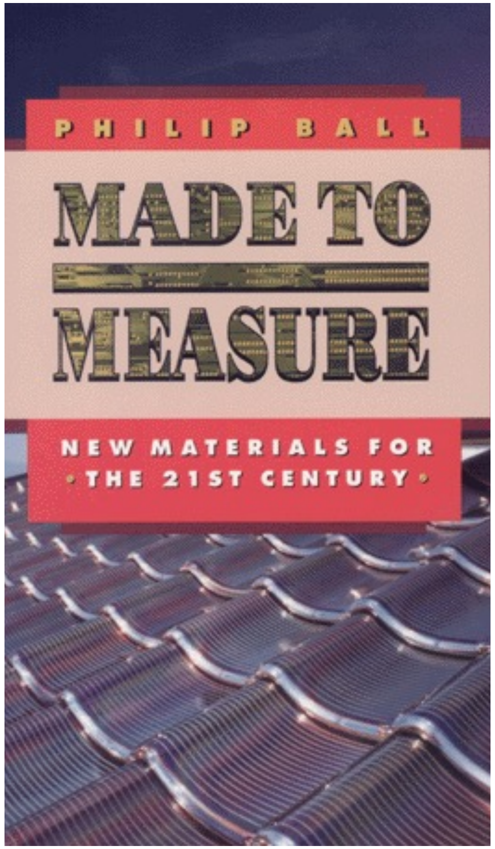
Non-equilibrium interfaces

Margarida Telo da Gama

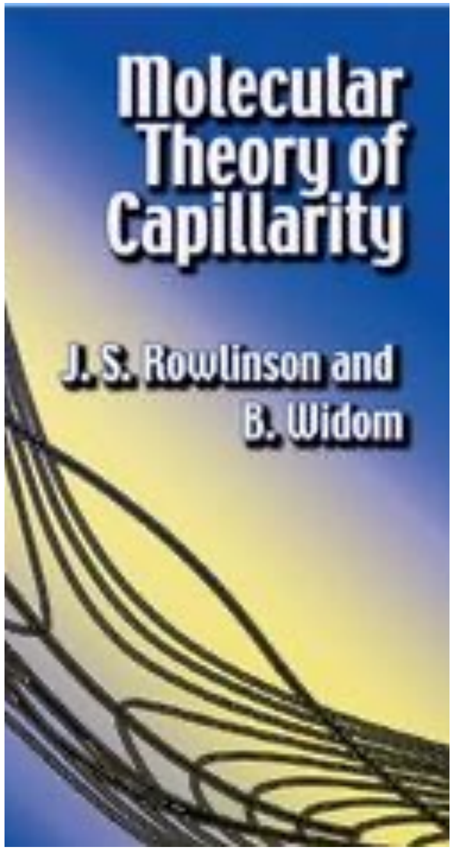
There seems to exist a certain degree of prejudice against surfaces, with things superficial beeing deemed of lesser pith and moment.

P Ball, 1997



This is most unjustified as ‘surfaces and interfaces are the seat of a variety of fascinating phenomena’.

J S Rowlinson and B Widom, 1982



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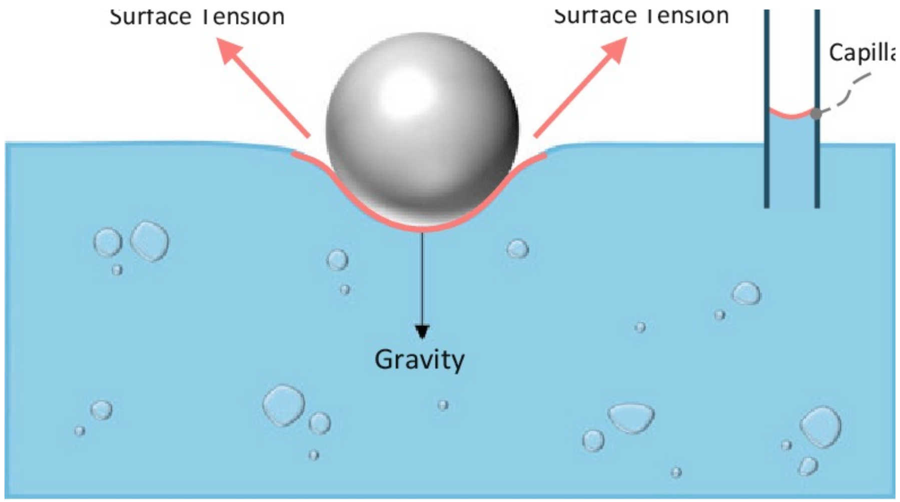
Equilibrium interfaces

Surface tension

- Excess free energy per unit area
- Tangential force per unit length

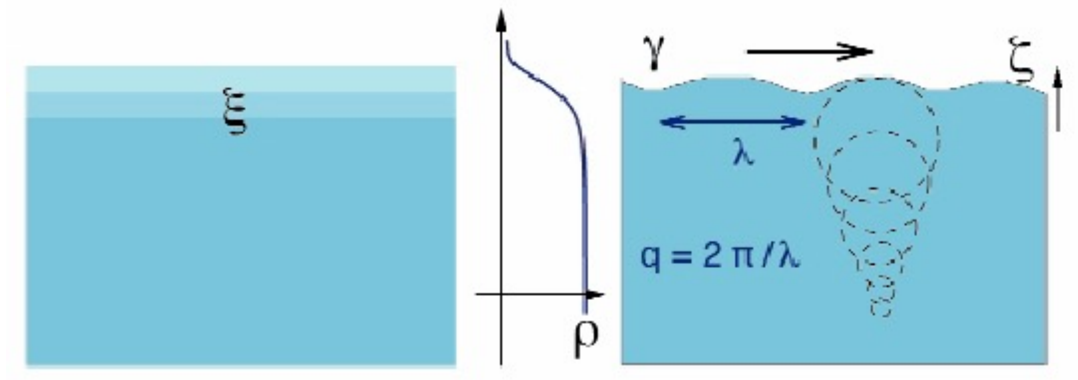


The balance between the cohesion of the liquid and its adhesion to the material of the container determines the degree of wetting, the contact angle and the shape of meniscus.

van der Waals and CW model

- The van der Waals description of a liquid-vapour interface (1893) predicts a smooth transition from the liquid density to the vapour density with a characteristic length related to the bulk correlation length.

- In the capillary wave model (1965), the interface structure is due to the propagation of thermally excited capillary waves with wave-vector q. Their amplitude is inversely proportional to the surface tension gamma.

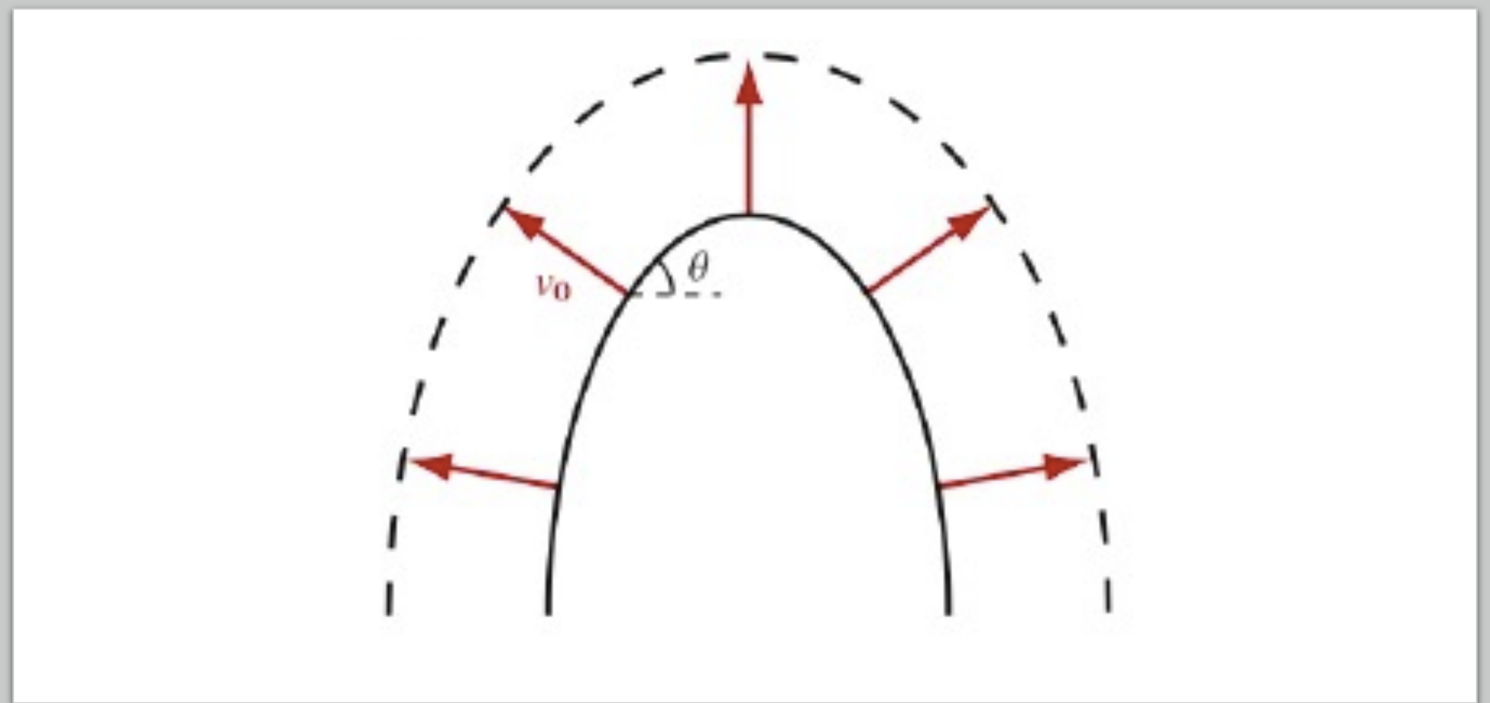


$$\zeta_q^2 = \frac{2kT}{L\gamma q^2}$$

F. P. Buff, R. A. Lovett, and F. H. Stillinger, Jr., Phys. Rev. Lett. **15**, 621 (1965)

Wet or non-wet ?
Rough or smooth ?
Wetting or roughening transitions ?

Non-equilibrium wetting

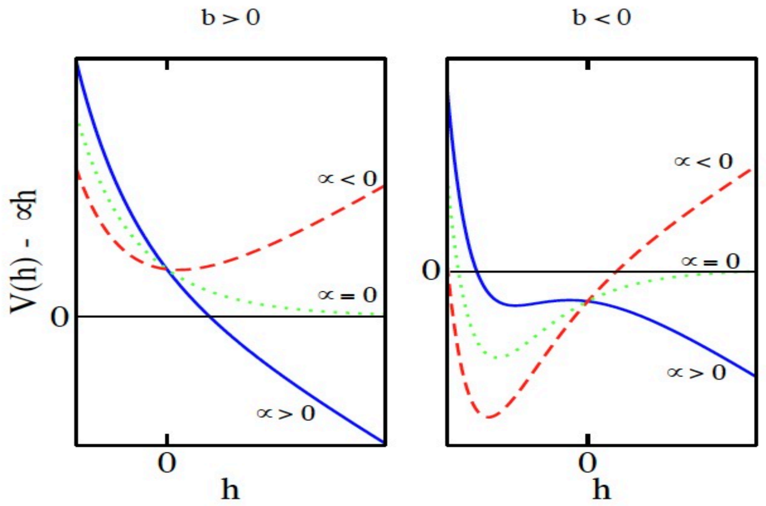


Generic interfacial growth (KPZ for $\lambda \neq 0$)

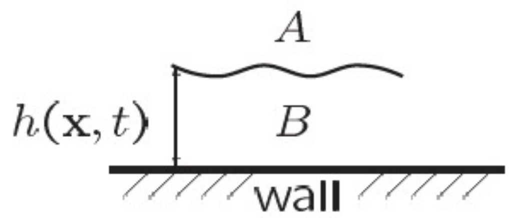
$$\frac{\partial h(x,t)}{\partial t} = \nu \frac{\partial^2 h(x,t)}{\partial x^2} + \lambda \left(\frac{\partial h(x,t)}{\partial x} \right)^2 + \eta(x,t),$$

Bound AB interface

Phases A and B coexist when $\mu = 0$

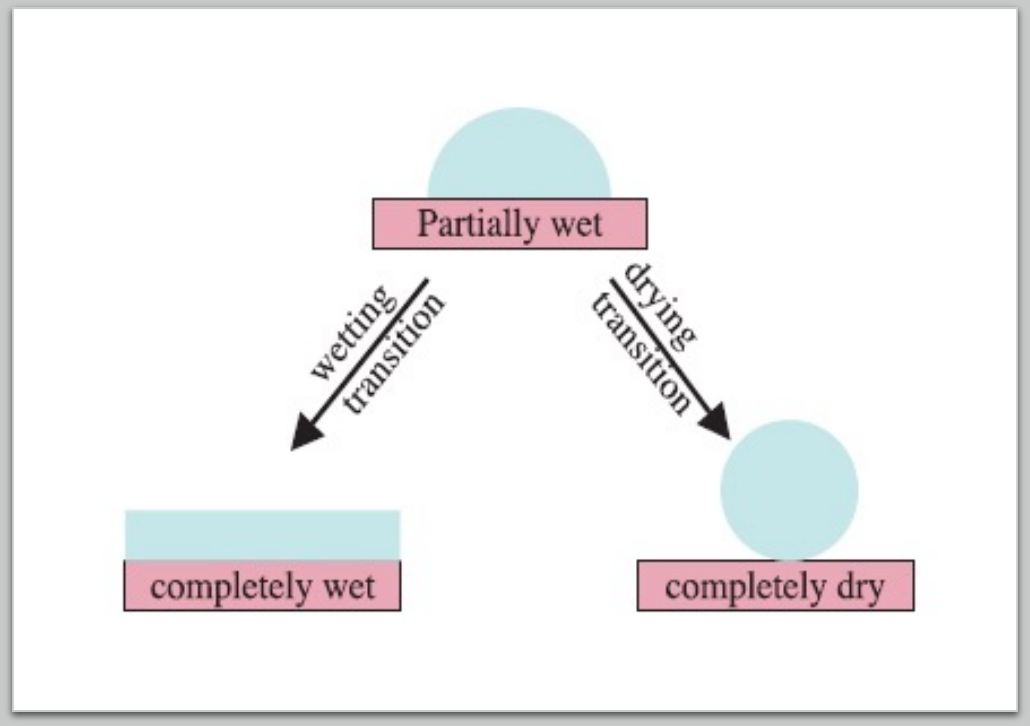


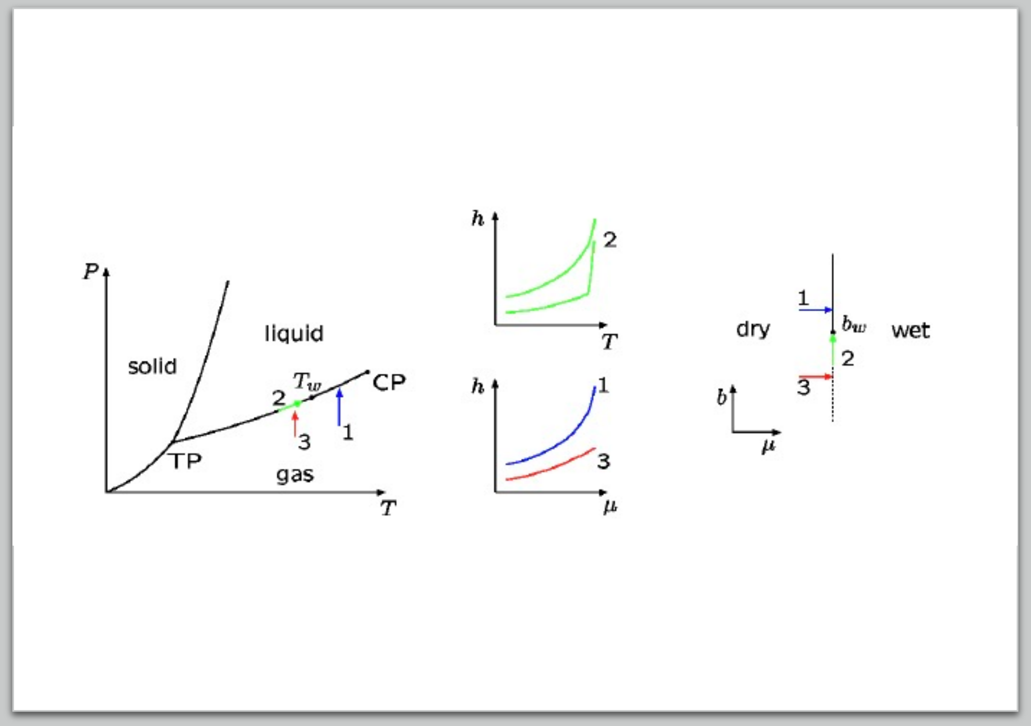
$$V(h) = b(T)e^{-h} + ce^{-2h},$$



$$\frac{\partial h(\mathbf{x},t)}{\partial t} = \nu \nabla^2 h + \mu - \frac{\partial V}{\partial h} + \eta(\mathbf{x},t),$$

Equilibrium wetting transition



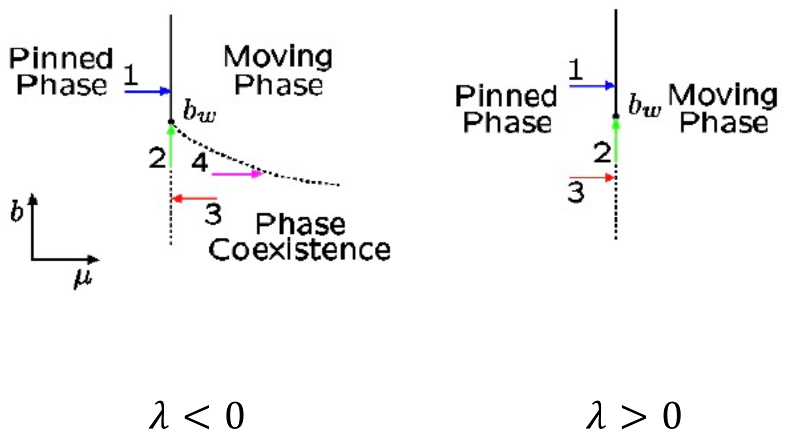


Non-equilibrium wetting & depinning

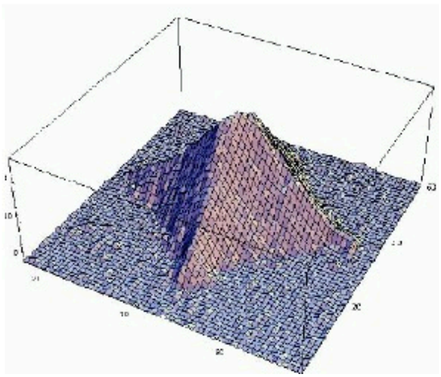
$$\frac{\partial h(\mathbf{x},t)}{\partial t} = \nu \nabla^2 h + \lambda (\nabla h)^2 + \mu - \frac{\partial V(h)}{\partial h} + \eta(\mathbf{x},t).$$

Wetting and drying are NOT symmetric: there is an extended coexistence for depinning & not for pinning

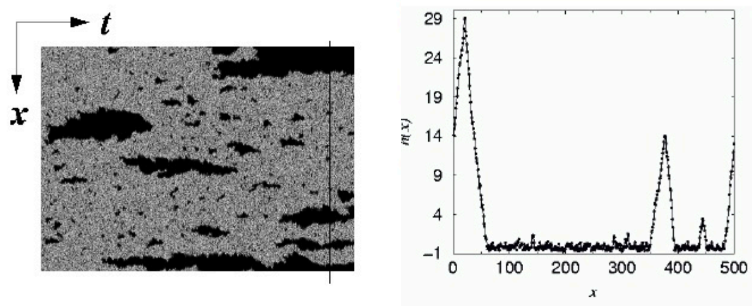
Different exponents



Extended coexistence of pinned and depinned phases in 2d & 1d



$\lambda < 0$



$\lambda < 0$

Thanks

Francisco de los Santos

Miguel Angel Muñoz

Stochastic Theory of Non-Equilibrium Wetting, F. de los Santos, M. M. Telo da Gama and M. A. Muñoz, Europhysics Letters, **57**, 803-809 (2002).

Non equilibrium Wetting Transitions with Short Range Forces, F. de los Santos, M. M. Telo da Gama and M. A. Muñoz, Physical Review E, **67**, 021607 (2003).

Nonequilibrium Bound Interfaces, F. de los Santos e M. M. Telo da Gama in Trends in Statistical Physics, (World Scientific, 2004).

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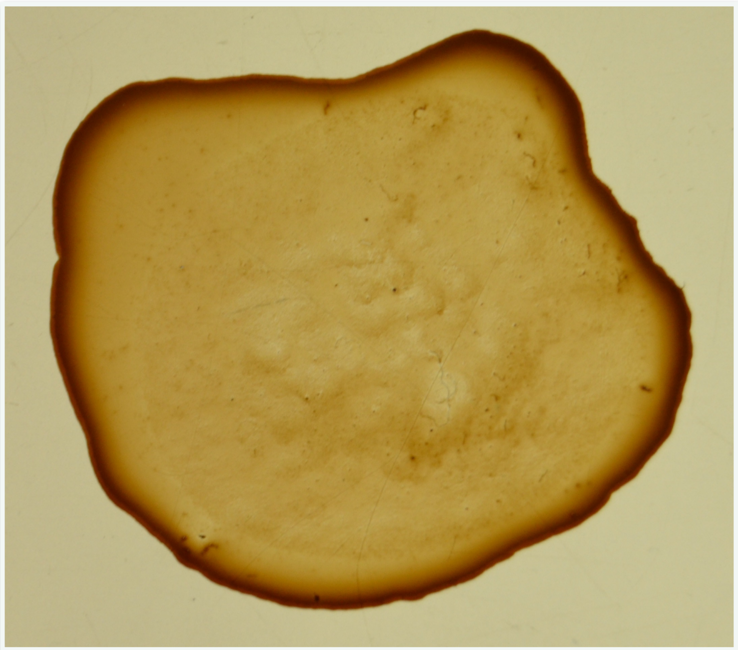
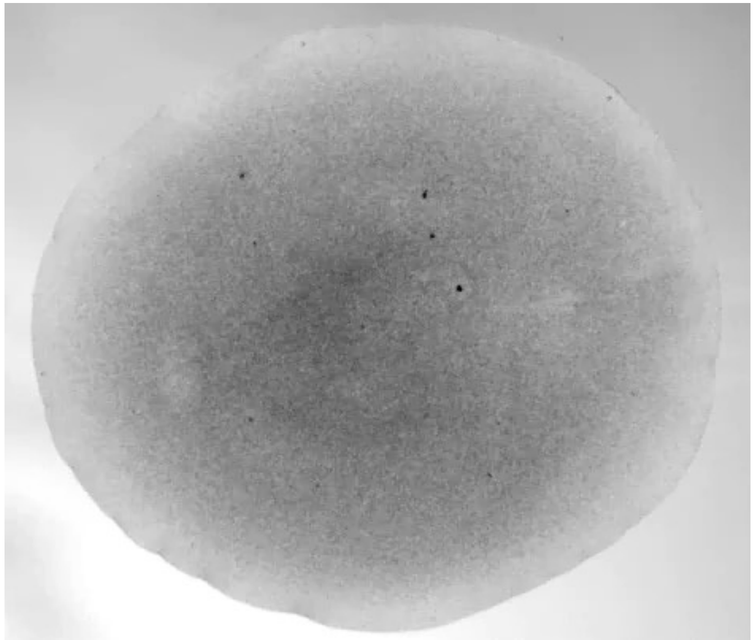
Interfacial roughening of anisotropic colloids

Evaporating drop

Coffee-ring left by spherical colloidal particles

Inhomogeneous density



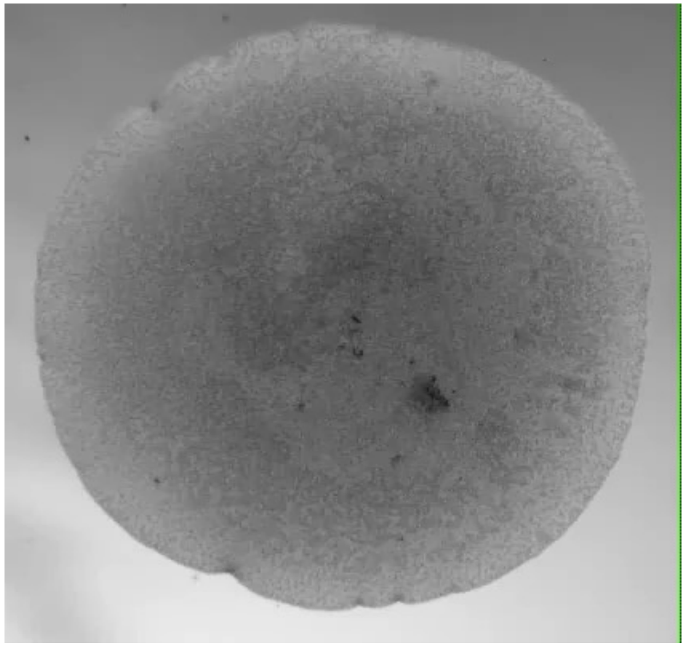


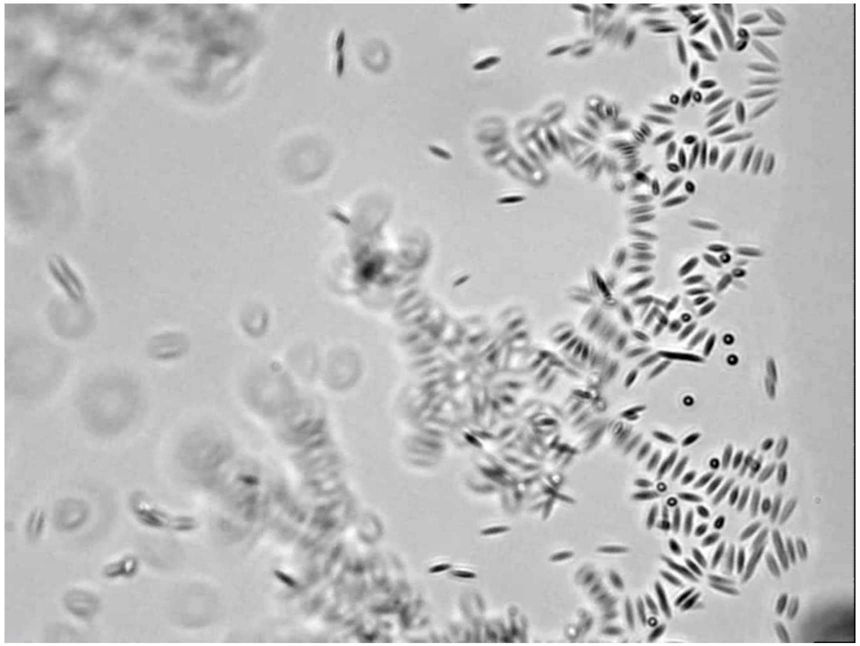
P.J. Yunker, T. Still, M.A. Lohr, A.G. Yodh, *Nature* **476**, 308 (2011)

Evaporating drop

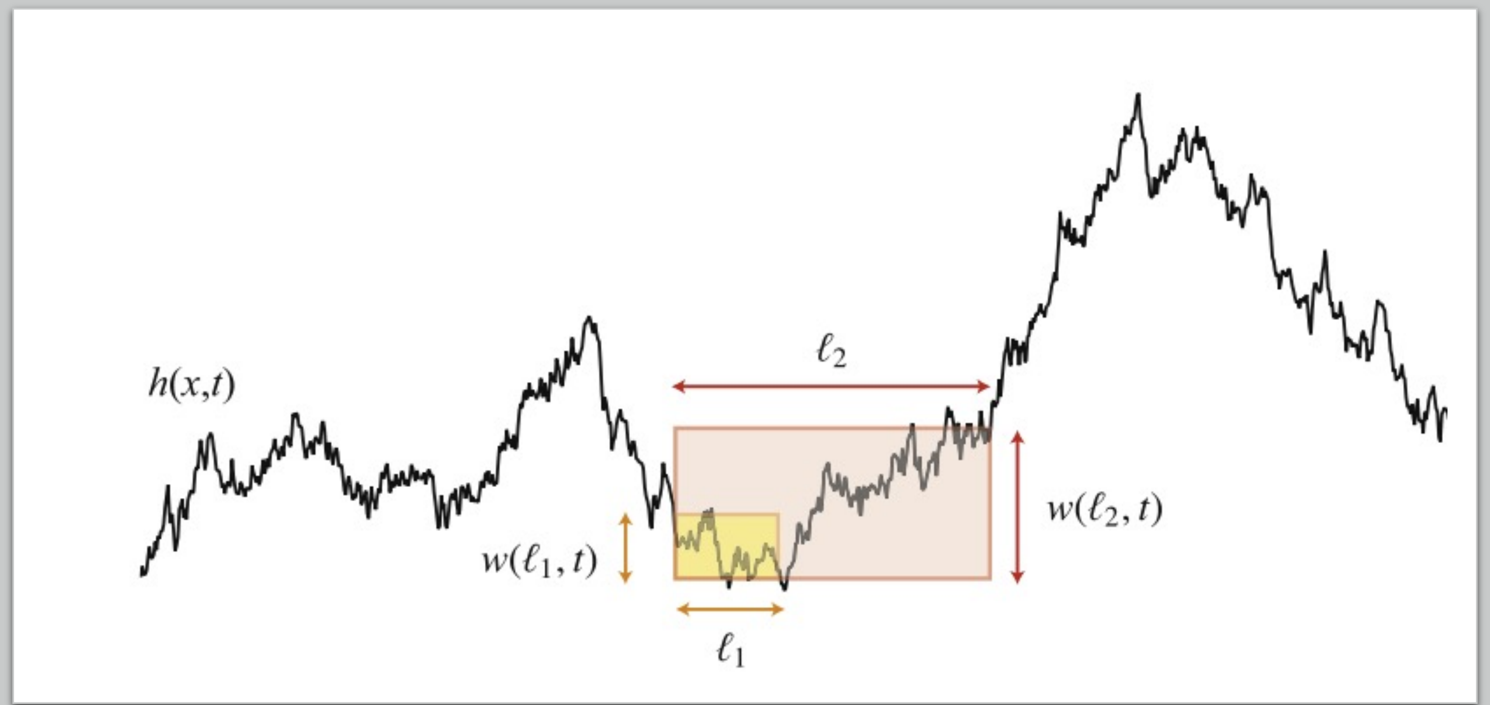
No coffee-ring left by anisotropic colloidal particles

Homogeneous density





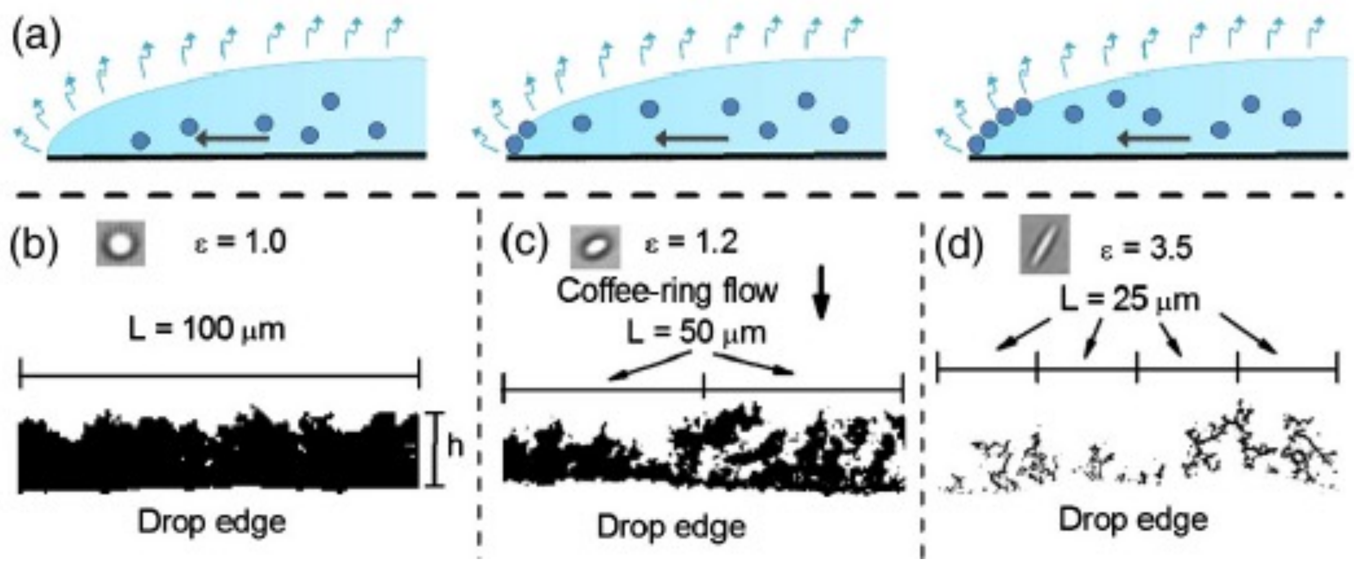
P.J. Yunker, T. Still, M.A. Lohr, A.G. Yodh, *Nature* **476**, 308 (2011)



Interfacial width

$$w(t) = \sqrt{\langle [h_i(t) - \langle h(t) \rangle]^2 \rangle}, \qquad w(L,t) = L^\alpha f\left(\frac{t}{L^z}\right),$$

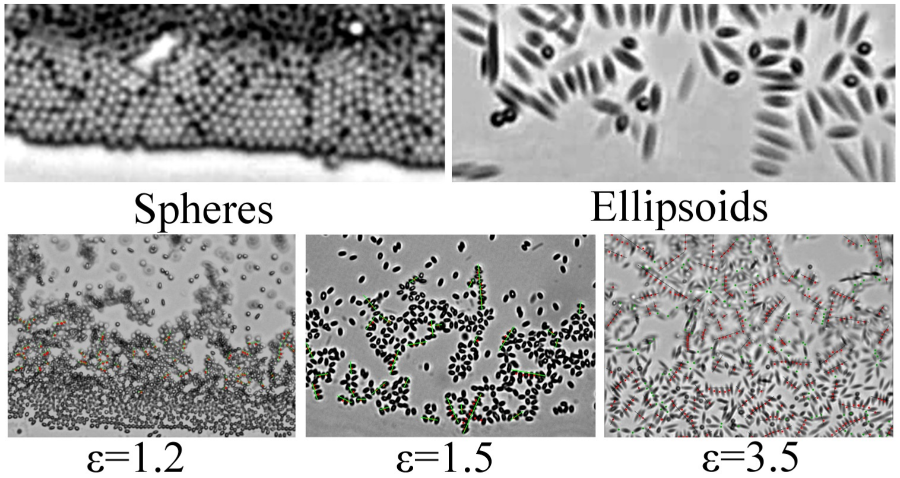
Different interfacial roughness regimes

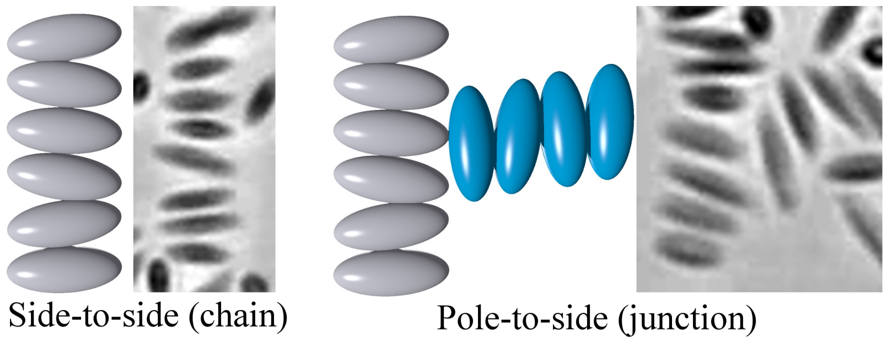


Transition from KPZ to KPZQ for anisotropic colloids

P. J. Yunker et al. *Phys. Rev. Lett.* **110**, 035501 (2013).
P. J. Yunker et al. *Phys. Today* **66**, 60 (2013).

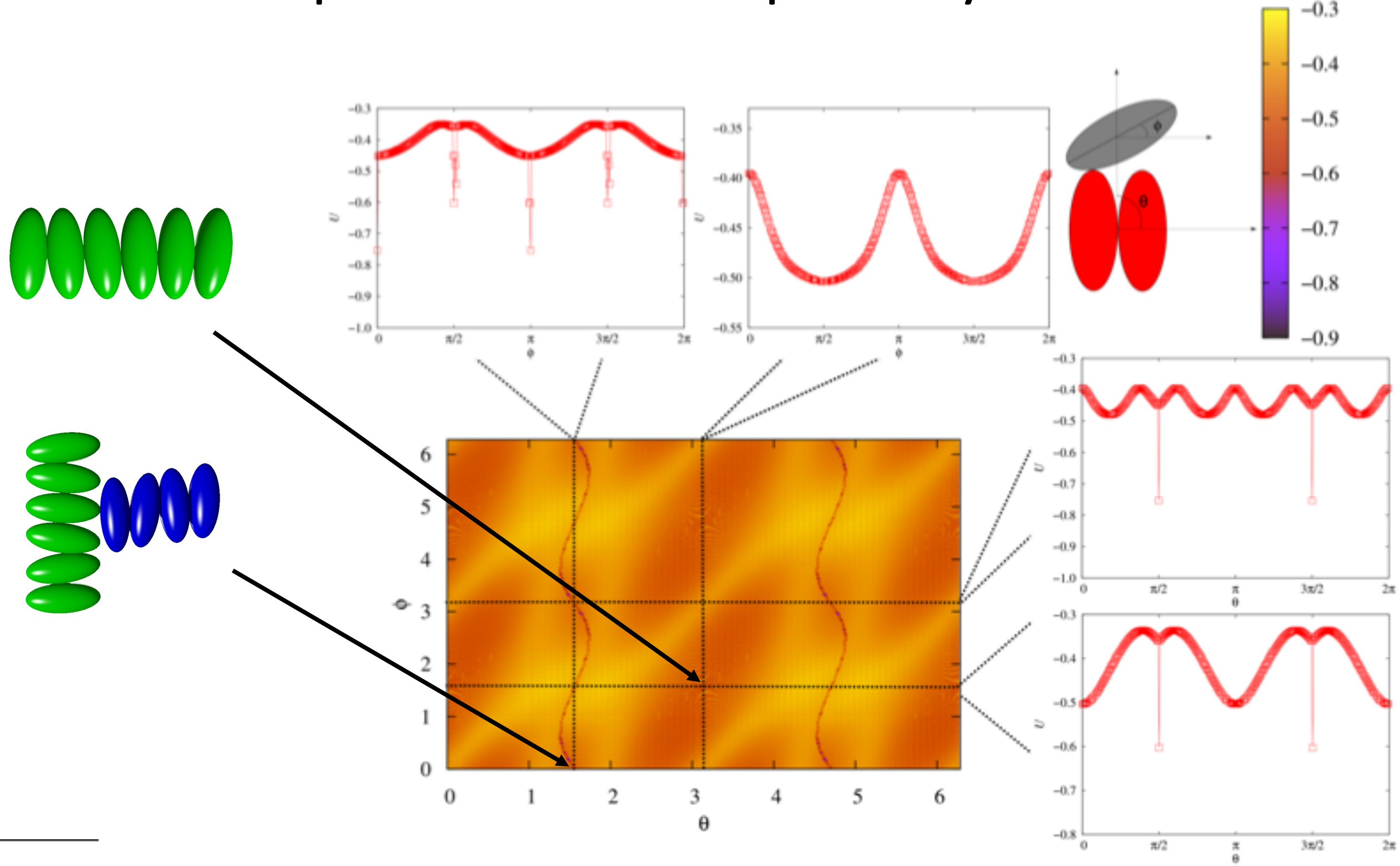
Chains & junctions driven by capillarity





C.S. Dias, P.J. Yunker, A.G. Yodh, N.A.M. Araújo, M.M. Telo da Gama, *Soft Matter* **14**, 1903 (2018)

Energy landscape of the capillary interactions

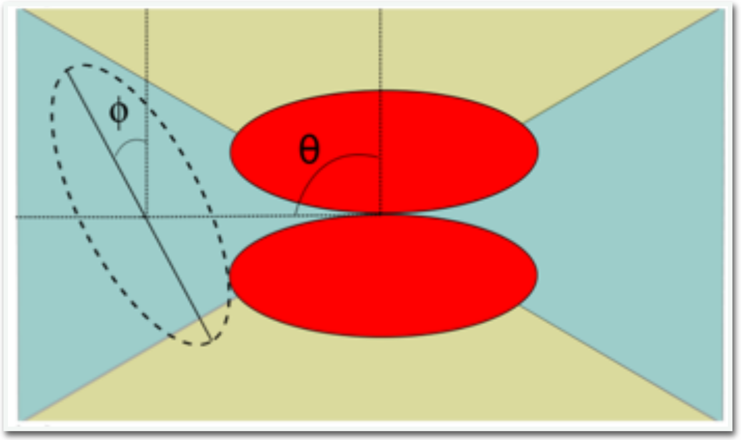


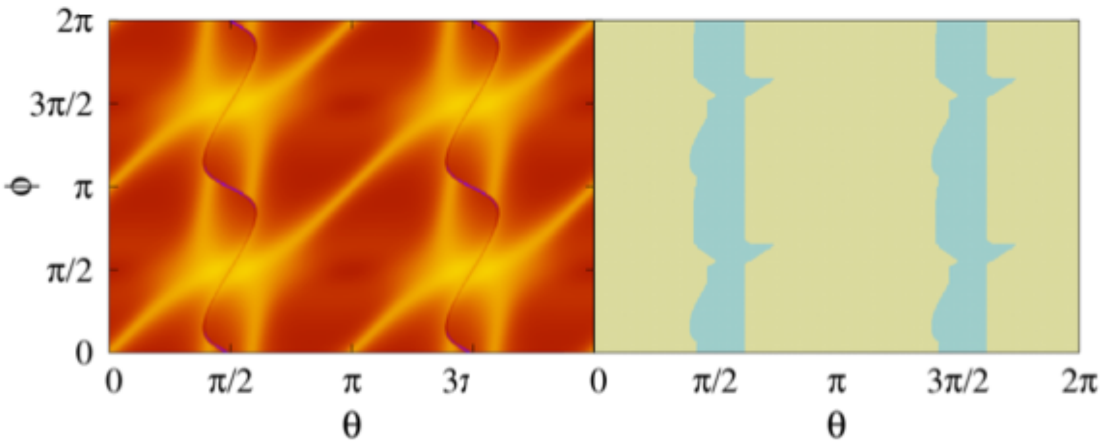
Derjaguin

$$U \approx -\frac{\pi^2}{24}\sqrt{\frac{2}{h_0\left(C_1 + C_2\right)}}$$

H. Lehle, E. Noruzifar, M. Oettel, *Euro. Phys. J. E* **26**, 151 (2008)

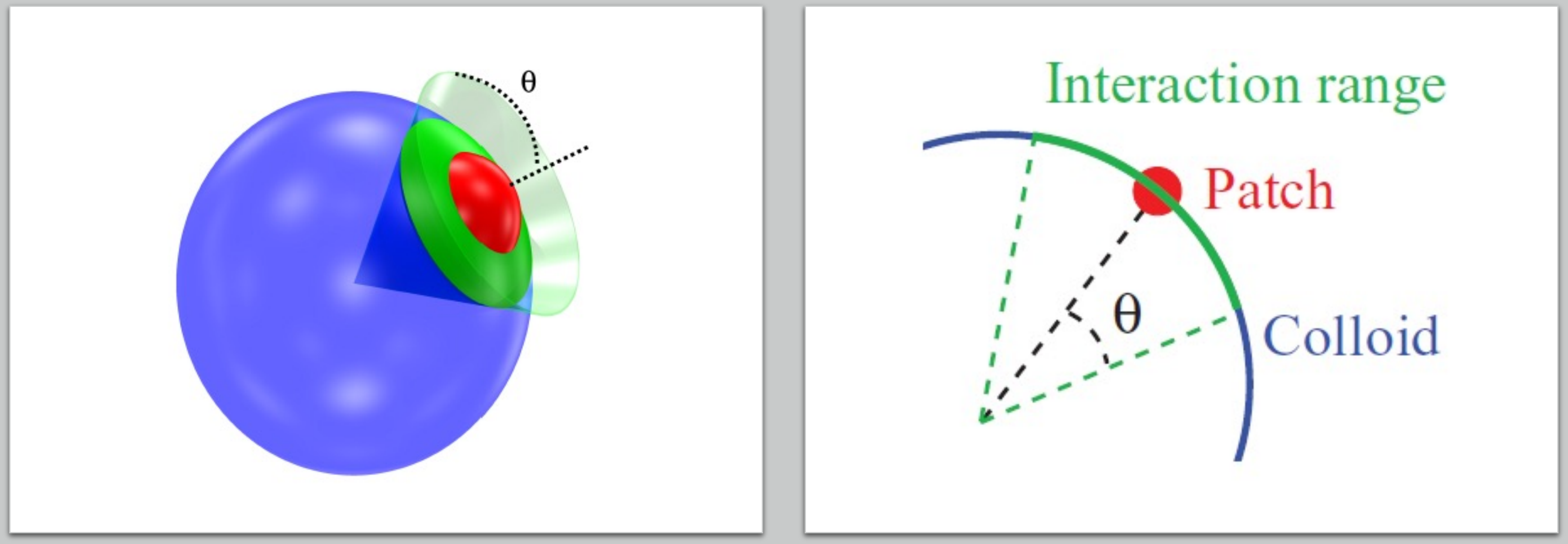
From the basins of attraction to bonding probabilities P_{AB}





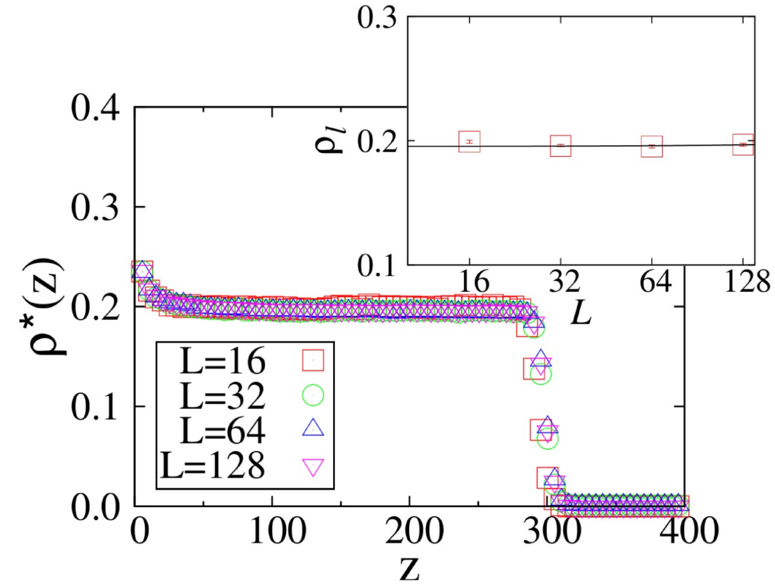
C.S. Dias, P.J. Yunker, A.G. Yodh, N.A.M. Araújo, M.M. Telo da Gama, *Soft Matter* **14**, 1903 (2018)
K.J. Schrenk, N.A.M. Araújo, J.S. Andrade Jr., H.J. Herrmann, *Scientific Reports* **2**, 348 (2012)

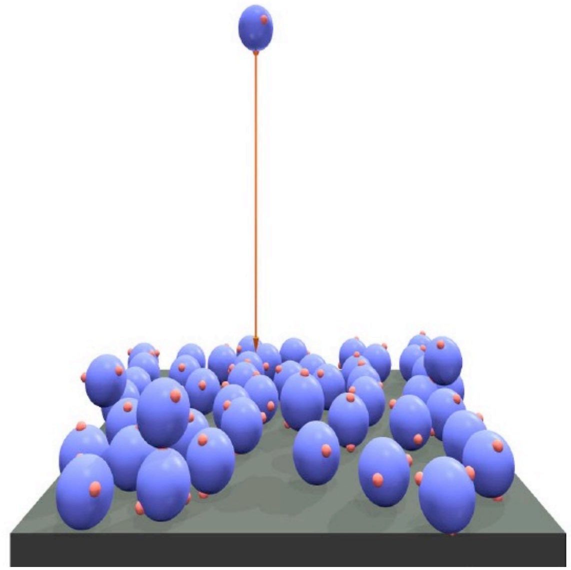
Stochastic kinetic model for patchy particles: Binding probability P_{AB}



C. S. Dias, N. A. M. Araújo, and M. M. Telo da Gama. *Phys. Rev. E* **87**, 032308 (2013).

Mass transport: advection

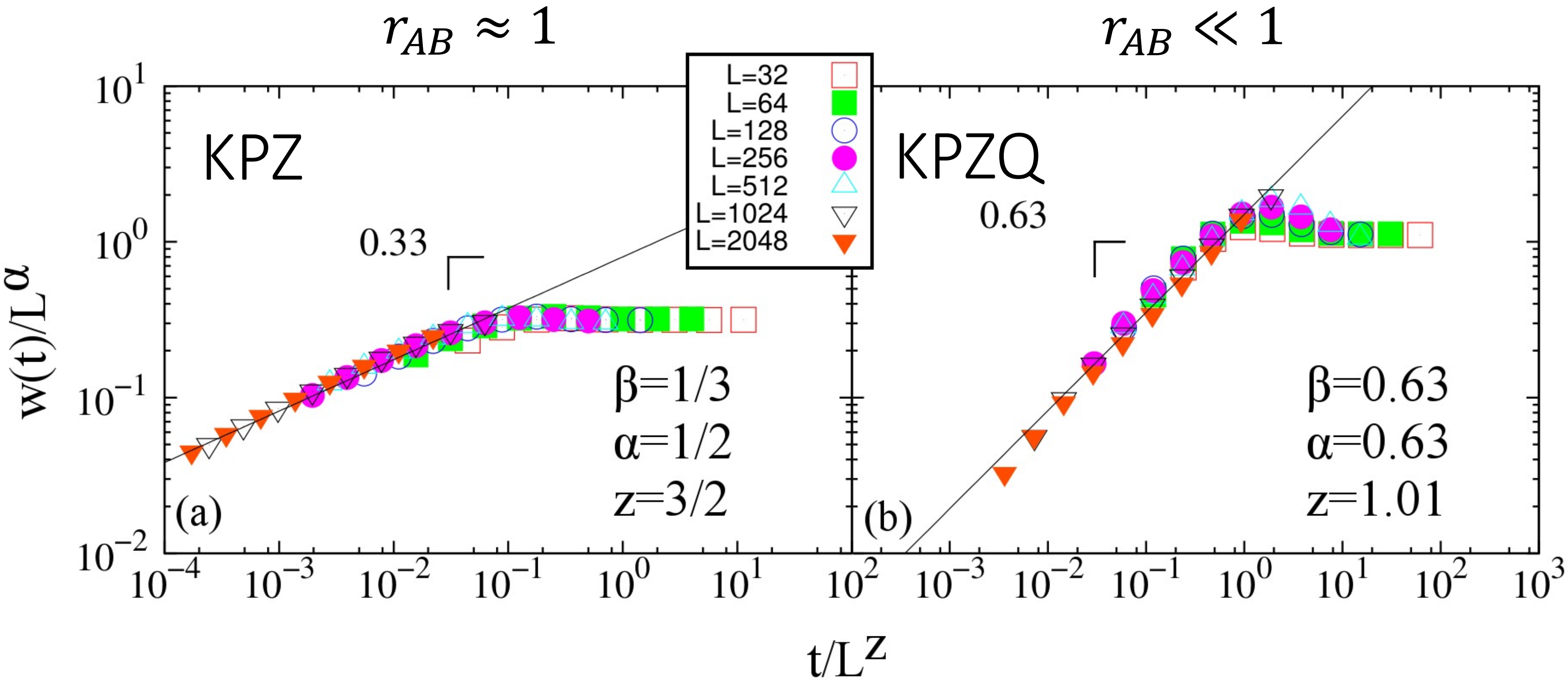




C. S. Dias, N. A. M. Araújo, and M. M. Telo da Gama. *J. Chem. Phys.* **139**, 154903 (2013).

Anisotropic bonding

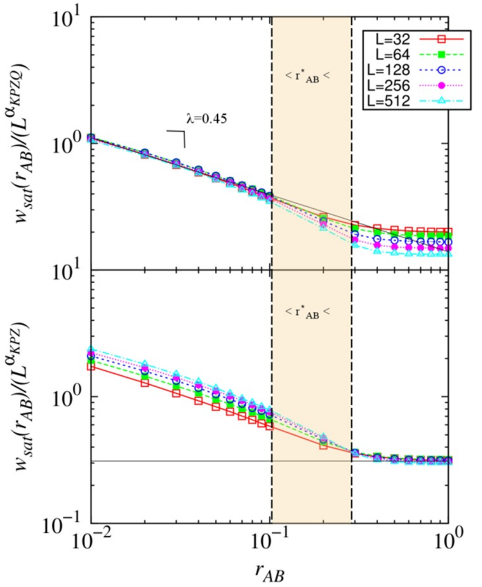
$$r_{AB} = \frac{P_{AB}}{P_{AA}}$$



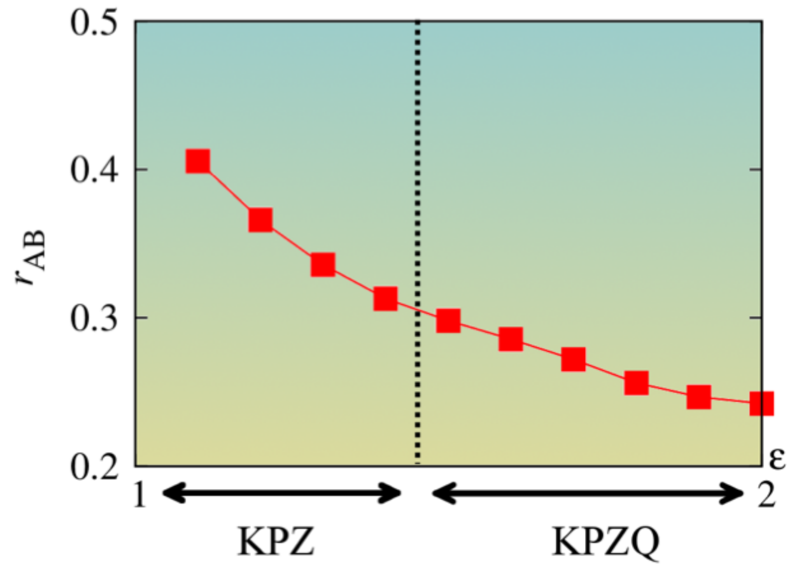
C. S. Dias, N. A. M. Araújo, and M. M. Telo da Gama. EPL **107**, 56002 (2014).

Interfacial width

$$r_{AB} = \frac{P_{AB}}{P_{AA}}$$

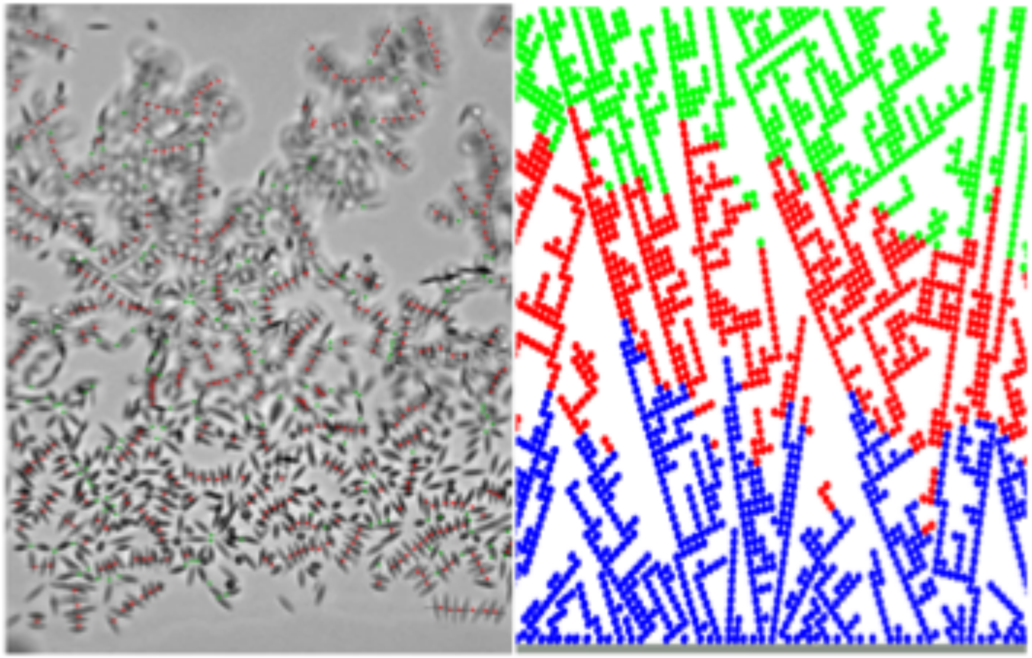


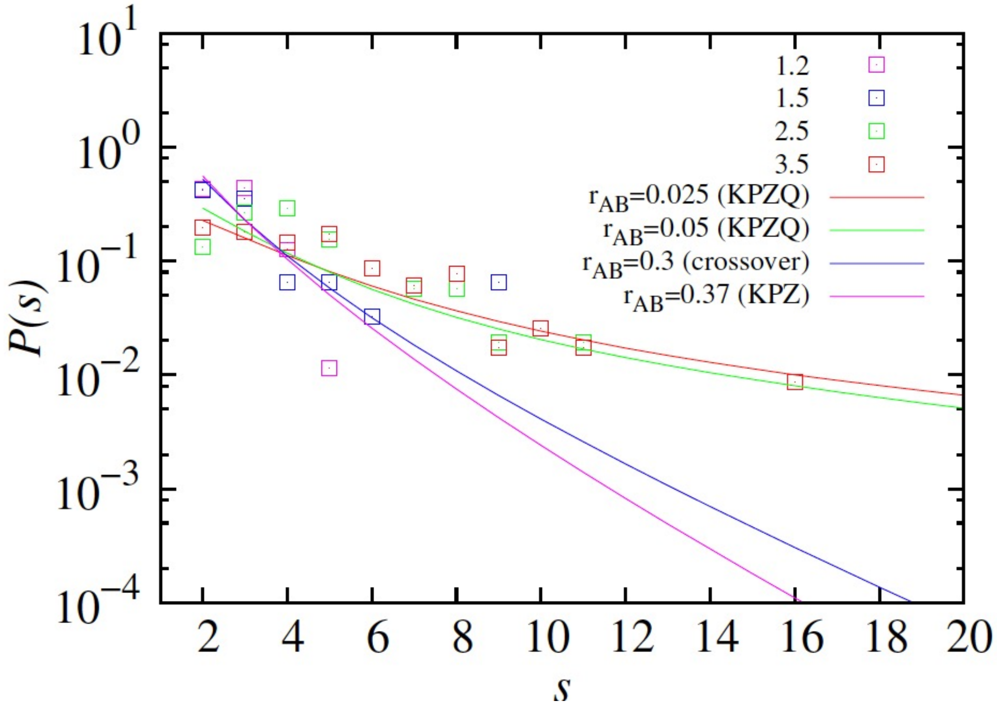
C. S. Dias, N. A. M. Araújo, and M. M. Telo da Gama. EPL **107**, 56002 (2014).



C.S. Dias, P.J. Yunker, A.G. Yodh, N.A.M. Araújo, M.M. Telo da Gama, *Soft Matter* **14**, 1903 (2018)

Cluster size distributions



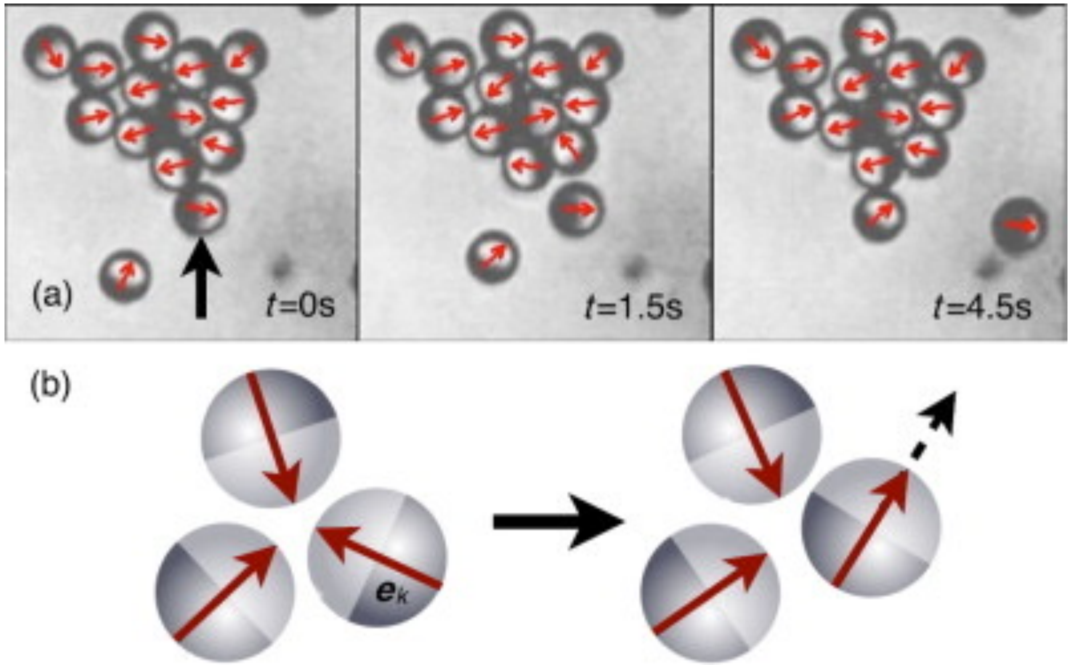


C.S. Dias, P.J. Yunker, A.G. Yodh, N.A.M. Araújo, M.M. Telo da Gama, *Soft Matter* **14**, 1903 (2018)

Active versus driven particles

New phases

Motility Induced Phase Separation



Ivo Buttinoni, Julian Bialké, Felix Kümmel, Hartmut Löwen, Clemens Bechinger, and Thomas Speck, Phys. Rev. Lett., 110, 238301 (2013)

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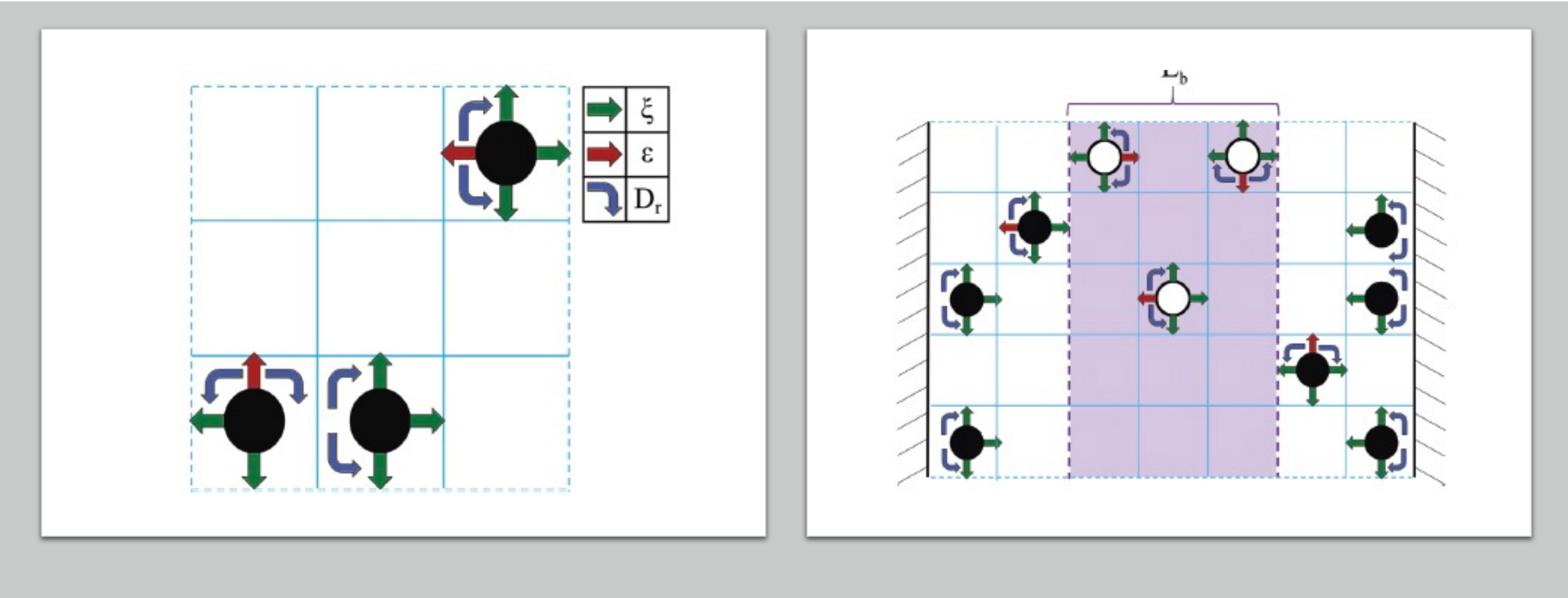
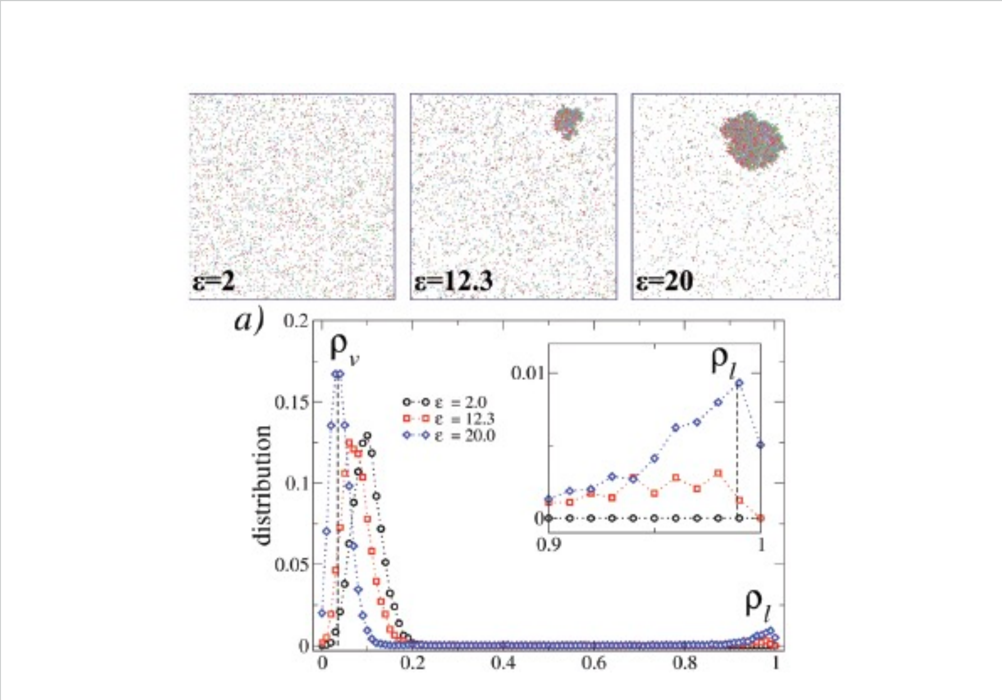
Wetting and interfacial roughness of Active Brownian Particles (ABP)

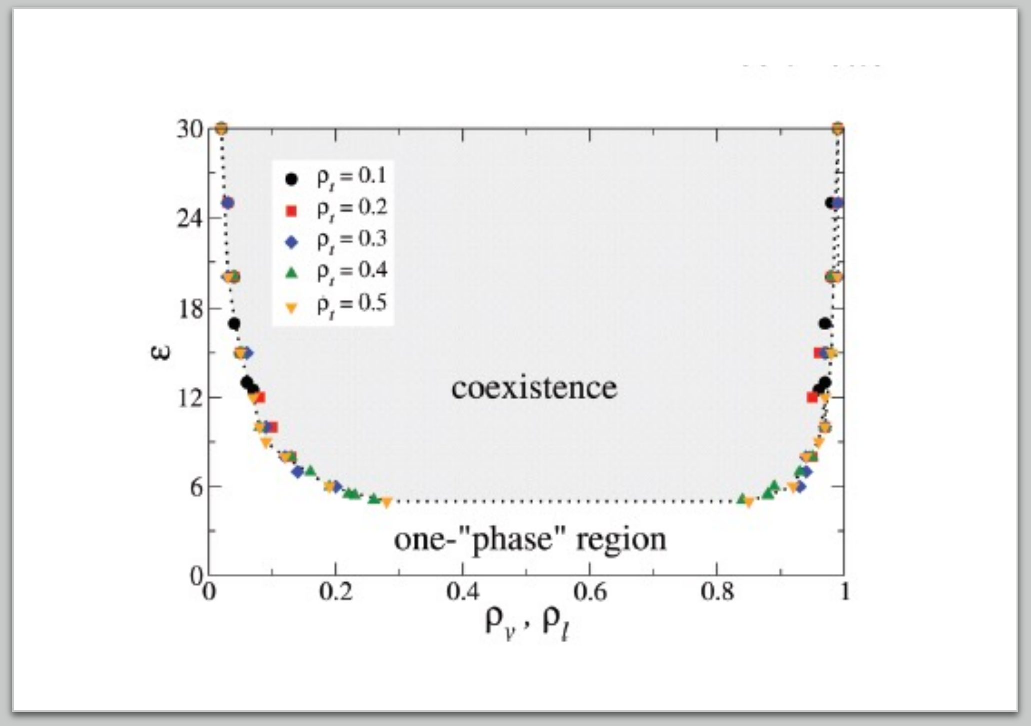
Lattice model of ABP: closed and open systems

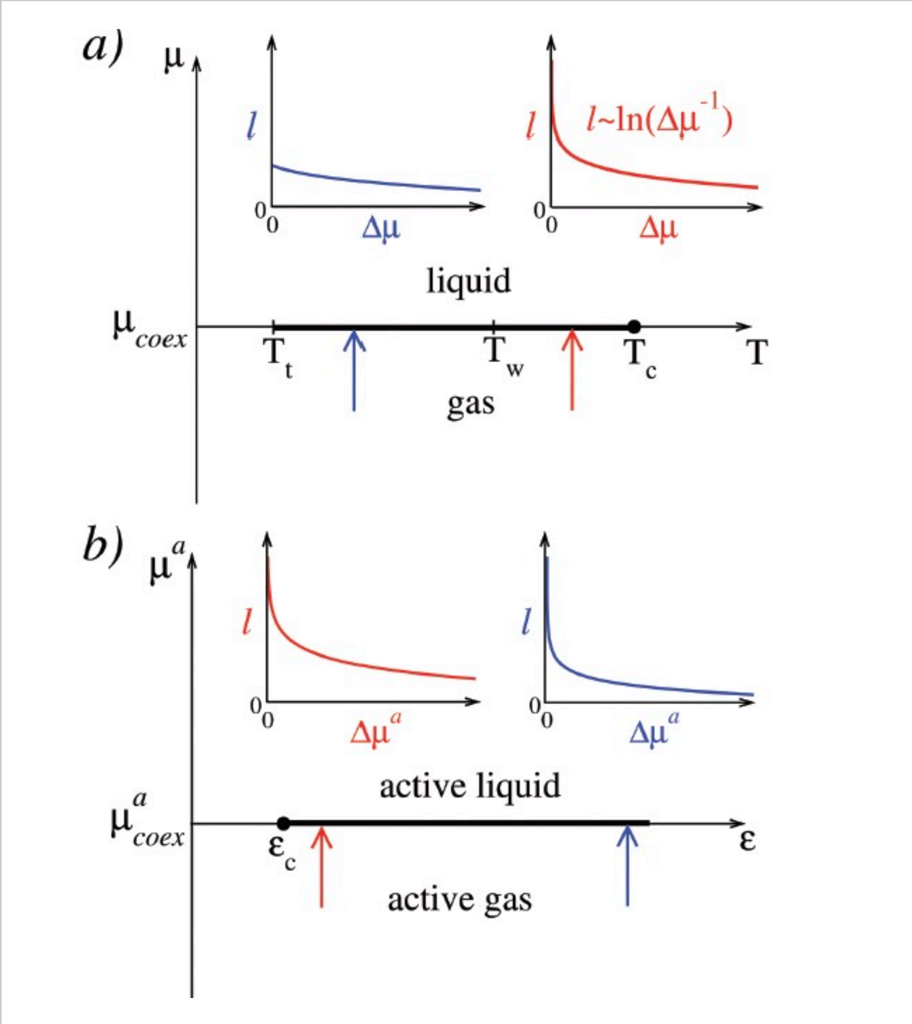


Motility Induced Phase Separation (MIPS):

Activity vs Density Phase Diagram





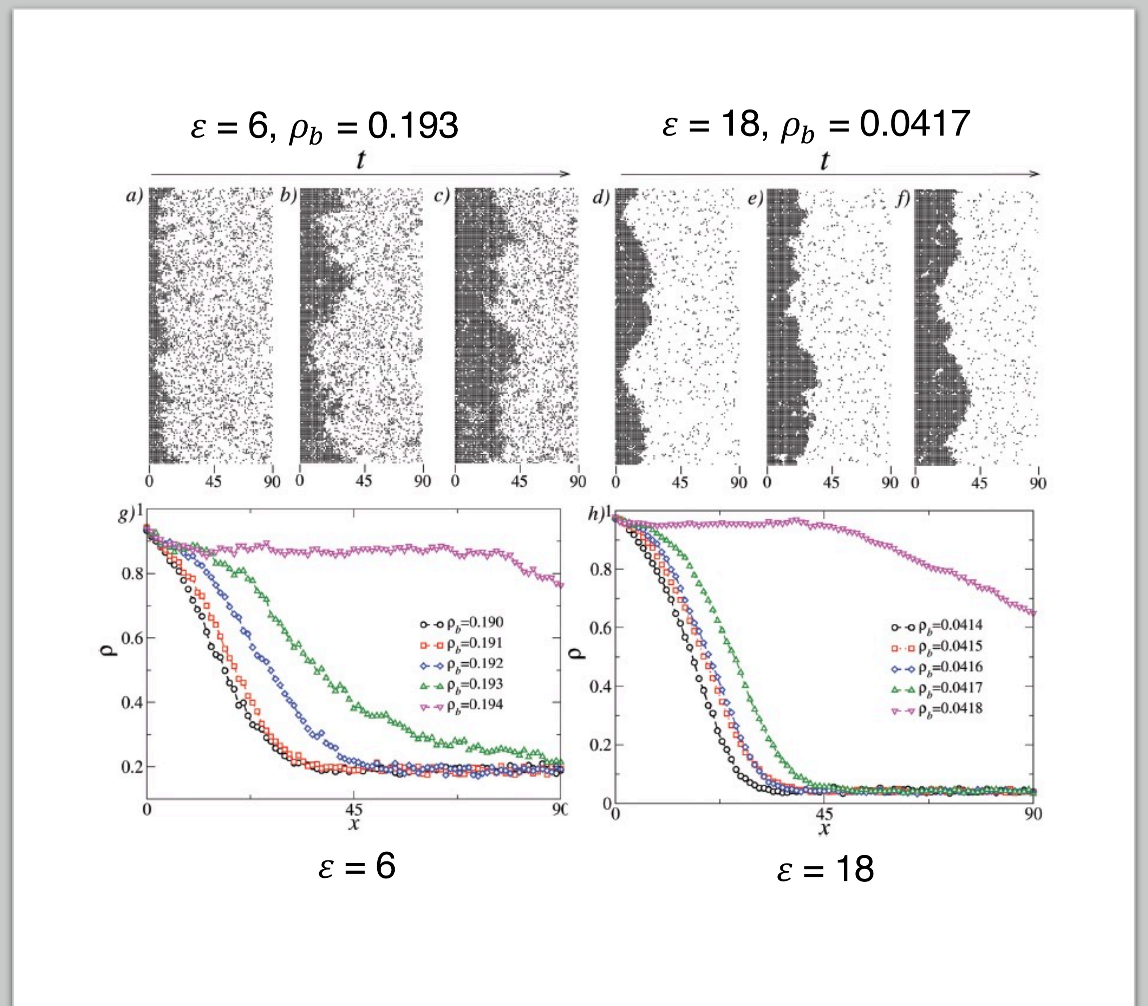


Recap

Complete wetting phase diagram

Density profiles:

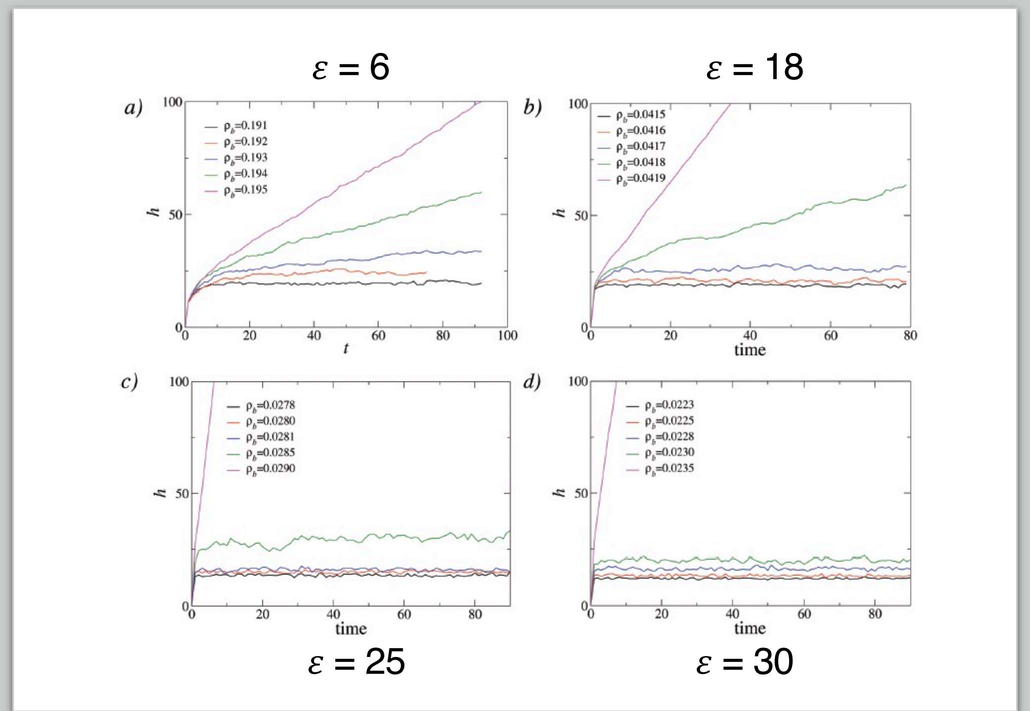
different bulk densities at low and high activity

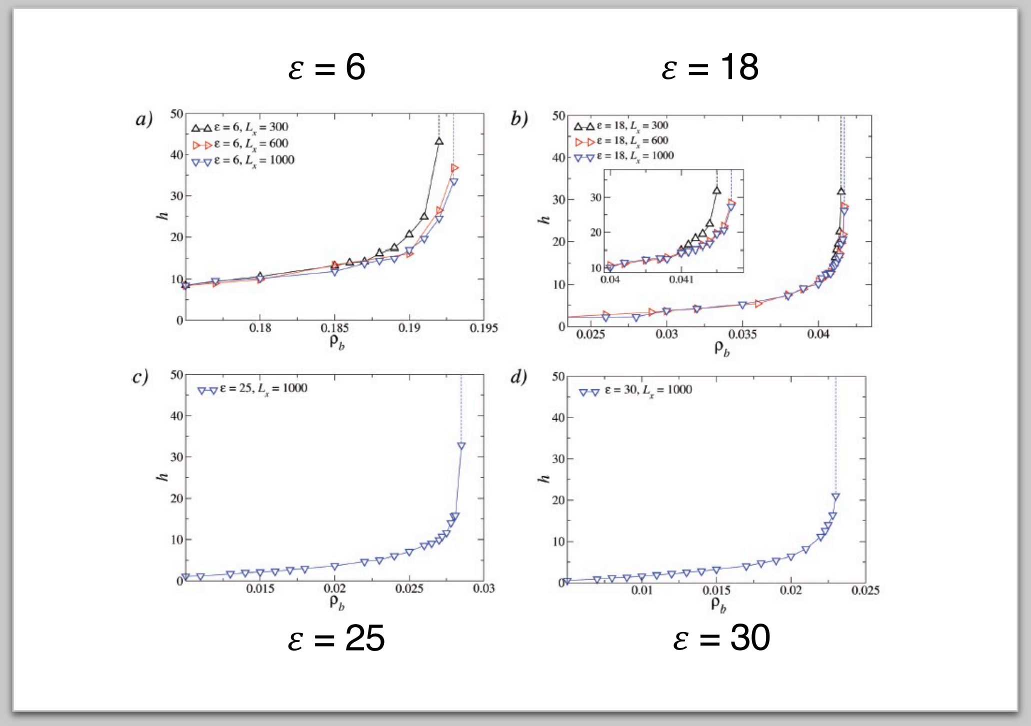


P. Neta, M. Tasinkevych, M. M. Telo da Gama, C. S. Dias, Soft Matter **17**, 2468-2478 (2021).

Film thickness:

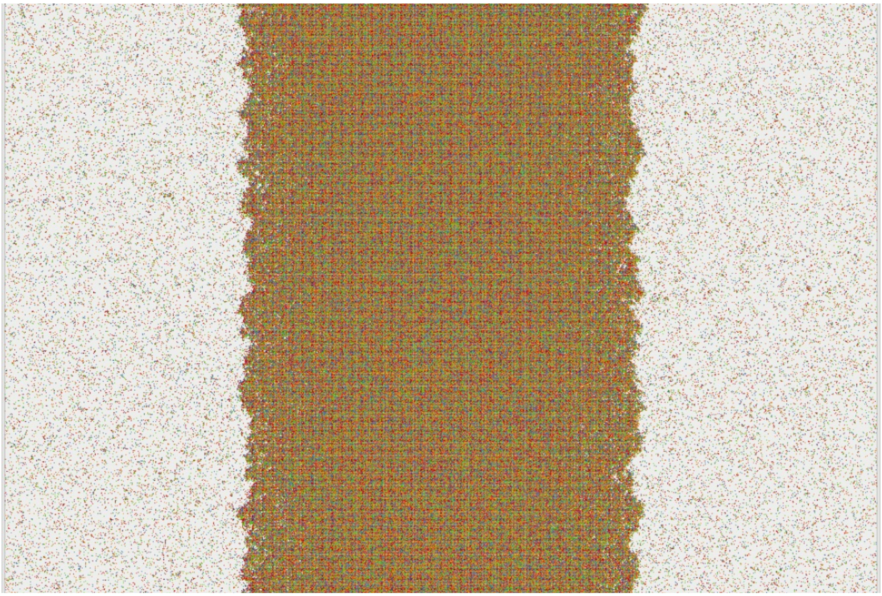
different bulk densities at low and high activity

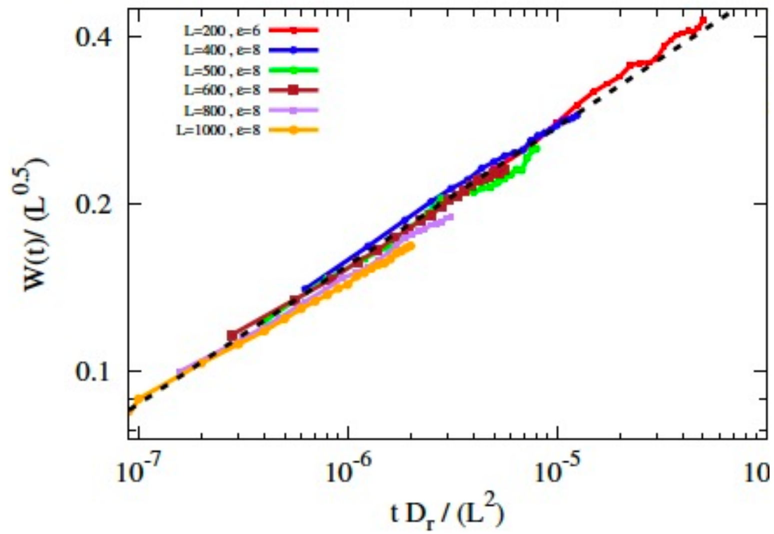




Wetting of a solid surface by active matter, P. Neta, M. Tasinkevych, M. M. Telo da Gama, C. S. Dias, Soft Matter **17**, 2468-2478 (2021).

Roughness of the interface of a closed system: Edwards-Wilkinson

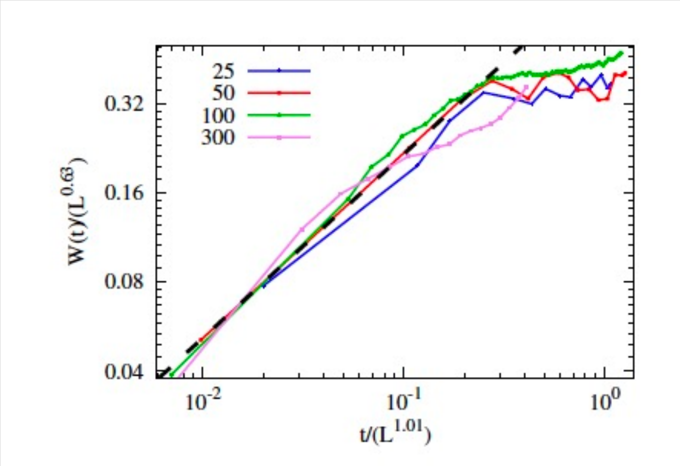


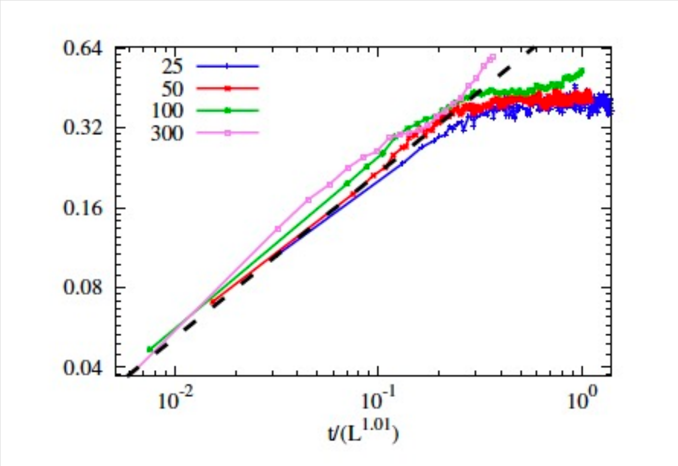


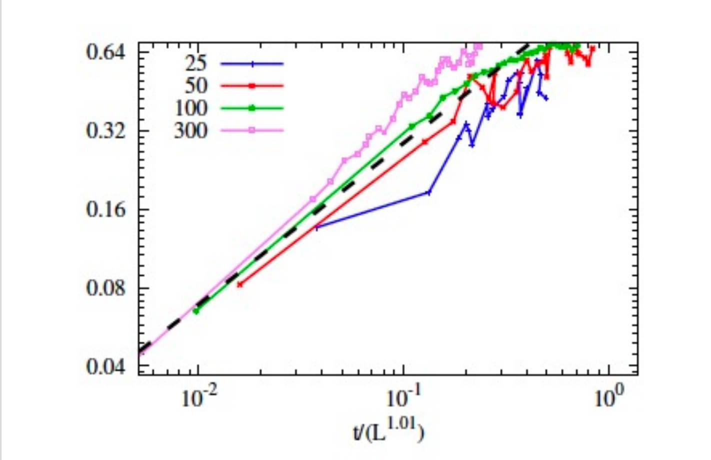
C. S. Dias, N. Araújo and M. M. Telo da Gama, work in progress.

Roughness of the interface of an open system: KPZQ

Activity decreases and bulk density increases from left to right







Thanks

Pedro Neta, Cristóvão Dias, Mykola Tasinkevych and Nuno Araújo