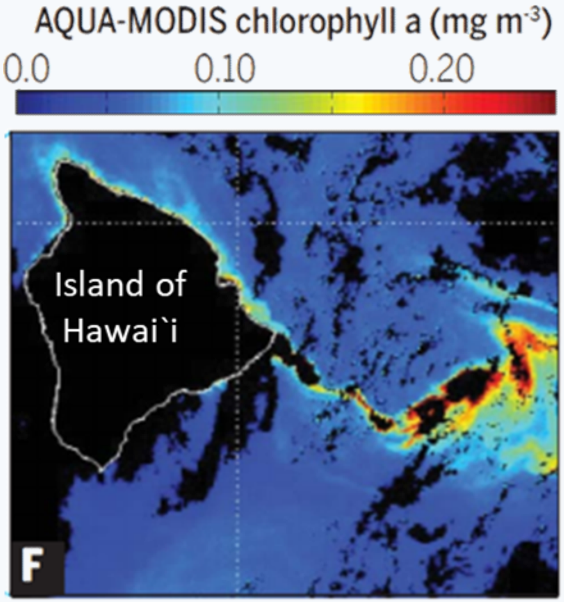
Encounter rate in marine snow dynamics

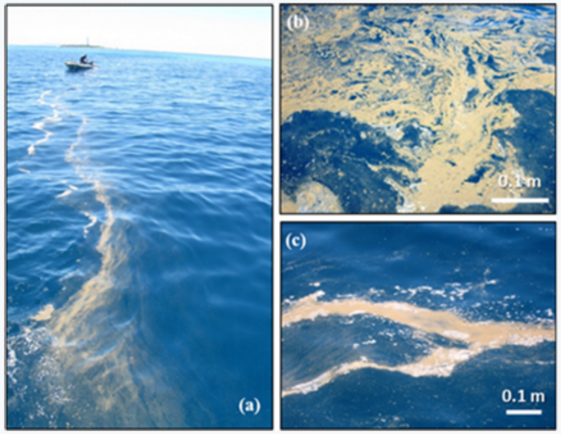
Jan Turczynowicz

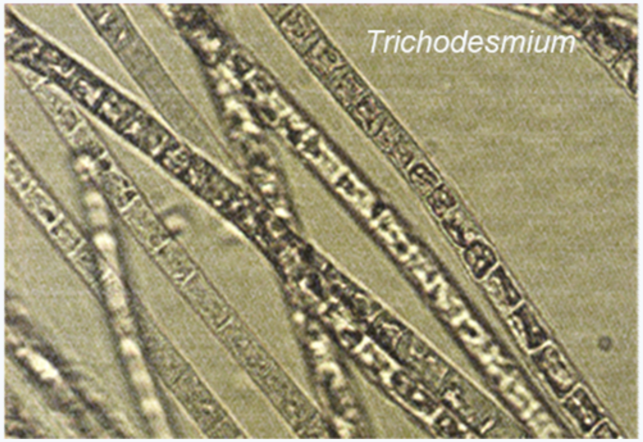
Institute of Theoretical Physics

Phytoplankton bloom



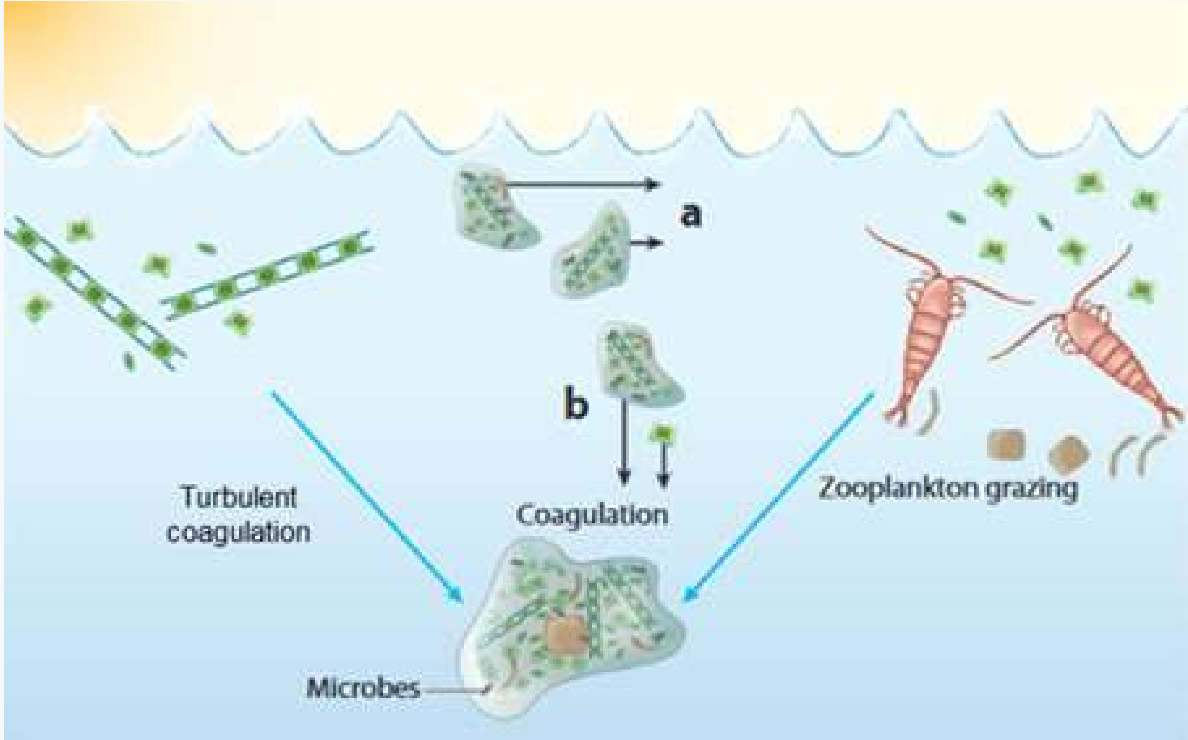
Wilson, S.T. *et al.*, *Kīlauea lava fuels phytoplankton bloom in the North Pacific Ocean.* Science **365**, (2019)





Spungin, D. *et alMechanisms of Trichodesmium demise within the New Caledonian lagoon during the VAHINE mesocosm experiment.* Biogeosciences **13**, (2016)

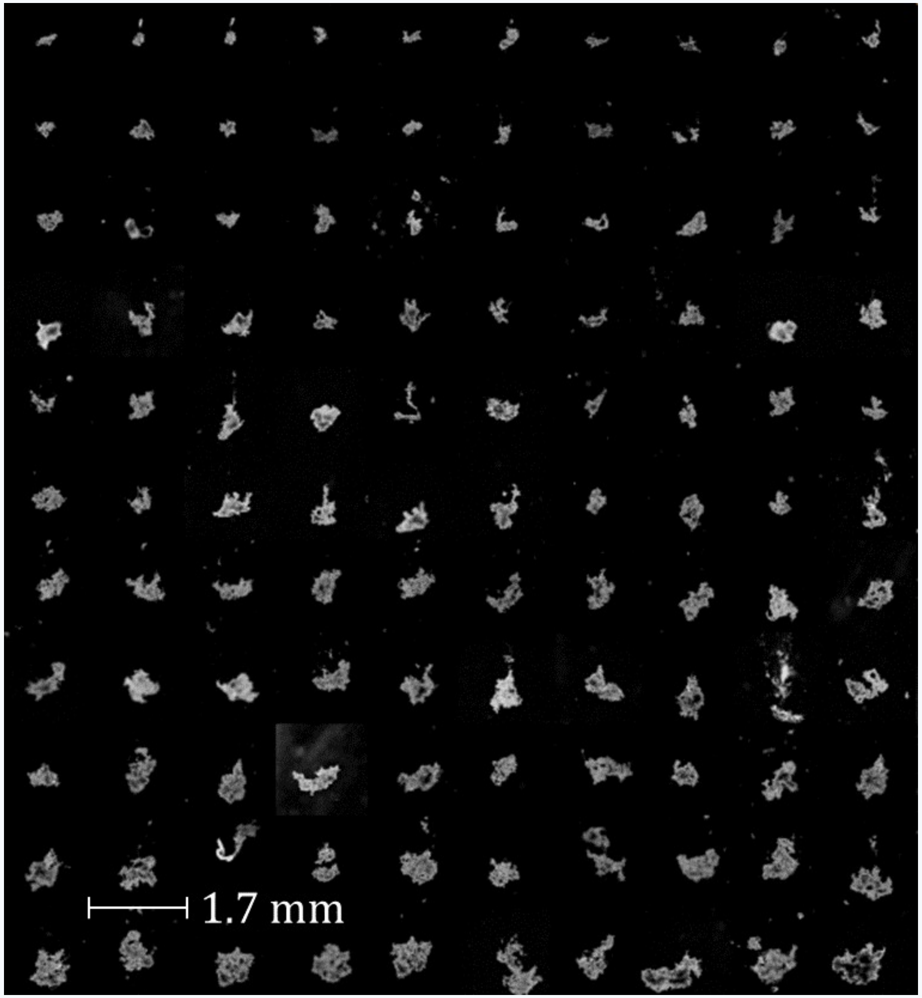
Coagulation



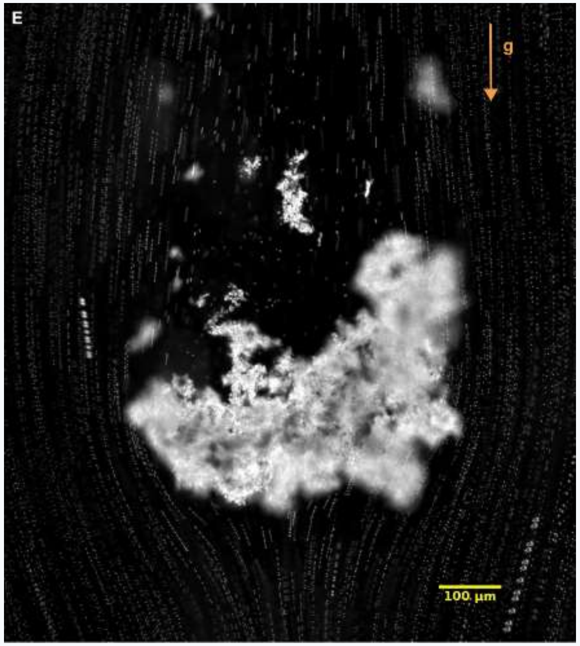
Sinking in form of **marine snow**

Burd, A.B. *et al.*, *Particle Aggregation.* Annual Review of Marine Science **1**, (2009)

Marine snow

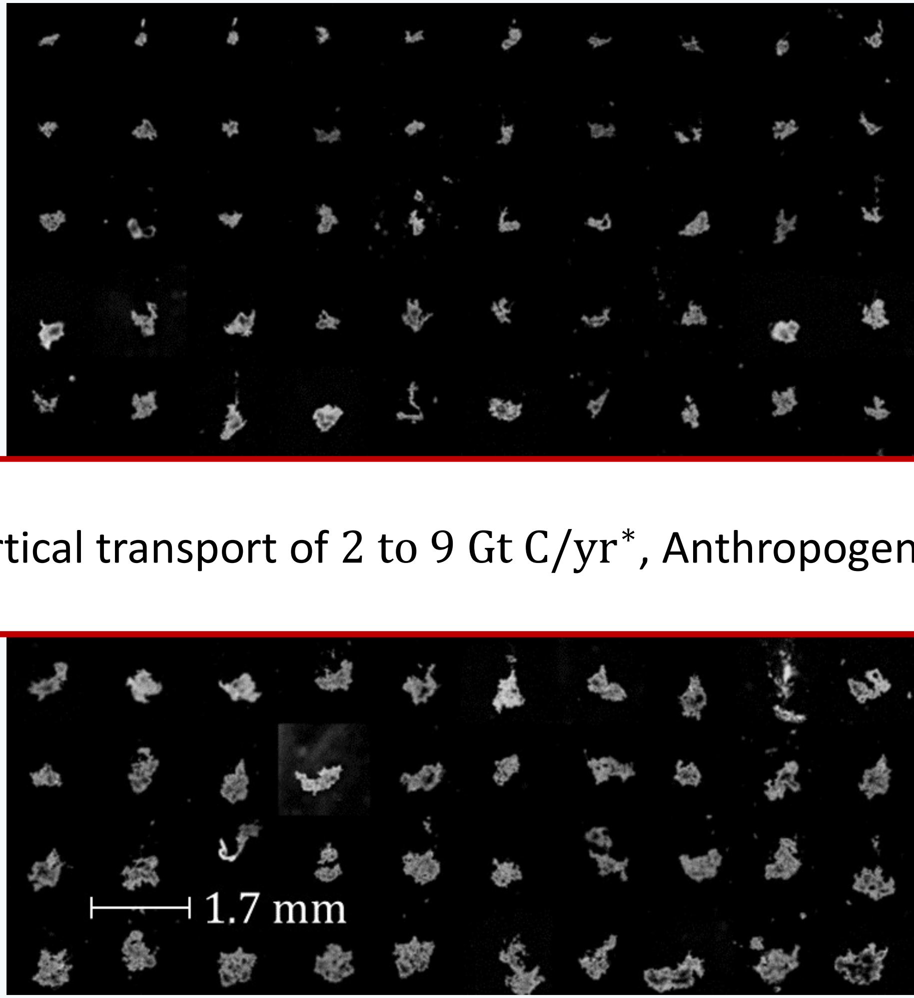


Taken from the depth of 80 m

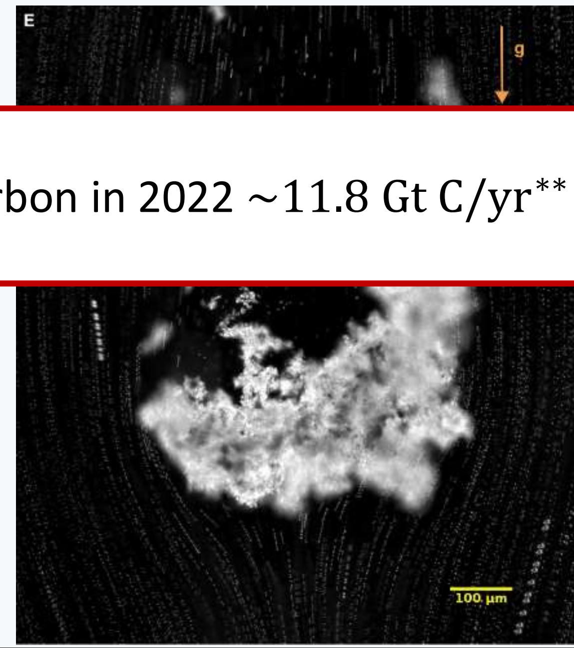


Chajwa, R. *et al.*, *Hidden comet tails of marine snow impede ocean-based carbon sequestration*. *Science* **386**, (2024)

Marine snow



Taken from the depht of 80 m



Vertical transport of 2 to 9 Gt C/yr*, Anthropogenic carbon in 2022 ~11.8 Gt C/yr**

*Boyd, P.W. *et al. Multi-faceted particle pumps drive carbon sequestration in the ocean.* Nature **568**, (2019)
Friedlingstein, P. et al. *Global Carbon Budget 2023.* Earth System Science Data **15, (2023)

Smoluchowski equation

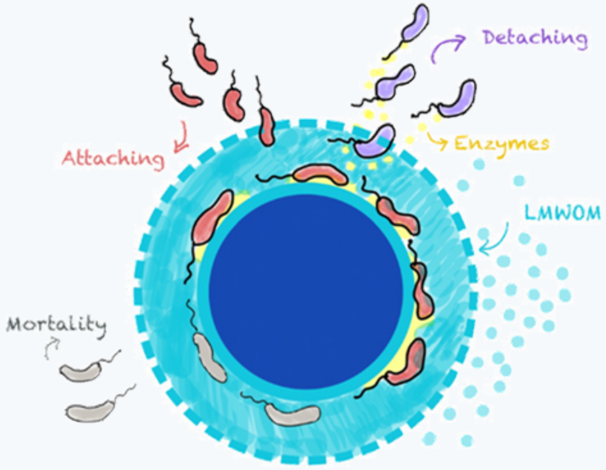
$$\partial_t \varphi = \partial_m(\kappa(z,m)\,\varphi) - \partial_z(u(z,m)\,\varphi) + \Gamma\big(z,m,\varphi(z,m)\big)$$

Where: z – depht, m – mass of particles, $\varphi(z,m)$ – concentration of particles for given mass and depth, $\kappa(z,m)$ – rate of demineralisation, $u(z,m)$ – settling velocity, $\Gamma\big(z,m,\varphi(z,m)\big)$ – aggregation term

Terms

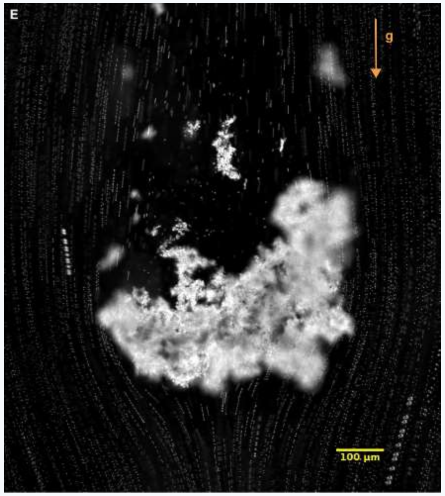
$$\partial_t \varphi = \partial_m(\kappa(z,m)\,\varphi) - \partial_z(u(z,m)\,\varphi) + \Gamma\big(z,m,\varphi(z,m)\big)$$

Eating by bacteria



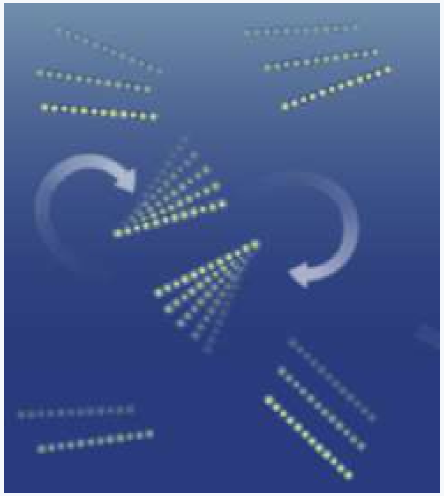
Nguyen, T.T.H. *et al. Microbes contribute to setting the ocean carbon flux by altering the fate of sinking particulates. Nat Commun* **13**, (2022)

Sedimentation



Chajwa, R. *et al.*, *Hidden comet tails of marine snow impede ocean-based carbon sequestration. Science* **386**, (2024)

Aggregation



Where: z – depht, m – mass of particles, $\varphi(z,m)$ – concentration of particles for given mass and depth, $\kappa(z,m)$ – rate of demineralisation, $u(z,m)$ – settling velocity, $\Gamma\big(z,m,\varphi(z,m)\big)$ – aggregation term

Collisions

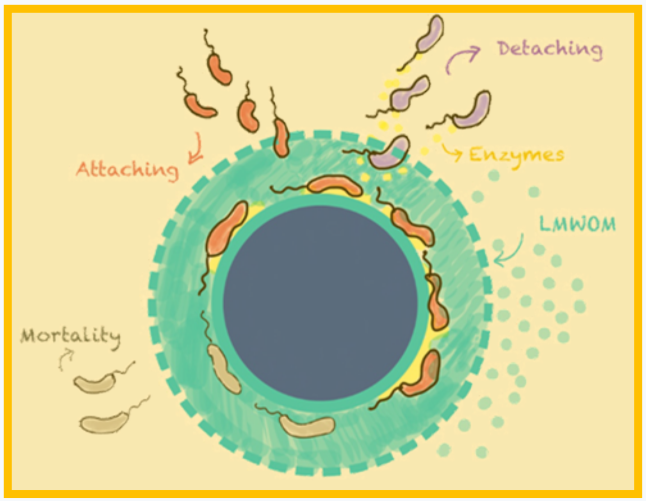
∂_t … $m))$

Terms depending on **encounter rate** between particles

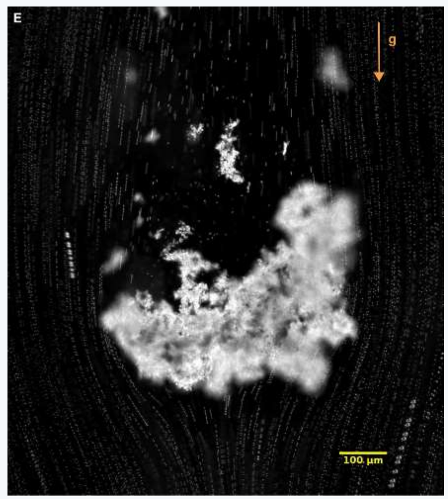
Eating by bacteria

Sedimentation

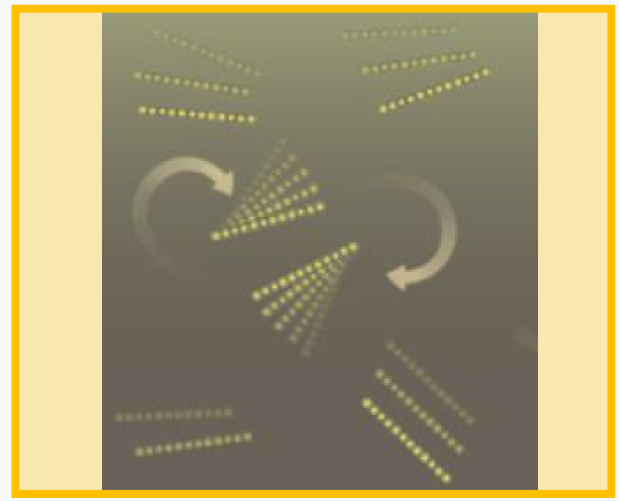
Aggregation



Nguyen, T.T.H. *et al. Microbes contribute to setting the ocean carbon flux by altering the fate of sinking particulates. Nat Commun* **13**, (2022)



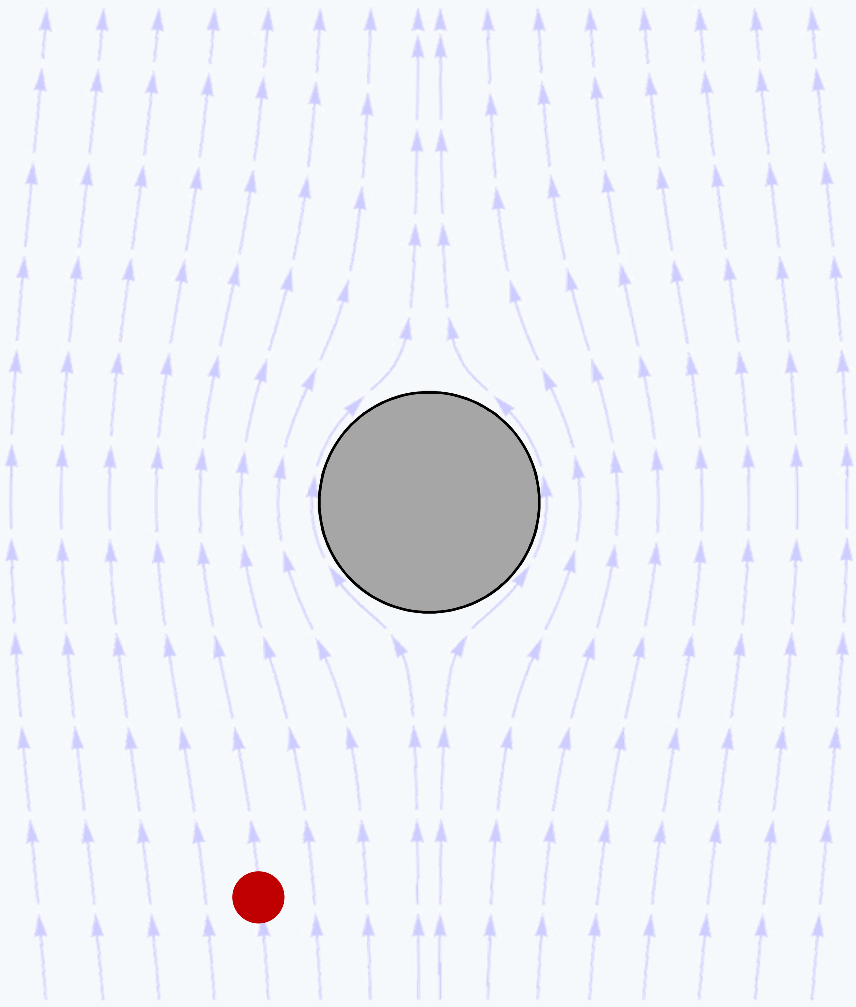
Chajwa, R. *et al.*, *Hidden comet tails of marine snow impede ocean-based carbon sequestration. Science* **386**, (2024)



Where: z – depht, m – mass of particles, $\varphi(z,m)$ – concentration of particles for given mass and depth, $\kappa(z,m)$ – rate of demineralisation, $u(z,m)$ – settling velocity, $\Gamma\big(z,m,\varphi(z,m)\big)$ – aggregation term

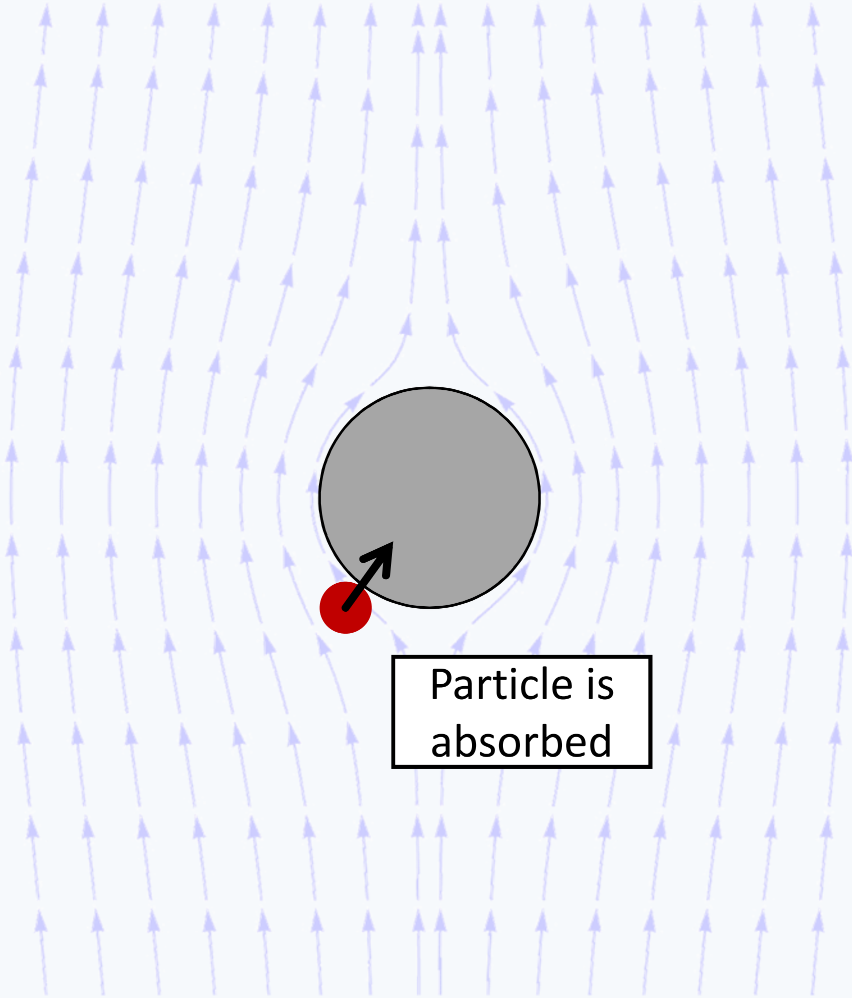
Encounter rate

$$Re \ll 1$$



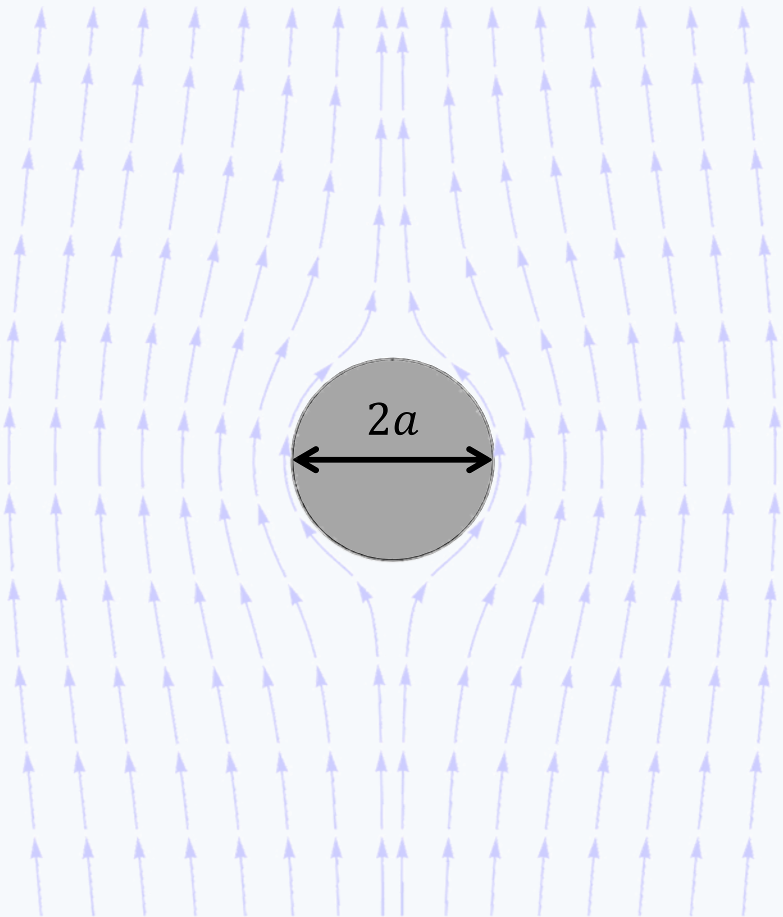
Encounter rate

$$Re \ll 1$$



Advection – diffusion

Stokes Flow: $\boldsymbol{u}(\boldsymbol{r})$



Advection – diffusion

$$\partial_t c = D\nabla^2 c - \boldsymbol{u}\cdot\nabla c$$

c constant in time,
dimensionless

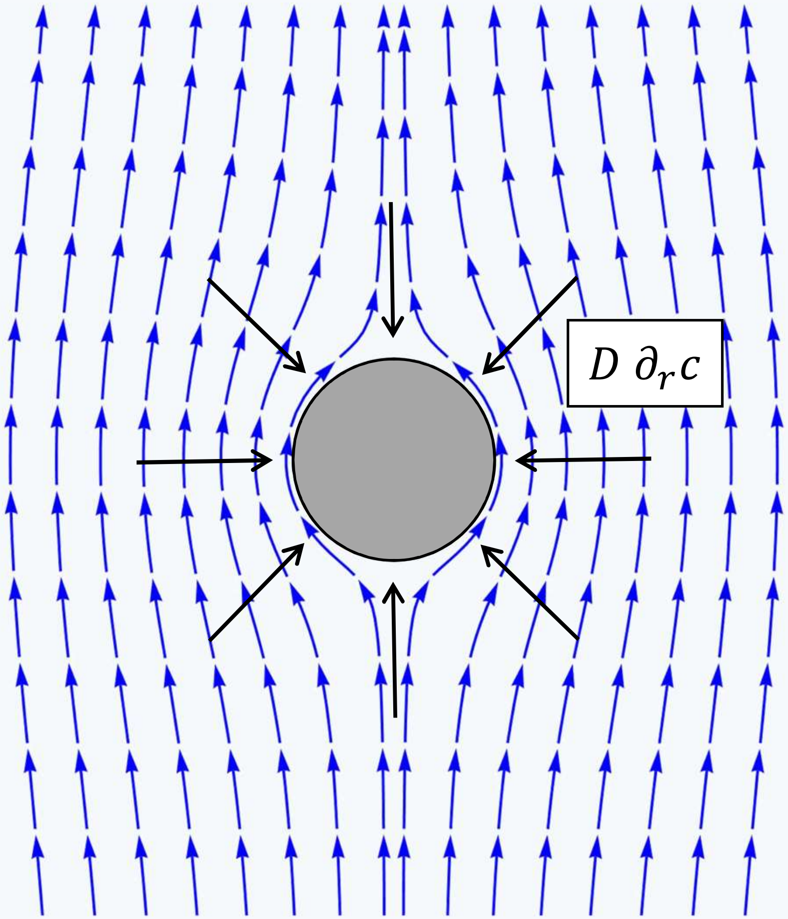
Advection – diffusion (dimensionless)

$$\nabla^2 c = Pe\,\boldsymbol{u}\cdot\nabla c$$

Where: U – sinking velocity, c – concentration of particles, D – diffusion constant, $\boldsymbol{u}$ – Stokes flow around a sinking sphere, a – sphere radius, $Ua/D = Pe$ – Peclet number

Encounter rate

Stokes Flow: $\boldsymbol{u}(\boldsymbol{r})$



Flux onto the sphere:

$$\Phi = D \int_S \partial_r c \, \mathrm{d}\Omega$$

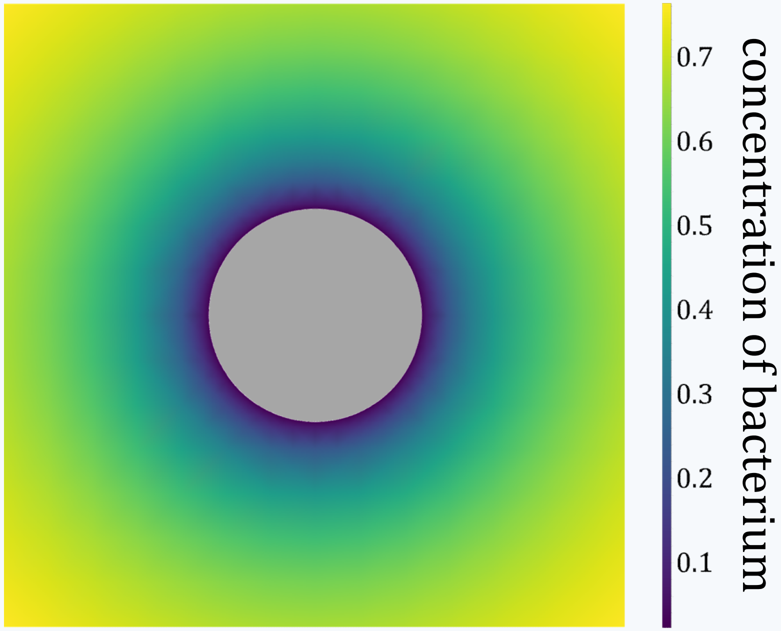
Where: c – concentration of particles, D – diffusion constant, $\boldsymbol{u}$ – Stokes flow around a sinking sphere, S – absorptive surface

Peclet number

Peclet number ($\mathrm{P}e = U\ a\ /\ D$)

Where: c – concentration of particles, D – diffusion constant, a – sphere radius, U – sinking velocity, r – particle radius

Diffusion dominates



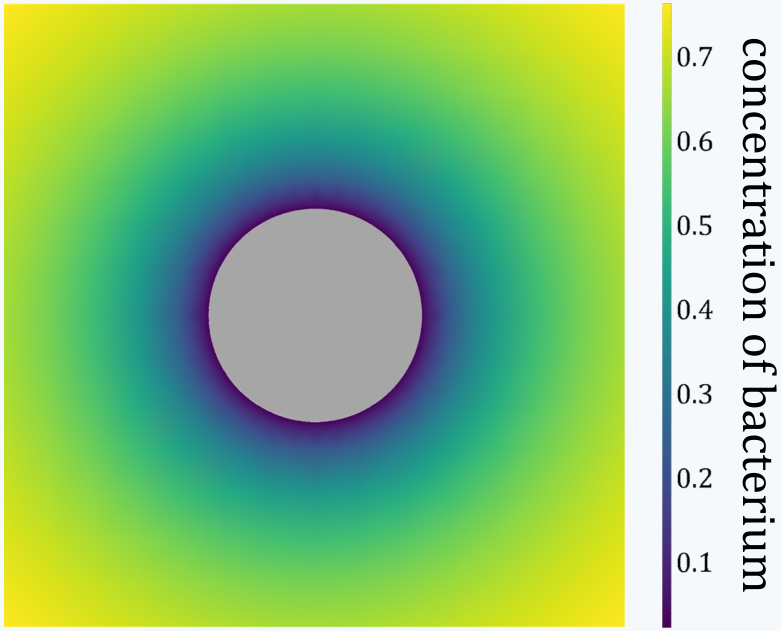
$$\Phi_{\mathrm{D}} = 4\pi a c D$$

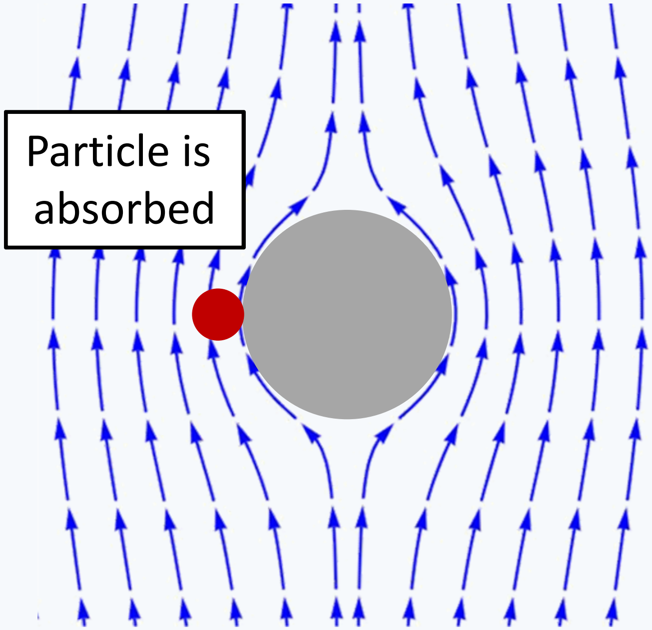
$\mathrm{Pe} \to 0$

Peclet number ($\mathrm{Pe} = U\, a\, /\, D$)

Where: c – concentration of particles, D – diffusion constant, a – sphere radius, U – sinking velocity, r – particle radius

Advection dominates





$$\Phi_{\mathrm{D}} = 4\pi a c D$$

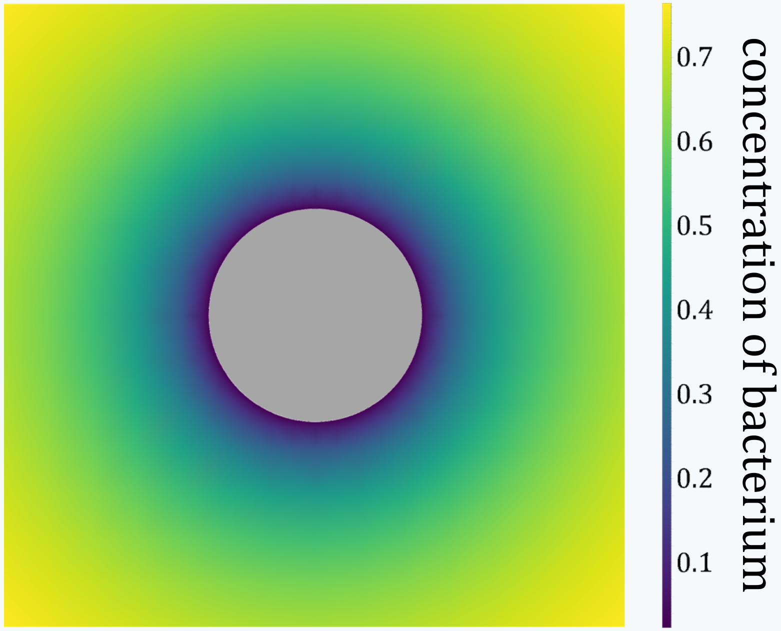
$Pe \rightarrow 0$

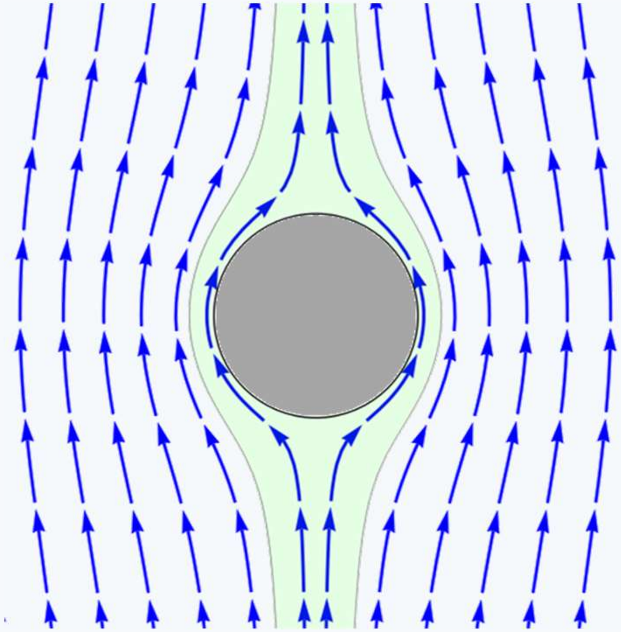
$Pe \rightarrow \infty$

Peclet number ($Pe = U\,a\,/\,D$)

Where: c – concentration of particles, D – diffusion constant, a – sphere radius, U – sinking velocity, r – particle radius

Limiting cases





$$\Phi_{\mathrm{D}} = 4\pi a c D$$

$$\Phi_{\mathrm{A}} = U\, c\, \pi\, r^2 \left(3 - \frac{r}{r+a}\right)/2$$

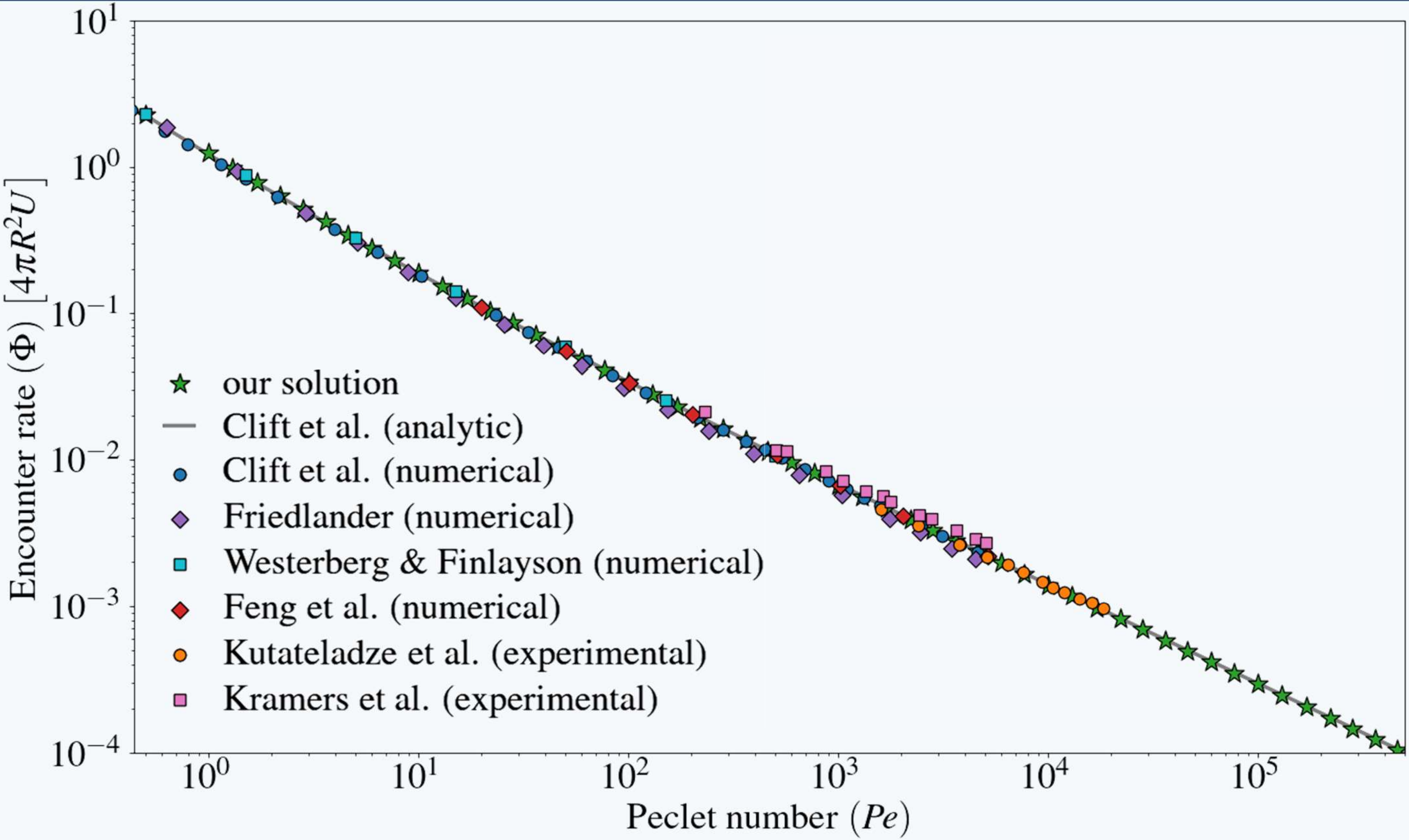
$\mathrm{P}e \to 0$

$\mathrm{P}e \to \infty$

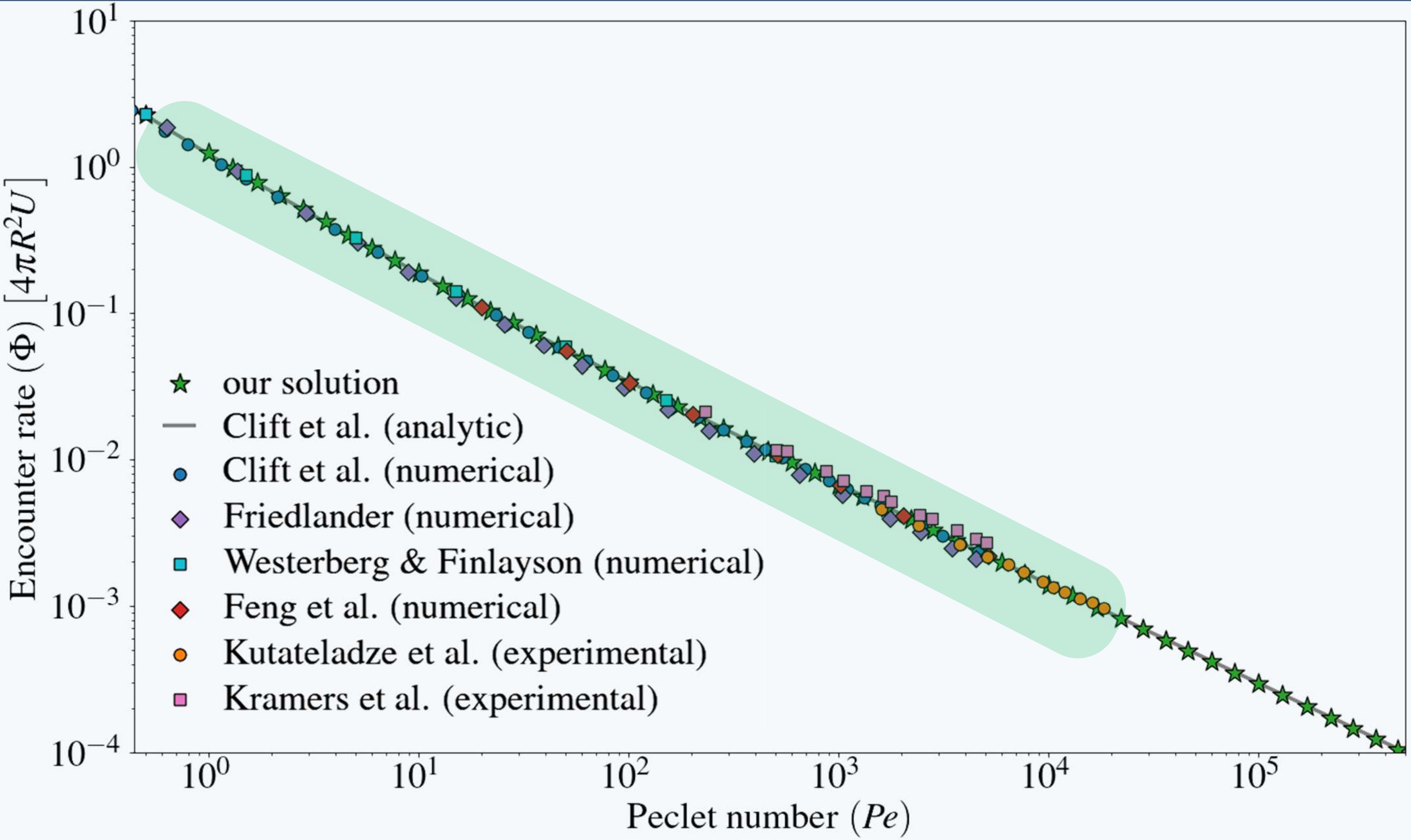
Peclet number ($\mathrm{P}e = U\, a\, /\, D$)

Where: c – concentration of particles, D – diffusion constant, a – sphere radius, U – sinking velocity, r – particle radius

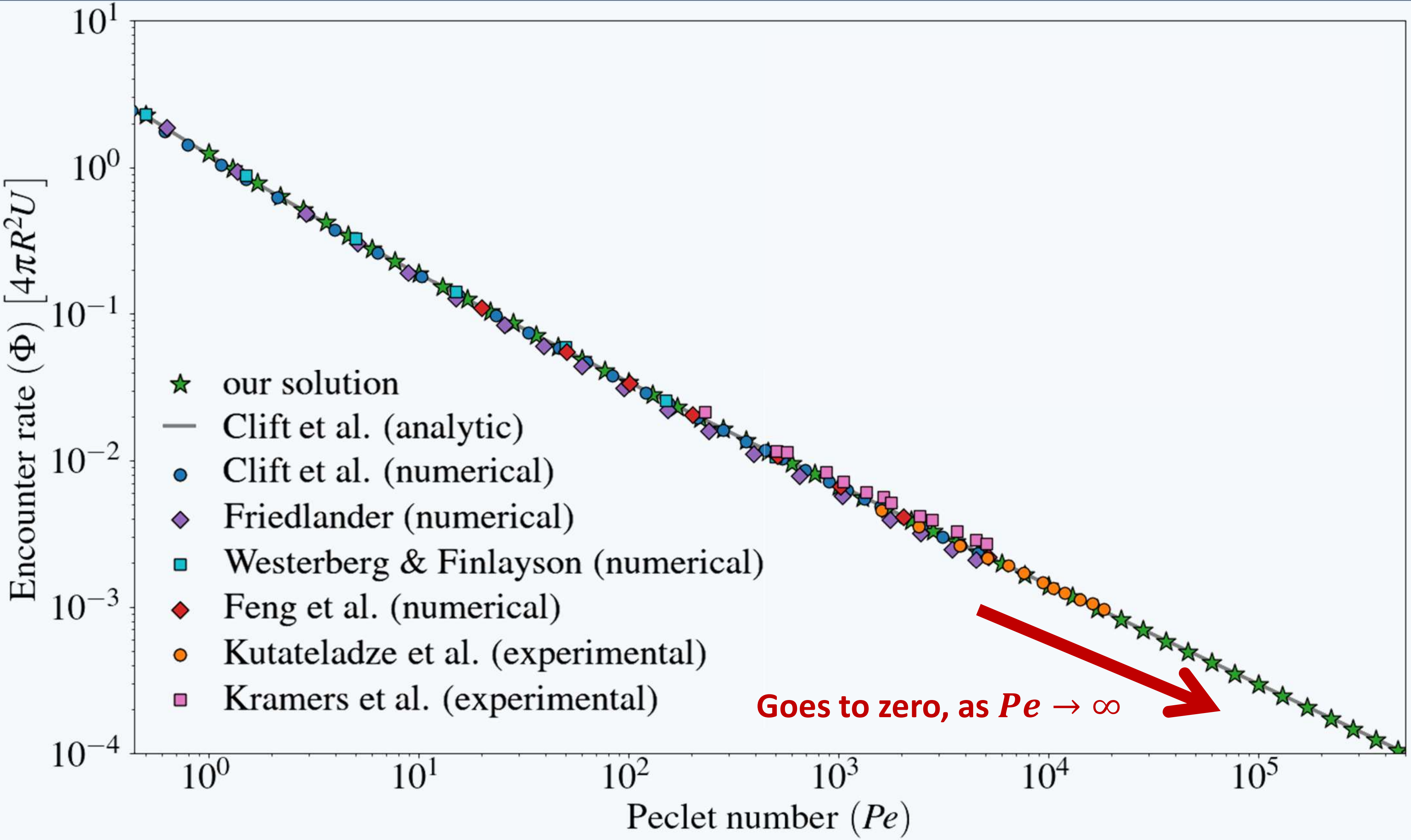
Literature comparison



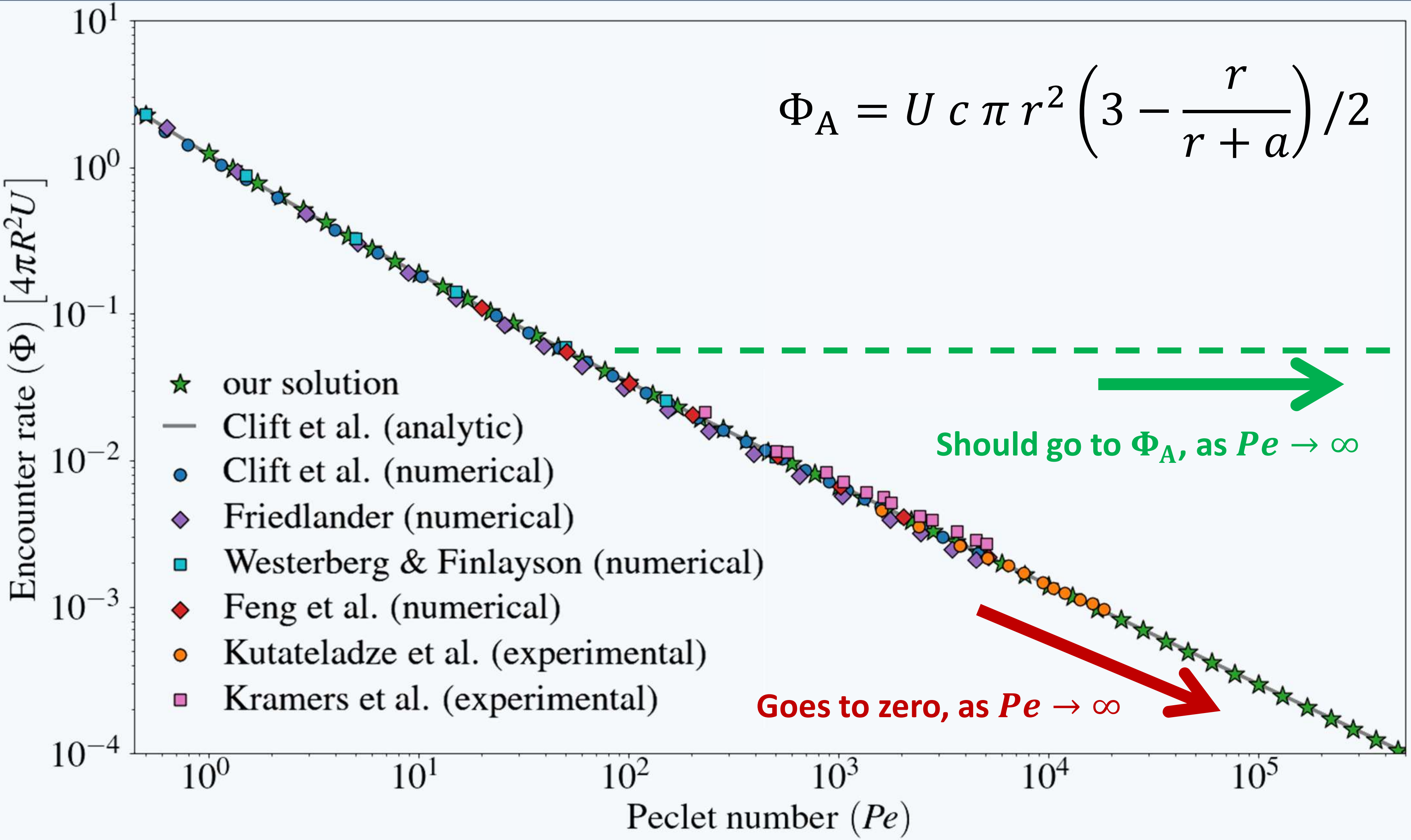
Literature comparison



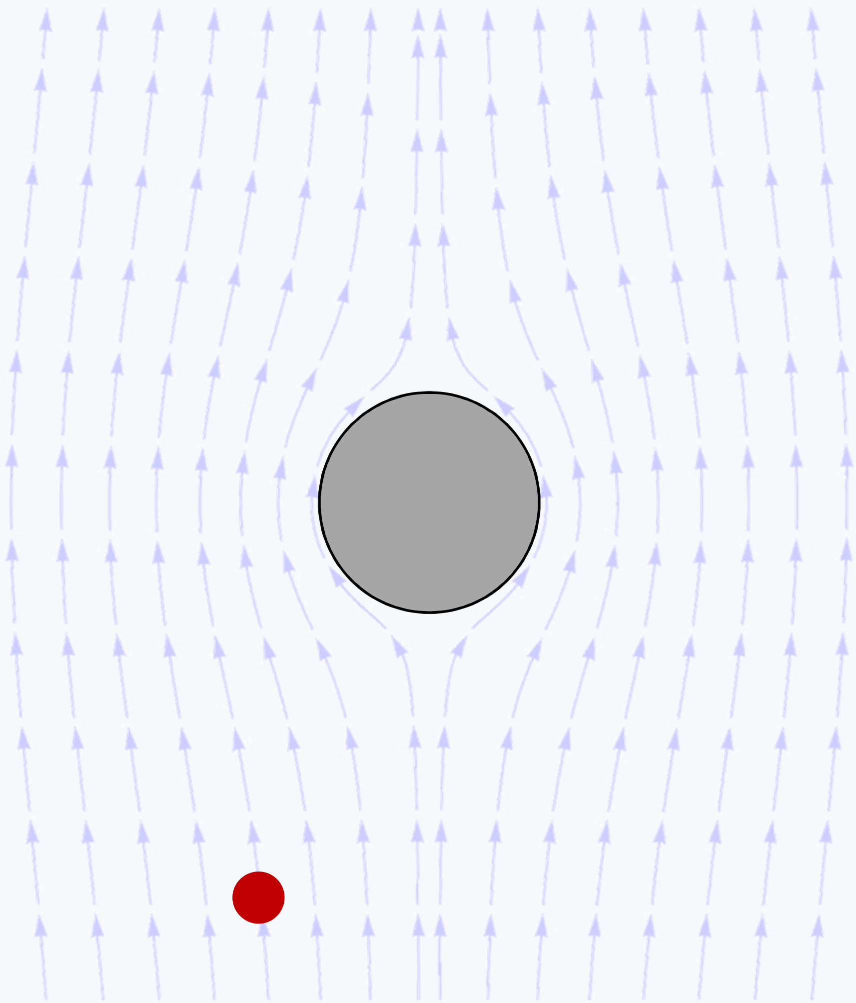
Literature comparison



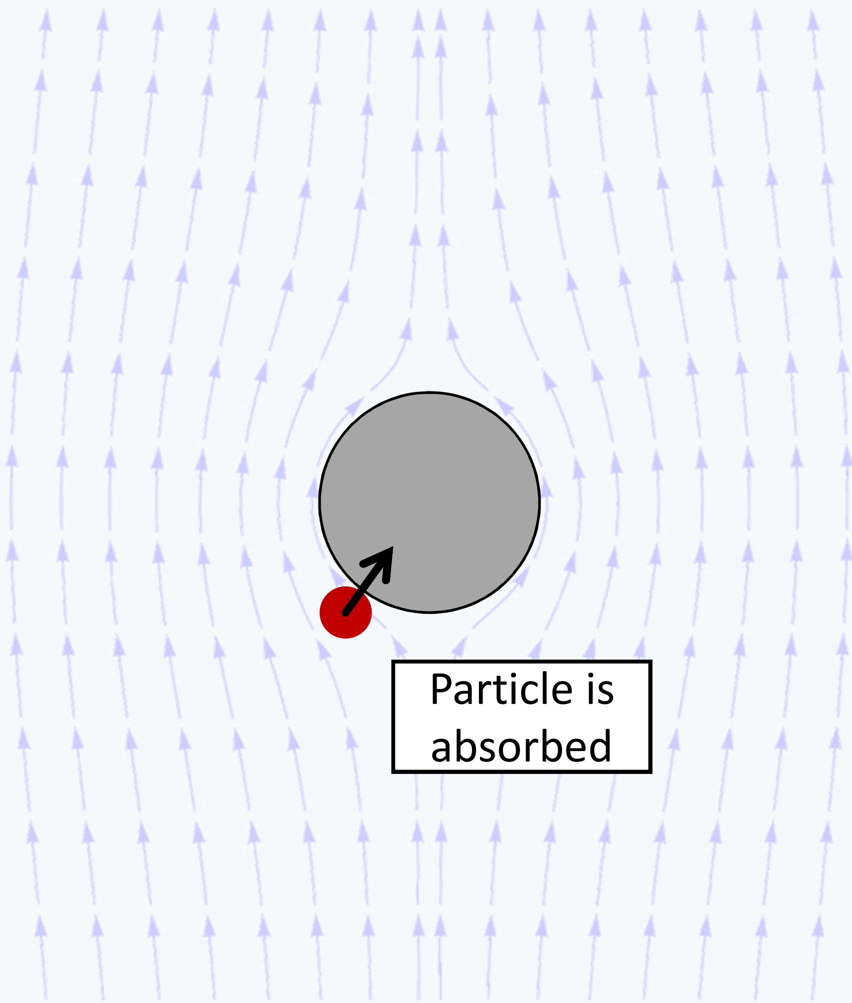
Literature comparison



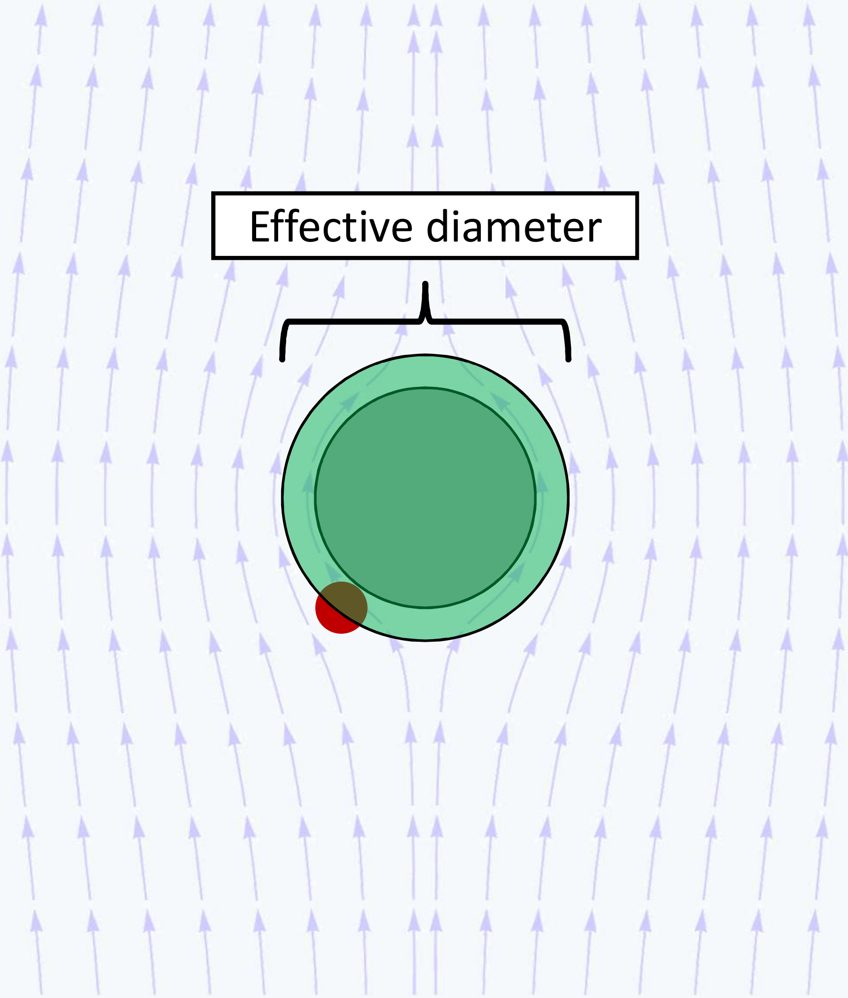
Non zero particle radius



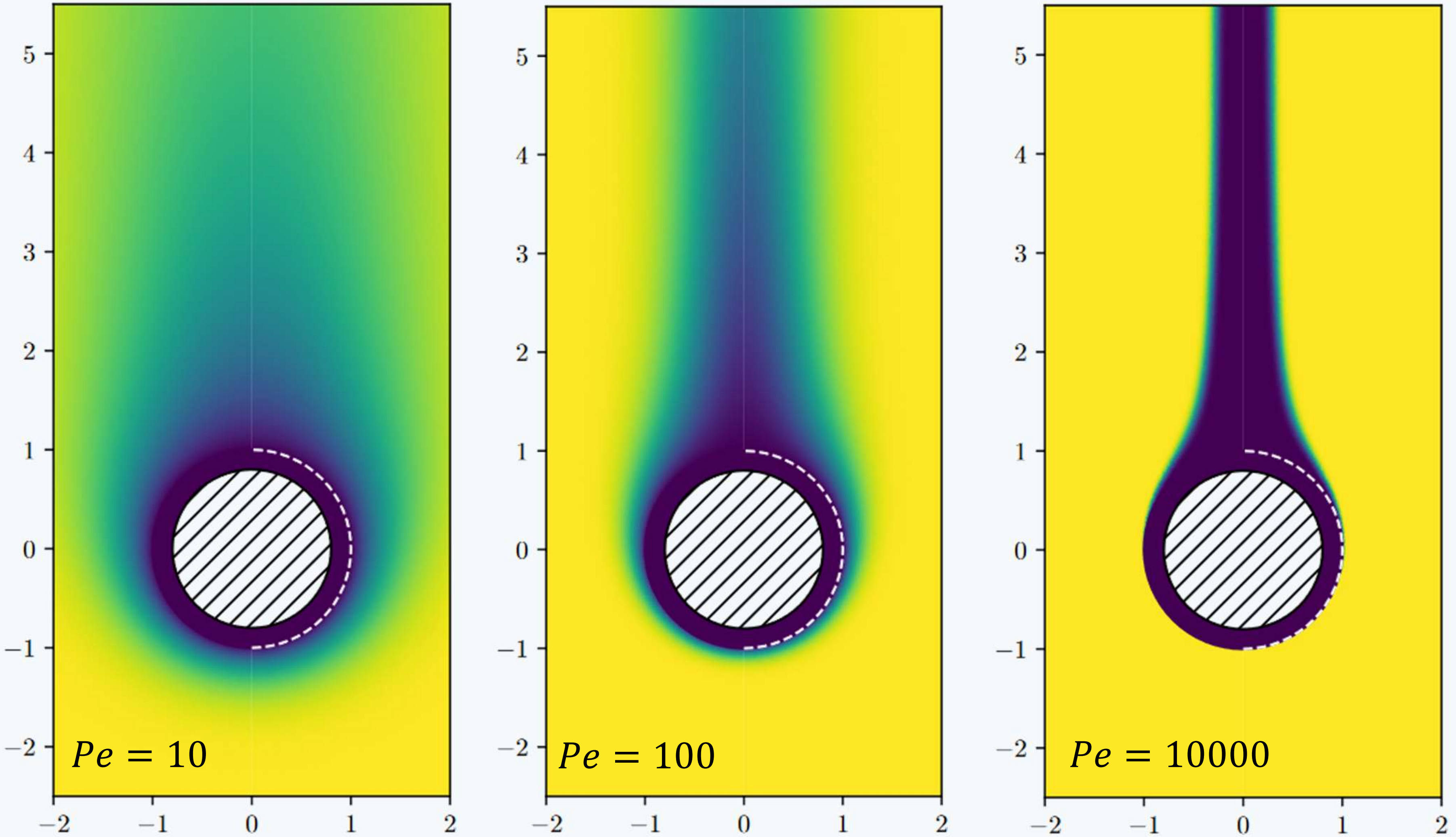
Non zero particle radius



Non zero particle radius

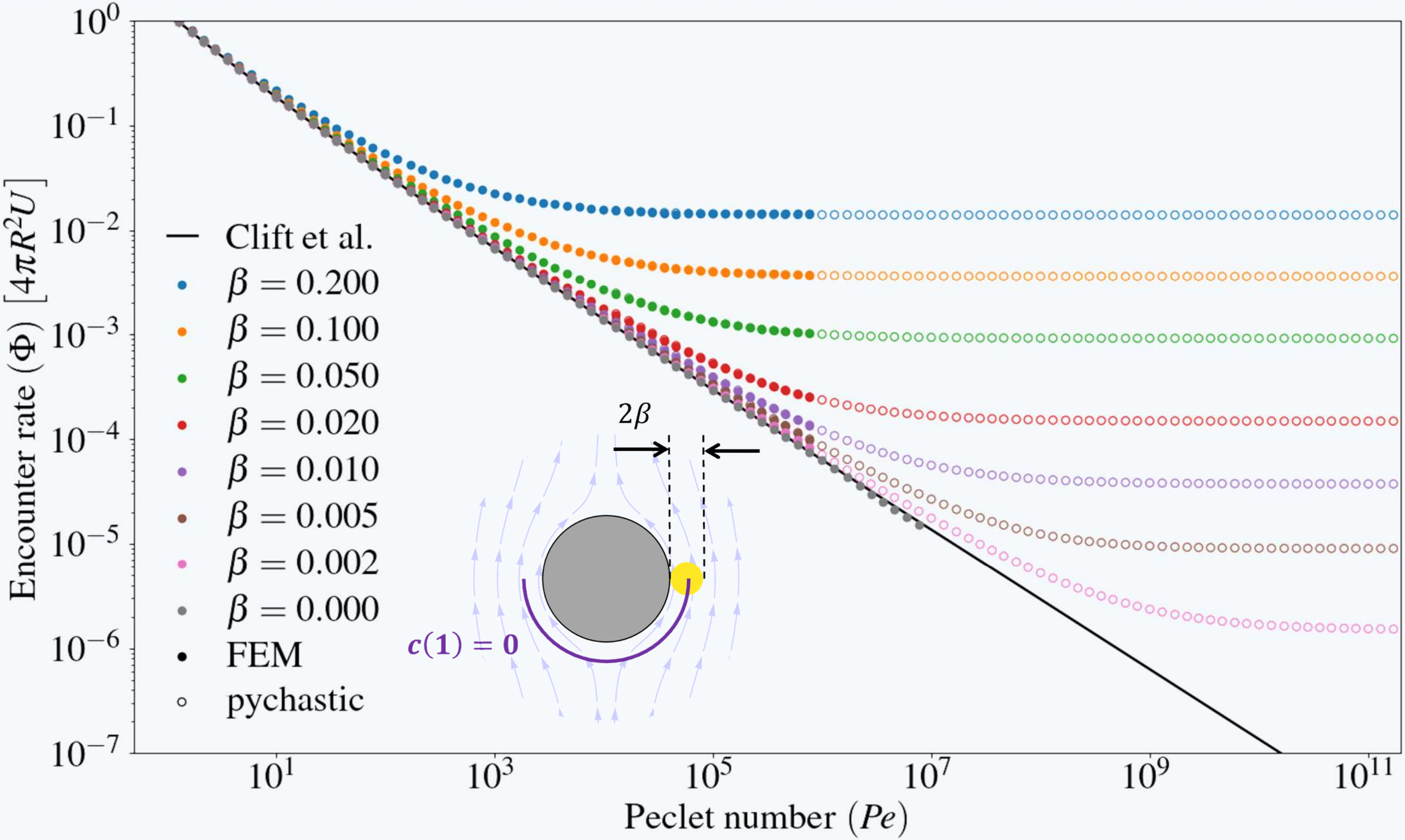


Concentration distribution



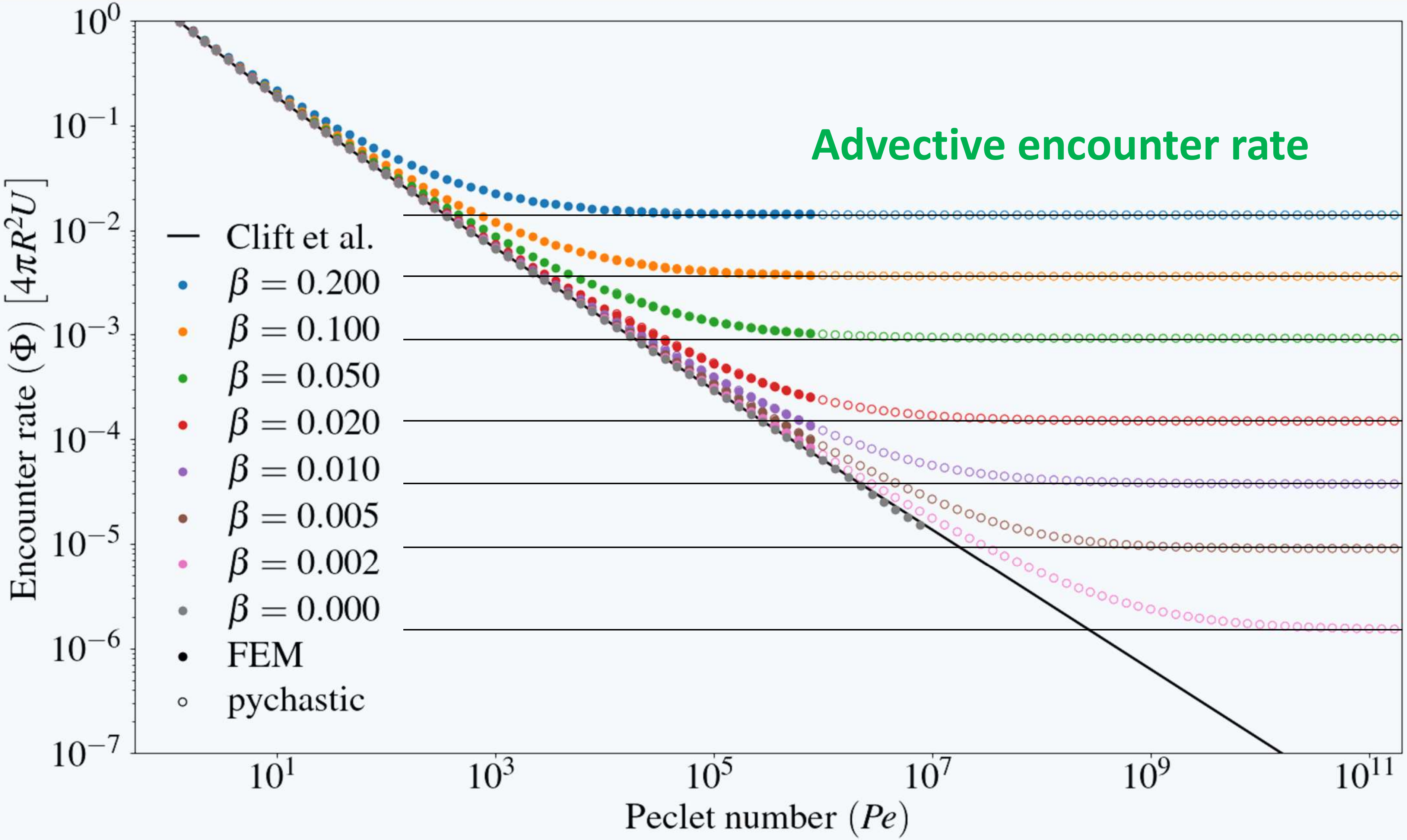
Peclet number (Pe)

Our results

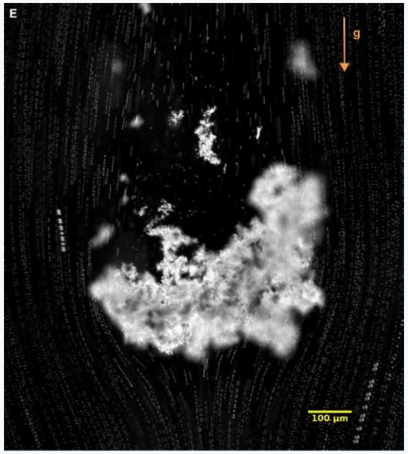


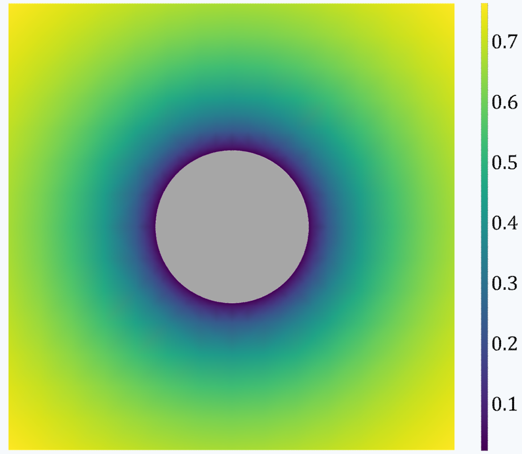
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Encounter rate (Φ) $[4\pi R^2 U]$
10^1
10^3
10^5
10^7
10^9
10^{11}
Peclet number (Pe)
Clift et al.
$\beta = 0.200$
$\beta = 0.100$
$\beta = 0.050$
$\beta = 0.020$
$\beta = 0.010$
$\beta = 0.005$
$\beta = 0.002$
$\beta = 0.000$
FEM
pychastic
2β
$c(1) = 0$

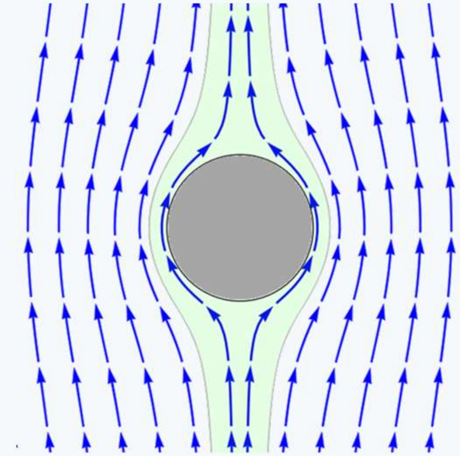
Advective kernel

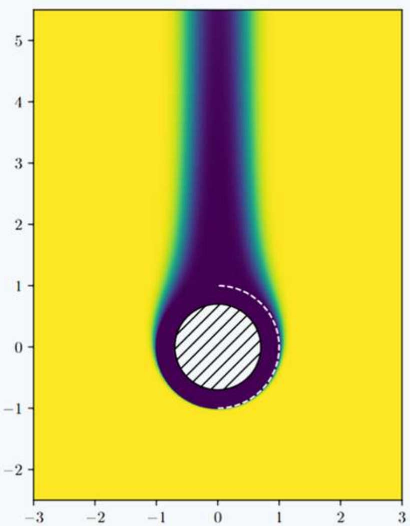


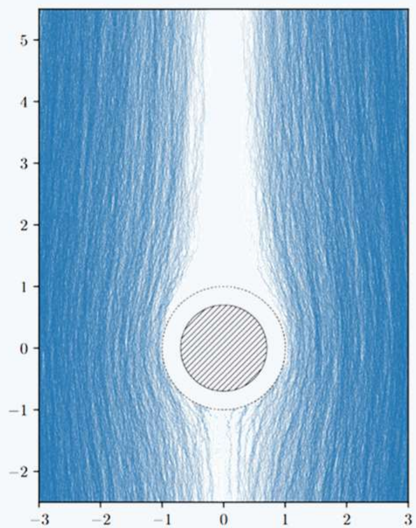
Summary

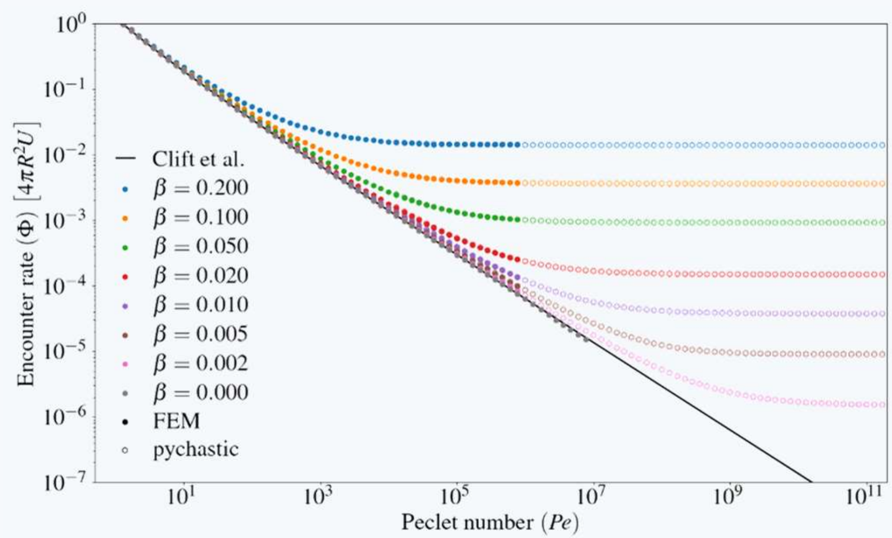

E
g
100 µm


0.7
0.6
0.5
0.4
0.3
0.2
0.1








Encounter rate (Φ) $[4\pi R^2 U]$
Peclet number (Pe)
Clift et al.
$\beta = 0.200$
$\beta = 0.100$
$\beta = 0.050$
$\beta = 0.020$
$\beta = 0.010$
$\beta = 0.005$
$\beta = 0.002$
$\beta = 0.000$
FEM
pychastic

Our team

Jan Turczynowicz
Radost Waszkiewicz
Maciej Lisicki
Jonasz Słomka

Thank you!