DNS OF TURBULENT CHANNEL FLOWS LADEN WITH FINITE-SIZE PARTICLES AT HIGH VOLUME FRACTIONS

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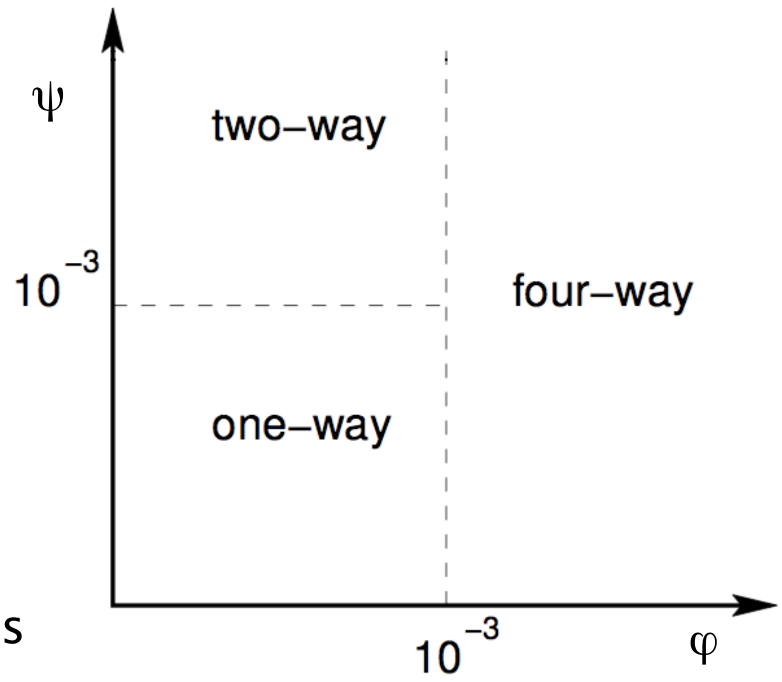
Suspensions of solid particles: Applications

- 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 suspensions

- Different coupling mainly depending on
  - ✓ Volume fraction ϕ
  - ✓ Mass fraction $\psi = \varrho_p / \varrho_f \, \phi$



- 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

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

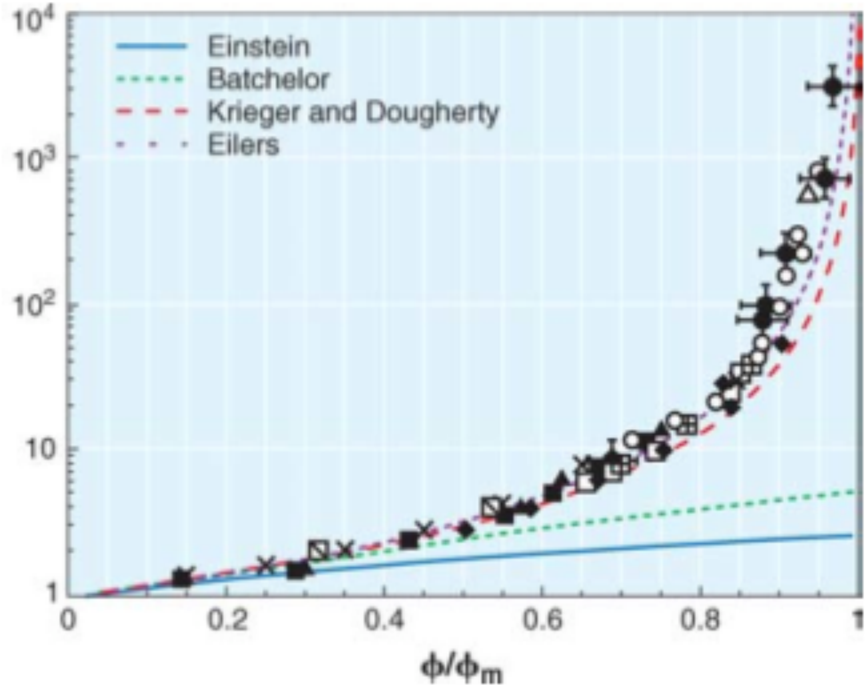
  Fully resolved particle simulations

Laminar suspensions of non-Brownian inertia-less spheres

- For athermal inertia-less spheres $(Pe > 10^3, Re < 10^{-3})$,

  the effective viscosity of the suspension:

  - Depends only on the volume fraction
  - $\mu_e/\mu_0 = \mu_r(\phi)$



- Expressions for viscosity:
  - Einstein formula for dilute limit:

    $\mu_r = 1 + 2.5\phi + O(\phi^2)$
  - Eilers' fitting:

$$\mu_r = \left(1 + \frac{1.25\phi}{1 - \phi/\phi_m}\right)^2$$

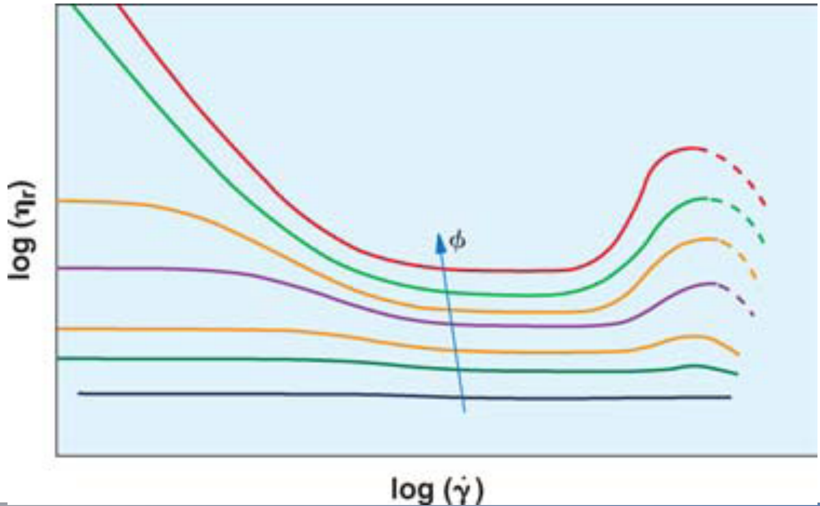
STICKEL & POWELL ARFM 2005

MORRIS & GUAZZELLI 2011

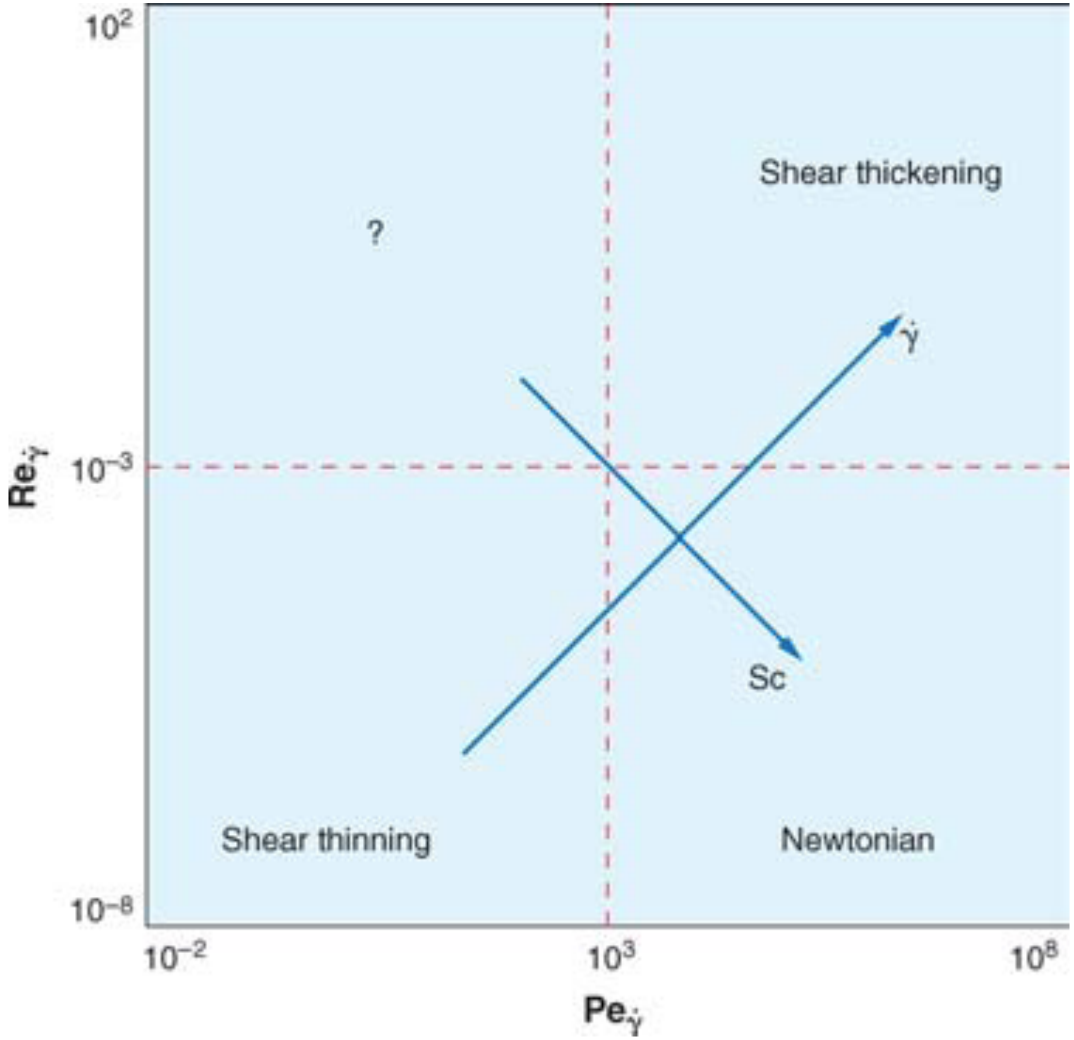
Laminar dense suspensions varying the shear rate

Assuming spherical particles with same density as the fluid:

- Reynolds number: $$Re = \frac{\rho \dot{\gamma} a^2}{\mu_0}$$
  ✓Inertial effects
- Peclet number: $$Pe = \frac{6\pi \mu_0 \dot{\gamma} a^3}{kT}$$
  ✓Brownian motions
- Volume fraction: $$\phi = n\,(4\pi/3)\,a^3/\mathcal{V}$$



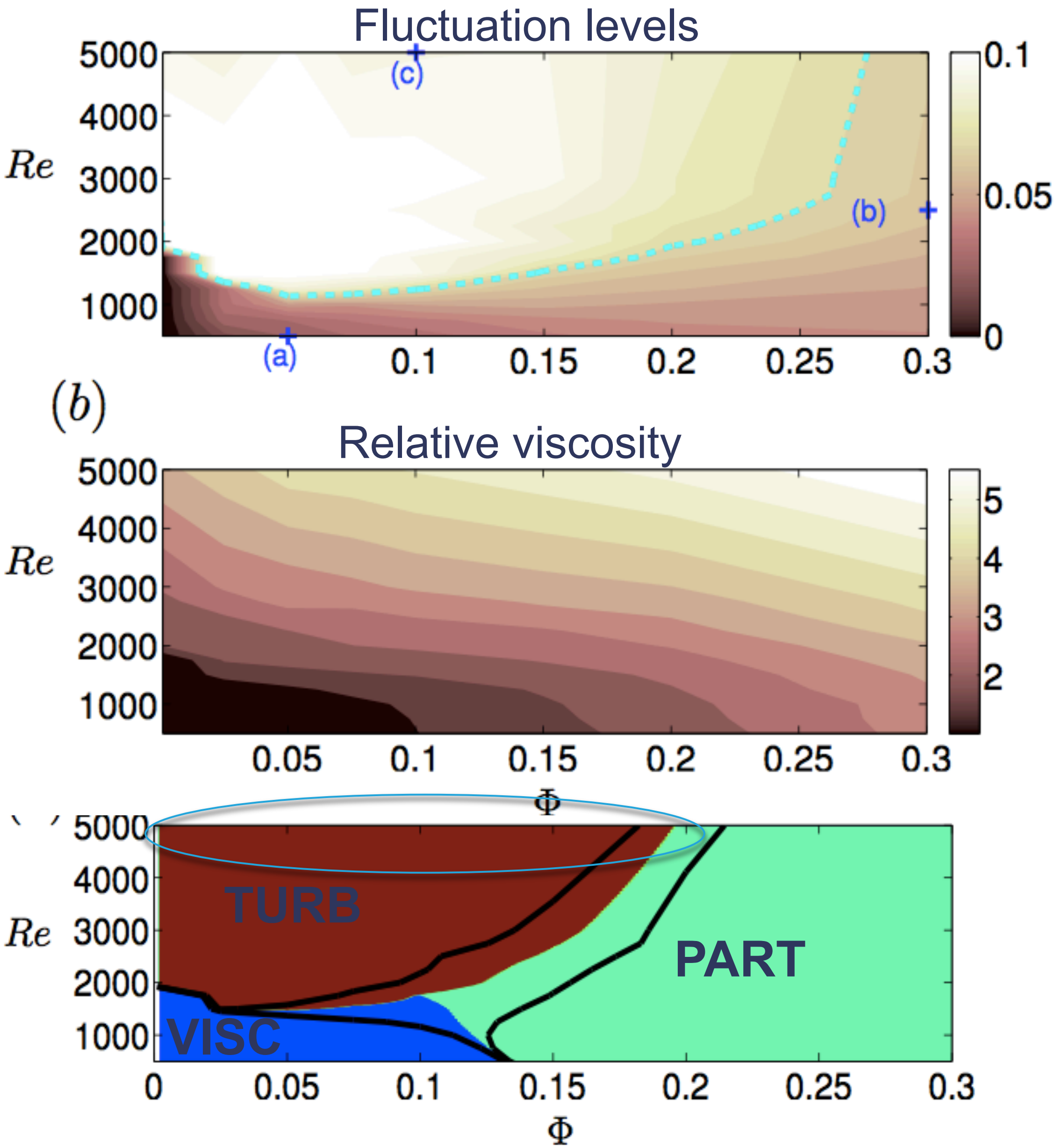
Phase-diagram of dense suspension



STICKEL & POWELL ARFM 2005

Regime diagram of inertial suspensions in a channel

LASHGARI ET AL. *ARXIV 2014*



<u>Different regimes:</u>

- ***Viscous-dominated:***
  Laminar regime, but influenced by the solid phase.

- ***Particle-dominated:***
  Particle dynamics strongly affects rheological and macroscopic flow features

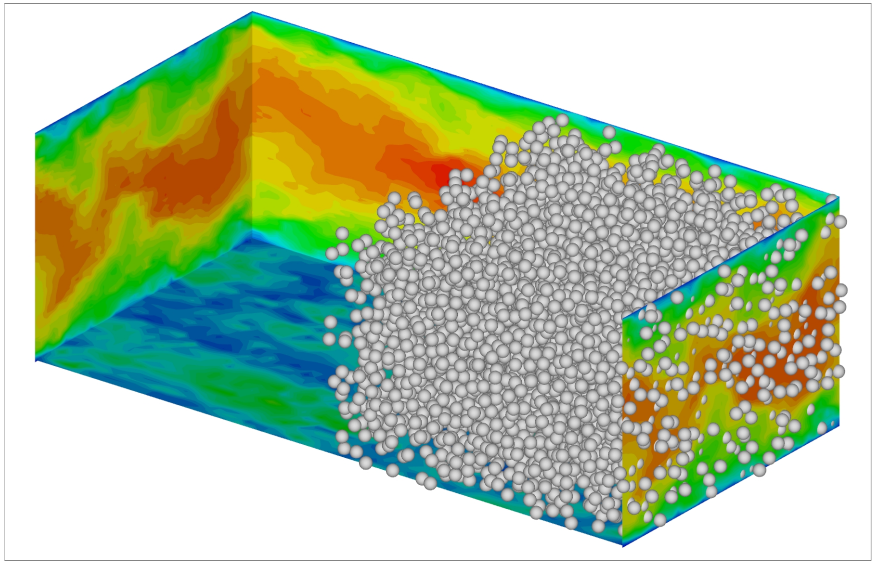
- ***Turbulence-dominated***
  Turbulence is the leading phenomenon, even if modulated by the particle presence…

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

Turbulent channel of particle suspension:
REAL conditions vs DNS conditions

- Pipe diameter: D=0.1-1 m
- Flow Velocity: U_0=1-10 ms^{-1}
- Reynolds number: Re=10^5-10^7
- Friction Reynolds n.: Re_τ=10^4-10^5
- Viscous length $\delta_\nu = D/Re_\tau$=1-100 μm
- Particle size d=1-1000 μm

- Particle size/ Viscous length d^+=1-1000
- Particle size/ Pipe Diameter d/D=10^{-6}-10^{-2}



Matching on the inner scales:

- Particle size/ Viscous length d^+= 20
- Particle size/ Channel width d/2h= 5 10^{-2}

- Channel width : 2h=0.01 m
- Flow Velocity: U_0=0.5 ms^{-1}
- Reynolds number: Re=5600
- Friction Reynolds n.: Re_τ=180
- Viscous length $\delta_\nu = h/Re_\tau$= 28 μm
- Particle size d=550 μm

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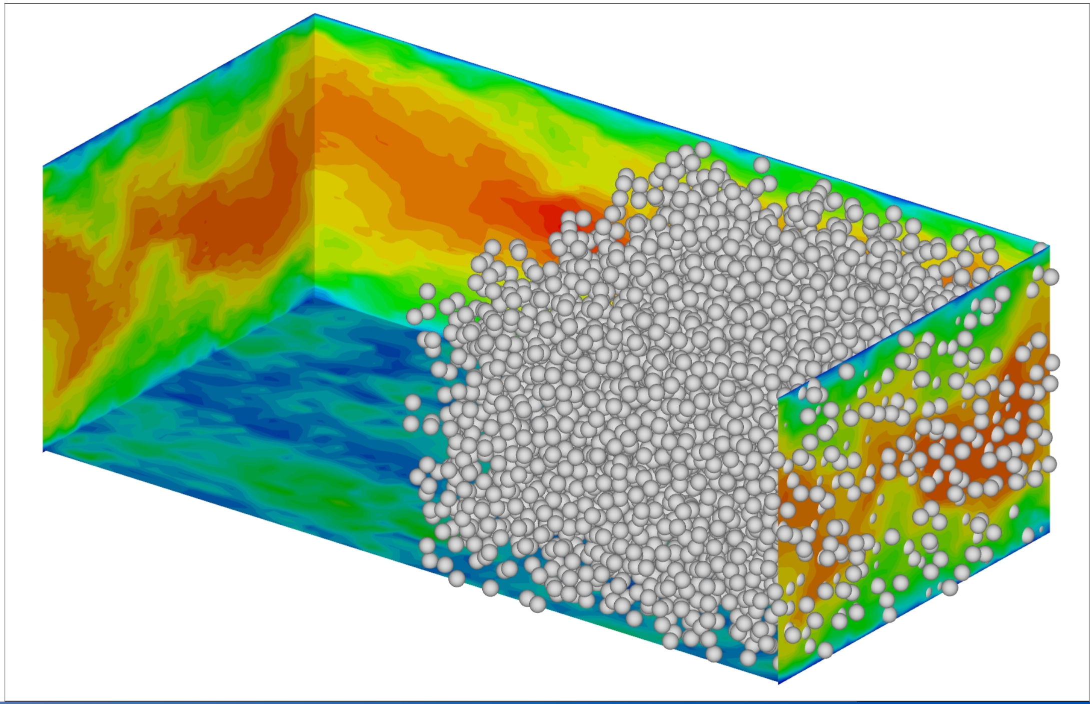
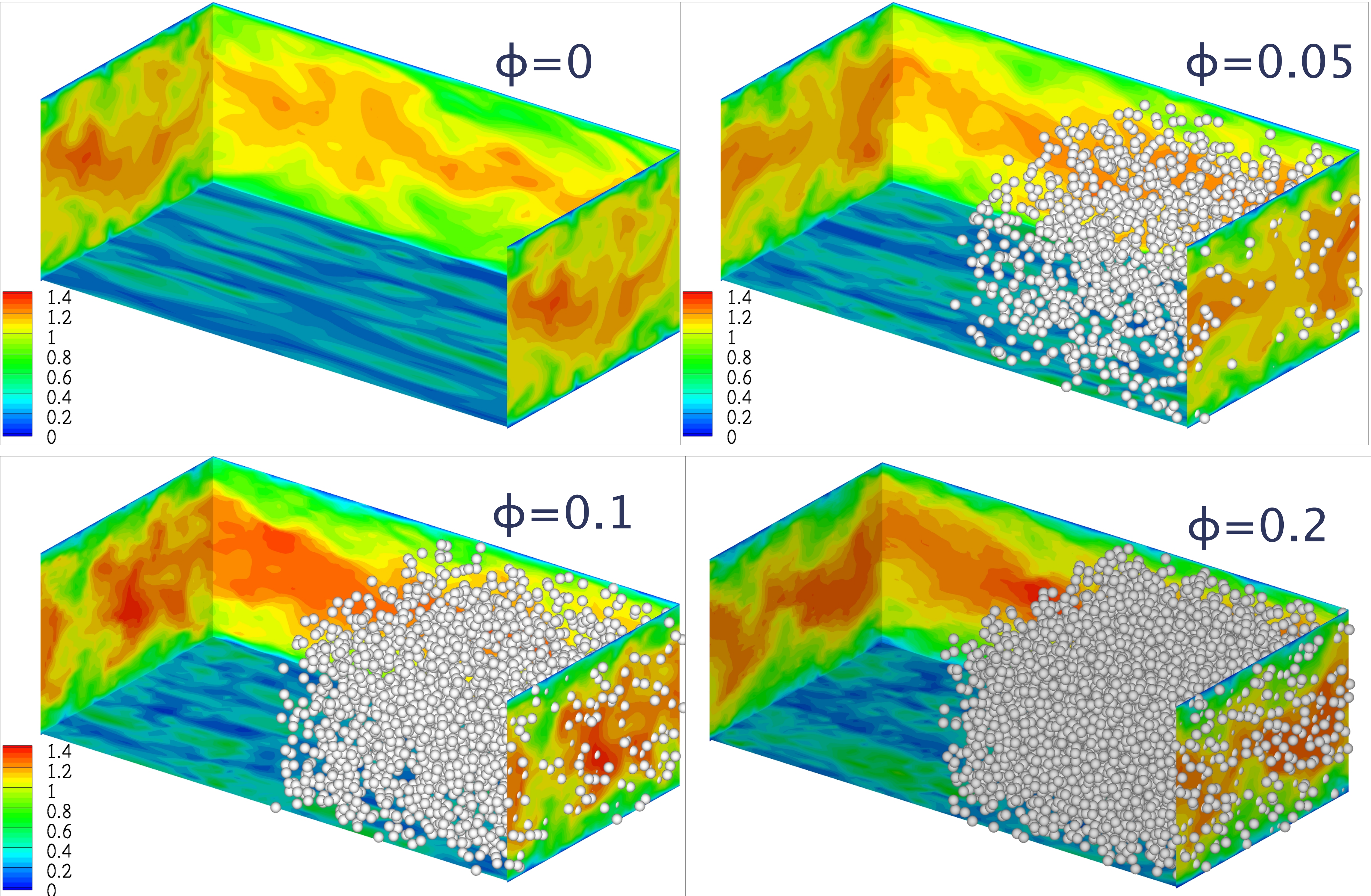
Turbulent channel flow simulations

- Volume fractions $\varphi=[0, 0.05, 0.1, 0.2]$
- Bulk Reynolds number: $Re_b=U_0 2h/\nu=5600$
- Friction Reynolds number $Re_\tau=180$ $(\phi=0)$
- Domain size $(x=6h,\ y=2h,\ z=3h)$
- Up to 10000 finite size particles
- Particle radius $a=h/36$ $(a^+\approx 10)$
- Mesh (864, 288, 432), 8 points per a
- Immersed Boundaries Method

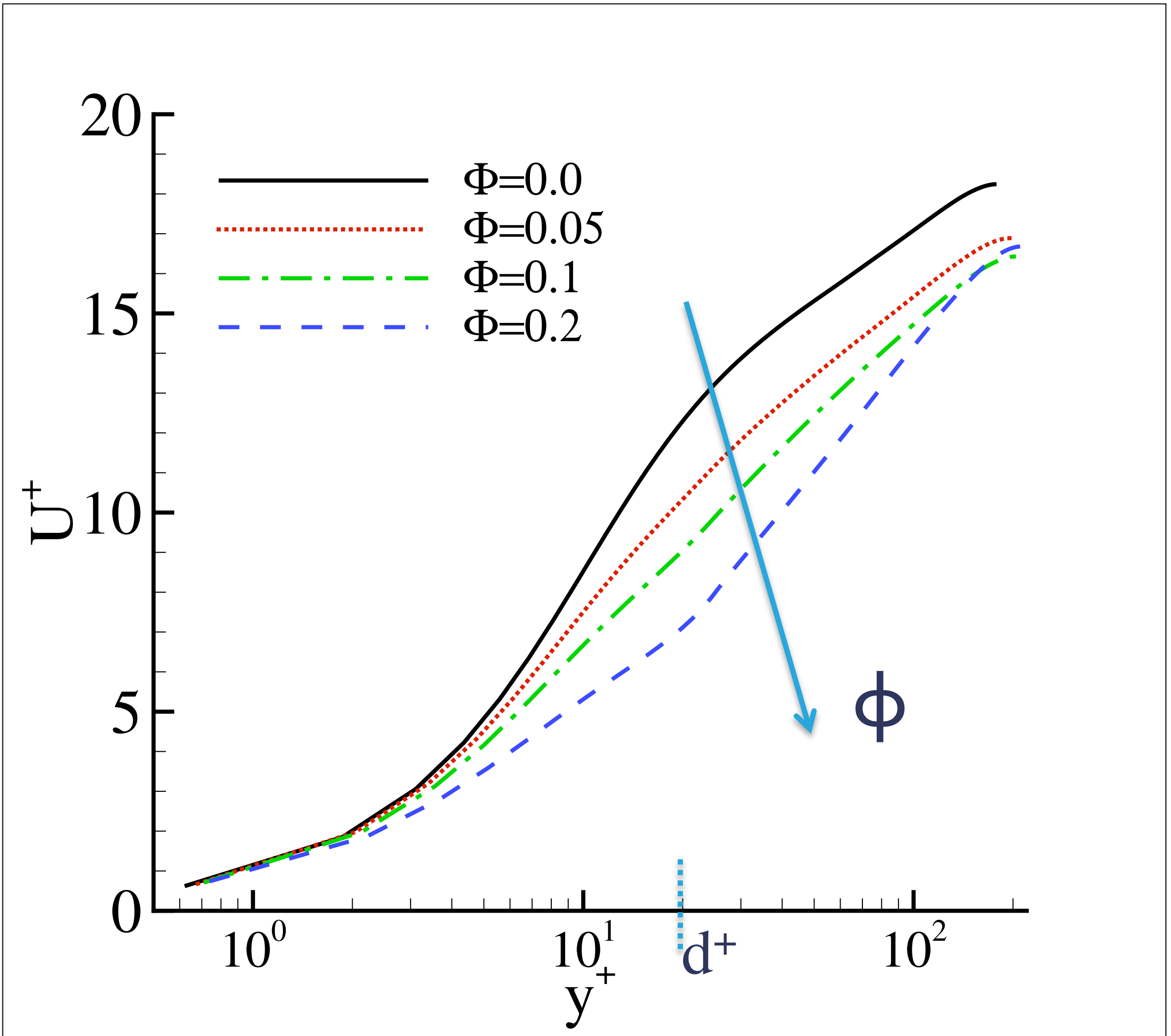


BREUGEM JCP 2012
LAMBERT ET AL JFM 2013
PICANO ET AL PRL 2013

Turbulent channel flow instantaneous snapshots



Mean fluid velocity (rescaled in inner units)



Φ	**0**	**0.05**	**0.1**	**0.2**
Re_T	180	195	204	216
1/k	2.5	2.8	3.1	4.5
B	5.5	2.7	0.27	-6.3

$Re_T = U_* h/\nu$ with $U_* = (\tau_w/\rho)^{0.5}$ measures the drag:

the overall drag increases with ϕ

Mean fluid velocity in $y^+=[50\text{-}150]$:

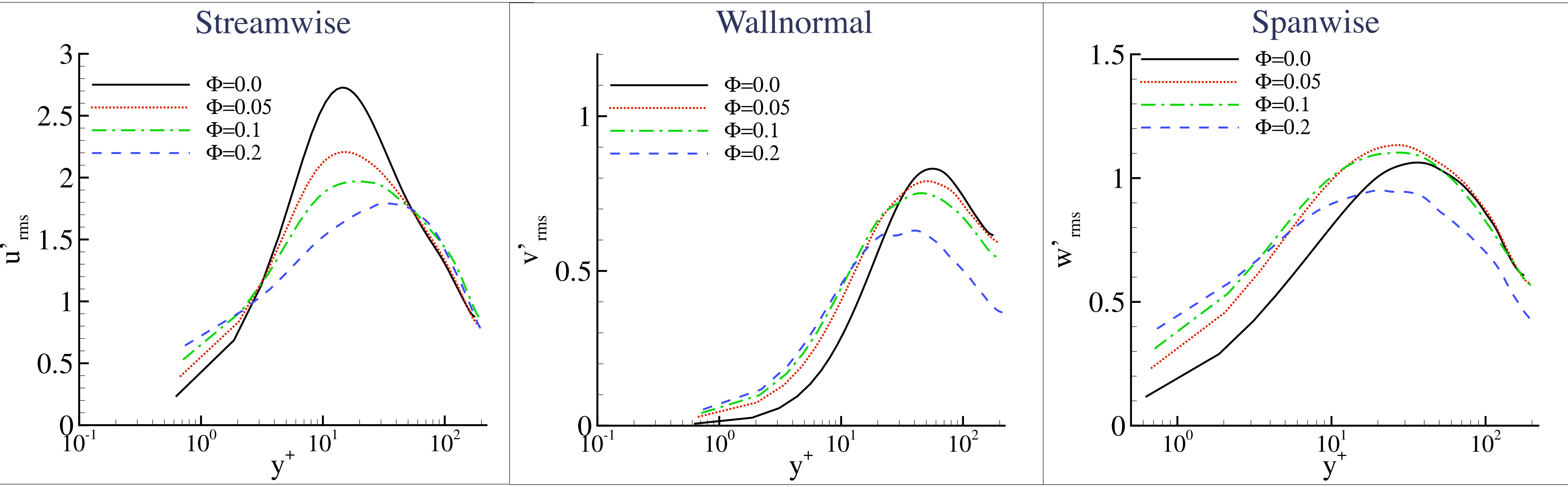
$$U^+ = (1/k)\log(y^+) + B$$

B decreases, but 1/k increases with ϕ:

$U^+ = U/U_*$; $y^+ = y/(\nu/U_*)$

Drag reduction at higher Re with wider log layers?

Turbulent fluid velocity fluctuations



The streamwise fluctuation peak strongly decreases with ϕ and move outwards

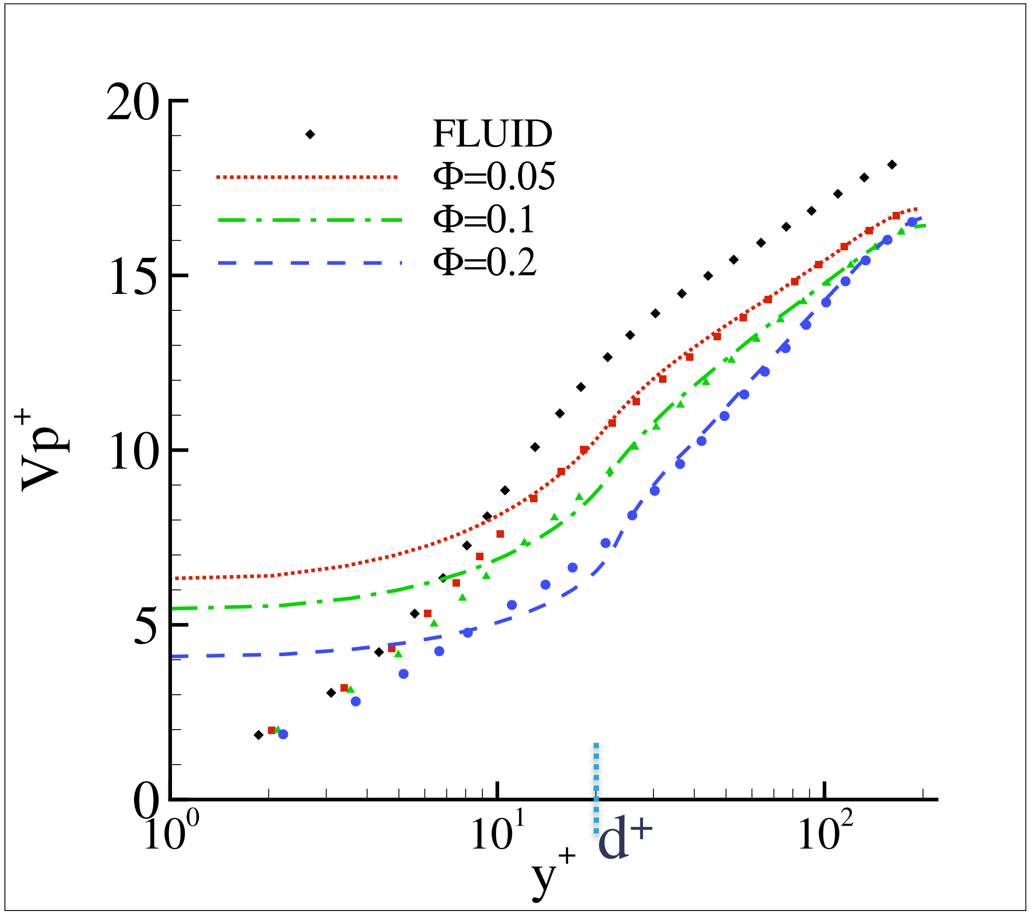
The wall-normal fluctuation peak decreases and moves inwards

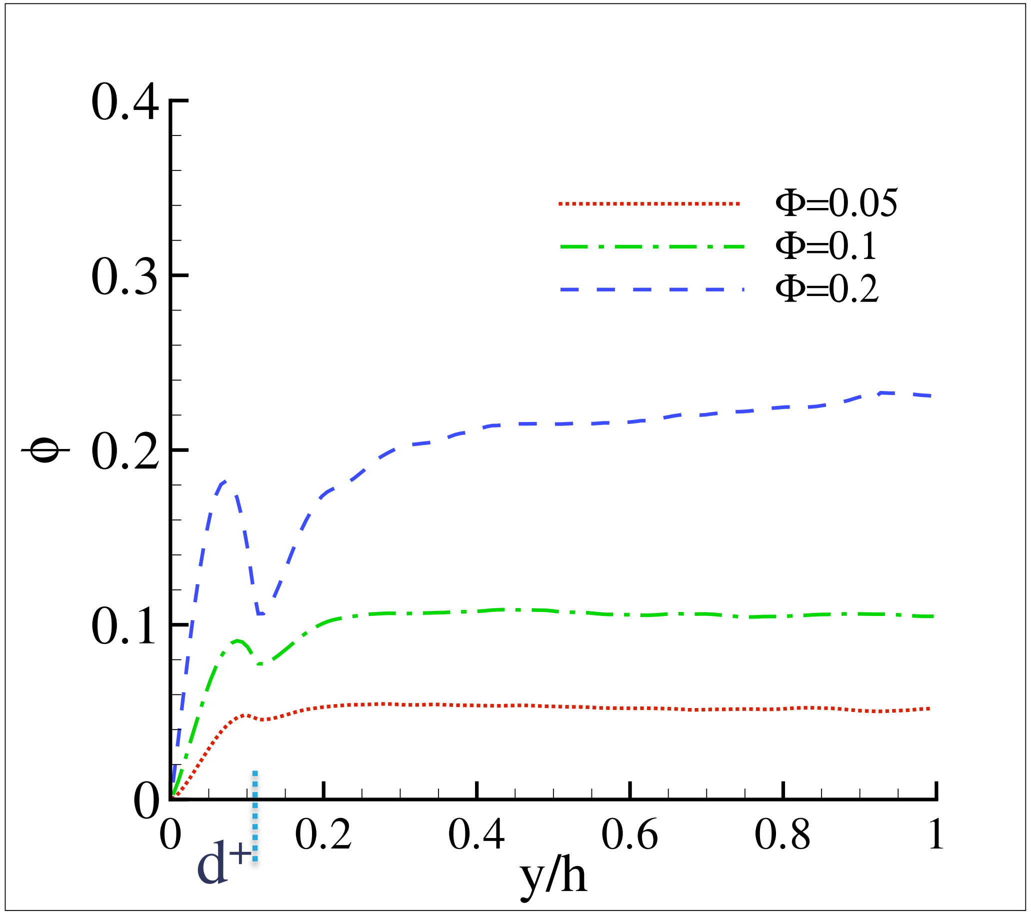
The spanwise peak moves inwards, increases up to ϕ=0.1 then decreases

Close to the wall, all fluctuations increases: *particle layering and wall interaction*

✓ *The denser case ϕ=0.2 shows a strong change of turbulence features in the entire channel*

Particle concentration and mean velocity





Mean particle and fluid velocity are almost identical since $y^+ \approx 20 \approx d^+$

Particle wall-layering is present, the first layer moves with an almost constant velocity that decreases with ϕ

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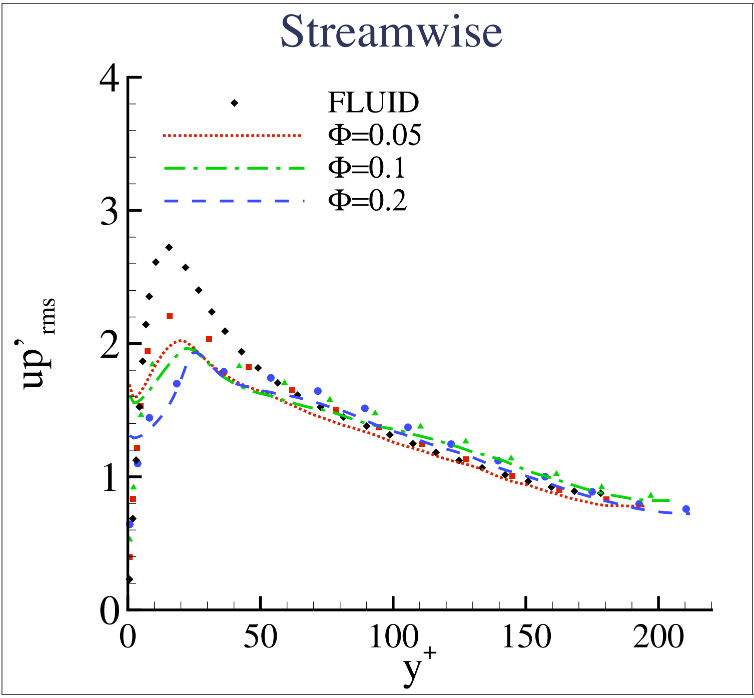
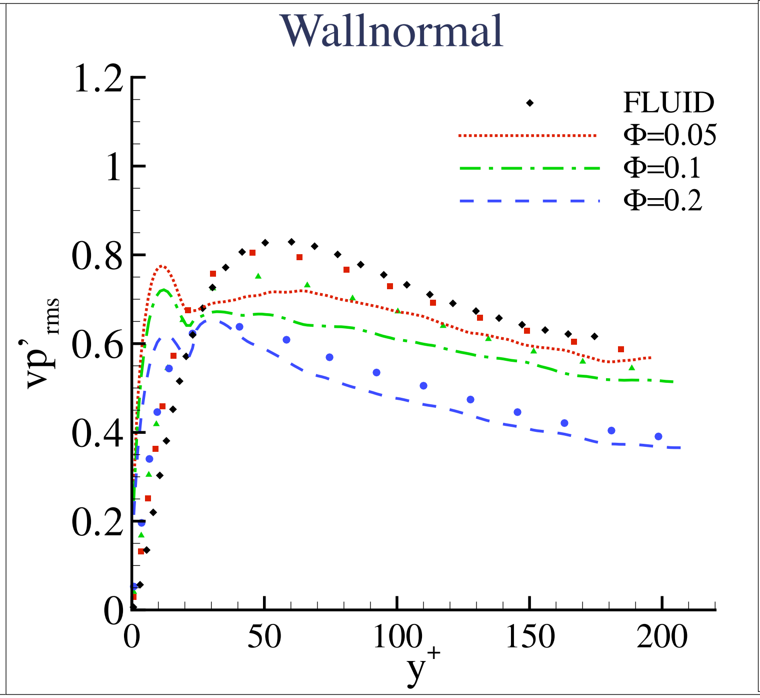
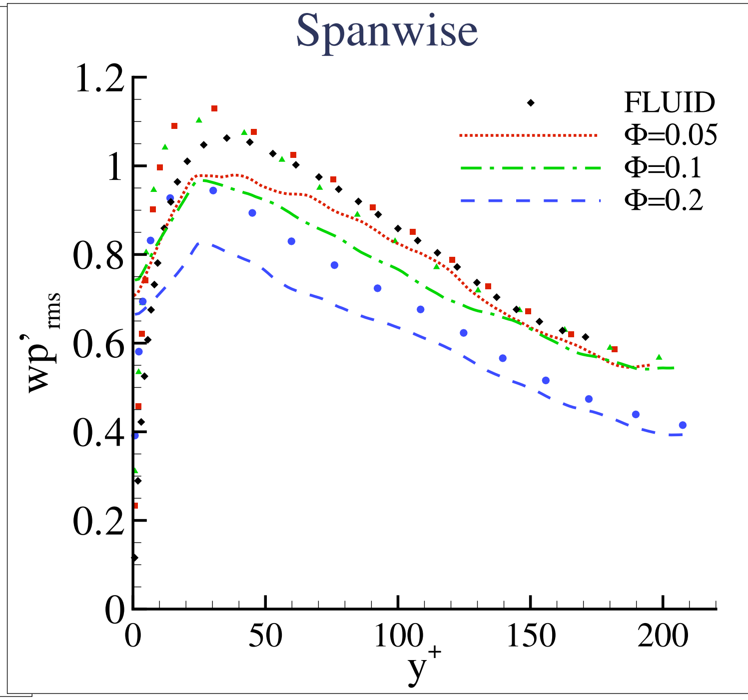
Particle velocity fluctuations







The particles usually fluctuate less than the fluid in the bulk region, but more in the near wall region.

The particle-wall interaction enhances the particle velocity fluctuations especially in the wall-normal direction

Mean Momentum equation

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

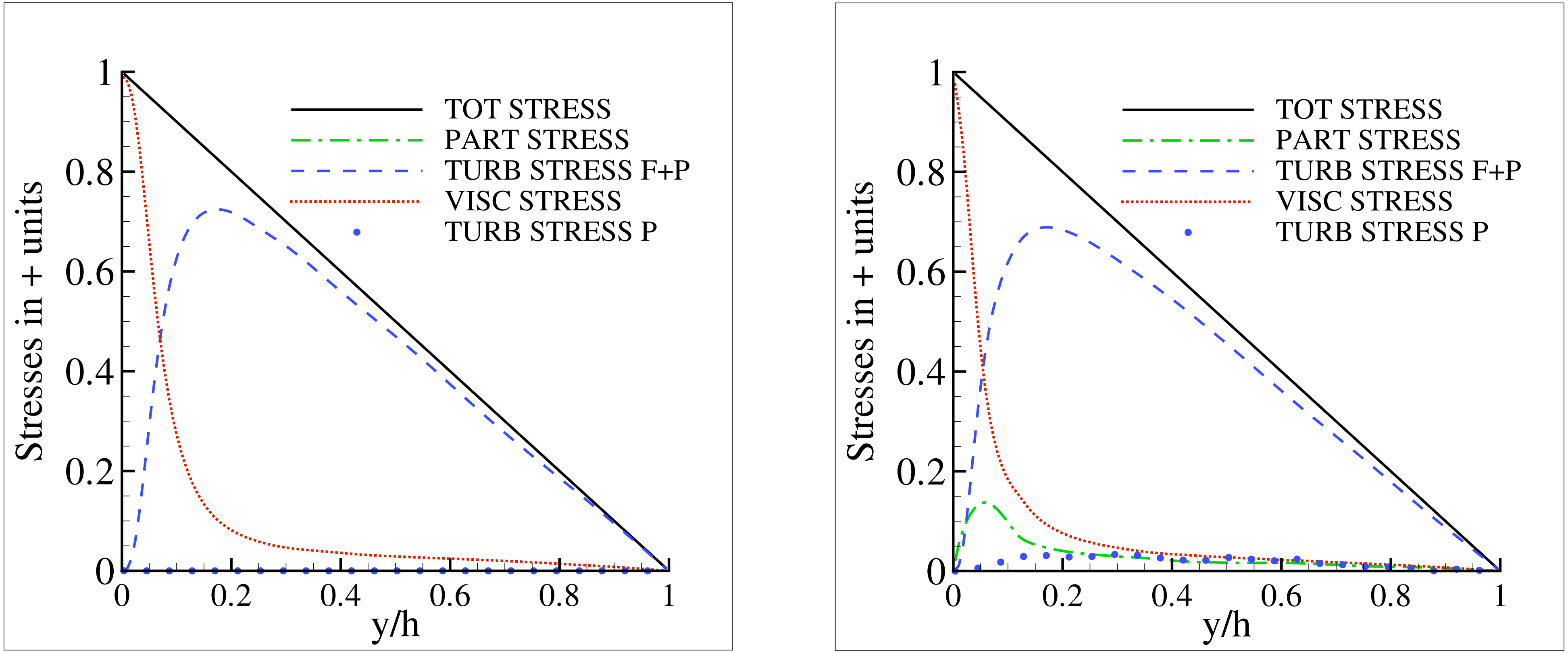
$$\tau(y)=-(1-\phi)<u^fv^f>-\phi<u^pv^p>+\nu(1-\phi)\frac{\partial U^f}{\partial y}+\frac{\phi}{\rho}<\sigma^p_{xy}>=\nu\frac{\partial U^f}{\partial y}\Big|_w(1-\frac{y}{h})$$

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

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

Momentum balance (normalized by $U_*^2=\tau_w/\rho$)

- Single phase and ϕ=0.05



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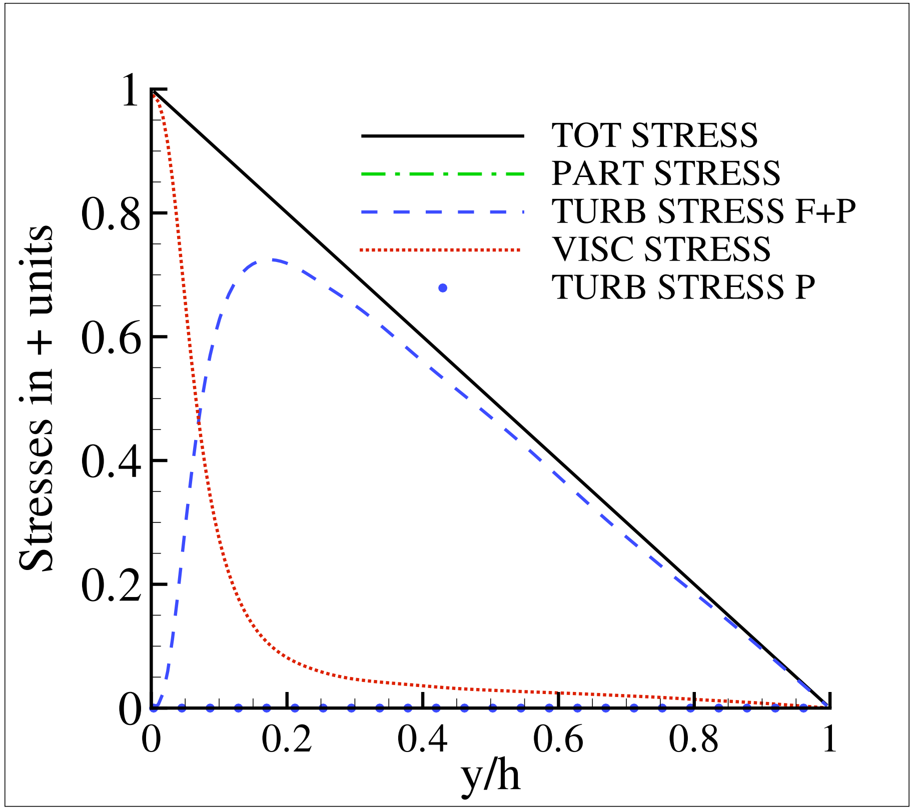
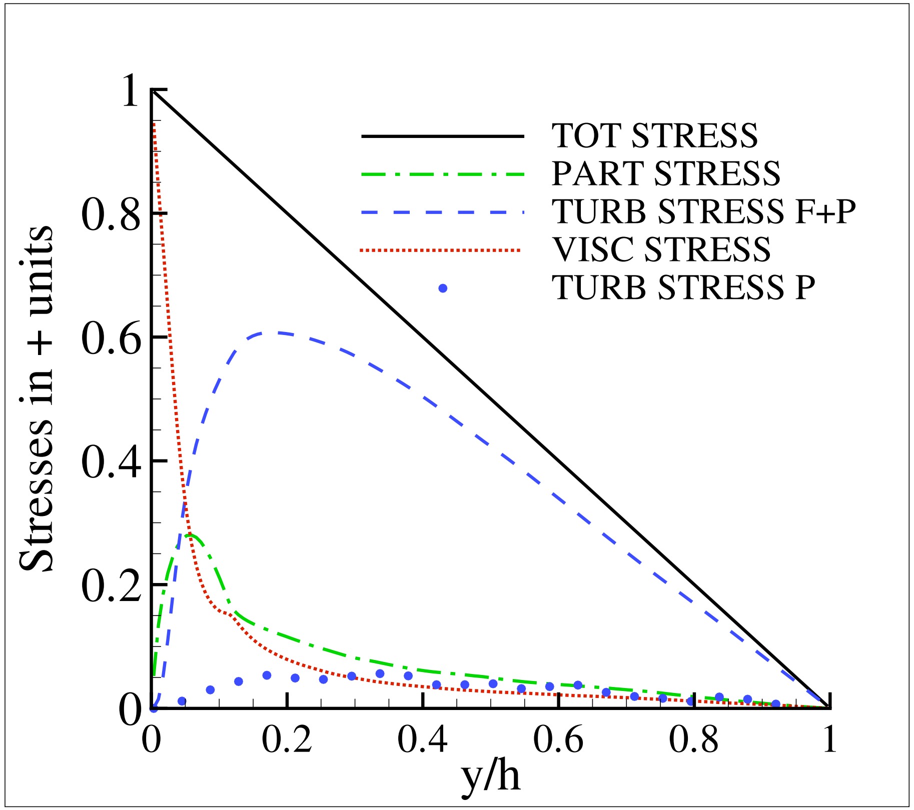
Momentum balance (normalized by $U_*^2=\tau_w/\rho$)

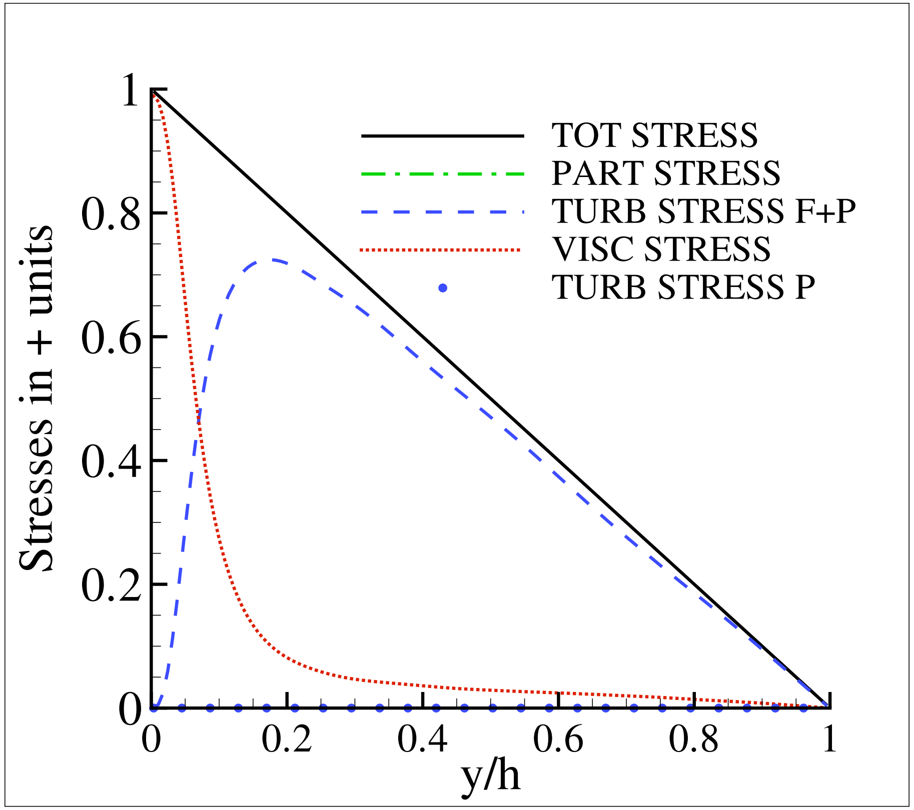
- Single phase and ϕ=0.1

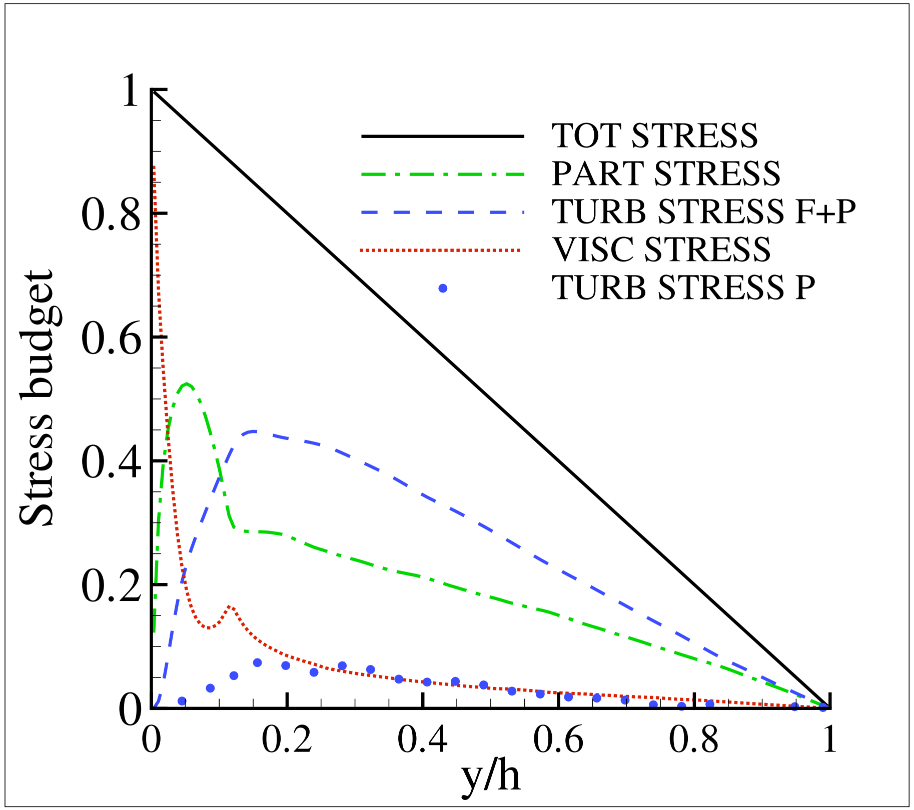


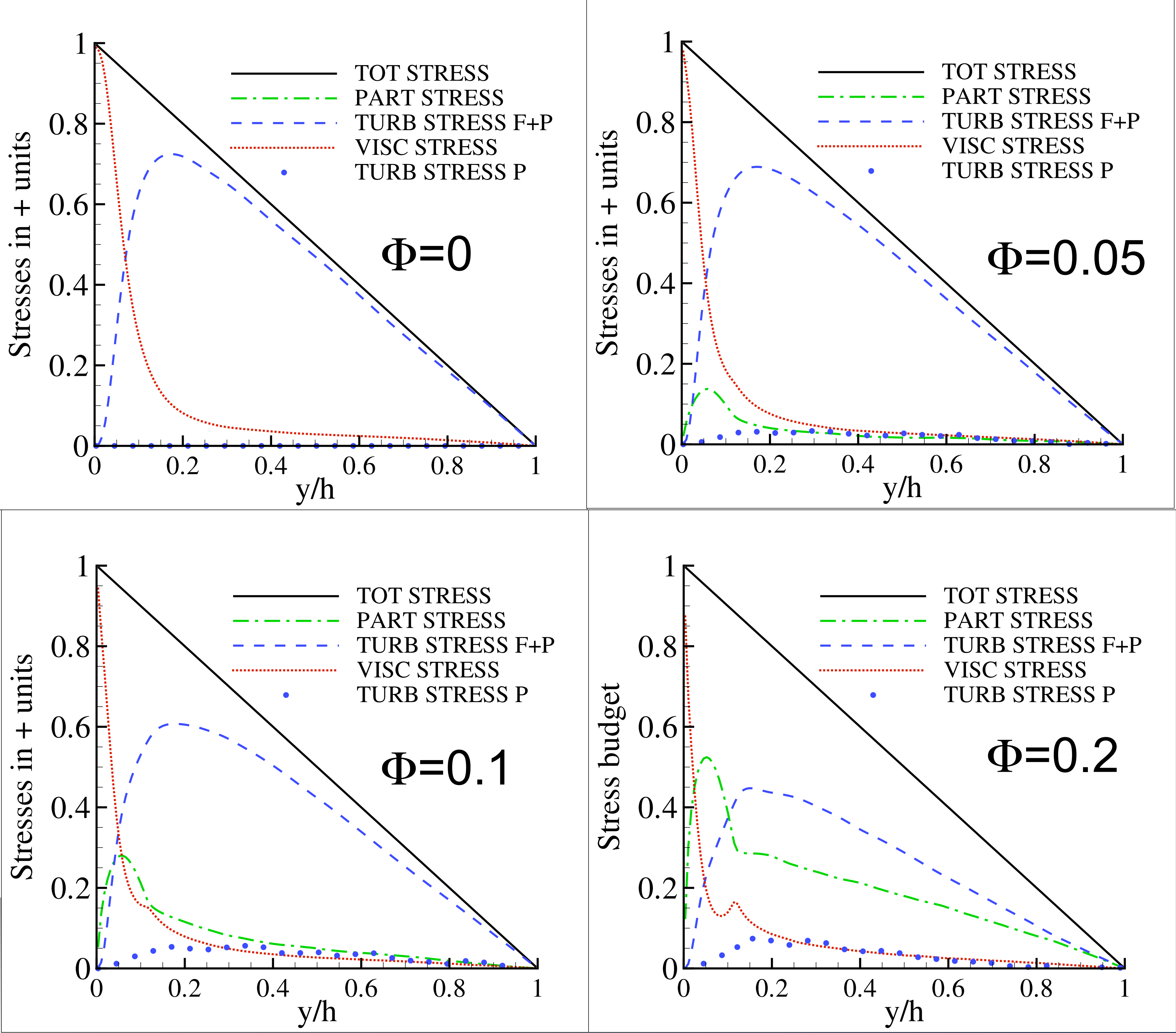


Momentum balance (normalized by $U_*^2=\tau_w/\rho$)

- Single phase and ϕ=0.2

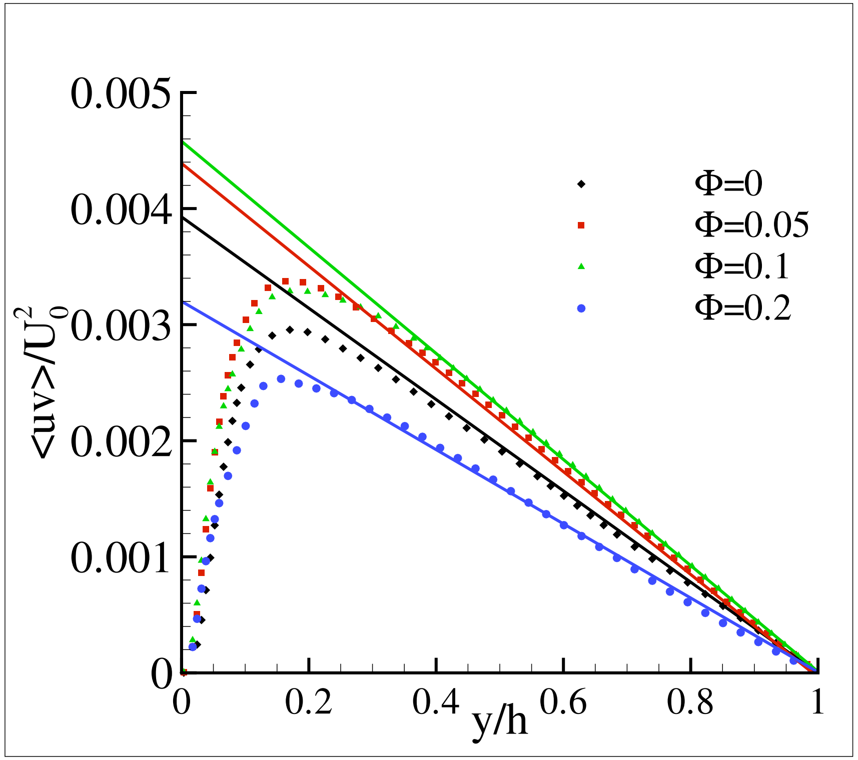


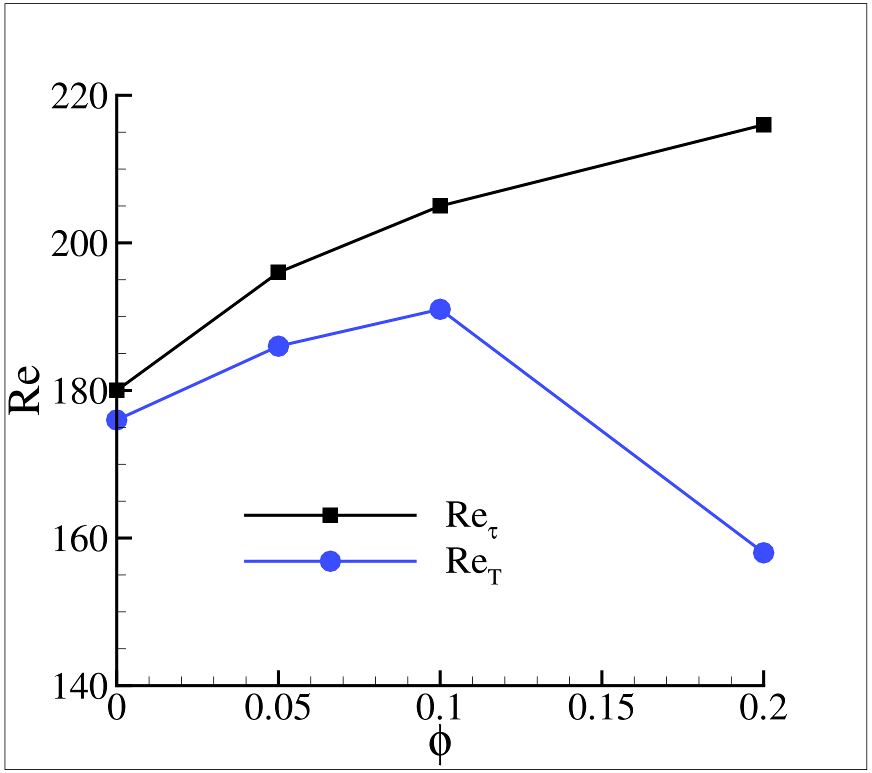




Φ=0
Φ=0.05
Φ=0.1
Φ=0.2
TOT STRESS
PART STRESS
TURB STRESS F+P
VISC STRESS
TURB STRESS P
Stresses in + units
Stress budget
y/h
0
0.2
0.4
0.6
0.8
1

Total drag increases, but Turbulent Drag reduction at ϕ=0.2





$$u_*^2|_{turb} = \frac{d}{dy}(< u^t v^t >)|_{y=0}$$

At ϕ=0 $u_*^2|_{turb} = u_*^2 + O(1/Re_h)$

The *turbulent* friction Reynolds number:

$$Re_T = u_*|_{turb}\, h/\nu$$

increases up to ϕ=0.1, but strongly decreases at to ϕ=0.2: Reduced turbulence activity at high ϕ

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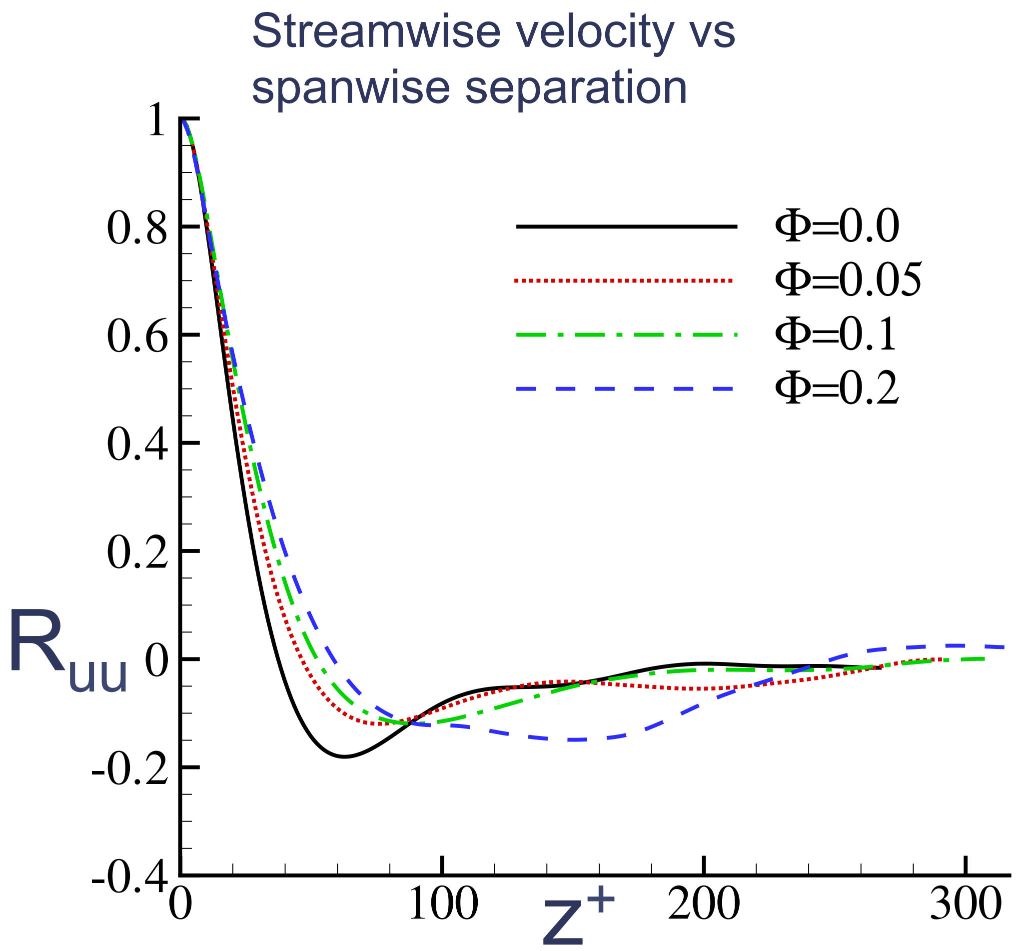
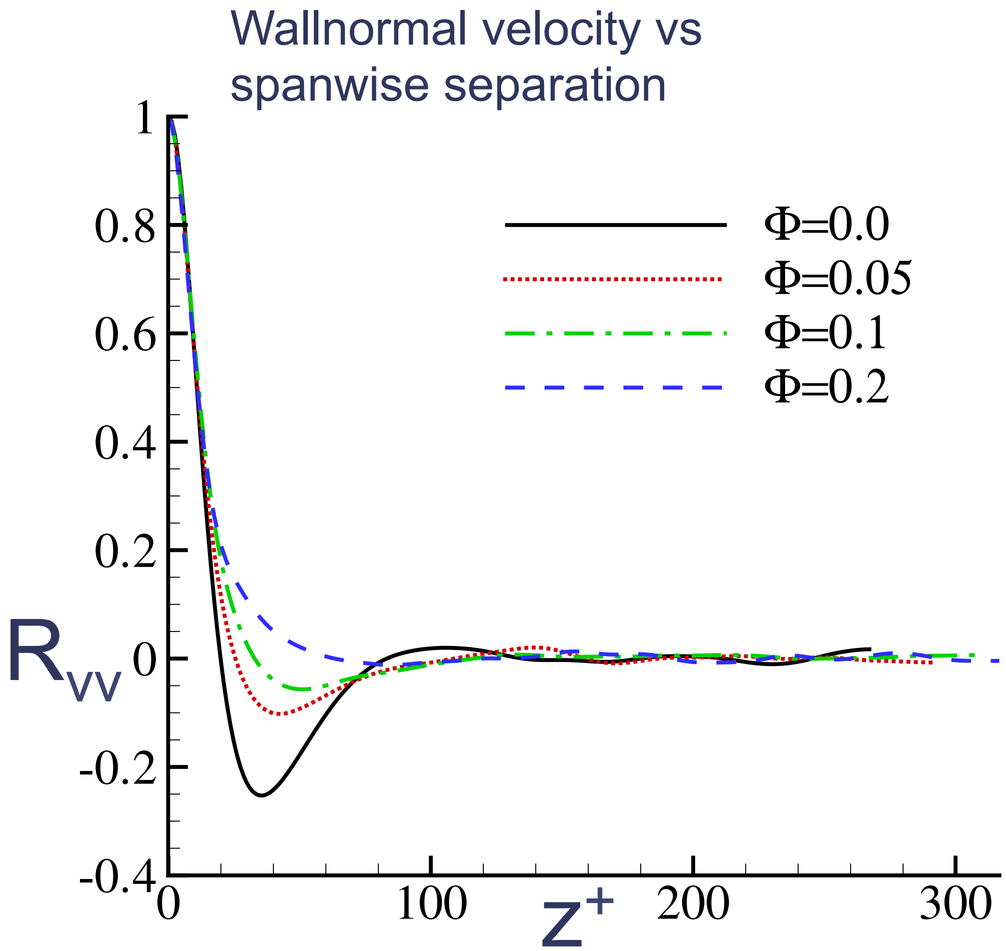
Structure of wall turbulence: Velocity correlations at $y^+ \approx 20$

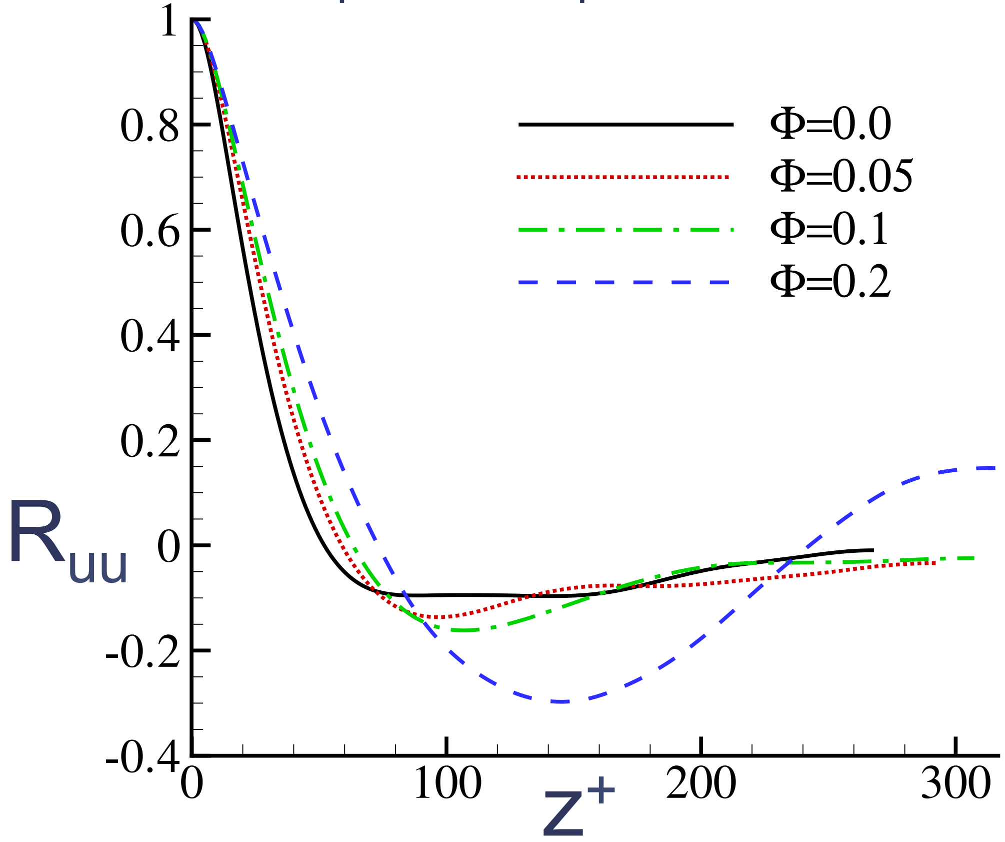




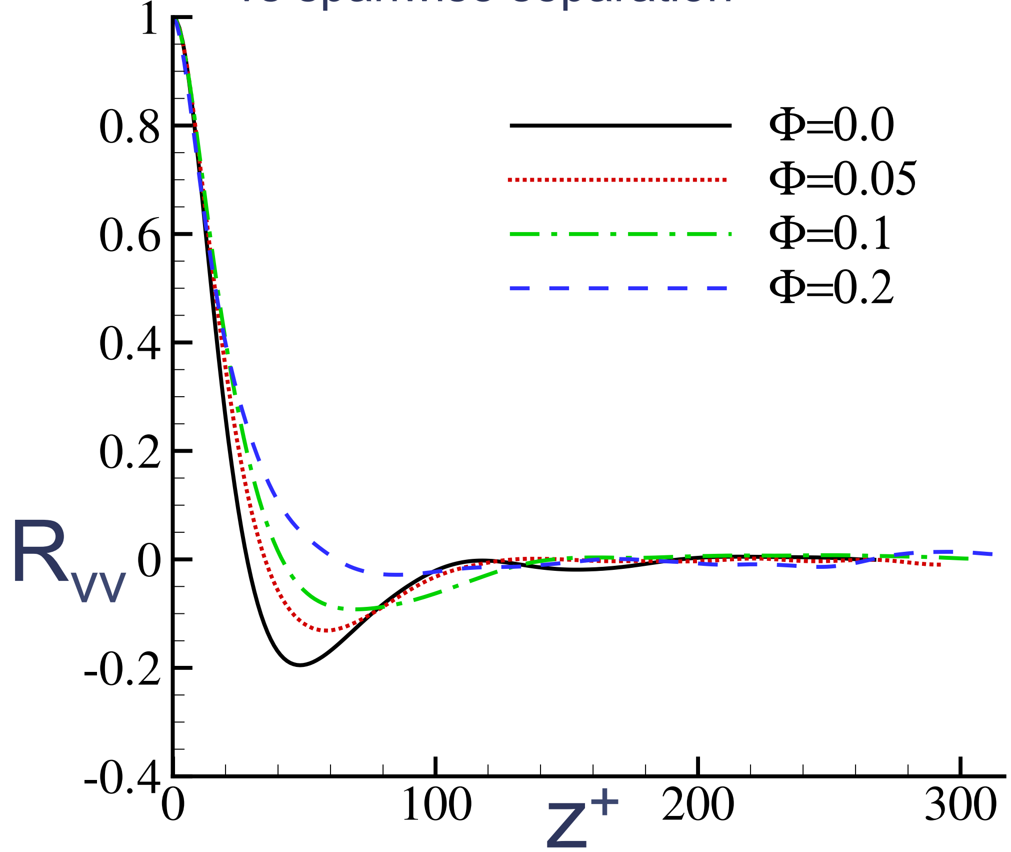
Weaker and wider streaks increasing the volume fraction

Structure of wall turbulence: Velocity correlations at $y^+ \approx 40$

Streamwise velocity correlation
vs spanwise separation



Wallnormal velocity correlation
vs spanwise separation



ϕ=0.2--> Formation of super-streaks (twice wider) without wallnormal correlation: Drag reduction??

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Final remarks

- DNS of channel flow at high volume fractions φ=0.2

- Total Drag (Friction Reynolds number) increases with φ

- The turbulence activity measured by Reynolds stress increases up φ=0.1, but reduces at φ=0.2

- The attenuated turbulence at φ=0.2 induces a strong reduction of the Von Karman constant k: *Drag reduction at high Reynolds number?*

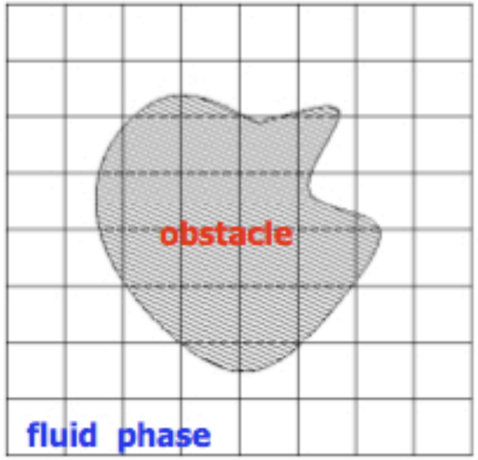
Effective viscosity, Friction velocity & Reynolds number

Immersed Boundary: a brief description

- No direct imposition of boundary conditions, but instead additional force:

$$\rho_f\left(\frac{\partial \mathbf{u}}{\partial t}+\nabla\cdot\mathbf{uu}\right)=-\nabla p_e-\nabla p+\mu_f\nabla^2\mathbf{u}+\rho_f\mathbf{f}$$

IB force that accounts for presence of solid obstacles (instead of using b.c.'s)



- Pros:
  - simple grids allow use of efficient solvers
  - no regridding needed for moving obstacles
  - "easy" implementation in numerical code
- Cons:
  - imposition of IB forces not straightforward
  - (possible) effects on accuracy, stability, consistency, conservation properties etc of used numerical method

Immersed Boundary Forcing

- Like standard, but with 2nd prediction velocity that includes IB forcing:

$$\underbrace{\left[\underline{u}^{n+1} + \Delta t \cdot \nabla \tilde{p}\right]}_{\underline{u}^{**}} = \underbrace{\underline{u}^{n} + \Delta t \cdot \left(-\nabla p^{n-1/2} + \underline{r}^{n+1/2}\right)}_{\underline{u}^{*}} + \Delta t \cdot \underline{f}^{n+1/2}$$

First prediction velocity:
no account of solid obstacles.

$$\nabla^2 \tilde{p} = \frac{1}{\Delta t} \nabla \cdot \underline{u}^{**}$$

$$\underline{u}^{n+1} = \underline{u}^{**} - \Delta t \cdot \nabla \tilde{p}$$

$$p^{n+1/2} = p^{n-1/2} + \tilde{p}$$

Correction pressure kept small
by updating pressure =>
$\underline{u}^{**} \approx \underline{u}^{n+1}$

- Compute IB force from requirement that at solid boundary:

$\boxed{\underline{u}^{**} = \underline{u}_d \text{ (= desired velocity at solid boundary)}}$

$$\boxed{\underline{f}^{n+1/2}\left(\underline{x}_{ijk}\right) = \frac{\underline{u}_d - \underline{u}^{*}}{\Delta t}}$$