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## Effective medium model of hyphal fluid mechanics

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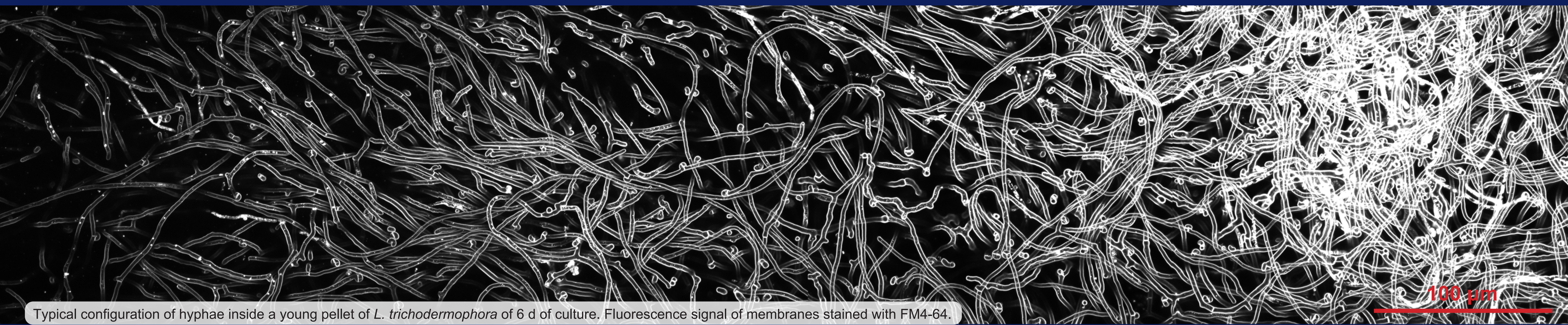
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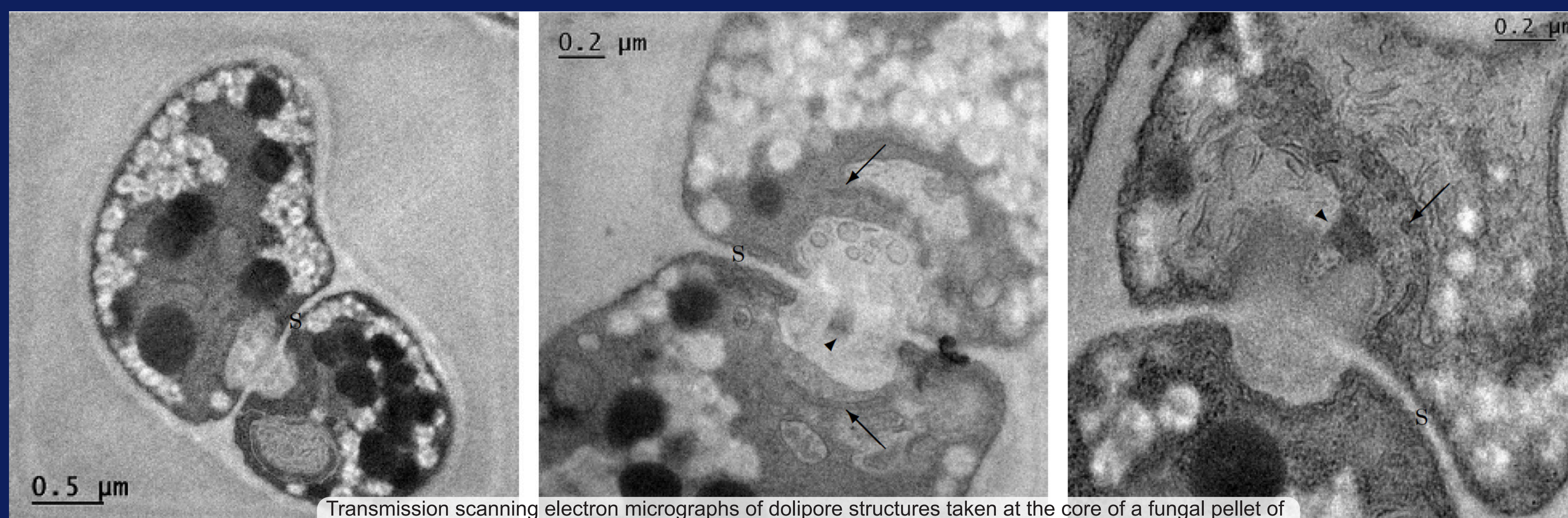


**Abstract:** Upscaled mathematical models for mass and momentum transport inside fungal pellets were derived and used to predict the average intracellular and extracellular velocity and permeability of pellets of *Laccaria trichodermophora*.



Typical configuration of hyphae inside a young pellet of *L. trichodermophora* of 6 d of culture. Fluorescence signal of membranes stained with FM4-64.

## HOW TO MODEL FLUID MECHANICS IN A FUNGAL PELLET?

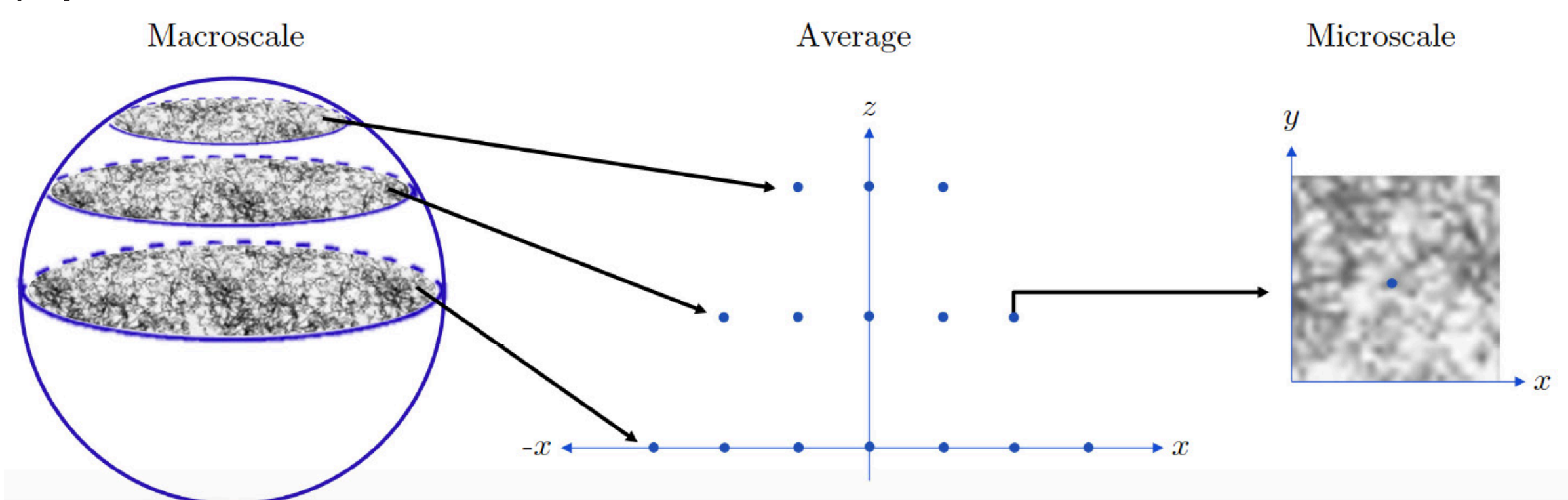


Transmission scanning electron micrographs of dolipore structures taken at the core of a fungal pellet of *L. trichodermophora* of 7 d of culture. s: septum, arrow: parenthosome, arrowhead: dolipore plug.



**Introduction:** Submerged cultures of filamentous fungi can be seen as hierarchical systems with different scale levels (1,2). Fluid mechanics provides the basis for studying the effects of shear stress on growth morphology (as mycelia, clumps, and pellets). It is necessary to show the interconnection between biomass growth, morphology changes (like pellet shaving), mass transport of chemical species, vacuolation, filamentous aggregation size during culture and applied mechanical forces (3). Fluid mechanics in this systems have scarcely been studied (4), even though they provide valuable information for knowledge building. A promising tool to solve this issue is mathematical modeling.

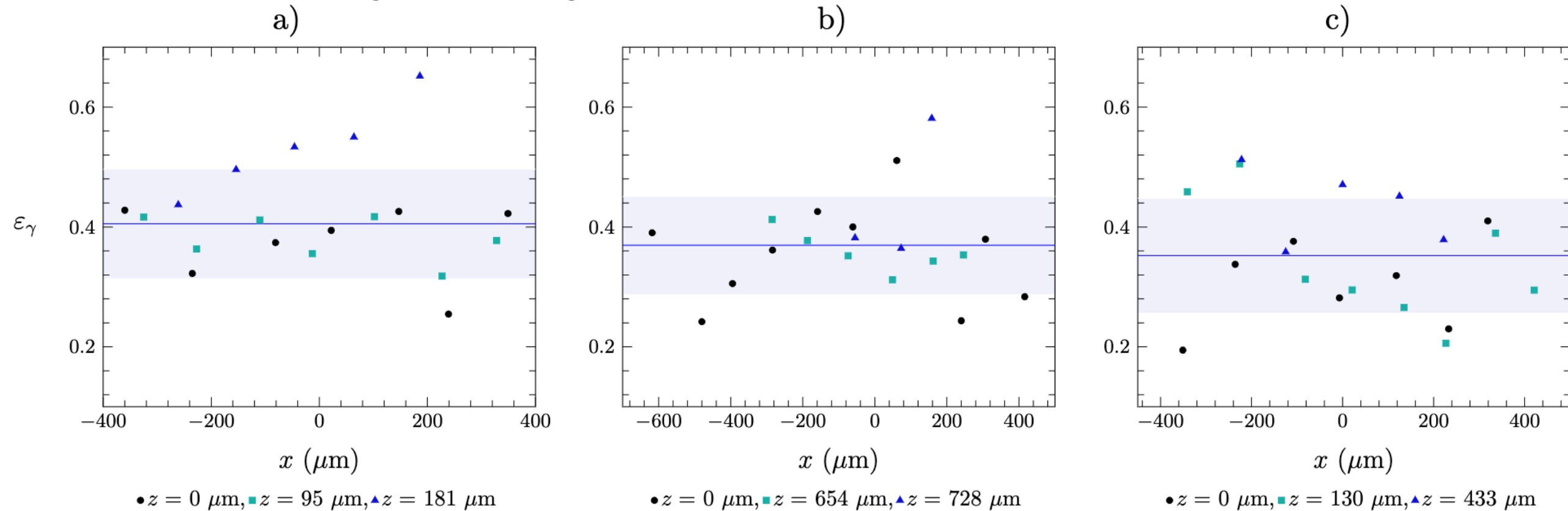
**Methodology:** An upscaling technique previously reported for porous media was used to derive the mathematical model. The mathematical model to be derived is not formulated for a particular fungal species; however, requires information about geometrical features to be solved for a specific system. Light, fluorescence, and electron microscopy techniques were used to produce a representative geometry of hyphae and pellets from submerged cultures of the model fungi *L. trichodermophora*. Average models were solved in 3D geometry in Comsol Multiphysics® and validated with direct numerical simulations.



**Figure 1.** Scheme of the averaging process at every position of the acquired images from light microscopy. The process consists on compacting the information of the representative averaging surfaces of the pellets section into points.

### Results and discussion

Identification of homogeneous regions inside the pellet



**Figure 2.** Spatial dependence of the volumetric fraction of the extracellular phase ( $\epsilon_\gamma$ ) in the z and x directions (with origin of the axes at the center of the pellets). Samples of pellets from a) 7 days-old pellet, b) 14 days-old pellet and c) 21 days-old pellet of *L. trichodermophora* cultures. The blue line indicates the average  $\epsilon_\gamma$  in each pellet, while the shaded blue region encompasses the corresponding standard deviation of the data. The average  $\epsilon_\gamma$  of the pellets was, in all cases, around 0.4.

**Conclusions:** *L. trichodermophora* pellets possess a homogeneous inner core, where a representative elementary volume could be defined, susceptible to a priori modeling with the upscaled mass and momentum balance equations. The derived mathematical model predicted the average intracellular and extracellular velocities in agreement with direct numerical simulations. No noticeable differences in the velocity fields were observed for the conditions studied here.

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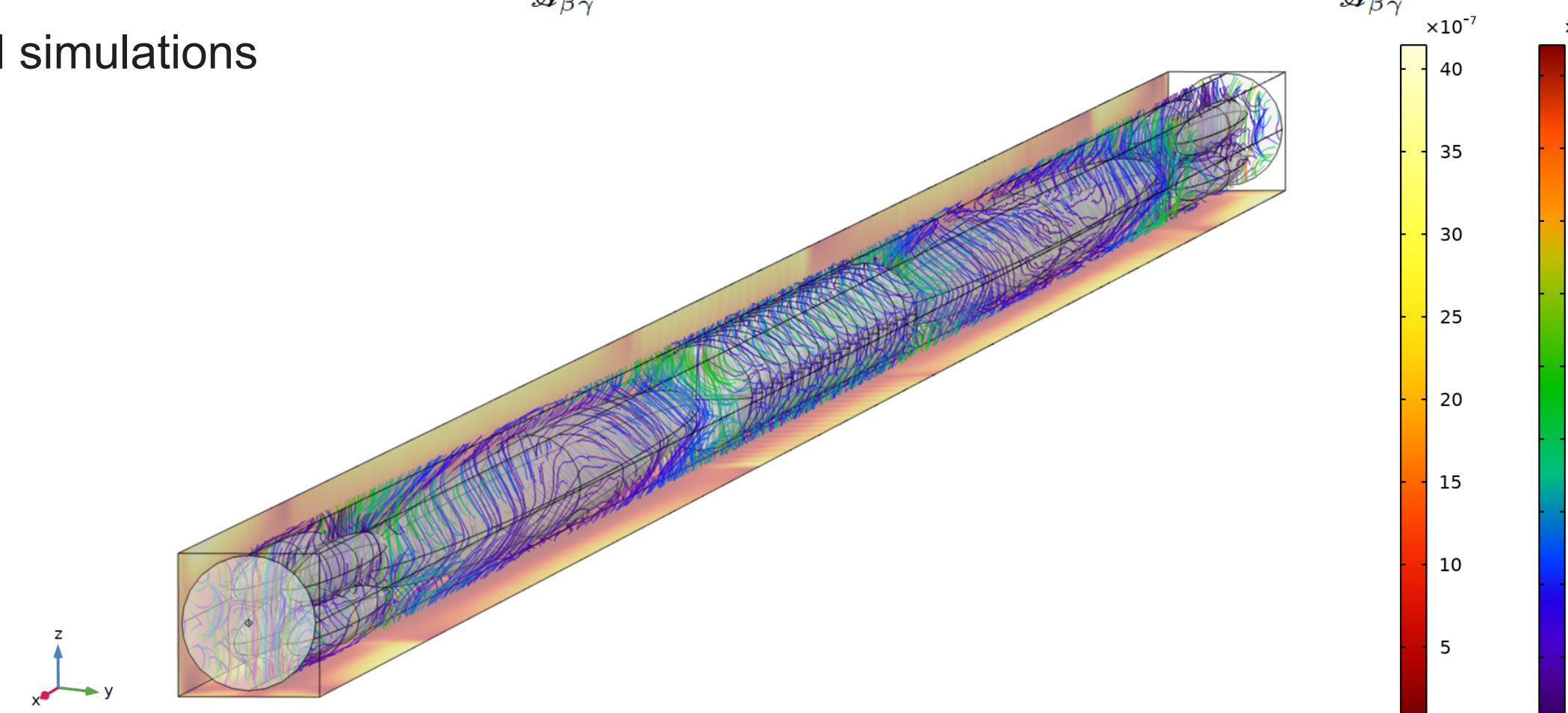
Upscaled mass and momentum models

$$\frac{d\epsilon_\alpha}{dt} + \nabla \cdot \langle \mathbf{v}_\alpha \rangle_\alpha = 0$$

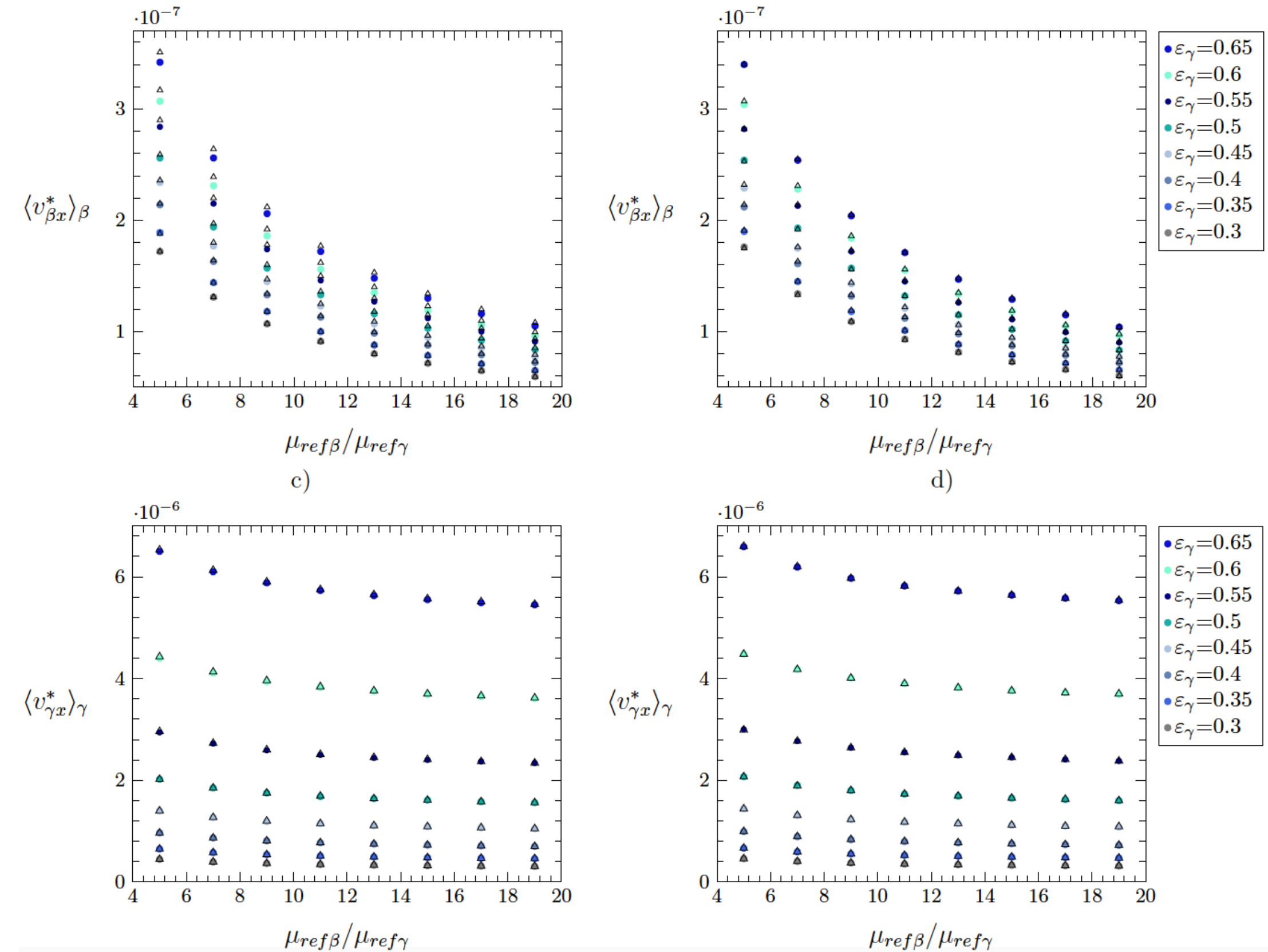
$$\langle \mathbf{v}_\alpha \rangle_\alpha = -\frac{\mathbf{H}_{\alpha\alpha}}{\mu_{ref\alpha}} \cdot (\nabla \langle p_\alpha \rangle_\alpha - \rho_\alpha \mathbf{g}) - \frac{\mathbf{H}_{\alpha\kappa}}{\mu_{ref\kappa}} \cdot (\nabla \langle p_\kappa \rangle_\kappa - \rho_\kappa \mathbf{g})$$

$$+ \frac{1}{\mu_{ref\alpha} V} \int_{\partial\beta\gamma} (2\gamma H \mathbf{n}_{\beta\gamma} + \nabla_s \gamma) \cdot \mathbf{D}_{\alpha\alpha} dA + \frac{\rho_\gamma - \rho_\beta}{\mu_{ref\alpha} V} \int_{\partial\beta\gamma} \mathbf{n}_{\beta\gamma} \cdot \mathbf{w} \cdot \mathbf{D}_{\alpha\alpha} dA$$

Numerical simulations



**Figure 3.** Fields of the velocity magnitude of the extracellular fluid and velocity magnitude streamlines of the intracellular fluid, in a periodic unit cell representative of a hyphal compartment divided by septa and an open dolipore.



**Figure 4.** x-component of the dimensionless average velocity in the a), b) intracellular and c), d) extracellular phases, considering a), c) fluid flow through dolipores or b), d) obstructured dolipores. The error % between the upscaled model predictions and the direct numerical simulations was <5% in all studied cases.