contact angle hysteresis

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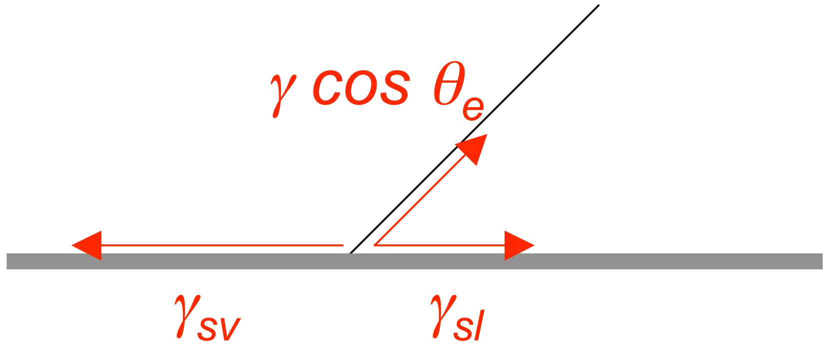
small droplets can ‘stick’ to window

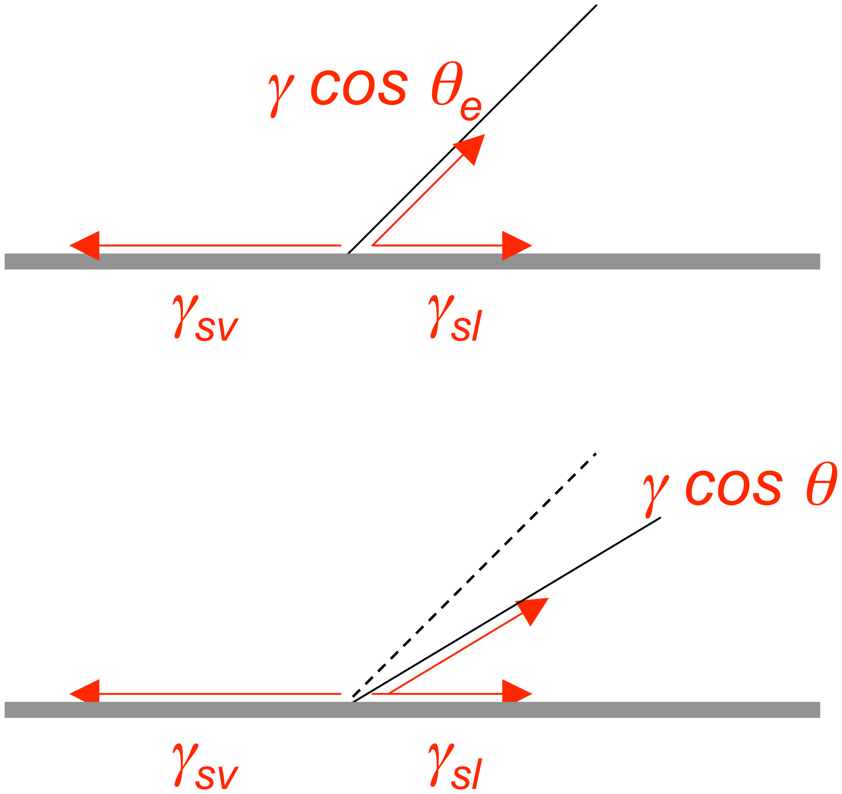
force on contact line

balance:



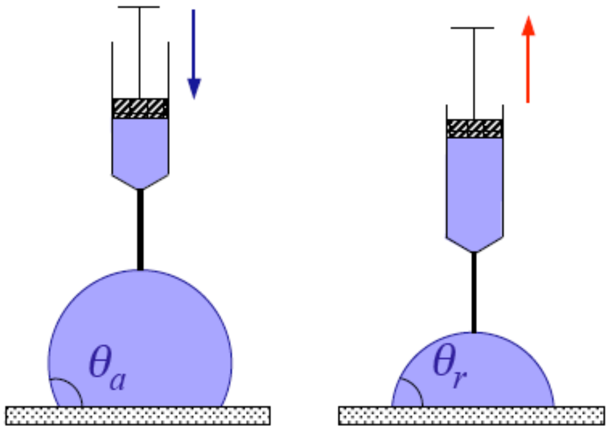
force on contact line

balance:



force on contact line: $f_{cl} = \gamma\,(\cos\theta - \cos\theta_e)$

advancing - receding angles

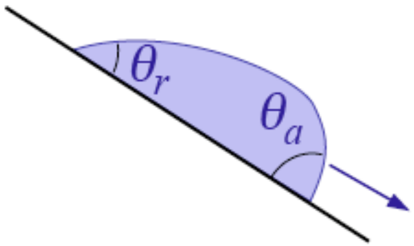


$$\theta_a > \theta_{Young} > \theta_r$$

hysteresis: no unique value for contact angle

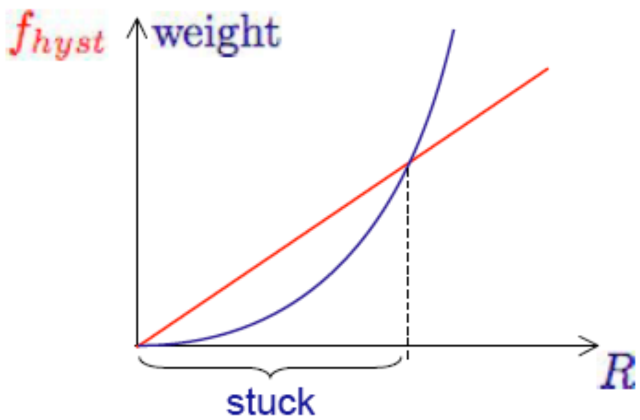
pinning force: $H = \gamma\,(\cos\theta_r - \cos\theta_a)$

'sticky' drops



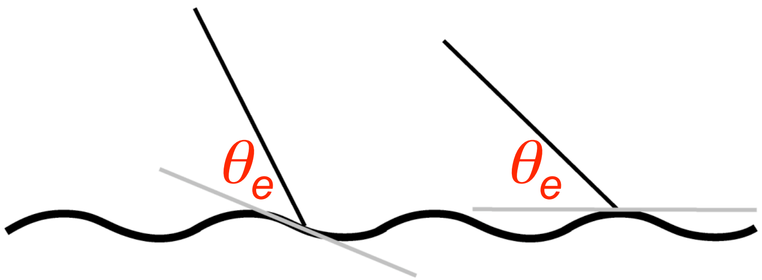
$$f_{hyst} \sim R\gamma\,(\cos\theta_r - \cos\theta_a)$$

$$\text{weight} \sim R^3 \rho g \sin\alpha$$



microscopic origin

geometric heterogeneity

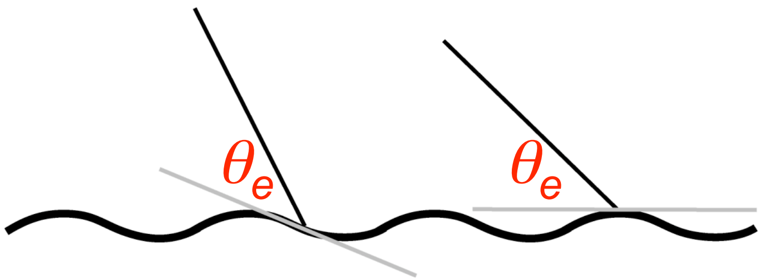


small scale 'roughness'

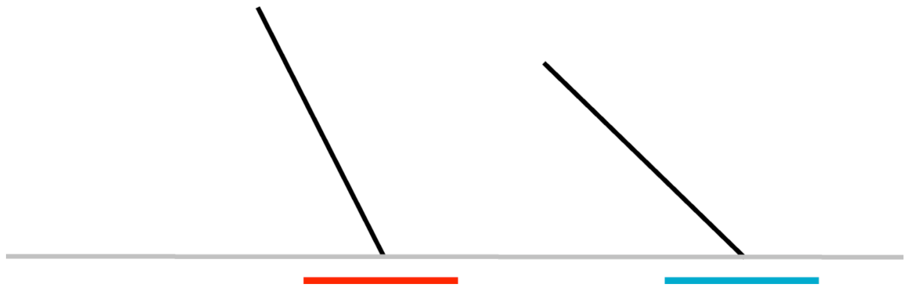
microscopic origin

geometric heterogeneity

chemical heterogeneity: $\theta_e(x,y)$



small scale ‘roughness’



large θ_e

smaller θ_e

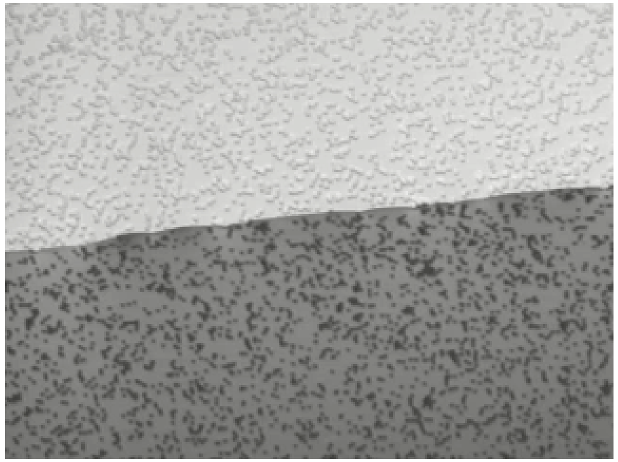
contact line shape?

contact line shape?

heterogeneity at larger scale: macroscopic ‘wetting defects’

single defect (500μm)

many defects (10μm)



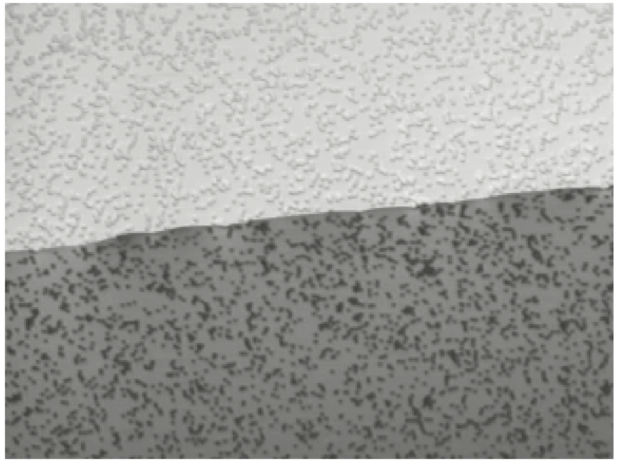
contact line shape?

heterogeneity at larger scale: macroscopic ‘wetting defects’

single defect (500μm)

‘simple’ dynamics

many defects (10μm)



collective dynamics
contact line is very ‘rough’

what will we do:

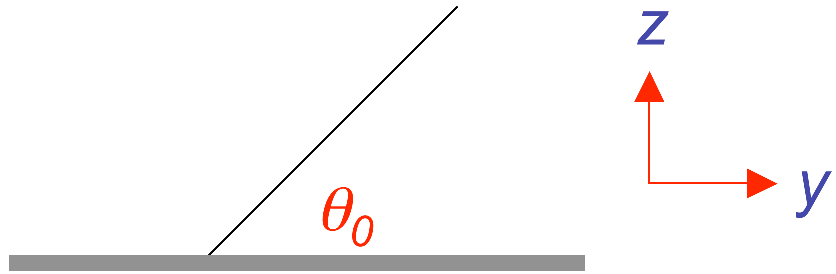
- contact line deformation of single defect
- Joanny - De Gennes model for hysteresis
- implications for dynamics...

literature:

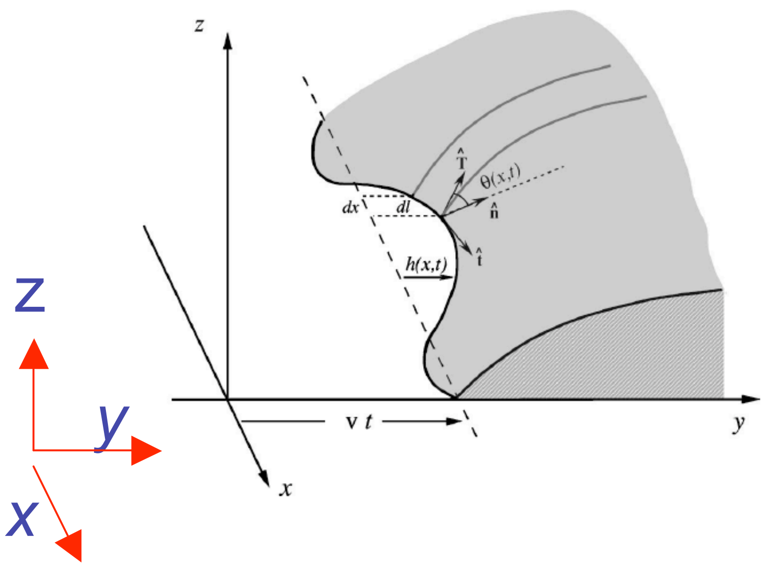
Joanny & De Gennes,
J. Chem. Phys. **81**, 552 (1984)

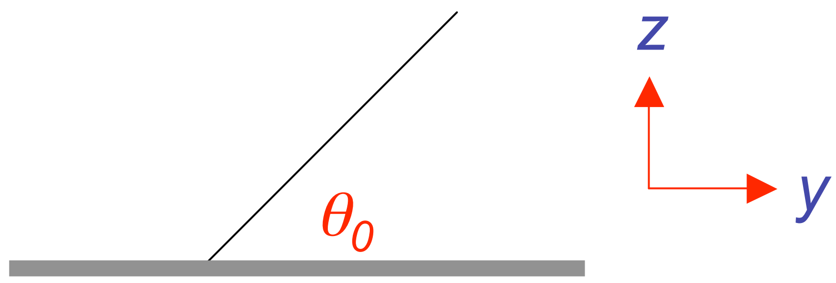
Bonn, Eggers, Indekeu, Meunier, Rolley,
to appear Rev. Mod. Phys. (2009)

contact line shape

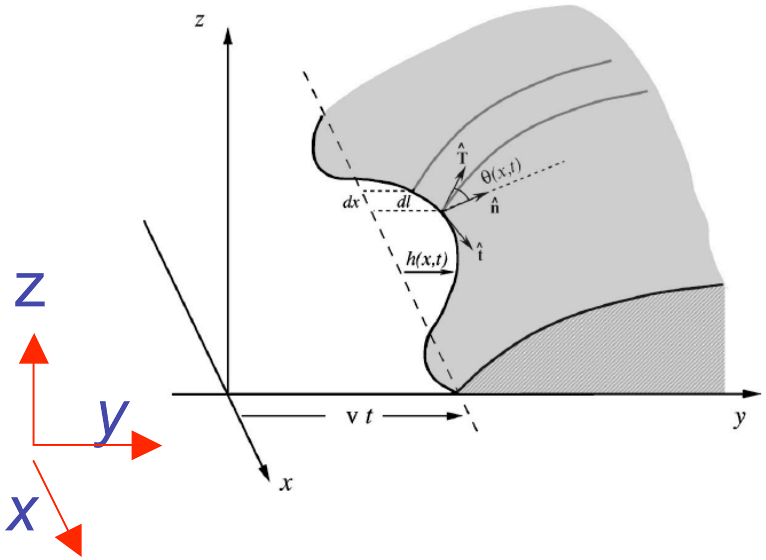


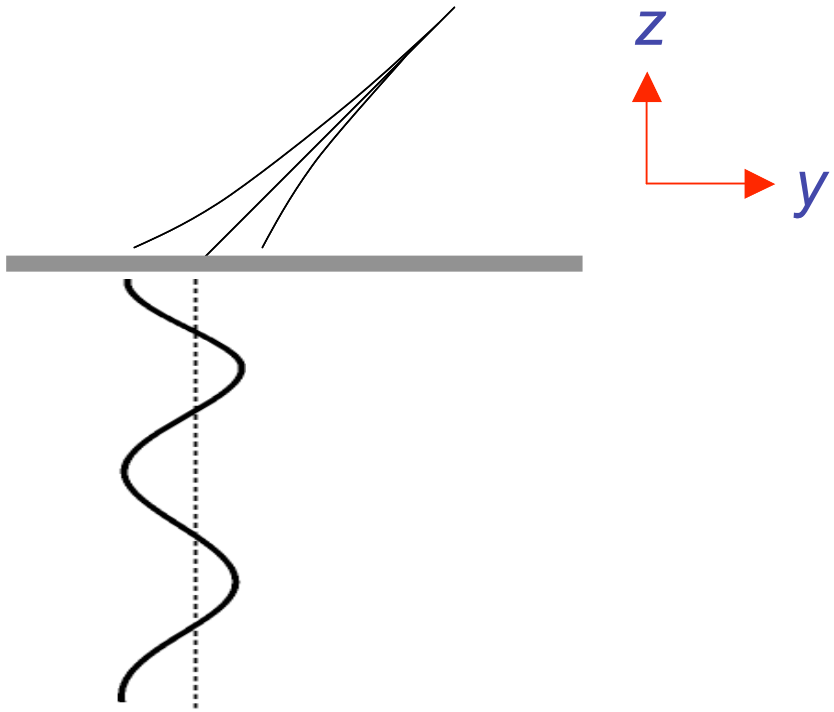
contact line shape





contact line shape



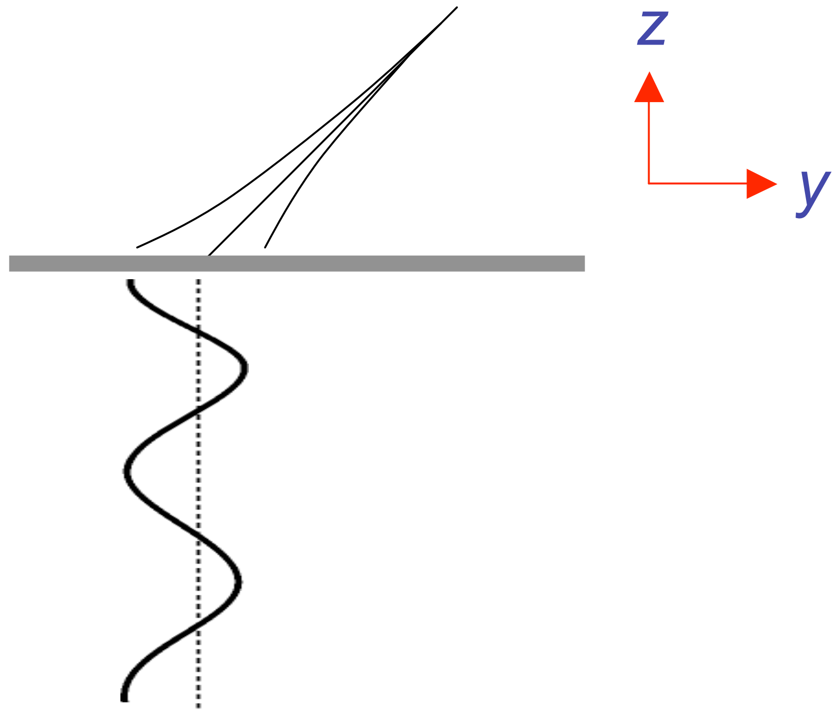


$\eta(x)$ contact line position

interface

interface $h(x,y)$?

$$h(x,y) = \theta_0 y + \ldots.$$

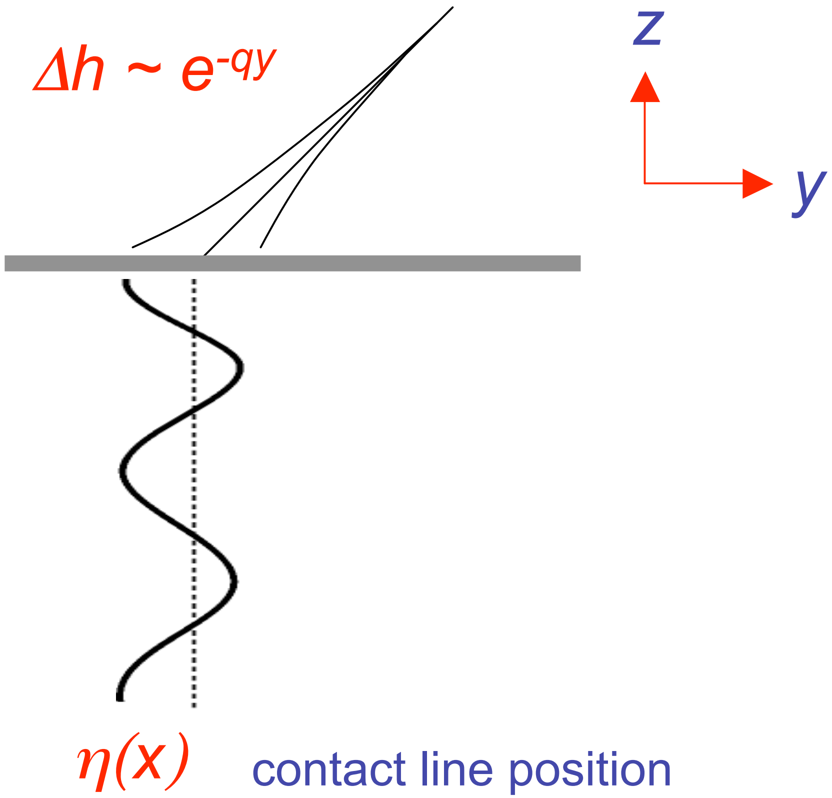


$\eta(x)$ contact line position

interface

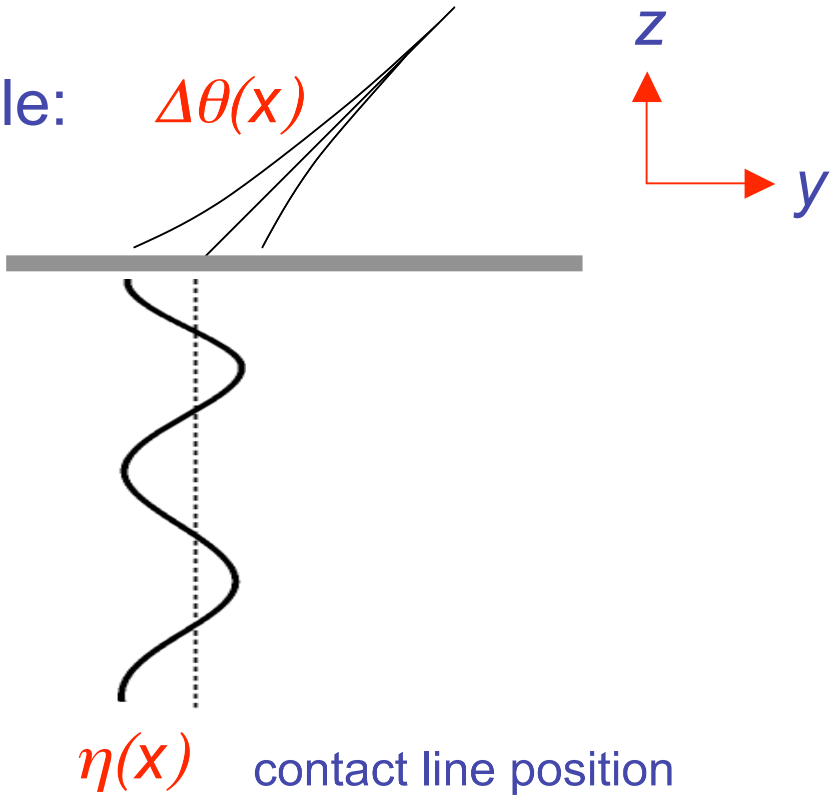
interface $h(x,y)$?

$$h(x,y) = \theta_0 y + A e^{iqx} e^{-qy}$$



interface

change in local contact angle: $\Delta\theta(x)$



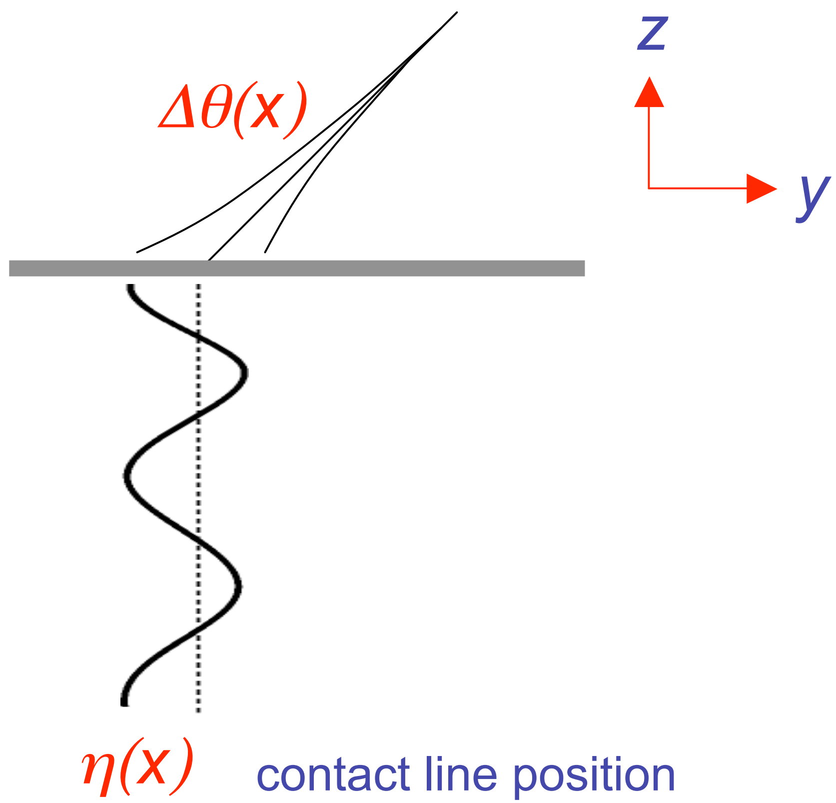
interface

increase of area

$$\Delta E \sim \gamma\, q\, A^2$$

contact line ‘elasticity’

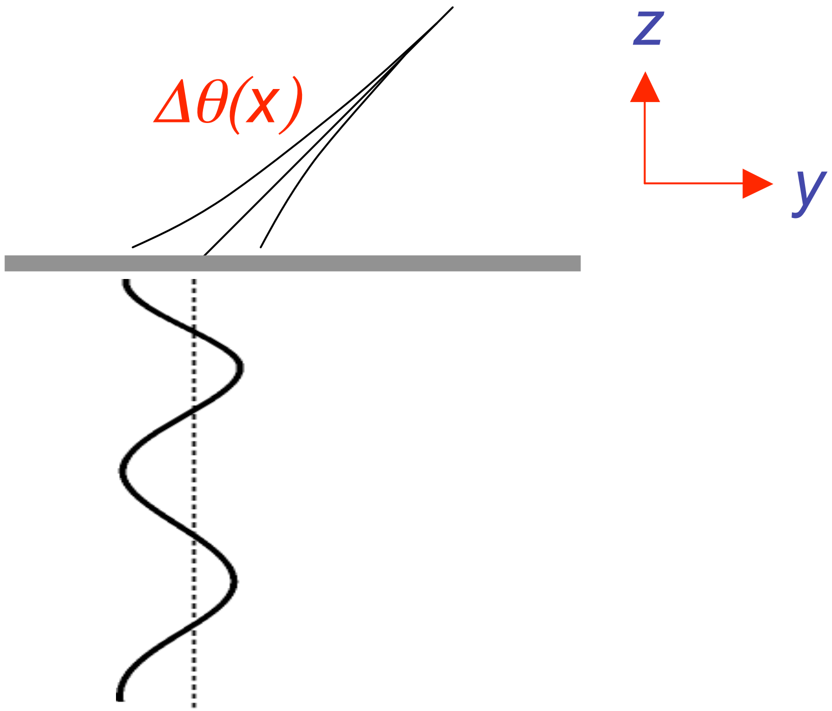
Joanny & De Gennes 1984

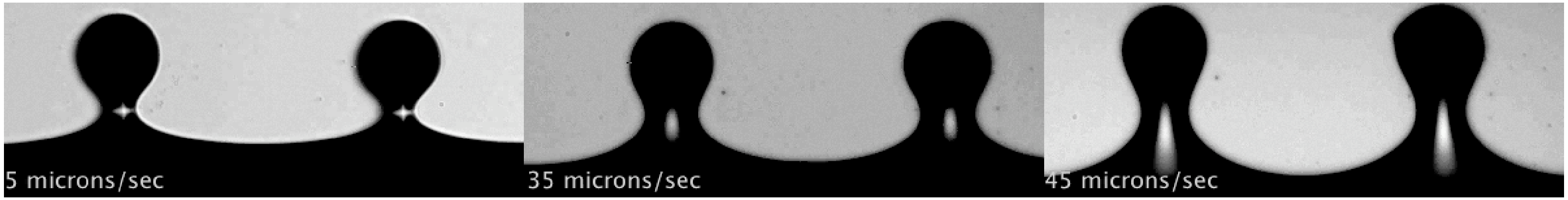


sinusoidal perturbations

increase of area:

$$\Delta E \sim \gamma\, q\, A^2$$



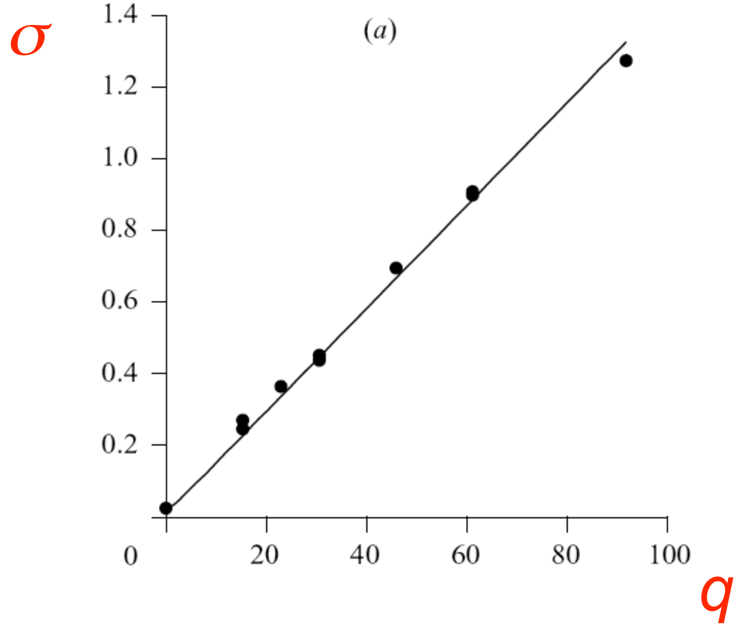


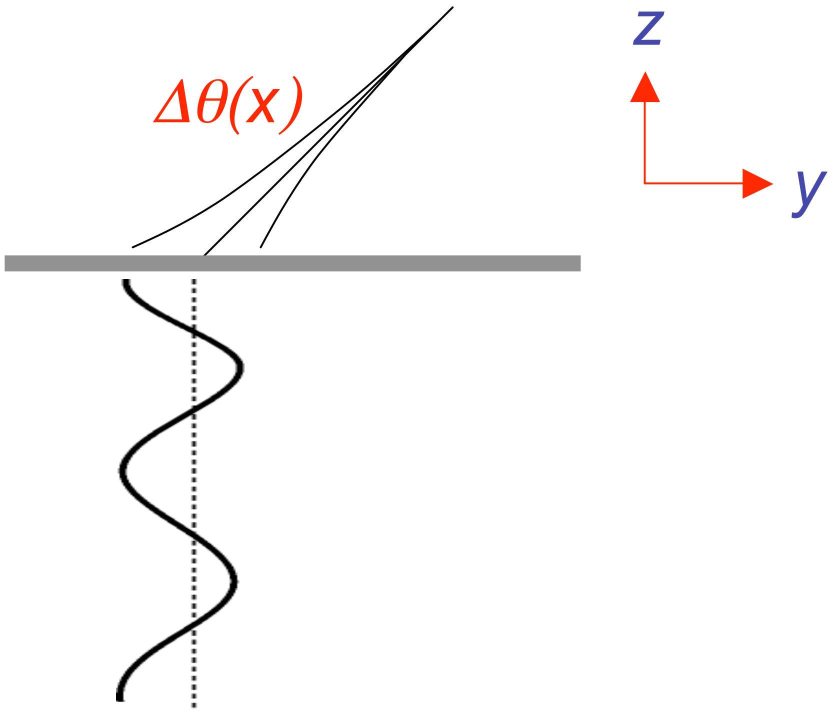
sinusoidal perturbations

increase of area:

$\Delta E \sim \gamma\, q\, A^2$

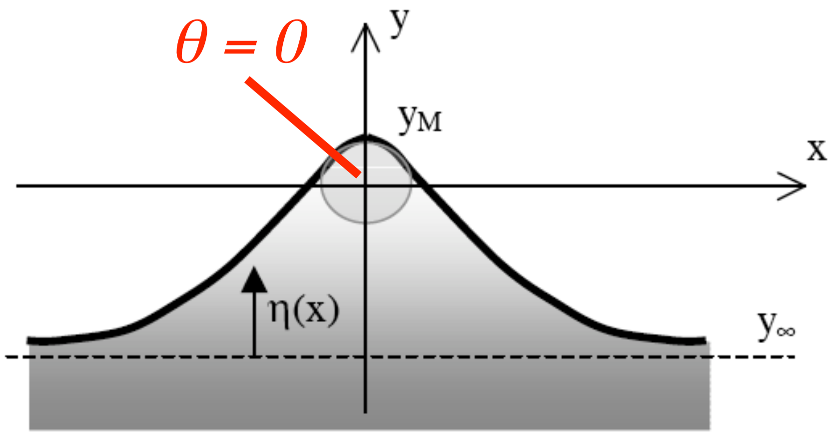
relaxation rate





Delon et al. JFM 2008

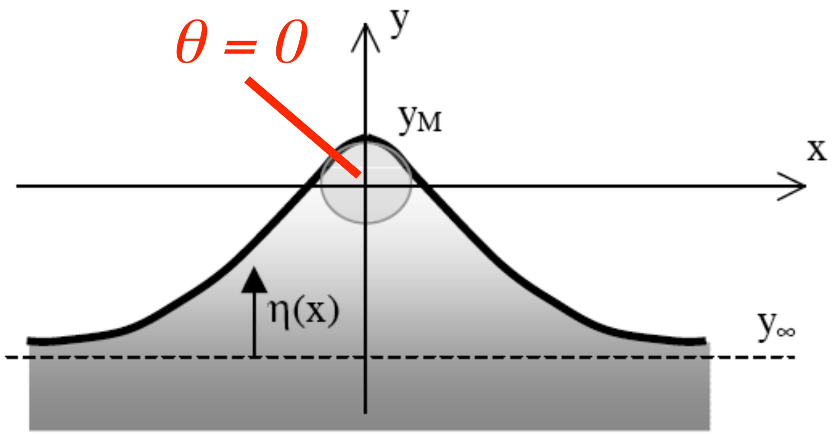
single defect



wetting defect is ‘pulling’, but....

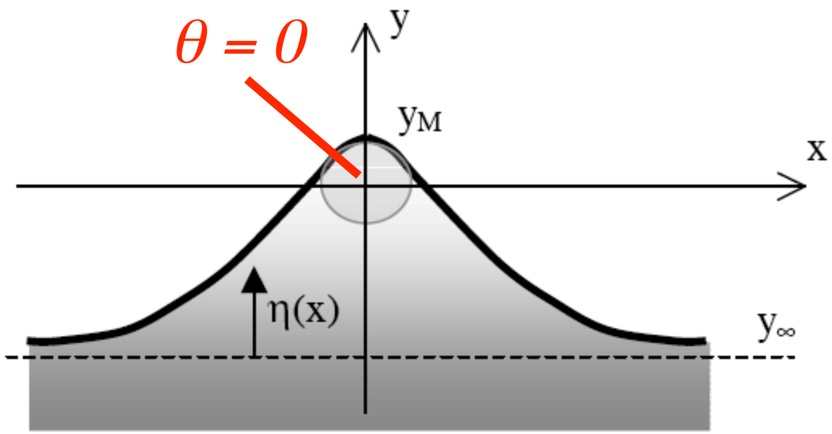
large deformations cost energy

single defect



$\eta(x)$ contact line shape ?

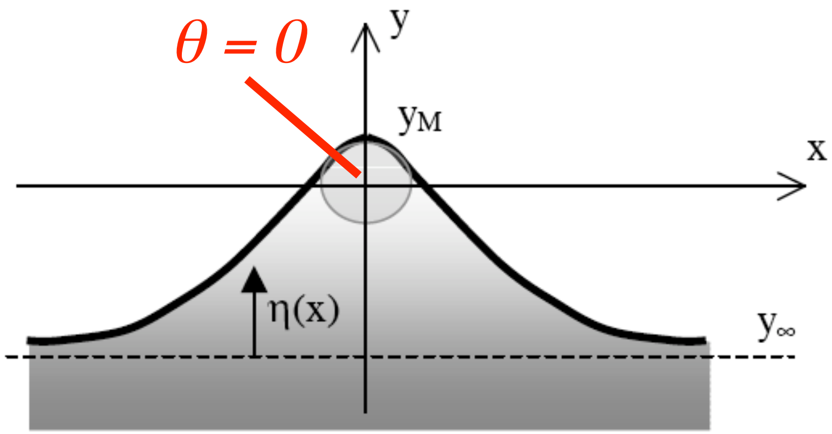
single defect



$\eta(x)$ contact line shape ?

$$h(x,y) = \theta_0 y + \ldots$$

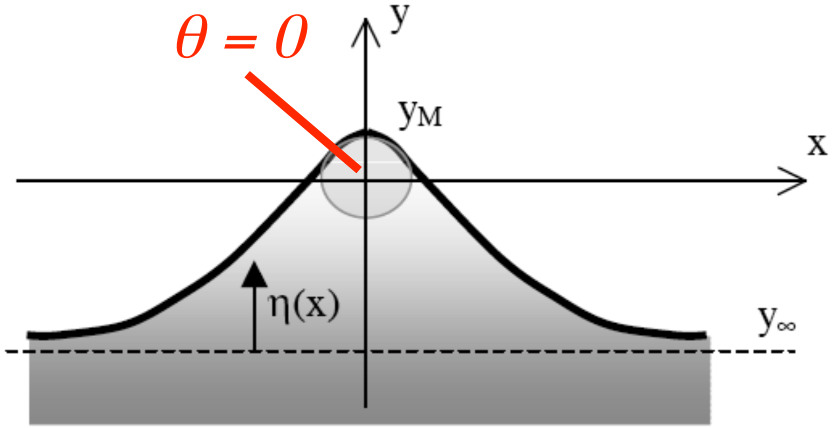
single defect



$\eta(x)$ contact line shape ?

$$h(x,y) = \theta_0 y - \frac{\theta_0}{2\pi} \int dq\, \tilde{\eta}(q)\, \underline{e^{iqx} e^{-qy}}$$

single defect

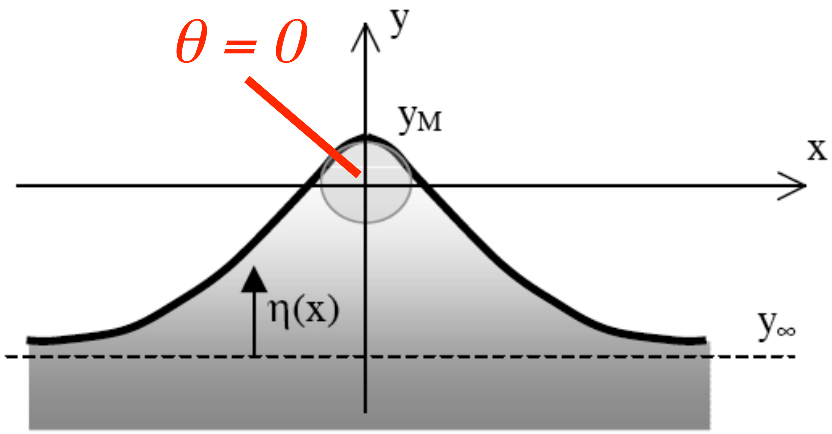


η(x) contact line shape ?

$$h(x,y) = \theta_0 y - \frac{\theta_0}{2\pi} \int dq\, \tilde{\eta}(q)\, \underline{e^{iqx} e^{-qy}}$$

imposing *θ(x)* at the contact line $\longrightarrow$ *η(x)*

single defect

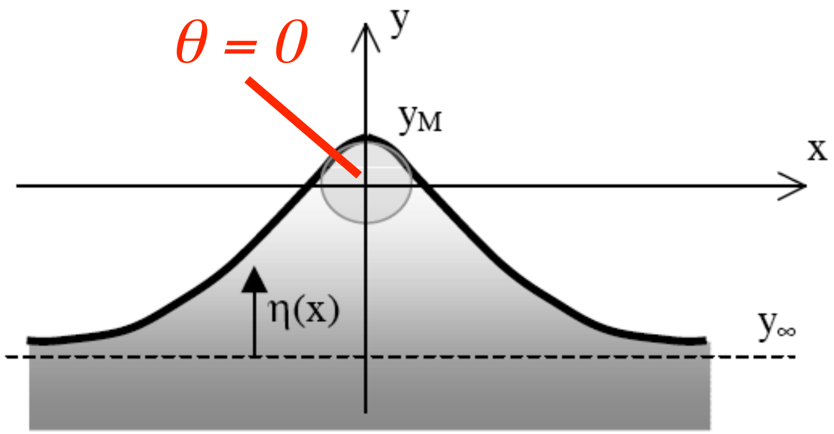


$\eta(x)$ contact line shape ?

$$h(x,y) = \theta_0 y - \frac{\theta_0}{2\pi} \int dq\, \tilde{\eta}(q)\, \underline{e^{iqx} e^{-qy}}$$

$$\theta \approx \frac{\partial h}{\partial y} = \theta_0 + \frac{\theta_0}{2\pi} \int dq\, \tilde{\eta}(q)\, \underline{q}\, e^{iqx} e^{-qy}$$

single defect

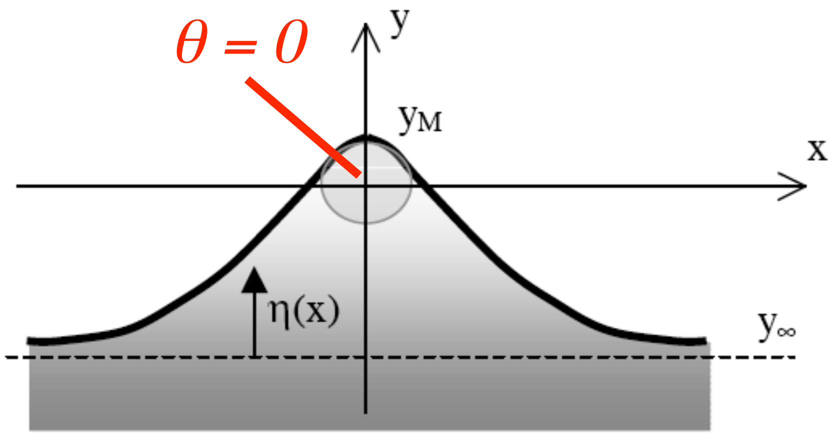


$\eta(x)$ contact line shape ?

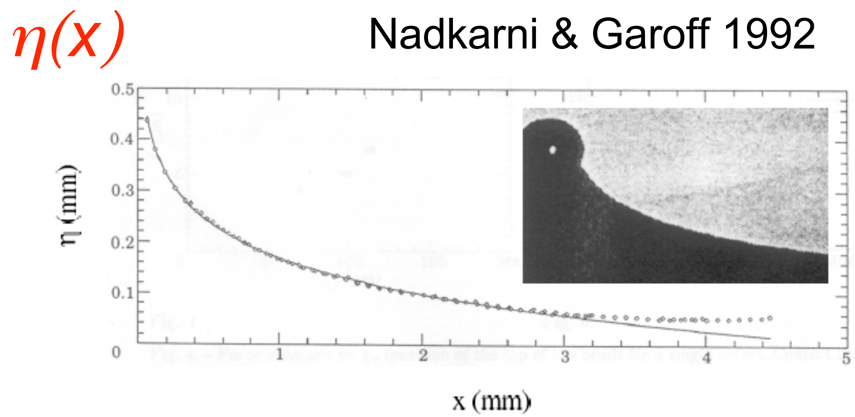
$$h(x,y) = \theta_0 y - \frac{\theta_0}{2\pi} \int dq\, \tilde{\eta}(q)\, \underline{e^{iqx} e^{-qy}}$$

$$\theta(x) \approx \theta_0 + \frac{\theta_0}{2\pi} \int dq\, \{\tilde{\eta}(q)\, q\}\, e^{iqx}$$

single defect



Nadkarni & Garoff 1992



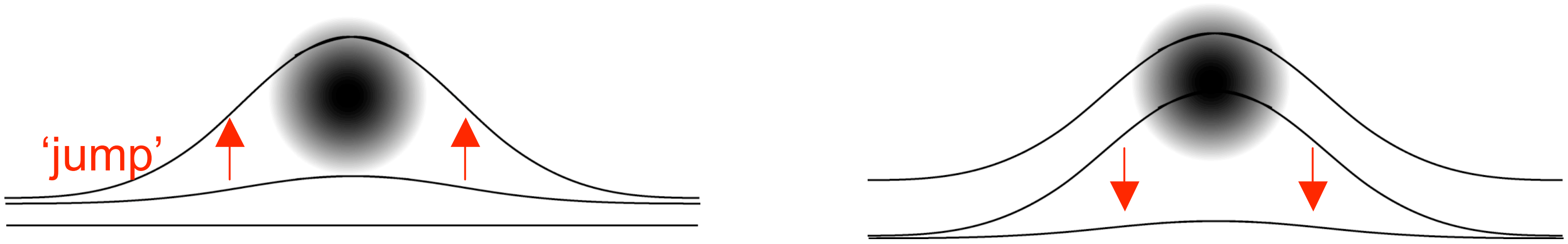
$$\eta(x) \sim \frac{F_{defect}}{\gamma} \ln\left(L/|x|\right)$$

$$F_{defect} \sim d\gamma\left(1-\cos\theta_e\right)$$

model for hysteresis

advancing

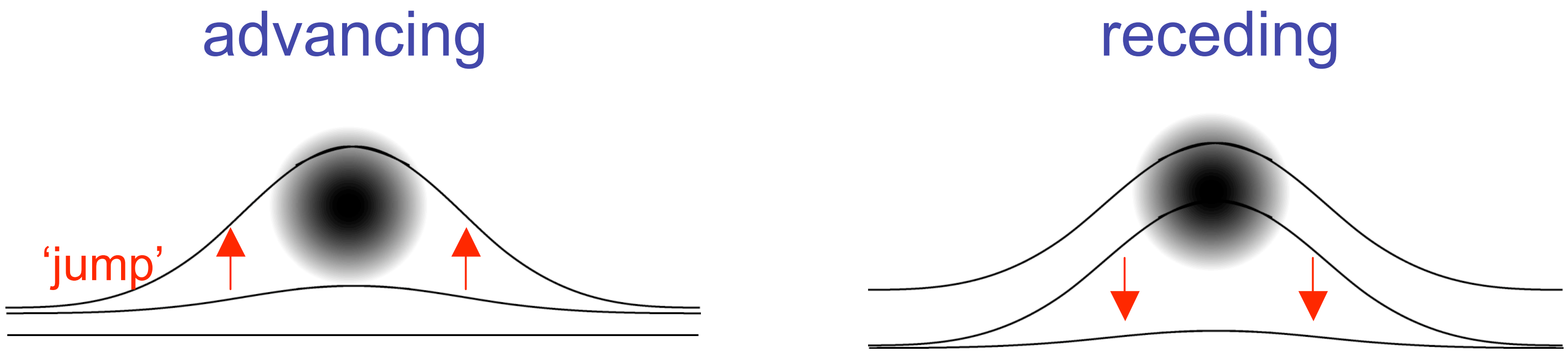
receding



asymmetry between advancing and receding

(for defects that are strong enough)

model for hysteresis



non-interacting defects,
density ρ

$$\gamma(\cos\theta_r - \cos\theta_a) \sim \rho\, F_d \eta_{\max}$$

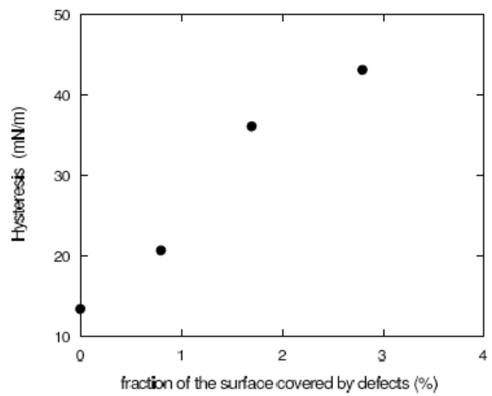
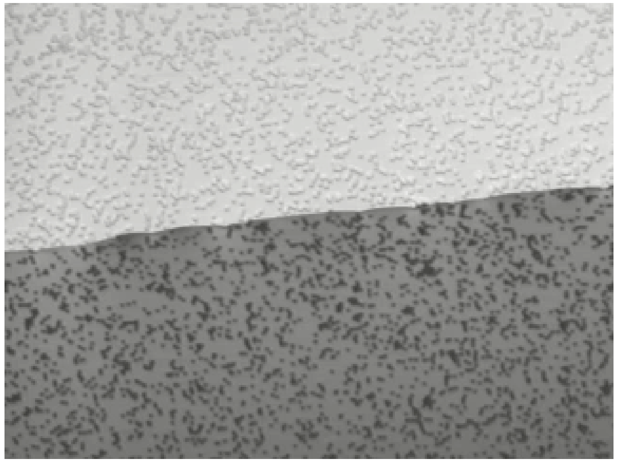


FIG. 48 Hysteresis as a function of the fraction X of the surface covered by defects (from Ramos *et al.* (2003)).

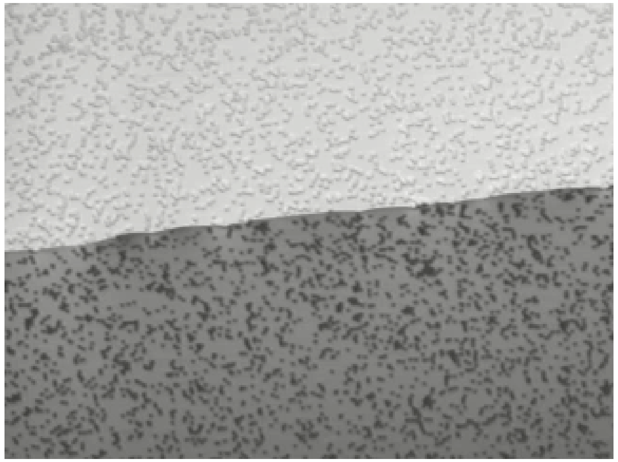
contact line dynamics, revisited

many defects (10μm)



contact line dynamics, revisited

many defects (10μm)



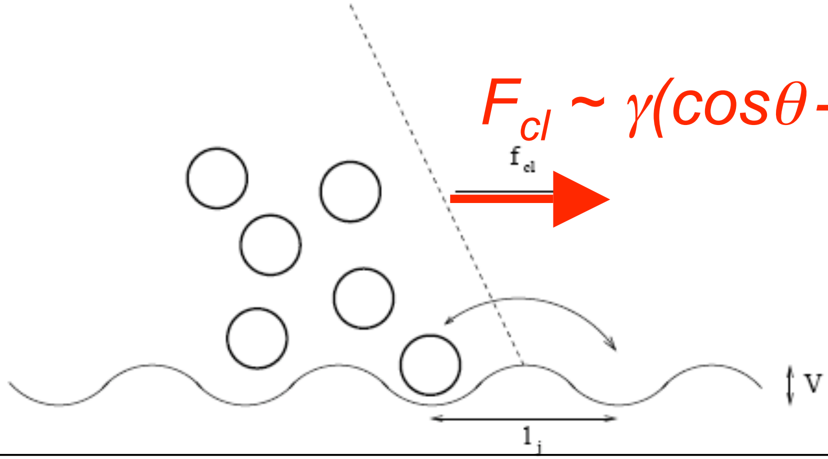
if we go very slowly...

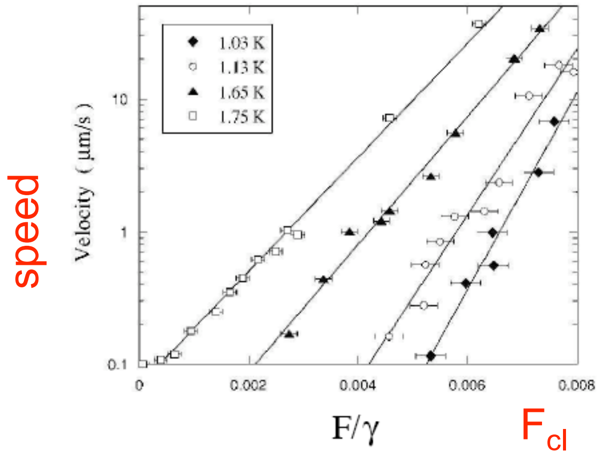
... thermally activated 'hopping' of molecules

contact line dynamics, revisited

thermally activated ‘hopping’ of molecules

$F_{cl} \sim \gamma(\cos\theta - \cos\theta_e)$



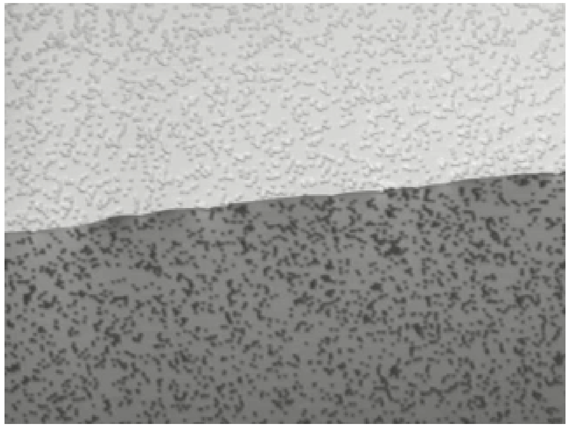


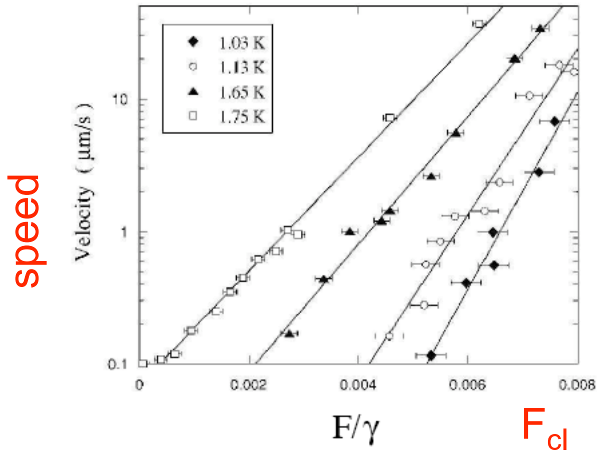
Rolley & Guthmann PRL 2007

$$U \sim \exp\left(-\frac{E - f_{cl} l_{micro}^2}{k_B T}\right)$$

contact line dynamics, revisited

thermally activated 'depinning' of contact line



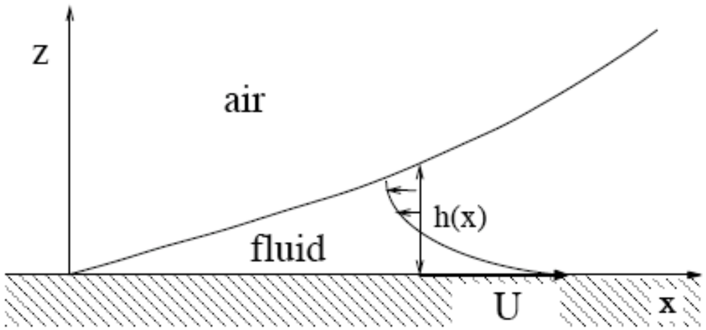


Rolley & Guthmann PRL 2007

$$U \sim \exp\left(-\frac{E - f_{cl} l_{micro}^2}{k_B T}\right)$$

coupling to hydrodynamics?

for significant *Ca*: lubrication + slip



microscopics shows up as ‘boundary conditions’

conclusion

- microscopic description of hysteresis

- ’interacting defects’ are difficult...
  depinning, contact line roughness

- coupling to hydrodynamics??