Transition to turbulence in the presence of finite-size particles

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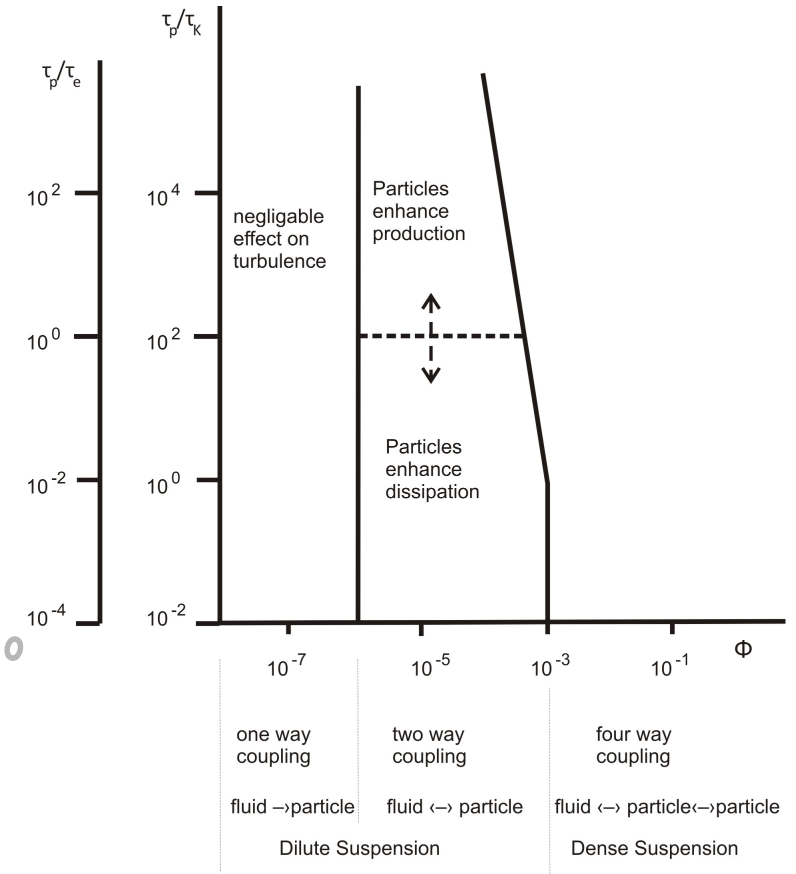
Suspensions of rigid particles: Applications

- Several processes and applications involve dense suspensions at high flow rates:
  - Waste slurries
  - Pharmaceutics
  - Cement industry
  - Paper making
  - Environmental flows: magma, mud, pyroclastic flows
  - …

Modeling suspension at high flow-rates

- Different interactions mainly depending on
  - ✓ Volume fraction ϕ
  - ✓ Mass fraction $\psi = \rho_p / \rho_f \ \phi$
  - ✓ Particle relaxation time (size)
- Different coupling mechanisms:
  - 1-way: particles are transported, but do not influence the flow
  - 2-way: particles influence the flow, but there is no mutual particle interaction
  - 4-way: all phases mutually interact: *dense* cases



Adapted from Elgobashi *et al.*

- Point-particle approximation *may* apply to 1- and 2-way regimes, but not in 4-way…

Fully resolved particle simulations

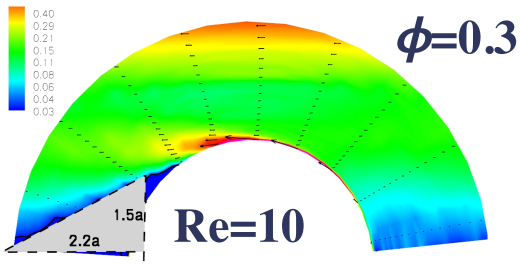
Purpose of the project: effect of inertia on suspensions

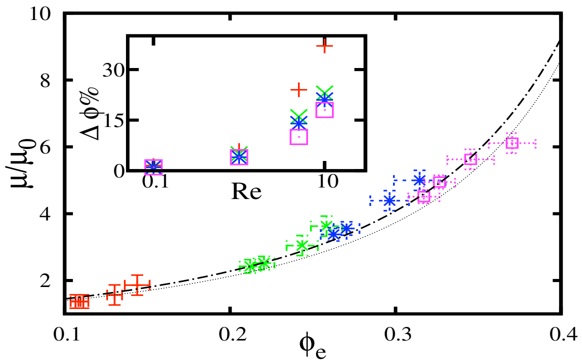
European Research Council
Established by the European Commission

Three different frameworks where inertia effects are crucial:

Laminar inertial suspension:

○ Why the effective viscosity increases (shear-thickening)? How does the effective viscosity depend on the Reynolds number?

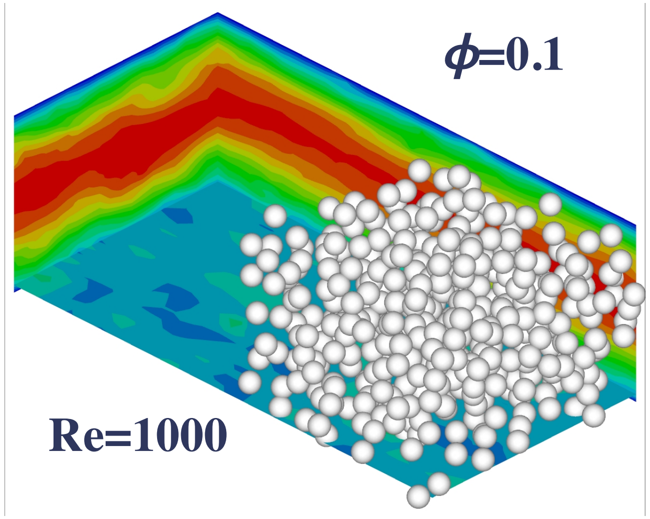




PICANO, BREUGEM, MITRA, BRANDT *PRL* 2013

Transition of suspension flows:

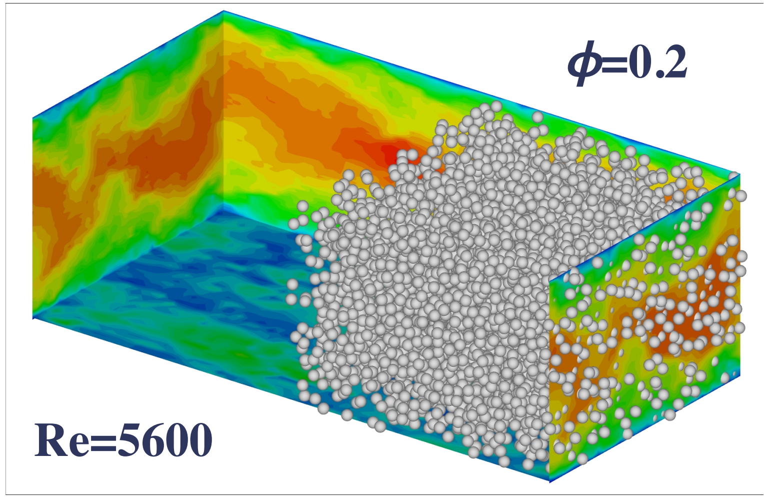
▪ how does the critical Reynolds number and the mechanisms behind transition change at high ϕ?



LASHGARI, PICANO, BREUGEM, BRANDT *IN PREP*.

Turbulent suspension flows:

▪ what turbulence and what is the interaction among the phases?



PICANO, BREUGEM, BRANDT *IN PREP*.

MATAS ET AL. PRL 2003
KULKARNI & MORRIS PF 2008
SHAO ET AL. JFM 2012
YEO & MAXEY PF 2013
KIDANEMARIAM ET AL. NJP 2013

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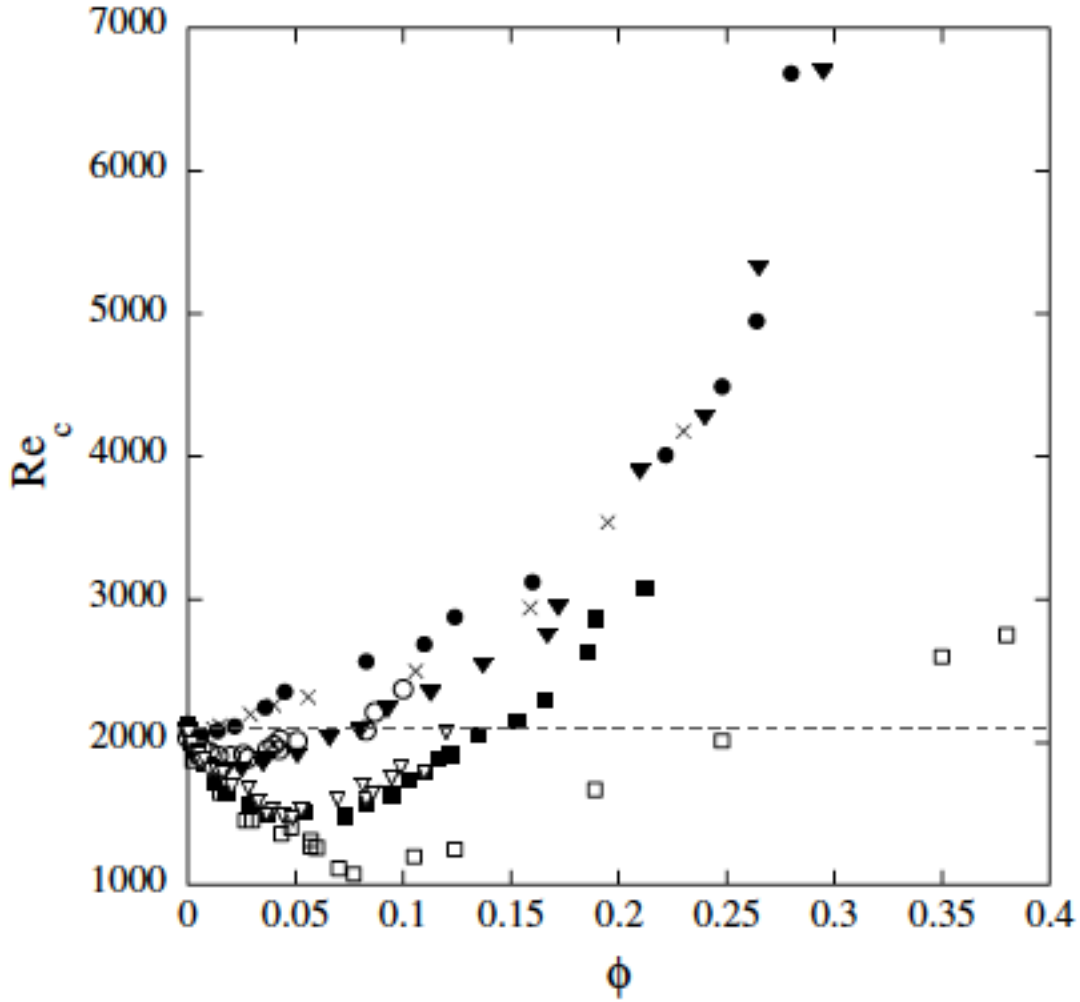
Experiments of transitional particle-laden pipe flow

- Sproull (1961): drag reduction in dusty gases
- Experimental study by Matas et al. 2003 on neutrally-buoyant finite size particle in pipe flow
- Spectrum of pressure drop between the entrance and exit has been used to quantify the transition

- Monotonic increase in Re_c, when D/d≥65 (× and •)
- Φ-dependent behavior of Re_c, when D/d≤65 (▼ ■ ▽ □)



Matas et. al. 2003, PRL

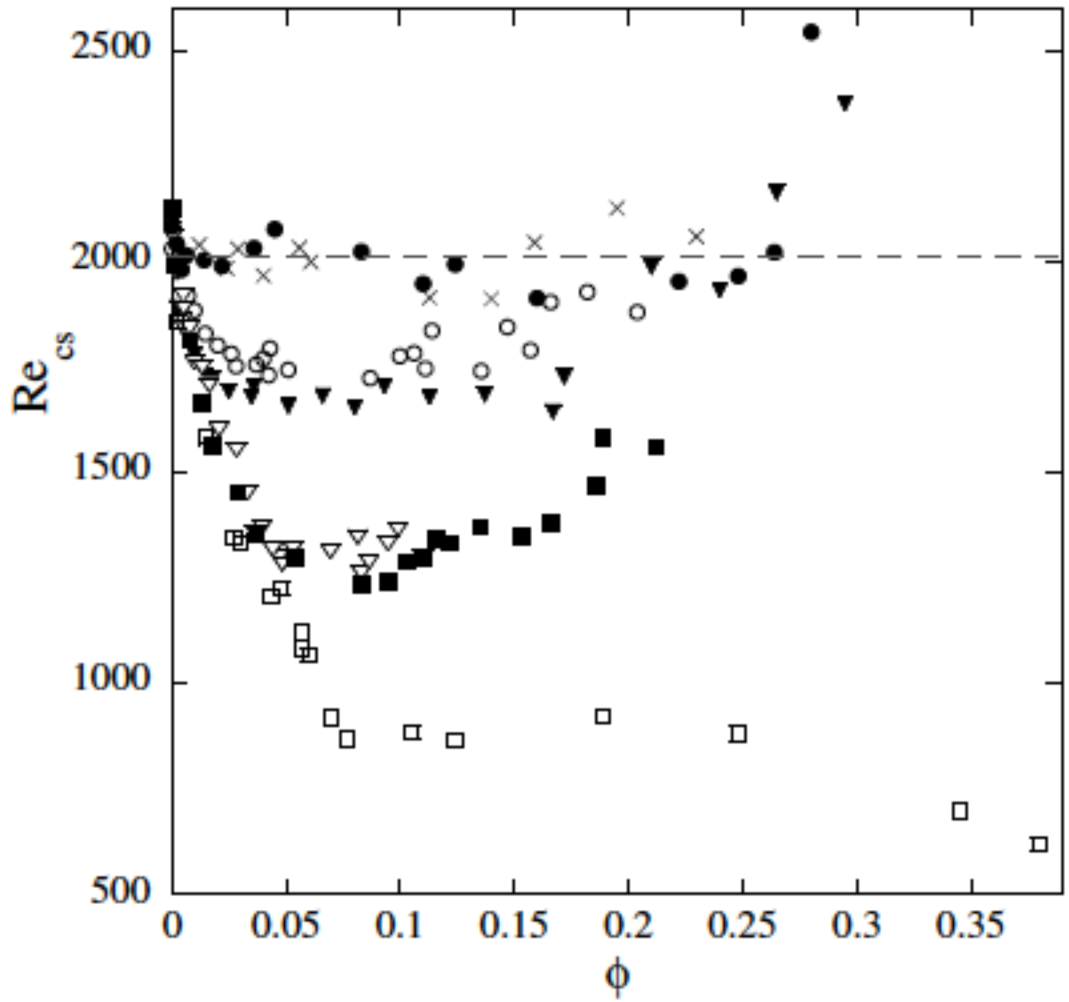
Experiments of transitional particle-laden pipe flow

- Critical Reynolds number is defined based on Krieger's viscosity
$$\frac{\mu_e}{\mu} = (1 - \phi/\phi_m)^{-1.82}$$

- For D/d ≥ 65, the critical Reynolds number remains constant, Re_c ~2100, but for large Φ it increases sharply due to "*additional dissipative mechanism*"

- For D/d < 65, the Krieger's scaling fails and the Re_c first decreases and then level off for high volume fractions

- Critical conditions for the Suspensions with the same value of D/d, (▽ & ■) and (▼& ○), collapse on the same curve



Matas et. al. 2003, PRL

Simulations of transitional pipe flow

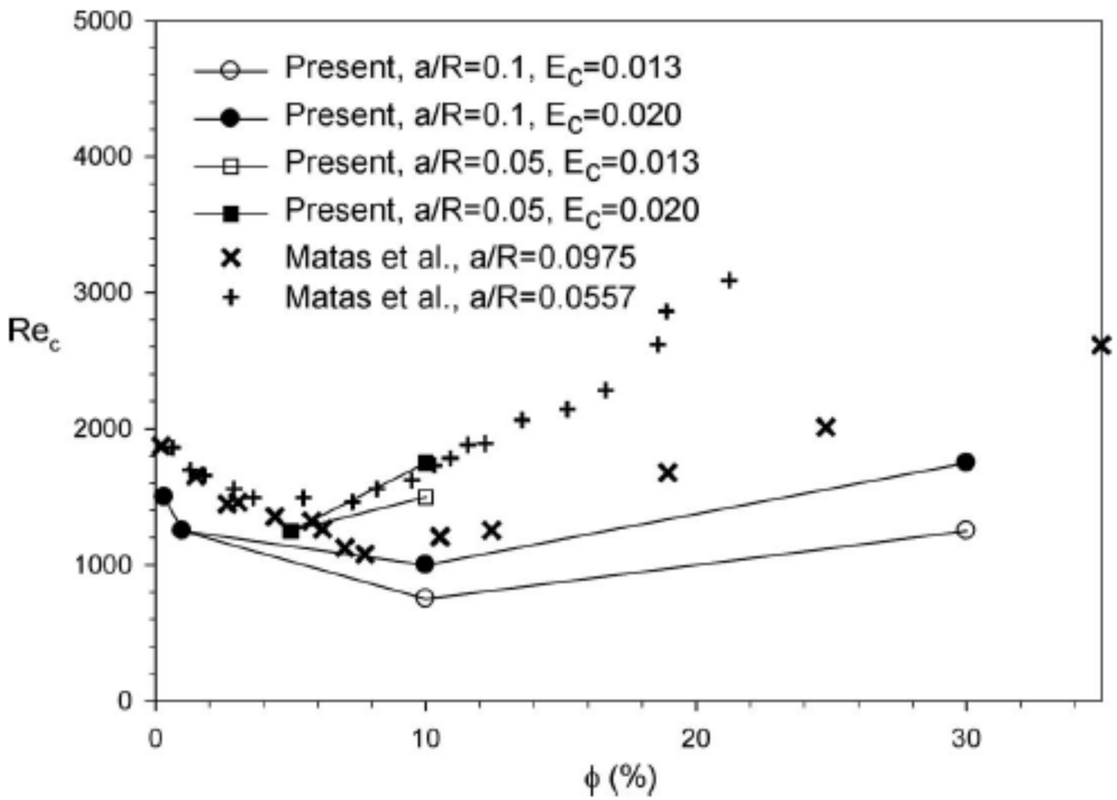
- Recent simulations of transition to turbulence with finite-size particles in pipe flow

- The kinetic energy of the streamwise velocity fluctuation used as an indicator for the transition

$$E(t) = \int\int\int [u'_z(x, y, z; t)]^2 dxdydz$$

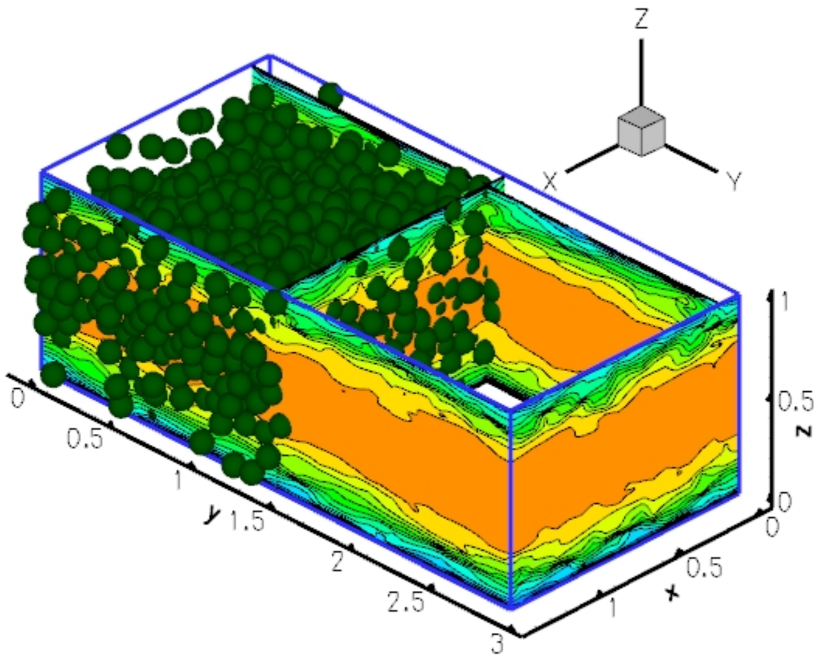
  - ✓ Laminar flow if max(E) < Ec
  - ✓ Turbulent flow if max(E) > Ec

- The results of Matas et. al. can be qualitatively reproduced by tuning the value of the critical energy, Ec, **but….**



Simulations of transitional channel flow

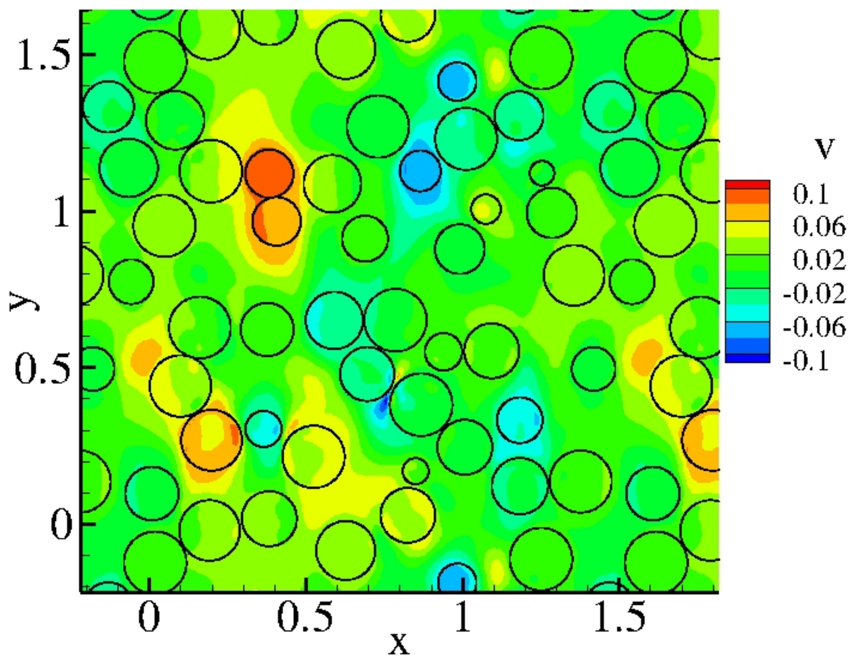
- Volume fractions ϕ=[0, 0.001, 0.025, 0.05, 0.075, 0.1, 0.15, 0.2, 0.3]
- Bulk Reynolds number: $Re_b=U_0 2h/\nu=500\text{-}5000$
- Friction Reynolds number $Re_\tau=15\text{-}210$
- Domain size ($z=2h$, $y=6h$, $x=3h$)
- Up to 2580 finite size particles
- Particle radius $a=h/10$ ($a^+=1.5\text{-}21$)
- Mesh (160, 240, 480), 16 points per a
- Immersed Boundary Method



Breugem 2012, JCP

Numerical simulations

- Finite-volume Navier-Stokes solver
- Immersed Boundary Method (IBM) for solid sphere tracking
- Couette flow of rigid solid spheres at *finite* particle Reynolds number
- Lubrication correction and soft-sphere collision model
- 2^{nd} order accurate in space
- Fully validate in several simple configurations see BREUGEM JCP2012



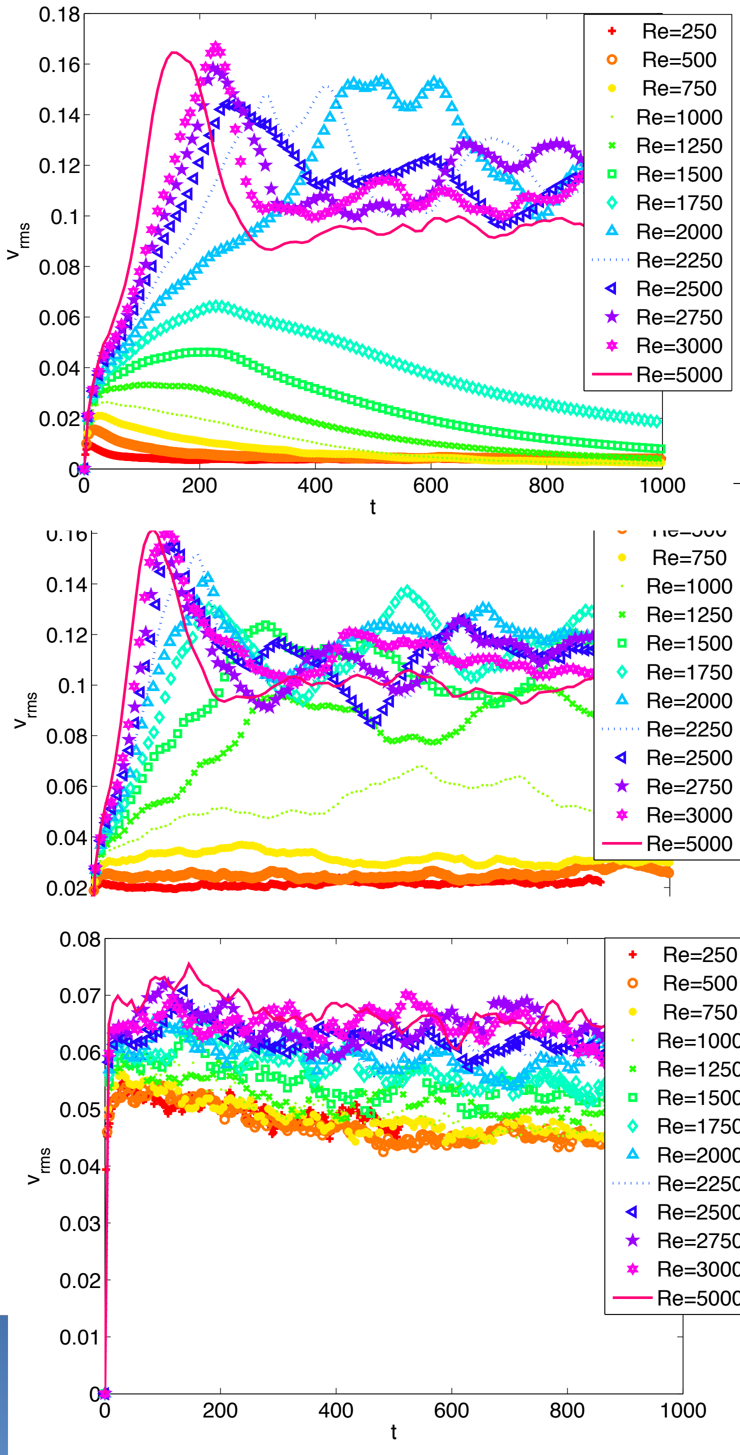
Transition to turbulence

- Large amplitude localized disturbance
- Time histories of the root-mean-square of the streamwise velocity fluctuations,

✓ difficulty of clearly defining a transition threshold at high volume fractions

✓ Sharp transition at low ϕ

✓ Velocity fluctuations smoothly increase with the Re and approach a lower regime value at small ϕ



Φ=0.001

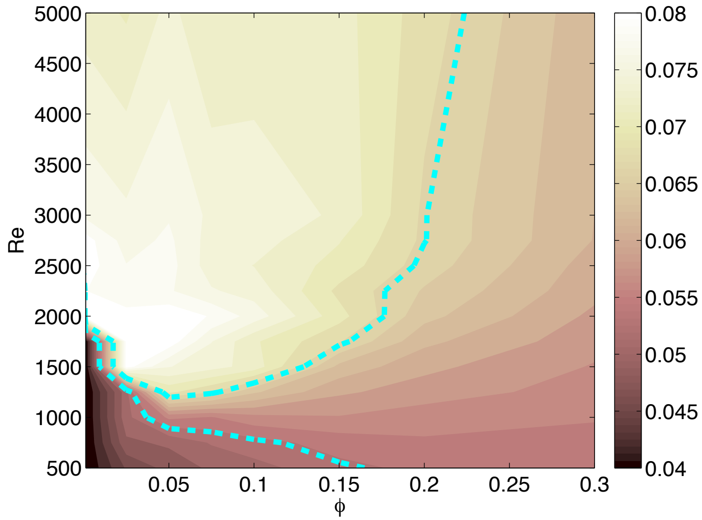
Φ=0.05

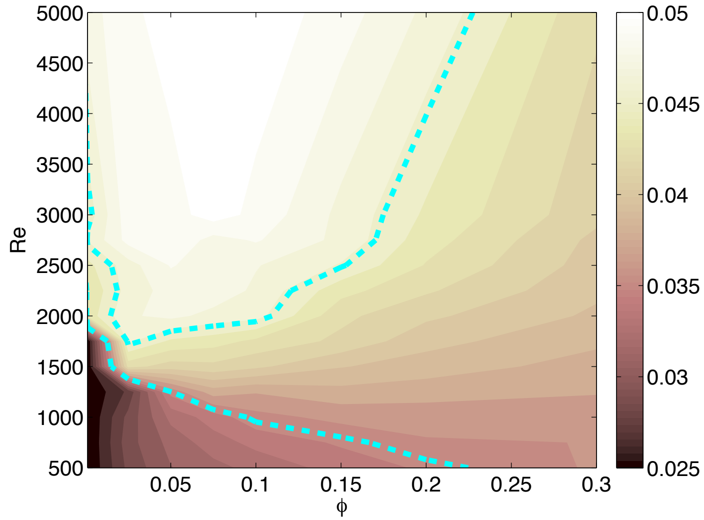
Φ=0.3

Three different regimes:

Velocity fluctuations, average over space and time

Stream-wise





Span-wise

Non-monotonic behavior of the transitional Reynolds number, in line with the experimental observation by Matas et al., sensitive to the chosen threshold as in simulations

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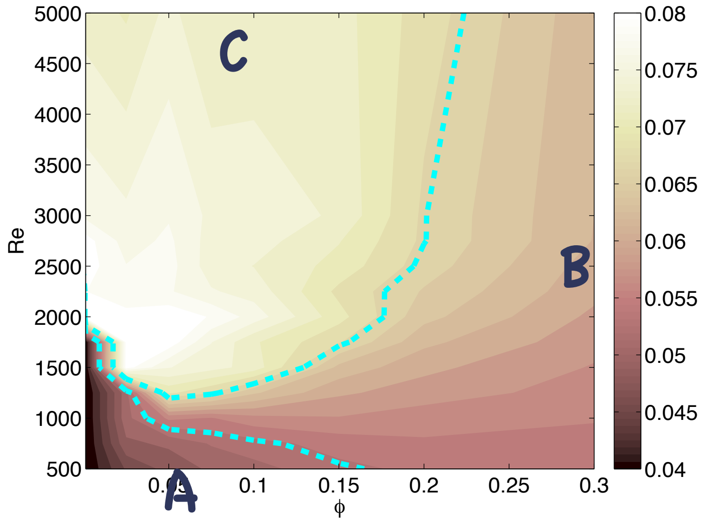
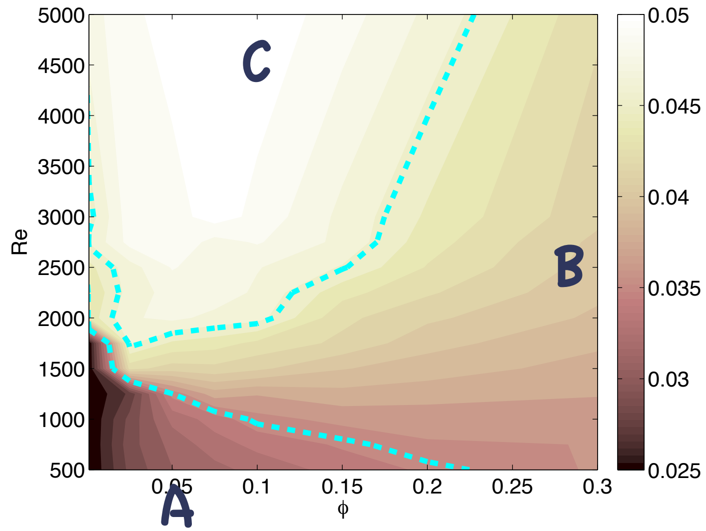
Three different regimes:

Velocity fluctuations, average over space and time

Stream-wise



Span-wise



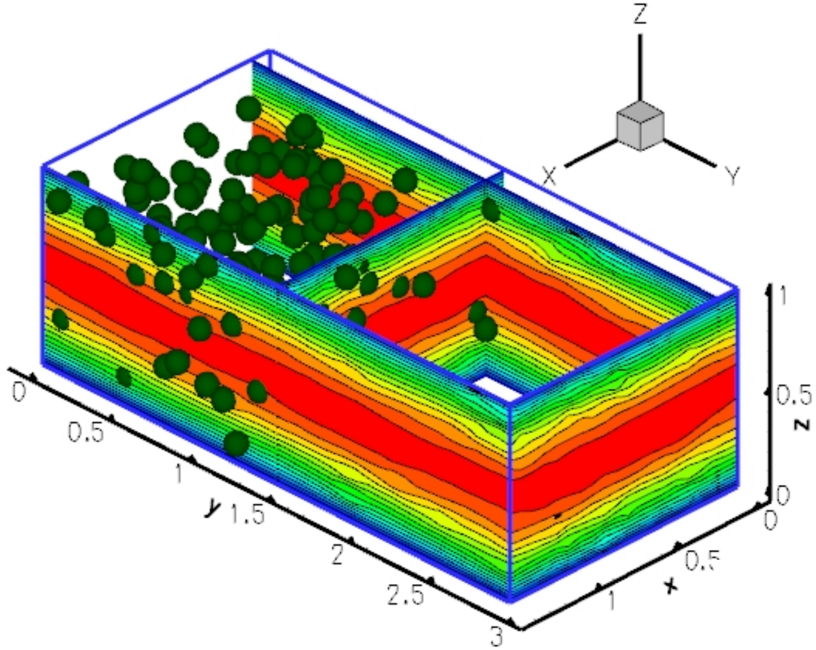
Three different regimes:

A) Laminar-like e.g. Re=500, Φ=0.05

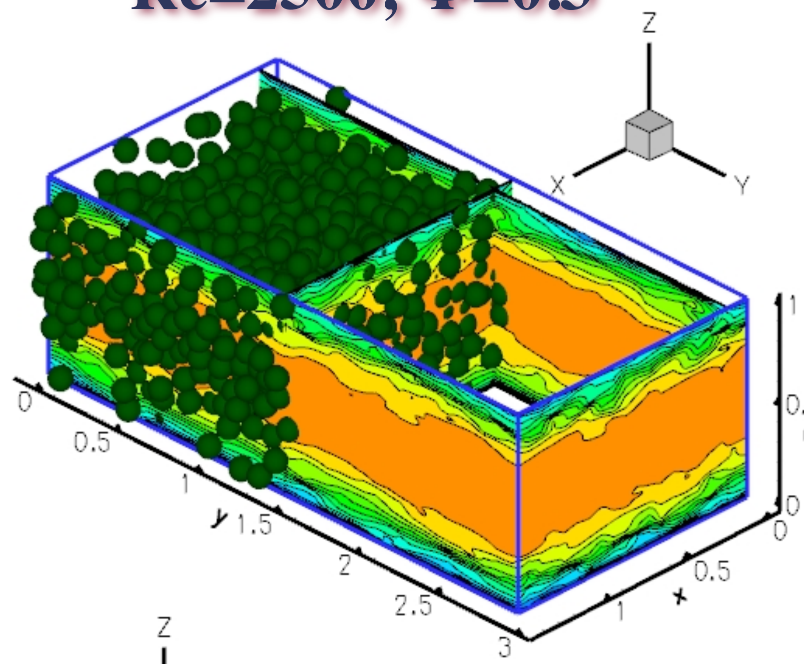
B) Inertial shear-thickening e.g. Re=2500, Φ=0.3

C) Turbulent-like e.g. Re=5000, Φ=0.1

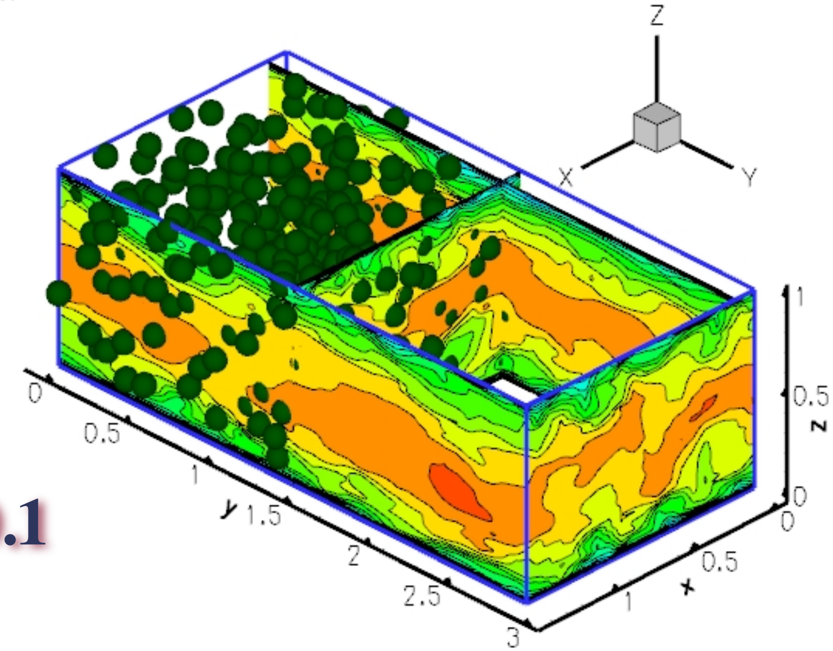
Re=500, Φ=0.05



Re=2500, Φ=0.3



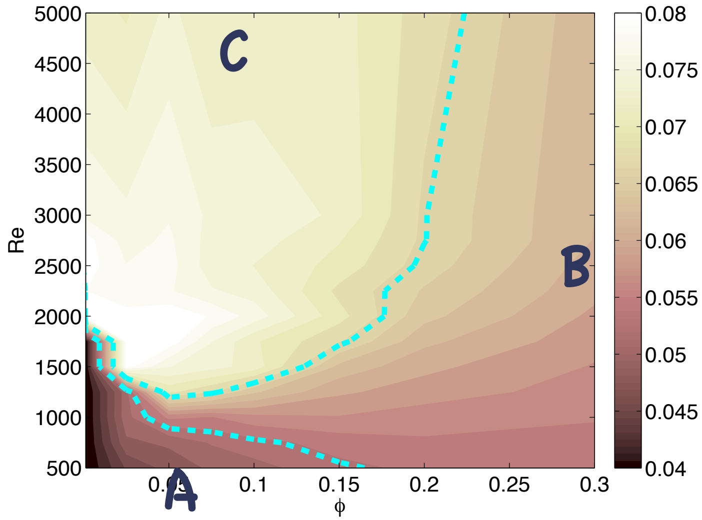
Re=5000, Φ=0.1

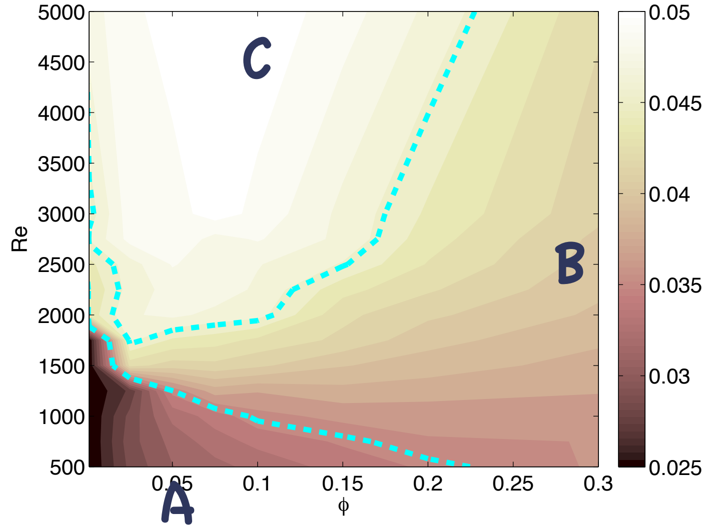


Three different regimes:

Velocity fluctuations, average over space and time

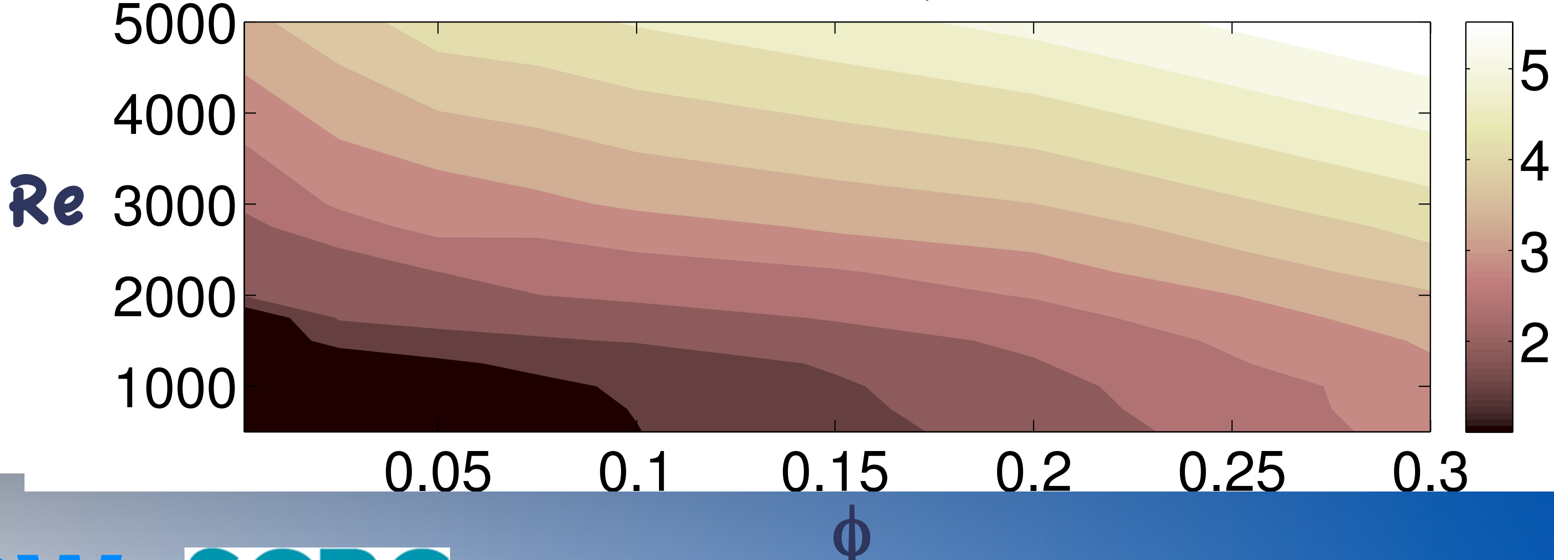
Stream-wise





Span-wise

Normalized average wall-friction: τ_w/τ_0



Momentum balance equation

- Averaging the total momentum equation and considering "phase-ensemble average", the momentum balance become

$$\rho\frac{\partial}{\partial t}\left[(1-\phi)U^f+\phi U^p\right]+\rho\nabla\cdot\left[(1-\phi)<U^fU^f>+\phi<U^pU^p>\right]$$
$$=\nabla\cdot\left[-(1-\phi)P^fI+2(1-\phi)\mu E^f)\right]+\nabla\cdot(\phi<\sigma^p>)-\rho\nabla\cdot\left[(1-\phi)<u^fu^f>+\phi<u^pu^p>\right]$$

- Considering the channel flow symmetries, total stress is:

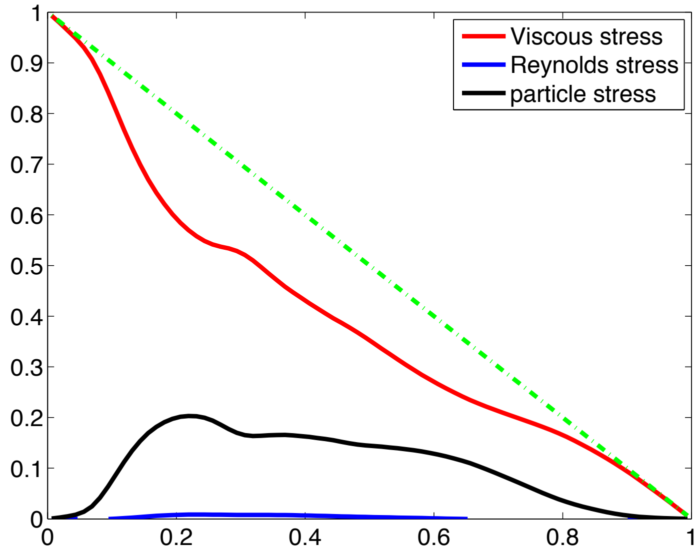
$$\tau(y)=-(1-\phi)<u^fv^f>-\phi<u^pv^p>+\nu(1-\phi)\frac{\partial U^f}{\partial y}+\frac{\phi}{\rho}<\sigma^p_{xy}>=\nu\frac{\partial U^f}{\partial y}\Big|_w(1-\frac{y}{h})$$

$$\boxed{\tau(y)=-<u^tv^t>+\nu(1-\phi)\frac{\partial U^f}{\partial y}+\frac{\phi}{\rho}<\sigma^p_{xy}>=u_*^2(1-\frac{y}{h})}$$

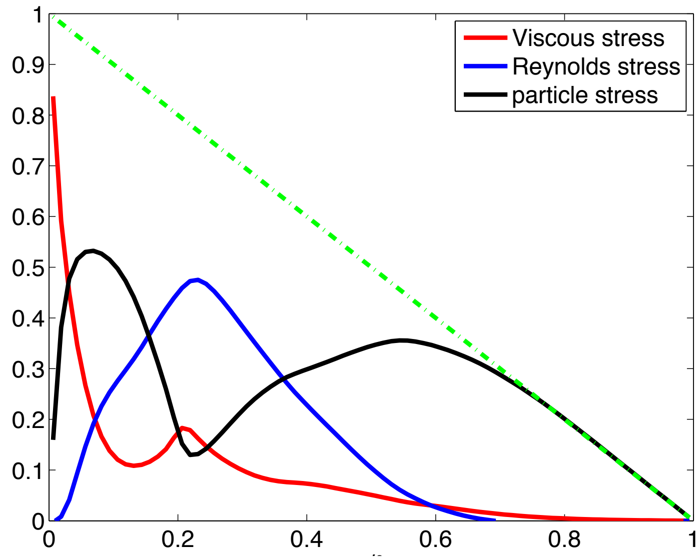
with $<u^tv^t>=(1-\phi)<u^fv^f>+\phi<u^pv^p>$

Stress budget for the three regimes

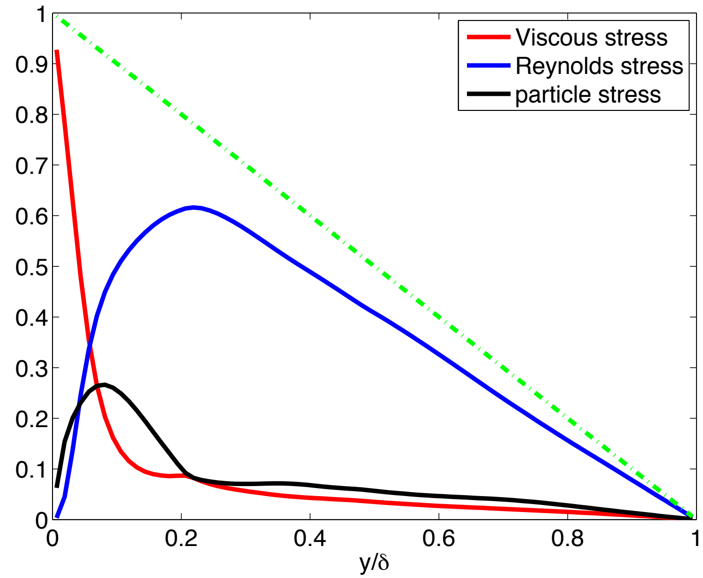
Re=500
Φ=0.05



Re=2500
Φ=0.3

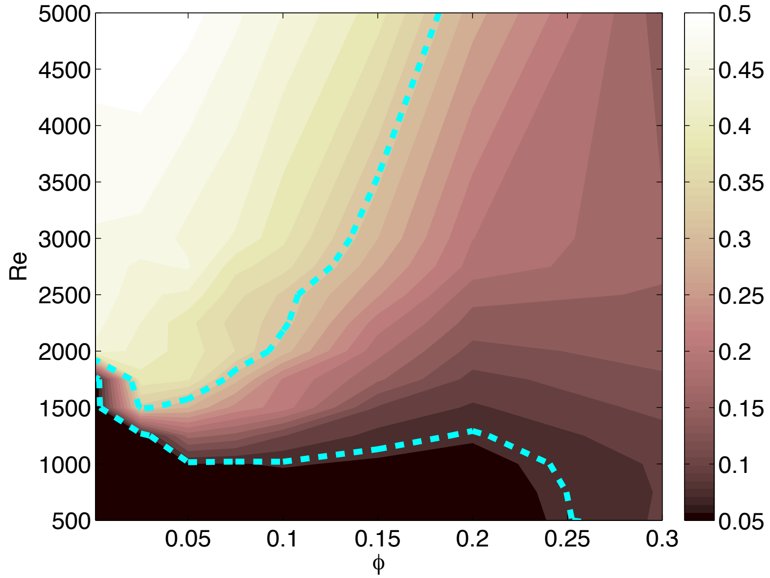


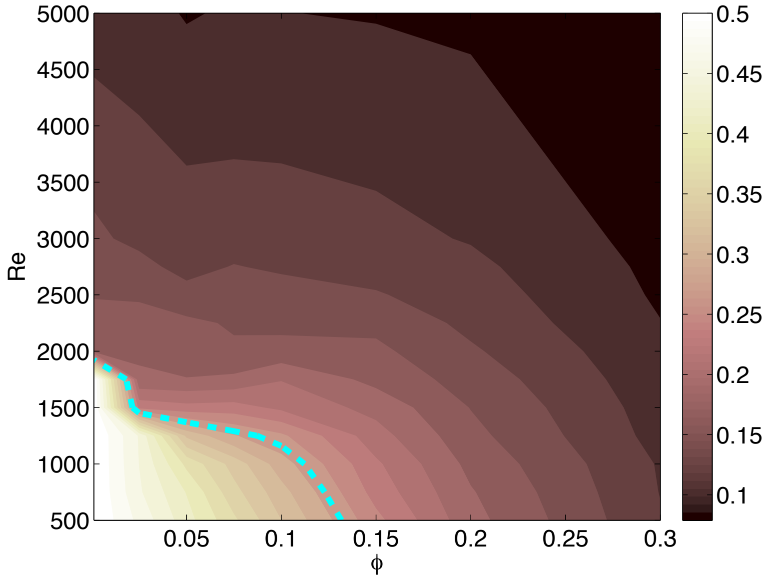
Re=5000
Φ=0.1



Average stress normalized by total stress

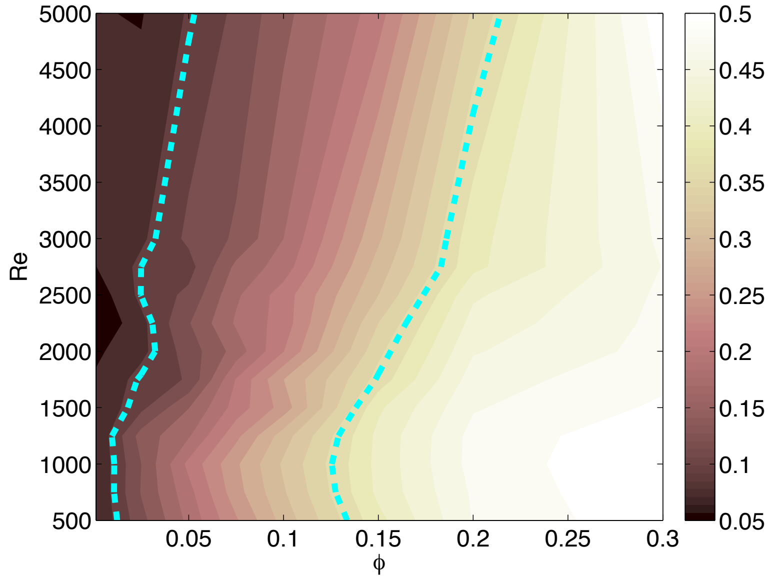
Average Reynolds stress contribution



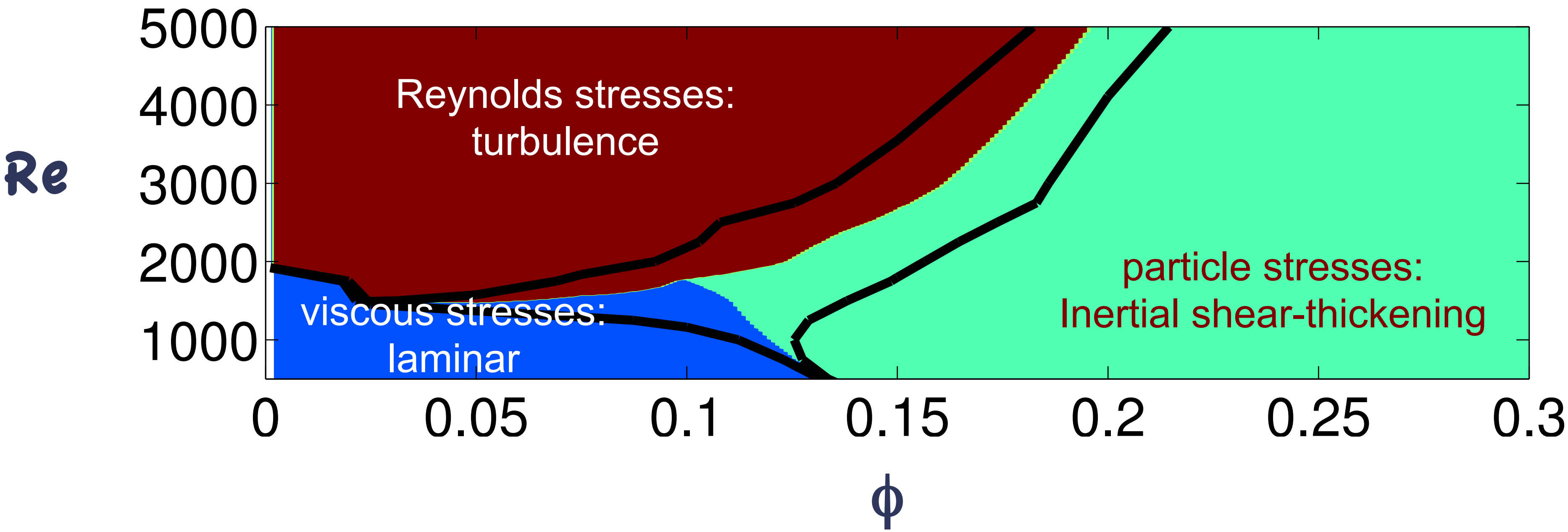


Average viscous stress contribution

Average particle stress contribution



Phase-space diagram



The flow characterized by the stress that gives the largest contribution to the total momentum transfer across the channel (relative majority)

The solid black lines show the boundary of the regions where each term in the stress budget is over 50% of the total stress (absolute majority)

<u>The three states coexist!(democracy)</u>

The idea of inertial shear-thickening

Inertial shear-thickening: an increase of the relative viscosity with the imposed shear rate (Reynolds number) at fixed ϕ without an increase of the Reynolds stresses

Look at the contributions to the total wall friction (dissipation) due to the viscous, particle and Reynolds stresses

The idea of inertial shear-thickening

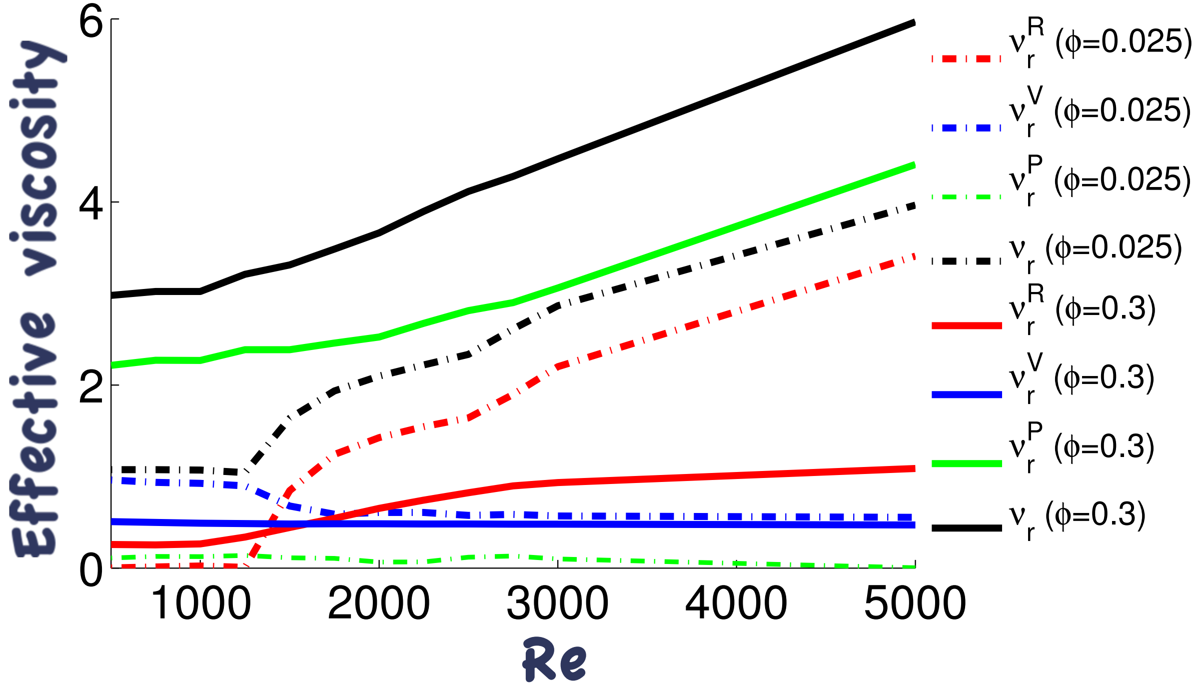
Low ϕ (dashed lines):

Viscous stress dominates until transition, then Reynolds stress dominate

High ϕ (solid lines):

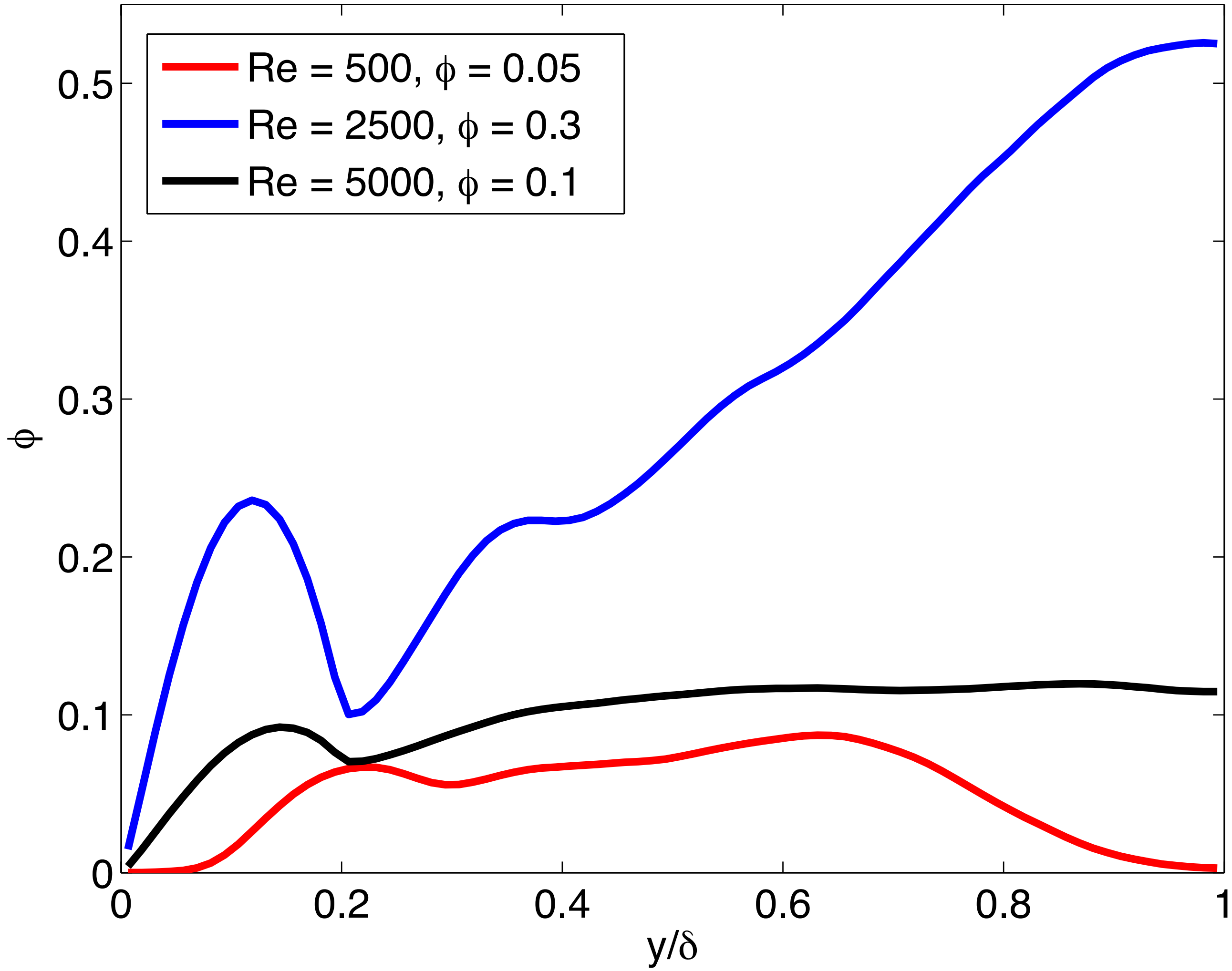
Significant increase of the viscosity related to the particle contribution

Inertial effects for large enough particles!



Contributions to the total wall friction due to the viscous, particle and Reynolds stresses for ϕ=0.025 and ϕ=0.3

Distribution of particles in the wall-normal direction



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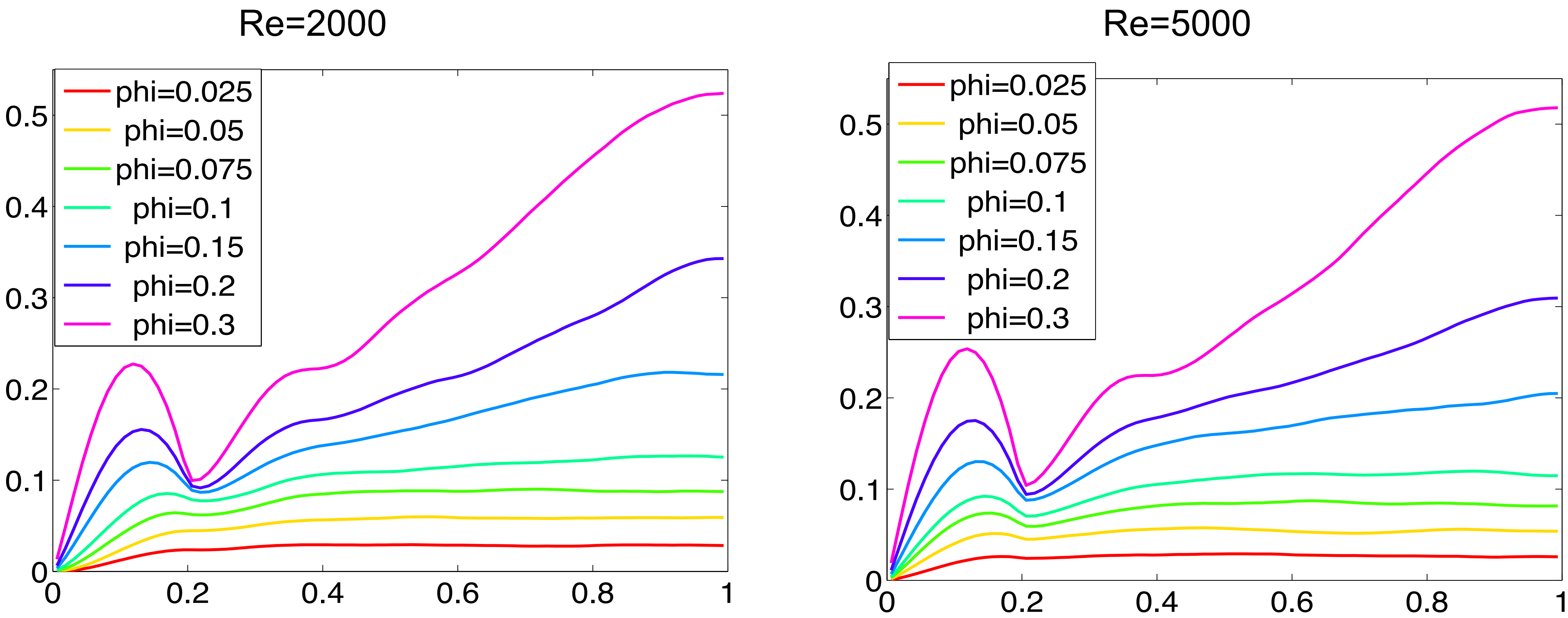
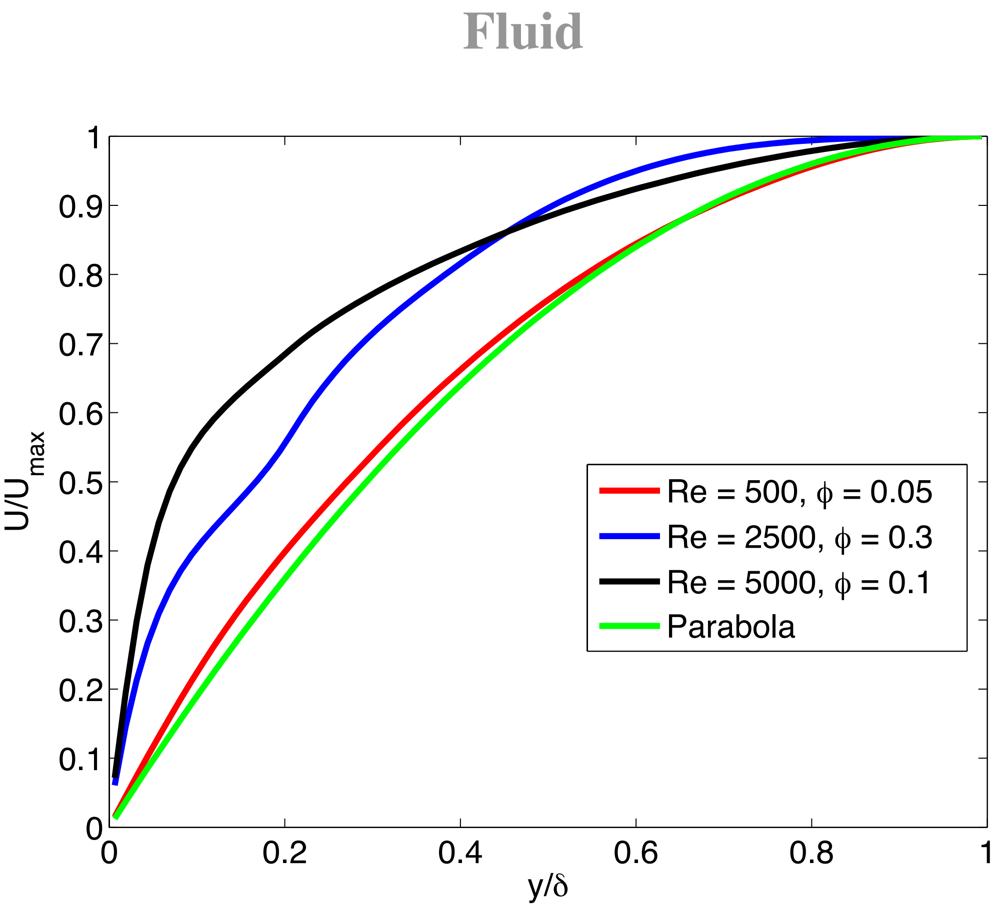
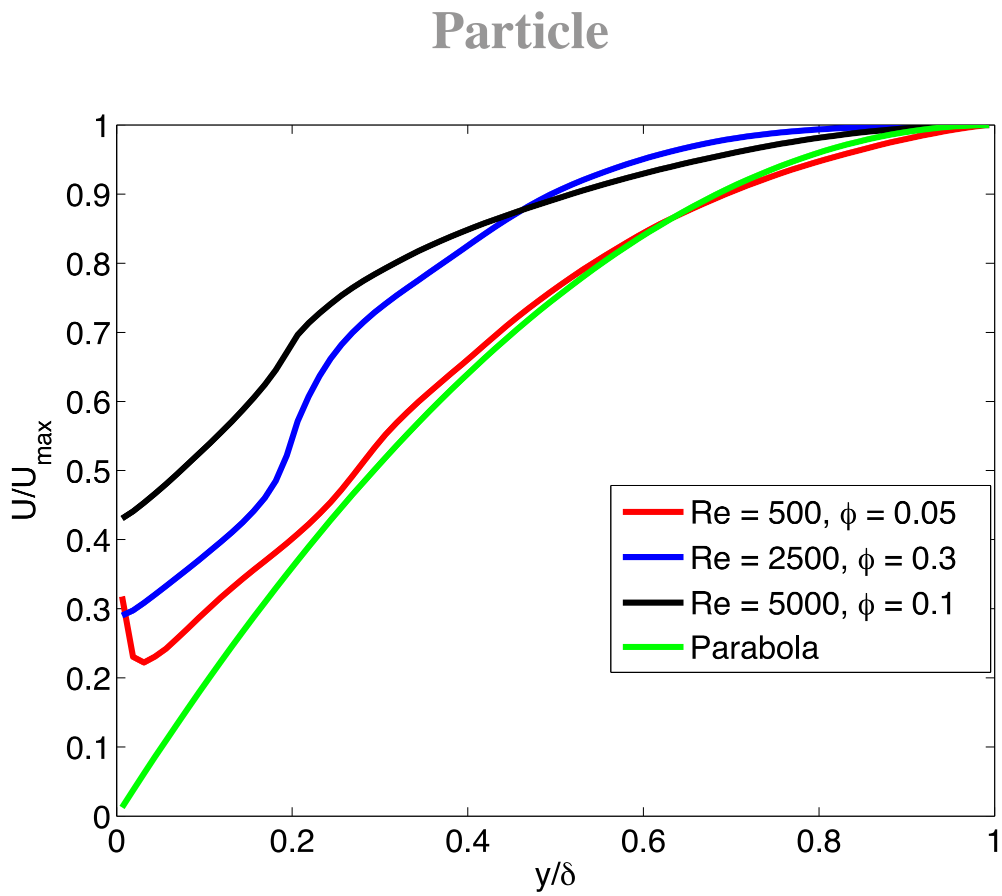
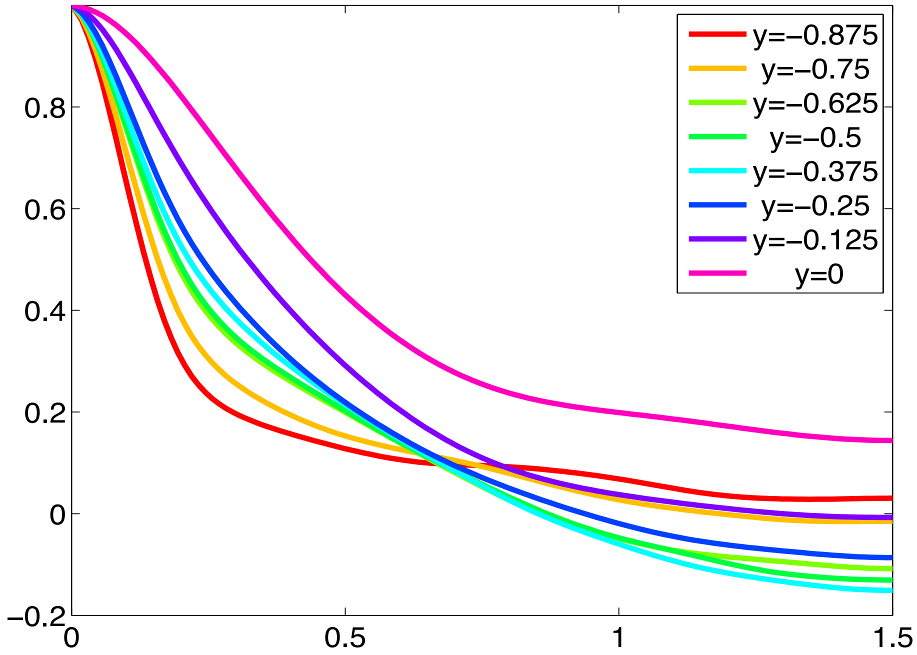


Mean velocity profile

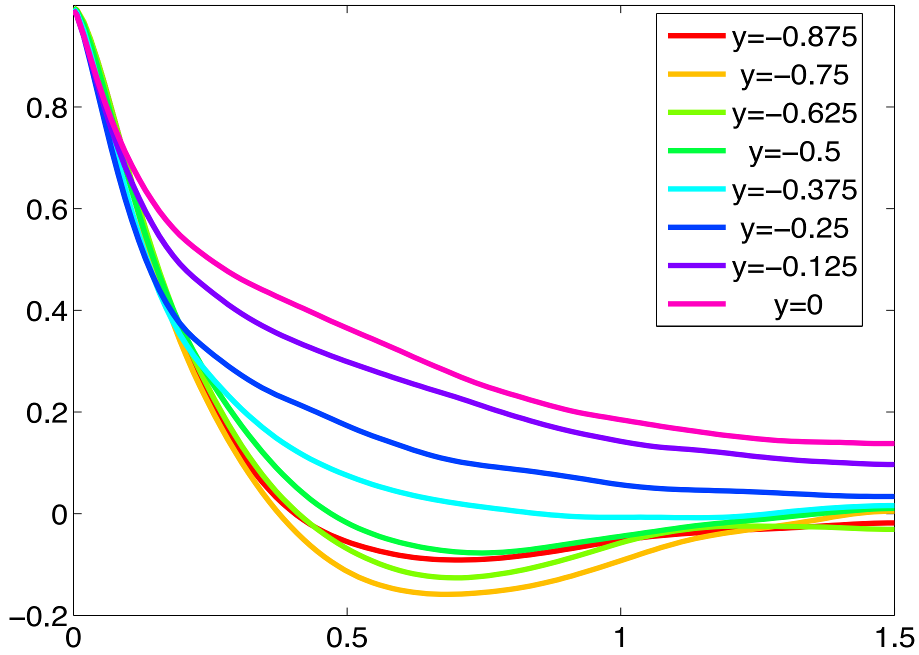




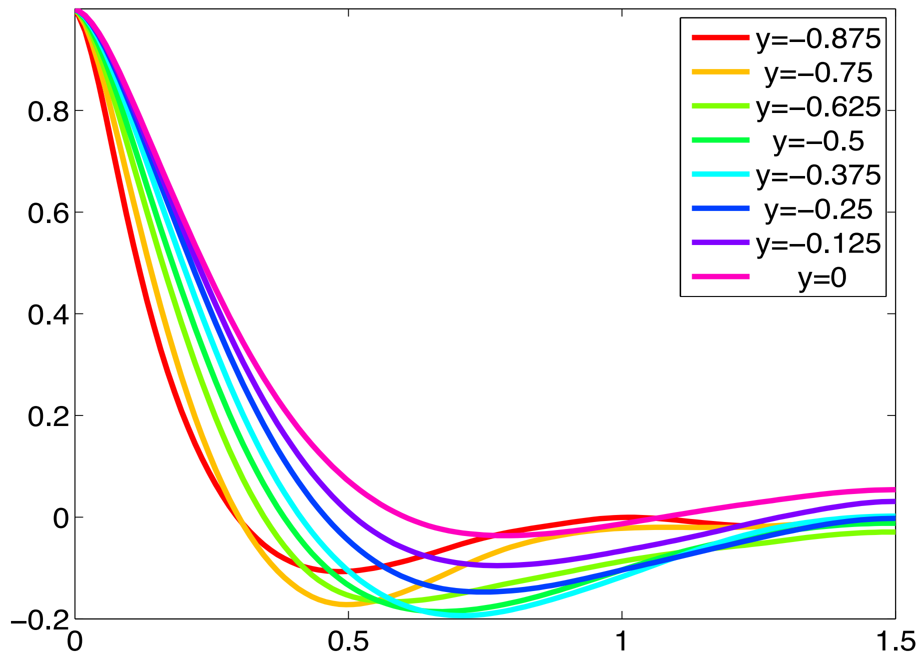
Re=500, Φ=0.05



Re=2500, Φ=0.3



Re=5000, Φ=0.1



Span-wise correlation

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Final remarks

- DNS of channel flow for a range of volume fractions ϕ and Reynolds numbers
- Three different regimes: laminar, turbulent and particle dominated at high ϕ
- Three different states in the presence of a particulate phase, with smooth transitions between them

Final remarks

- Viscous dominated regime at low Reynolds numbers and particle volume fractions

- Turbulent regime with increased dissipation and mixing due to Reynolds stress

- Particulate regime: intense form of continuous inertial shear thickening, induced by inertial effects at the particle size at large enough nominal volume fractions