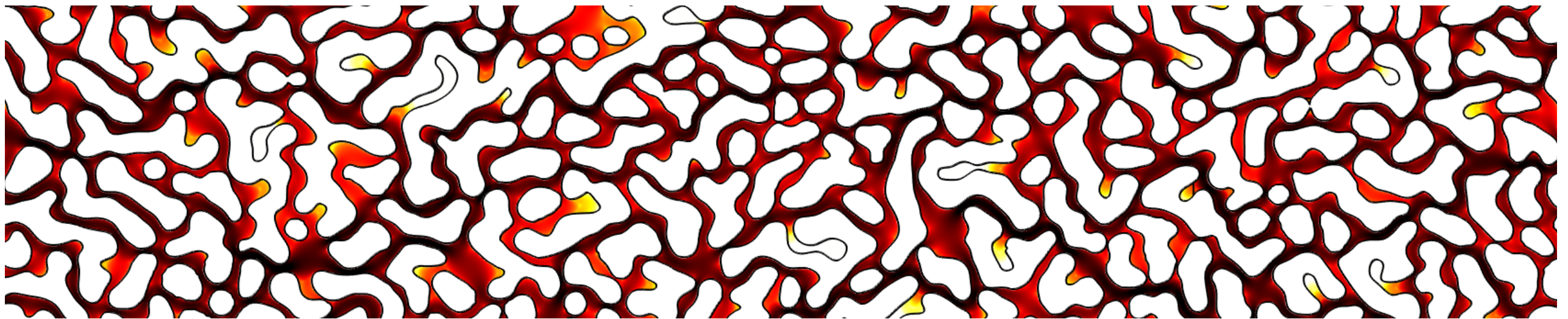


Dead-end sites and their influence on anomalous transport in porous media



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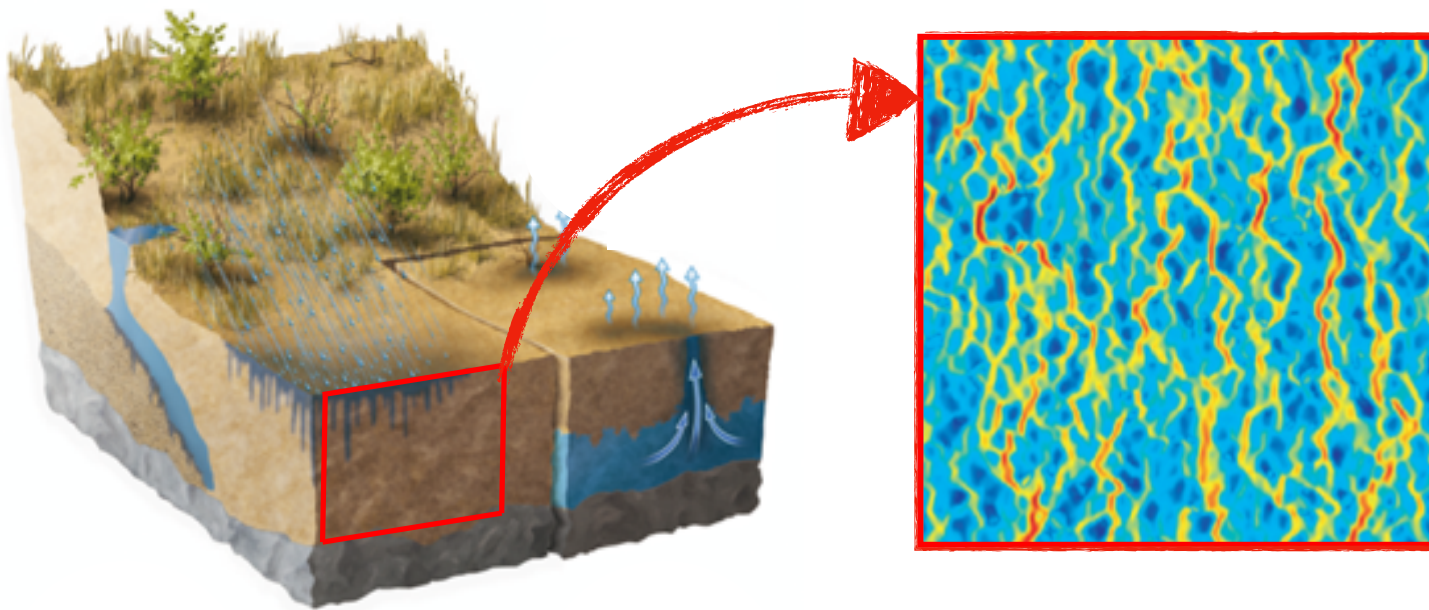
ankurdeep.bordoloi@unil.ch



Heterogeneity in porous media influences the transport

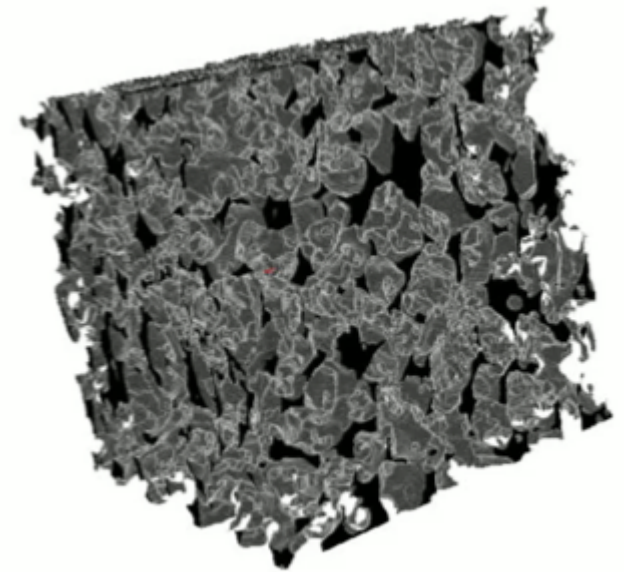
Flow through confined spaces

- Close to boundaries
- Typically laminar
- Low velocities (below 1m per day)
- Dominated by viscous forces



Heterogeneous velocity field
(Le Borgne et al. Phys. Rev. Lett. 2008)

Natural pore structure contains complex heterogeneity



X-ray tomography of pore structure
(Mostaghimi et al. S.P.E. J. 2012)

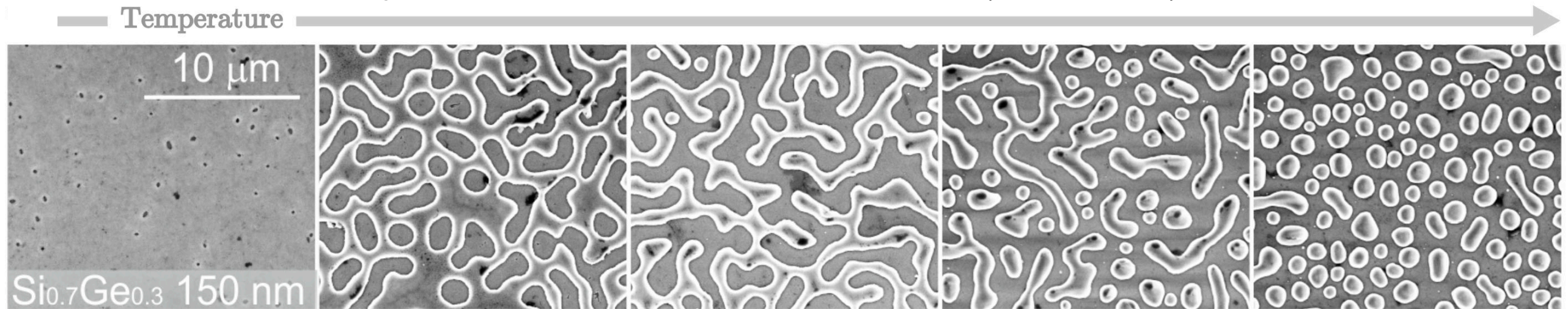
Pore space heterogeneity

- Wide range of pore size
- Morphological diversity

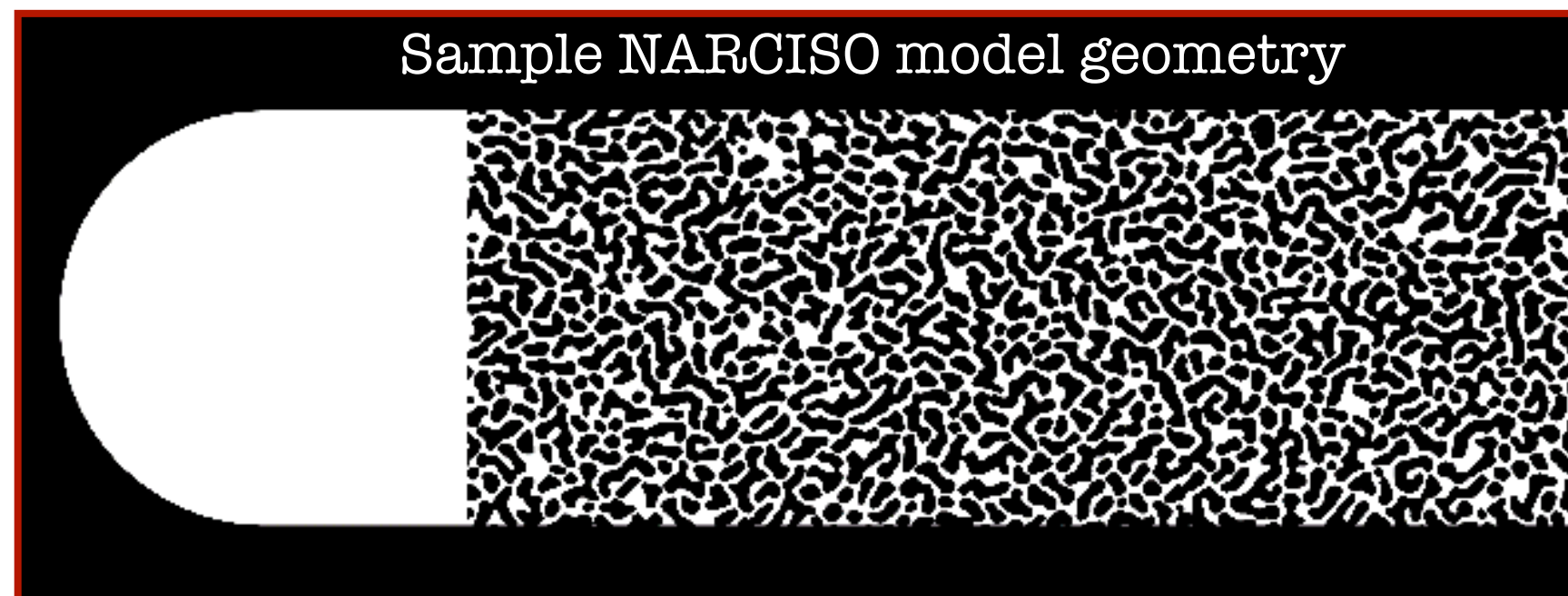
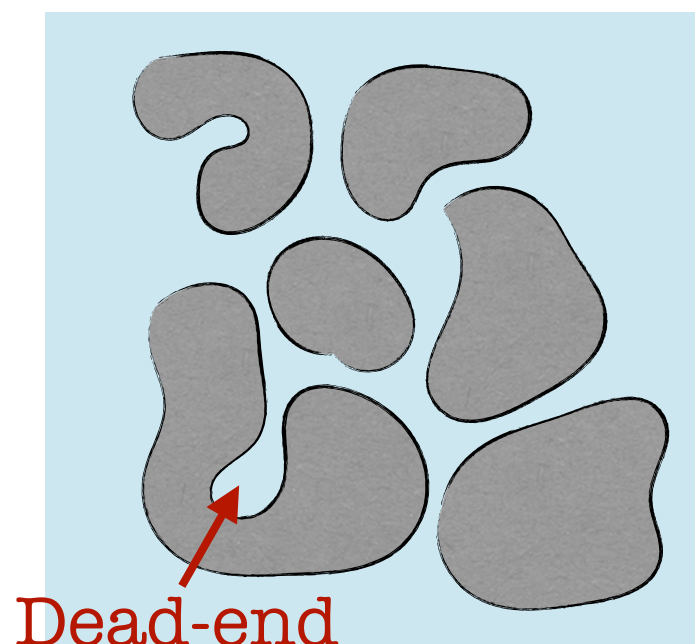
Heterogeneity can be due to pore size variation and morphological diversity

Example of morphological diversity (current study)

Natural instability of semi**C**onductors th**I**n **S**olid (NARCISO) model



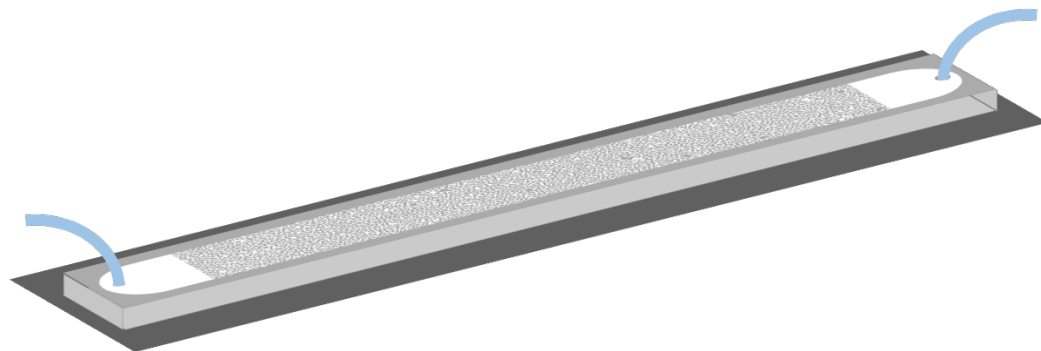
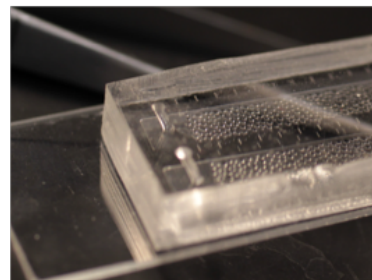
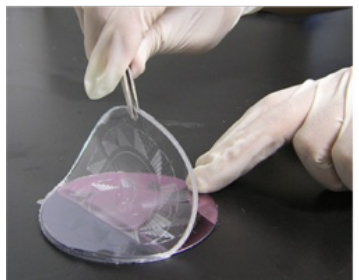
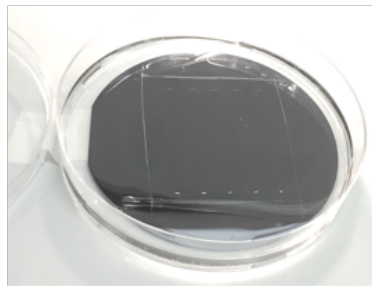
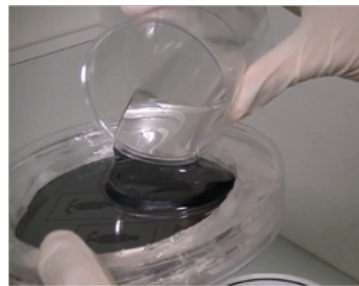
Pattern designed via spinoidal solid state dewetting (Salvalaglio et al, PRL, 2020)



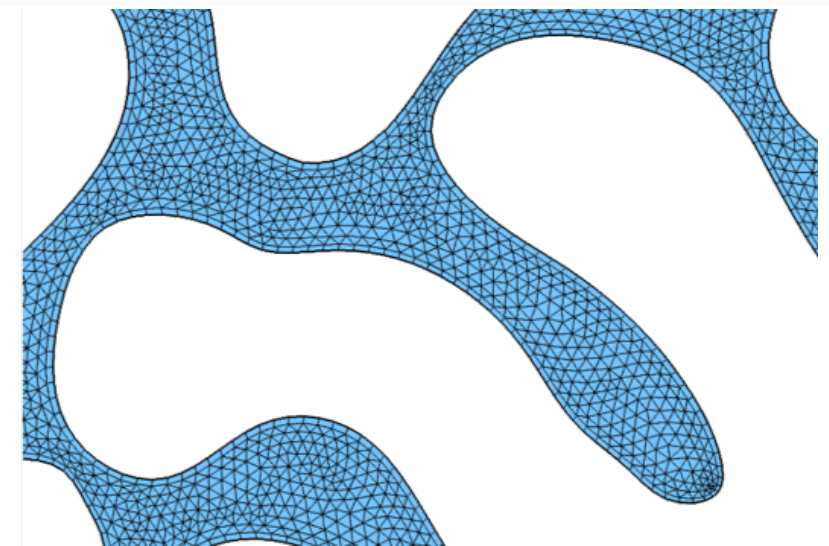
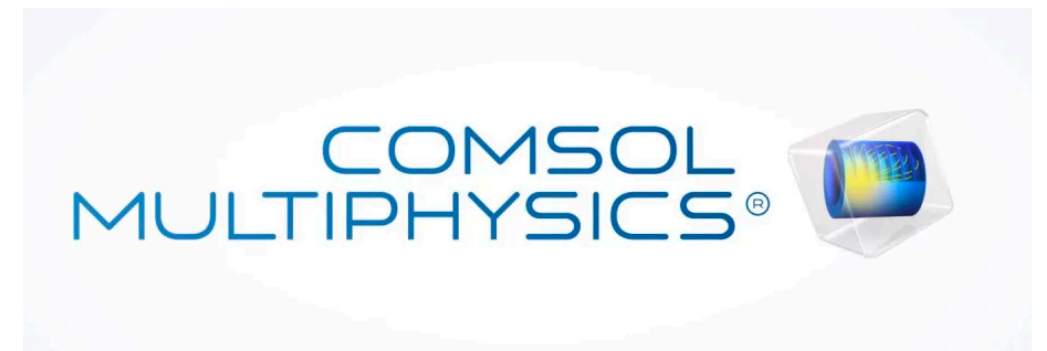
Unlike HDM, NARCISO model contains **dead-end sites!**

Study: effects of dead end sites on colloidal transport

Microfluidic experiments



Numerical simulation



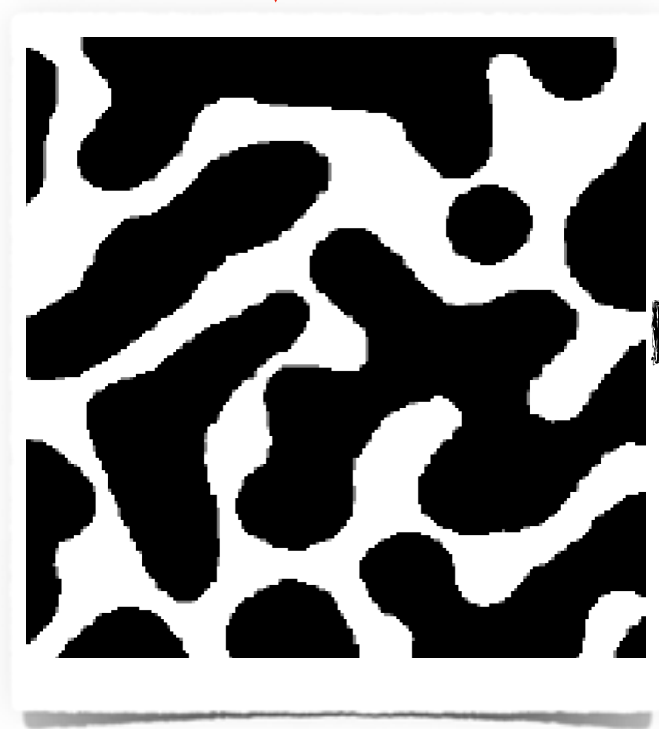
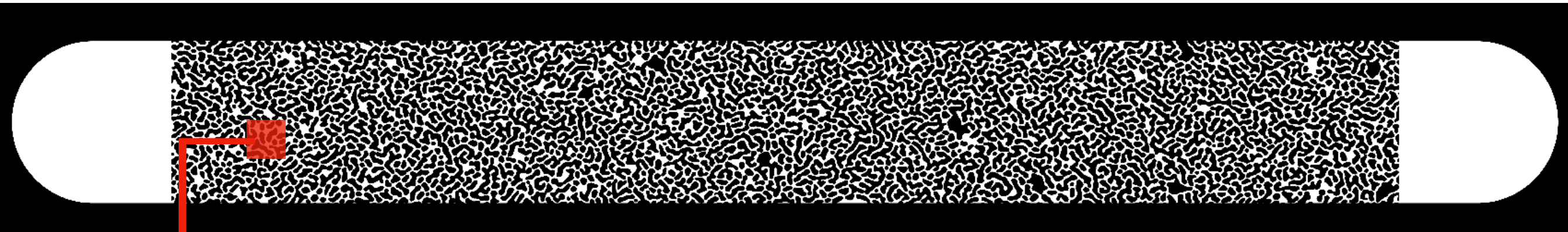
Stokes flow solution:

$$0 = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\rho \nabla \cdot \mathbf{u} = 0$$

Pore space characterisation: size

Size characterisation based on maximum inscribed circle



Raw binary image

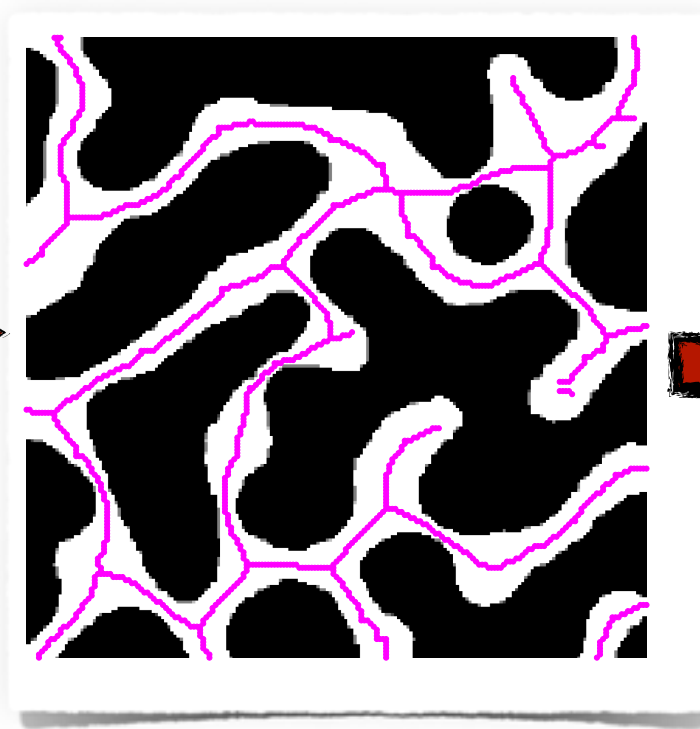
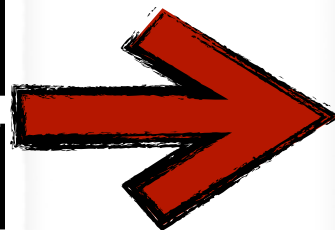
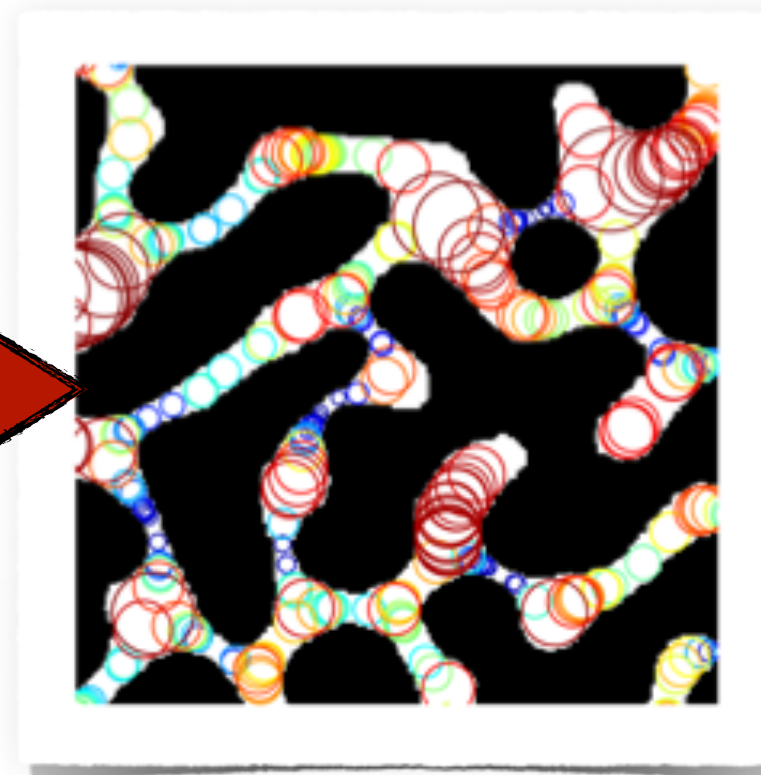
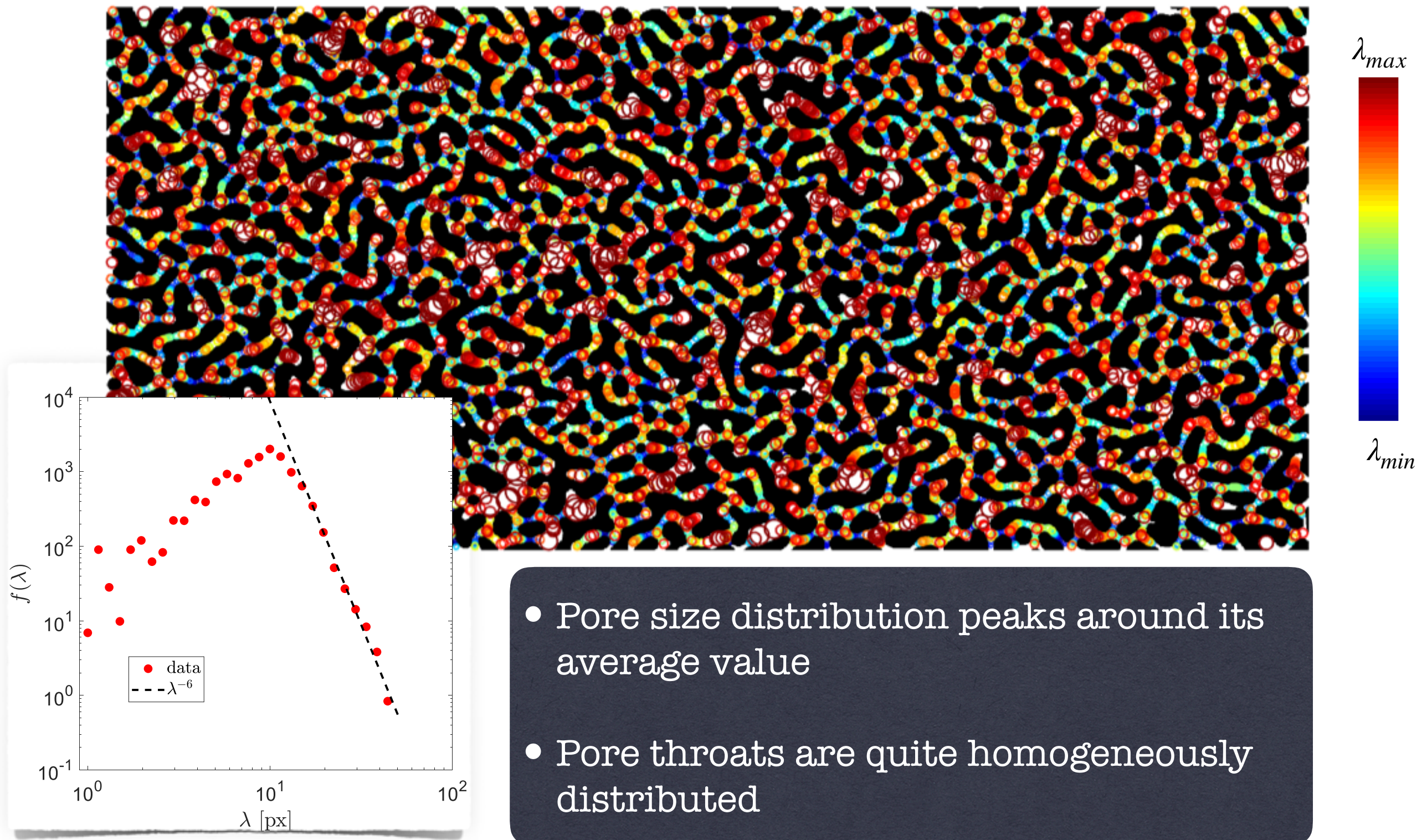


Image skeleton



Maximum inscribed Circle
(MIC)

Pore space characterisation: size

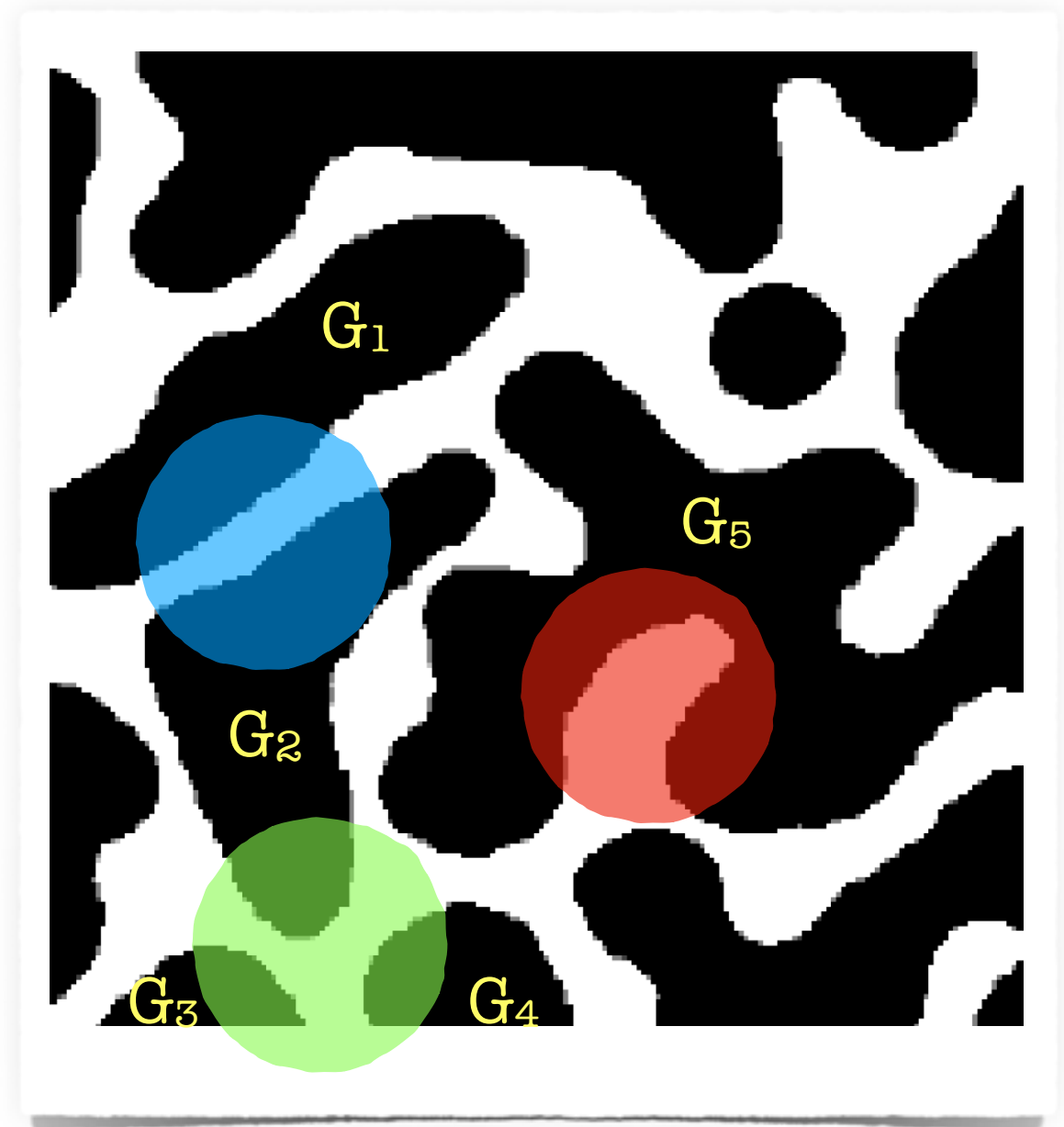


PDF of pore size parameter (λ)

Pore space characterisation: morphological diversity

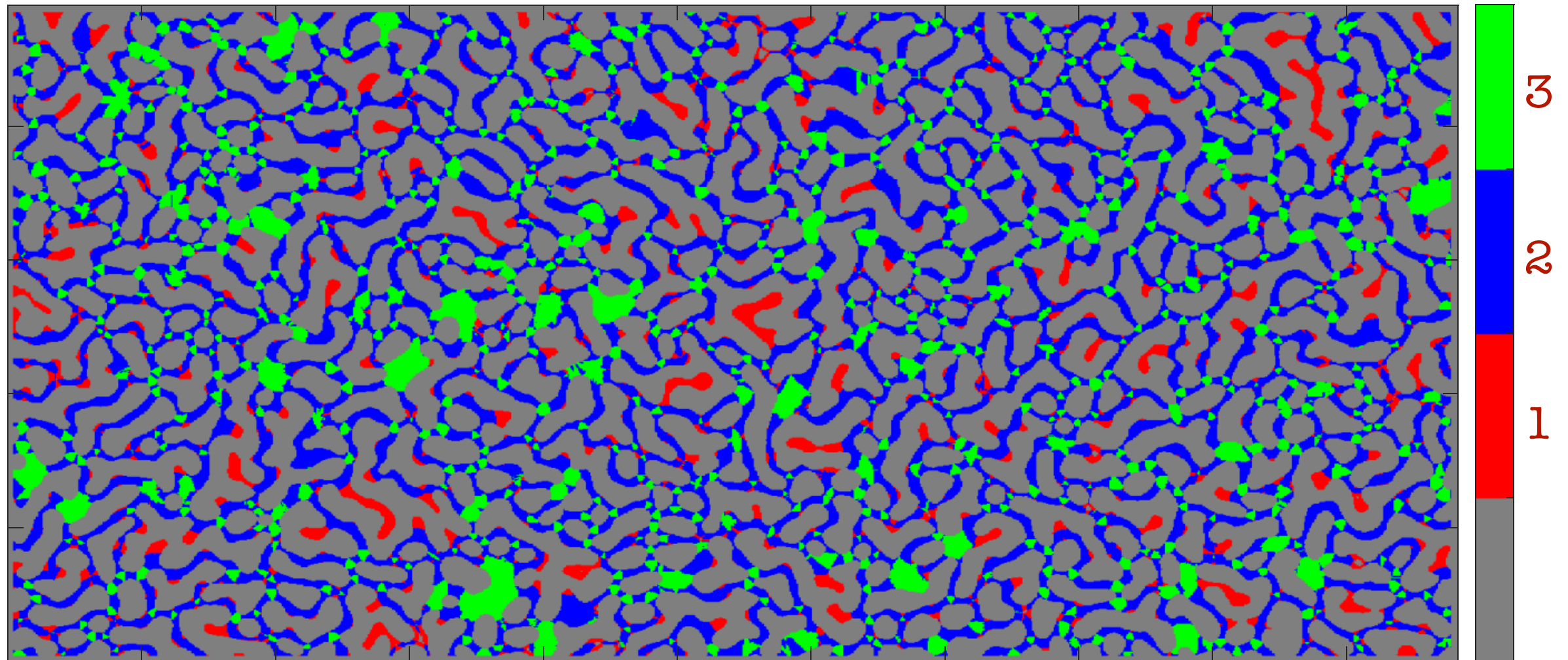
Segregation index

- **Dead-end** (pore space surrounded by singular grain: G_5)
- **Pore throat** (pore space surrounded by two grains: G_1, G_2)
- **Pore juncture** (pore space surrounded by multiple grains > 2 : G_2, G_3, G_4)



Pore space characterisation: morphological diversity

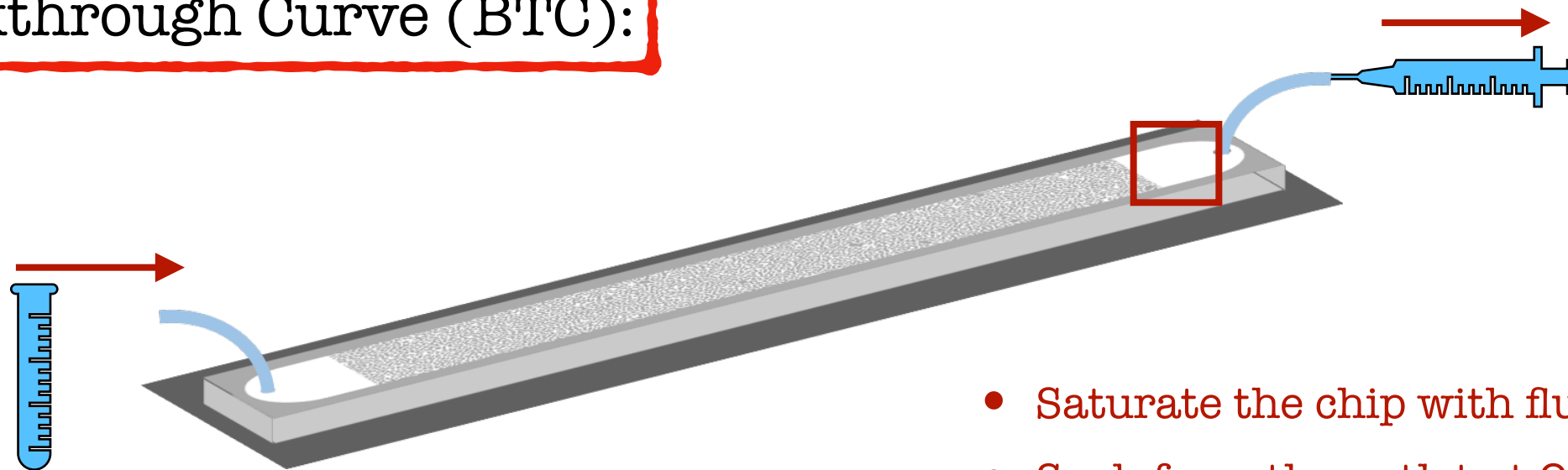
Segregation index map



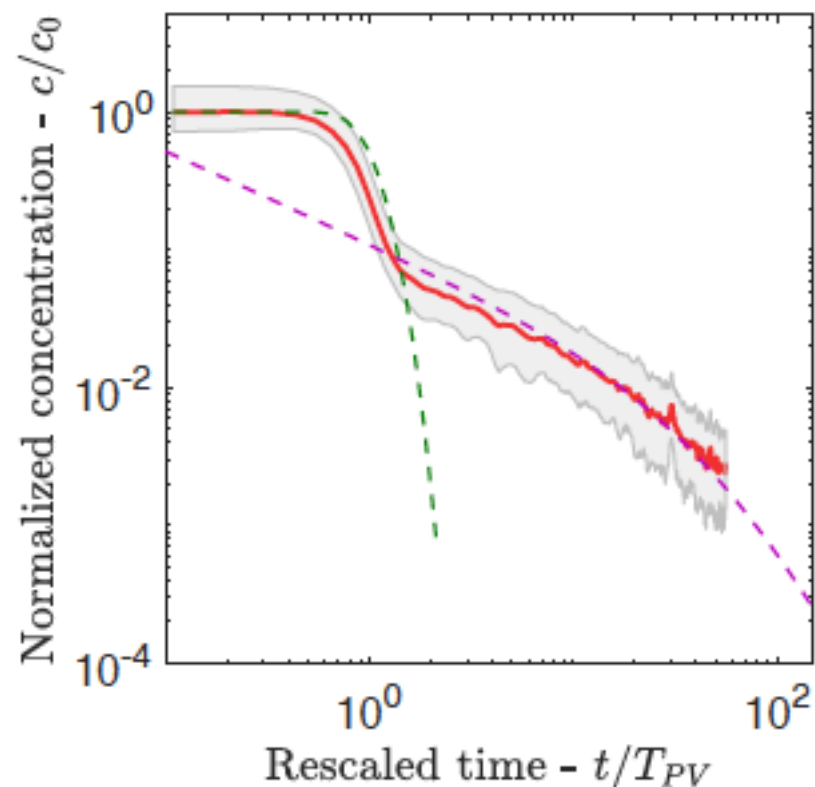
- **Dead-end** (pore space surrounded by singular grain)
- **Pore throat** (pore space surrounded by two grains)
- **Pore juncture** (pore space surrounded by multiple grains > 2)

Microfluidic experiment

Breakthrough Curve (BTC):



- Saturate the chip with fluorescence beads
- Suck from the outlet at Q
- Record fluorescence images at the outlet
- $T_{PV} = 5-6$ mins, total time about 10 hours



- **Exponential decay:** Advection dominated flow through fast channels (pore throats, junctures)

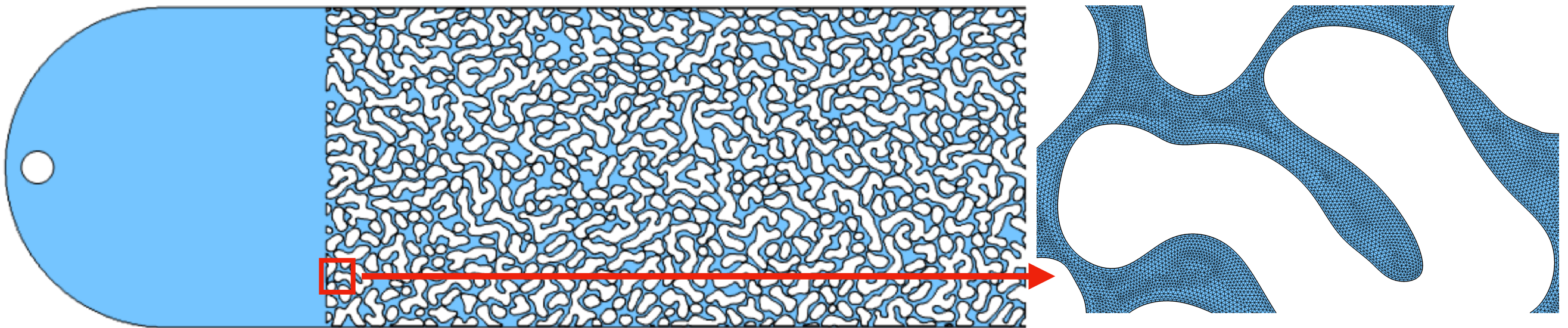
$$c/c_0 \sim e^{-t/\tau}; \tau = 4D^*/u_m^2$$

$$D^* = 9.5 \times 10^{-5} \text{ mm}^2/\text{s}$$

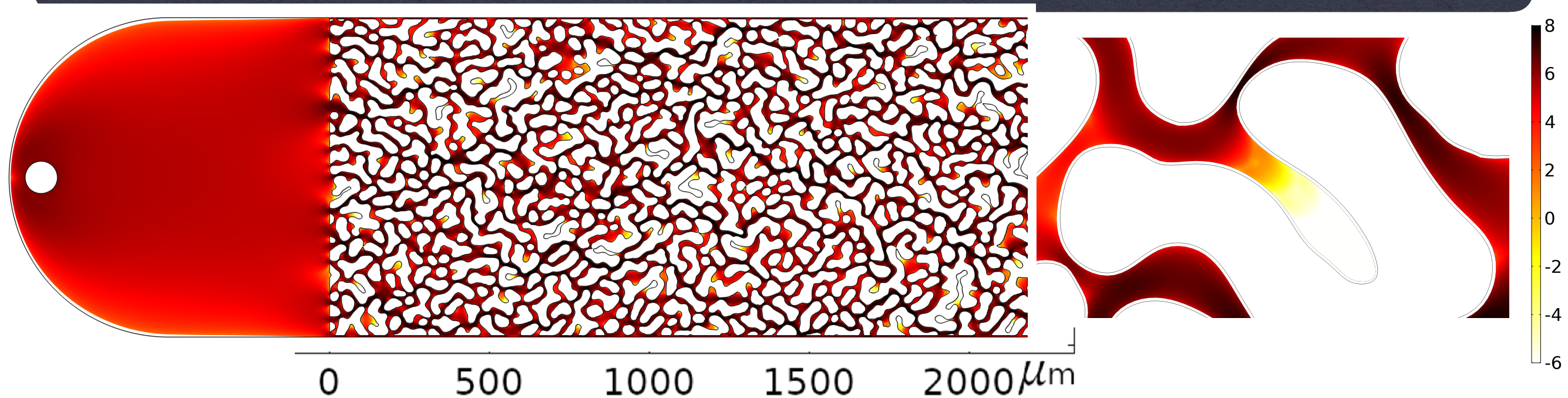
- **Long-tail decay:** Slow escape from dead end pores (diffusion?)

Numerical simulation: velocity field

COMSOL simulation with minimum element size of $0.14\ \mu\text{m}$ and maximum element size of $12\ \mu\text{m}$

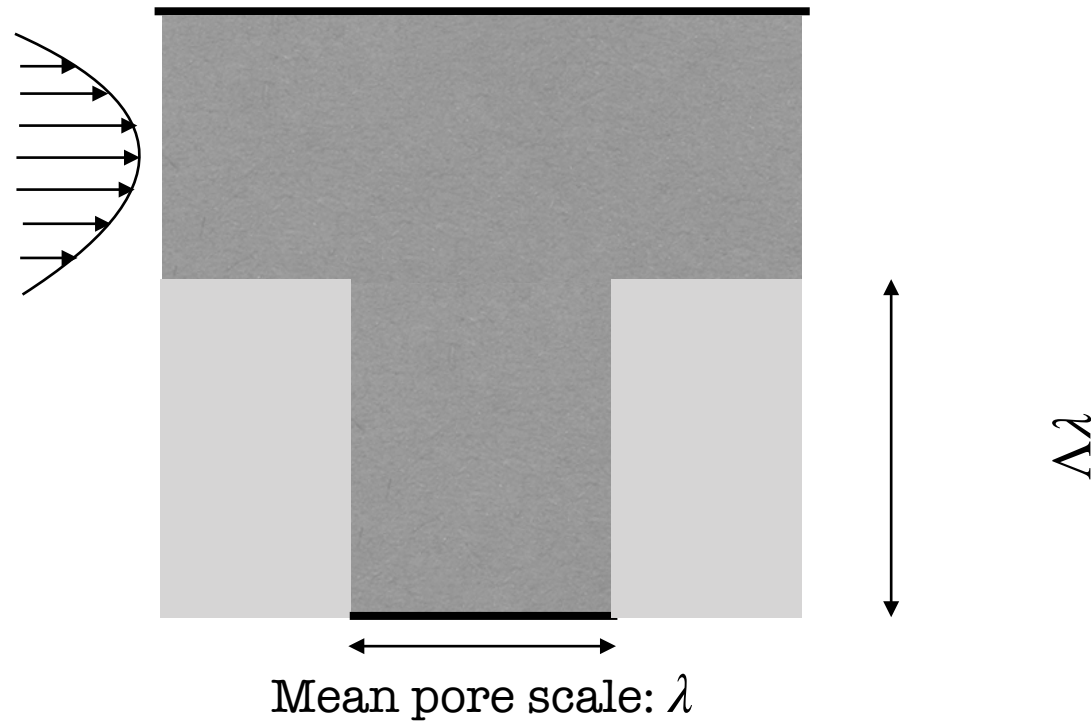


Creeping flow solution for an inlet flow rate of $0.5\ \mu\text{L}/\text{min}$



Model dead-end site as rectangular cavity

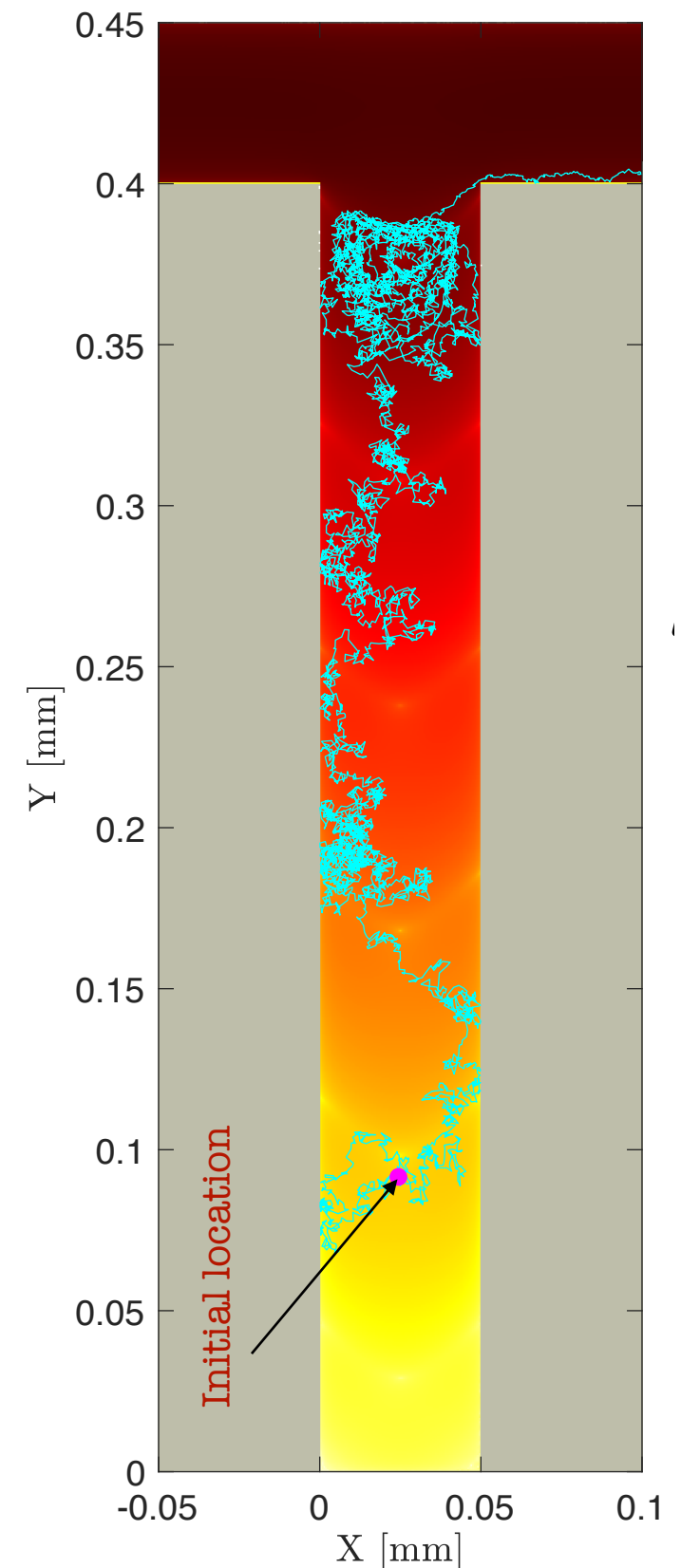
Characterise a dead-end site of area $\mathbf{A}$ as a rectangular cavity of aspect ratio Λ , such that $\mathbf{A} = \Lambda\lambda^2$



- Solve Stokes flow for velocity field in cavity
- Particle tracking of randomly distributed markers

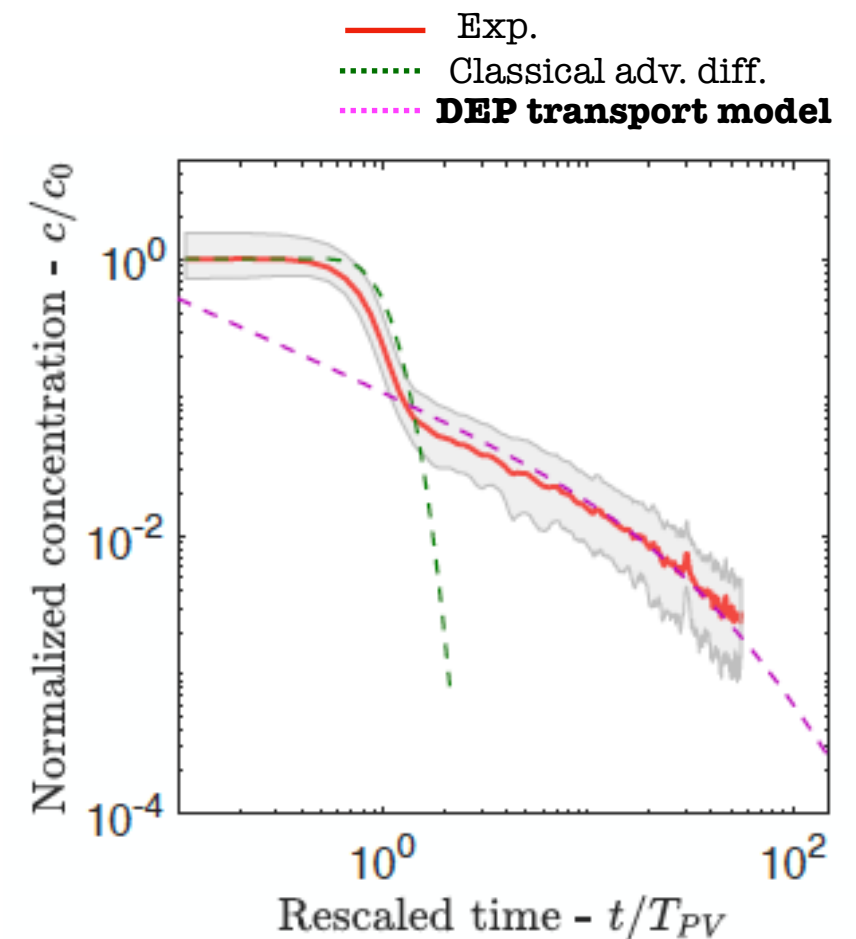
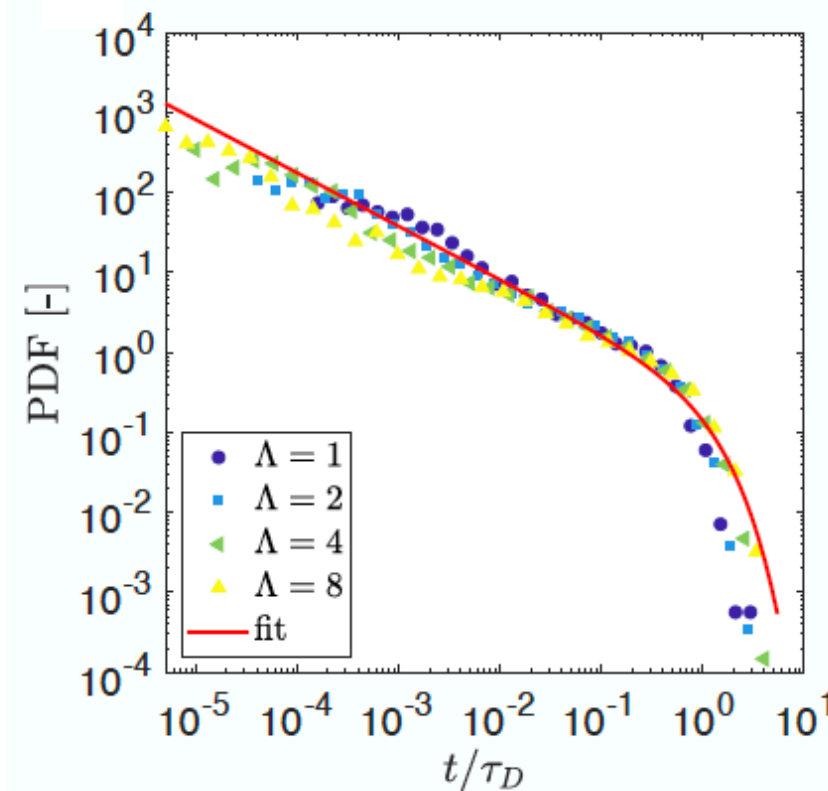
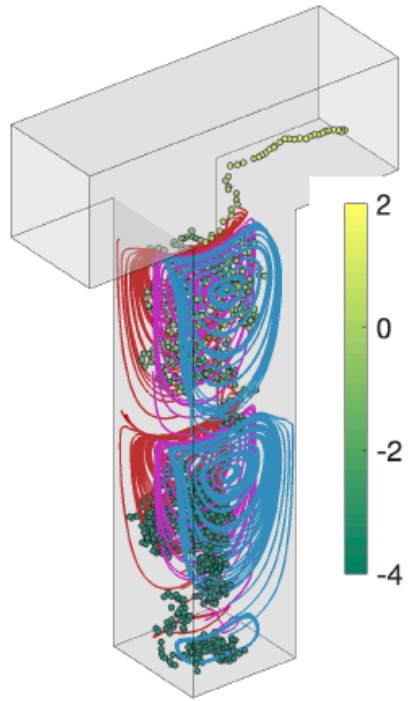
$$X_i^{n+1} = X_i^n + V_i^n \Delta t + \xi \sqrt{2D\Delta t}$$

- Compute exit time of 10^4 particles



Can the entire porous media be modelled as a collection of rectangular cavities?

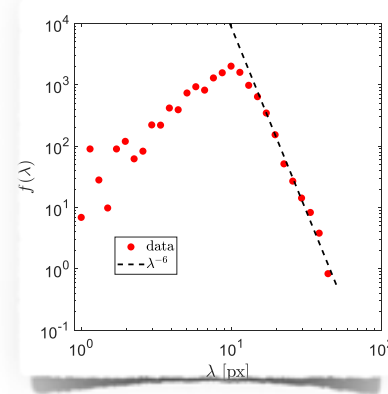
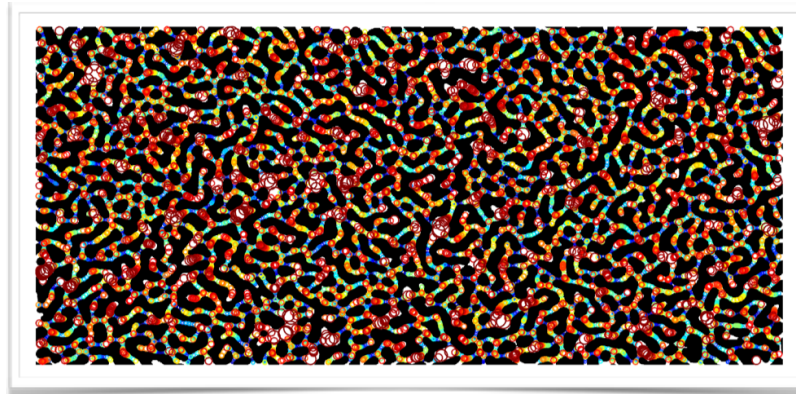
PDF of escape time (BTC)



We use the diffusive escape time distribution as a building block to upscale macroscopic transport i.e. BTC

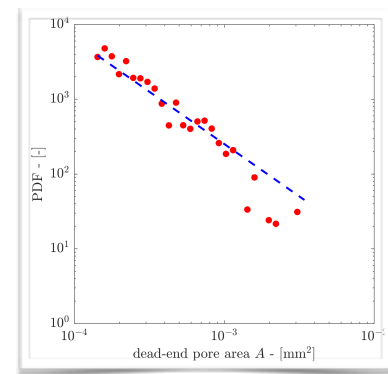
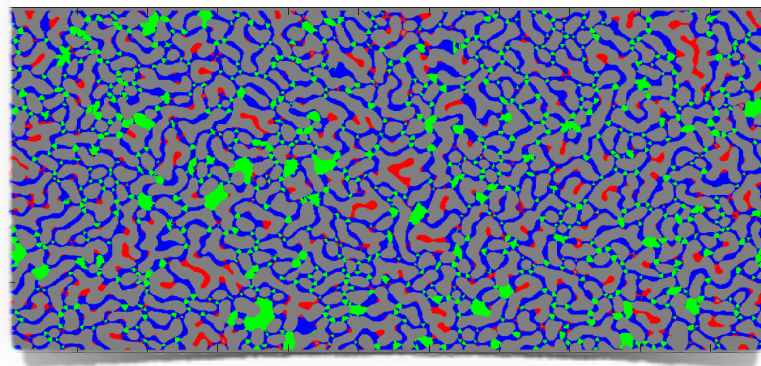
Summary

- MIC based characterisation of pore size distribution



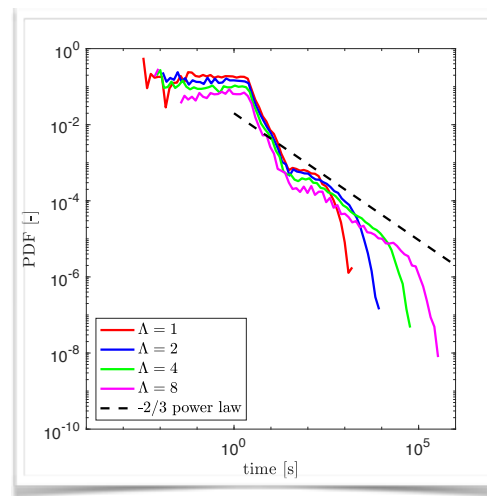
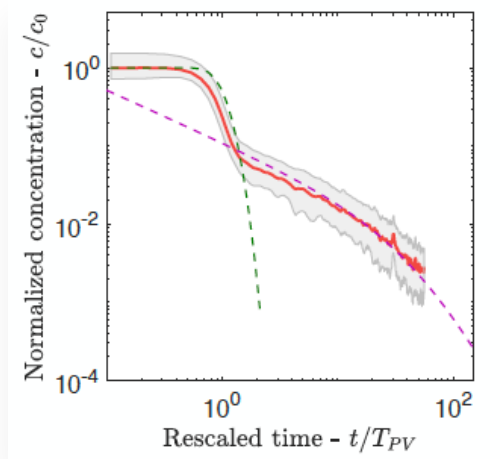
Pore size is fairly homogeneous

- Characterisation of morphological diversity: dead-end sites!



PDF(Area) of dead-ends $\sim -2/3$ power law

- Long tails of $-2/3$ power law in BTC affected by dead end sites



Transport model based on collection of dead-end sites