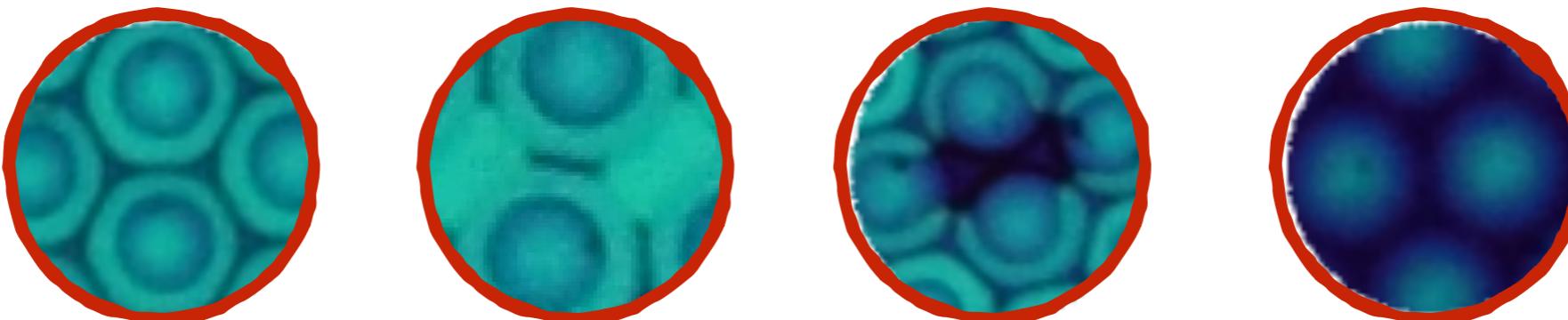




Pore-scale Modelling of Multiphase Flow in Porous Media

Considering wettability and disordered microstructure



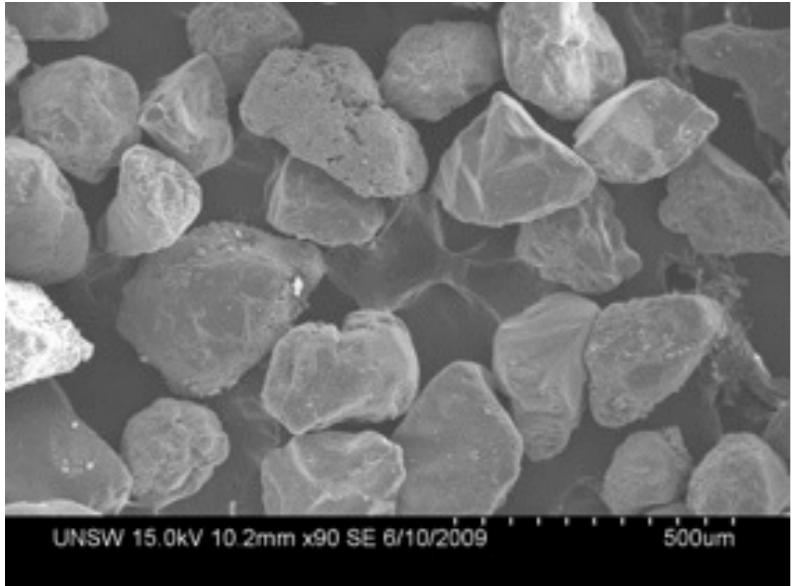
Yixiang Gan

School of Civil Engineering
The University of Sydney, Australia

Email: yixiang.gan@sydney.edu.au

Twitter: @drgan

Phases and interfaces in granular / porous media



contact
stiffness

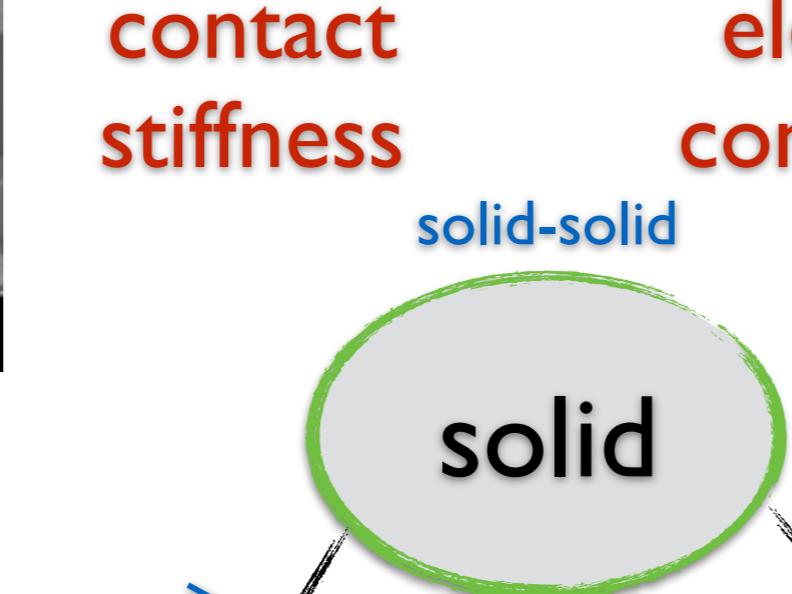
electrical
conduction

solid-solid

hydrophobicity:
contact angle

liquid-solid

gas-solid



Interfaces

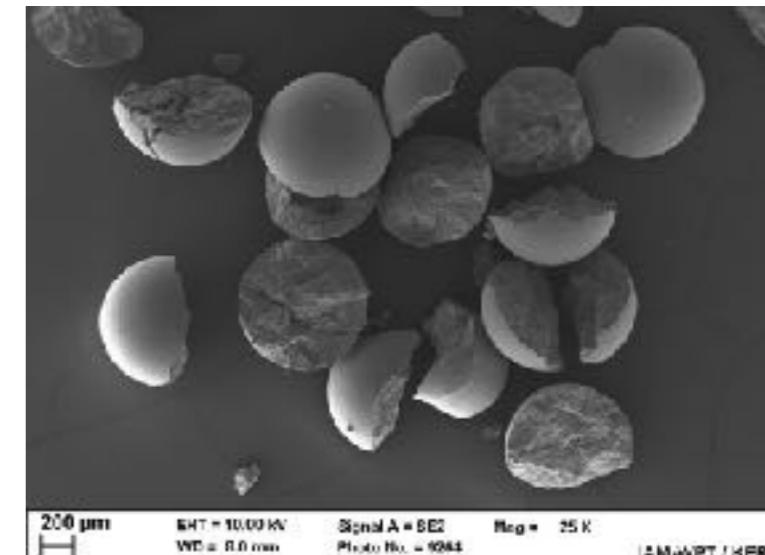
liquid

gas

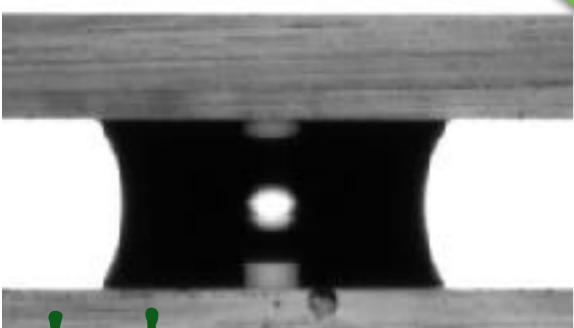
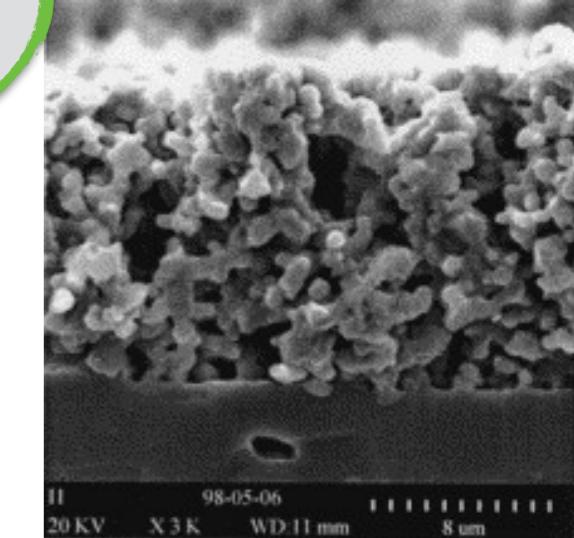
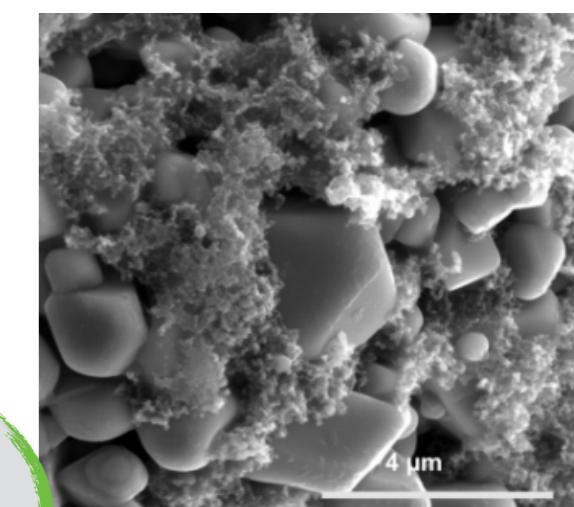
liquid-gas

surface
tension

phase change
evaporation

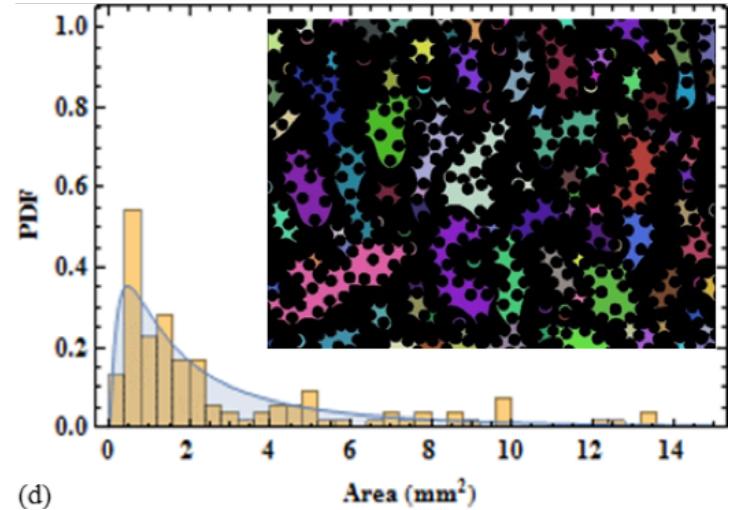
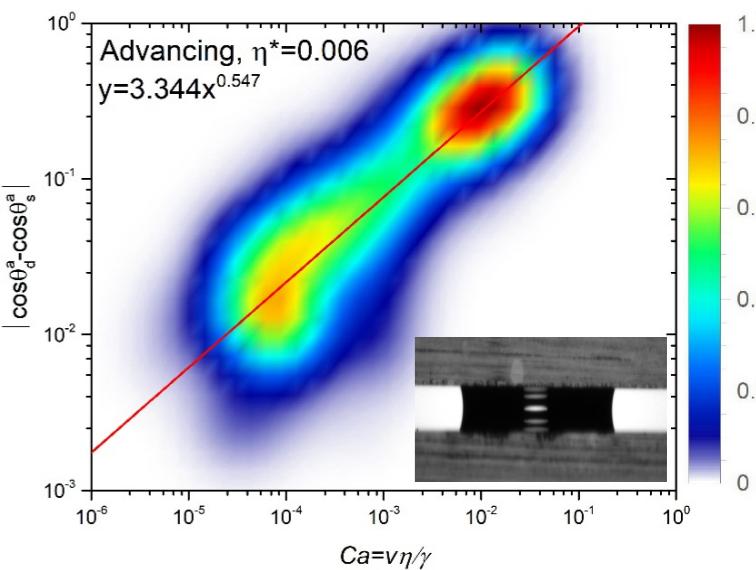
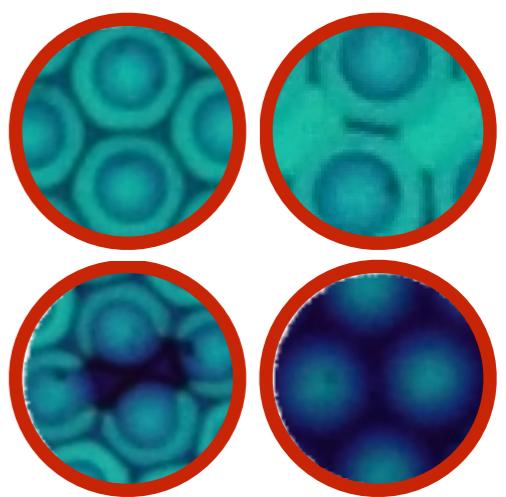


thermal
conduction



Outline

- Wettability and contact angle dynamics
- Disorder index
- Drainage in porous media
- Liquid displacement in disordered media



Sharon Li



Yanyao Bao



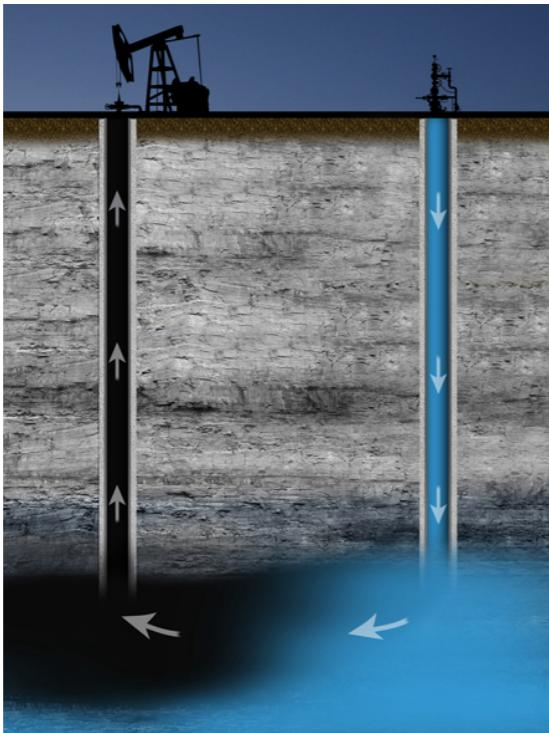
Guanzhe Cui



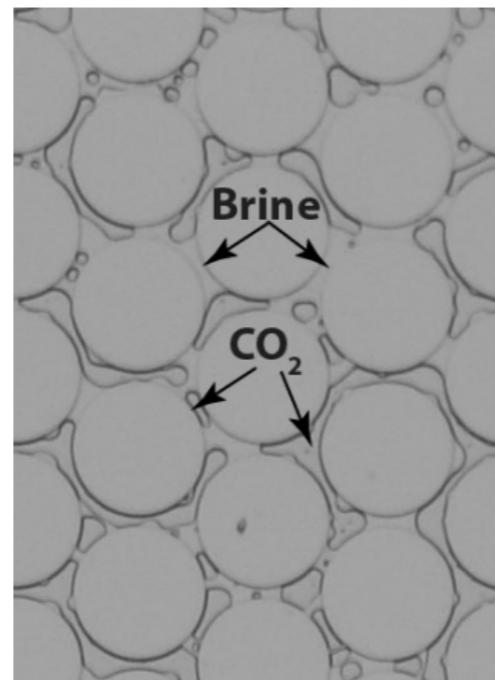
Zhongzheng Wang



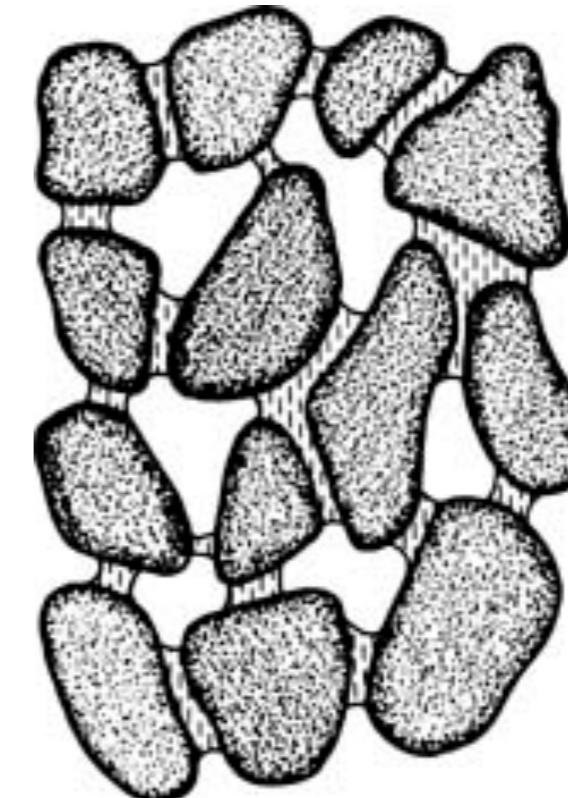
Background



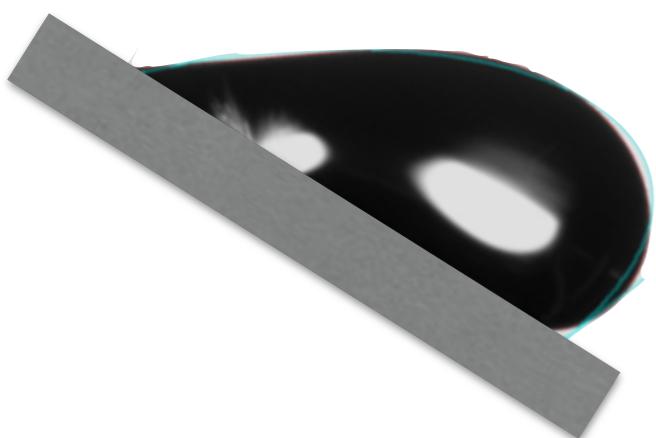
oil recovery



carbon storage

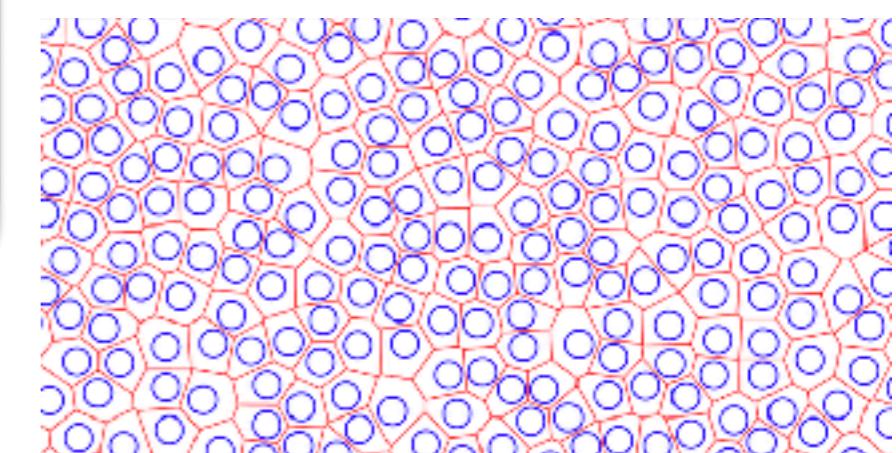


soil mechanics



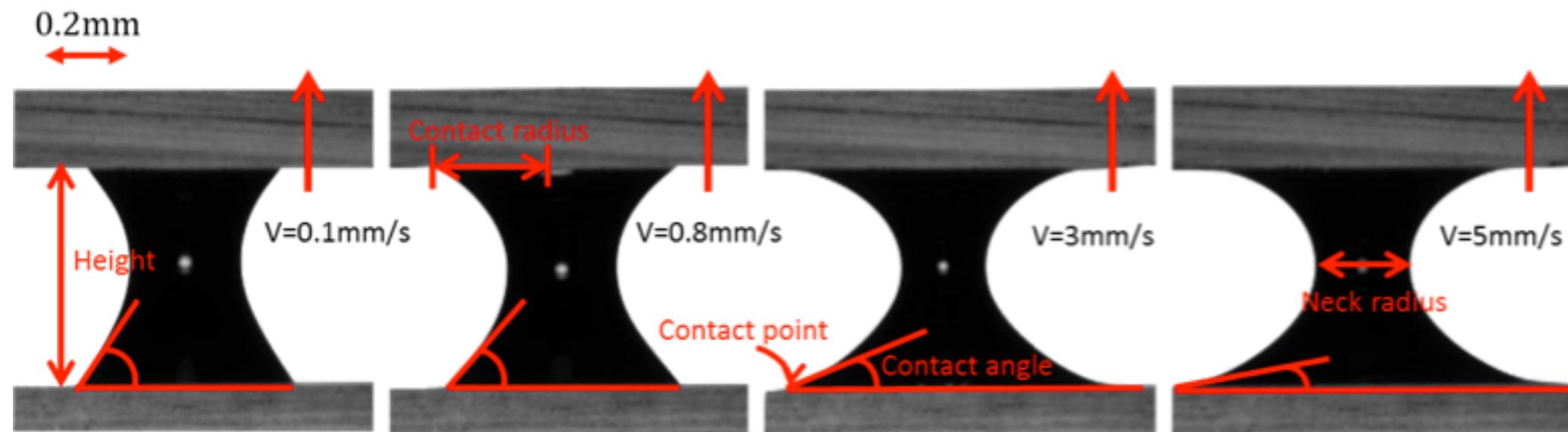
Multiphase Flow
in Porous Media

Wettability,
Contact Angle Dynamics



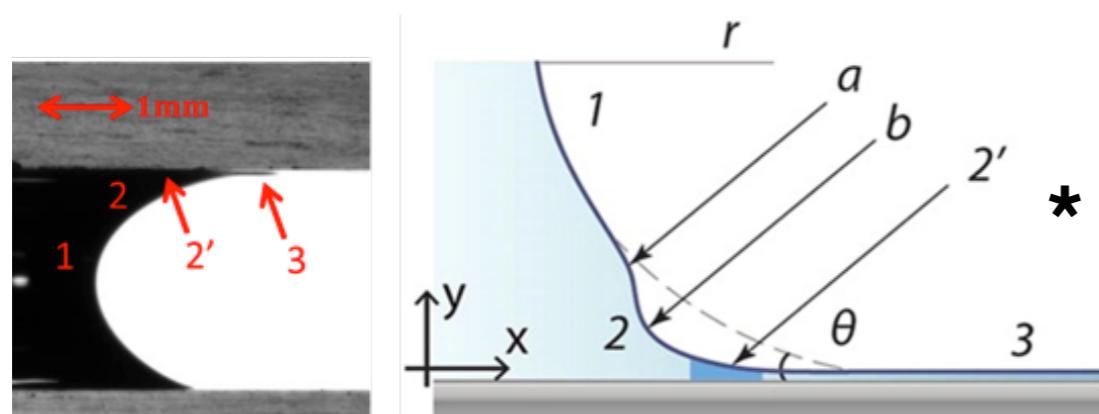
Disordered
Microstructure

Contact angles dynamics (liquid bridge experiments)

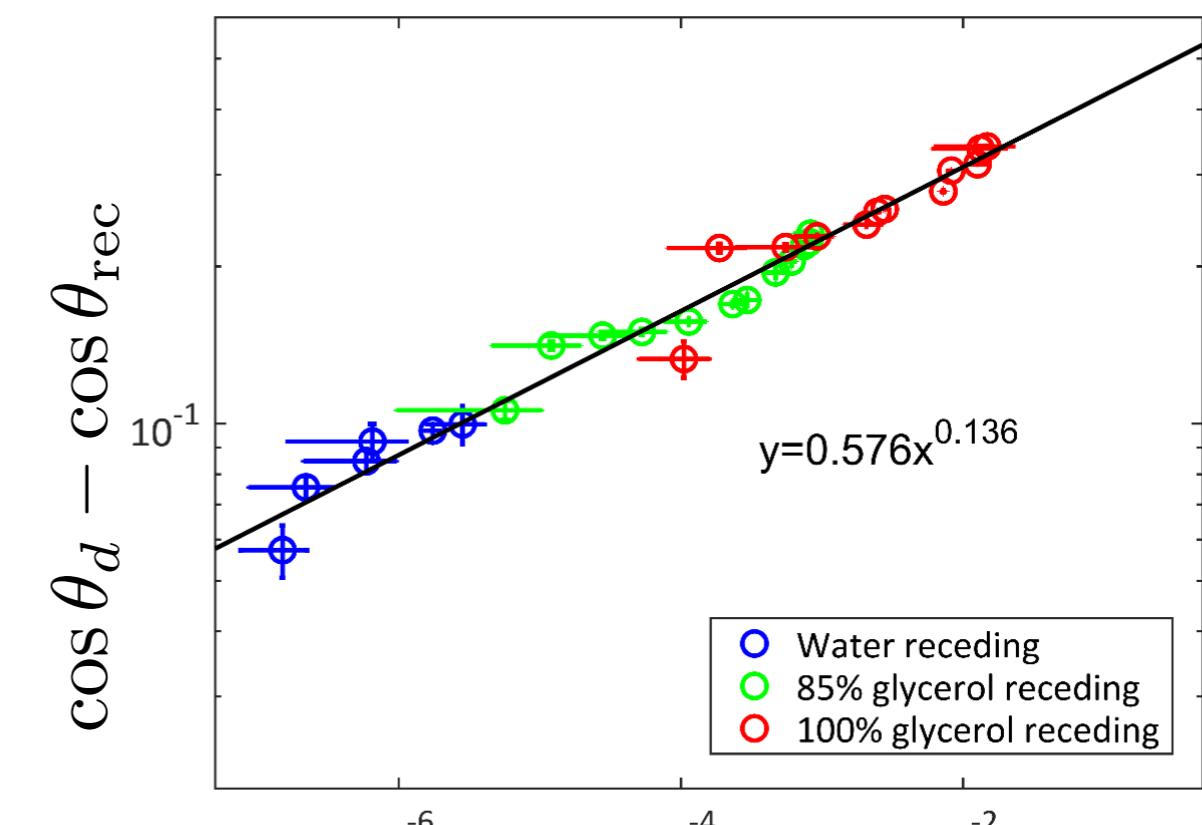


$$\cos \theta_d - \cos \theta_{\text{rec}} \propto (\text{Ca}^*)^\alpha$$

$$\cos \theta_{\text{adv}} - \cos \theta_d \propto (\text{Ca}^*)^\alpha$$



* Kuchin and Starov (2016) Hysteresis of contact angle of a meniscus inside a capillary with smooth homogeneous solid walls, Langmuir, 2016, 32 (21), pp 5333–5340.



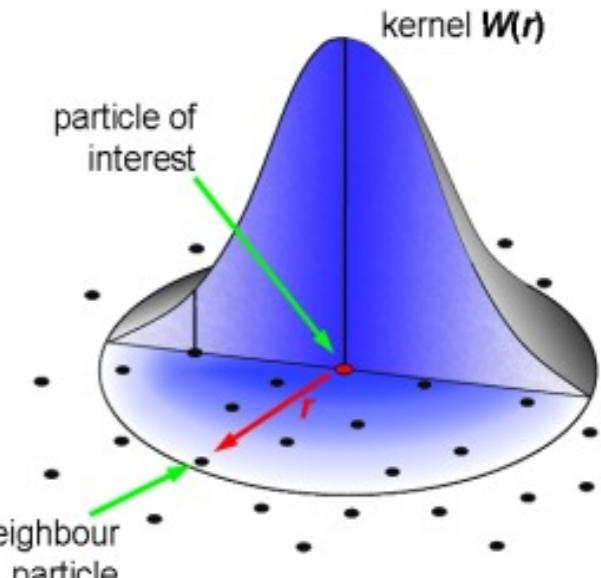
$$\text{Ca}^* = \frac{v\eta}{\gamma}$$

Shi, Z., Zhang, Y., Liu, M., Hanaor, D.A. and Gan, Y., 2017. Dynamic contact angle hysteresis in liquid bridges. arXiv preprint arXiv: 1712.04703.

Contact angles dynamics (SPH simulation)

- **SPH kernel function**

$$A_i = \sum_j \frac{m_j}{\rho_j} A_j W(r_{ij}, h)$$



- **Modifications for multiphase interactions**

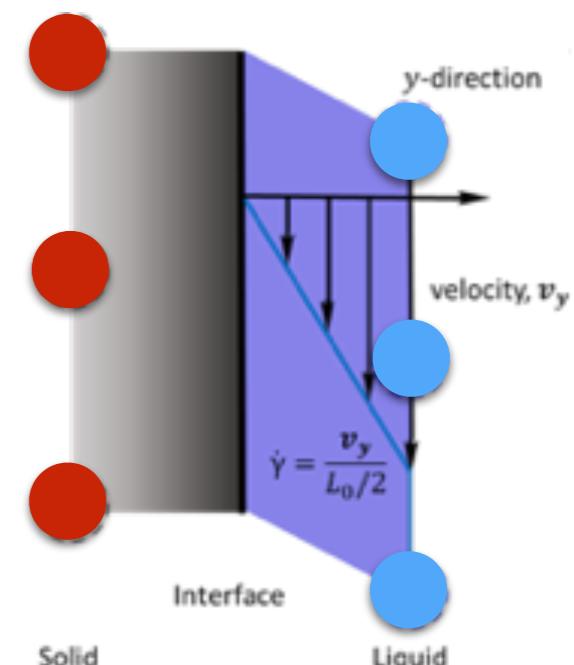
- **Inter-“particle” forces** —> surface tension

$$\dot{\boldsymbol{v}}_i = \sum_j \left[\dots + \frac{\boldsymbol{F}_{ij}^{\text{inter}}}{m_j} \right] \quad \boldsymbol{F}_{ij}^{\text{inter}} = - \frac{dU_L(r)}{dr} \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{|\boldsymbol{r}_i - \boldsymbol{r}_j|}$$

Smoothed Particle Hydrodynamics

- **Interfacial properties** —> contact angle

$$\boldsymbol{F}_{L-S}^{\text{inter}} = - \frac{dU(r)}{dr} \frac{\boldsymbol{r}_L - \boldsymbol{r}_S}{|\boldsymbol{r}_L - \boldsymbol{r}_S|}$$

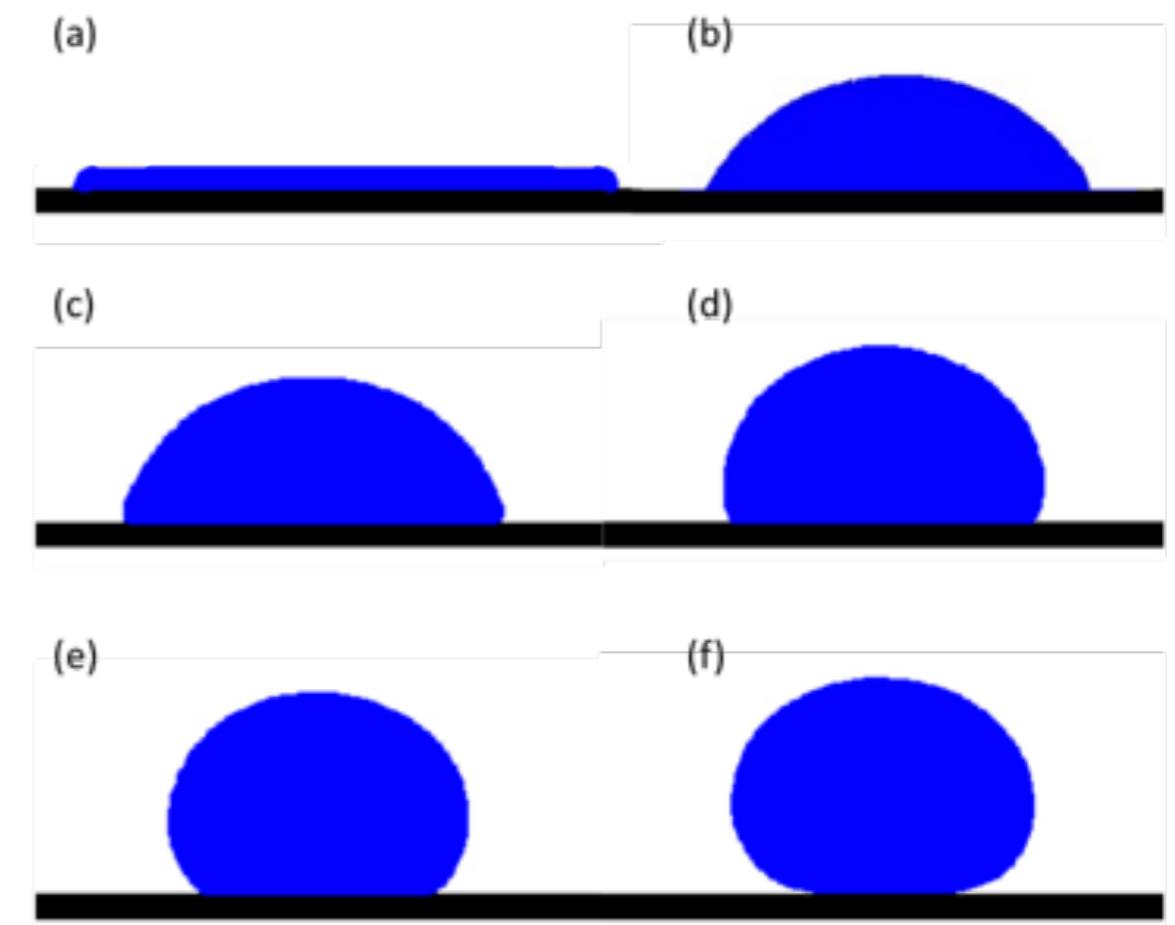
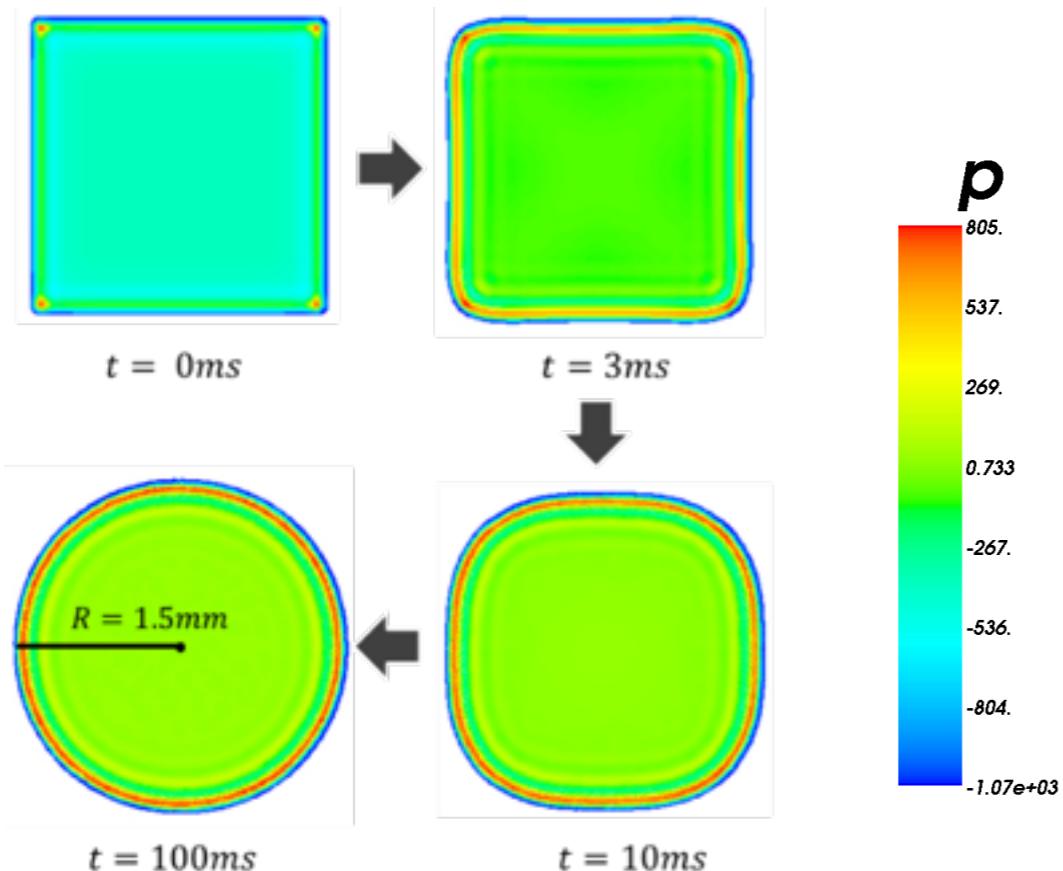


Shearing at solid-liquid interface

- **Tangential forces** —> dynamic contact angle

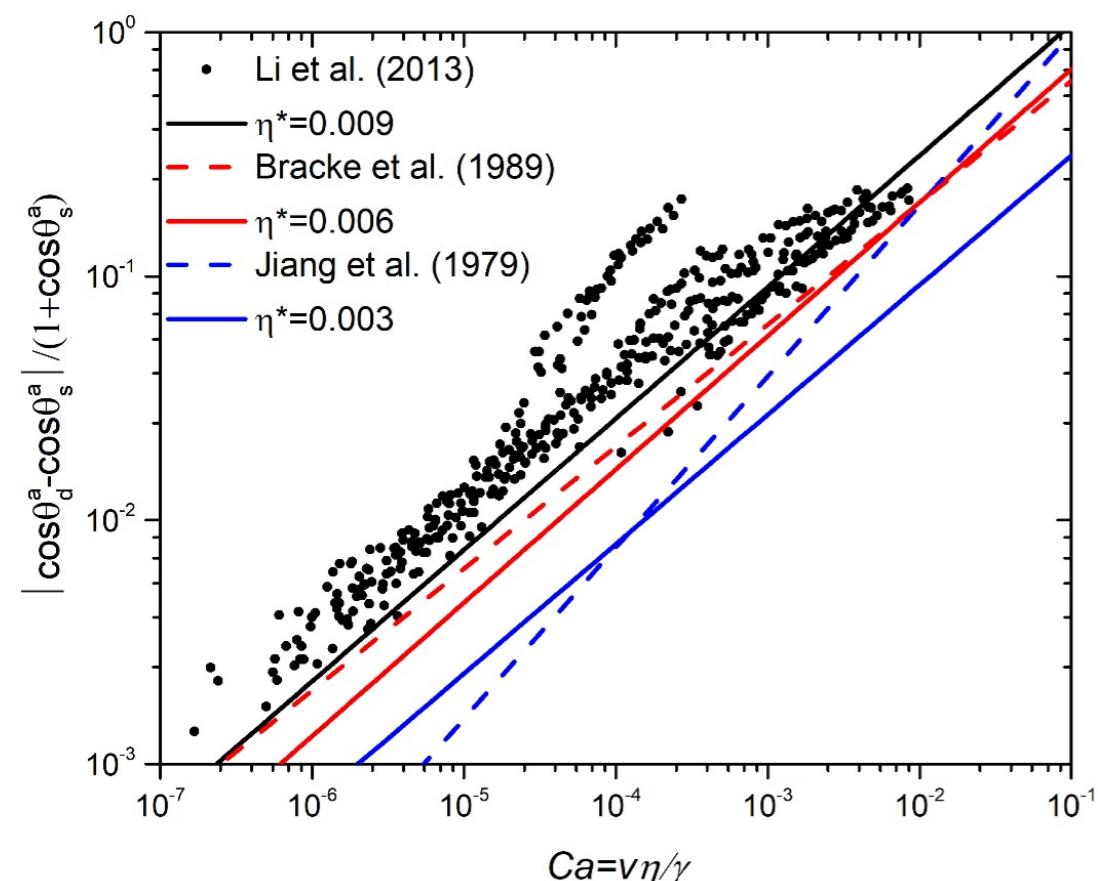
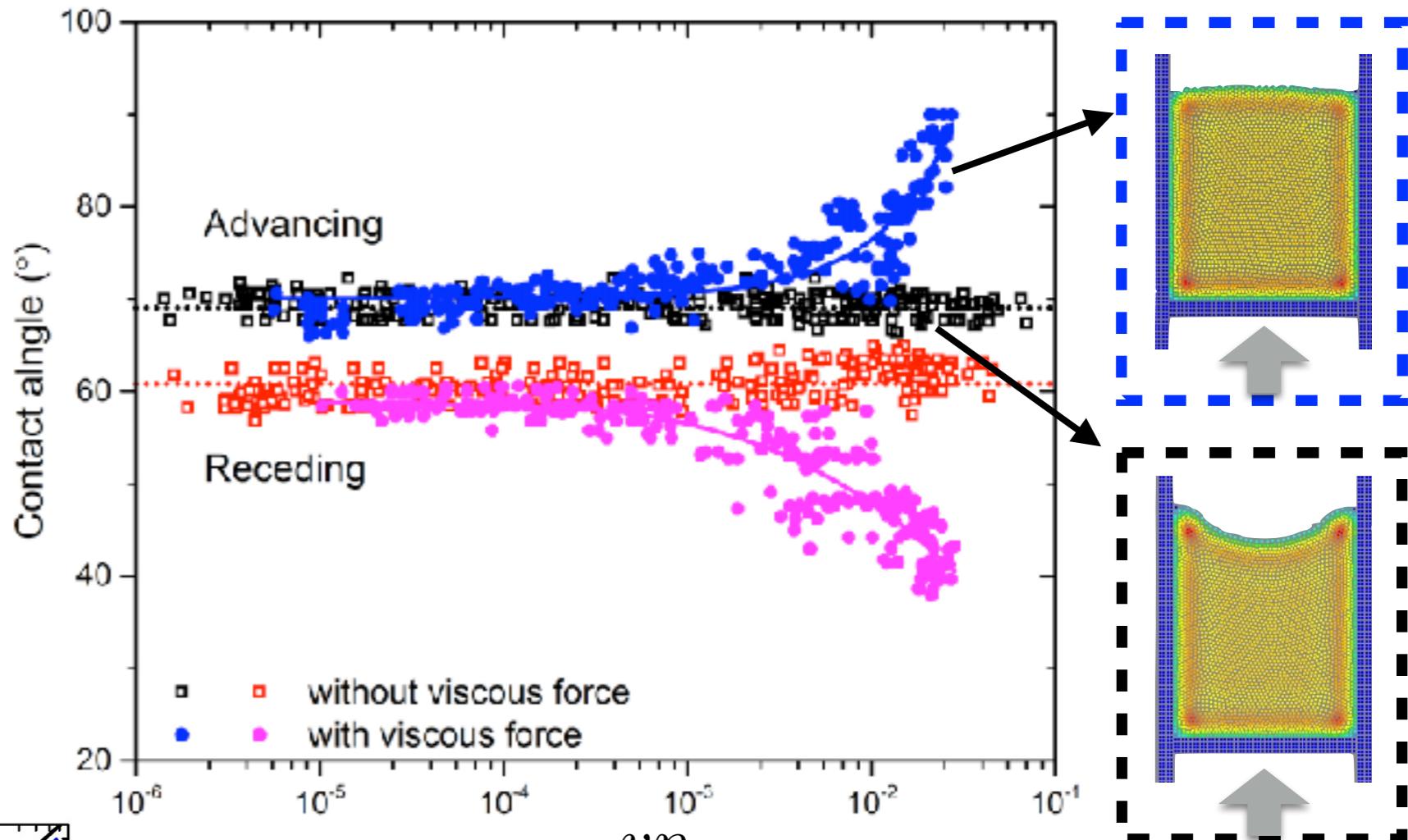
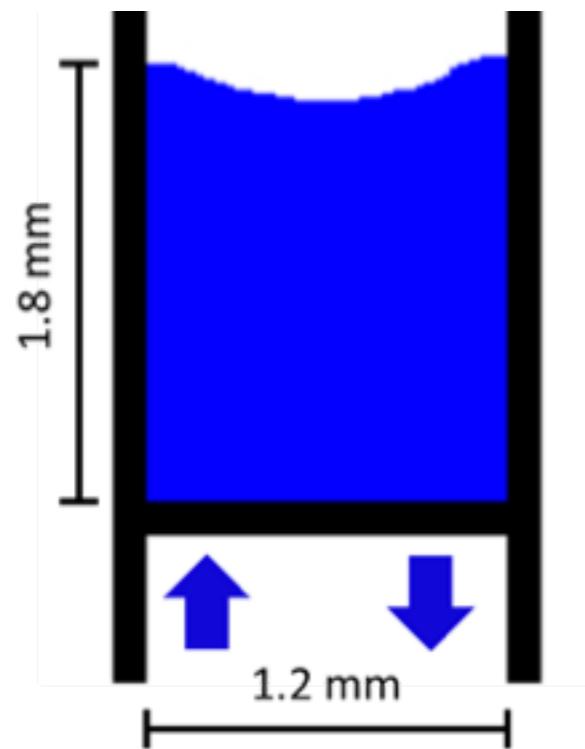
hysteresis $F_t \propto f(\eta, v_{ij}^t, d)$

Surface tension and contact angle



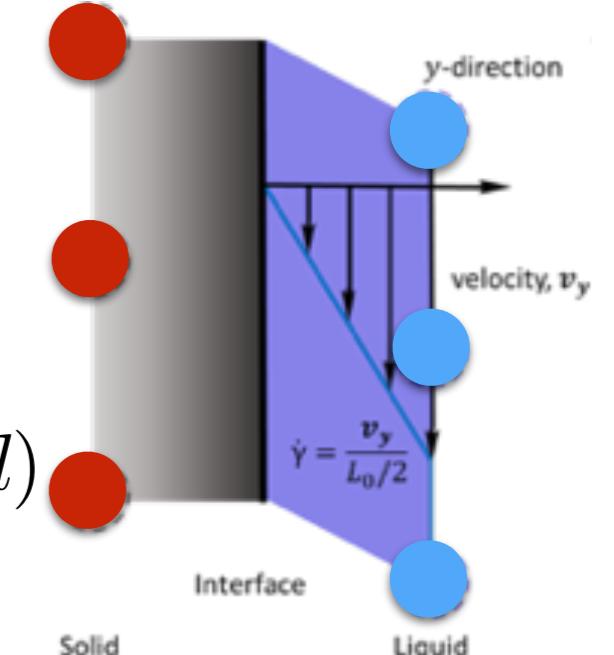
Shape evolution of a droplet and wettability of droplet on solid surface.

Contact angles dynamics (SPH simulation)

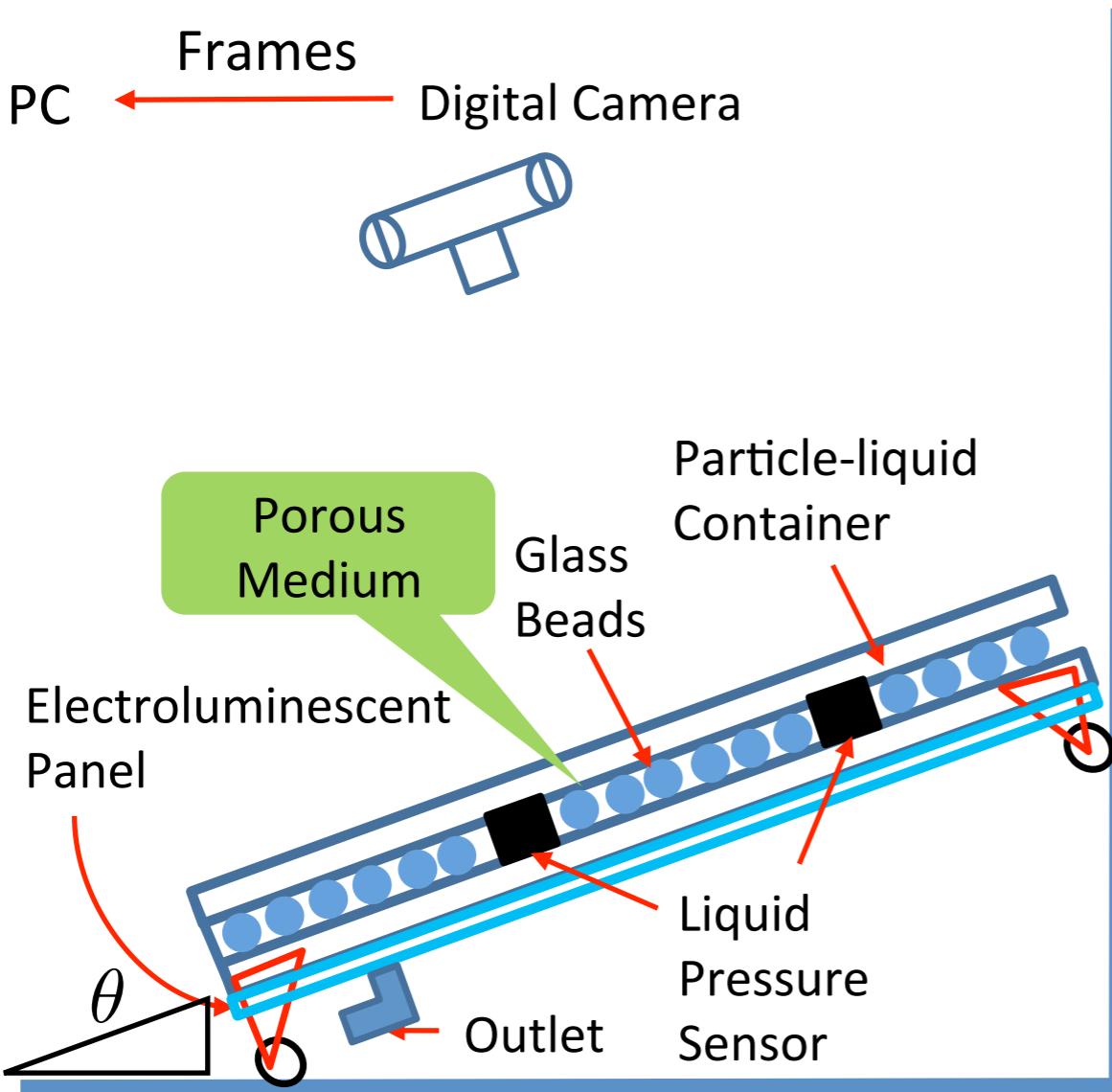


$$Ca^* = \frac{v\eta}{\gamma}$$

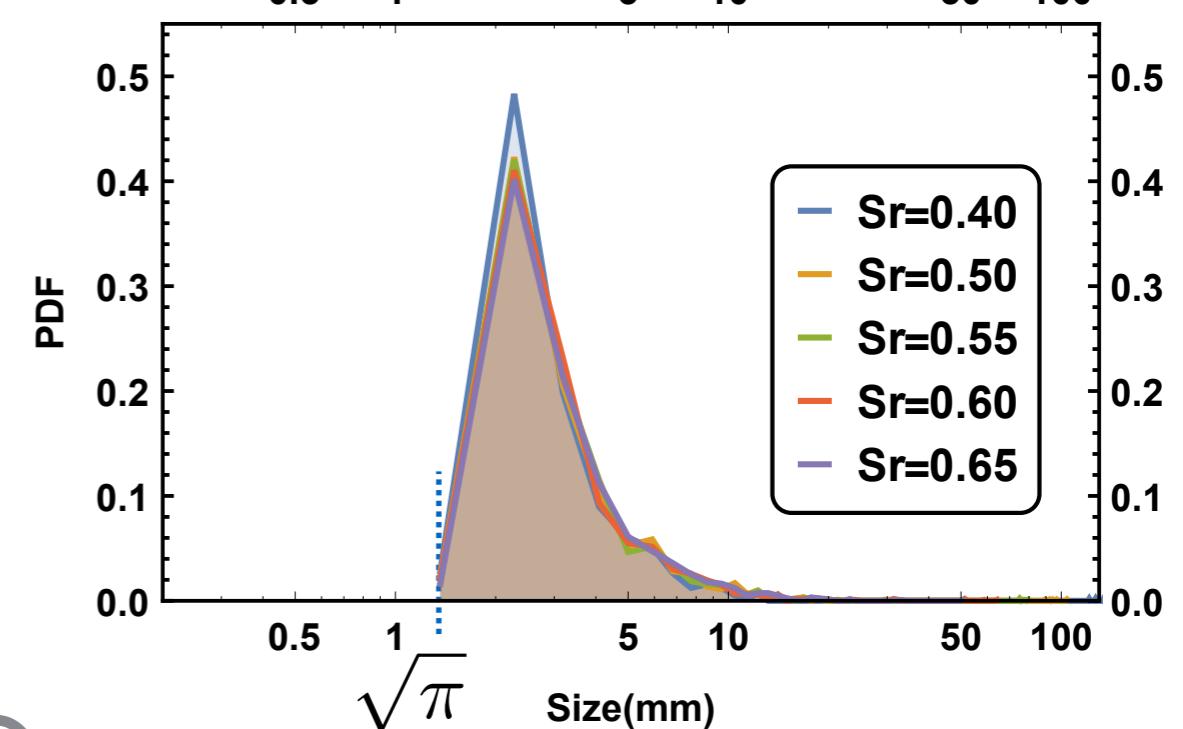
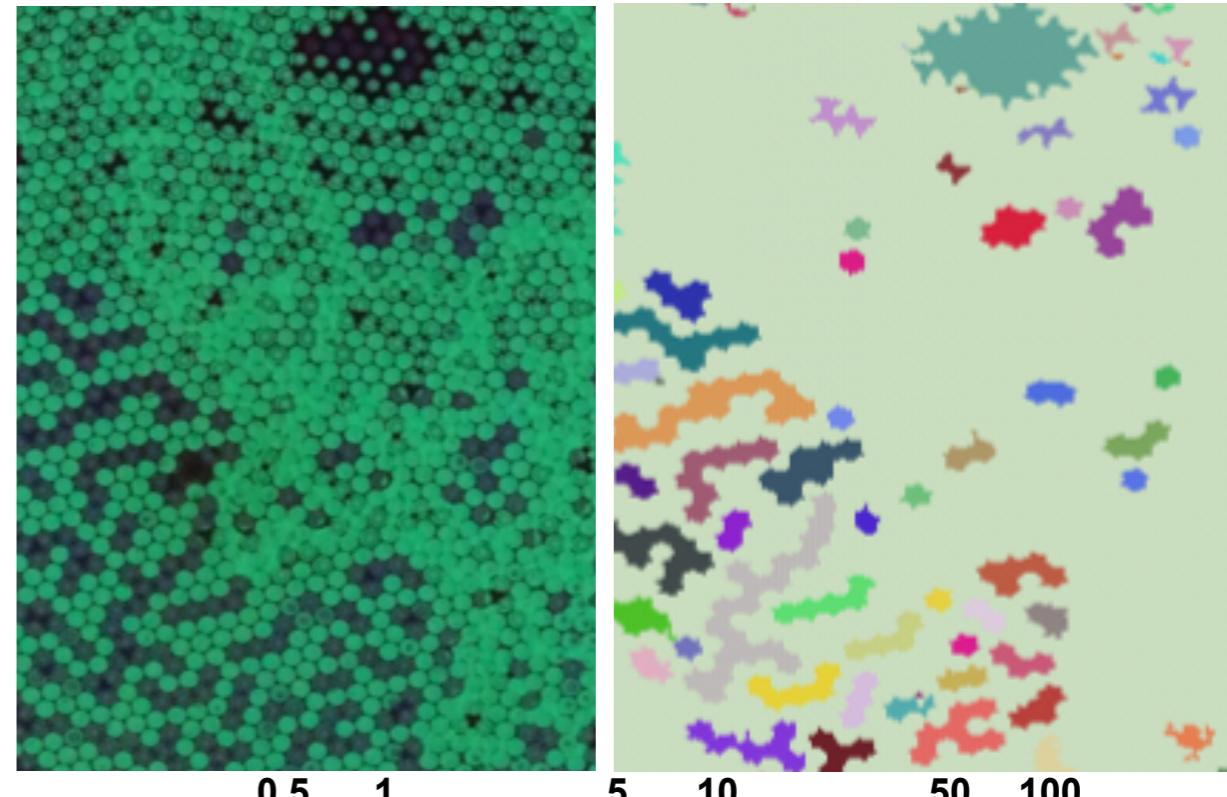
$$F_t \propto f(\eta, v_{ij}^t, d)$$



Drainage experiments: Saturated clusters



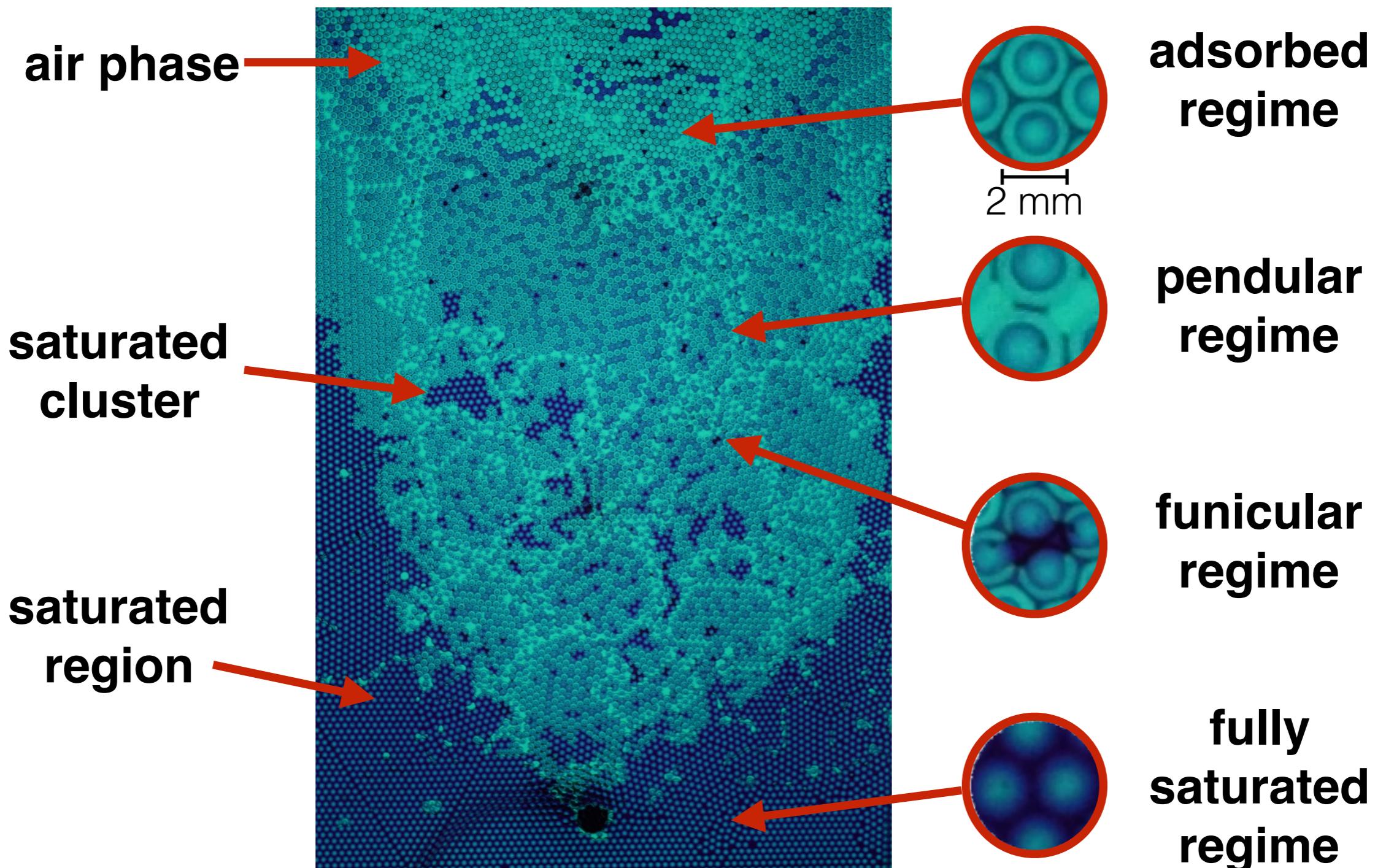
$$Bo = \frac{\rho g \sin \theta a^2}{\gamma} \quad Ca = \frac{\eta v a^2}{\gamma k}$$



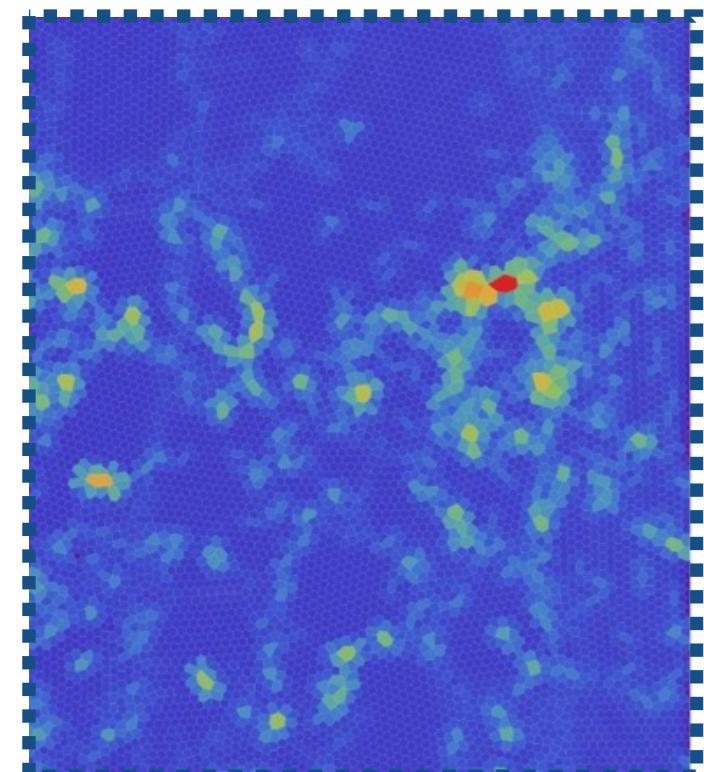
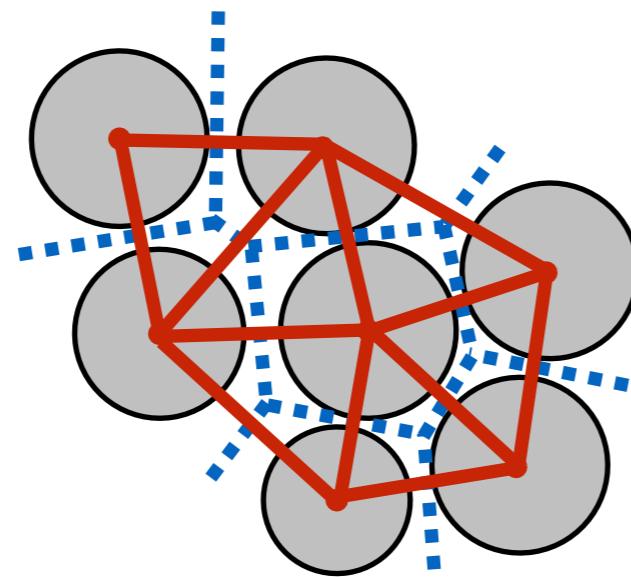
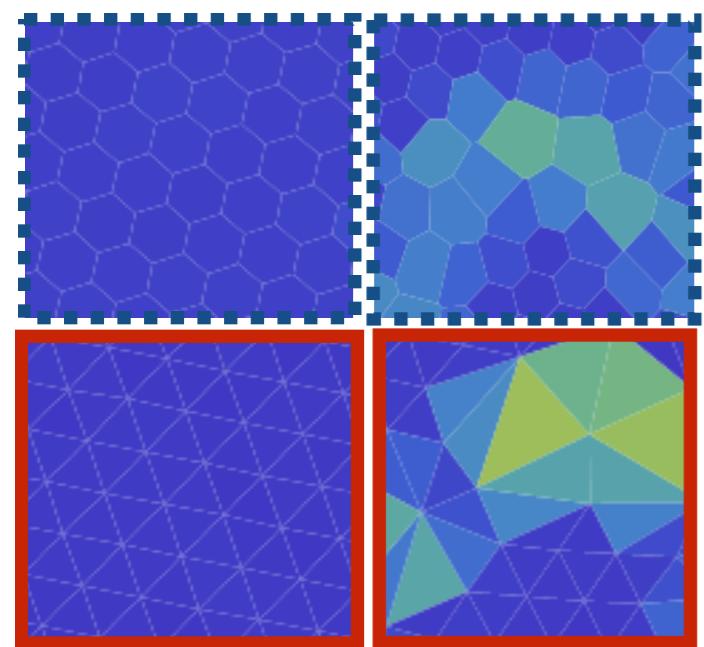
$$Bo^* = Bo - Ca$$

Li, S., Liu, M., Hanaor, D. and Gan, Y., 2018. Dynamics of Viscous Entrapped Saturated Zones in Partially Wetted Porous Media. *arXiv preprint arXiv:1802.07387*.

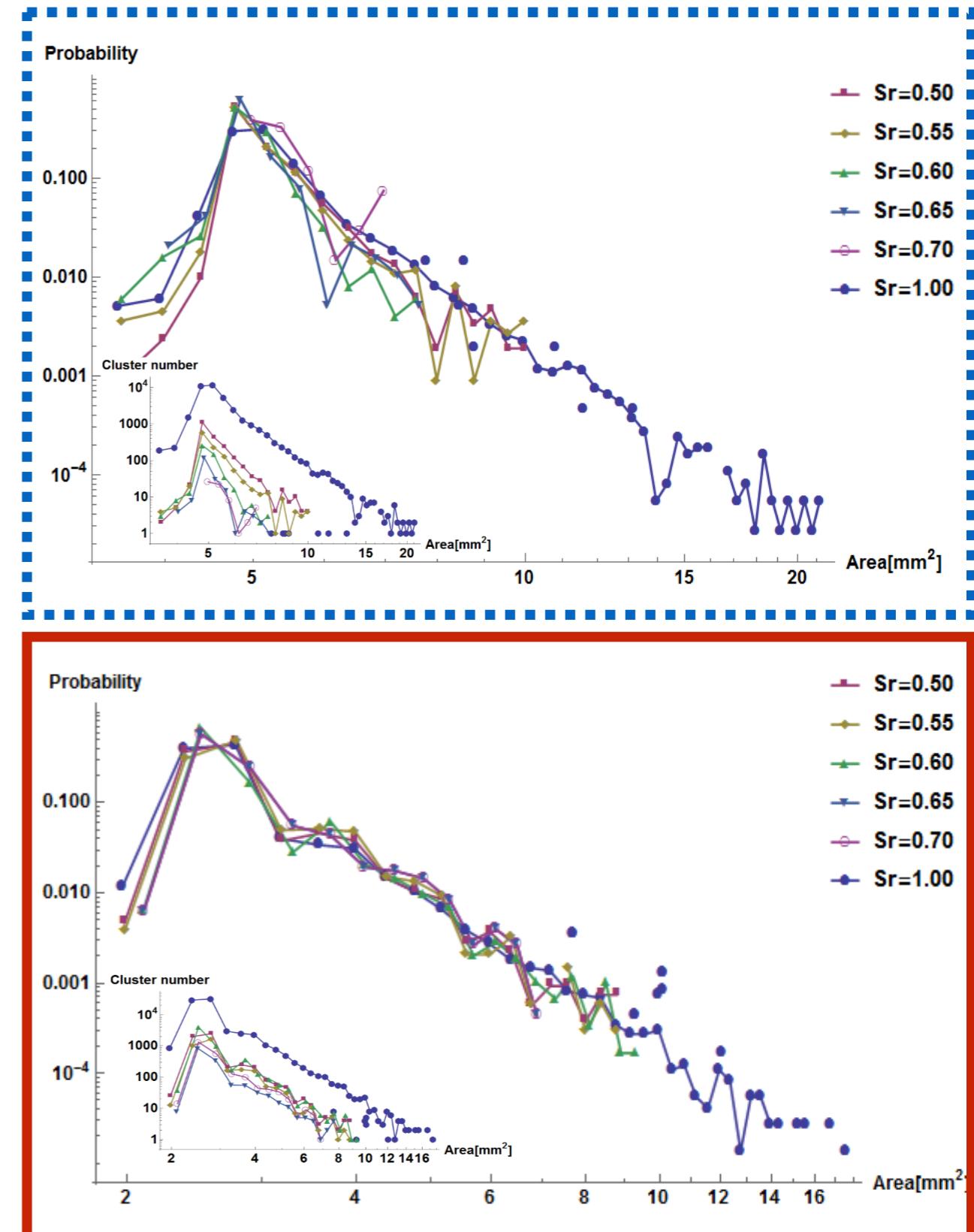
Saturated clusters: regimes (experiments)



Saturated clusters vs topological features (experiments)

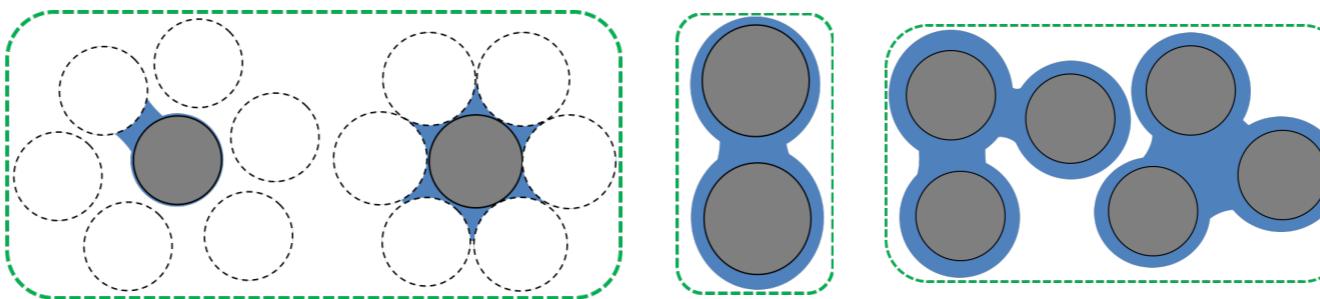


Delaunay triangulation

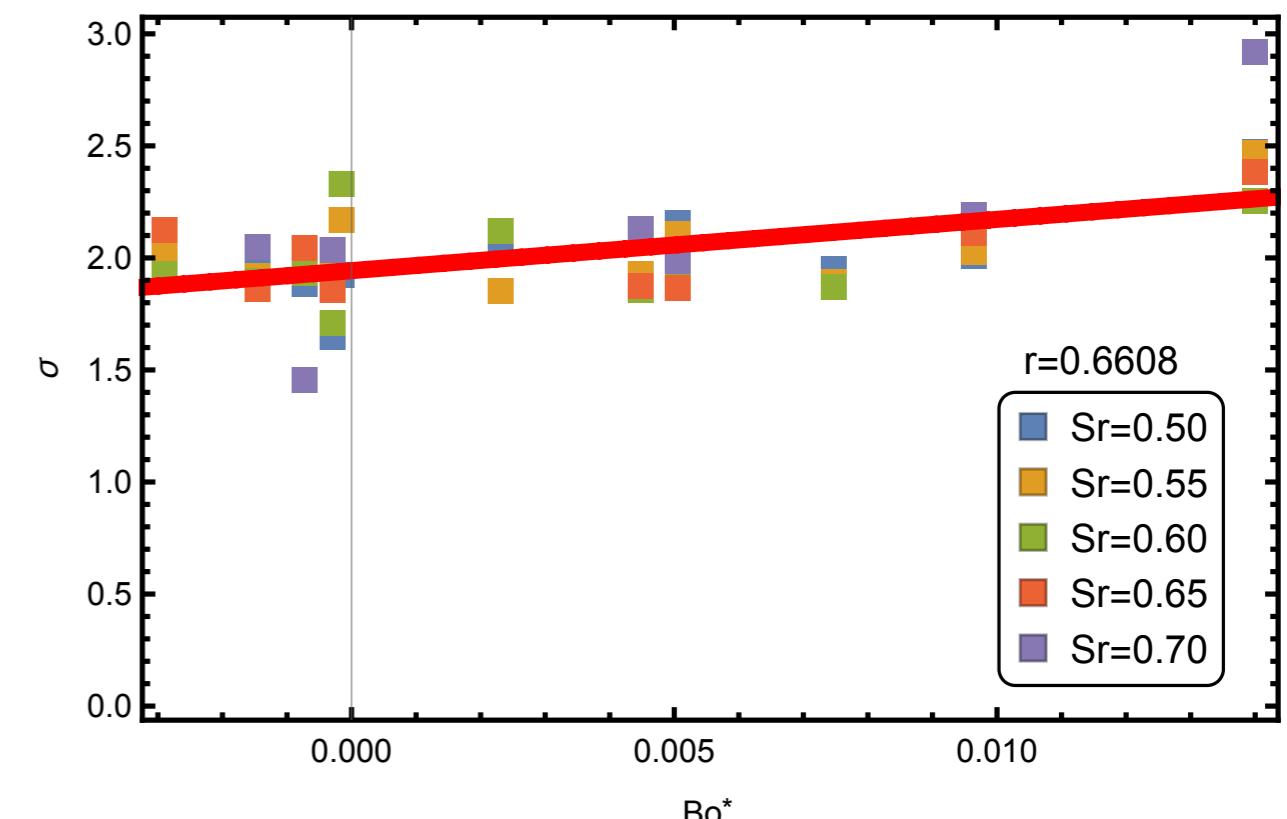
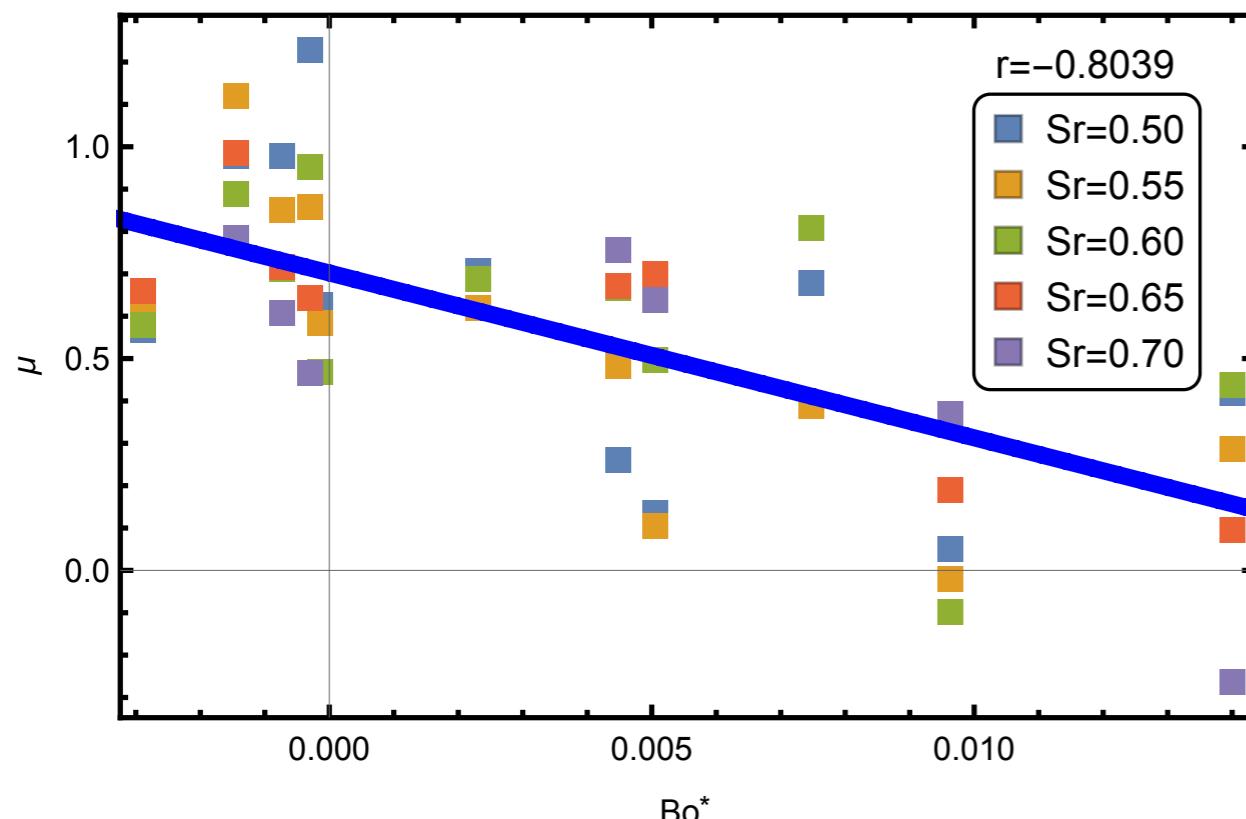


Li, S., Liu, M., Hanaor, D. and Gan, Y., 2018. Dynamics of Viscous Entrapped Saturated Zones in Partially Wetted Porous Media. *arXiv preprint arXiv:1802.07387*.

Saturated clusters distribution (experiments)



$$f(x, \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$



Plot of lognormal distribution (a) scale parameter μ and (b) shape parameter σ as a function of generalised Bond number Bo^* for different saturation levels.

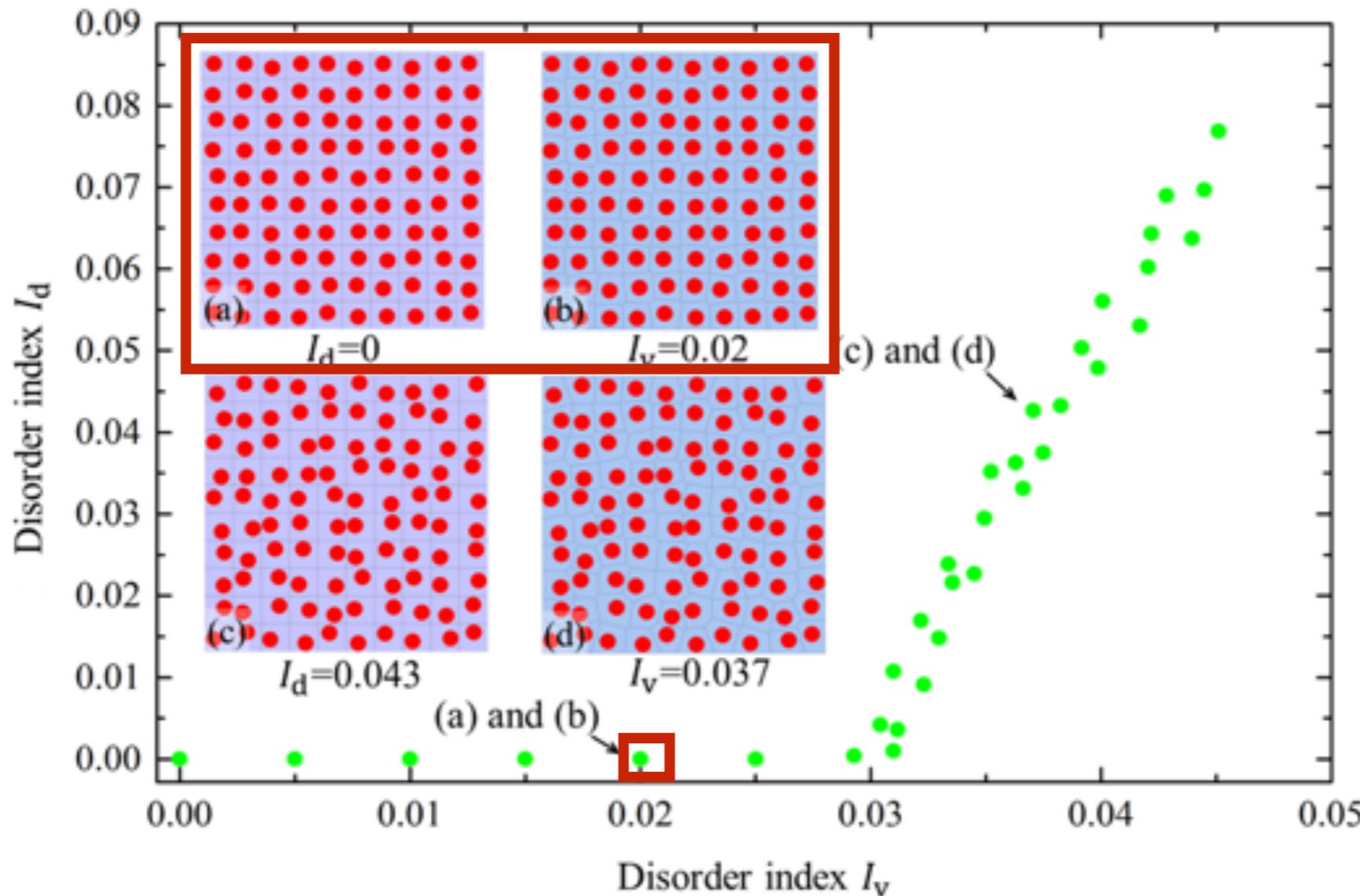
$$Bo = \frac{\rho g \sin \theta a^2}{\gamma}$$

$$Ca = \frac{\eta v a^2}{\gamma k}$$

$$Bo^* = Bo - Ca$$

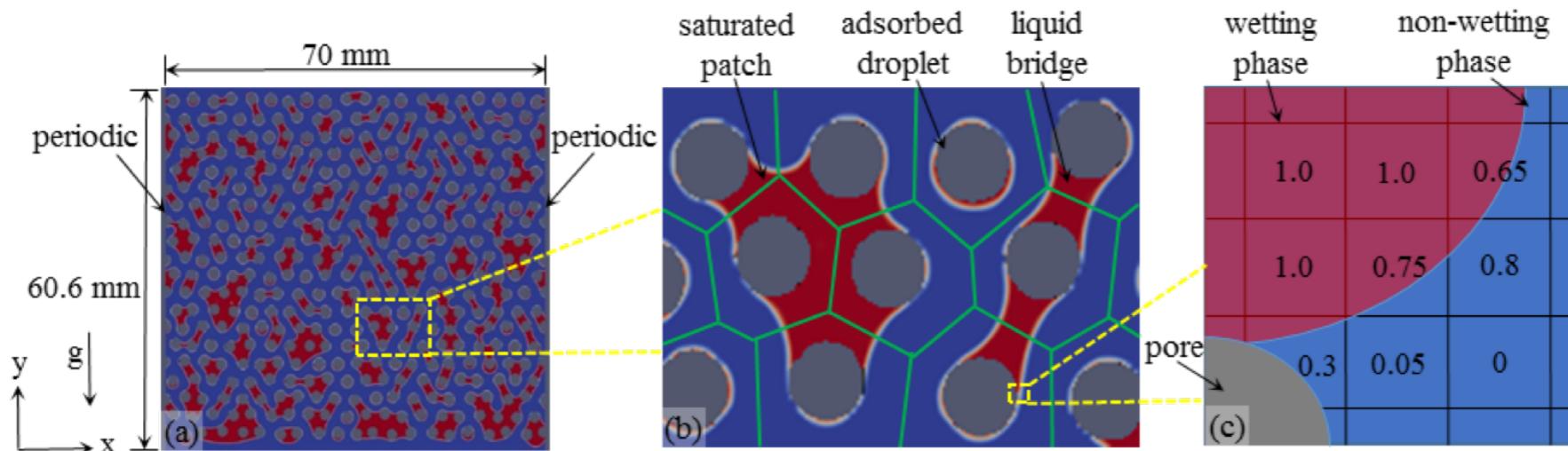
Disorder Index for Pore Space

$$I_V = [\langle \phi_i^2 \rangle - \phi^2]^{1/2}$$

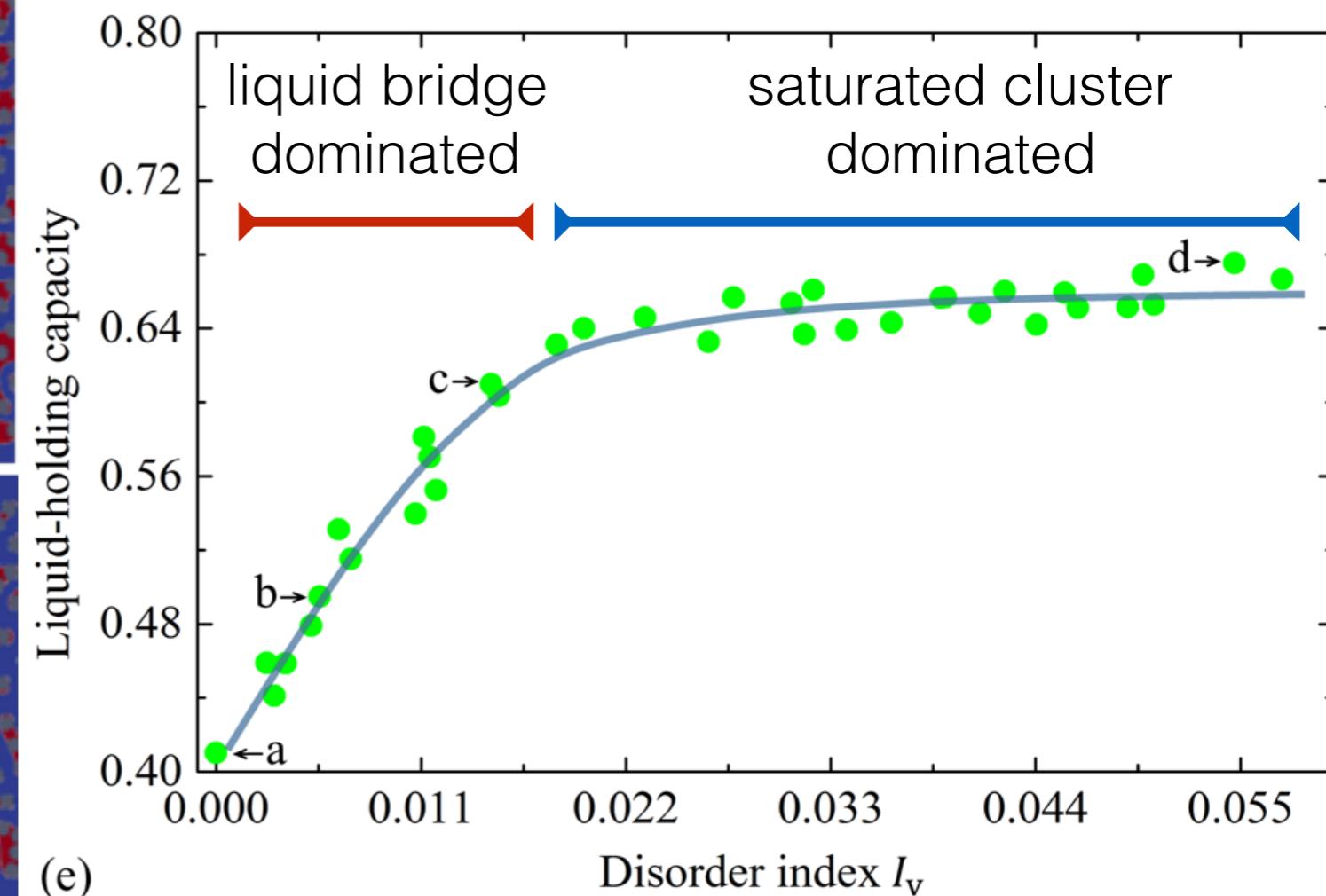
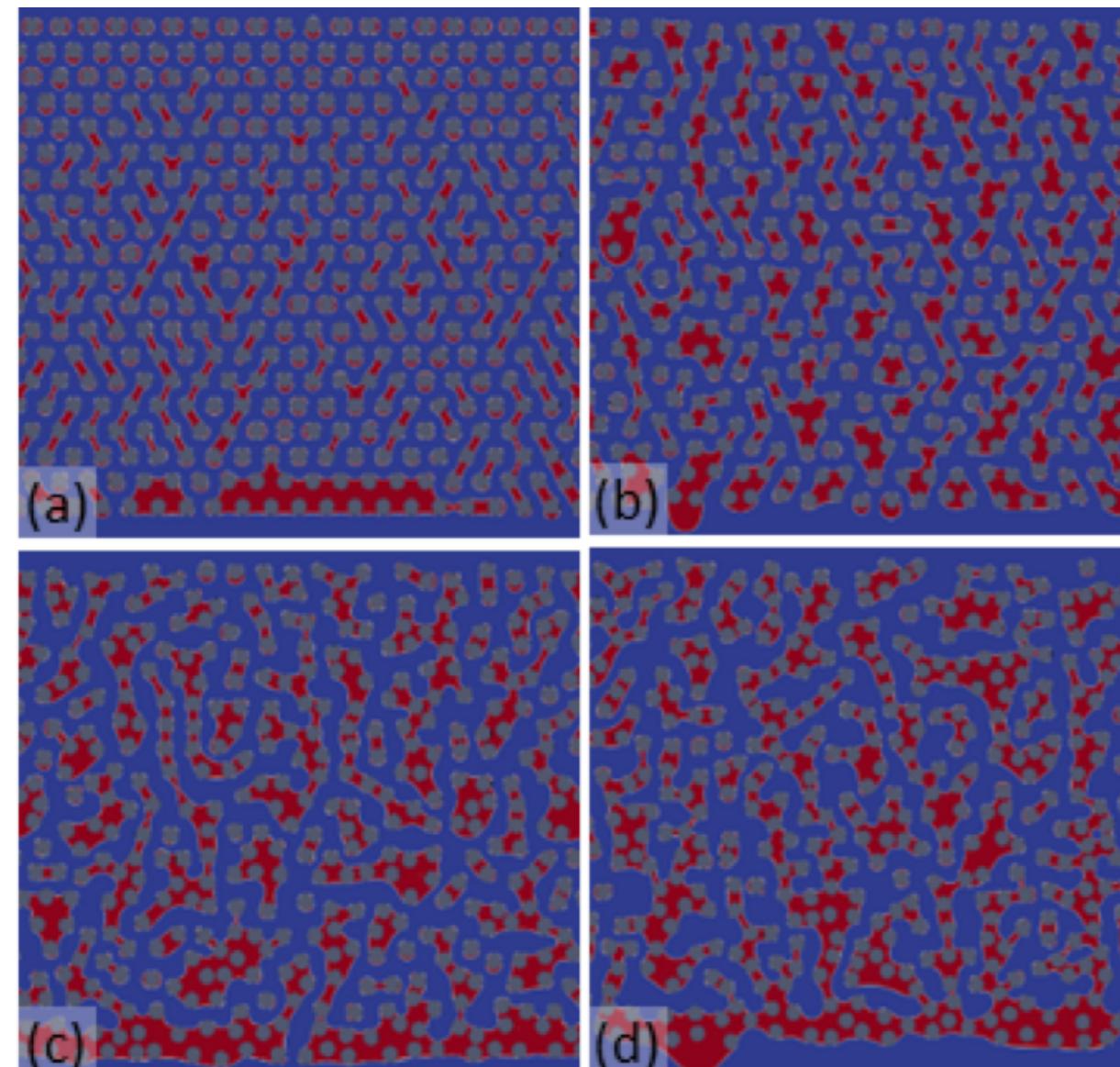


Disorder index (I_d) originally defined in Laubie et al.(2017), Phys. Rev. Lett., and the modified index (I_v) is formulated based on the Voronoi tessellation of the pore space. Main difference between these two definition is in the “**small perturbation**” region, where I_v is sensitive to the local changes.

Drainage Simulations: Disorder



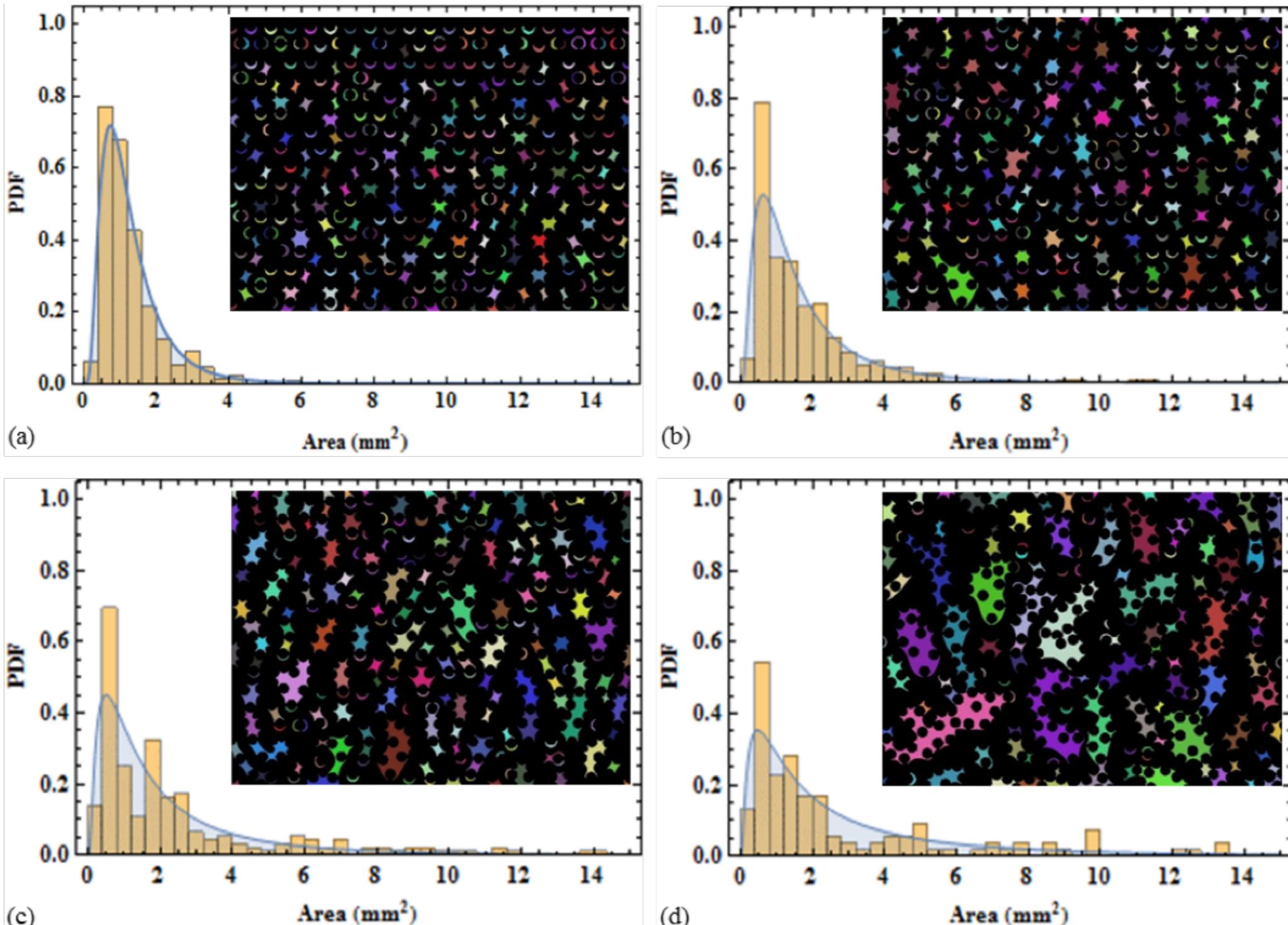
VOF method
in OpenFoam



$$Bo = \frac{\Delta \rho g R^2}{\gamma} e \quad Ca = 0$$

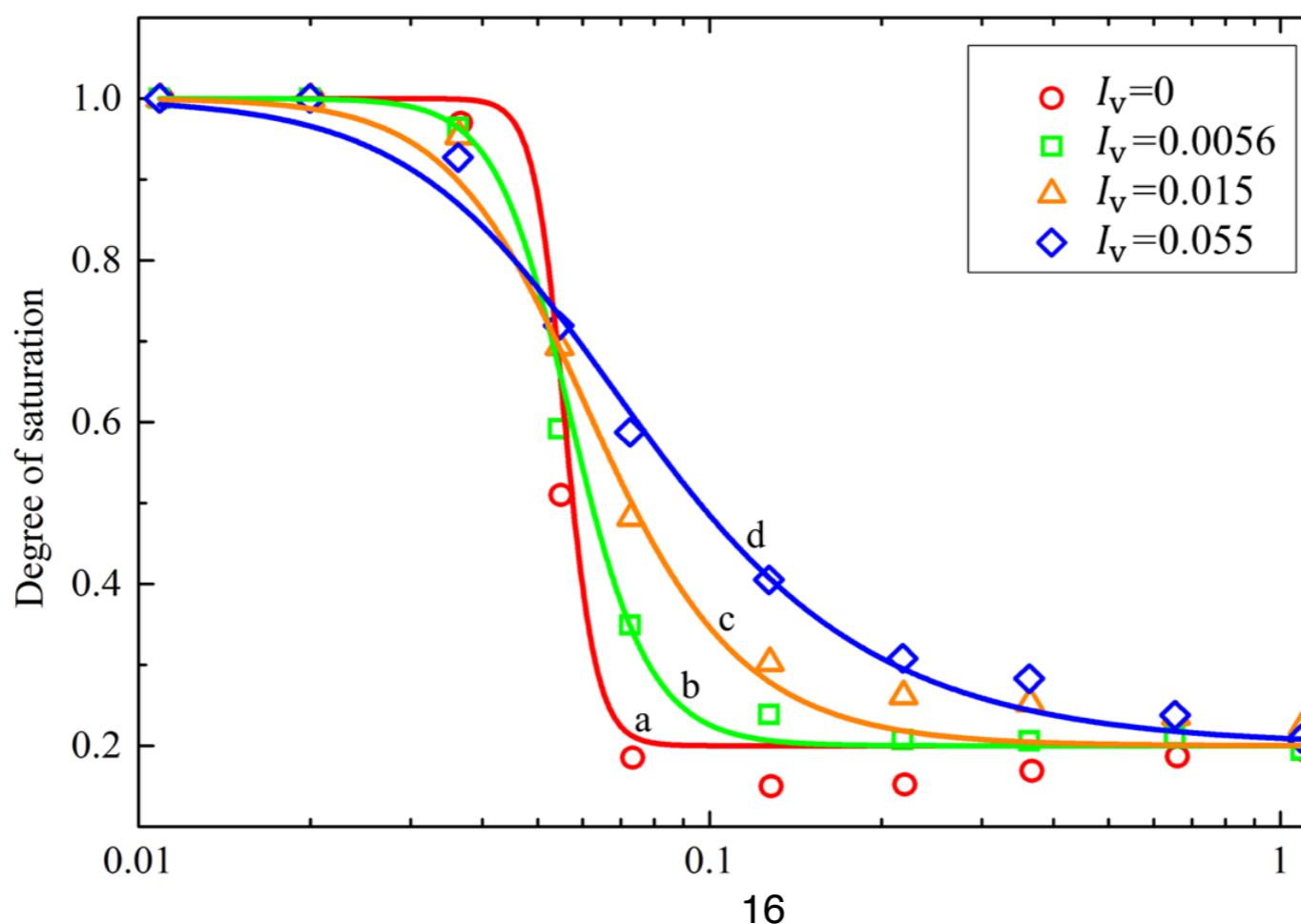
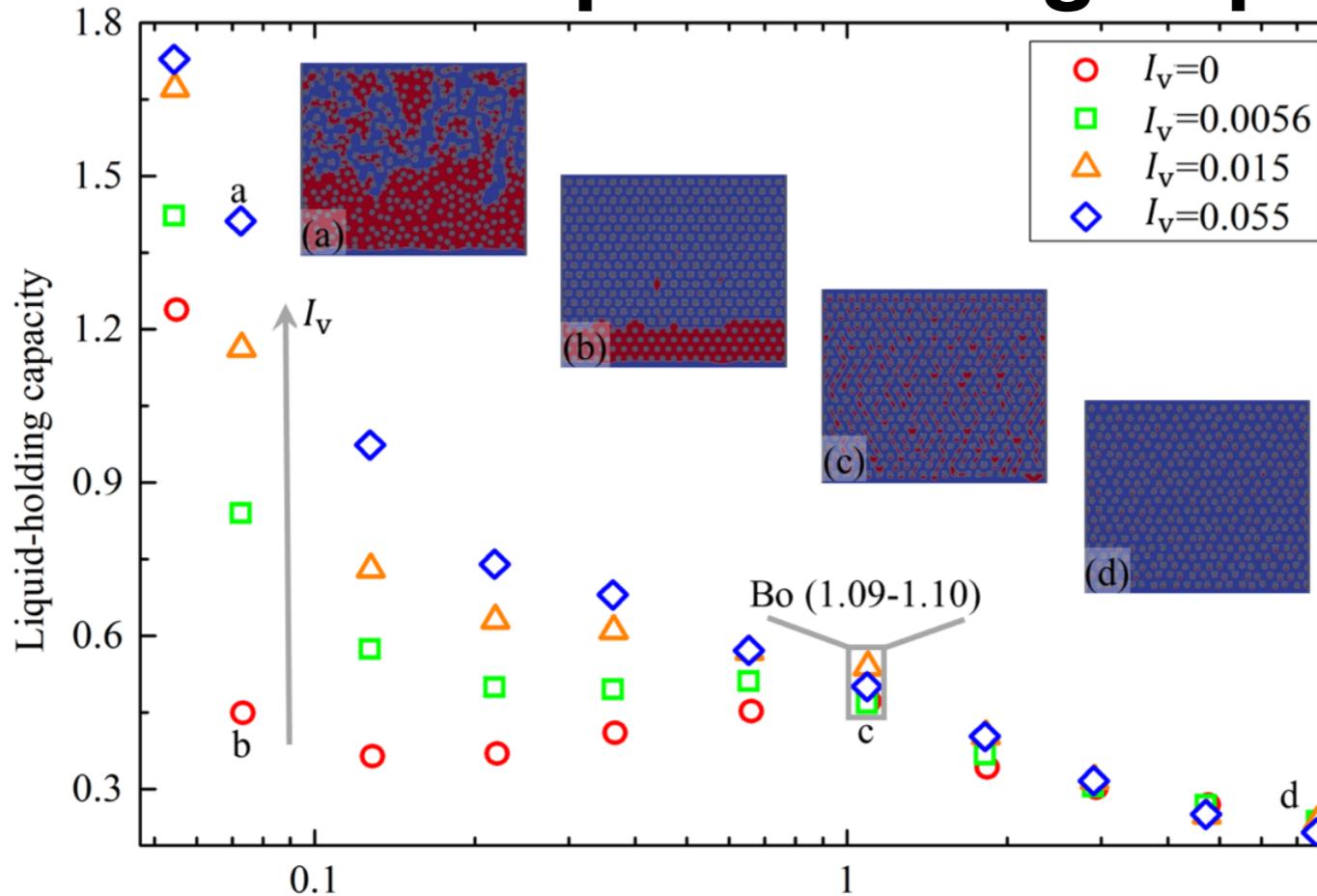
Drainage Simulations: Saturated clusters

$$f(x, \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$



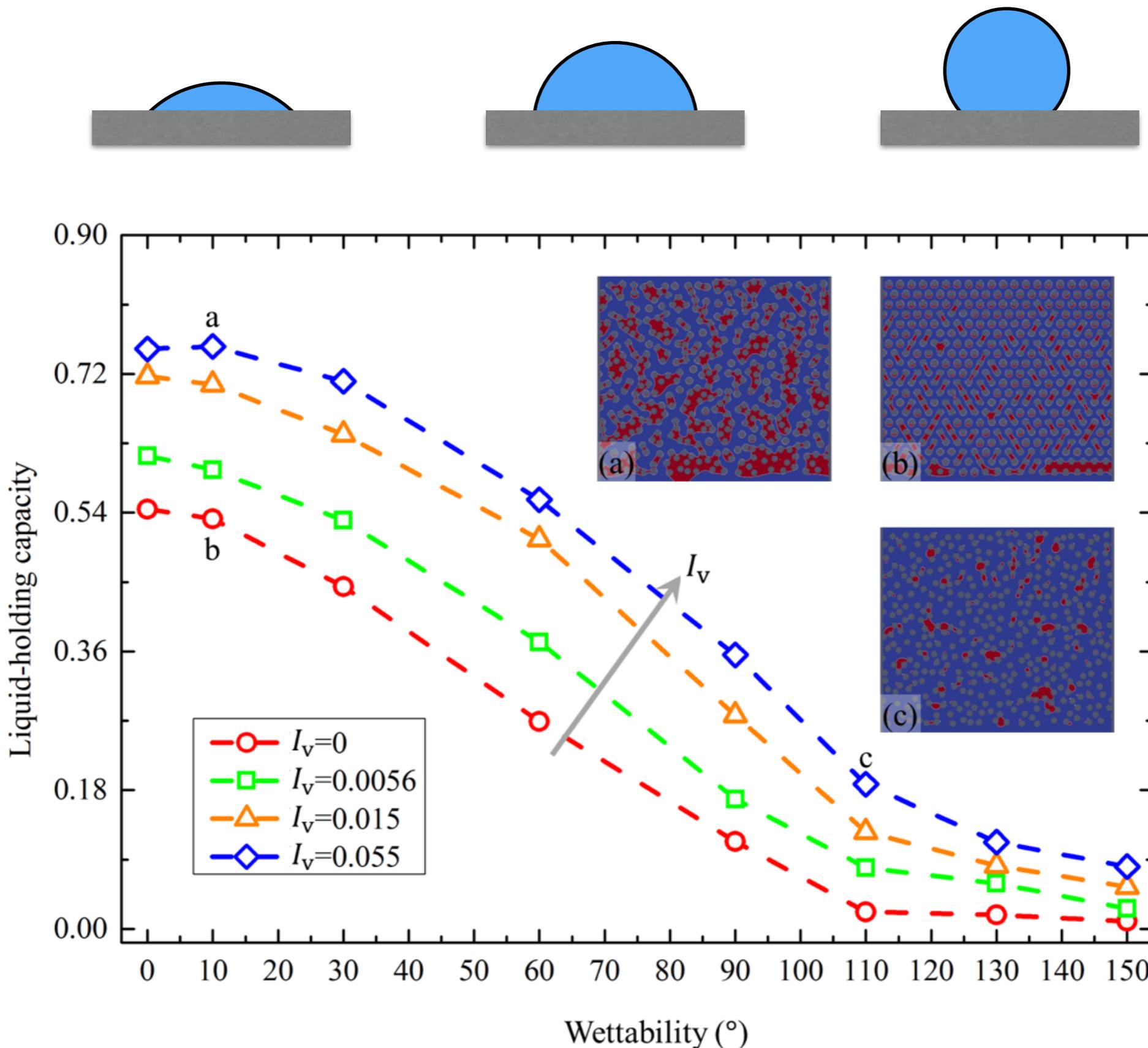
Probability density function (PDF) and lognormal distribution of saturated zones area:
(a) $Iv=0$; (b) $Iv=0.0056$; (c) $Iv=0.015$; (d) $Iv=0.055$.

Drainage Simulations: Liquid holding capacity

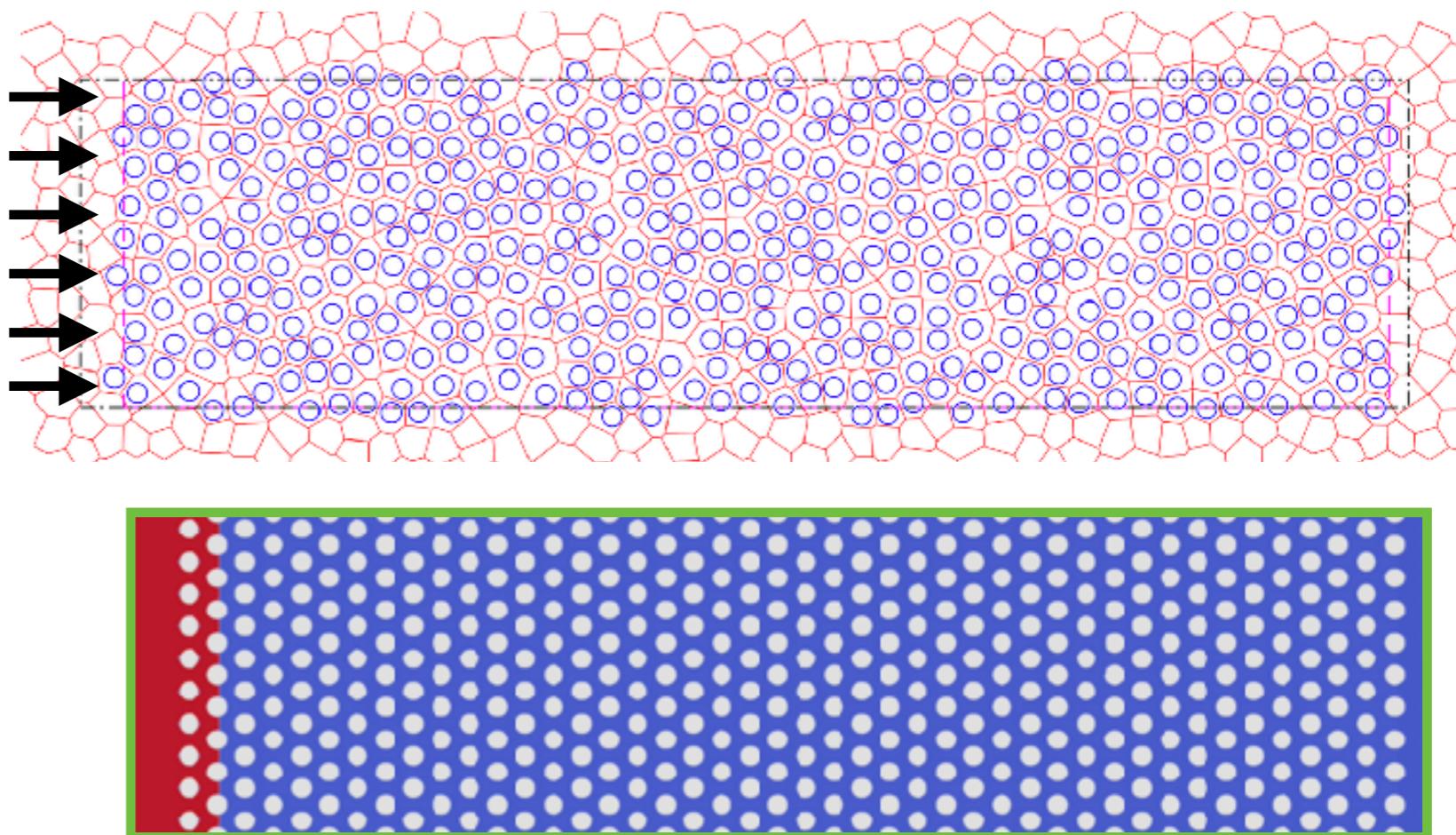
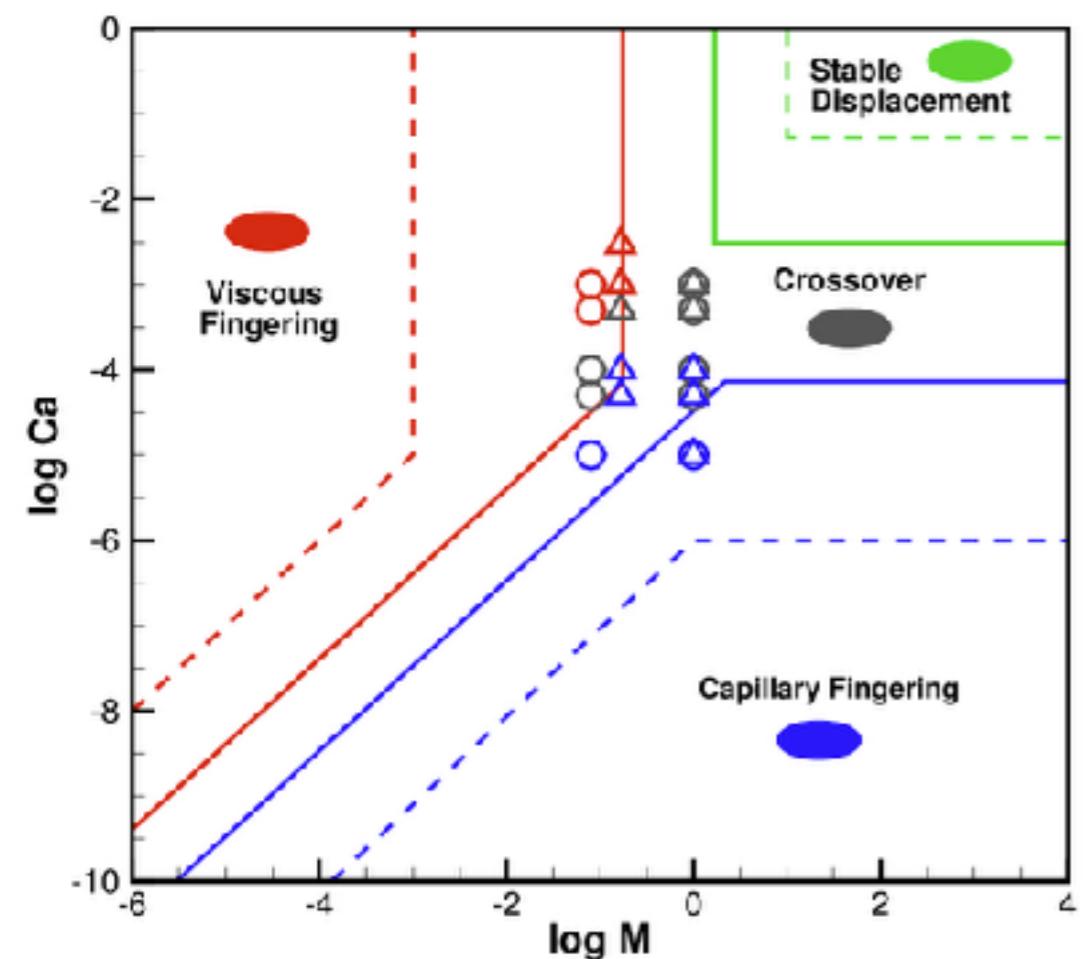


$$Bo = \frac{\Delta \rho g R^2}{\gamma} e$$

Drainage Simulations: Wettability



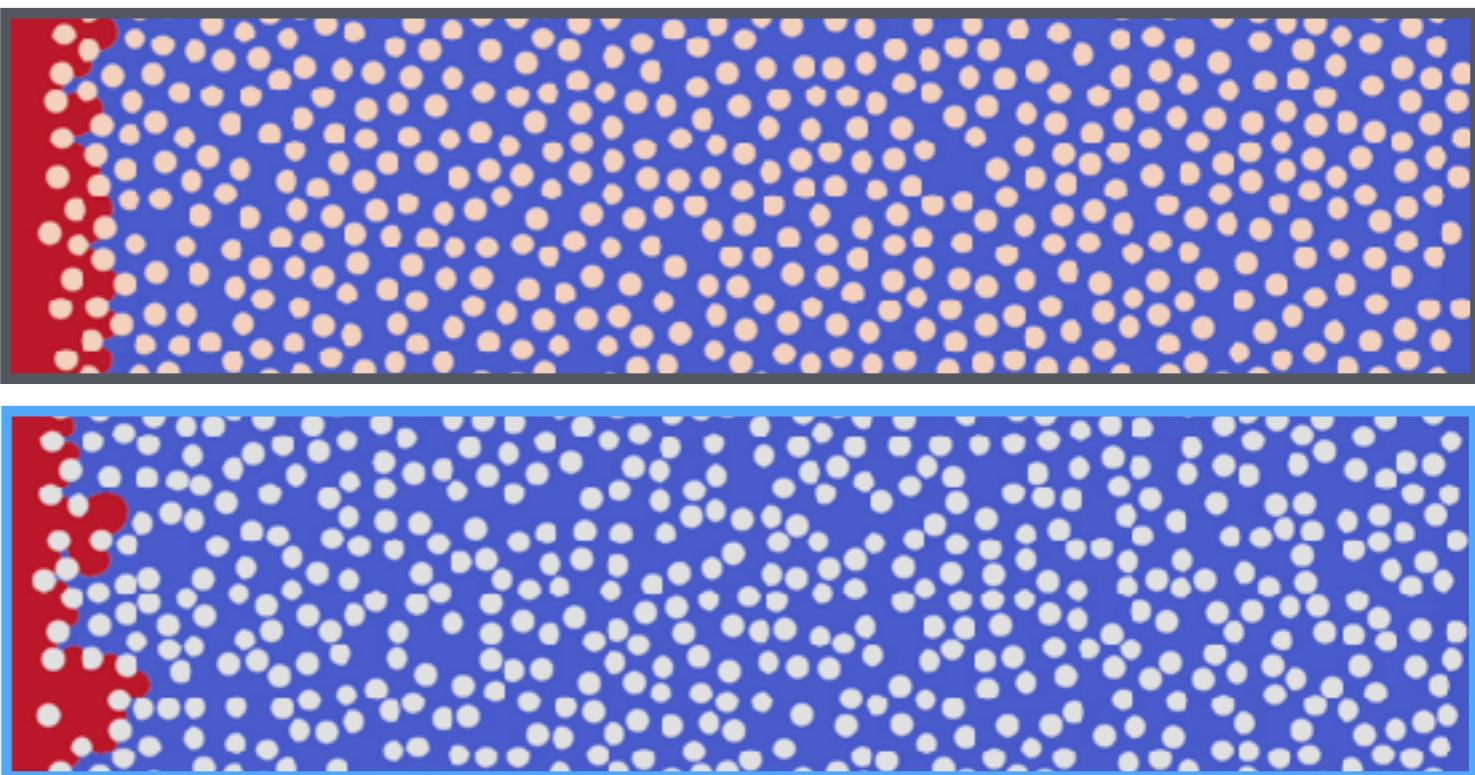
Liquid Displacement Simulations: Disorder



Displacement phase diagram as functions of viscosity ratio and Capillary number (Liu et al., 2015, Physics of Fluids).

$$Ca = \frac{V_{\text{inj}} \mu_{\text{def}}}{\gamma} = 0.0186$$

$$Bo = 0$$



Conclusions

- **Wettability and contact angle dynamics:** experiments and simulations using modified SPH, successfully capturing dynamic contact angles.
- **Disorder index:** a modified index IV based on Voronoi tessellation for better describing multiphase flow in porous media.
- **Drainage efficiency** and saturated cluster distributions are studied with different Bond number (gravity) and wettability, combined with disordered microstructure.
- **Fluid displacement** patterns, stable or fingering, can be controlled by the degree of disorder, and final saturation and interfacial length are well correlated with topological features.

