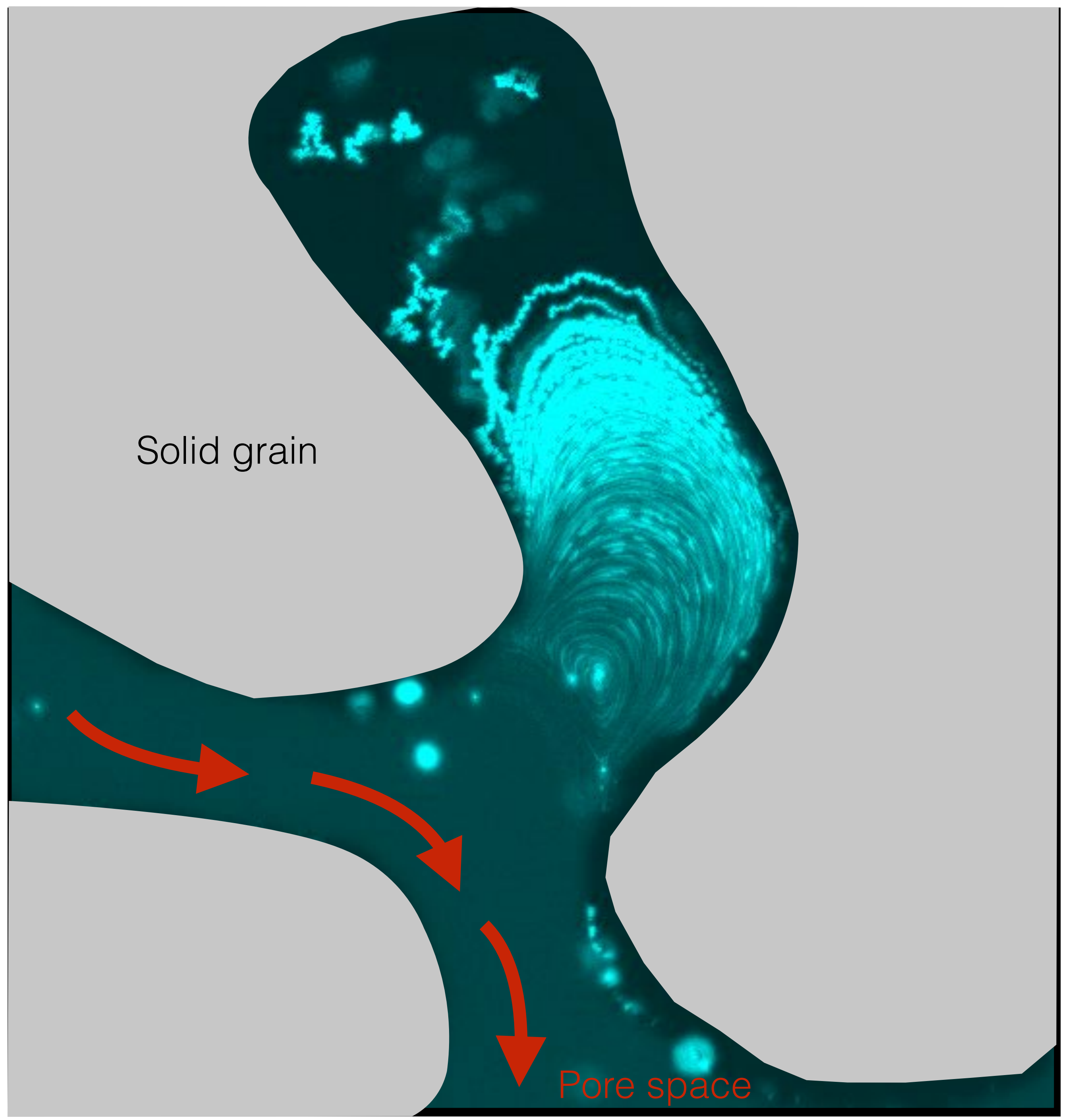
Structure induced vortices control anomalous dispersion in porous media

A. D. Bordoloi, D. Scheidweiler, M. Dentz, M. Abbarchi, M. Bouabdellaoui and **Pietro de Anna**



Superposition of 1,000 microscopic pictures of fluorescent colloids

https://arxiv.org/abs/2112.12492

Structure induced laminar vortices control anomalous dispersion in porous media

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We combine theoretical, numerical and experimental tools, to study how the fundamental processes of flow, transport and mixing shape **environmental systems characterized by confinement**.

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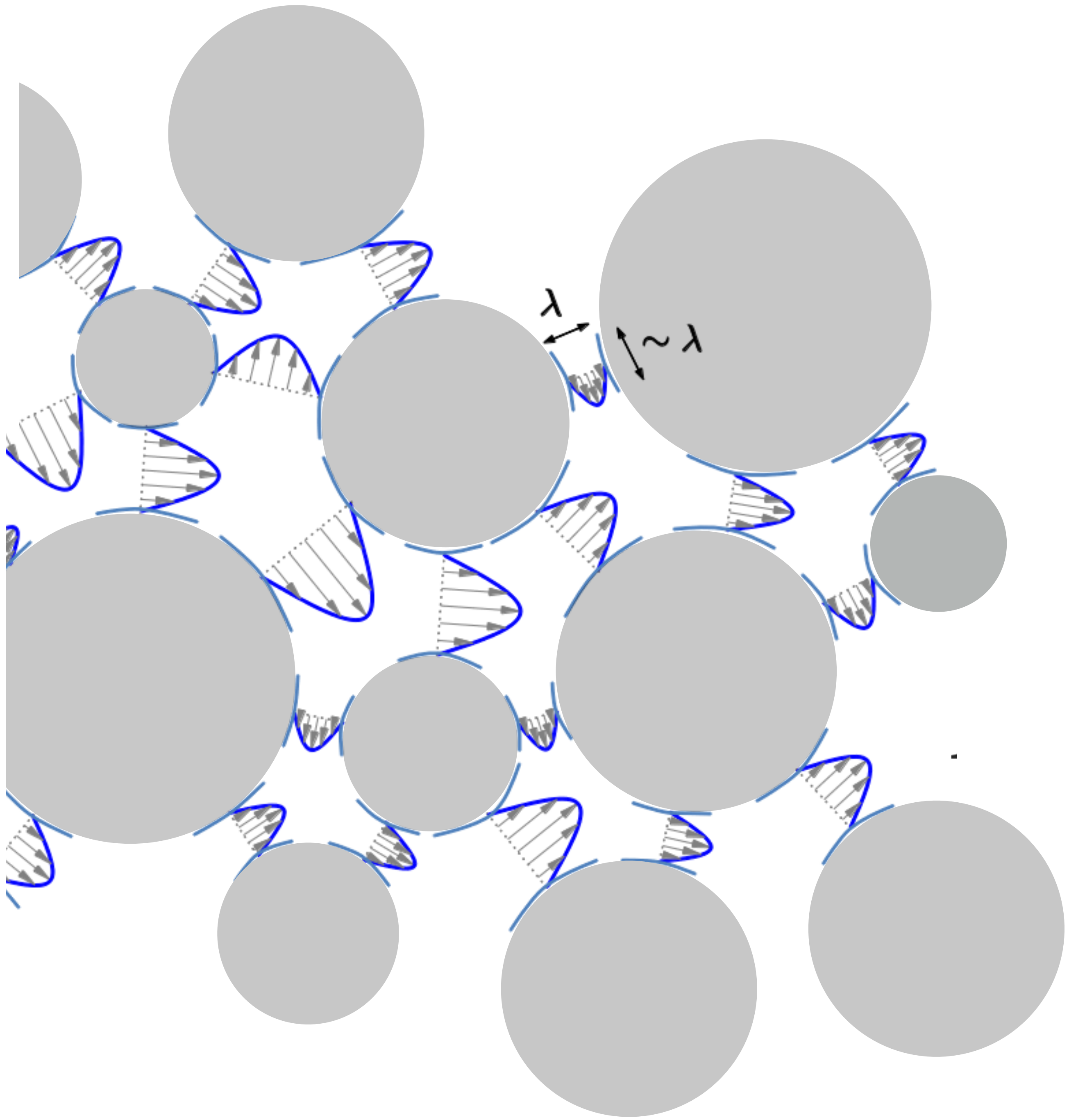
Host medium structure, fluid flow and transport

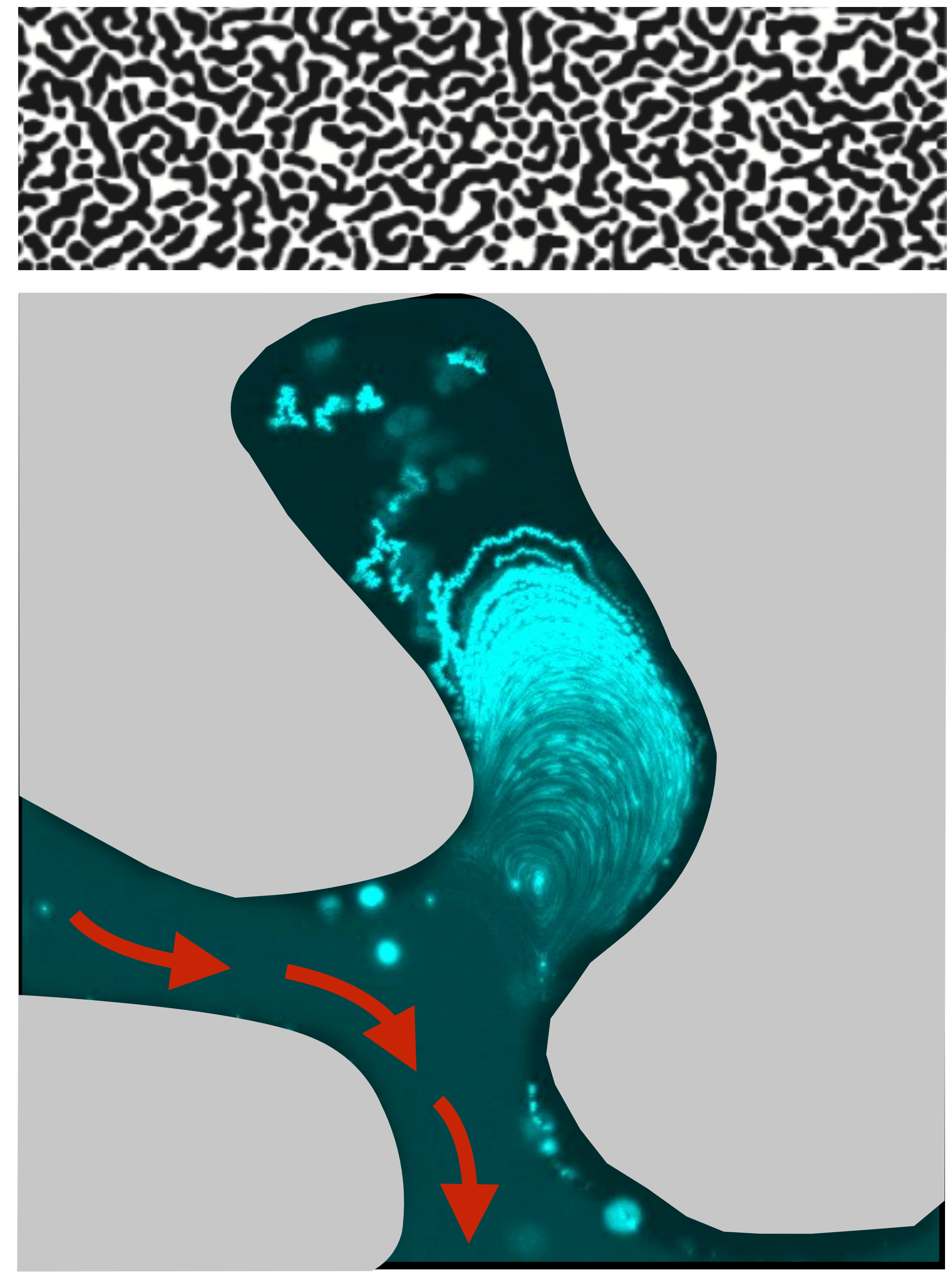
pore size variability



Pore throat size controls low velocity distribution that controls asymptotic advective transport.

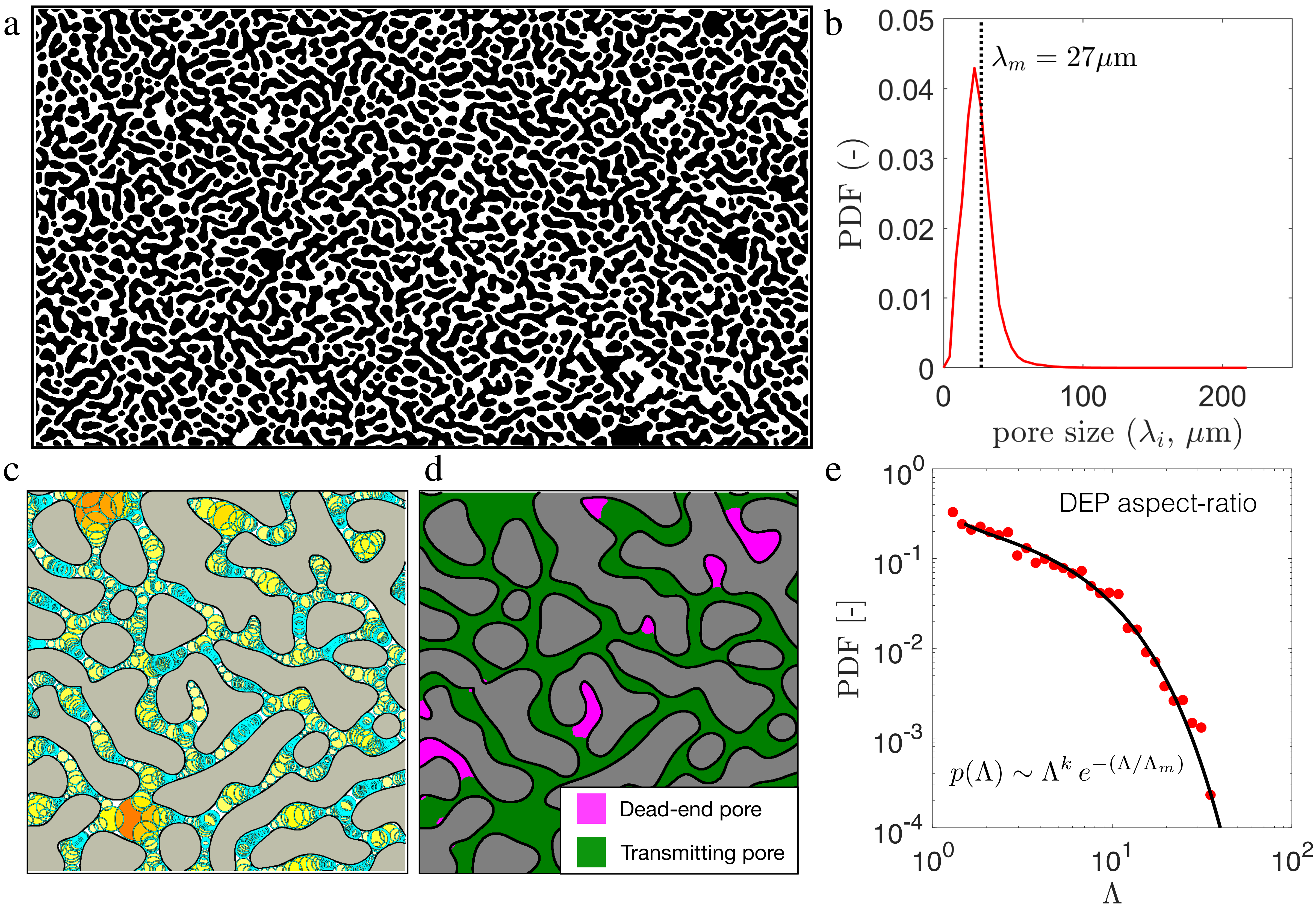
de Anna et al. *Phys. Rev. Fluids 2017*

shape variability distributed



Grains characterised by cavities lead to formation of **DEAD END PORES**

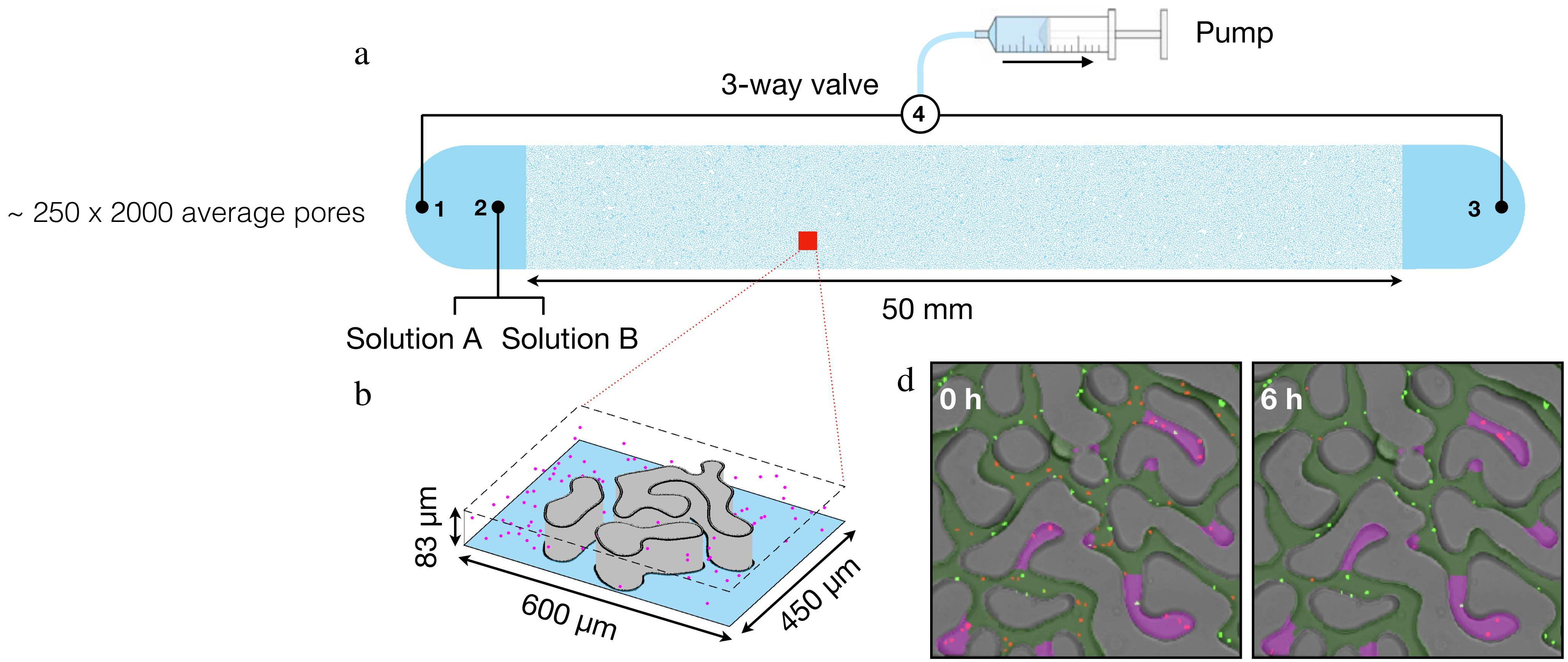
Flow experiments through dewetted and multi-porous structures



These structures are characterised by a dual nature: **transmitting pores** (TP) that can host effective fluid transfert and **dead-end pores** (DEP) that cannot.

https://arxiv.org/abs/2112.12492

Flow experiments through dewetted and multi-porous structures

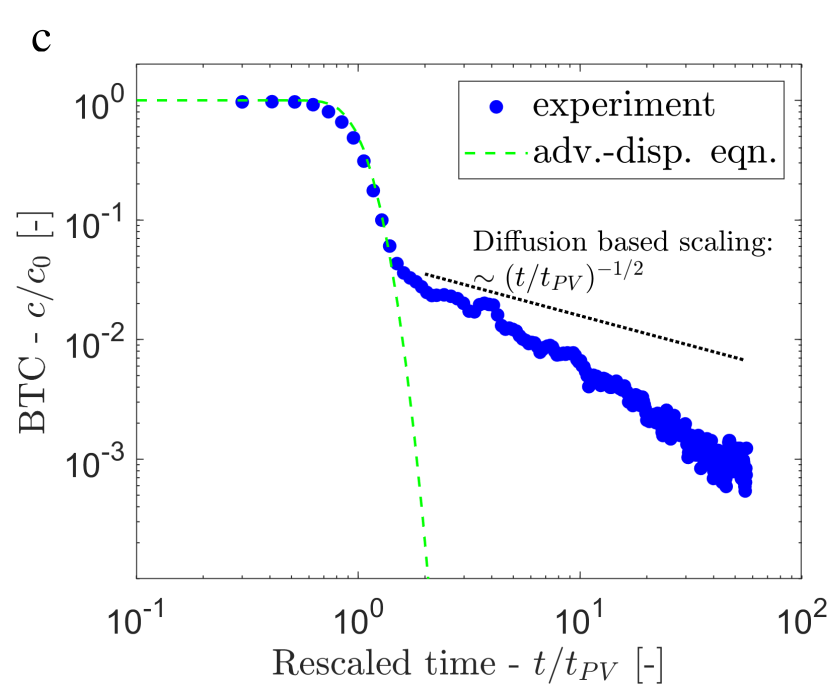


Characteristic advection time over a pore volume

$$t_{PV} = \frac{V}{Q} = \frac{L}{q} \sim 21\,\mathrm{min}$$

Advection-Dispersion eq.

$$\frac{\partial c}{\partial t} = -q\frac{\partial c}{\partial x} + D^* \frac{\partial^2 c}{\partial x^2}$$



We continuously inject a front of water to displace a colloidal suspension of fluorescent micro-spheres (diameter 0.5 um) while monitoring the outlet suspension concentration.

The porous systems has a dual flow structure: in a **TP** the flow is similar to the one though a pipe and effectively transport colloids towards the outlet, while in **DEP** colloids experience very low velocities and diffuse.

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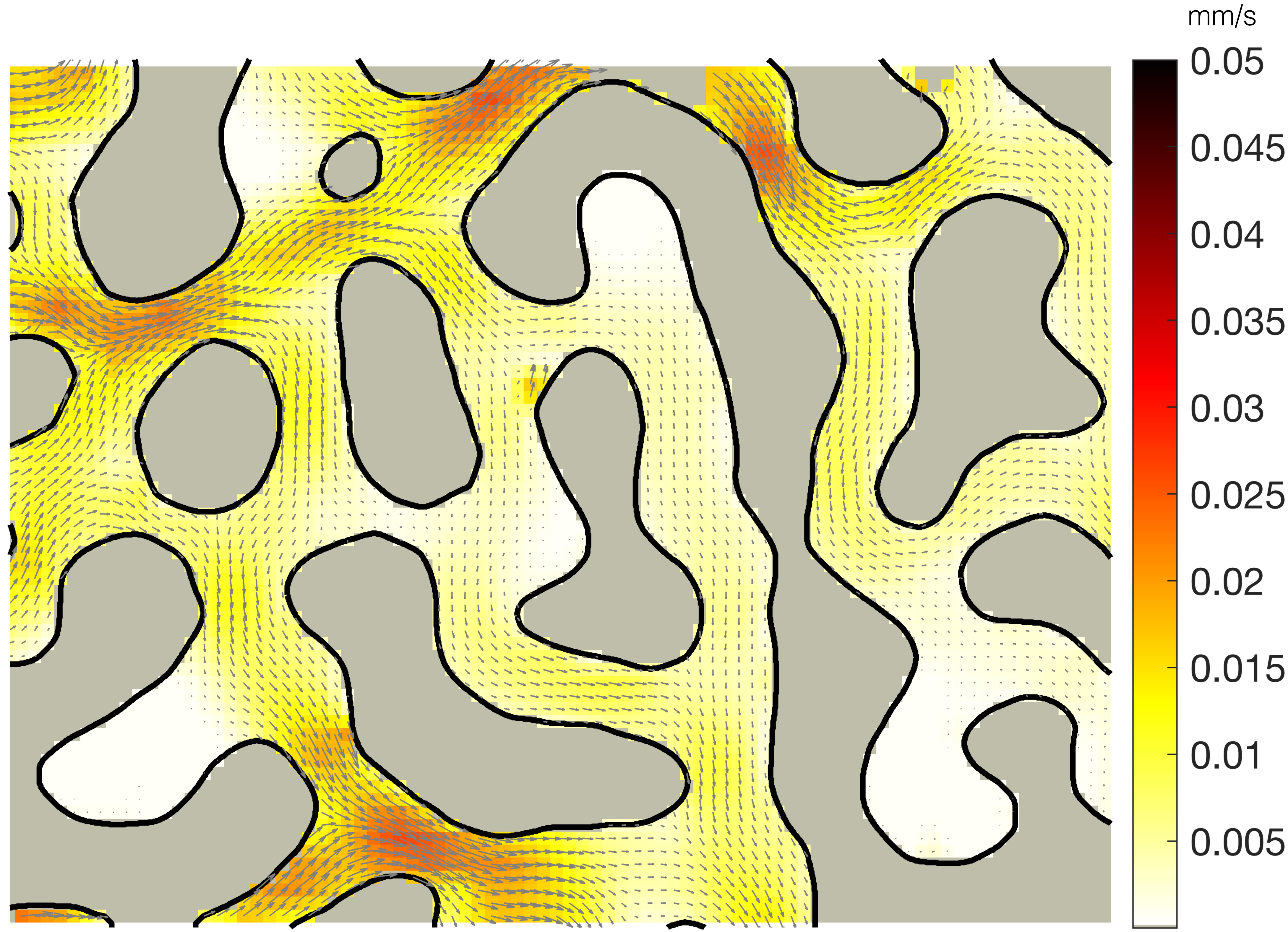
Fluid velocity within pores: Particle Image Velocimetry

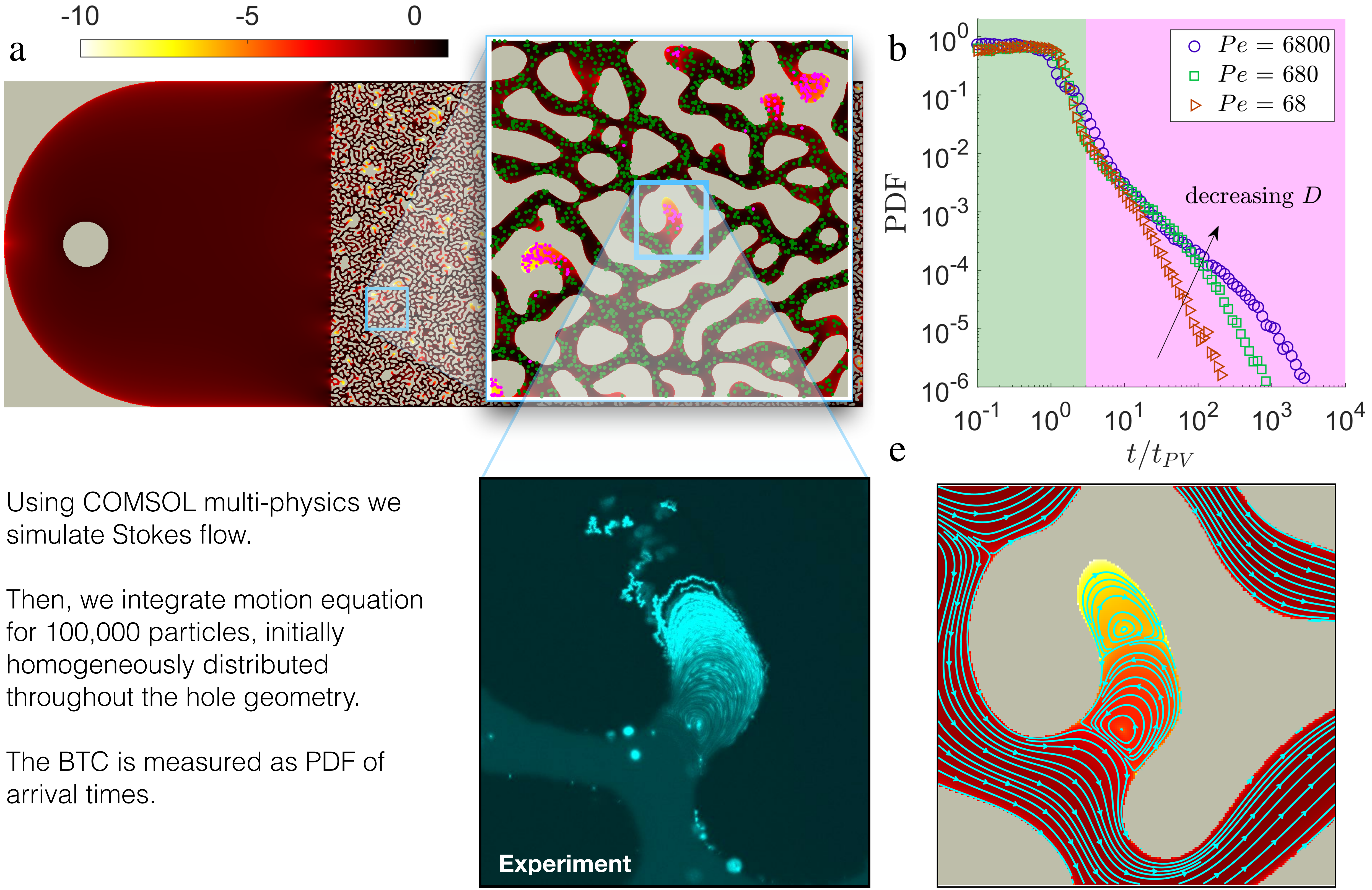


Particle Image Velocimetry - PIV

Master thesis of Federico Pasotti 2021

Simulations of flow and colloidal transport

The flow structures within DEP are closed laminar vortexes of rapid decaying intensity.



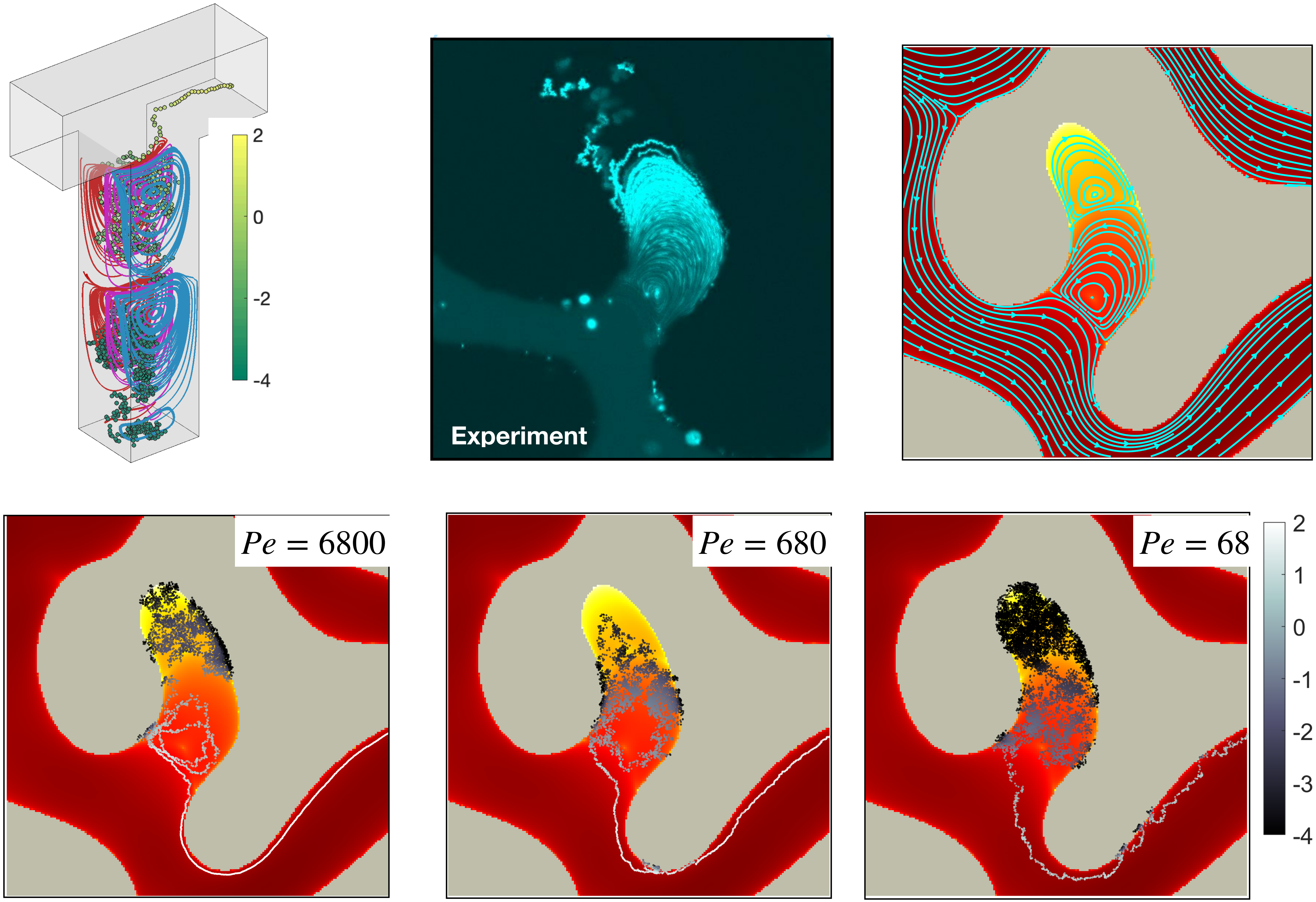
Using COMSOL multi-physics we simulate Stokes flow.

Then, we integrate motion equation for 100,000 particles, initially homogeneously distributed throughout the hole geometry.

The BTC is measured as PDF of arrival times.

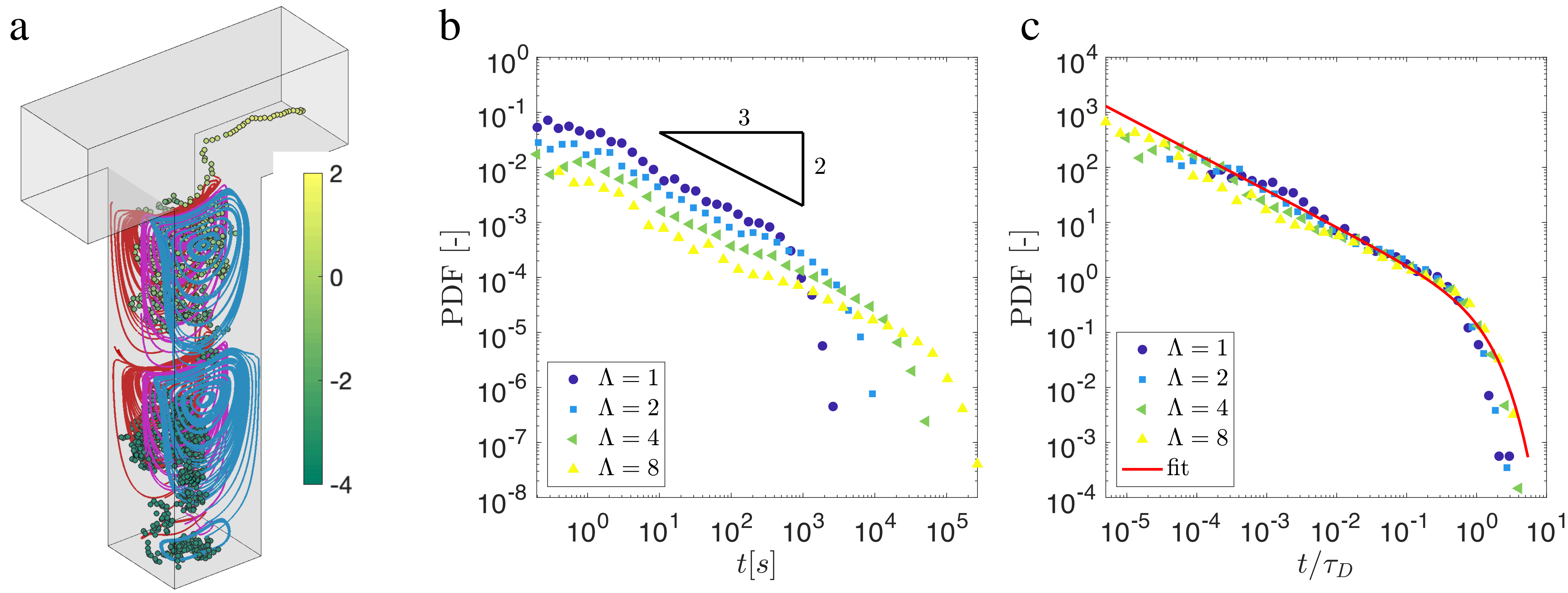
Simulations of flow and colloidal transport

The DEP flow structures are very similar to the one within a *"flow driven cavity"*.

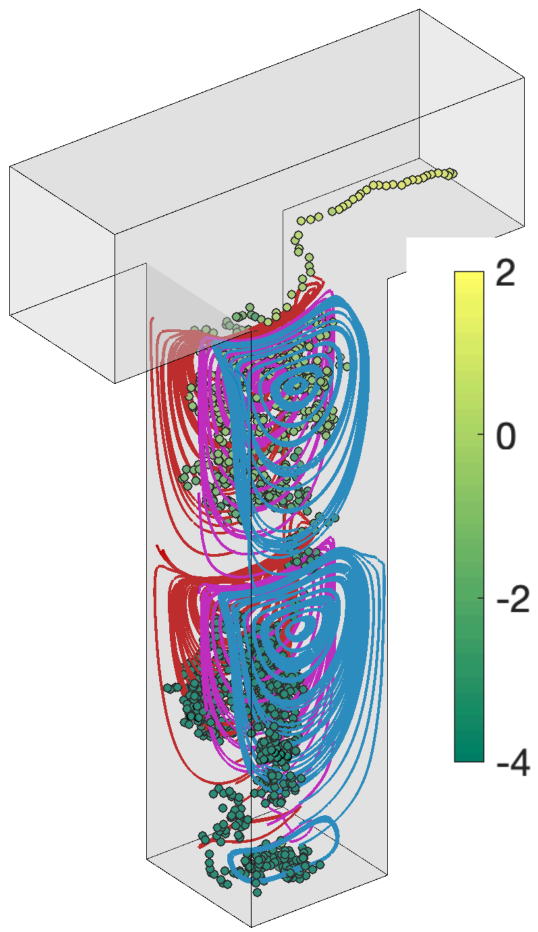


Modelling flow and transport through dead-end pores

BreakThrough Curve (BTC) through a single DEP (cavity) varying the aspect-ratio: simulation results.



Modelling flow and transport through dead-end pores



$$\frac{\partial c}{\partial t} = -q\frac{\partial c}{\partial x} + D^*\frac{\partial^2 c}{\partial x^2}$$

Macroscopic Advection-Dispersion eq.
Describes the transport through TP

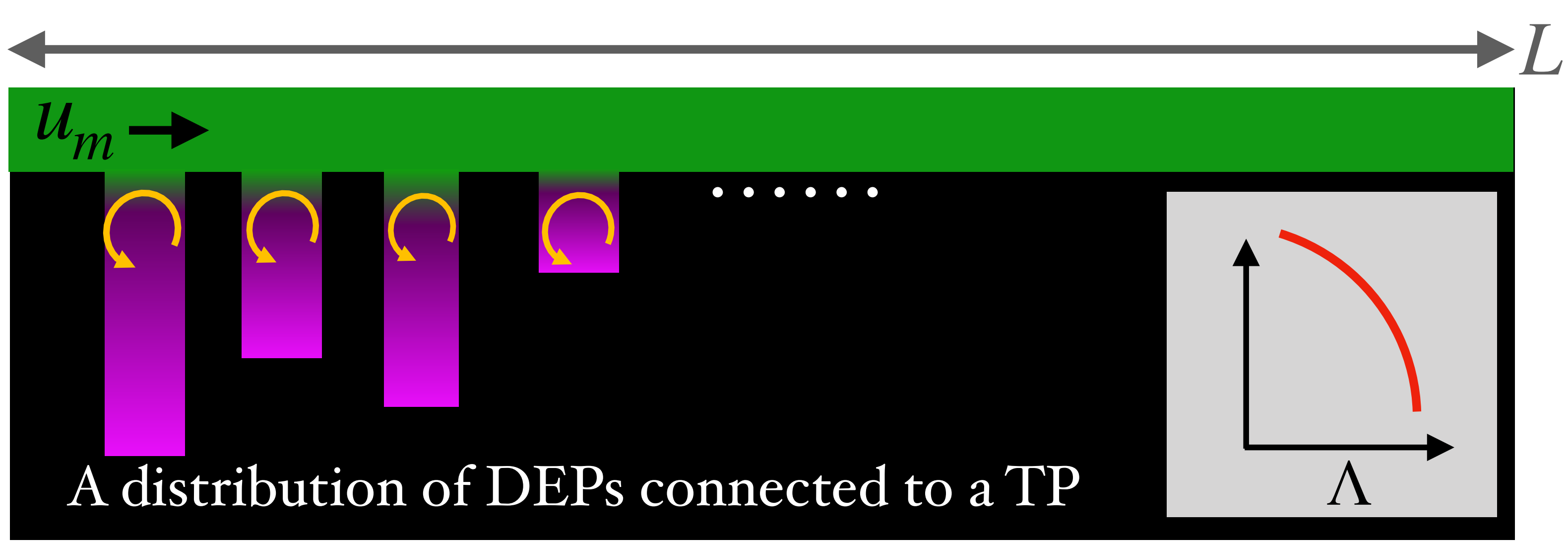
$$p_t(t) = \frac{(t/\tau_D)^{-2/3}\, e^{-t/\tau_D}}{\Gamma(1/3)}$$

Distribution of escape time from a DEP

Overall BTC depends on the initial DEP/TP occupancy α and the DEP size distribution $f_D(\tau_D)$

$$\mathrm{BTC}(t) = (1-\alpha)\,\frac{1}{L}\int_0^L f_0(t,x)\,dx + \alpha\int_0^\infty p_t(t/\tau_D)\,\tau_D^{-1}\,f_D(\tau_D)\,d\tau$$

We understand and model the transport through such **dual structures** as follows: transport effectively happens only through TP, while **DEP provide a delay**. Thus the overall colloidal population is displaced as a sequence of jumps about the average velocity (with Gaussian distributed noise) with an initial delay.



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Modelling flow and transport through dead-end pores

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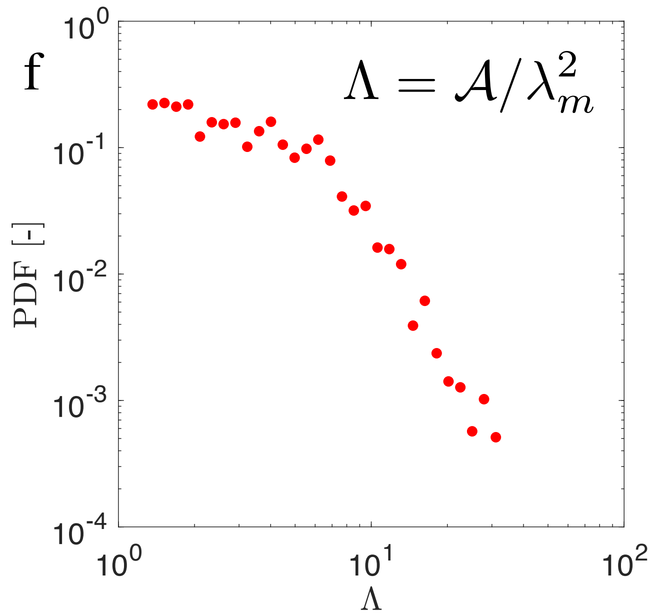
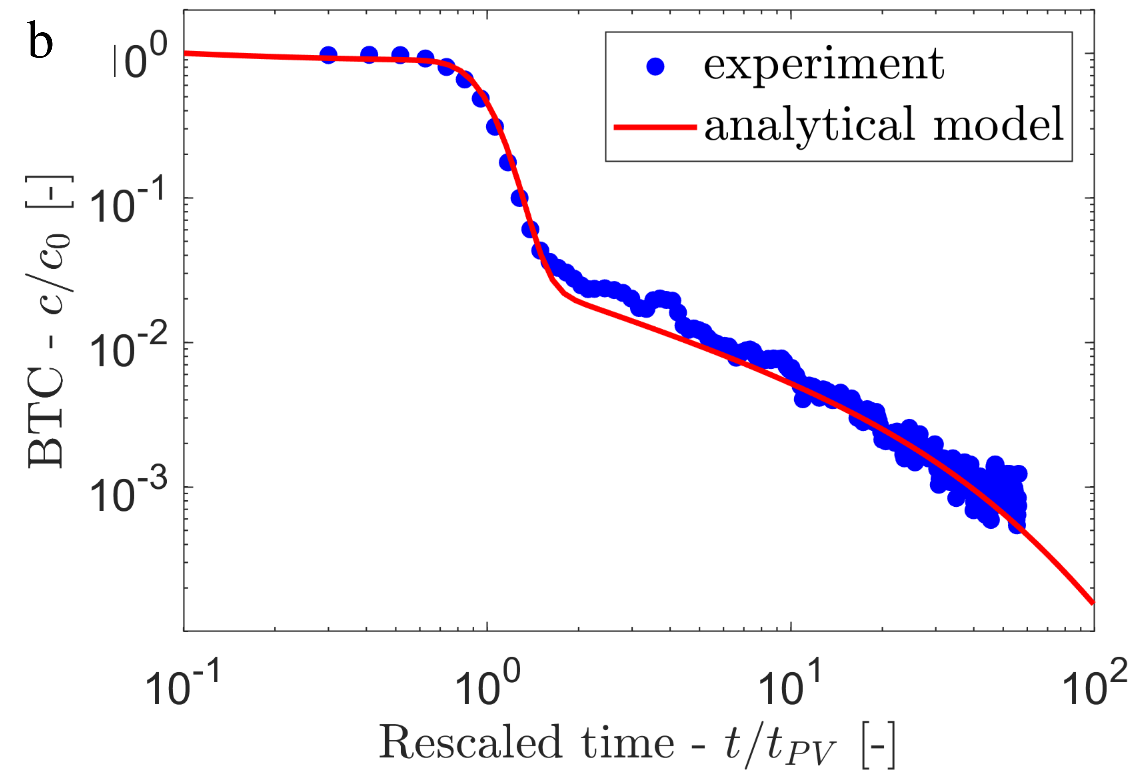


$$\tau_D = \frac{(\Lambda\lambda_m)^2}{D}$$



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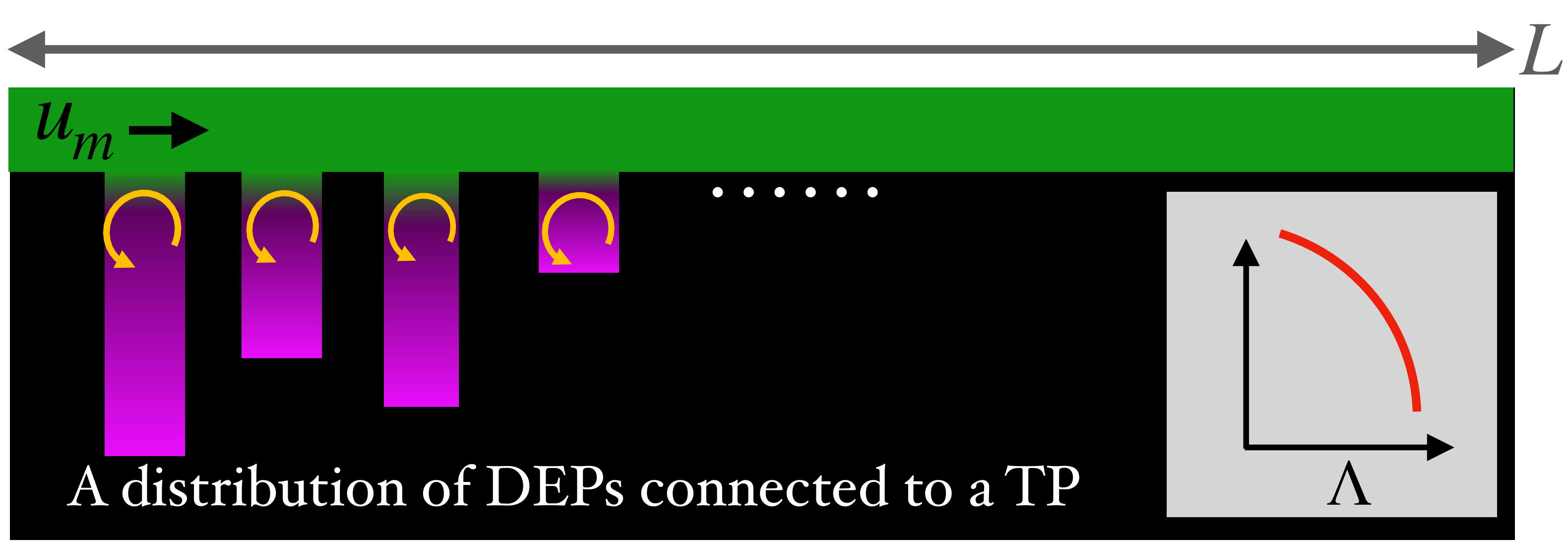

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Modelling flow and transport through dead-end pores

We studied the impact of the three controlling parameters on anomalous dispersion.

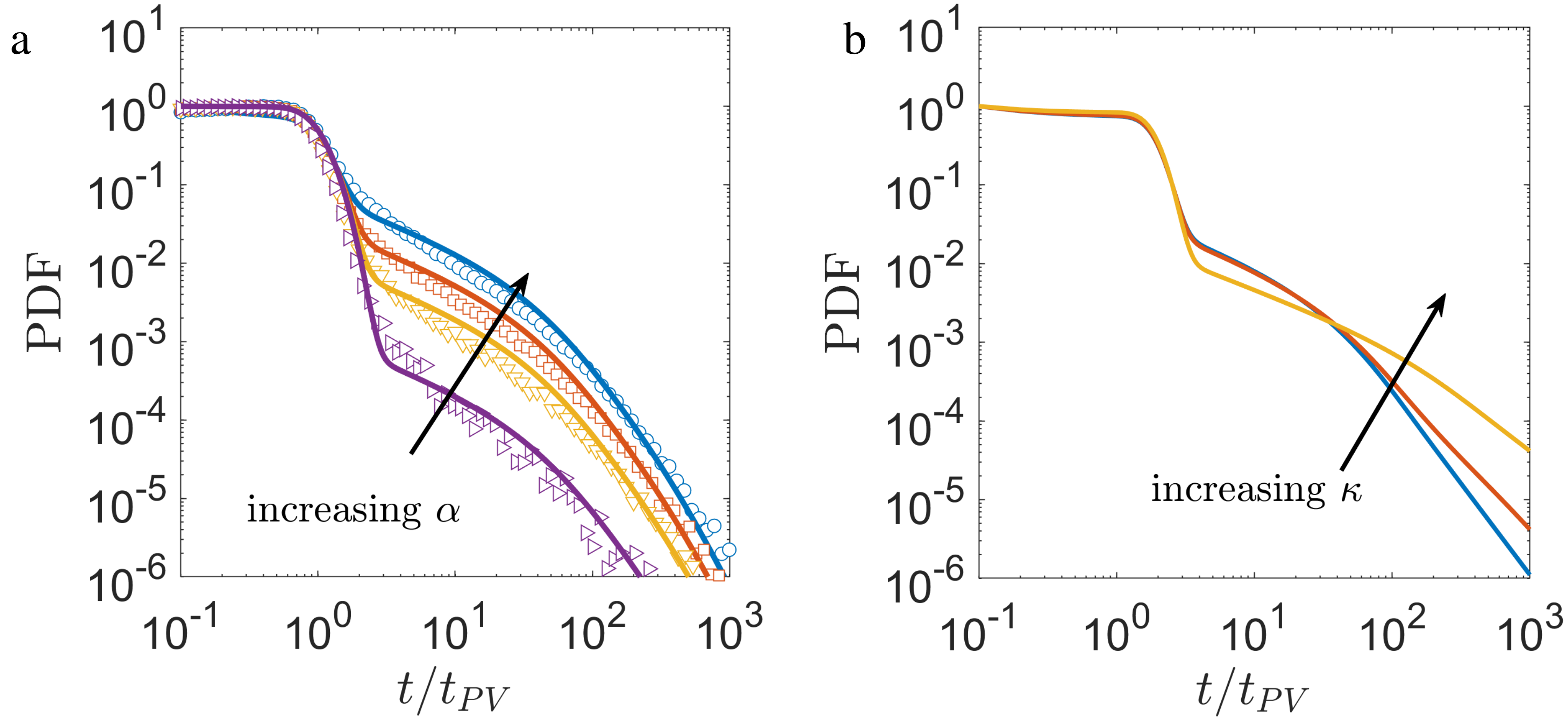
Initial particles distribution among TP and DEP α

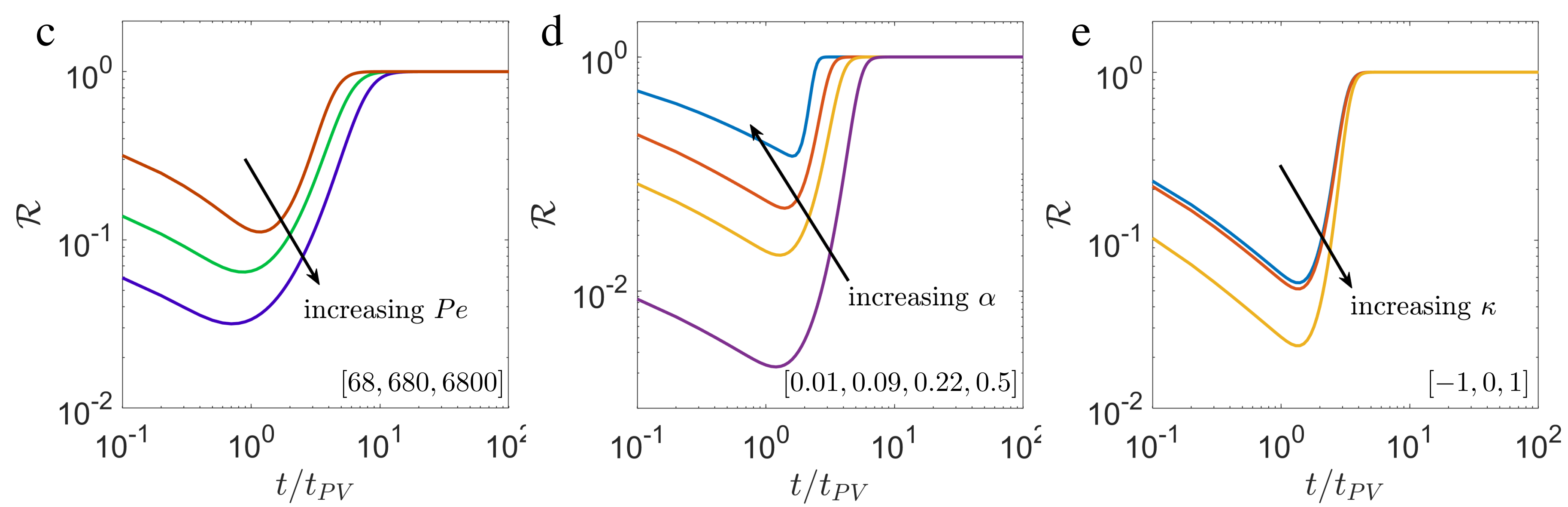
Distribution of DEP aspect-ratio

$$p(\Lambda) \sim \Lambda^k \, e^{-(\Lambda/\Lambda_m)}$$

Peclet number

$$Pe = \frac{\lambda_m \, q}{D}$$





$$\mathrm{BTC}(t) = \underbrace{(1-\alpha)\,\frac{1}{L}\int_0^L f_0(t,x)\,dx}_{BTC_{TP}} + \underbrace{\alpha\int_0^\infty p_t(t/\tau_D)\,\tau_D^{-1}\,f_D(\tau_D)\,d\tau}_{BTC_{DEP}}$$

$$\mathcal{R} = \frac{BTC_{DEP}}{BTC}$$

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