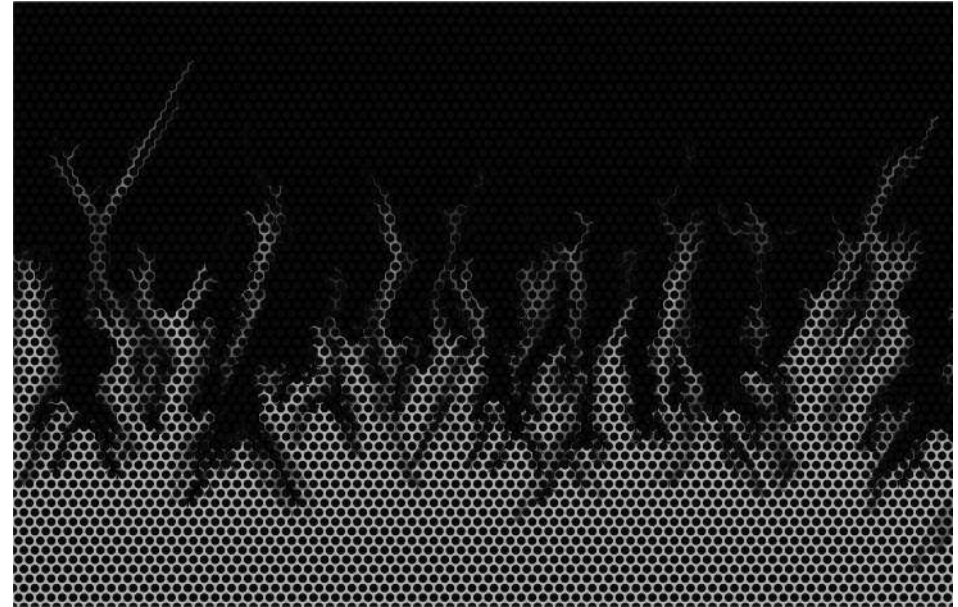
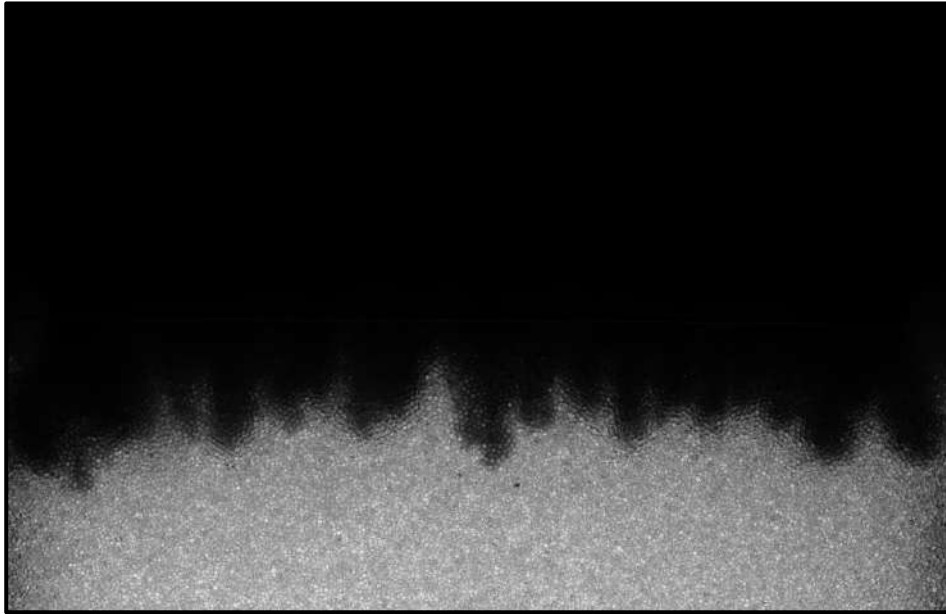


Convective mixing in confined porous media: a pore-scale study



M. De Paoli^{1,2}, C. Howland¹, R. Verzicco^{1,3,4} & D. Lohse^{1,5}

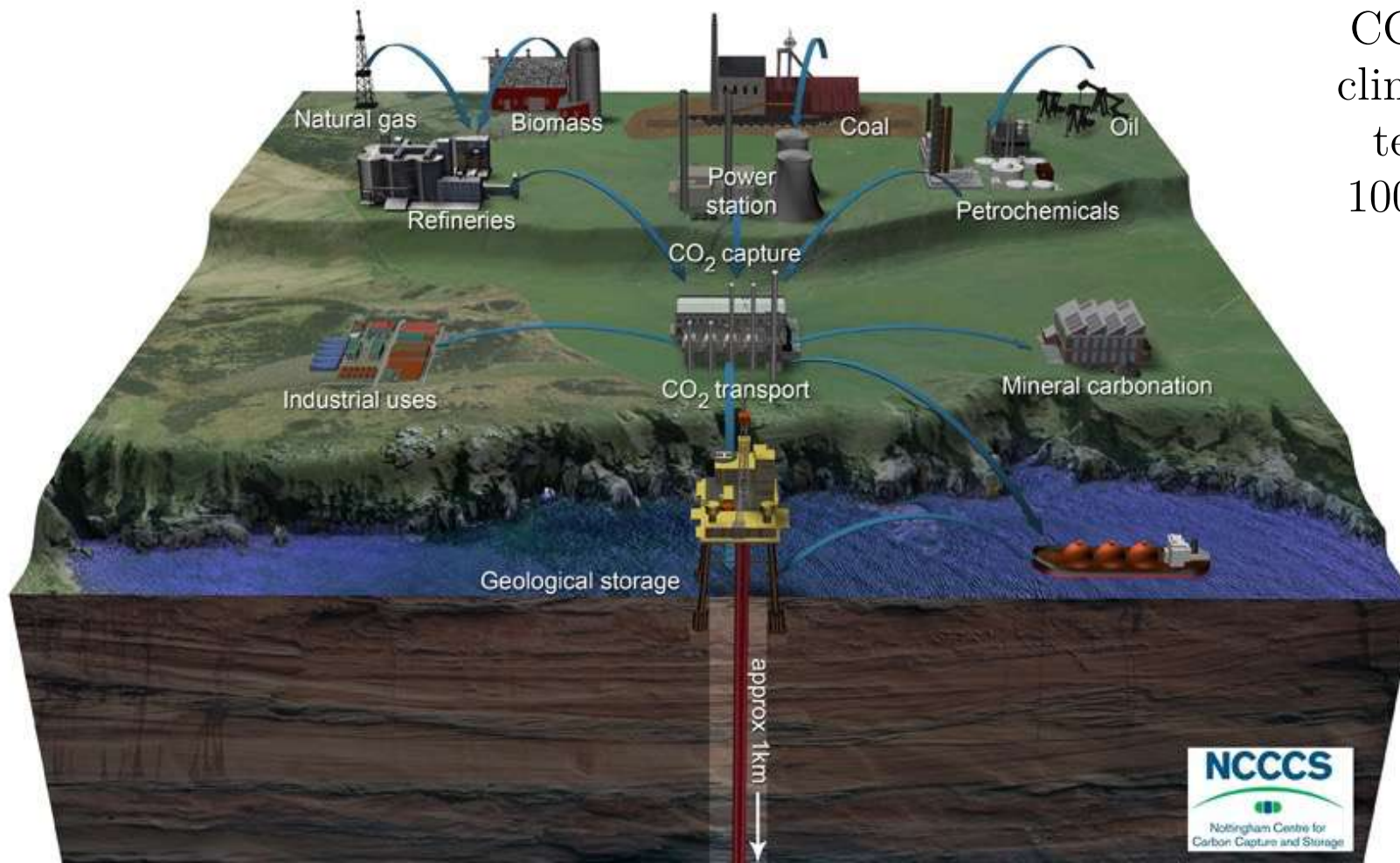
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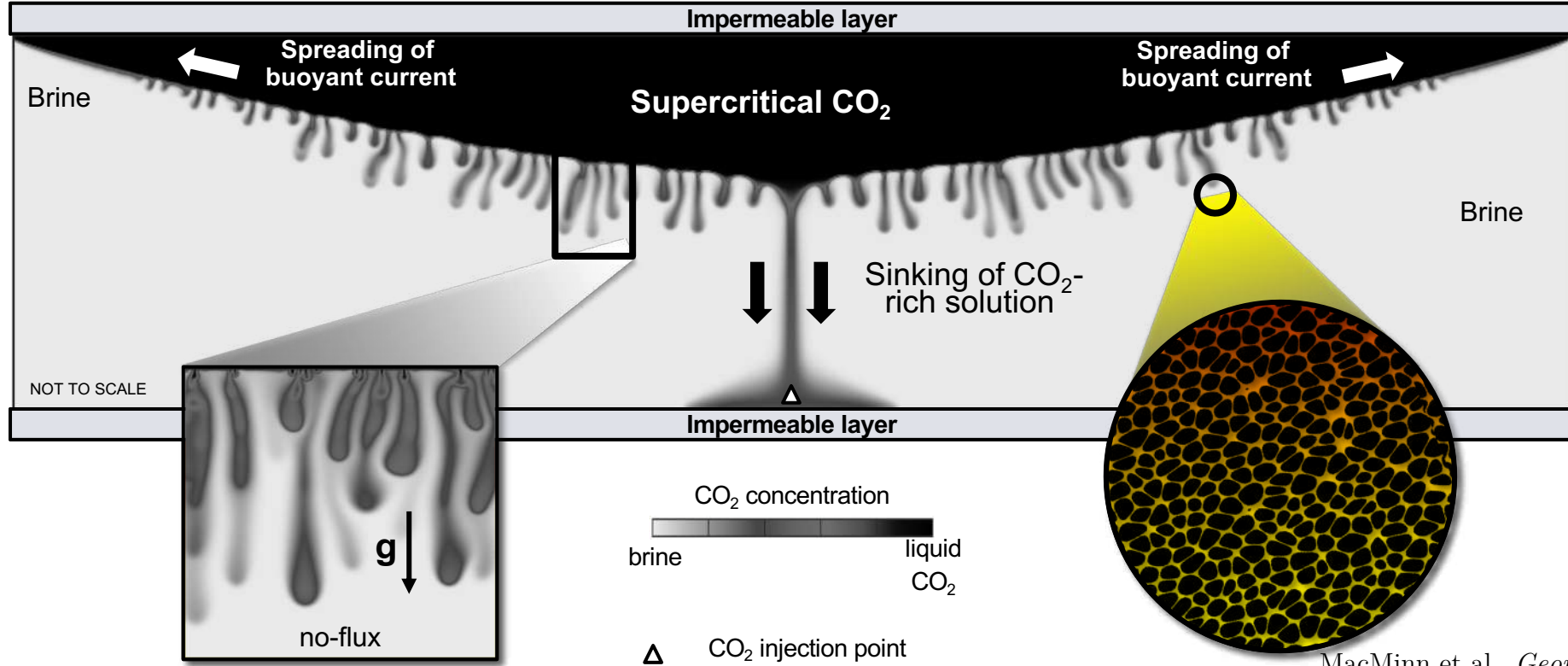


CCS can work as unique climate change mitigation technology for at least 100 years [Szulczewski *et al.*, (*PNAS*) 2012]

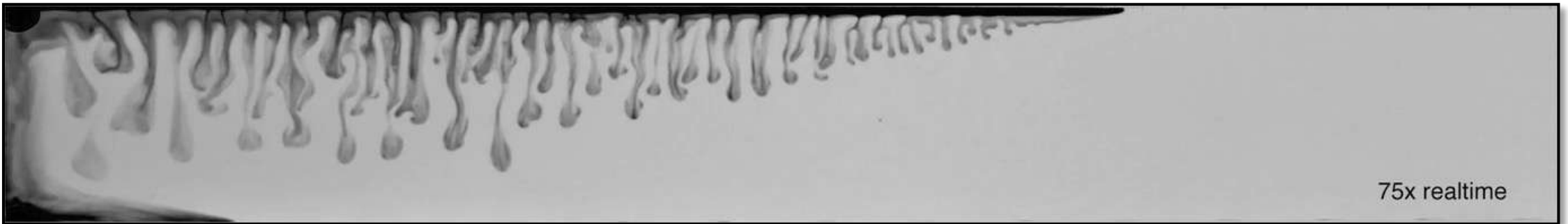
Injection point 

Convection in complex multiphase and multiscale systems

De Paoli, *Phys. Fluids* (2021)

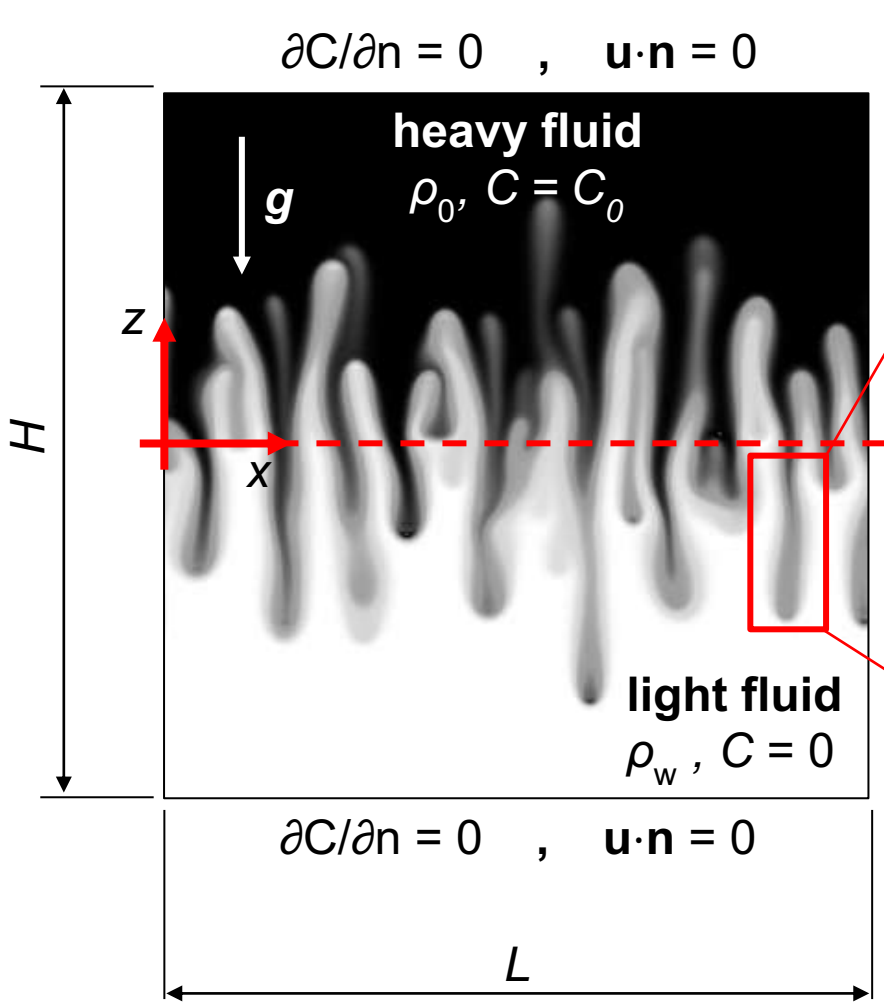


MacMinn et al., *Geophys. Res. Lett.* (2013)

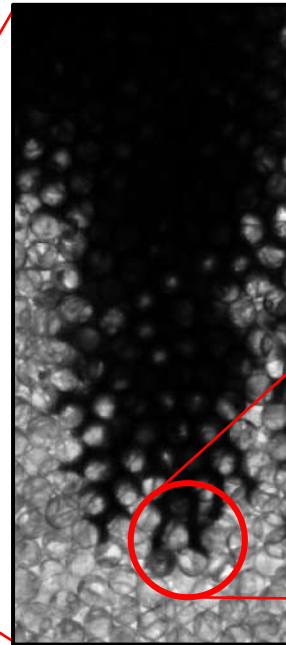


Convective mixing in confined porous media: a pore-scale study

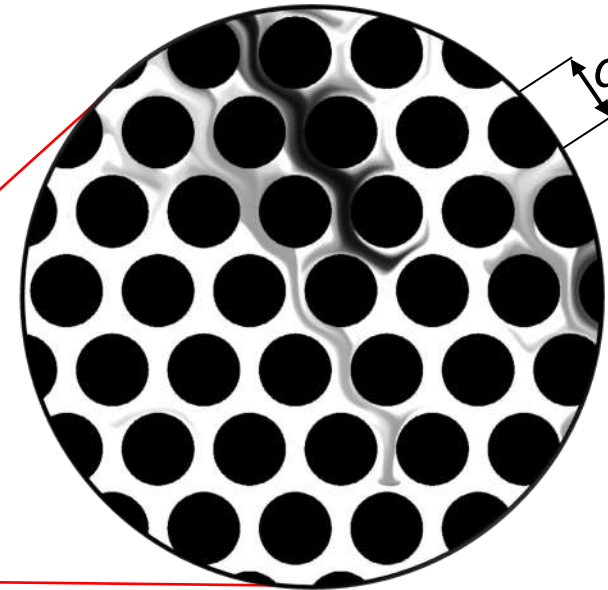
Marco De Paoli, Physics of Fluids Group, University of Twente



experiments

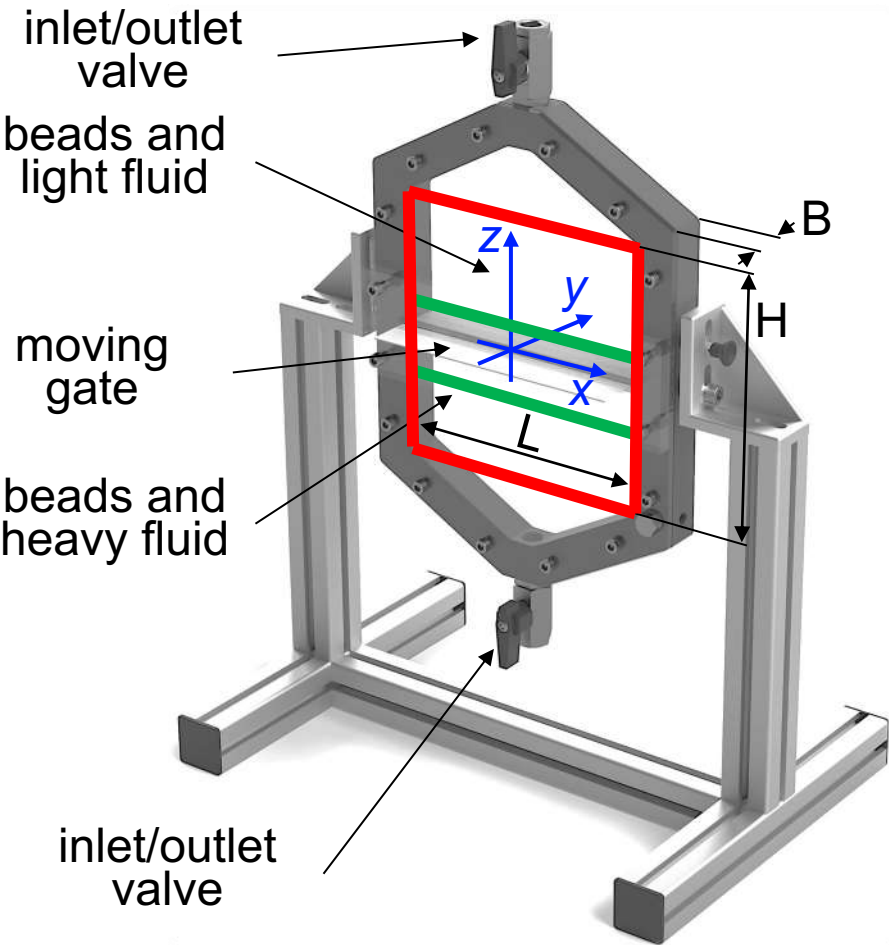


simulations

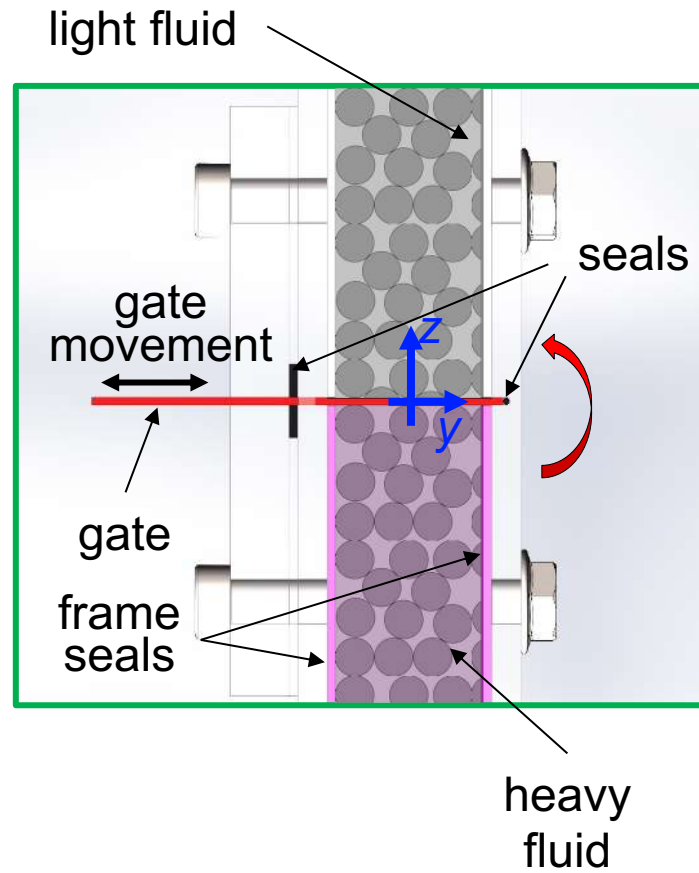


- High Schmidt number
- Porosity matched $\phi = 0.37$
- Solid impermeable to solute
- Linear dependency $\rho(C)$

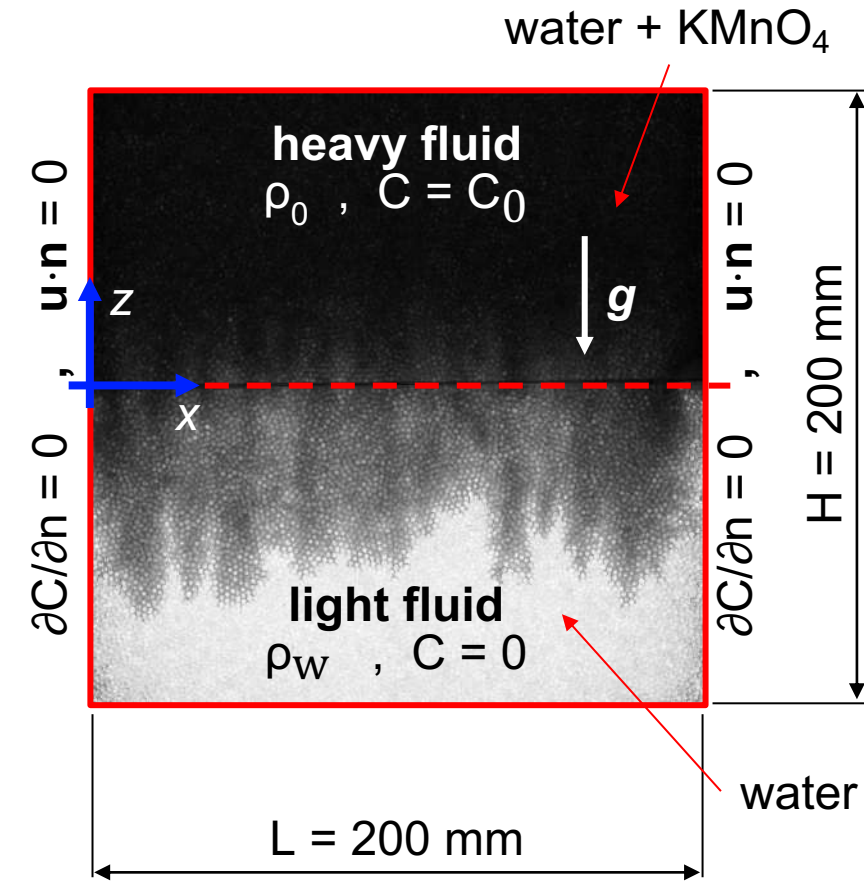
(a) Hele-Shaw cell

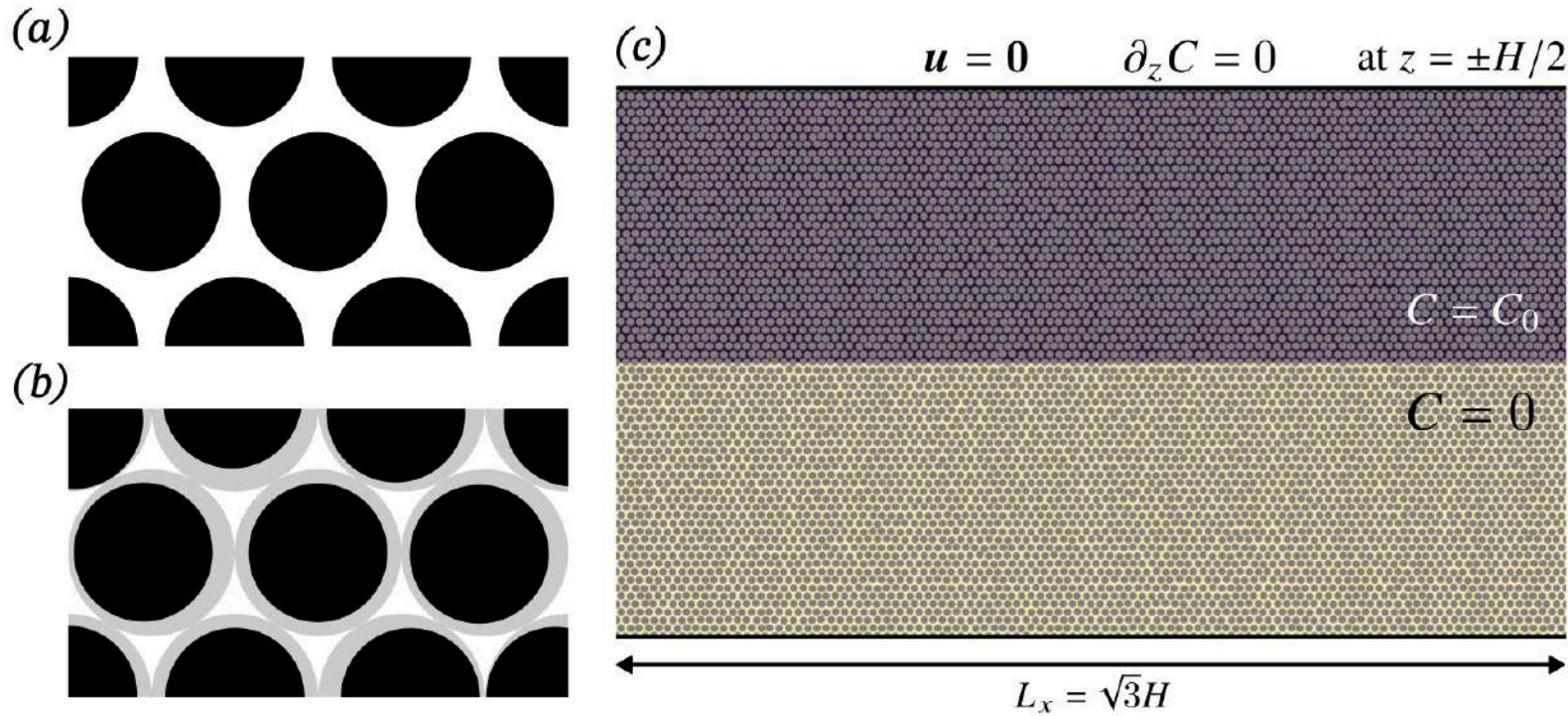


(b) gate (side view)



(c) measurement region





Advanced finite difference (AFiD, open source)
+
Immersed Boundaries Method

Resolution:

- velocity: ≥ 32 points per diameter
- concen.: ≥ 128 points per diameter

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\rho_0^{-1} \nabla p + \nu \nabla^2 \mathbf{u} - g\beta C \hat{\mathbf{z}},$$

$$\partial_t C + (\mathbf{u} \cdot \nabla) C = D \nabla^2 C,$$

$$\rho = \rho_0 \left[1 + \frac{\Delta \rho}{\rho_0 C_0} (C - C_0) \right]$$

experiments

| Name | H/d | ϕ | Sc | Ra | Ra_d | Ra^* | Pe | Re |
|------|-------|--------|------|------------------------|---------------------|---------------------|---------|--------|
| E1 | 200 | 0.37 | 558 | 4.535×10^{10} | 5.669×10^3 | 2.173×10^3 | 0.289 | 0.0005 |
| E2 | 200 | 0.37 | 558 | 9.099×10^{10} | 1.137×10^4 | 4.359×10^3 | 0.580 | 0.0010 |
| E3 | 200 | 0.37 | 558 | 1.824×10^{11} | 2.280×10^4 | 8.737×10^3 | 1.163 | 0.0021 |
| E4 | 200 | 0.37 | 558 | 3.637×10^{11} | 4.546×10^4 | 1.742×10^4 | 2.320 | 0.0042 |
| E5 | 114 | 0.37 | 558 | 4.667×10^{10} | 3.126×10^4 | 6.846×10^3 | 1.595 | 0.0029 |
| E6 | 114 | 0.37 | 558 | 9.099×10^{10} | 6.096×10^4 | 1.335×10^4 | 3.110 | 0.0056 |
| E7 | 114 | 0.37 | 558 | 1.820×10^{11} | 1.219×10^5 | 2.671×10^4 | 6.222 | 0.0112 |
| E8 | 114 | 0.37 | 558 | 3.626×10^{11} | 2.429×10^5 | 5.320×10^4 | 12.395 | 0.0222 |
| E9 | 67 | 0.35 | 558 | 4.490×10^{10} | 1.515×10^5 | 1.627×10^4 | 5.795 | 0.0104 |
| E10 | 67 | 0.35 | 558 | 9.495×10^{10} | 3.204×10^5 | 3.441×10^4 | 12.256 | 0.0220 |
| E11 | 67 | 0.35 | 558 | 1.834×10^{11} | 6.189×10^5 | 6.646×10^4 | 23.672 | 0.0425 |
| E12 | 67 | 0.35 | 558 | 3.670×10^{11} | 1.239×10^6 | 1.330×10^5 | 47.370 | 0.0850 |
| E13 | 50 | 0.37 | 558 | 4.506×10^{10} | 3.605×10^5 | 3.454×10^4 | 18.393 | 0.0330 |
| E14 | 50 | 0.37 | 558 | 9.101×10^{10} | 7.281×10^5 | 6.976×10^4 | 37.150 | 0.0666 |
| E15 | 50 | 0.37 | 558 | 1.824×10^{11} | 1.460×10^6 | 1.398×10^5 | 74.474 | 0.1336 |
| E16 | 50 | 0.37 | 558 | 3.622×10^{11} | 2.898×10^6 | 2.777×10^5 | 147.861 | 0.2652 |

flow scales and parameters

$$k = \frac{d^2}{36k_C} \frac{\phi^3}{(1-\phi)^2} \quad U = \frac{g\Delta\rho k}{\mu} \quad \ell = \frac{\phi D}{U} \quad Sc = \frac{\mu}{\rho_0 D}$$

simulations

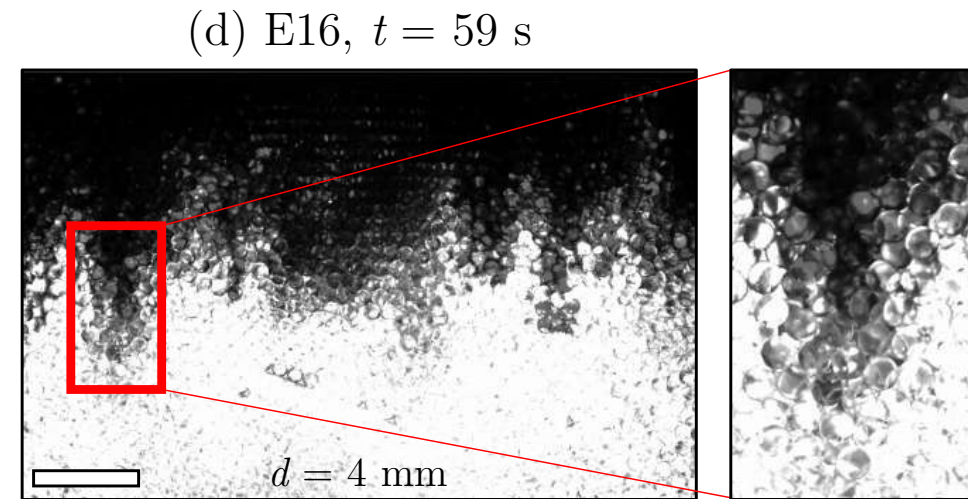
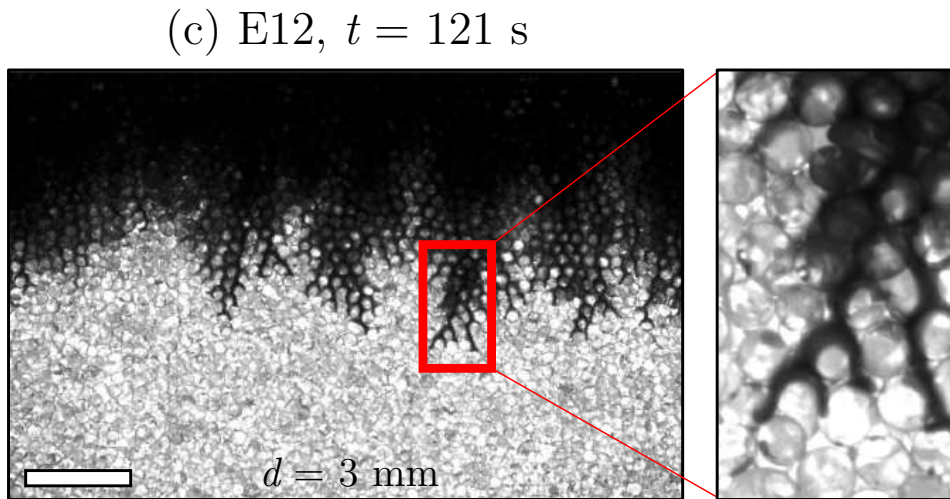
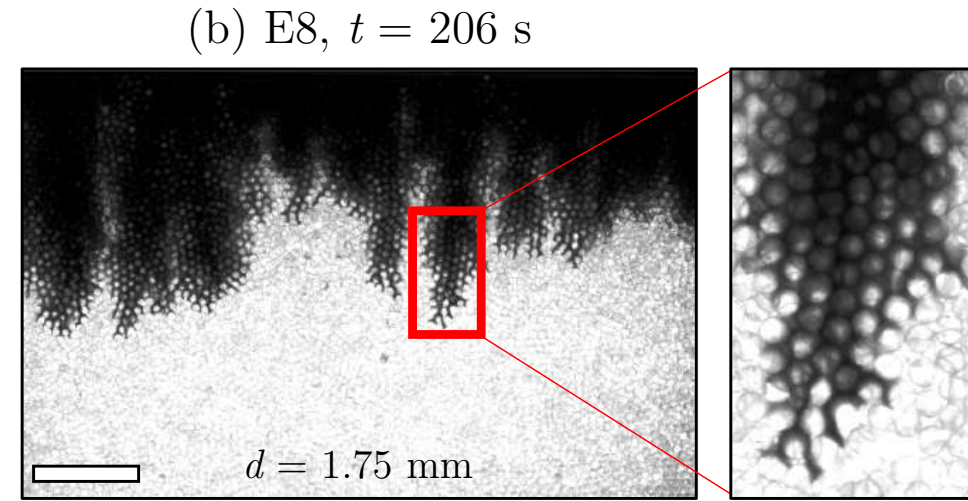
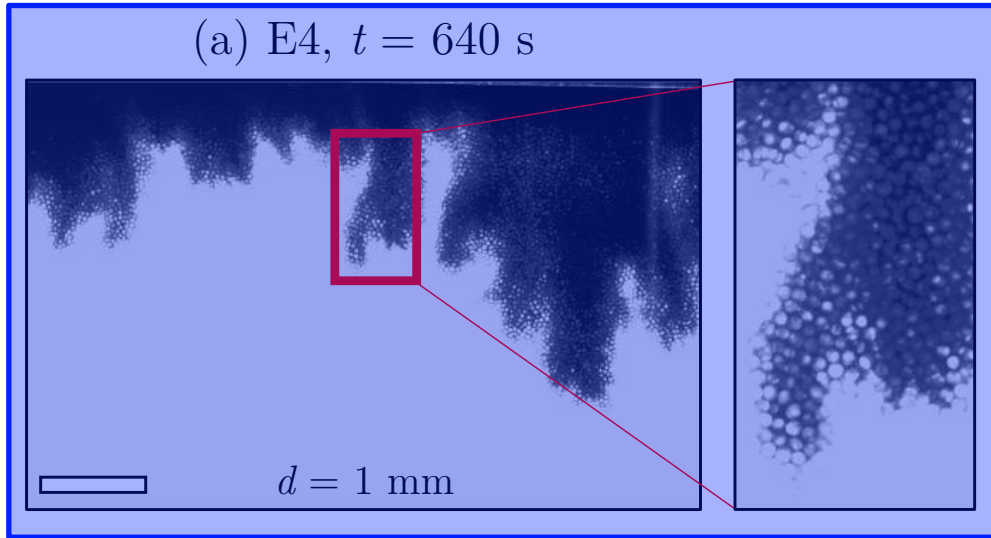
| Name | H/d | ϕ | Sc | Ra | Ra_d | Ra^* | Pe | Re |
|------|-------|--------|------|------------------------|---------------------|---------------------|--------|--------|
| S1 | 17 | 0.37 | 100 | 5.268×10^8 | 1.000×10^5 | 3.334×10^3 | 5.102 | 0.0510 |
| S2 | 17 | 0.37 | 100 | 1.666×10^9 | 3.162×10^5 | 1.054×10^4 | 16.135 | 0.1614 |
| S3 | 17 | 0.37 | 100 | 5.268×10^9 | 1.000×10^6 | 3.334×10^4 | 51.024 | 0.5102 |
| S4 | 35 | 0.37 | 100 | 4.214×10^9 | 1.000×10^5 | 6.669×10^3 | 5.102 | 0.0510 |
| S5 | 35 | 0.37 | 100 | 1.333×10^{10} | 3.162×10^5 | 2.109×10^4 | 16.135 | 0.1614 |
| S6 | 35 | 0.37 | 100 | 4.214×10^{10} | 1.000×10^6 | 6.669×10^4 | 51.024 | 0.5102 |
| S7 | 52 | 0.37 | 100 | 1.422×10^{10} | 1.000×10^5 | 1.000×10^4 | 5.102 | 0.0510 |
| S8 | 52 | 0.37 | 100 | 4.498×10^{10} | 3.162×10^5 | 3.163×10^4 | 16.135 | 0.1614 |
| S9 | 52 | 0.37 | 100 | 1.422×10^{11} | 1.000×10^6 | 1.000×10^5 | 51.024 | 0.5102 |
| S10 | 70 | 0.37 | 100 | 3.372×10^{10} | 1.000×10^5 | 1.334×10^4 | 5.102 | 0.0510 |
| S11 | 70 | 0.37 | 100 | 1.066×10^{11} | 3.162×10^5 | 4.218×10^4 | 16.135 | 0.1614 |
| S12 | 70 | 0.37 | 100 | 3.372×10^{11} | 1.000×10^6 | 1.334×10^5 | 51.024 | 0.5102 |

dimensionless parameters

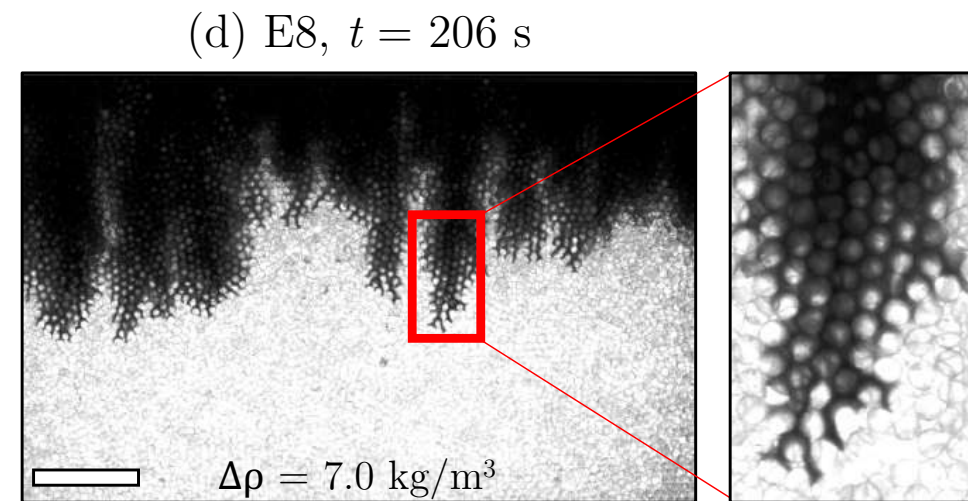
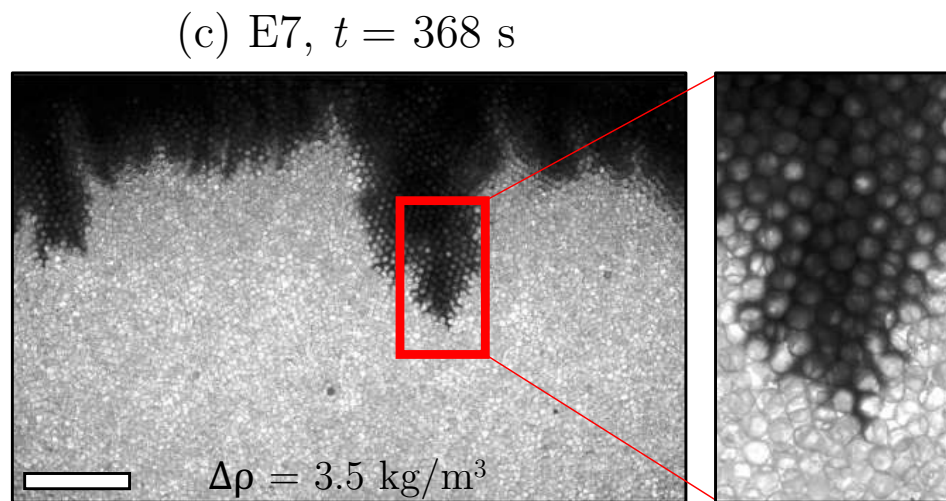
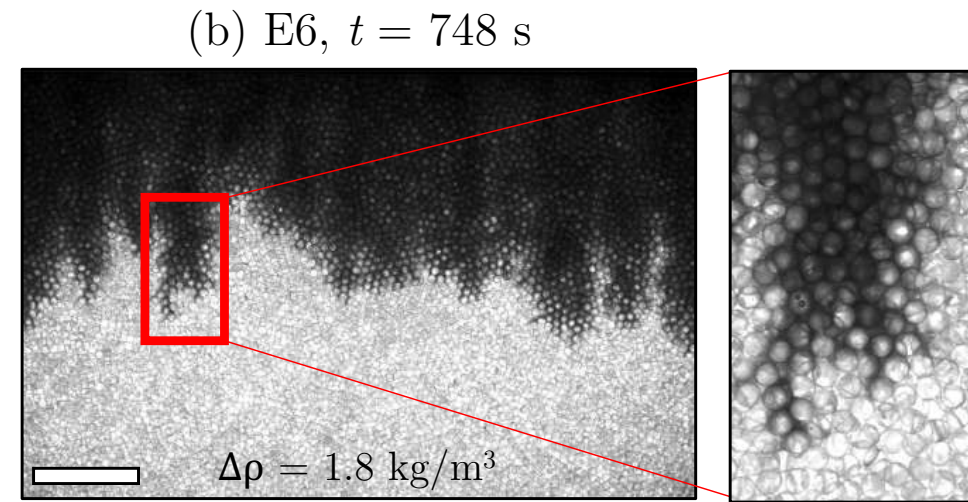
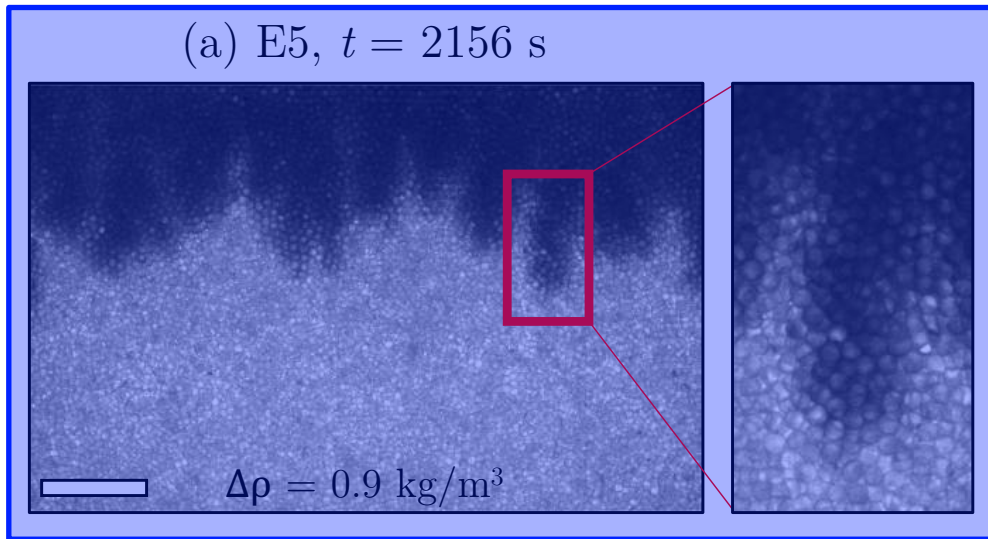
$$Da = k/H^2 \quad Ra = \frac{g\Delta\rho H^3}{\mu D} \quad Ra_d = \frac{g\Delta\rho d^3}{\mu D}$$

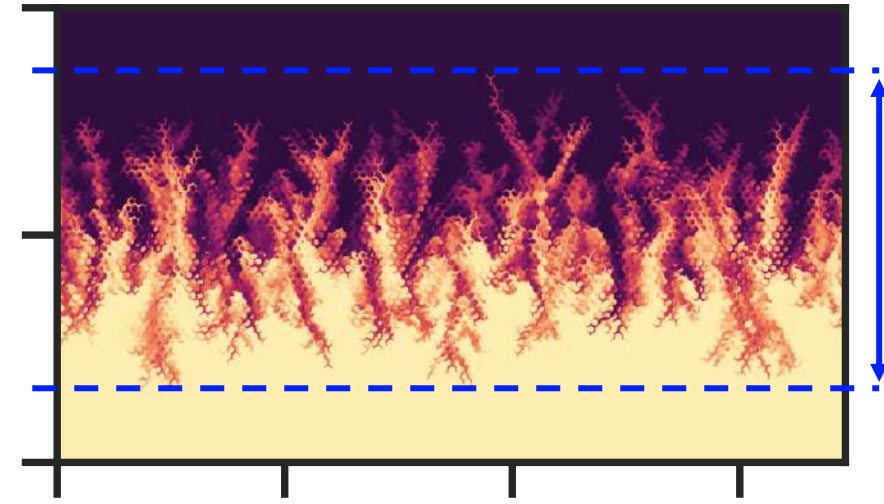
$$Ra^* = \frac{Ra Da}{\phi} \quad Re = \frac{Ra^* Da^{1/2}}{Sc} \quad Pe = Ra^* Da^{1/2}$$

Influence of d ($\Delta\rho = 7 \text{ kg/m}^3$)



Influence of $\Delta\rho$ ($d = 1.75$ mm)





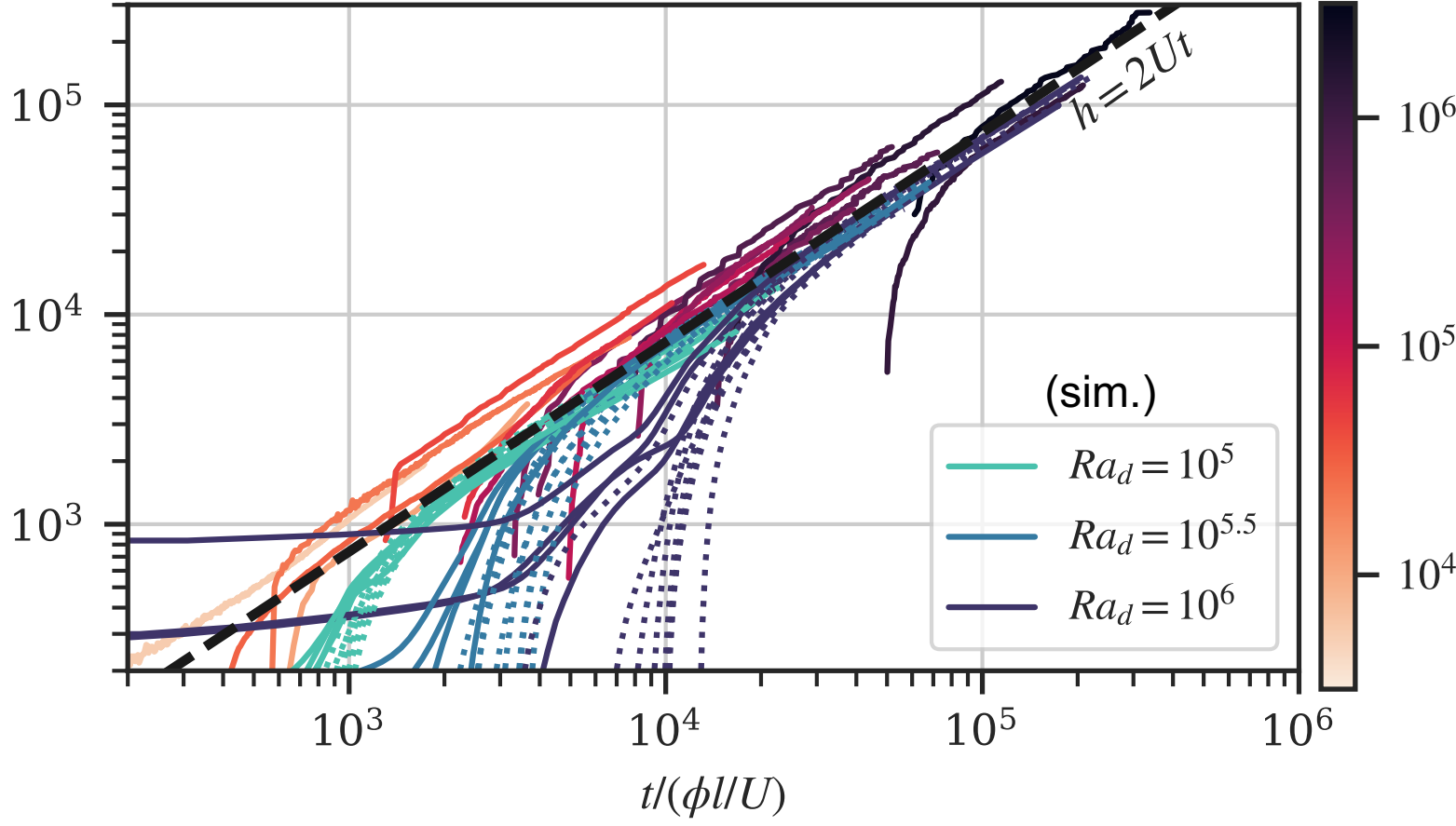
$$U = \frac{g\Delta\rho k}{\mu}$$

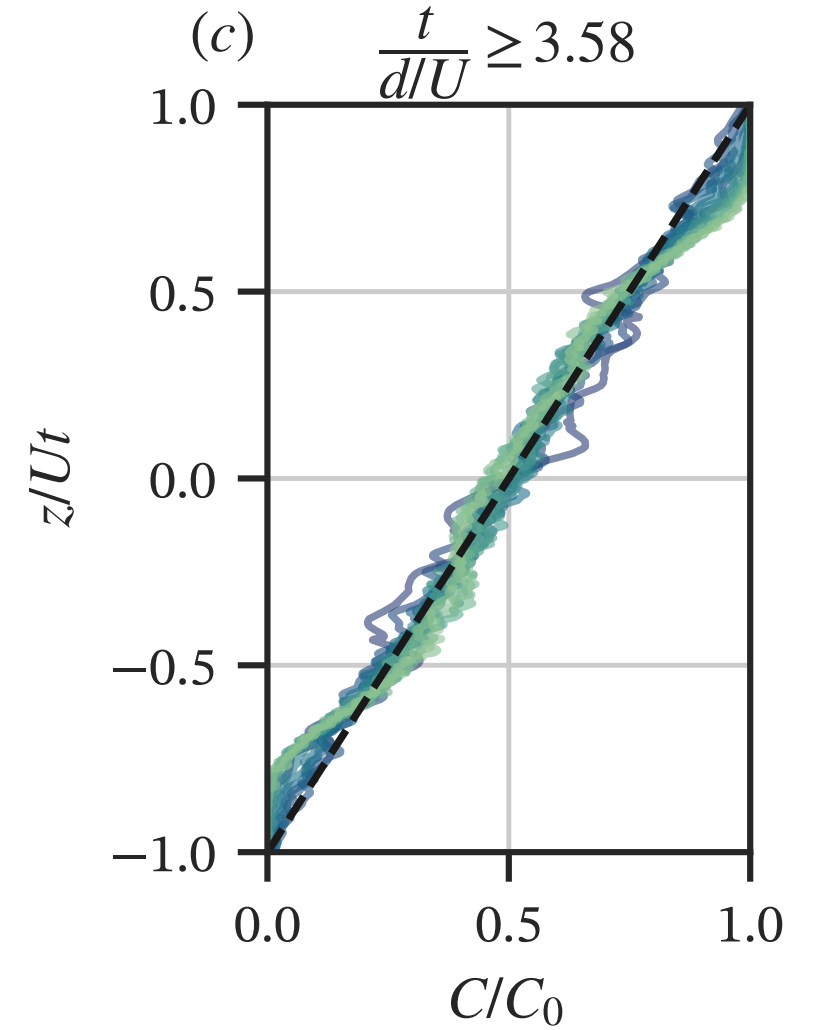
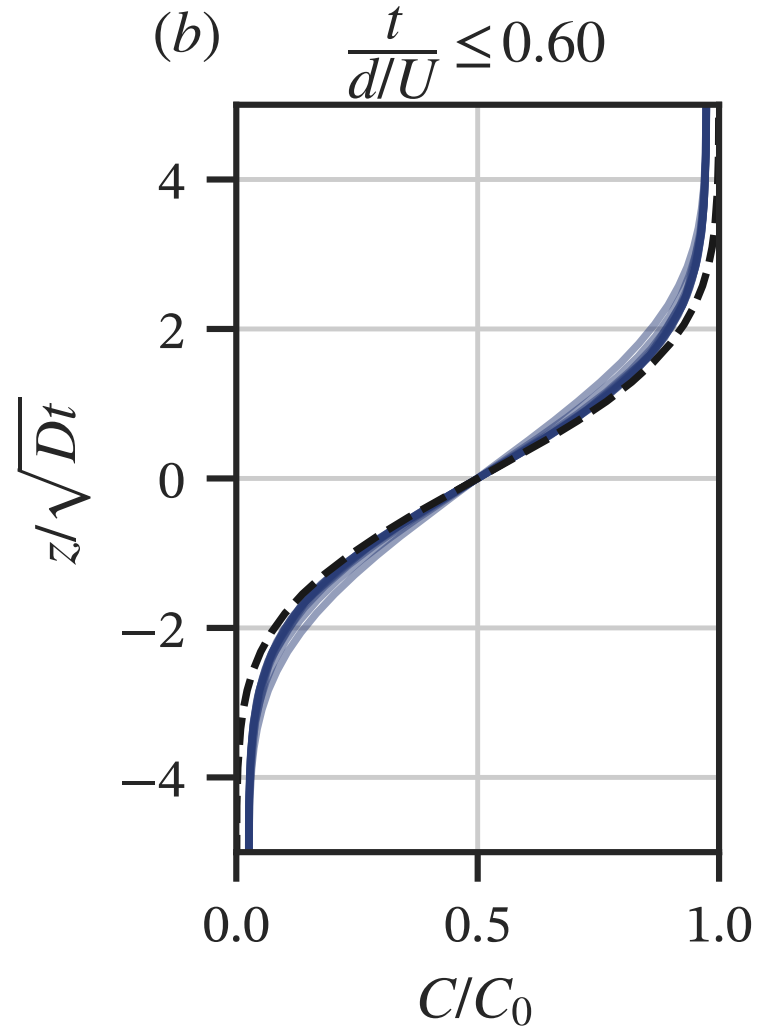
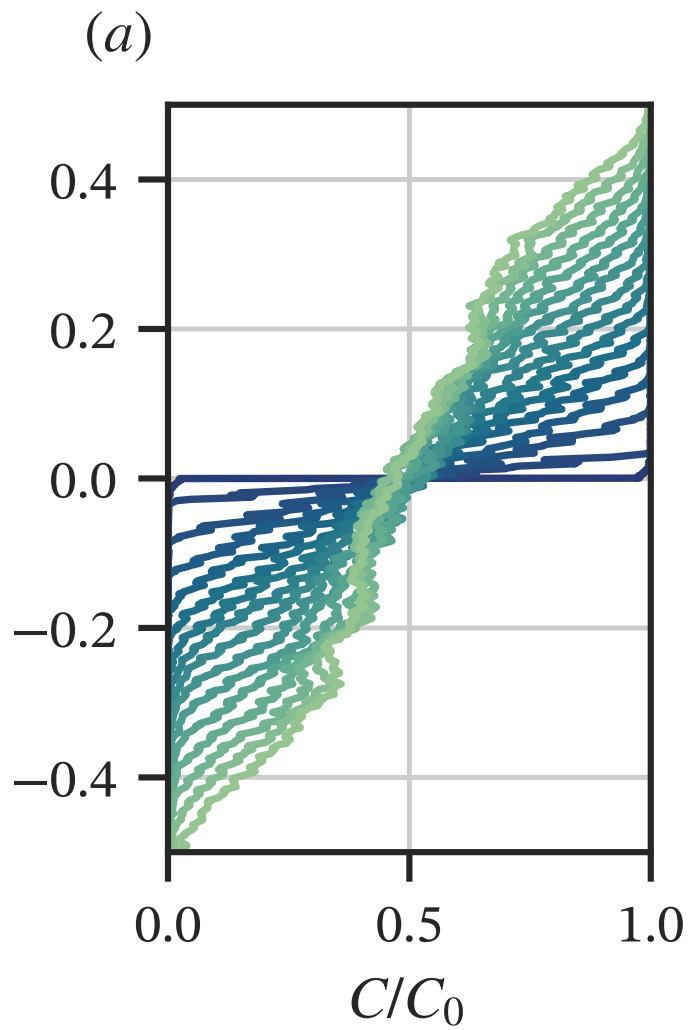
$$\ell = \frac{\phi D}{U}$$

$$Ra_d = \frac{g\Delta\rho d^3}{\mu D}$$

$h(t)$

h/l





$$\chi = D \langle |\nabla C|^2 \rangle_f = \frac{D}{V_f} \int_{V_f} |\nabla C|^2 dV$$

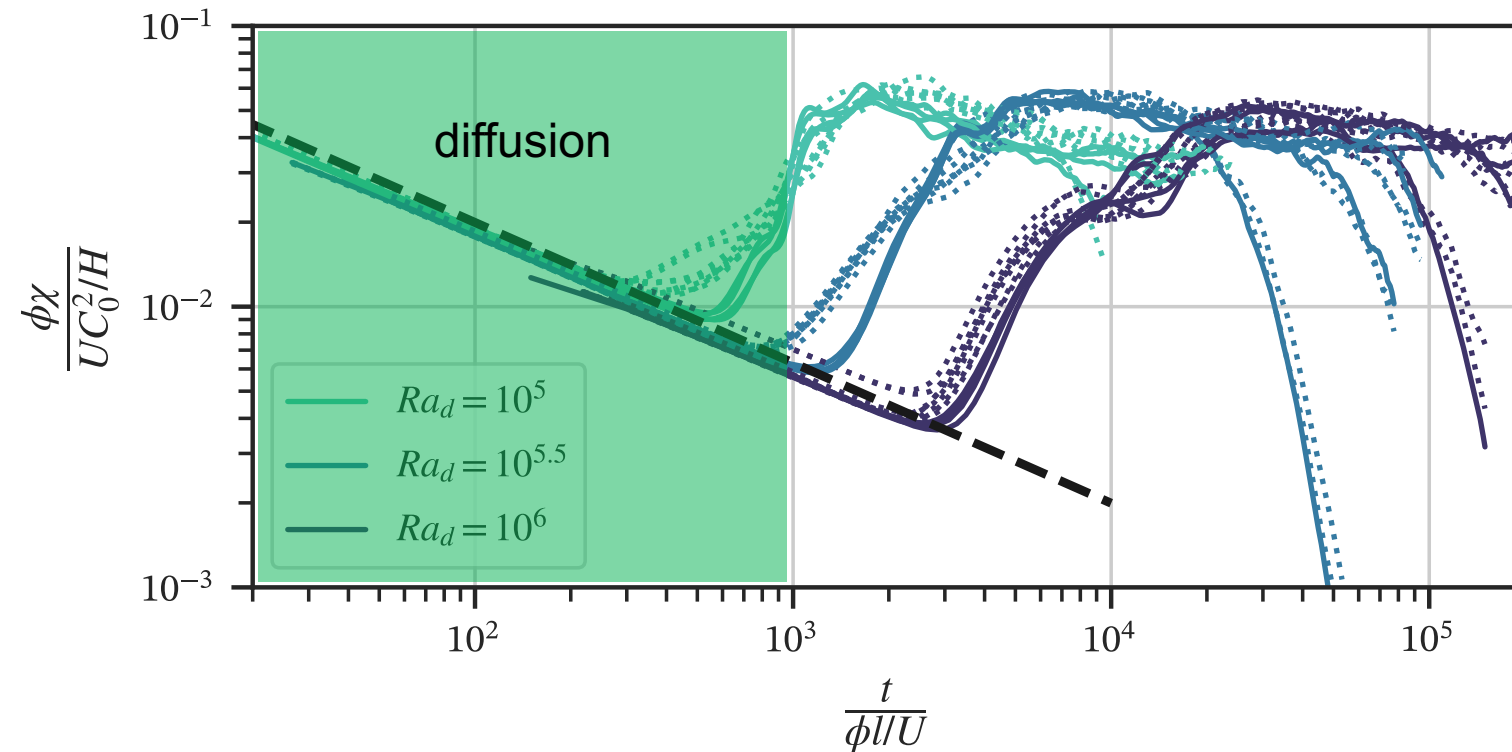
Can we model this mixing/dissolution process?

Diffusion:

$$C = C_0 + \frac{\Delta C}{2} \operatorname{erf} \left(\frac{z}{\sqrt{2\kappa t}} \right)$$

$$\partial_z C = \frac{\Delta C}{2\sqrt{\pi\kappa t}} \exp \left(-\frac{z^2}{2\kappa t} \right)$$

$$\begin{aligned} \chi &= \kappa \langle |\nabla C|^2 \rangle = \frac{\kappa}{H} \int_{-\infty}^{\infty} |\partial_z C|^2 dz \\ &= \sqrt{\frac{\kappa}{8\pi t}} \frac{(\Delta C)^2}{H} \end{aligned}$$



$$\chi = D \langle |\nabla C|^2 \rangle_f = \frac{D}{V_f} \int_{V_f} |\nabla C|^2 dV$$

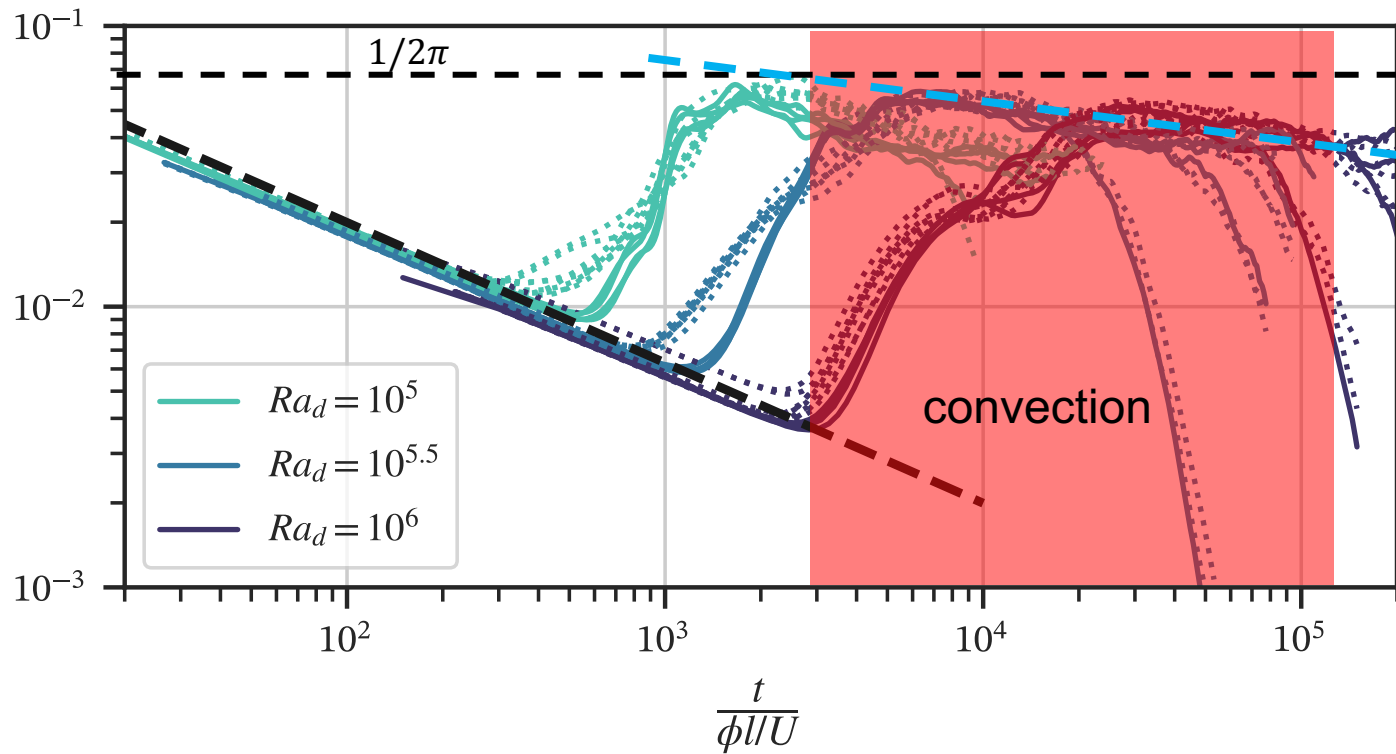
Convection

$$\chi = \kappa \langle |\nabla C|^2 \rangle = \kappa \frac{L_m}{H} \langle |\nabla C|^2 \rangle_{ML},$$

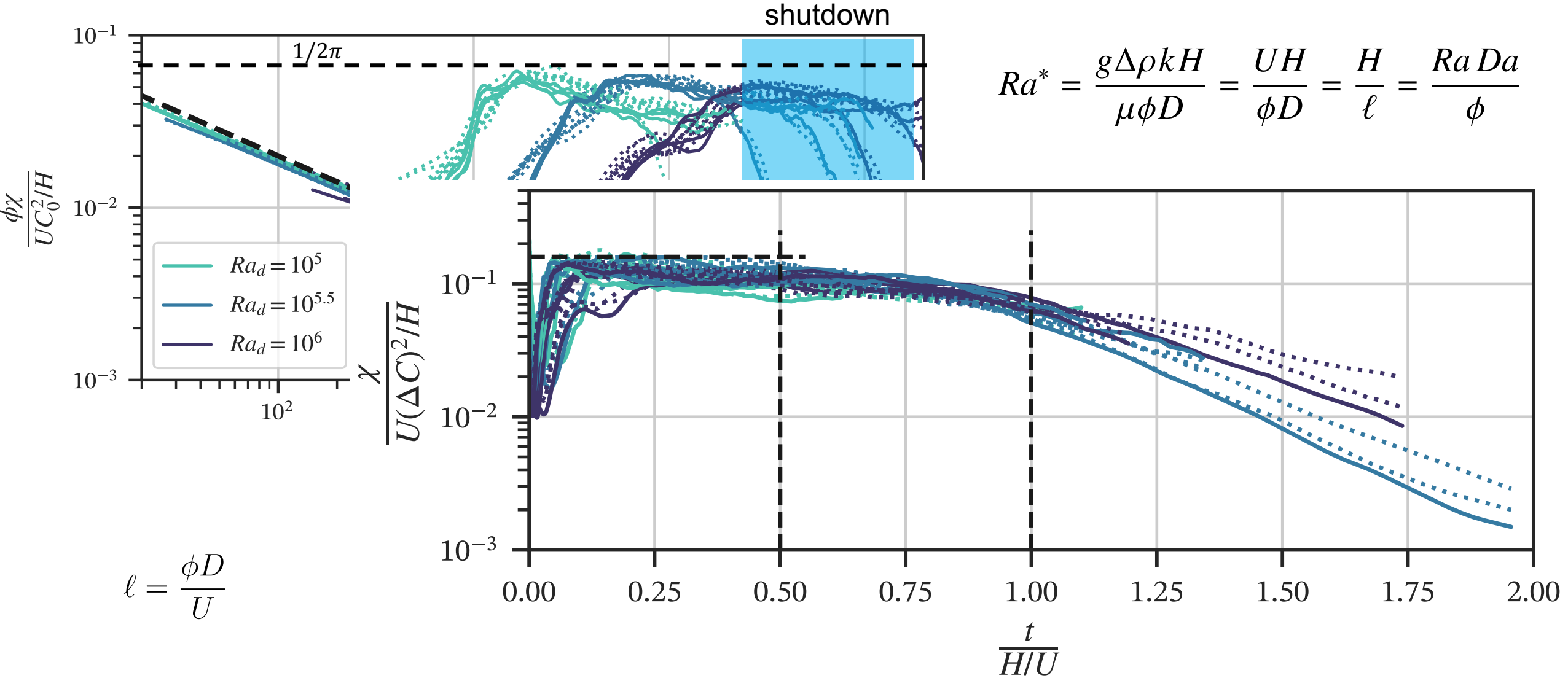
$$|\nabla C| \approx \frac{\Delta C}{2\sqrt{\pi \kappa t}}$$

$$L_m \approx 2Ut,$$

$$\chi \approx \kappa \frac{2Ut}{H} \frac{(\Delta C)^2}{4\pi \kappa t} = \frac{1}{2\pi} \frac{U_d (\Delta C)^2}{H}$$

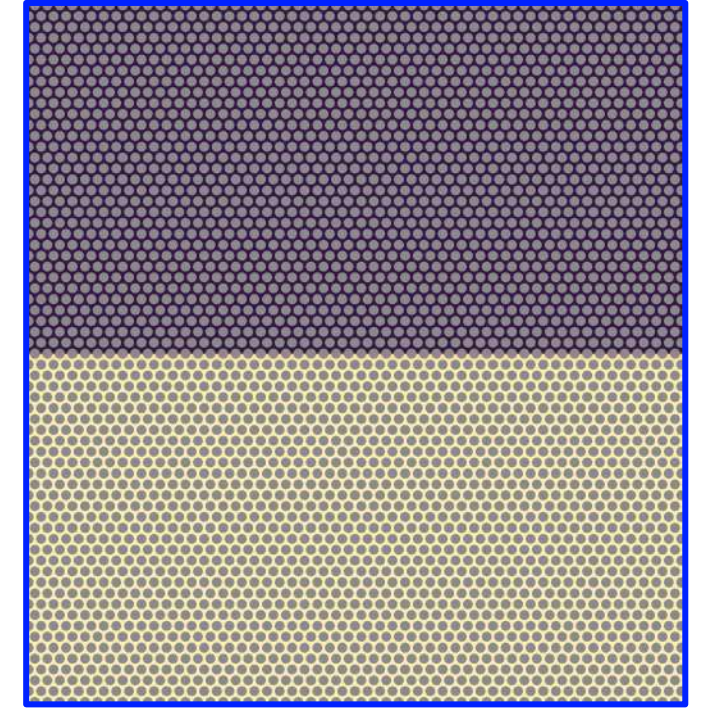
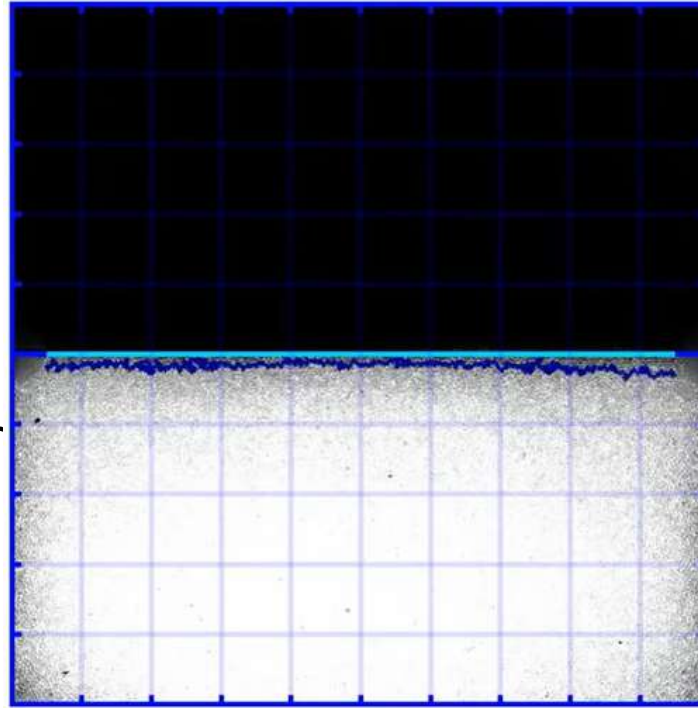


$1/2\pi$ is the maximum value of dissipation. Practically, χ decreases with time



Thank you for your attention! Questions?

- Simulations and experiments are used as complementary tools
- Multiple length scales are relevant at different phases of the process
- Mixing length predicted experimentally exhibits a self-similar behaviour that agrees well with theoretical prediction
- Mixing measured numerically via mean scalar dissipation has a self-similar behaviour.
- We explain theoretically the scaling laws observed



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FWF

Der Wissenschaftsfonds.



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arxiv.org/abs/2310.04068



High-resolution images, movies and slides are available upon request to m.depaoli@utwente.nl