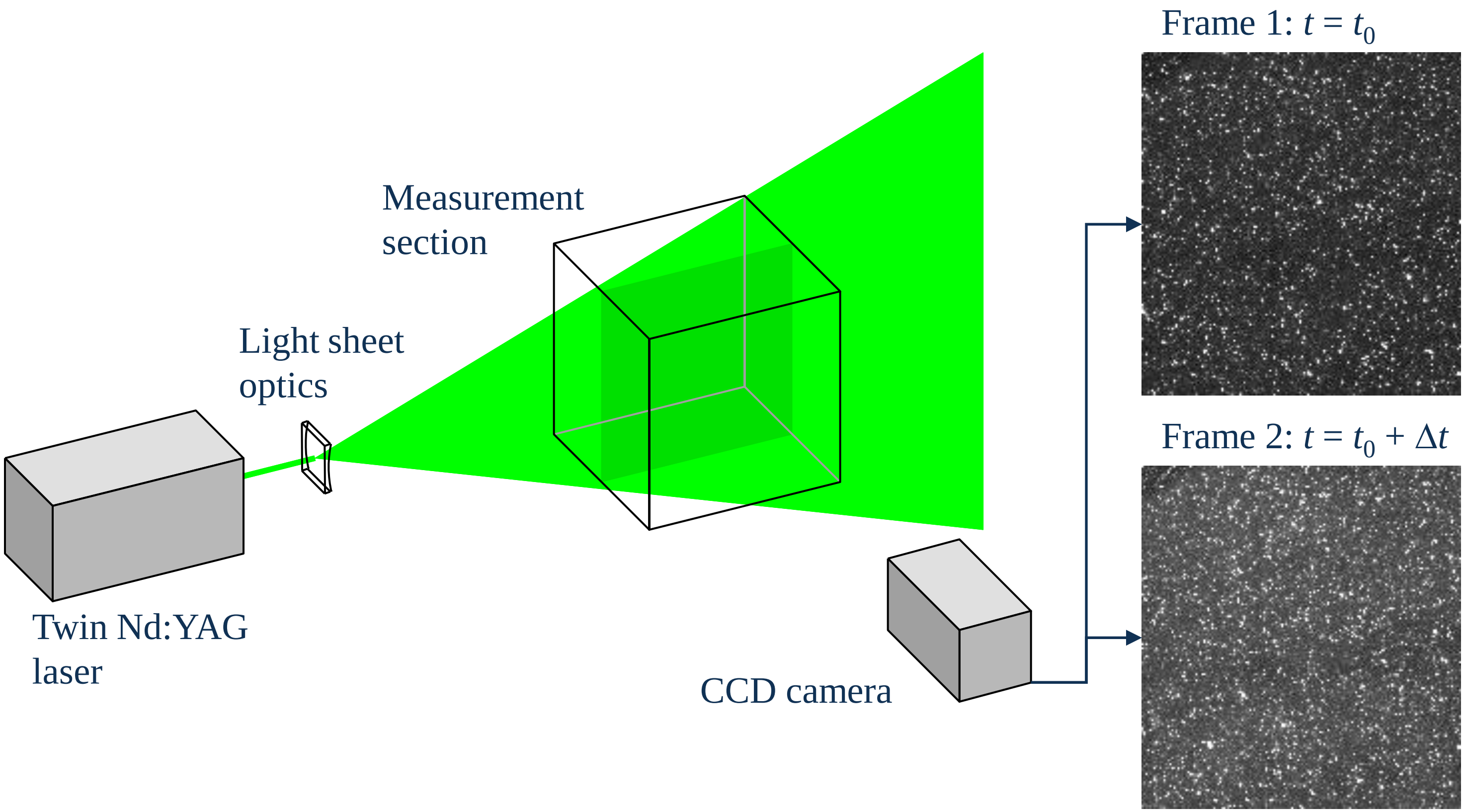
- **Closure is needed for:**
    - *Particle fluctuations*
    - *Particle/fluid cross-correlations*
    - *Fluid fluctuations*
  - Simplest method is to use a gradient transport (mixing length) model
    - *Shown to be inconsistent for many applications*
  - Alternative: Provide separate evolution equation for higher order terms
      - Particle kinetic stress equation
      - Particle/fluid covariance equation
      - Fluid kinetic stress equation
    - *Will require third-moment correlations models to complete the closure*
- **Experiments**
  - Simultaneous measurements of both fluid and particles are needed
    - *Provides check for model developments*
    - *Can be performed under conditions not readily accessible to DNS/LES*
      - Particles larger than the turbulent fluid scales, finite $Re_p$

# What is PIV? (single phase flow)



Particle Image Velocimetry (PIV):

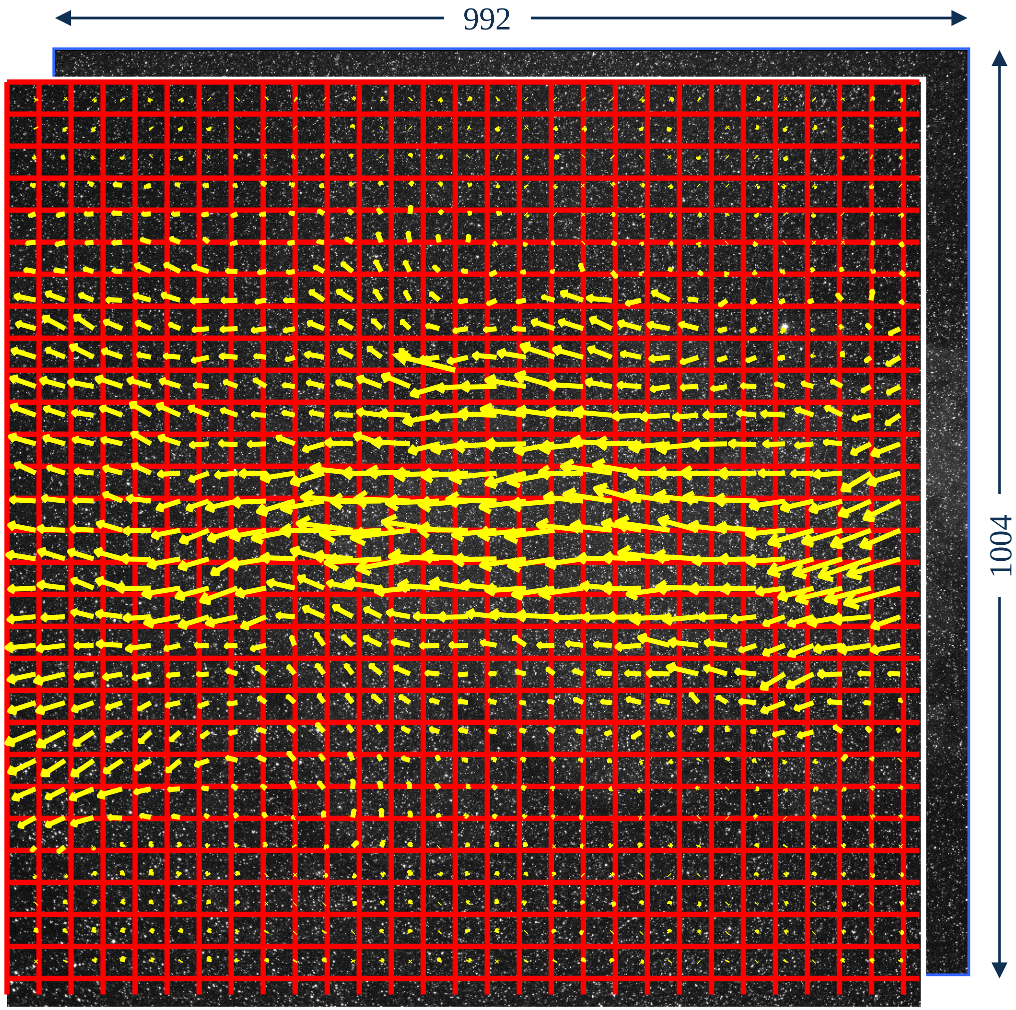
Quantitative imaging method to infer local fluid motion from displacement of tracer particles

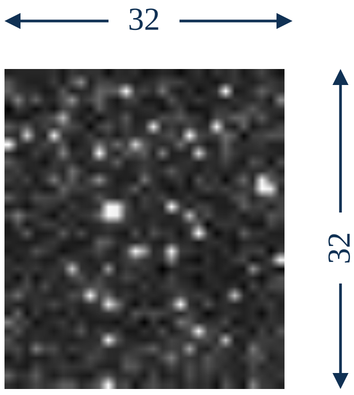



Slide from C. Poelma of TU Delft

# Result of PIV interrogation

Particle Image Velocimetry (PIV)



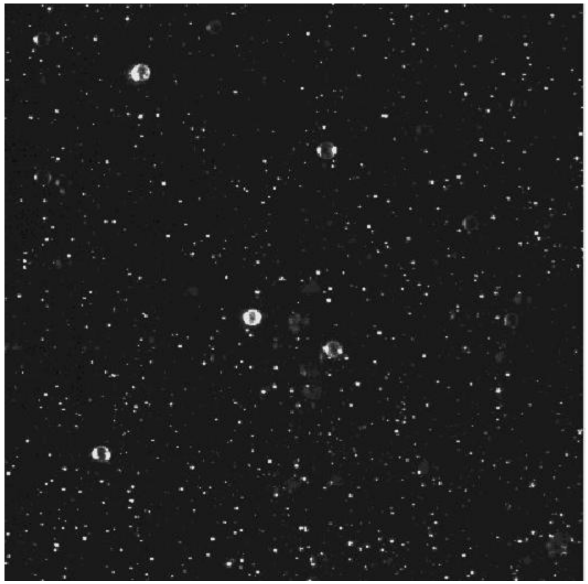



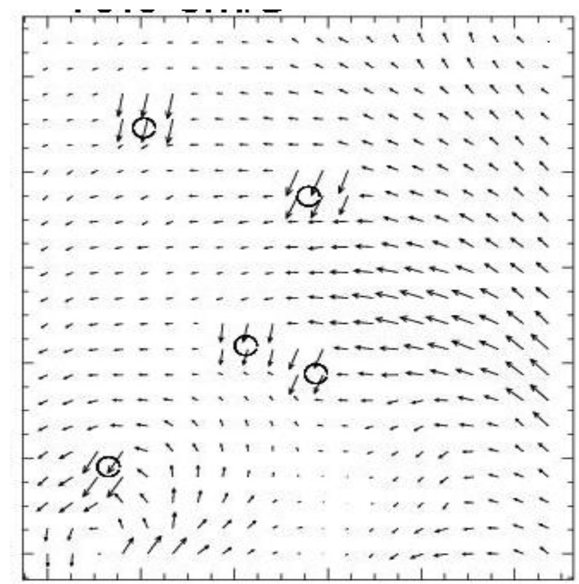

- divide image pair in *interrogation regions*
- small region: ~ uniform motion
- compute displacement
- *repeat !!!*

Slide from J. Westerweel of TU Delft

# Difficulty with Two-Phase PIV

- **Coupled but distinct motion in different phases**

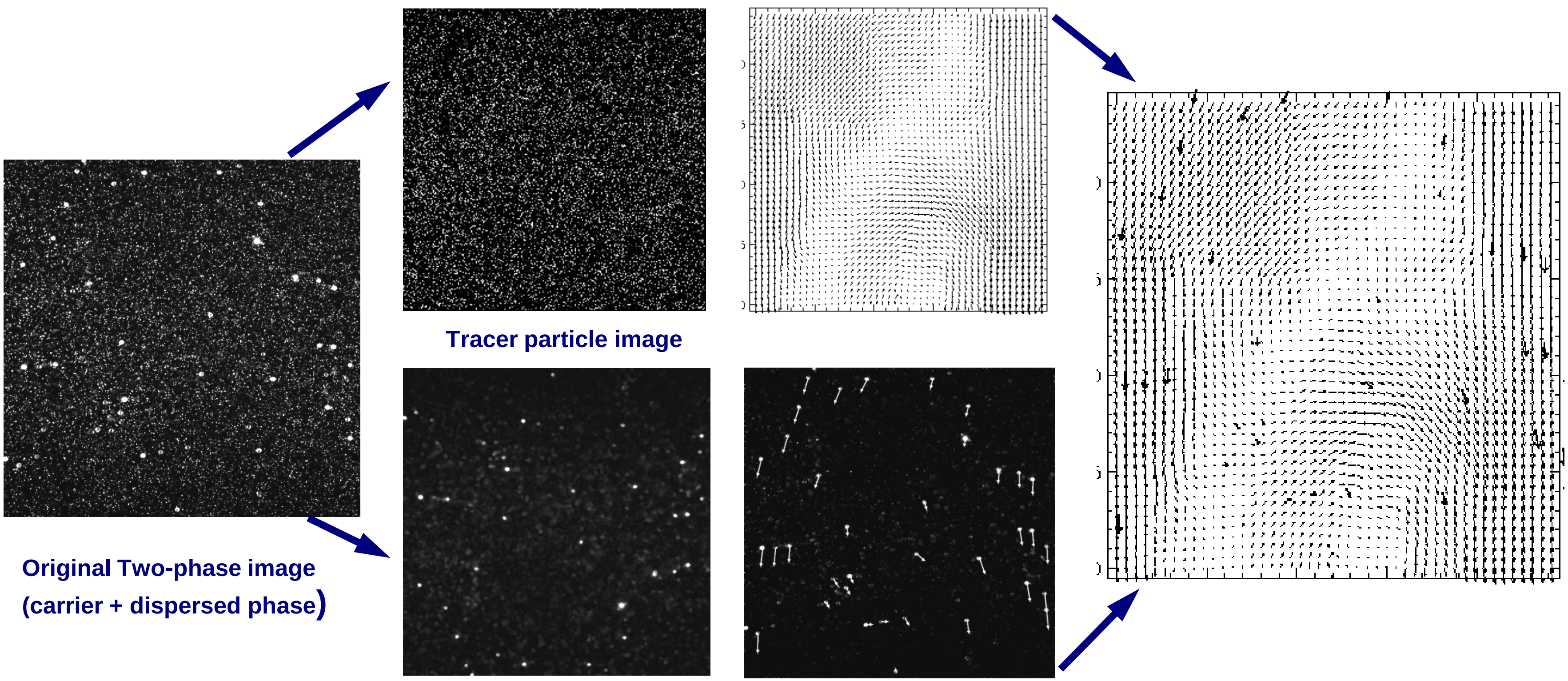




- **Need to separate the images of the phases**
  - How to discriminate the sediment from the fluid? *Image characteristics*
- **Strengths**
  - Snapshot of flow structure (fluid velocity, sediment velocity, concentration)
- **Limitations**
  - Flow must be optically dilute (must see through it, volume fraction < 1%)
  - Usually prefer large size separation between tracer seed and dispersed phase
  - Difficult to reliably discriminate size
  - Dynamic range: 100 to 1 is typical, can be better, but challenging

# Single camera Two-Phase PIV Implementation

- **Simultaneous Velocity Measurement of both phases**
  - *Use median filtering technique to separate images*
  - *Particle tracking of dispersed phase*
    - combine with size/intensity filter (Khalitov & Longmire, 2002)
  - *Cross-correlation PIV of carrier fluid*



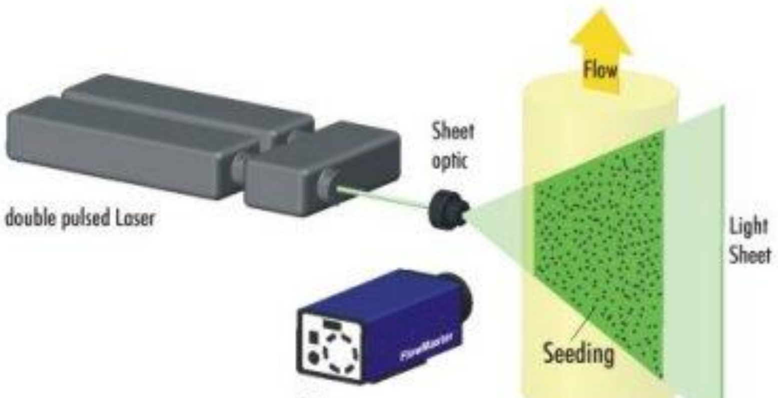
**Original Two-phase image (carrier + dispersed phase)**

**Tracer particle image**

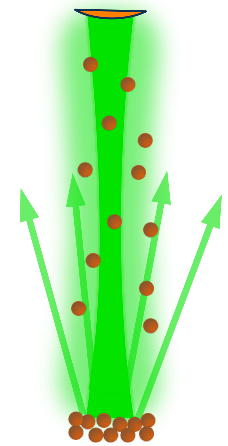
**Dispersed Image**

# Dispersed phase measurement by sheet illumination

- **Sheet illumination considerations**
  - What is the effective sampling volume for a particle in a light sheet? Can't we just count particles?

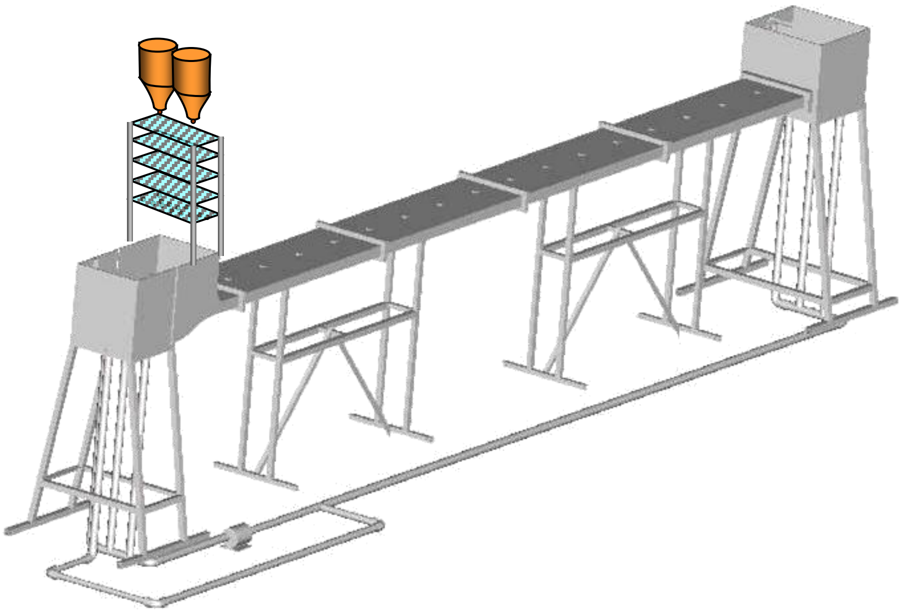


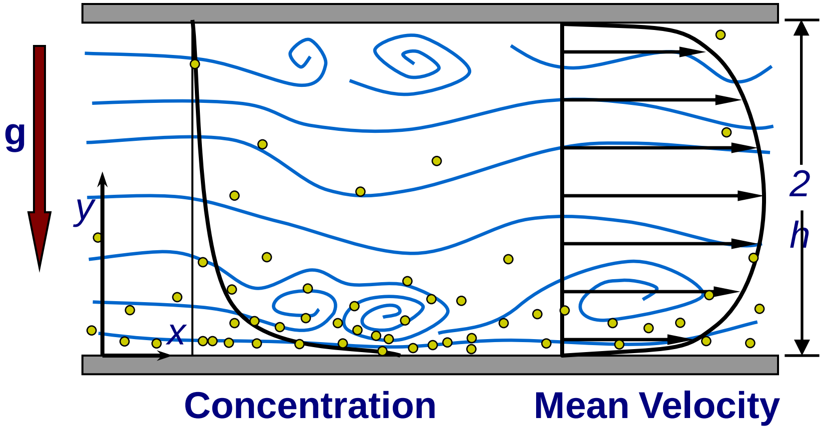

Courtesy of LaVision, Inc.



- **Works fine for small image regions far from boundaries, but in general one needs to account for:**
  - Focusing & attenuation of sheet
  - Scattered illumination
  - Boundary reflections

# Experimental Facility






- **Planar Horizontal Water Channel**
  - 4 × 36 × 488 cm, recirculating flow
  - Pressure gradient measurements
    - *fully-developed by* x = *250 cm*
  - Particles introduce to settling chamber outlet across span

# Experimental Conditions

- **Both single-phase and two-phase experiments conducted**
- **Carrier Fluid Conditions**
  - Water, $Q$ = 7.6 l/s
  - $U_c$ = 59 cm/s, $u_\tau$ = 2.8 cm/s, $Re_\tau$ = 570
  - Flowrate kept the same for two-phase experiments
  - Tracer particles: 10 μm silver-coated, hollow glass spheres, $SG$ = 1.4

- **Dispersed Phase Conditions**
  - Glass beads: (specific gravity, $SG$ = 2.5)
  - Standard sieve size range: $180 < D < 212$ μm
  - Settling velocity, $v_s$ = 2.2 to 2.6 cm/s
  - Corrected Particle Response Time, $\tau_p$ = 4.5 ms
  - $St^+ = \tau_p/\tau^+ \sim 4$
  - Bulk Mass Loading: $dM/dt$ = 4 gm/s, $M_p/M_f \sim 5 \times 10^{-4}$
  - Bulk Volume Fraction, $\alpha = 2 \times 10^{-4}$

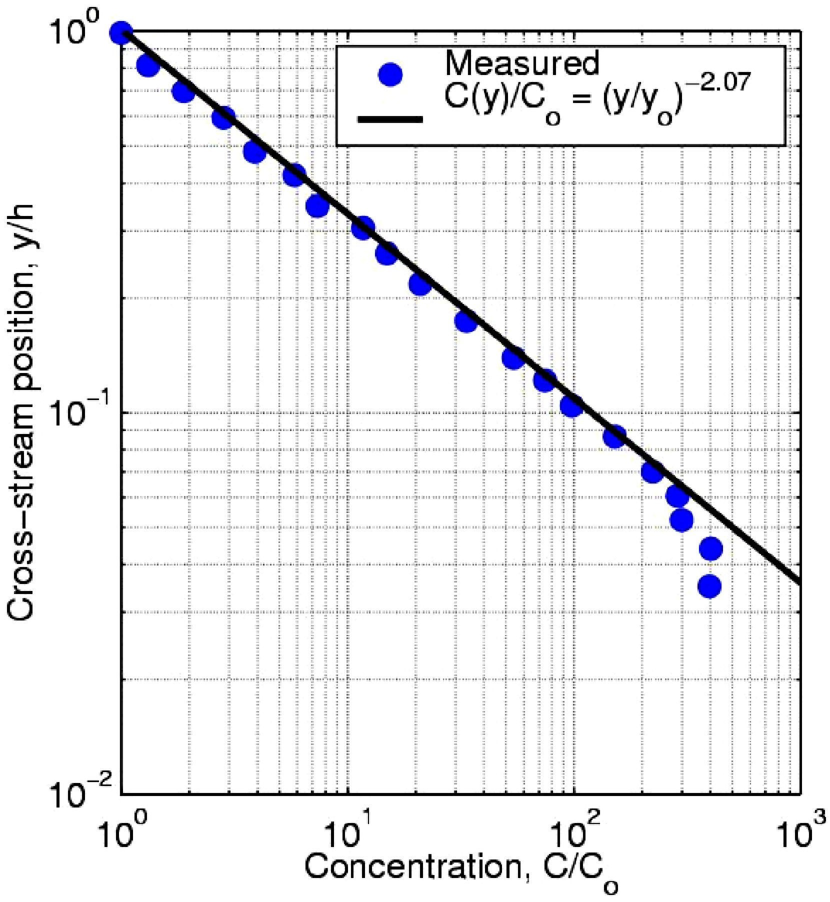
# Two-Phase Flow: Mean Concentration Profile

- Concentration follows a power law
  - *Equivalent to Rouse distribution for infinite depth*

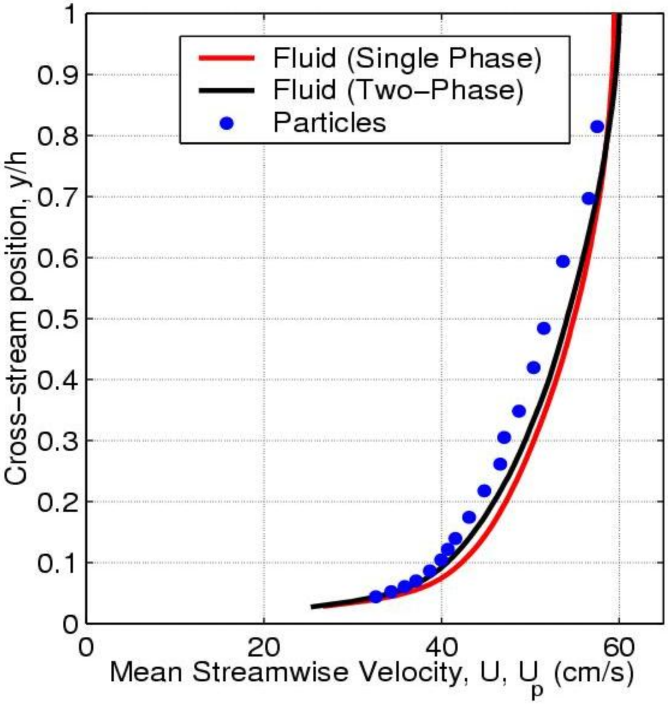
$$\frac{C(y)}{C(y_o)} = \left( \frac{h-y}{y} \frac{y_o}{h-y_o} \right)^a \cong \left( \frac{y_o}{y} \right)^a$$

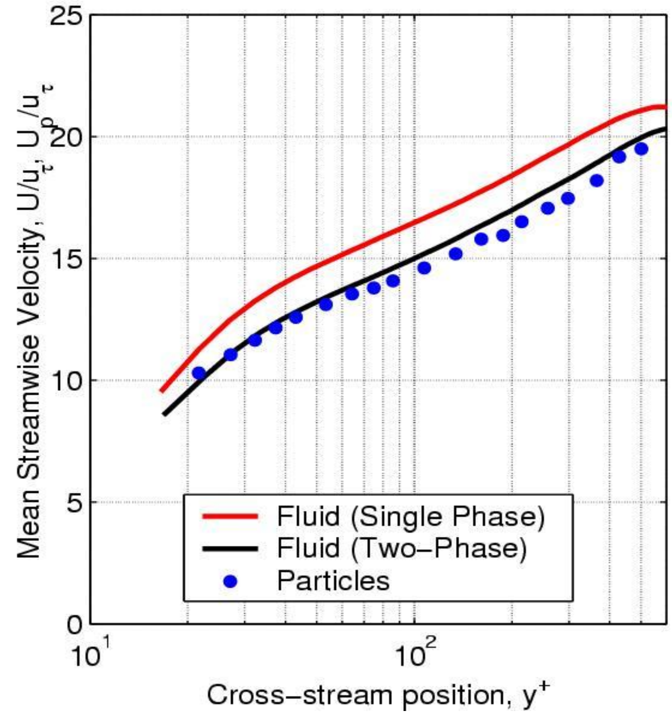
$$a = \frac{v_s}{\kappa u_\tau} = \frac{2.44 cm/s}{(0.40)(2.95 cm/s)} = 2.07$$

  - *Based on mixing length theory, but still gives good agreement*



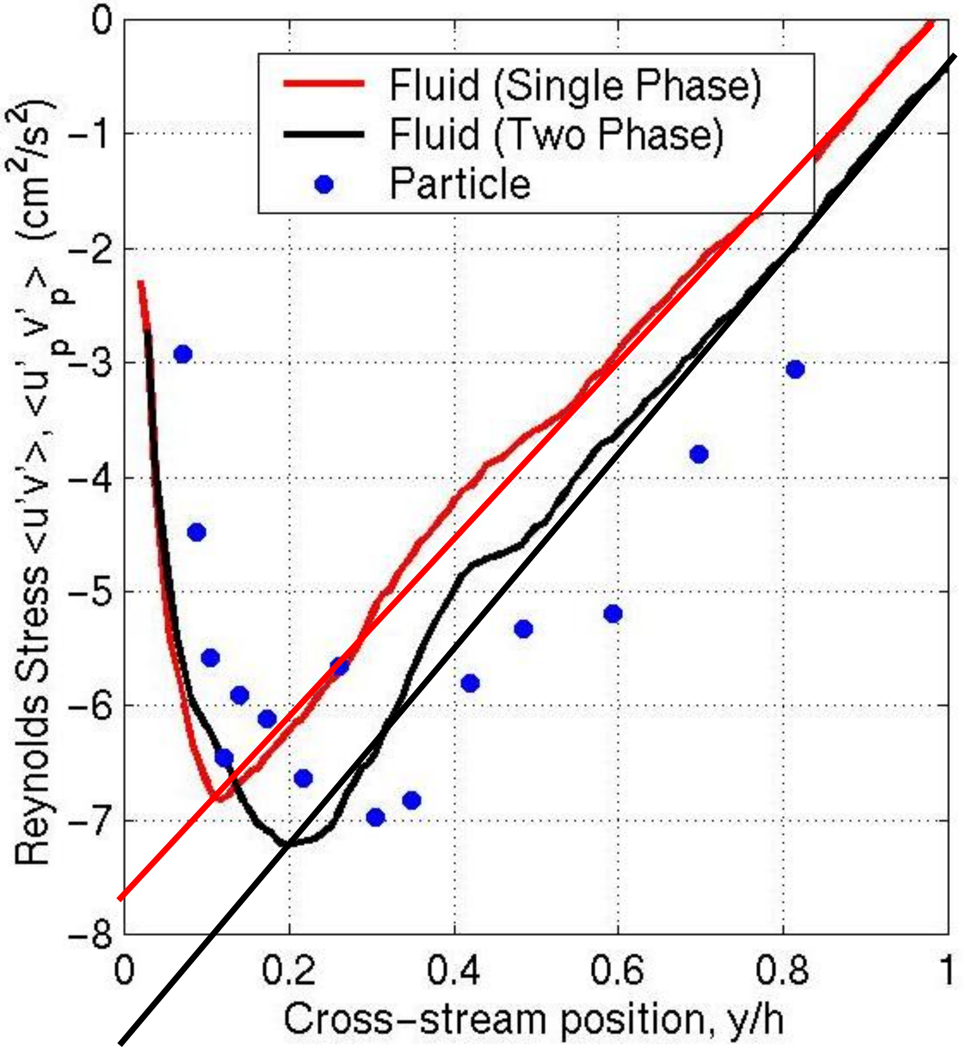
# Mean Velocity




- Particles alter mean fluid profile
  - *Skin friction increased by 7%; qualitatively similar to effect of fixed roughness*
- Particles lag fluid over most of flow
  - *Observed in gas/solid flow (much large Stokes number… likely not same reasons)*
  - *Particles on average reside in slower moving fluid regions?*
    - Reported by Kaftori et al, 1995 for $\rho_p/\rho_f = 1.05$ (current is heavier ~ 2.5)
    - Organization of particles to low speed side of structures – a la Wang & Maxey (1993)?
- Particles begin to lead fluid near inner region – transport lag across strong gradient

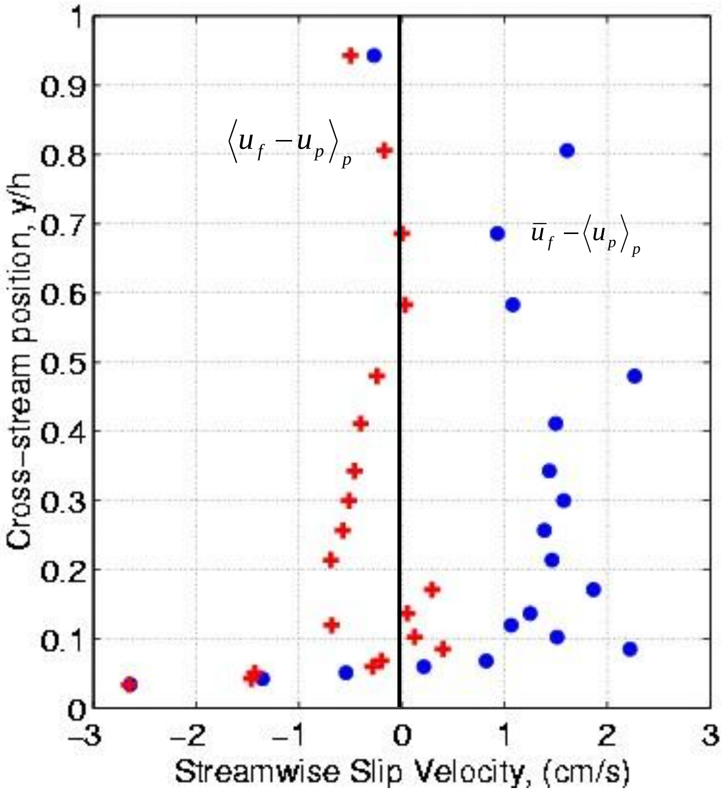
# Two-Phase Flow: Reynolds Stress

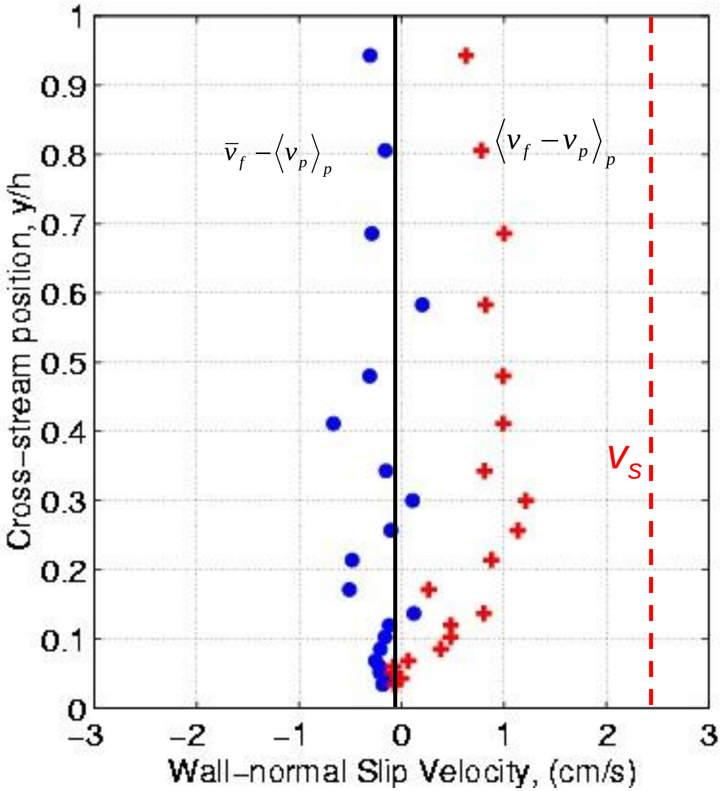



- Fluid Reynolds stress maximum displaced further from wall by particle distortion

- Particle Reynolds stress less than fluid close to the wall, greater than the fluid away from the wall.

# Particle Slip Velocity, $\bar{u}_f - \langle u_p \rangle_p$ $\langle u_f - u_p \rangle_p$



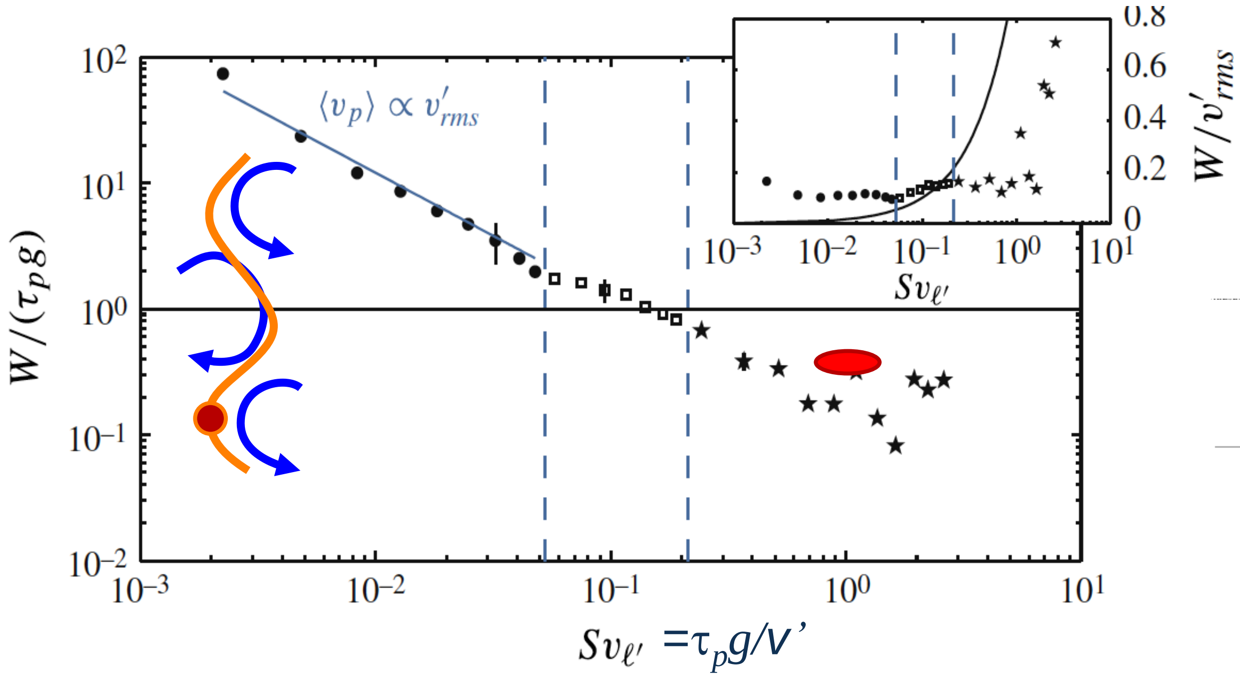



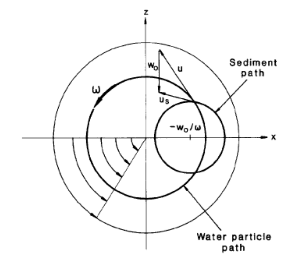

- Streamwise direction
  - *Particle-conditioned slip (✚) is generally small in outer flow*
  - *Mean slip (•) and particle conditioned slip are similar in near wall region*
- Wall-normal direction
  - *Mean slip (•) is negligible*
  - *Particle-conditioned slip (✚) approximately 40% of steady-state settling velocity (2.4 cm/s)*

# Effective settling velocity

- **Direct measure of settling velocity shows hinder effects**
  - $W/w_0 \sim 0.4$

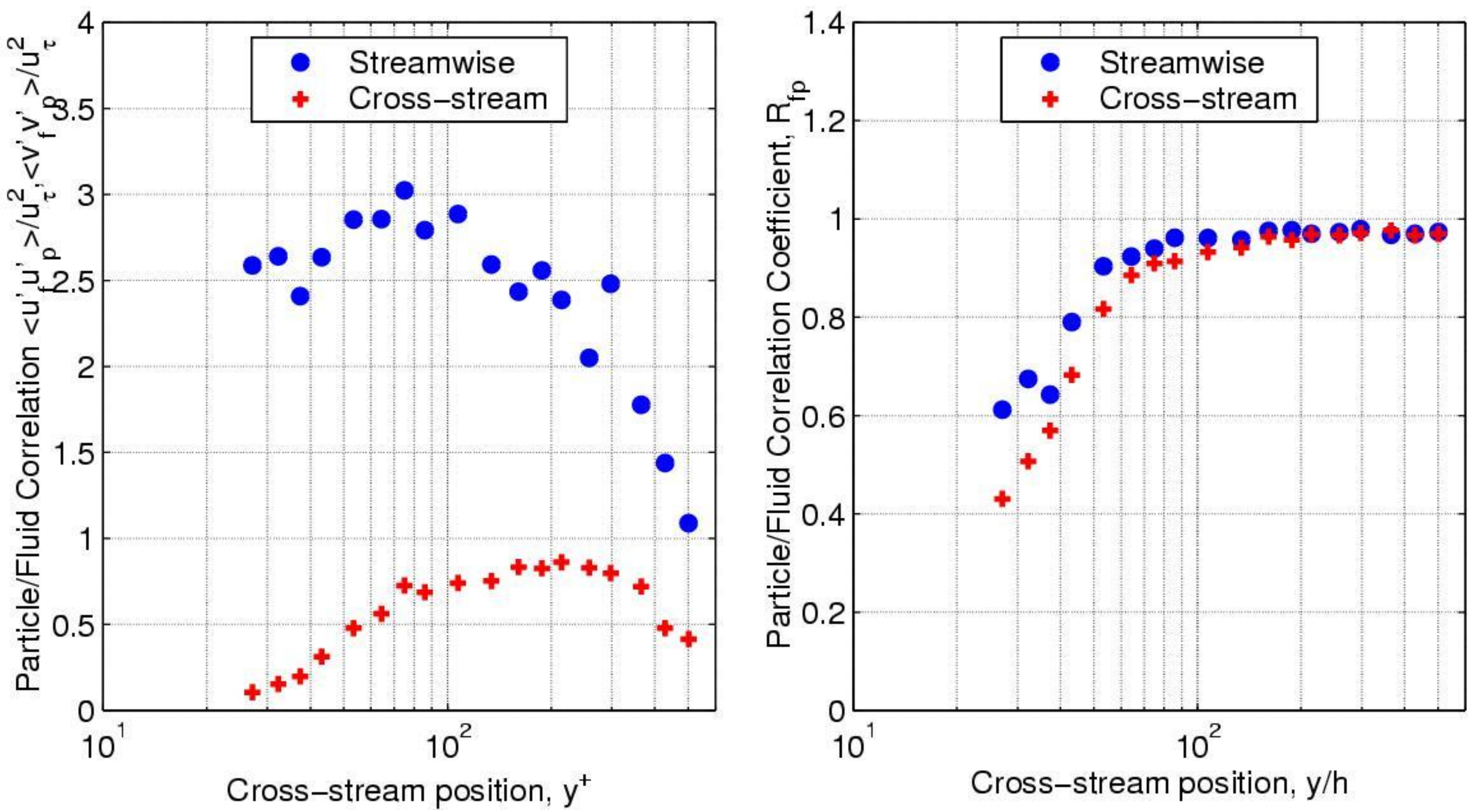
G. H. Good, S. Gerashchenko and Z. Warhaft



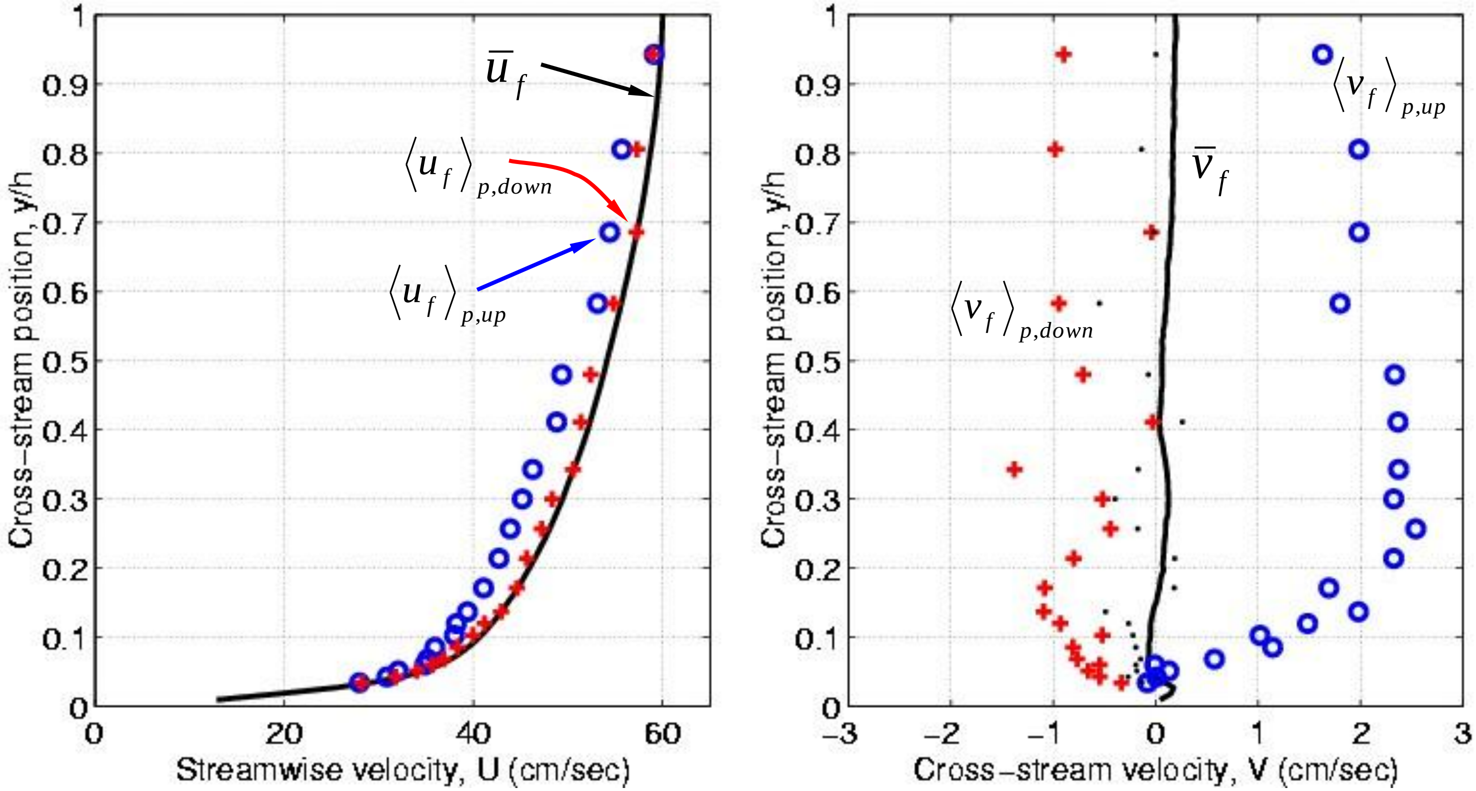

- Noted in sediment community by Murray(1970), Nielsen(1993), Kawanisa & Shiozaki (2008)
  - *Enhancement: "fast-tracking" – Maxey & Corrsin (1986)*
  - *Hindered: non-linear drag – Ho, vortex trapping, loitering*

# Two-Phase Flow: Particle/Fluid Correlation




- Particle/Fluid motion highly correlated in outer wall region
  - *$R_{fp}$ is high, approximately 1 for $y^+ > 60$*
  - *Particles adjust to local flow conditions rapidly*

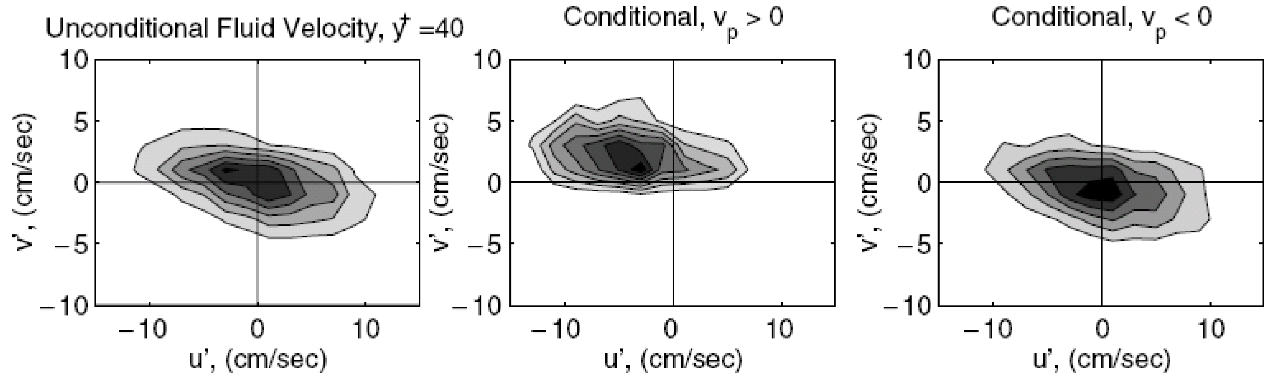
# Particle Conditioned Fluid Velocity Profiles



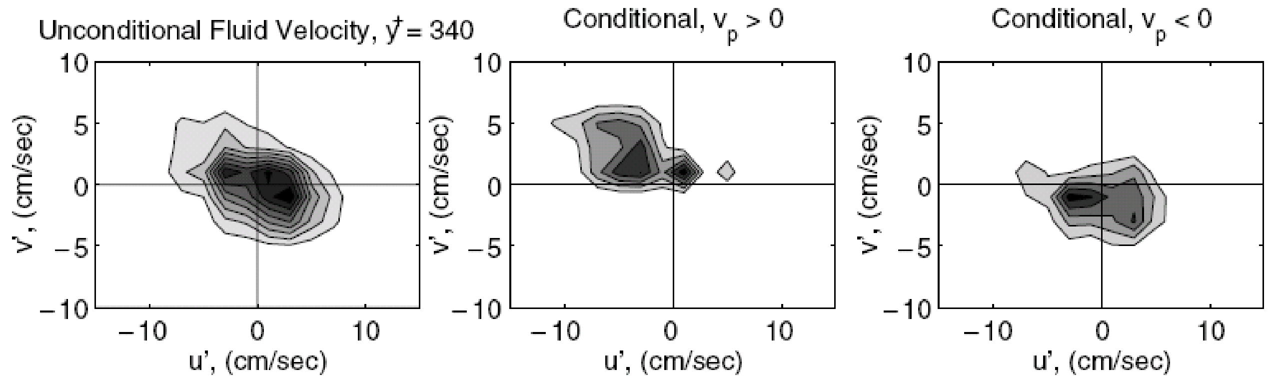

- Average fluid motion at particle locations:
  - *Upward moving particles are in fluid regions moving slower than mean fluid*
  - *Downward moving particles are in fluid regions which on average are the same as the fluid*
  - *Indicates preferential structure interaction of particle suspension*

# Suspension and Sedimentation: Quadrant Analysis

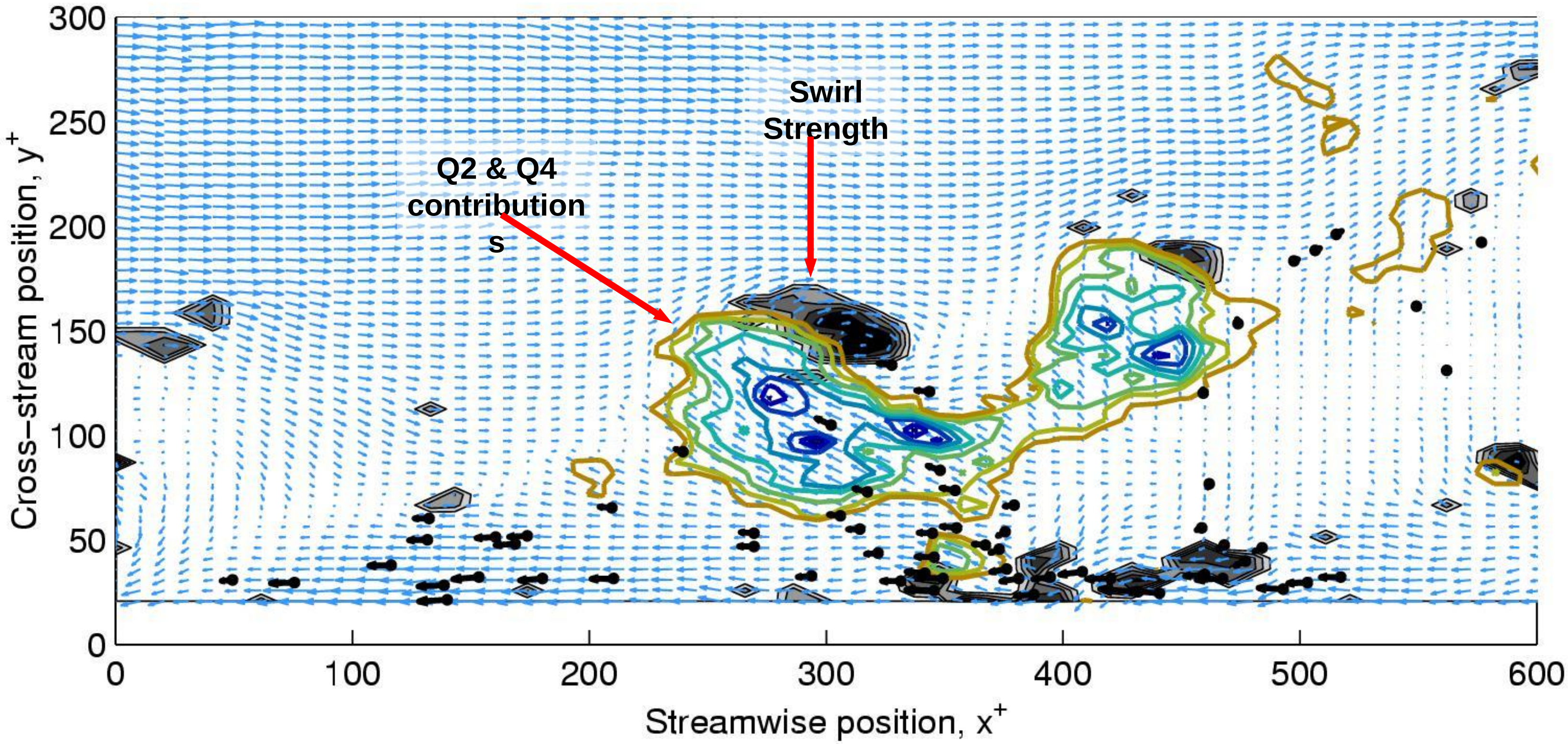
- Conditionally sampled fluid velocity fluctuations
  - *Upward moving particles primarily in quadrant II*
  - *Downward moving particles are almost equally split in quadrant III and IV*



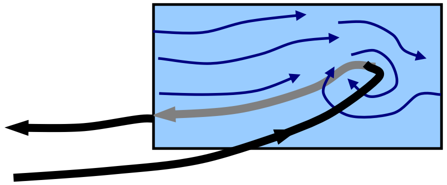

- Persistent behavior
  - *Similar quadrant behavior in far outer region*
  - *Distribution tends towards axisymmetric case in outer region*



# Event structures: Quadrant II hairpin




- **Similar structures found**
  - Appropriate spacing
  - Not as frequent
    - *Re effects? ($Re_\theta$ = 1183)*
    - *Smaller field of view?*
- **Evidence suggests packets contribute to particle suspension**



# Particle Kinetic Stress

- **Turbulence budget for particle stresses**
  - *(Wang, Squires, Simonin,1998)*

0

$$\left[\frac{\partial}{\partial t} + U_{2,m}\frac{\partial}{\partial x_m}\right]\langle u'_{2,i}u'_{2,j}\rangle_2 = P_{2,ij} + D_{2,ij} + \Pi^{d}_{2,ij} + \Pi^{p}_{2,ij}$$

- Production by mean shear

$$P_{2,ij} = -\langle u'_{2,i}u'_{2,m}\rangle\frac{\partial U_{2,j}}{\partial x_m} - \langle u'_{2,j}u'_{2,m}\rangle\frac{\partial U_{2,i}}{\partial x_m}$$

- Transport by fluctuations

$$D_{2,ij} = -\frac{1}{\alpha_2}\frac{\partial}{\partial x_m}\left[\alpha_2\langle u'_{2,i}u'_{2,j}u'_{2,m}\rangle_2\right]$$

- Momentum coupling to fluid
  - (destruction)

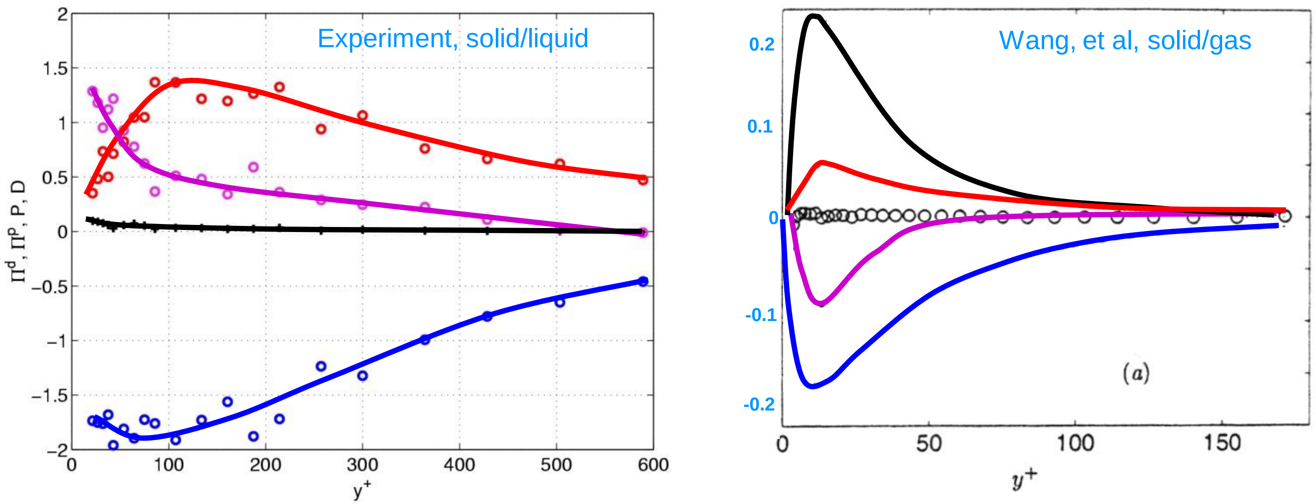
$$\Pi^{d}_{2,ij} = -\left\langle \frac{\rho_1}{\rho_2}\frac{3}{2}\frac{C_d}{d}|\mathbf{v}_r|u'_{2,i}u'_{2,j}\right\rangle_2$$

- Momentum coupling to fluid
  - (production)

$$\Pi^{p}_{2,ij} = \left\langle \frac{\rho_1}{\rho_2}\frac{3}{4}\frac{C_d}{d}|\mathbf{v}_r|\left[u'_{1,i}u'_{2,j} + u'_{1,j}u'_{2,i}\right]\right\rangle_2$$

# Streamwise Particle Kinetic Stress Budget

- **Streamwise Particle/Fluid Coupling: $\Pi^{d}_{2,11}$, $\Pi^{p}_{2,11}$**
  - Compare results to Wang, Squires, & Simonin (1998)
    - *Gas/solid flow ($\rho_2/\rho_1$=2118), $Re_\tau$ = 180, No gravity, $St^+$~700*
    - *Computations, all 4 terms are computed; Experiments, all but $D_{2,ij}$ computed*




(—) $D_{2,ij}$; (—) $\Pi^{d}_{2,ij}$; (—) $\Pi^{p}_{2,ij}$; (—) $P_{2,ij}$; (○) sum

  - Interphase terms are qualitatively similar

    *Similar general shapes, $\Pi^{d}_{11} > \Pi^{p}_{11}$*
  - Quantitative difference
    - *Magnitudes different: $\Pi^{d}_{11} / \Pi^{p}_{11}$~1.3 vs 3, overall magnitudes are 10 to 20 times greater*
      - Interphase terms are expected to increase with incresed fluid density and decreased $St^+$
    - *Dominant interphase transfer ($\Pi$) greatly diminishes importance of mean shear (P)*
    - *Turbulent transport (D) has opposite sign because of small shear production (P)*

# Model Approximations

- **Model 1 (Simonin, Deutsch & Boivin, 1995)**
  - In limit of small $Re_p << 1$, $\tau^F_{12}=\tau_p$, which is constant

$$\tau^F_{12} = \frac{\rho_2}{\rho_1}\frac{4}{3}\frac{d}{\langle C_D\rangle}\frac{1}{\langle|\mathbf{v}_r|\rangle}$$

$$\Pi^d_{2,ij} = -\left\langle \frac{\rho_1}{\rho_2}\frac{3}{2}\frac{C_d}{d}|\mathbf{v}_r|u''_{2,i}u''_{2,j}\right\rangle_2$$

  - For finite $Re_p$, try to separating $\tau^F_{12}$

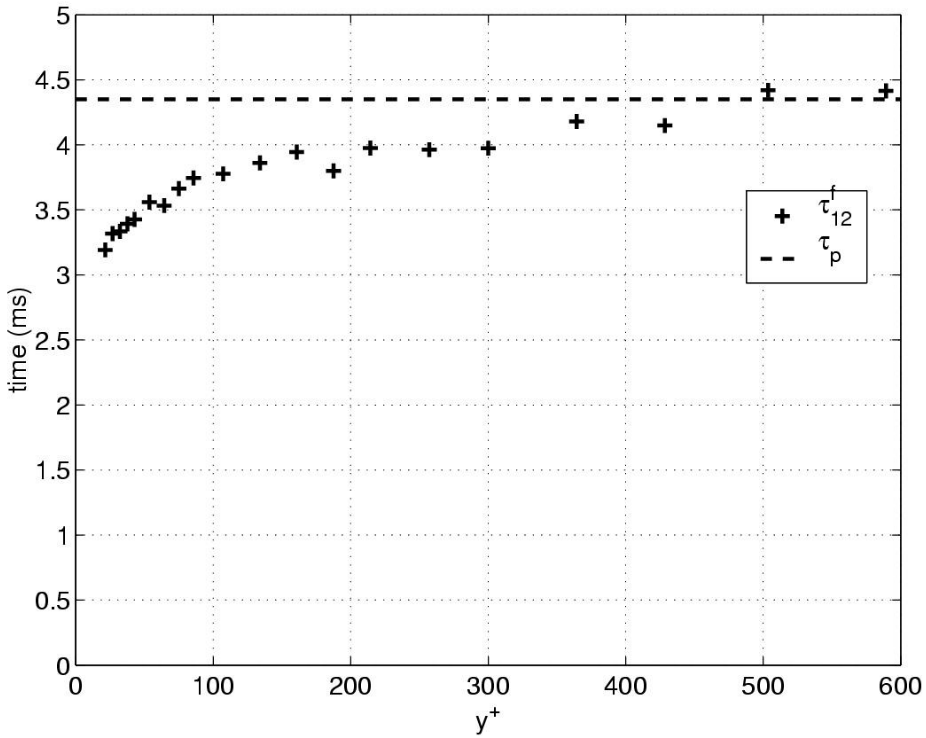
$$\Pi^p_{2,ij} \approx \frac{1}{\tau^F_{12}}\left[\langle u'_{1,i}u'_{2,j}\rangle + \langle u'_{2,i}u'_{1,j}\rangle\right]$$

$$\Pi^d_{2,ij} \approx -\frac{2}{\tau^F_{12}}\langle u''_{2,i}u''_{2,j}\rangle$$

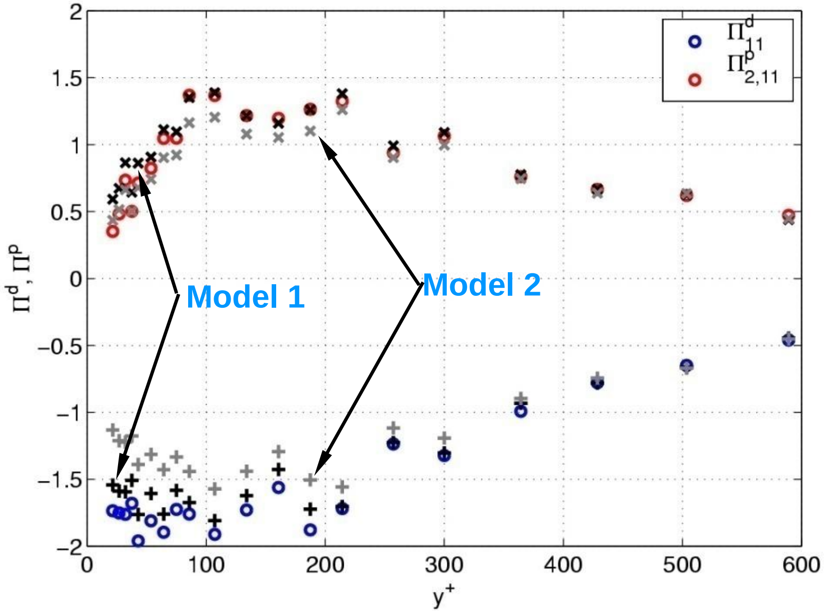
- **Model 2**
  - Use $\tau_p$ instead of local $\tau^F_{12}$

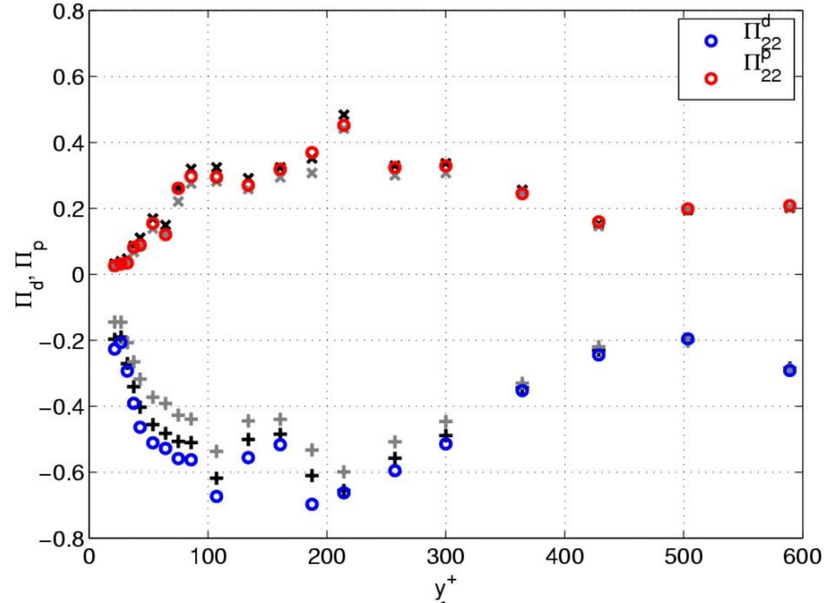
$$\Pi^p_{2,ij} \approx \frac{1}{\tau_p}\left[\langle u'_{1,i}u'_{2,j}\rangle + \langle u'_{2,i}u'_{1,j}\rangle\right]$$

$$\Pi^d_{2,ij} \approx -\frac{2}{\tau_p}\langle u''_{2,i}u''_{2,j}\rangle$$



# Particle Stress Model Comparison




- **Model 1**
  - *$\Pi^p_{ij}$ agrees within 5% for $y^+$>50, overestimates ~30% near wall*
  - *$\Pi^d_{11}$ agrees within 10% or better, consistently underestimates near the wall*
- **Model 2**
  - *OK in outer region where $Re_p$ is small*
  - *Up to 30% underestimate relative to Model 1 near wall*

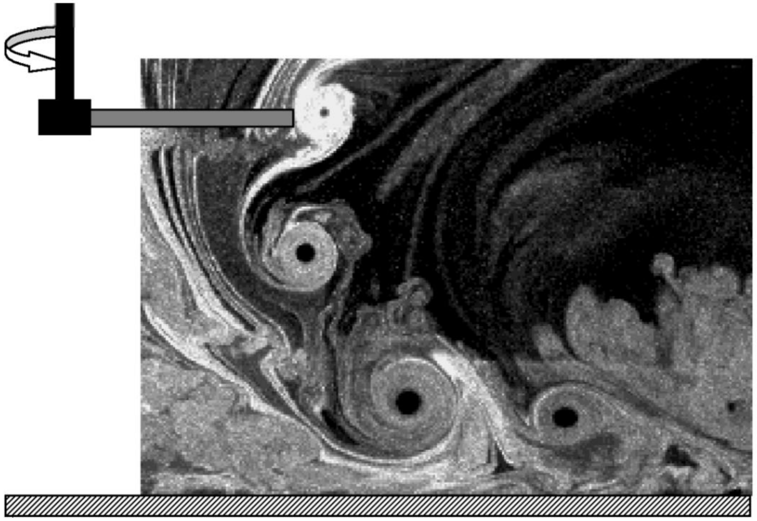
# Part II: Dust suspension by impinging jets

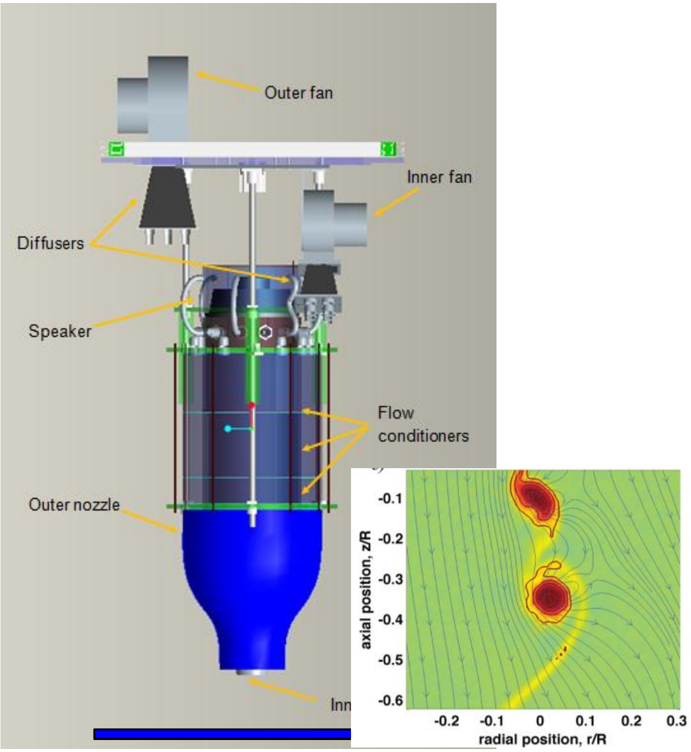
# Interesting detail…

Photograph by Zoltan Szoboszlay of NASA Ames Flight Research Center

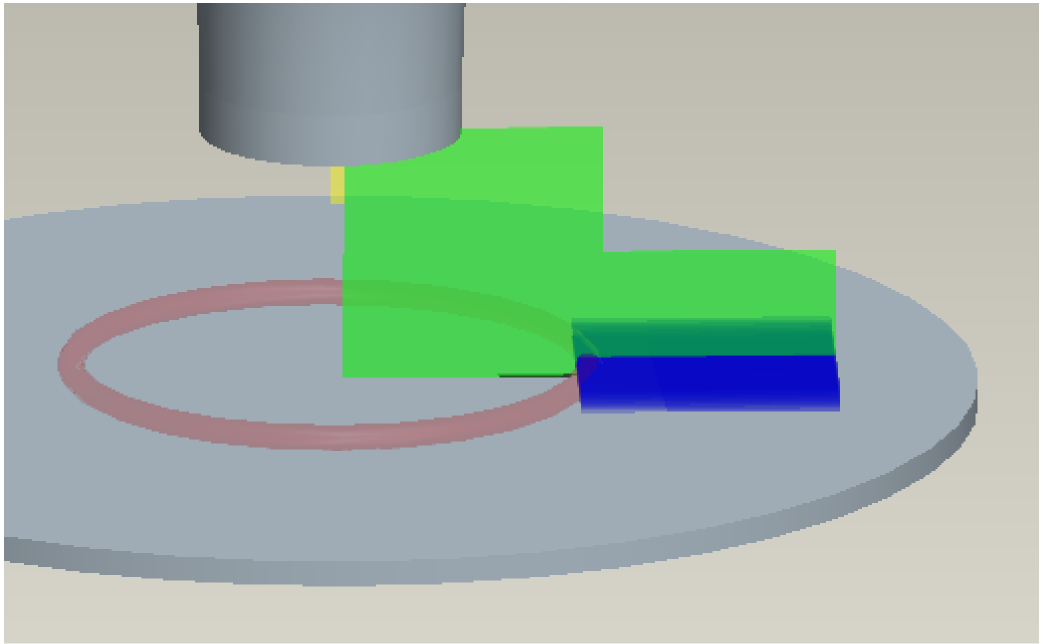
# Experimental Set up

- **Mimic rotorcraft in ground effect with simple prototype flow**
  - Forced impinging jet
    - *Maintain intense vortex structure embedded within stagnation flow*
    - *Does not retain helical nature of rotorcraft wake*





# Current Imaging Planes

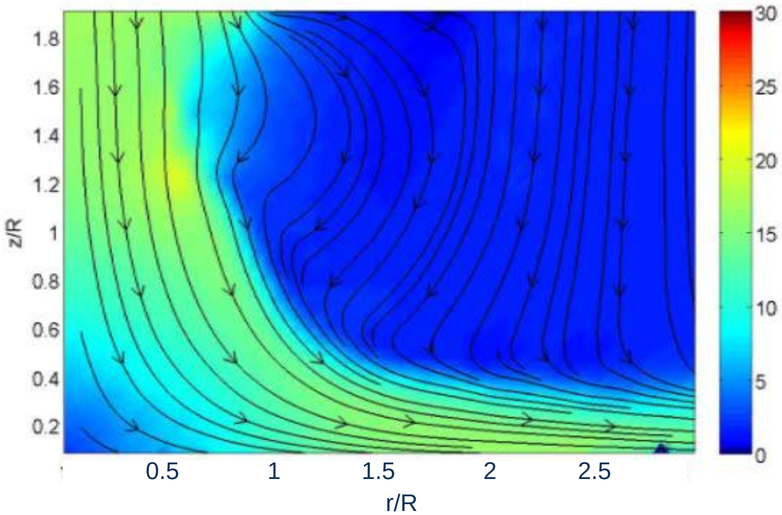


- **Three vertical planes (PIV)**
  - Vortex ring trajectory
  - Vortex ring development
  - Vortex ring breakdown
- **Stacked horizontal planes (Stereo PIV)**
  - Measure breakdown at different heights on the vortex ring
- **Data Collection**
  - 4 MP sensor
  - 37 phase angles
  - 50 image pairs per phase angle
    - *(high order statistics not fully converged)*

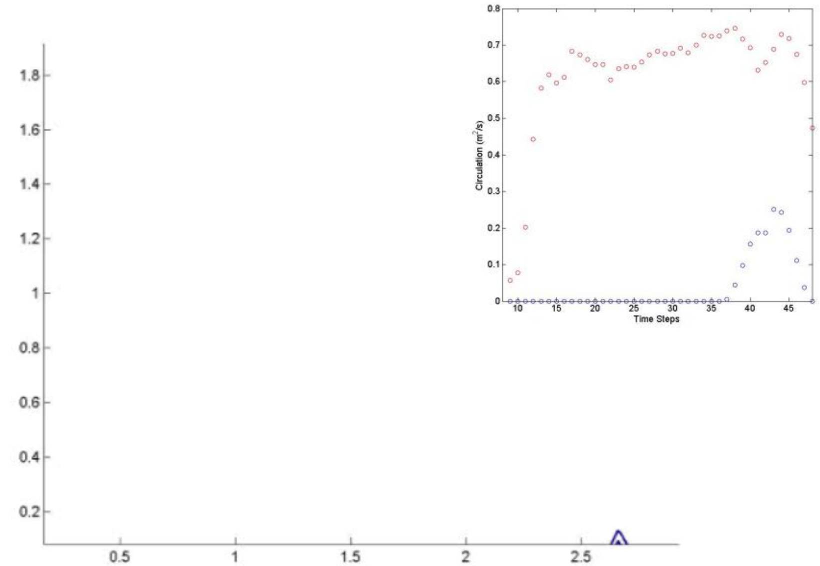
Laser Sheet width ~ 1.5 mm

# Chosen Waveform Imaging

- **Single phase characterization**
  - 13.3 ms sine wave pulse, repeated at 2 Hz interval, $V_{jet}$ ~ 10 m/s
  - $h/D_j = 1$ ($D_j = 10$ cm)




*Ensemble Average Velocity*

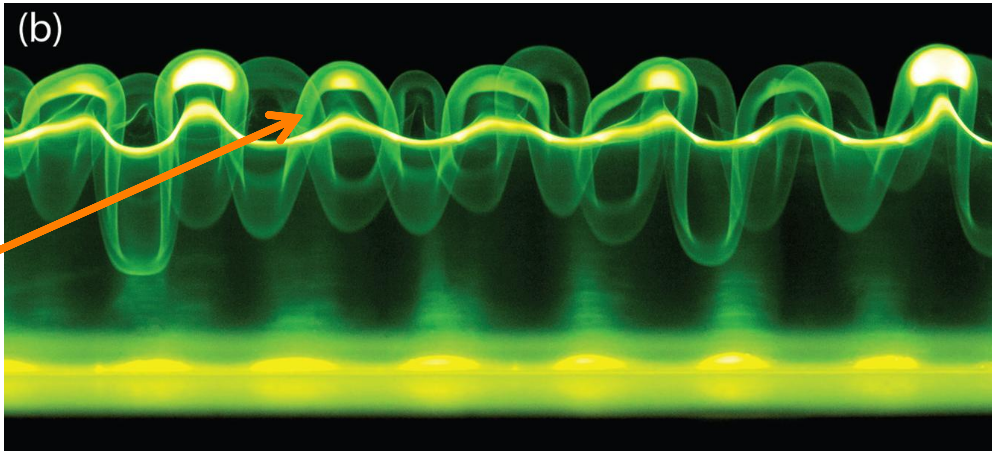



*Vorticity Contours*

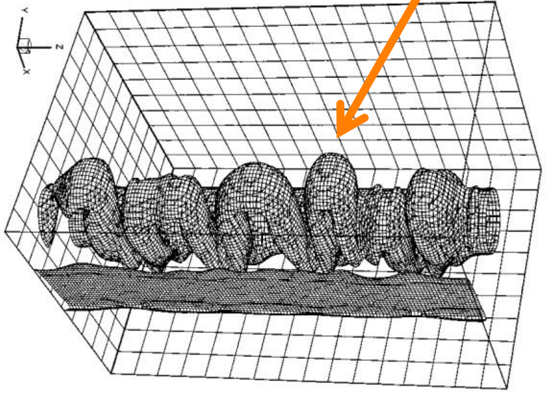
- Vortex formation highly repeatable up to point of destabilization during wall interaction
- Nominal strength, $\Gamma$ ~ 0.7 $m^2/s$, Re = $\Gamma/\nu$ ~ 50,000

# Secondary Vortex Instability

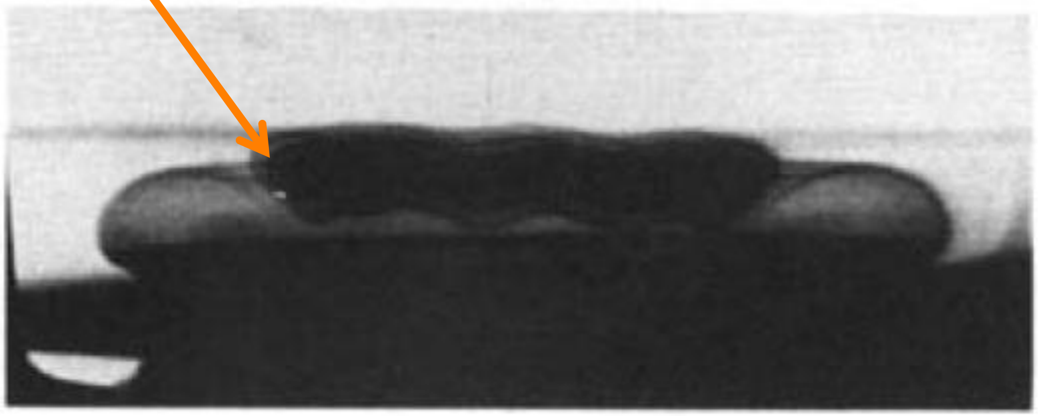
- Azimuthally unstable wrapping of the secondary vortex




*Harris, Miller, and Williamson, Phys. Fluids 2010*



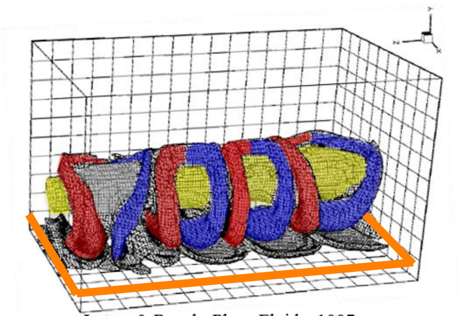
*Luton and Ragab, Phys. Fluids 1997*



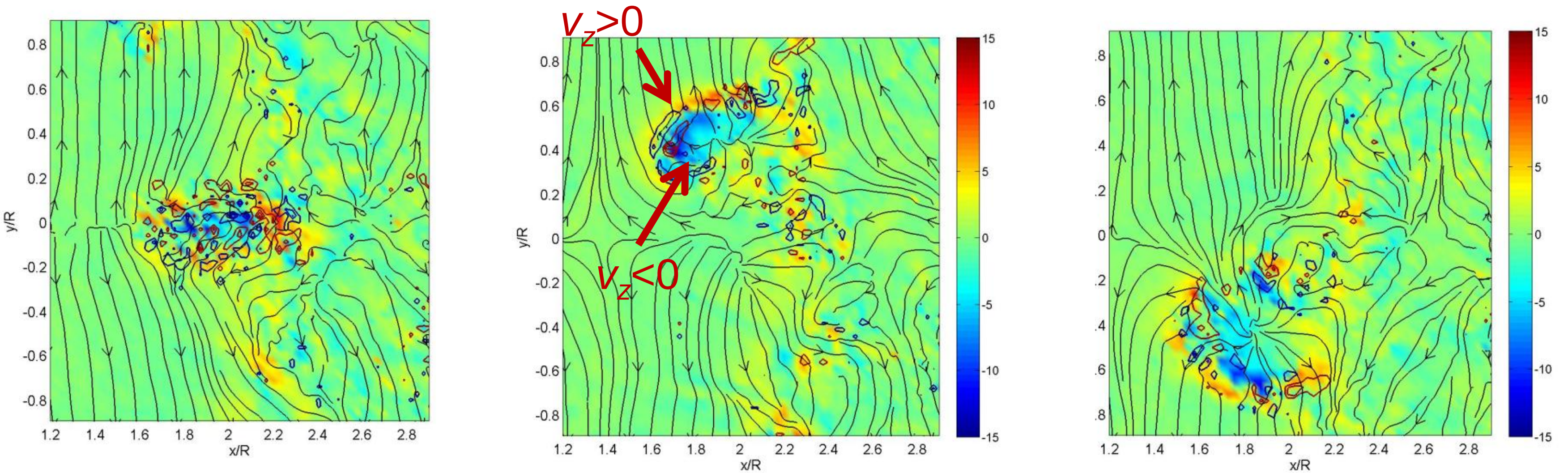
*Walker & Smith J., Fluid Mech. 1987*

# Instantaneous Breakdown Imaging

- Consistent structures of  out-of-plane velocity
- Azimuthally unstable
- Instantaneous snapshots:

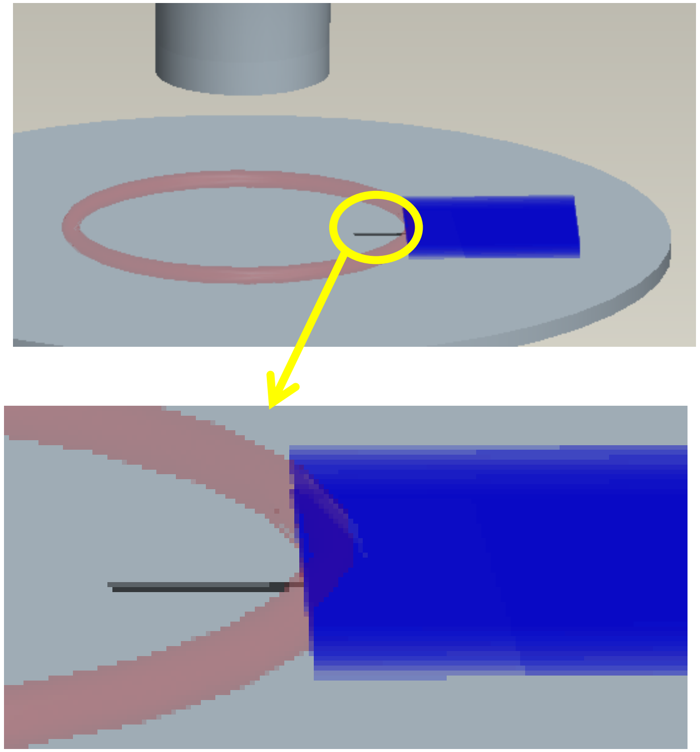


Luton & Ragab, Phys. Fluids, 1997

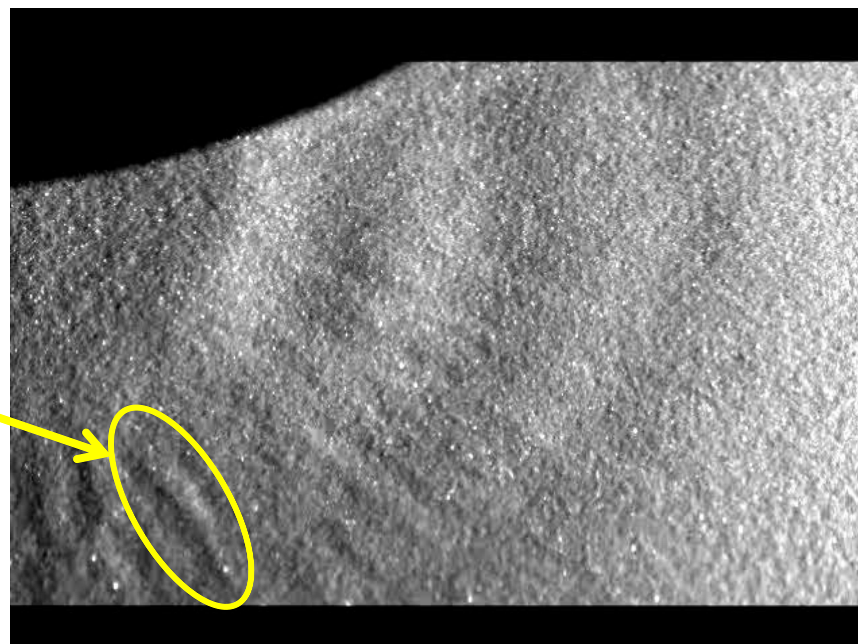



1mm above ground plane

# Axial Fence Introduction



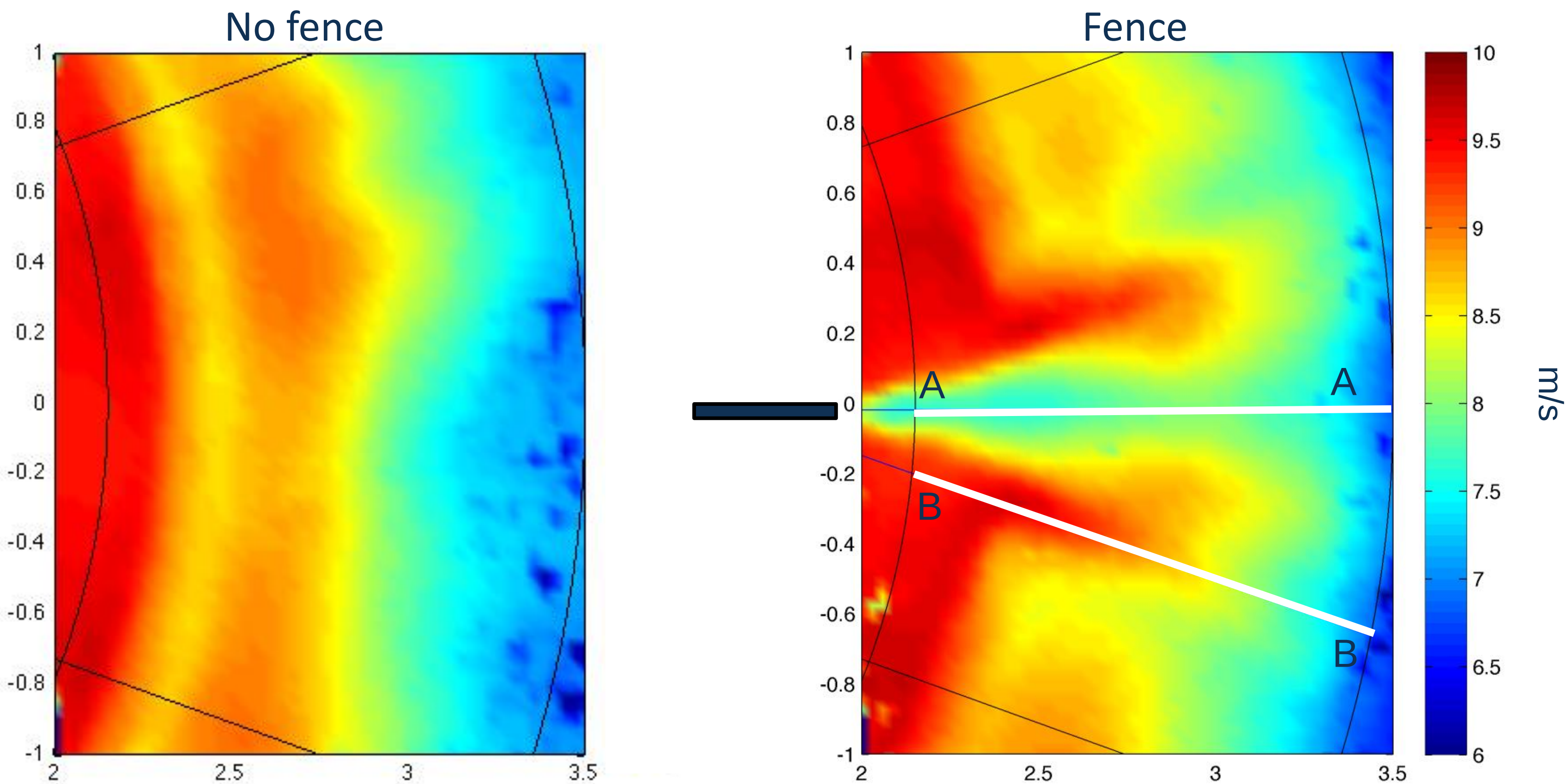
- **Wrapping instigated by examing the influence of small radial "fence"**
  - Small height: $d/D_{vortex} \sim 0.05$
  - Length, $l/D_{vortex} \sim 1$
- Current data extracted from $z/R = 0.025$ only
- Fence-like structures occur in brownout flow



Naturally occurring radial fence.
Sediment collisional instability?

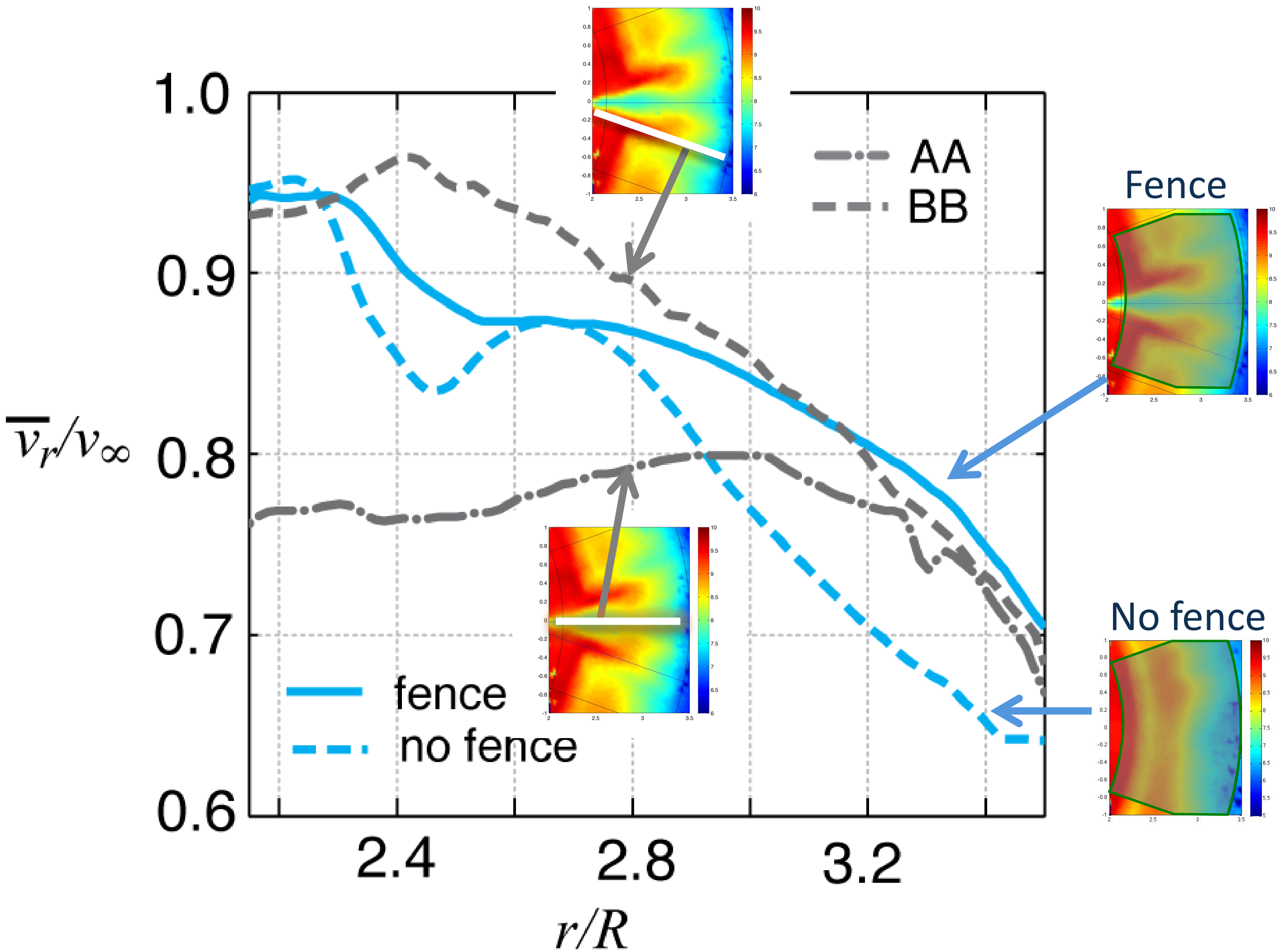
# Time-Average Radial Velocity Fields

$$f(r,\phi,z,t) = \underbrace{\bar{f}(r,\phi,z)}_{\text{Time-average}} + \underbrace{\tilde{f}(r,\phi,z,t/T)}_{\text{periodic}} + \underbrace{f'(r,\phi,z,t)}_{\text{stochastic}}$$




- AA and BB illustrate the high- and low-speed streak region

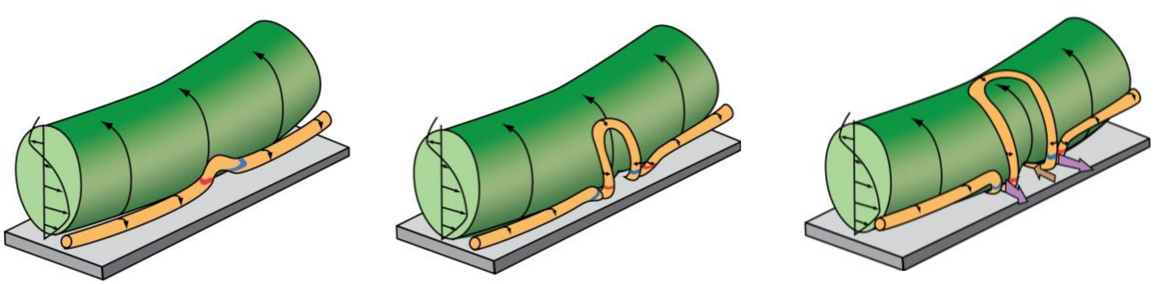
# Average Radial Velocity Fields




- Peak radial velocity similar in early near-wall flow, up to +15% downstream for fence
- High-speed streak 25% greater than low-speed region in early wake, similar downstream

# Near-wall Evolution

- **Near wall primary & secondary vortex signature**
  - Wall-normal velocity and wall-normal vorticity

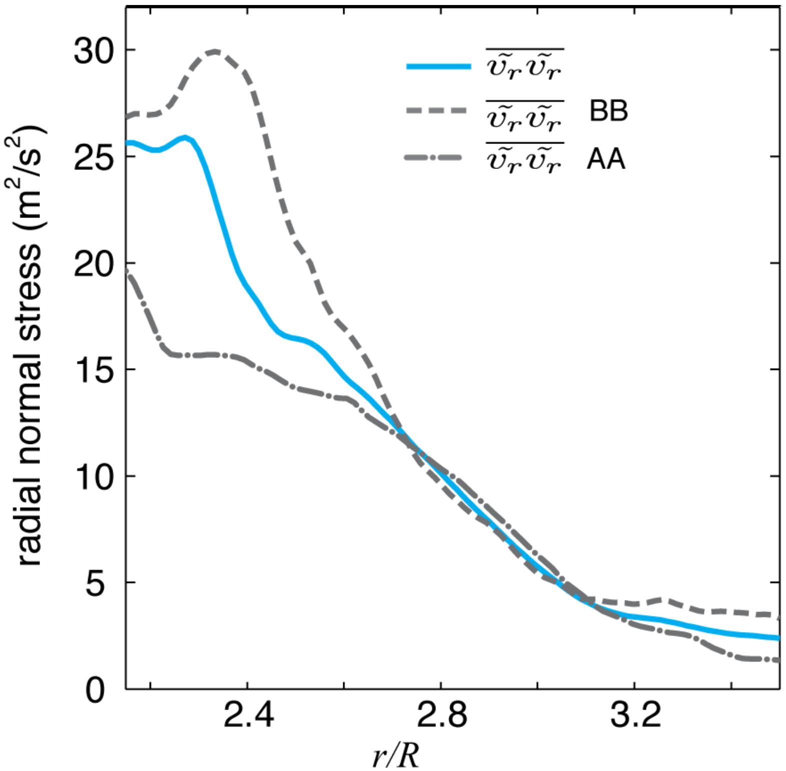
# Periodic vs. Stochastic Radial Stress

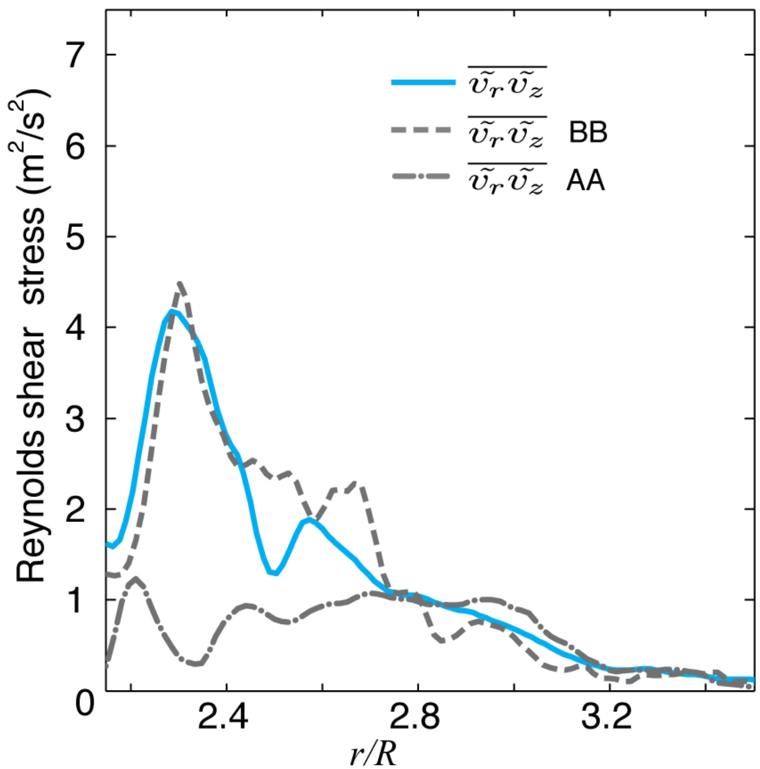
- Periodic stresses are up to order of magnitude larger
- Stochastic variations become dominant past r/R > 3

# Reynolds Shear Stresses

- Radial stresses are up to 2.5 times larger than Reynolds stresses

# Profiles of Turbulent Stress




**Observations:**

- Radial normal stress ($v_r v_r$) typically 3 to 10x $r$-$z$ shear stress ($v_r v_z$)
    - *Near wall location restricts $v_z$ magnitude, also normal stress is + only*
- Presence of fence temporarily enhances time-average of fluctuating stress
- Coherent stress dominates for r/R < 3 (closest approach r/R~2)
- Stress in high-speed region can be 2x that in low-speed region

# Experimental Conditions

**Table 1** Flow Conditions and particle characteristics

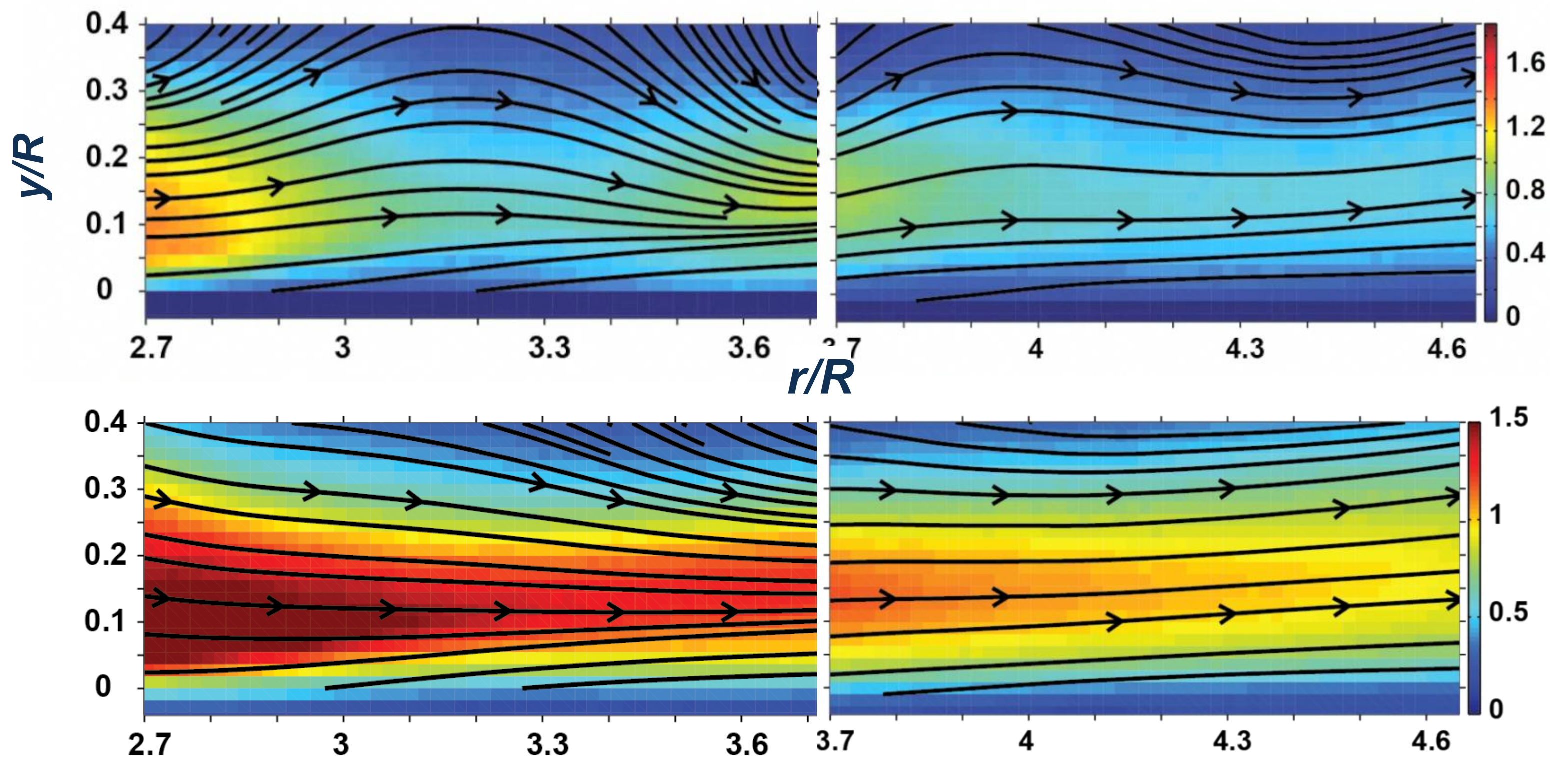
| | |
|---|---|
| Nozzle radius, $R$ (cm) | 5 |
| Mean jet exit velocity, $V_0$ ($ms^{-1}$) | 4.1 |
| Forcing frequency, $n$ (Hz) | 50 |
| Velocity fluctuation amplitude, $\Delta V$ ($ms^{-1}$) | ±4 |
| Fluid density, $\rho_f$ ($kgm^{-3}$) | 1.2 |
| Kinematic Viscosity, $\nu$ ($m^2s^{-1}$) | $1.56\times10^{-5}$ |
| Particle density, $\rho_p$ ($kgm^{-3}$) | 2500 |
| Particle mean diameter, $d_p$ (μm) | 50 |
| Size range (μm) | 45-63 |
| Thickness of the sediment bed (cm) | 1.2 |
| Standoff height (cm) | 10 |
| Stokes number based on vortex core size | 15 |

$$St = \frac{\tau_p}{\tau_f}$$

$$\tau_p = \frac{\rho_p}{\rho_f}\frac{d_p^2}{18\nu}$$

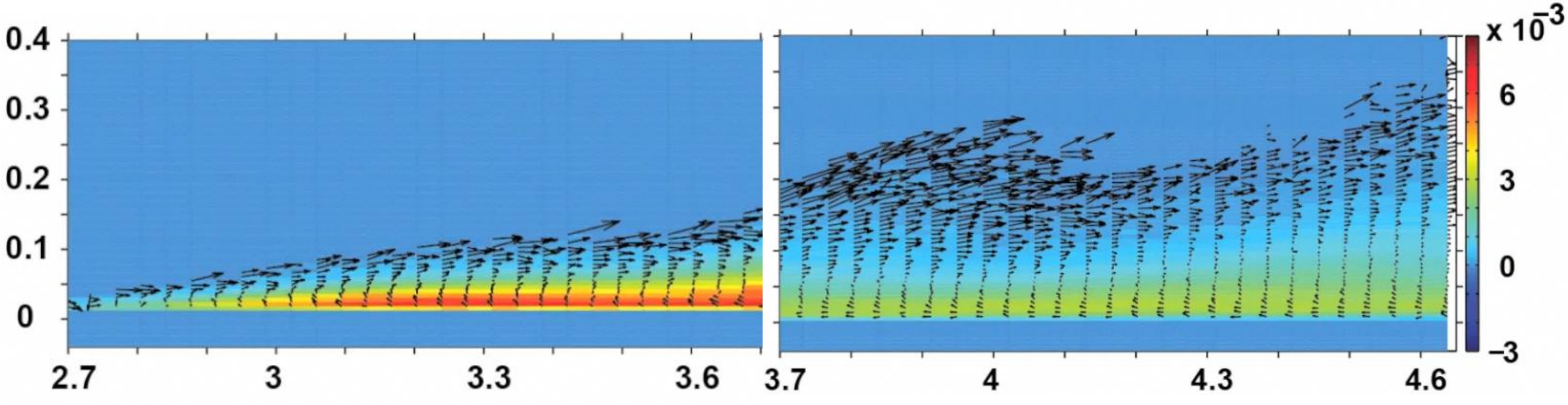
# Two-phase conditions: Fluid Velocity

- **Ensemble-averaged two-phase flow is similar to single-phase**
  - Increased variablity in vortex-wall interaction
  - Secondary vortex is not visible (but may be present)
  - Mean flow is in form of strong wall jet



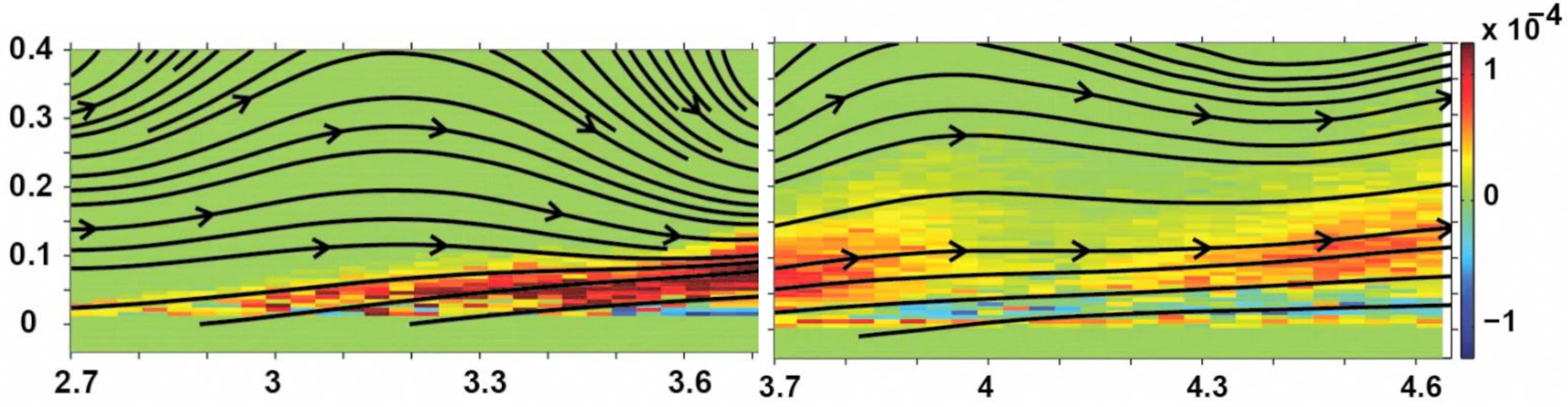
# Particle Concentration & Slip vector

- **The evolution of the suspended load**
  - Predominantly radial scouring along the ground in upstream plane
  - Concentration is highest at the point of closest vortex approach
  - Slip velocity $\langle \boldsymbol{u}_f - \boldsymbol{u}_p \rangle$ is directed radially outward in outer flow and radially inward close to the ground
    - *Greater suspension heights in downstream plane*
    - *Slip magnitude is larger in downstream plane*



# Vertical Flux

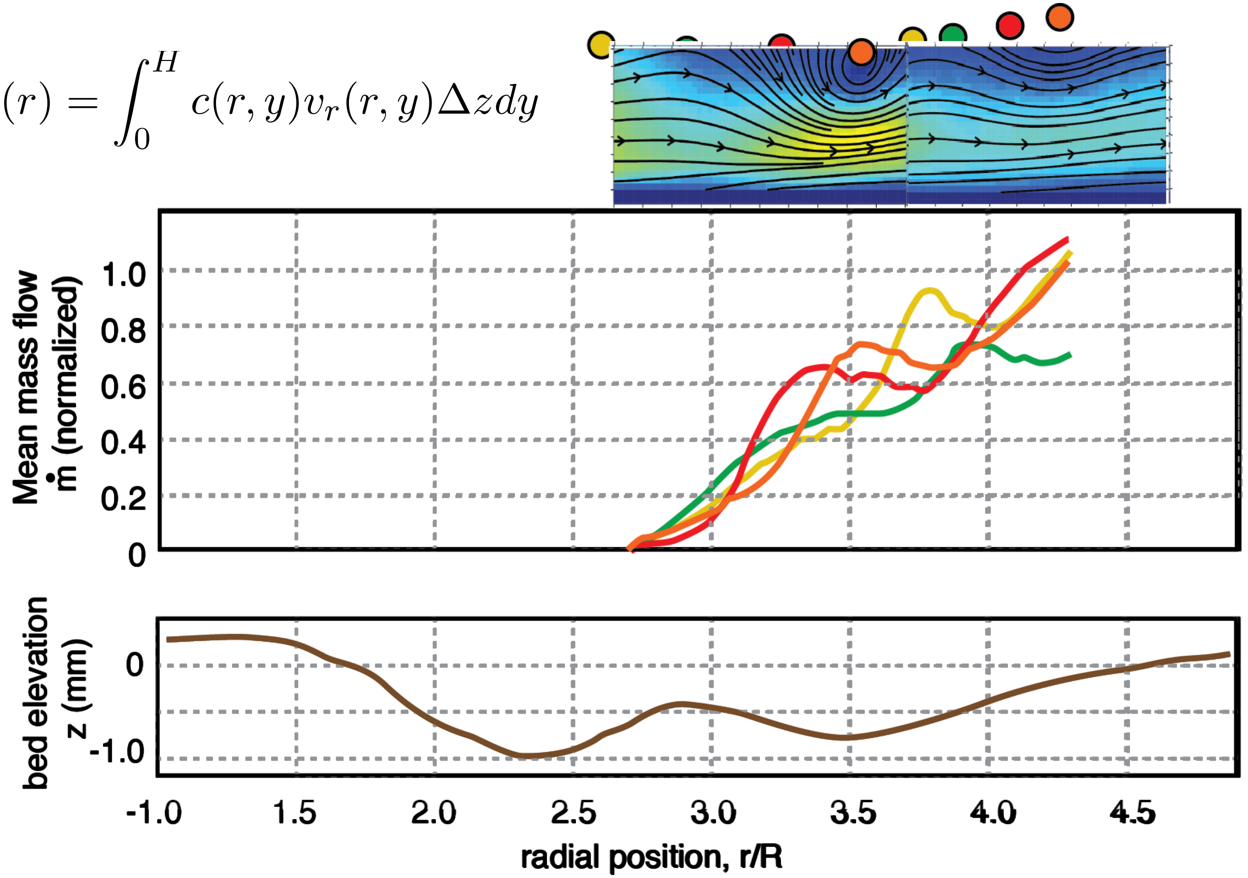
- Unsteady transport into/within suspended load



# Horizontal Flux

- **Evolution of suspended/saltating flow**
  - observed by change in transported horizontal mass flow rate:

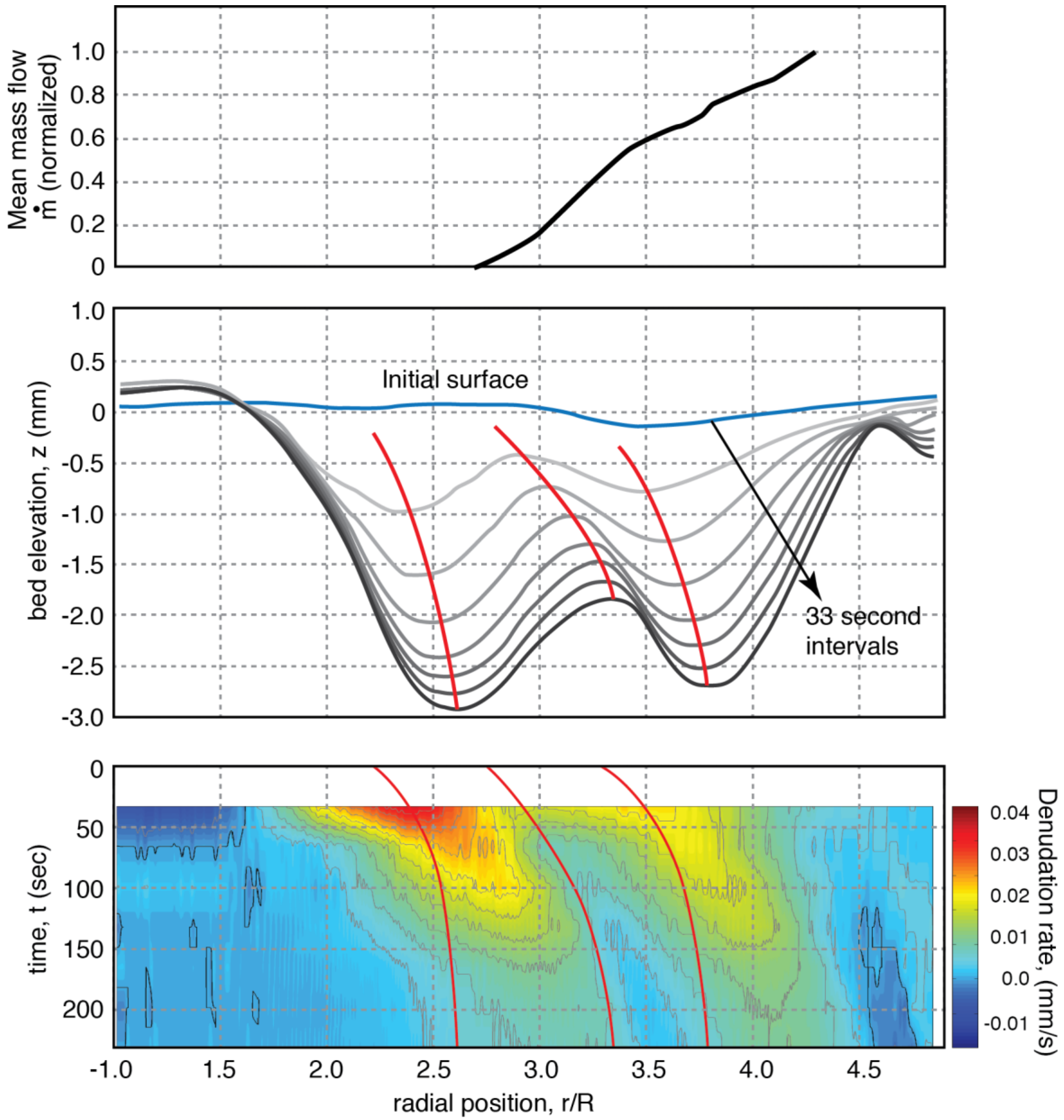
$$\dot{m}(r) = \int_0^H c(r,y) v_r(r,y) \Delta z dy$$




  - Sediment waves forced by strong vortical surface flow
  - Suspension strongest following first crest

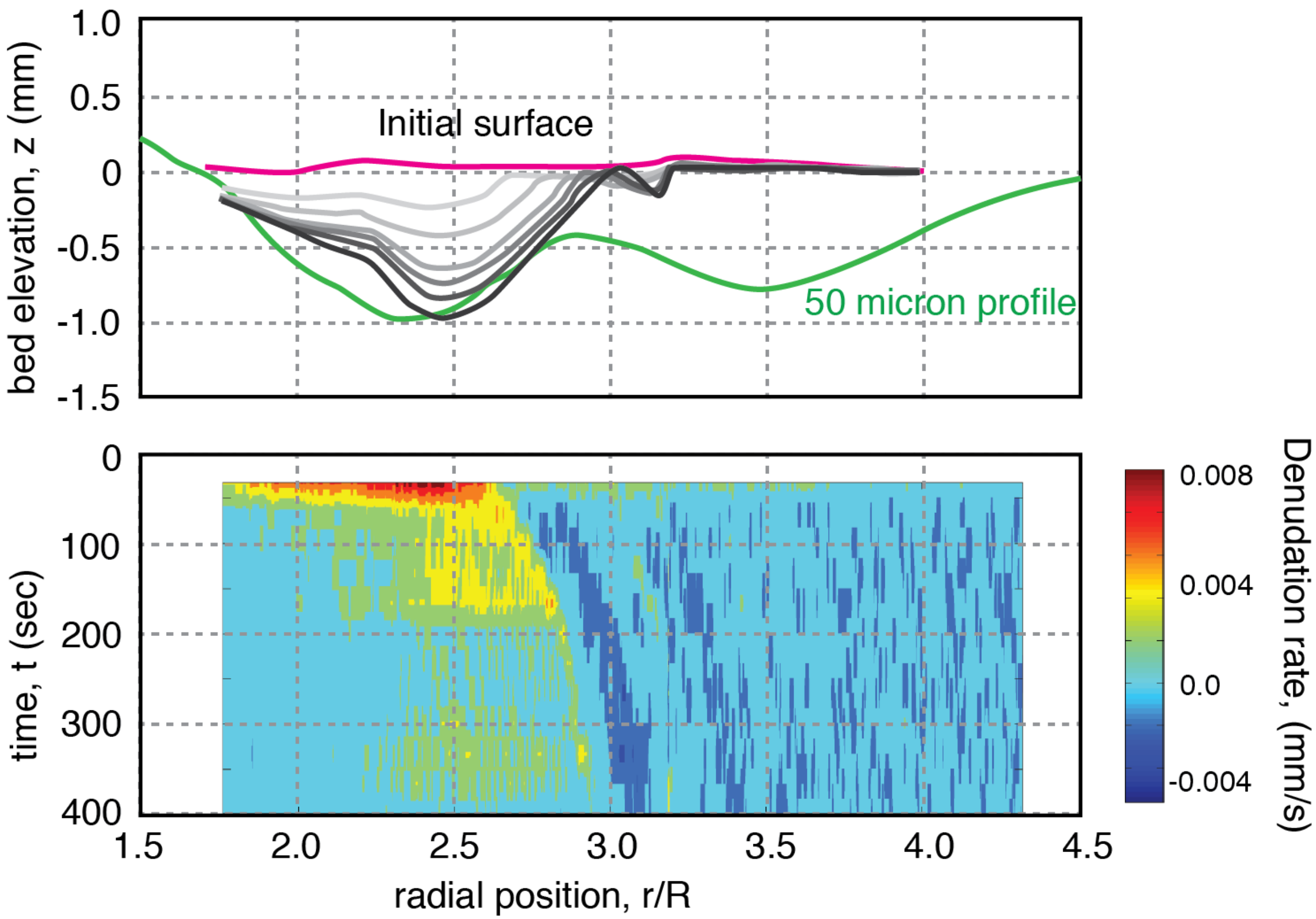
# Bed form evolution

- **Following evolution:**
  - Two ripples quickly form and deepen, and move downstream
  - Erosion rate starts high, and then gradually relaxes
- **What controls the wavelength?**



# Bed forms with larger particles

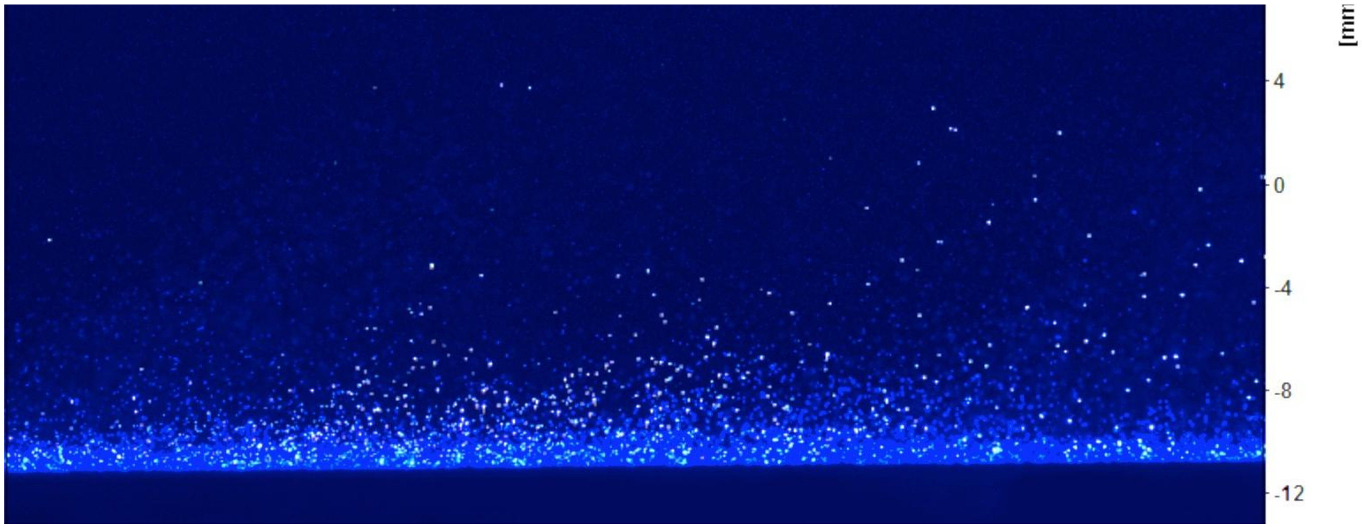
- **Repeat with 150 micron…**




- More gradual evolution (expected)
- Wavelength similar, but only 1 ripple… decelerating wall jet

# Bed forms important to suspension

Flat bed




Small bedforms