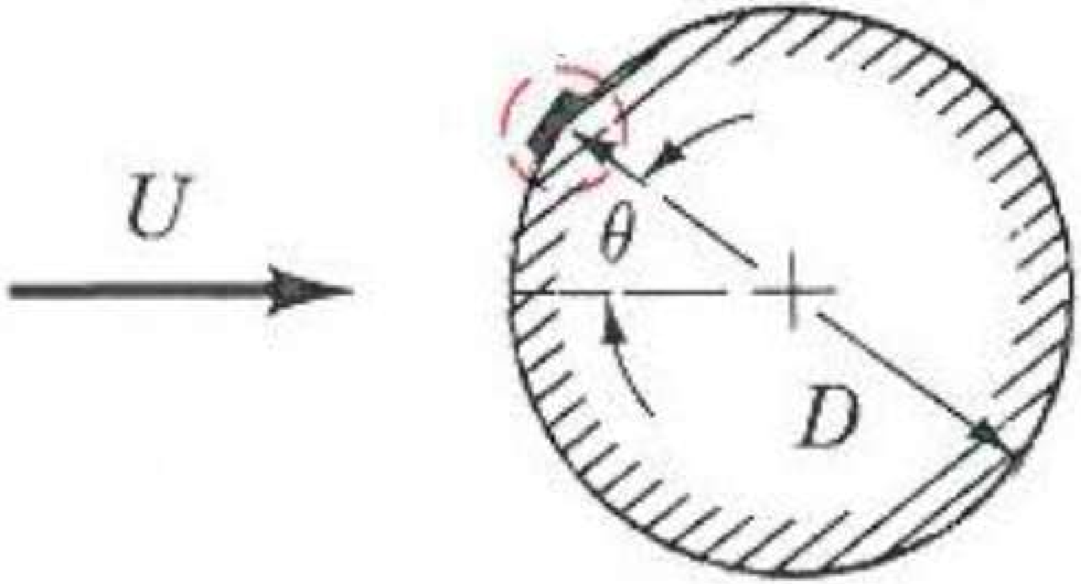
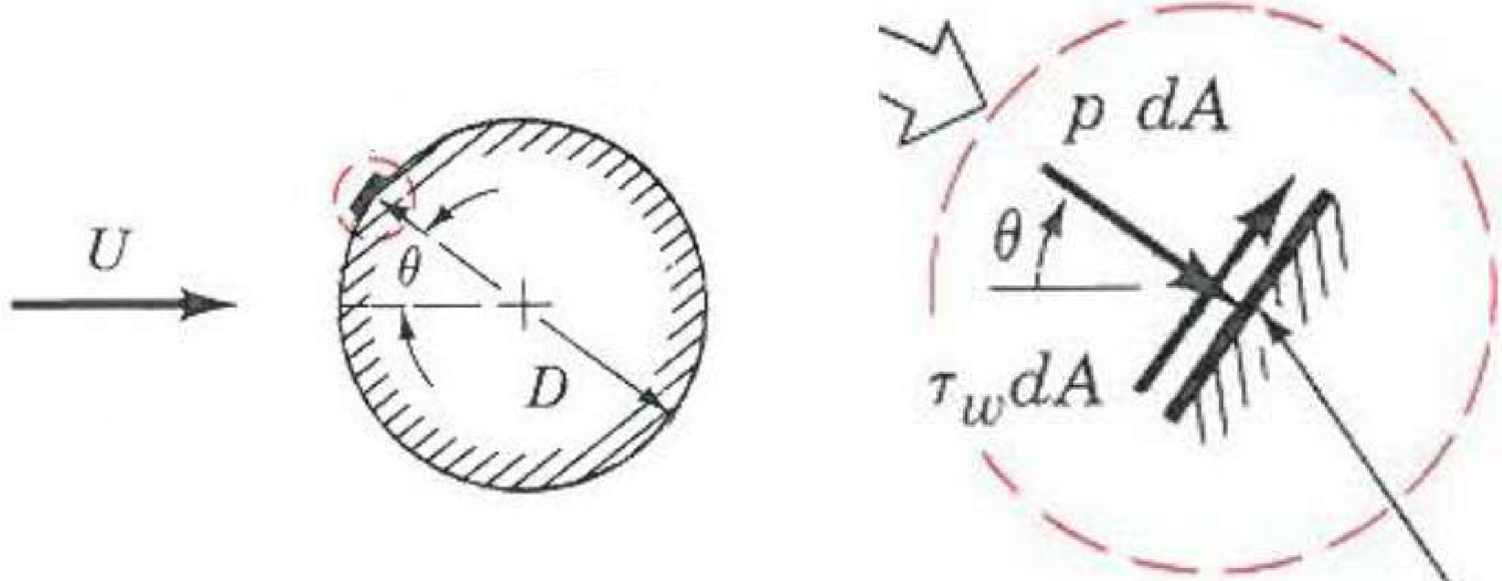
Fluid – particle interaction force (normal and tangential components)

Let us get the forces in *any chosen two* directions



Munson et al., 2010
Van der Akker, 2009

Fluid – particle interaction force (look in more detail



$$dA = b\frac{D}{2}d\theta$$

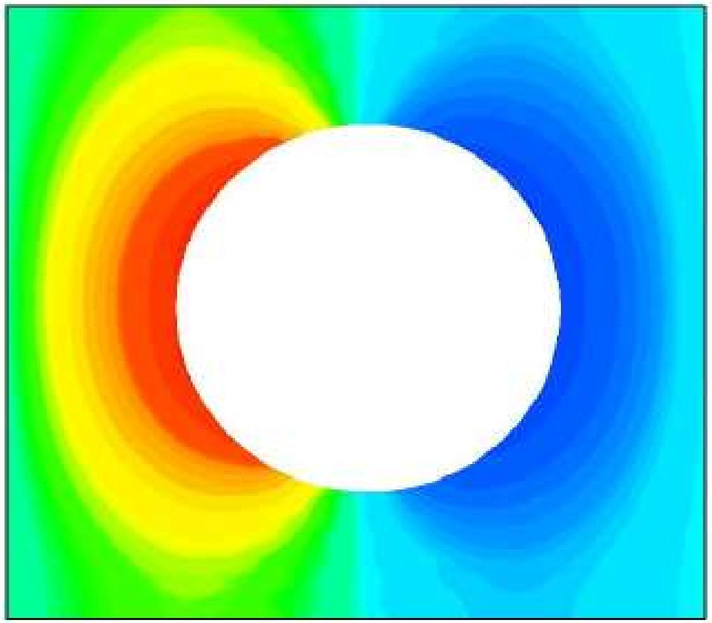
$$\int dF_x = \int p \cos\theta \, dA + \int \tau_w \sin\theta \, dA$$ ⟹ **Drag**

$$\int dF_y = -\int p \sin\theta \, dA + \int \tau_w \cos\theta \, dA$$ ⟹ **Lift**

Fluid – particle interaction force: interesting situations

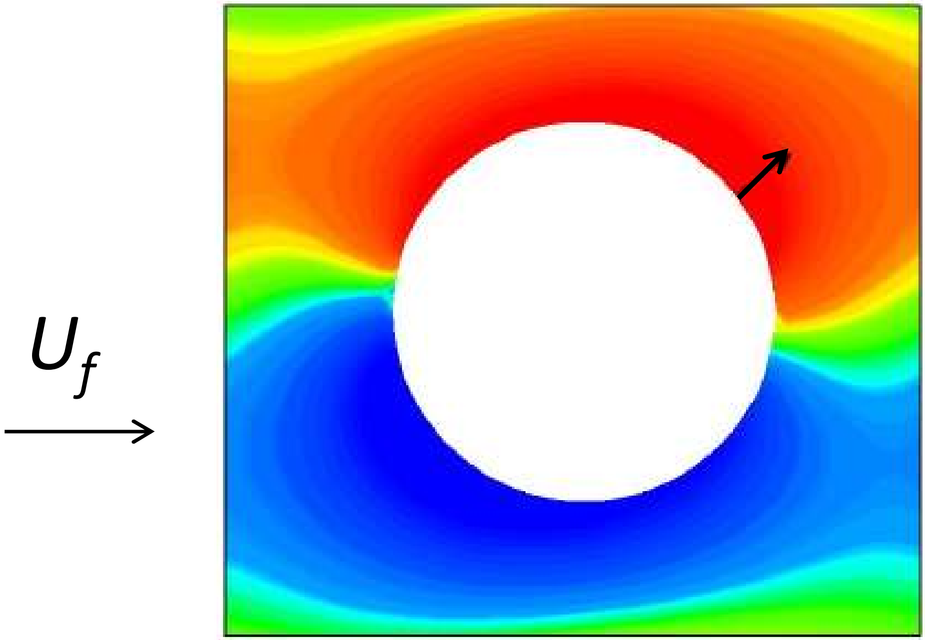
Distribution of pressure – flow over ***a stationary particle***

U_f

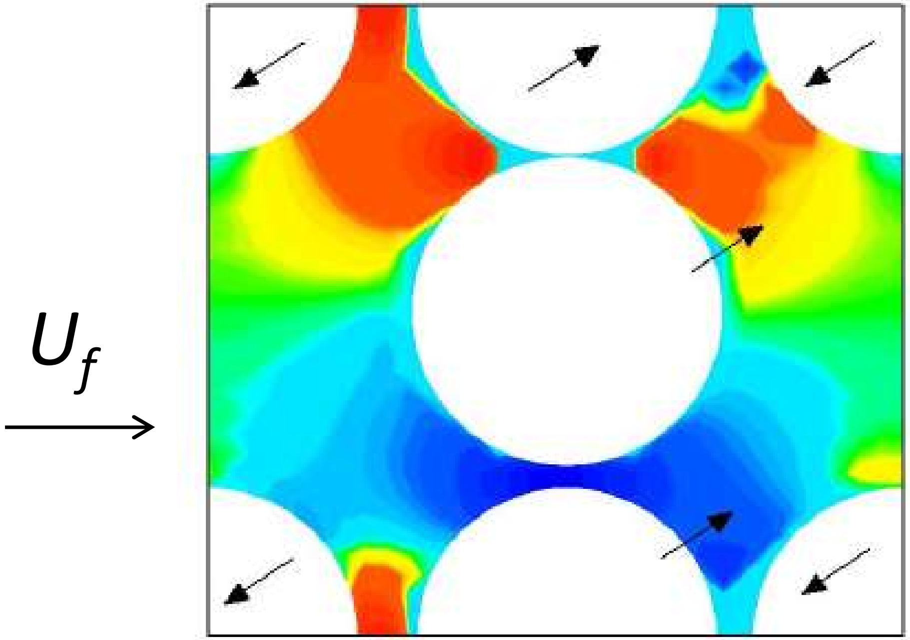


What happens in other cases (contours of pressure are shown)?

A particle **moving in a different direction** than the mean fluid flow



Collection of particles **moving in a different direction** than the mean fluid flow



Drag force

For highly viscous flows: viscous drag (Stokes law) – only this one an analytical solution

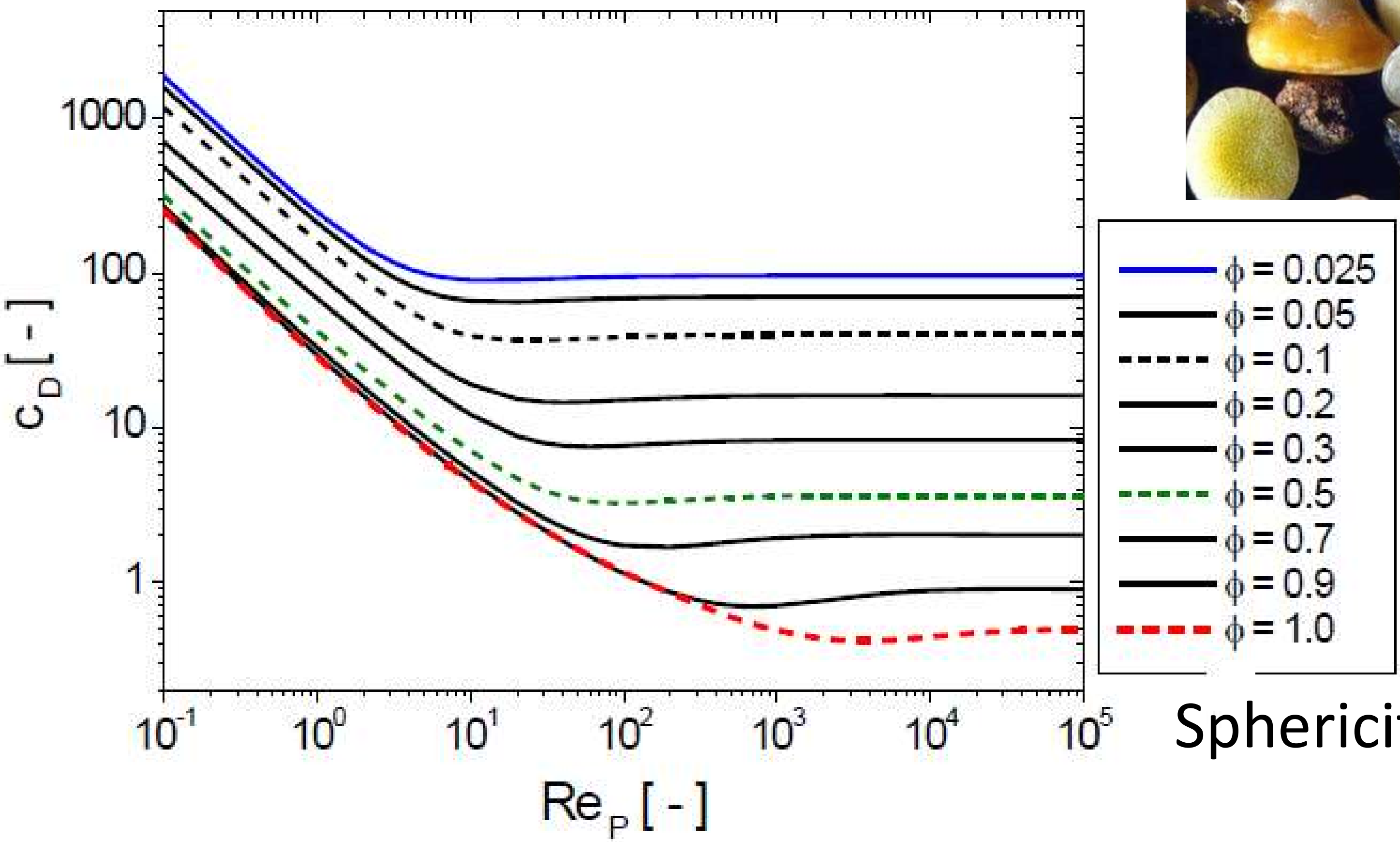
$$\boldsymbol{F_D} = 3\pi\, \mu_f\, d_P\left(\boldsymbol{u}_f - \boldsymbol{u}_{\mathrm{P}}\right)$$

- Form drag: $1/3\ FD$
- Skin (friction) drag: $2/3\ FD$

What else can affect the drag force? See next slides.

Drag force - Effect of particle shape?

C_D: the drag force coefficient (to be explained later)

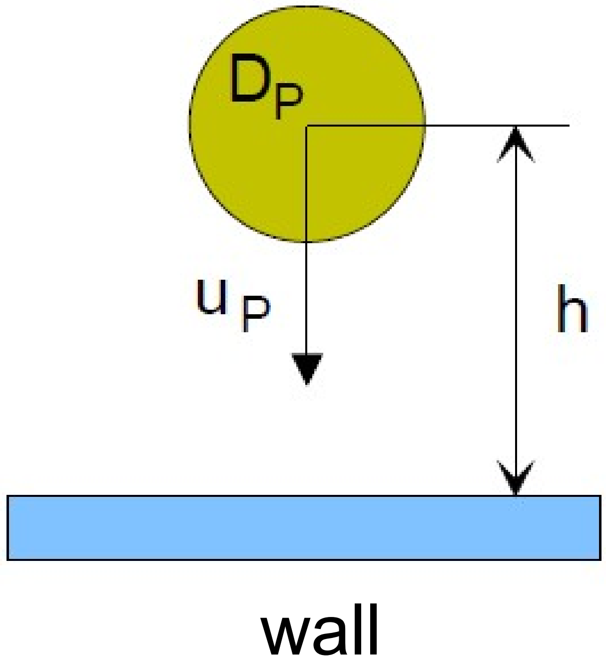


Sphericity

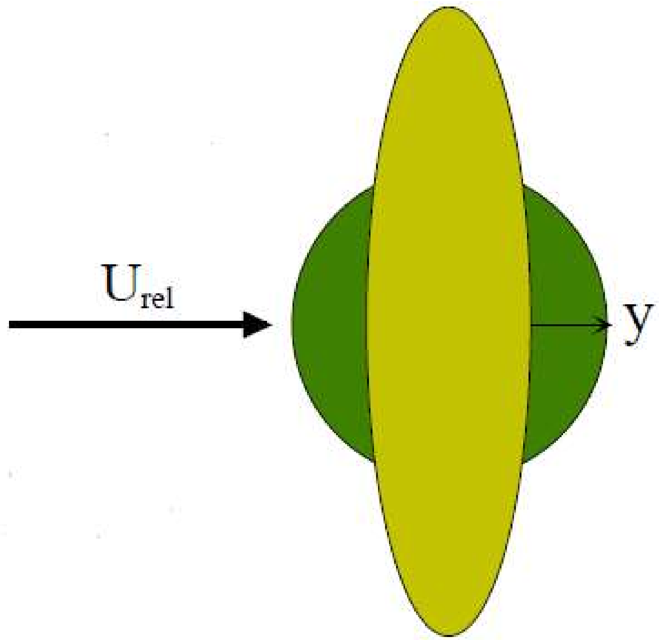
Drag force - Effect of wall?

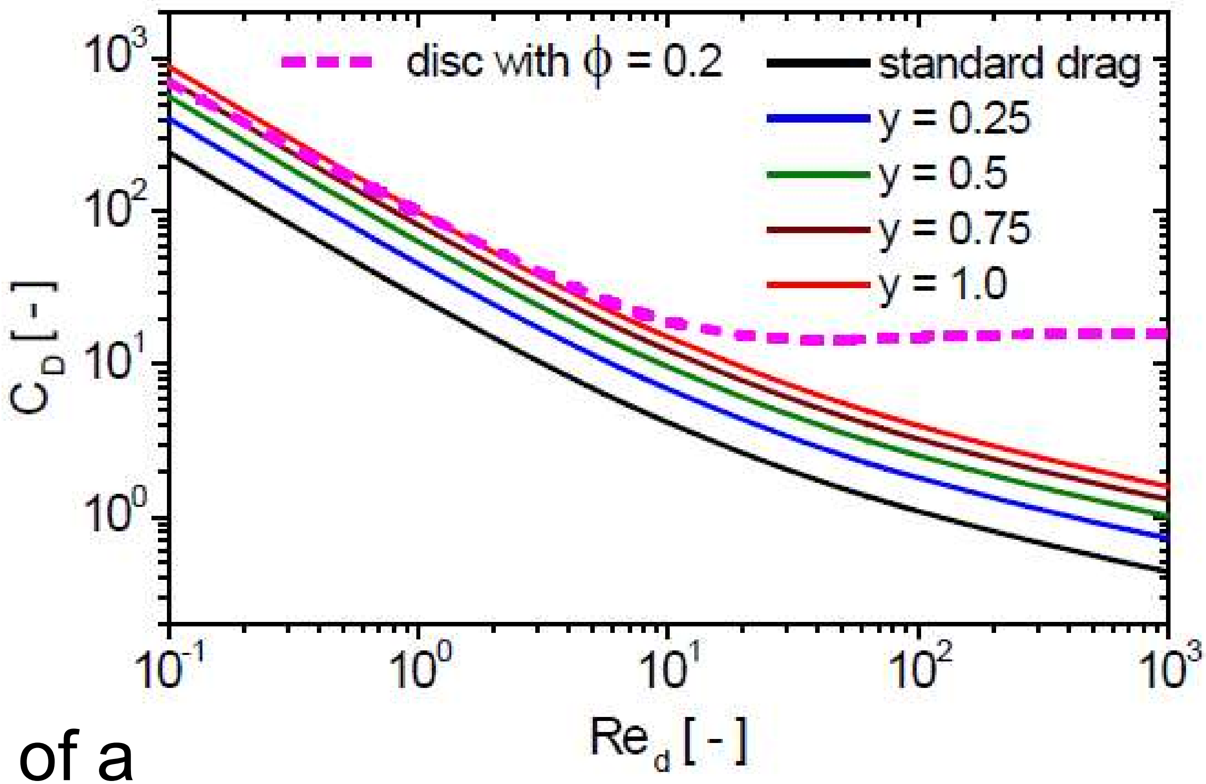
Drag force increases – introduction of correction coefficients in modelling

$$\frac{C_D}{C_{D,Stokes}} = 1 + const\,\frac{d_p}{h}$$



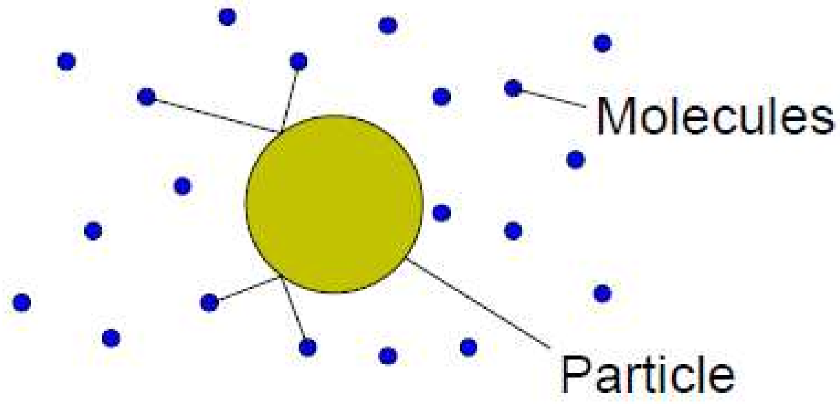
Drag force – Oscillating and/or distorted particles





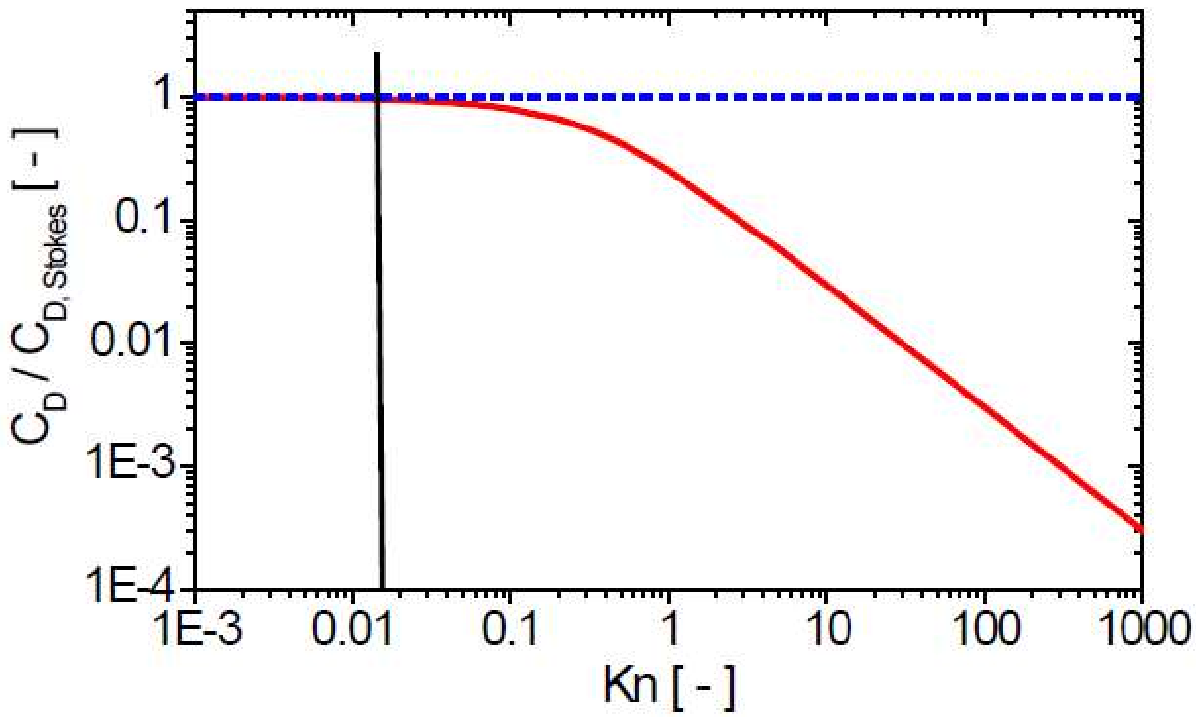
C_D: function of the form of a droplet

Drag force – what if the surrounding flow is not a continuum?



A particle "sees" individual molecules

Kn – particle Knudsen number (particle diameter/mean free path)

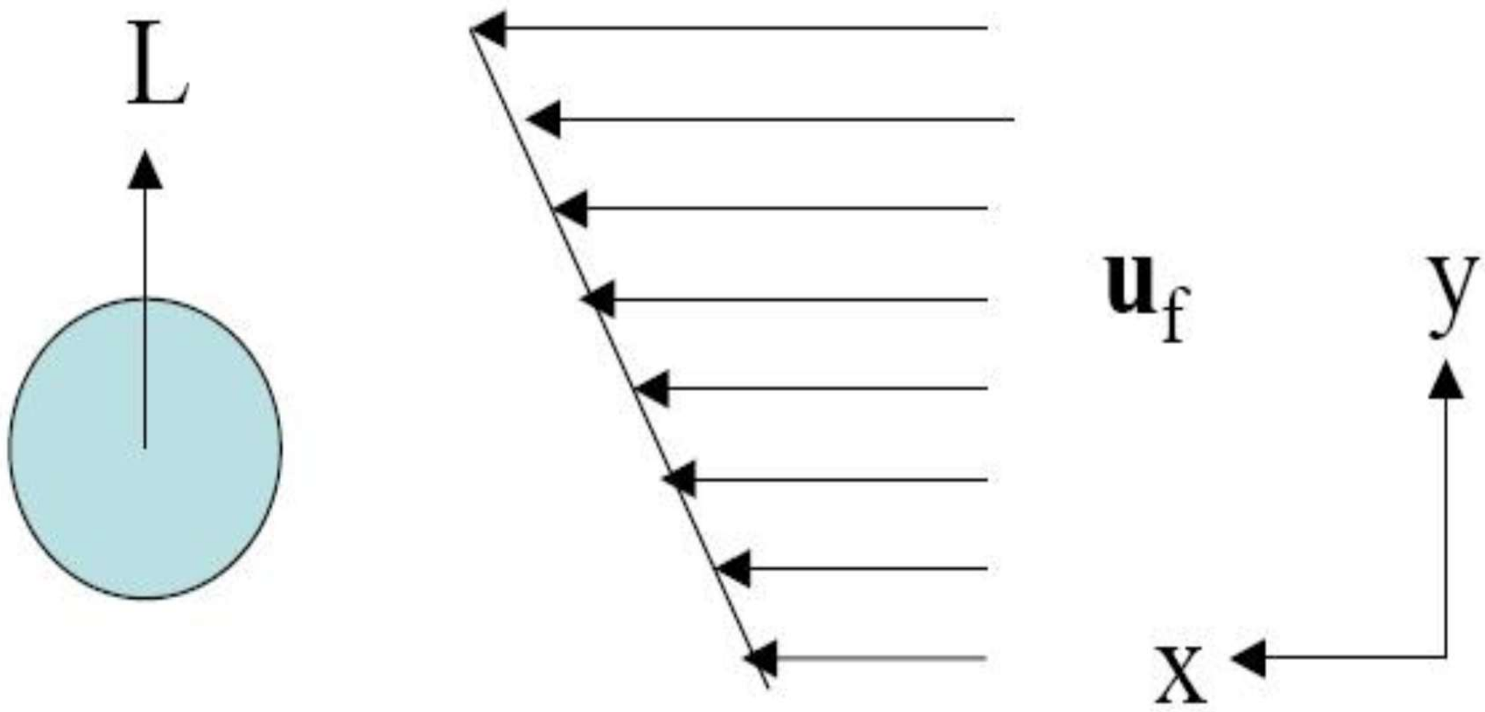


Transverse forces can come from:

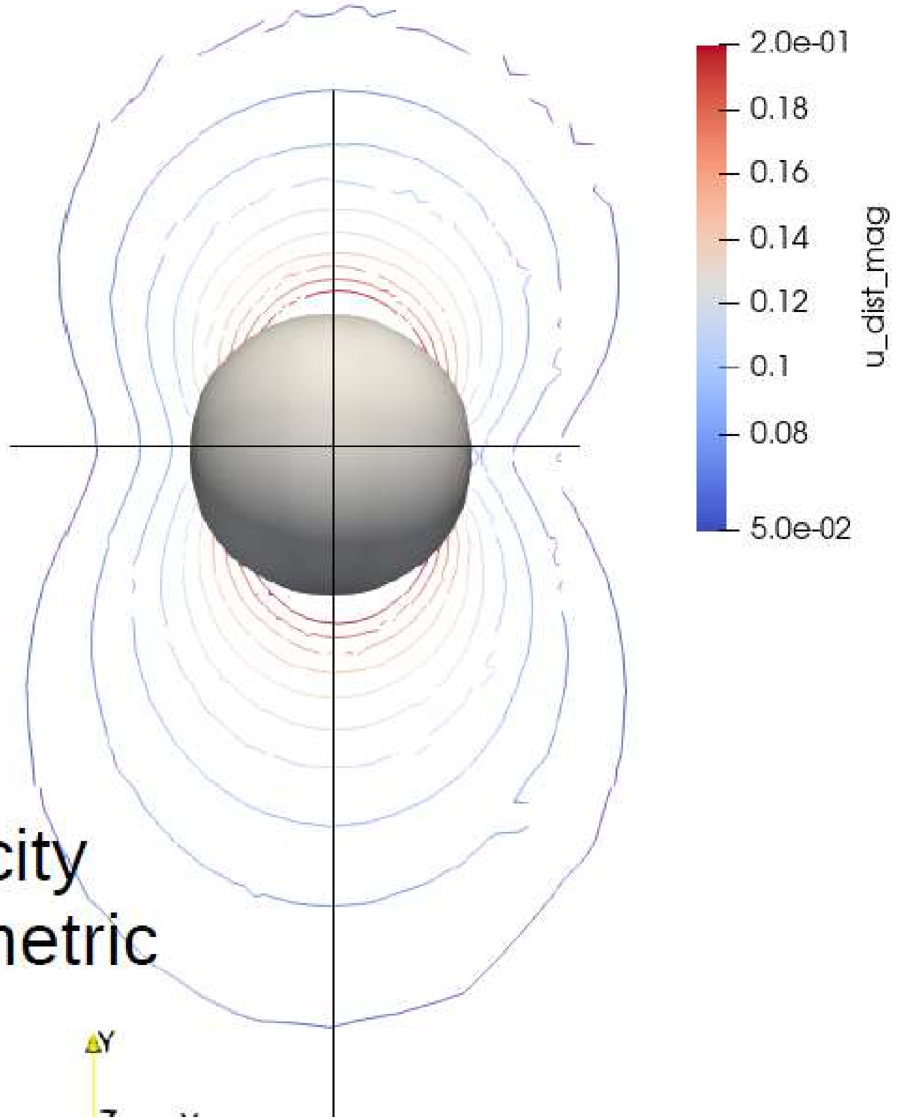
- if the flow is non uniform – presence of a velocity gradient
- if the particle is rotating (velocity gradient, collisions)
- if the particle moves in the vicinity of a wall

Transverse forces

Saffmann force – due to presence of a velocity gradient (shear)



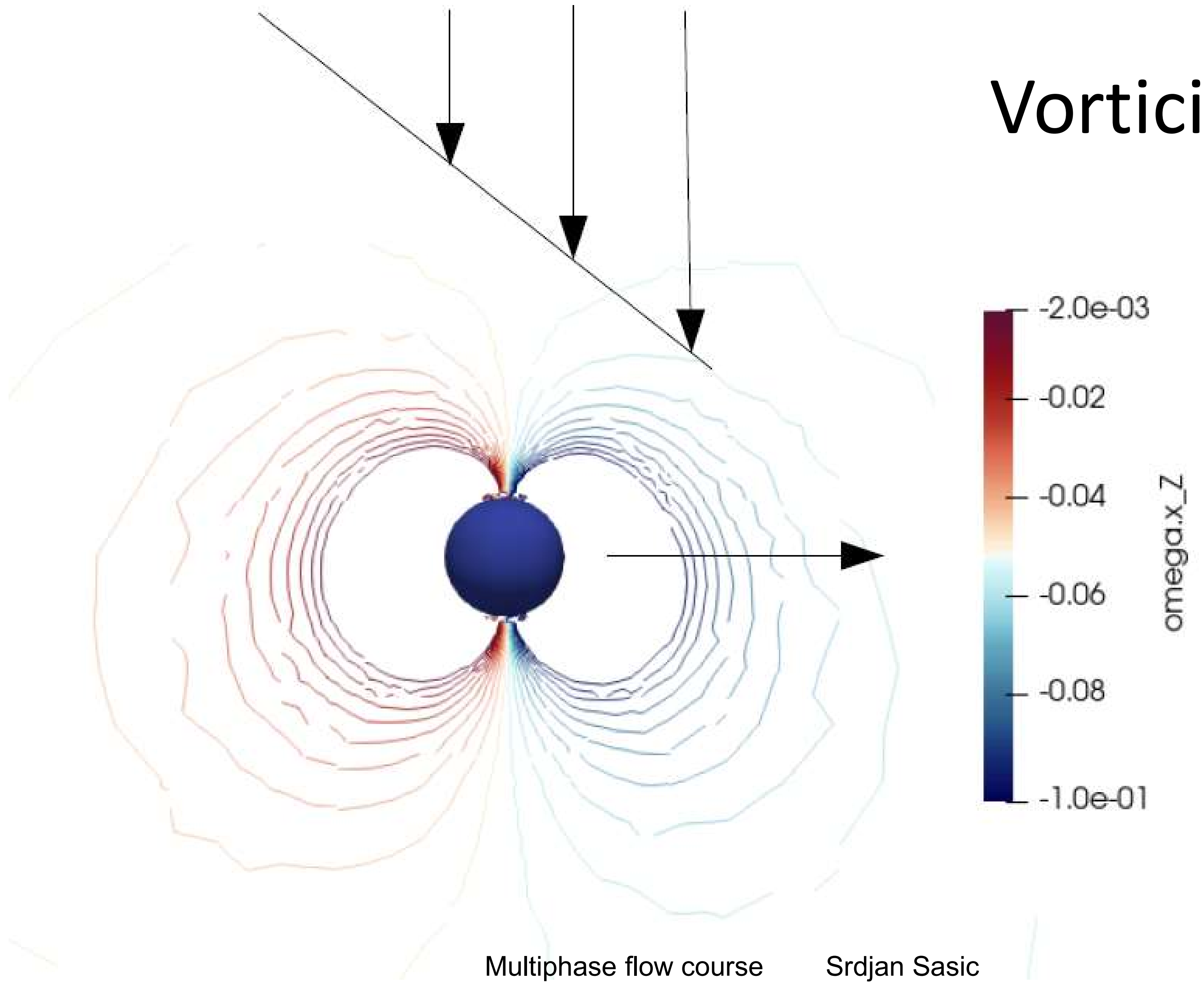
Why do we have a force if we have such a disturbance velocity field?



Disturbance velocity field almost symmetric

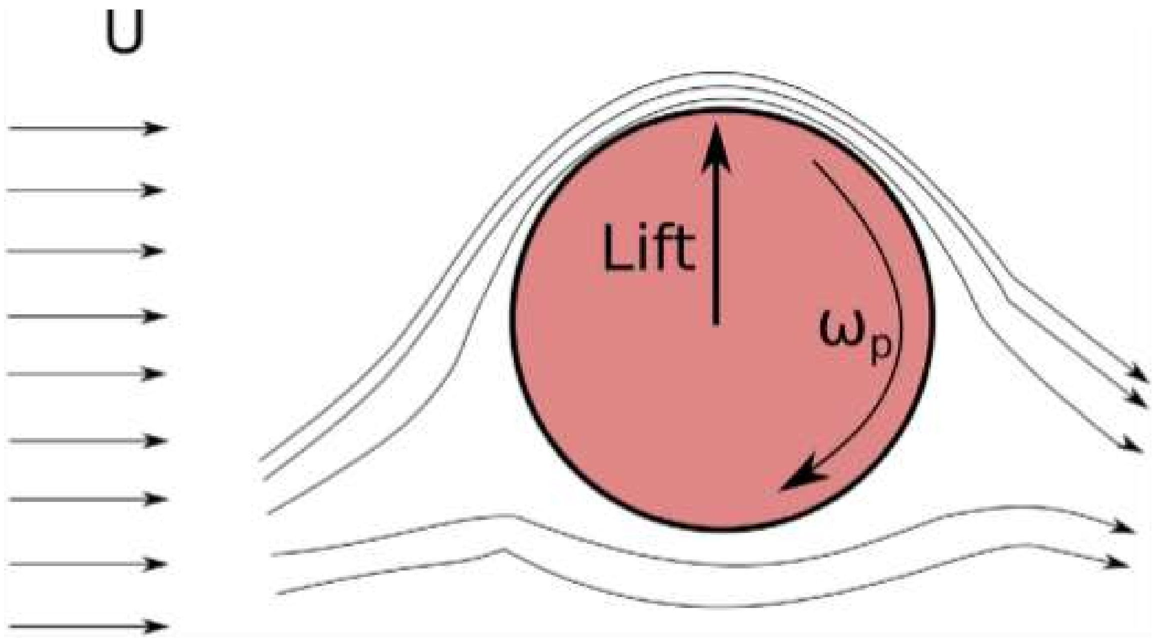
Something else is not symmetrical

Vorticity!



Transverse forces

Magnus force – due to perturbation of the mean flow caused by angular motion of the particle



Saffmann lift force – presence of a velocity gradient in the direction normal to the main flow

$$\mathbf{F}_{saff} = 1.61\, d_P^2 \sqrt{\rho_f \mu_f}\, \frac{\left(\mathbf{u}_f - \mathbf{u}_\mathrm{P}\right) \times \boldsymbol{\omega}_f}{\sqrt{\left|\omega_f\right|}}; \qquad \boldsymbol{\omega}_f = rot\, \mathbf{u}_f$$

Magnus lift force – particle rotating in a fluid flow (rotation introduced due to, e.g., collisions)

$$\mathbf{F}_{mag} = \frac{\pi}{8} d_P^3\, \rho_f \left(\frac{1}{2} \nabla \times \mathbf{u}_\mathrm{f} - \boldsymbol{\omega}_P \right) \times \left(\mathbf{u}_f - \mathbf{u}_\mathrm{P} \right)$$