Lecture 15
Dynamic Approach Curves

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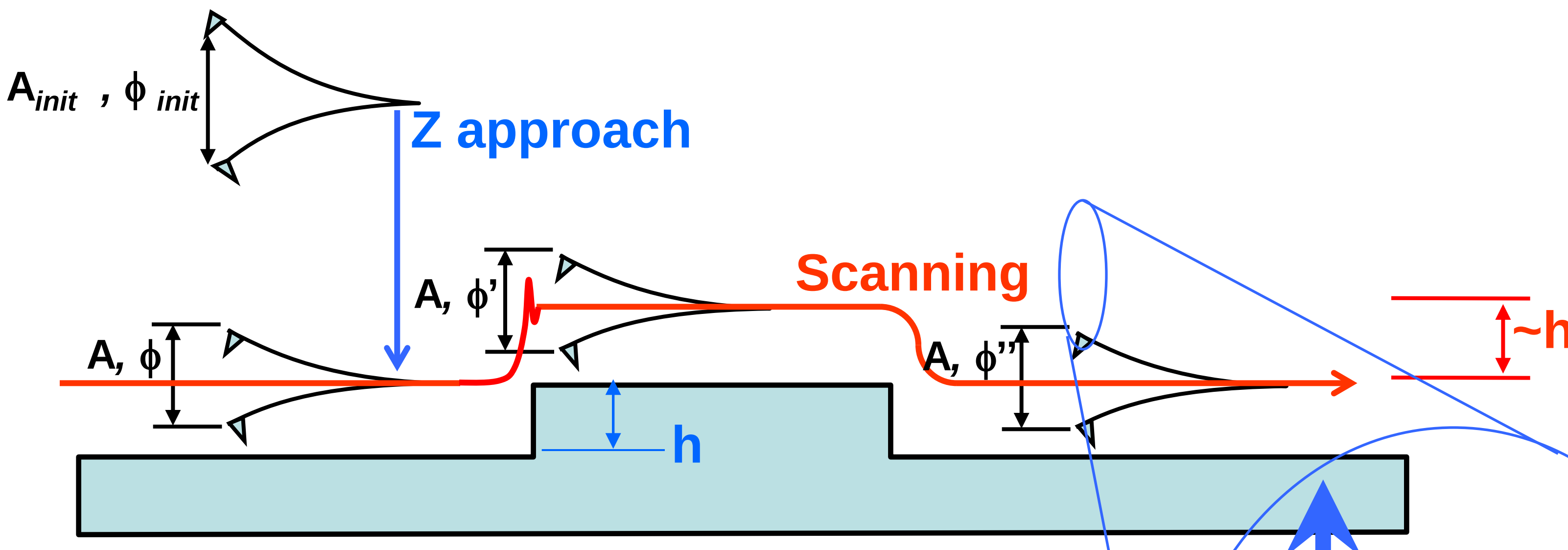
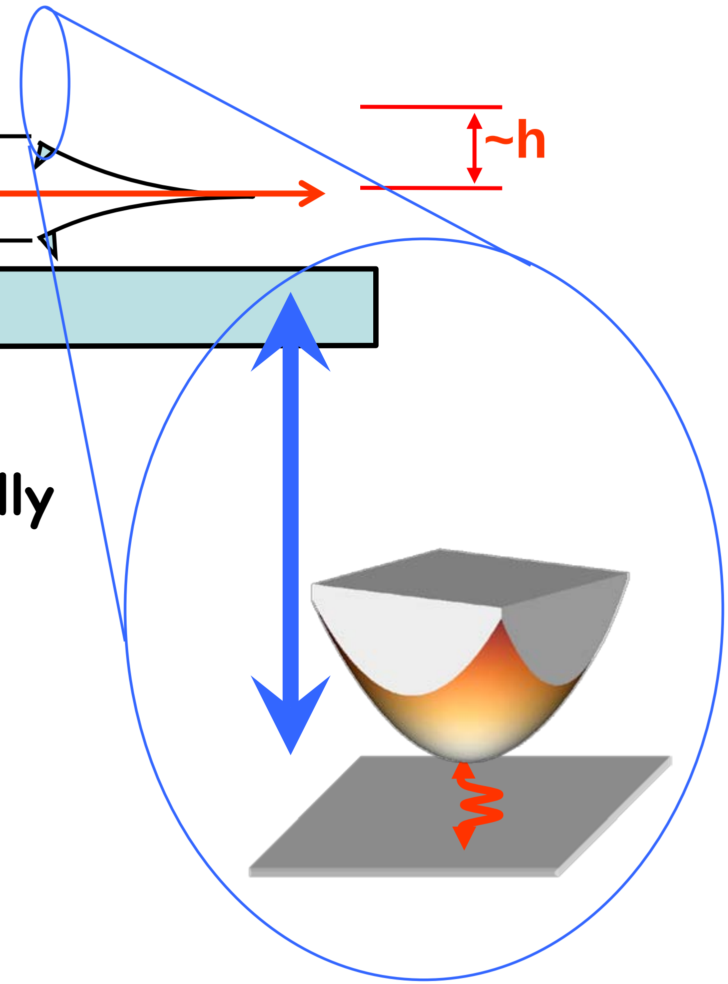
AM-AFM (aka Tapping Mode, IC mode)





Key points

- Drive frequency is always fixed ω, usually near ω_0
- During approach A, ϕ change due to tip-sample interaction forces
- During scan ϕ is a free variable and changes naturally while scanning

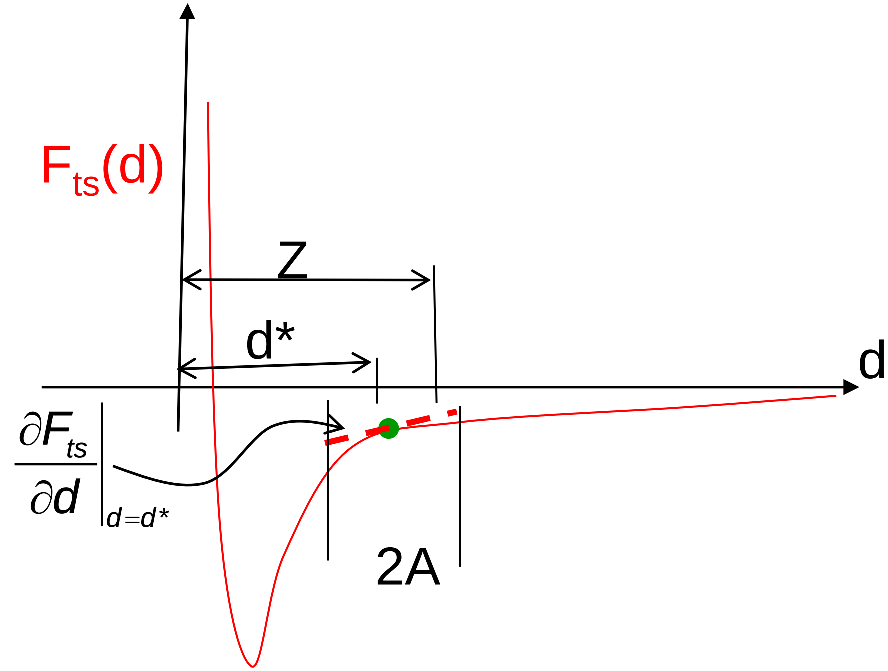
Linearization valid when A<<slope/curvature

$$\frac{\ddot{x}}{\omega_0^2} + \left(1 - \frac{1}{k}\frac{\partial F_{ts}(d)}{\partial d}\bigg|_{d=d^*}\right)\bar{x} + \frac{1}{\omega_0 Q}\dot{x} = \frac{1}{k}\left(F_0 \sin(\omega t)\right)$$

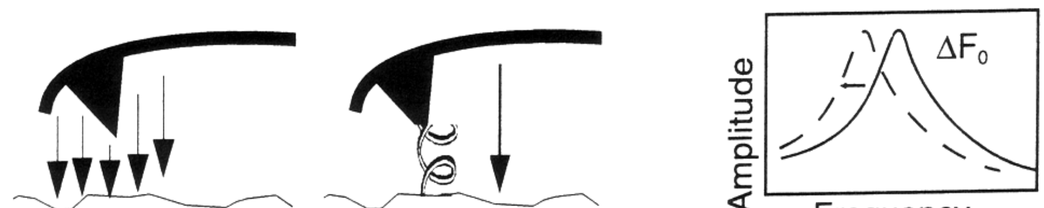
Or

$$\ddot{x} + \omega_0^2\left(1 - \frac{1}{k}\frac{\partial F_{ts}(d)}{\partial d}\bigg|_{d=d^*}\right)\bar{x} + \frac{\omega_0}{Q}\dot{x} = \frac{\omega_0^2}{k}\left(F_0 \sin(\omega t)\right)$$

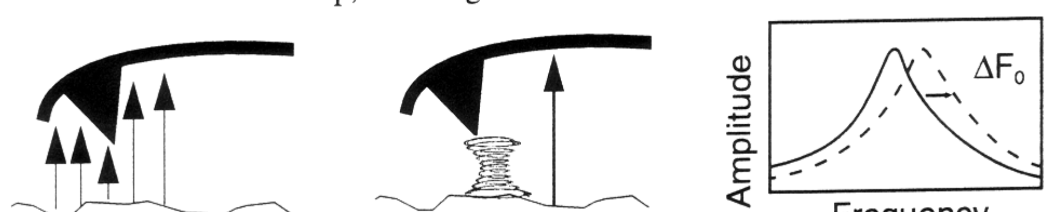
$$\hat{\omega}_0^2 = \omega_0^2\left(1 - \frac{1}{k}\frac{\partial F_{ts}(d)}{\partial d}\bigg|_{d=d^*}\right)$$



- When $\frac{\partial F_{ts}}{\partial d}\Big|_{d=d^*} > 0$ attractive force and natural frequency decreases
- When $\frac{\partial F_{ts}}{\partial d}\Big|_{d=d^*} < 0$ rep. regime and natural frequency increases



Attractive gradient equivalent to additional spring in tension attached to tip, reducing the cantilever resonance frequency.



Repulsive gradient equivalent to additional spring in compression attached to tip, increasing the cantilever resonance frequency.

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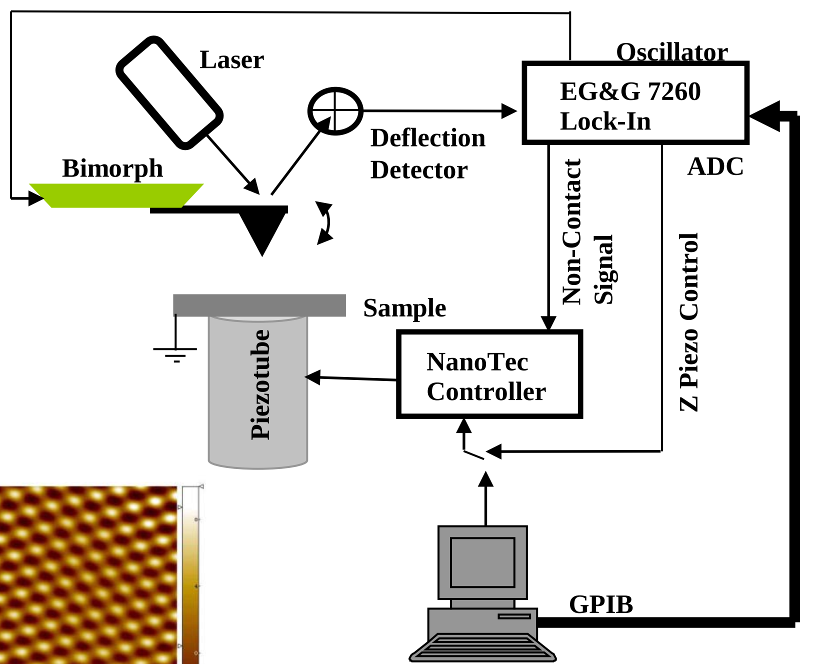
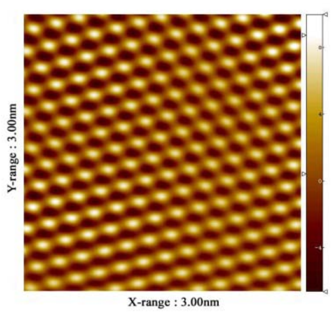
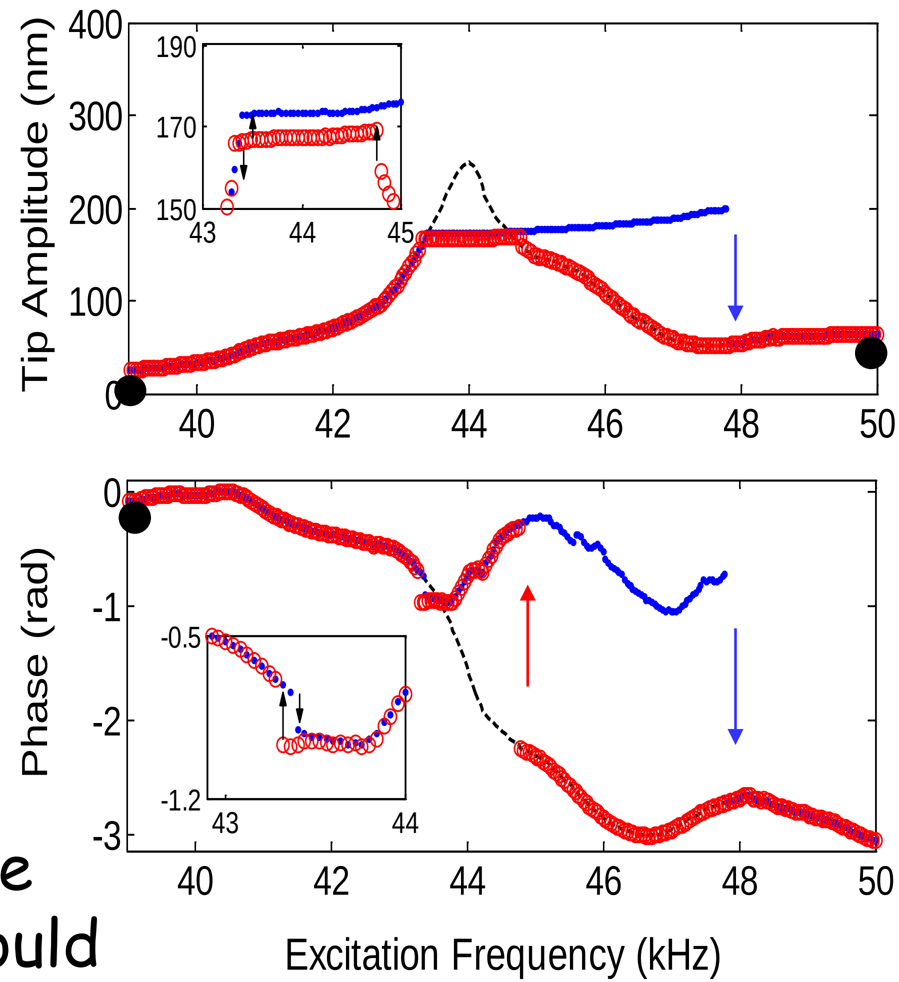
Typical tuning curves near the sample

- **Si tip / HOPG sample z=90 nm, frequency sweep**







- In reality the tuning curves are not what linearized analysis would suggest

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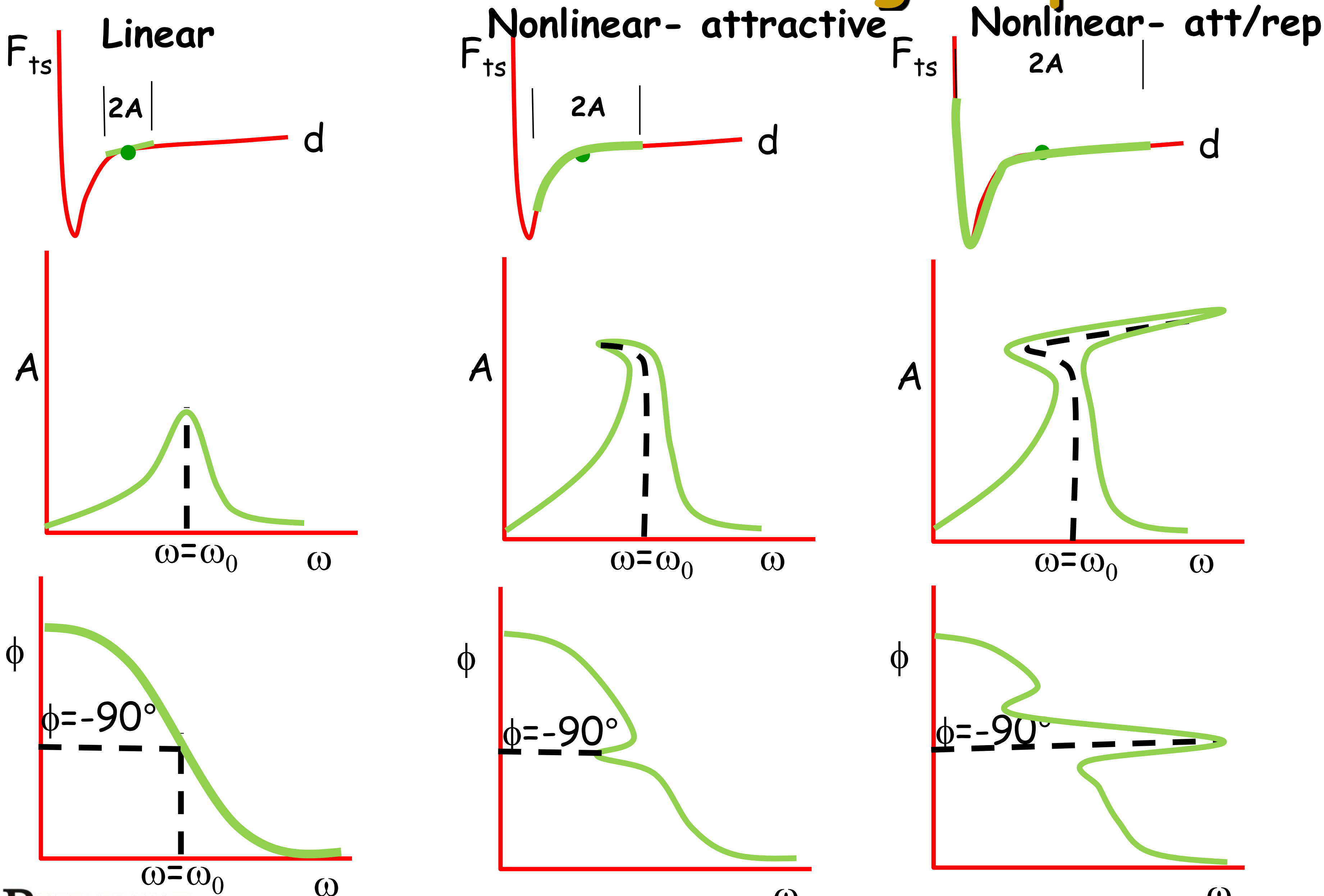
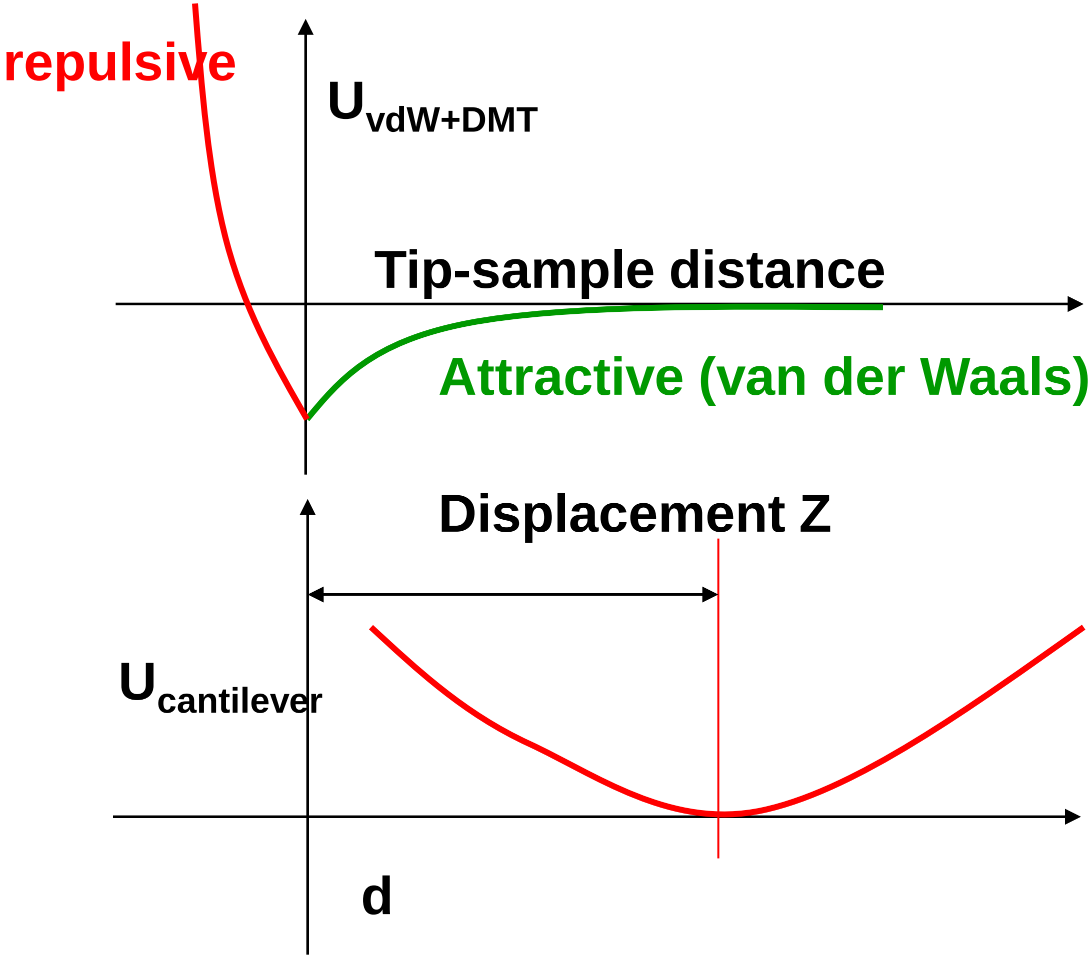
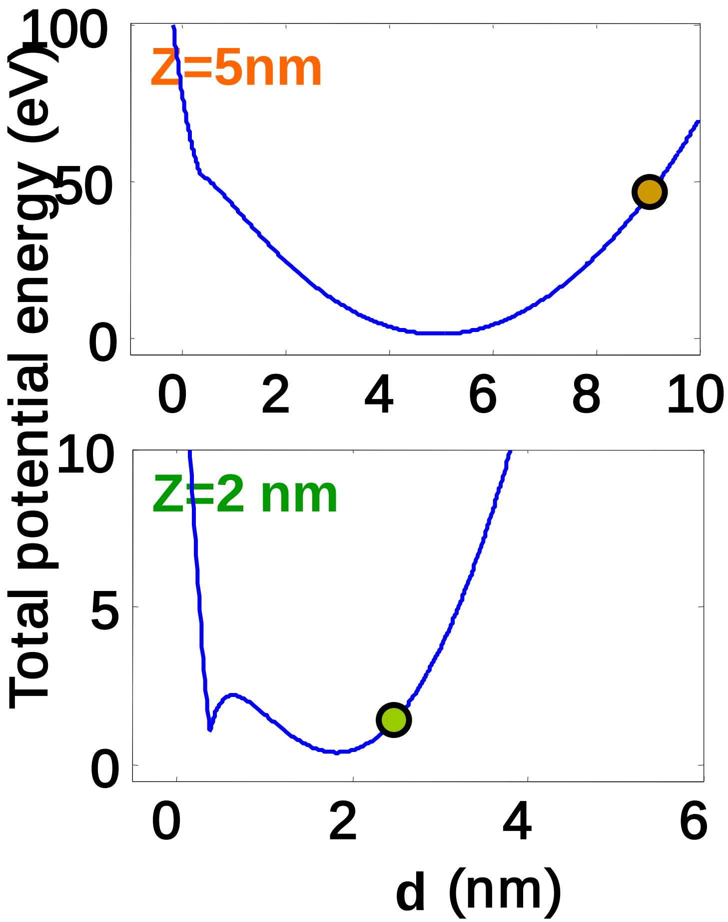
Lee et al, Phys Rev B (2002)

Linear vs. nonlinear tuning response



Physical mechanisms





- Total potential energy from interaction + beam elasticity
- Number of equilibria changes with Z

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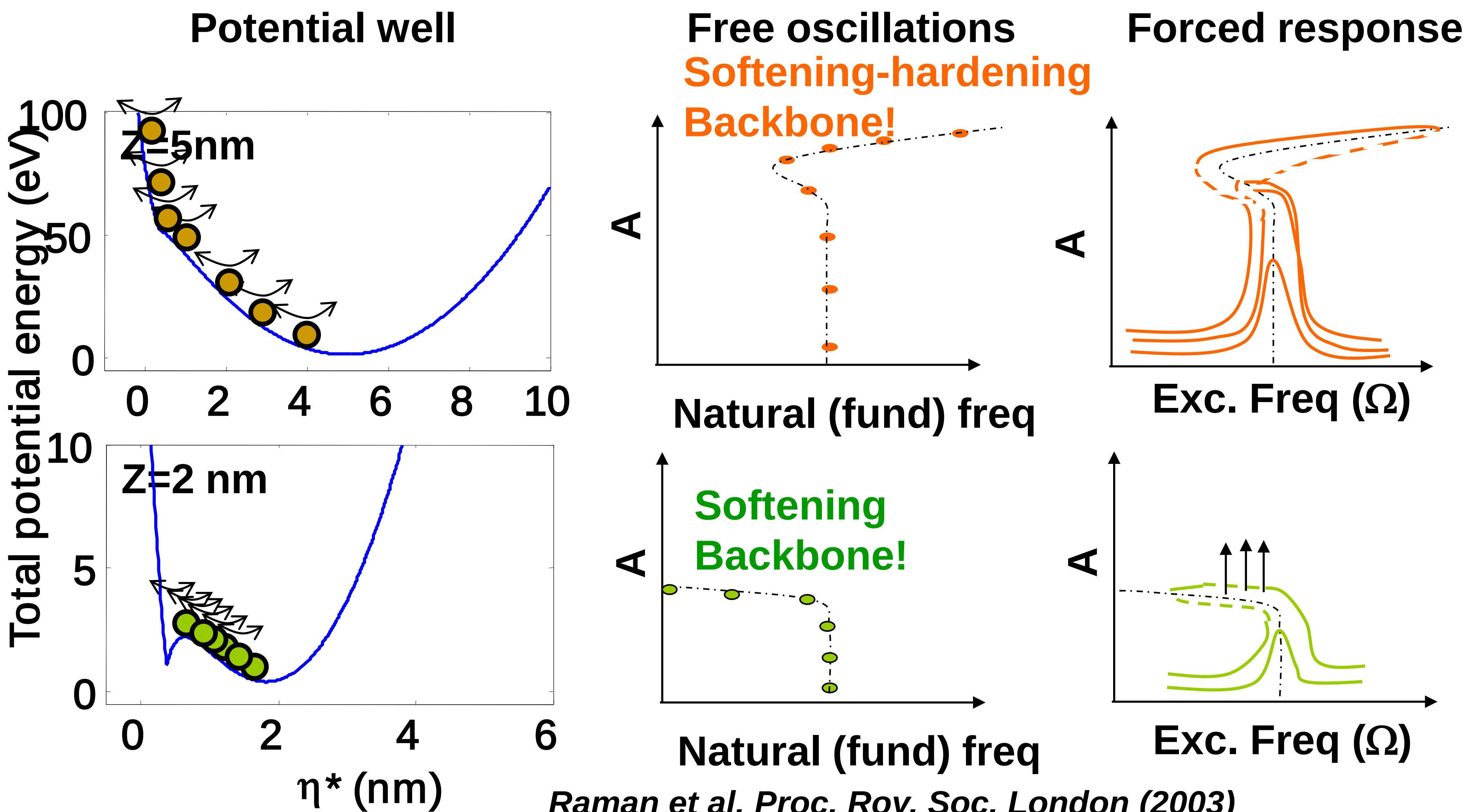
Physical mechanisms



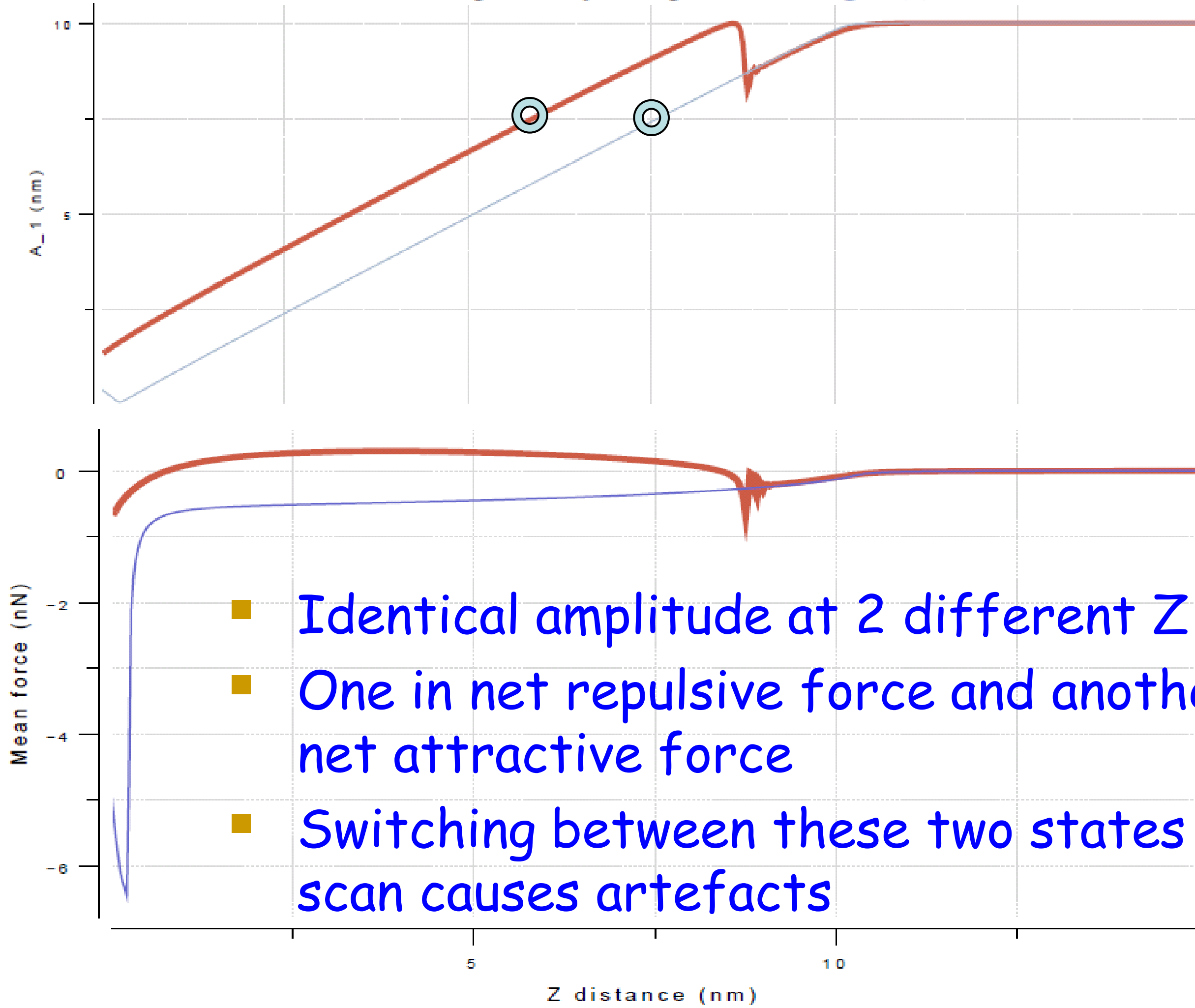
Raman et al, Proc. Roy. Soc. London (2003)

- Softening nonlinearity ⇔van der Waals forces (attractive)
- Hardening nonlinearity ⇔ sample elasticity (repulsive)

Implications for AM-AFM

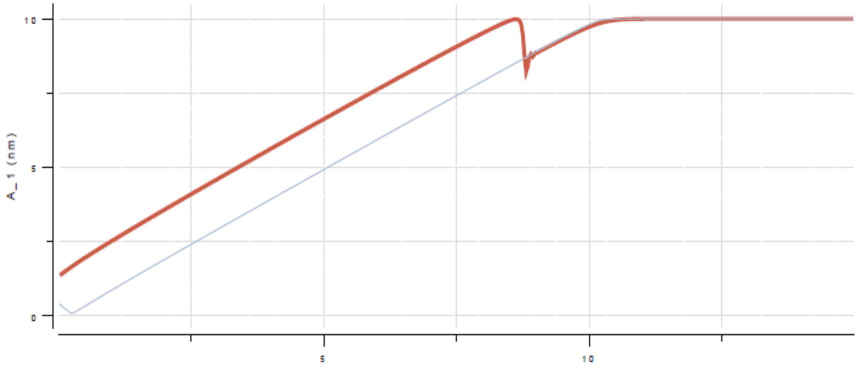
- Consider the following dynamic approach retract curves using VEDA (parameters following example in Garcia and Perez)

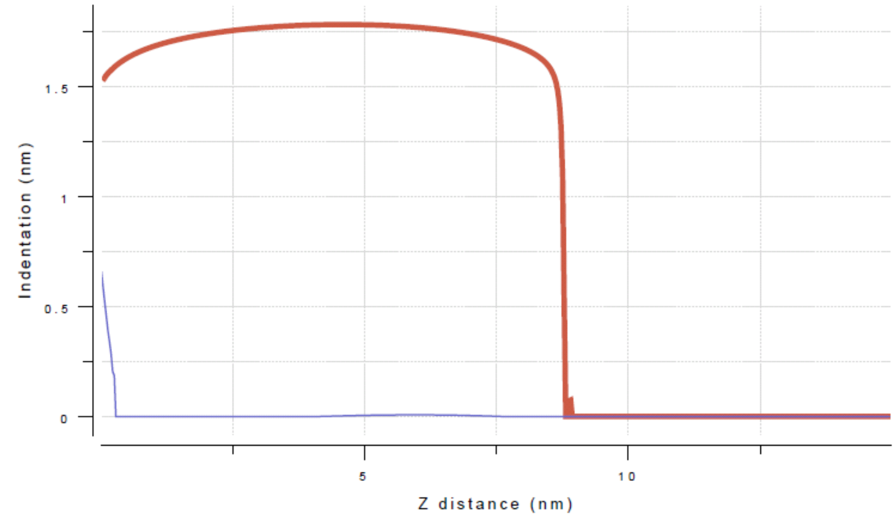
The dependence of the low and high oscillation solutions on the rest of the tip–surface separation for a system characterised by R, A_0, $f_0 = f$, k, Q, H, γ and E^* of 20 nm, 10 nm, 350 kHz, 40 N/m, 400, 6.4×10^{-20} J, 30 mJ/m^2 and 1.51 GPa, respectively, are plotted in Fig. 7(a). The collection of L and H

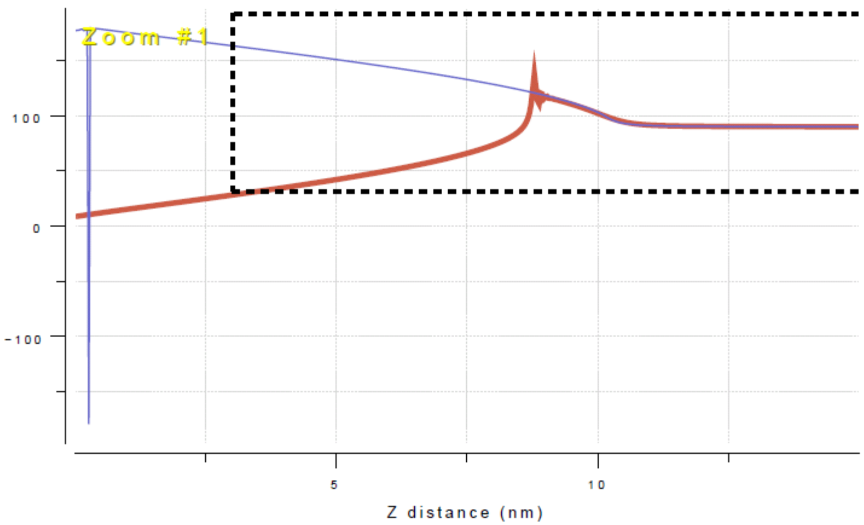


- Identical amplitude at 2 different Z values!!
- One in net repulsive force and another with net attractive force
- Switching between these two states during a scan causes artefacts

Recognizing attractive and repulsive regimes

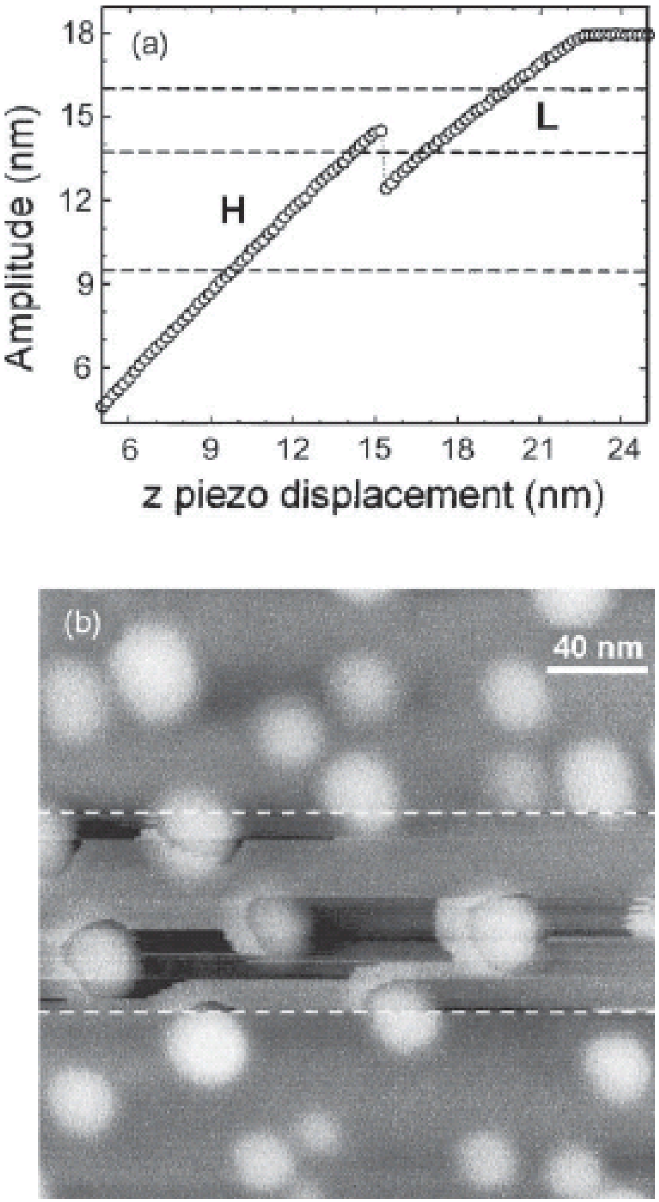


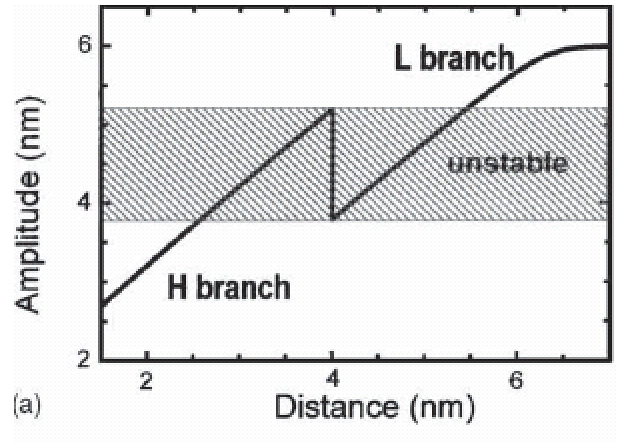




- In attractive regime, phase lag is greater than 90 degrees while in repulsive regime it is less than 90 degrees

Attractive-repulsive instability

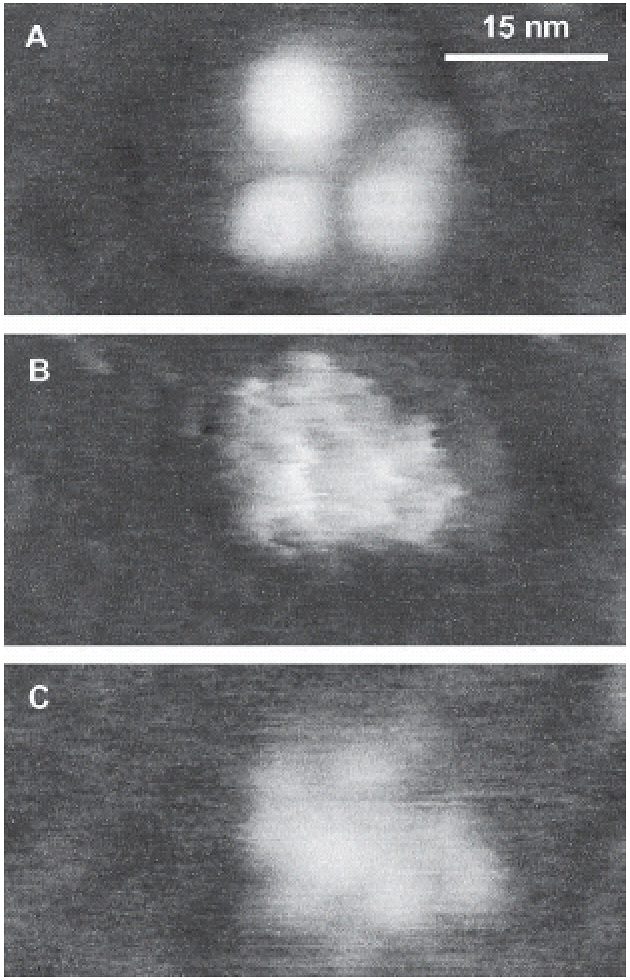




- Soft cantilevers, small amplitudes-> more attractive regime
- Stiff levers, larger amplitudes -> repulsive regime

Fig. 11. Experimental determination of the low and high amplitude branches. (a) Amplitude curve, the L and H branches are plotted by open circles. Dashed lines indicate the A_{sp} values used to image a 200 × 200 nm^2 InAs quantum dot sample. (b) The system evolves from stable imaging in the L state A_{sp} = 16 nm (top) to unstable imaging due to switching between H and L states A_{sp} = 13.8 nm (middle) and finally to stable imaging in the H state A_{sp} = 9.5 nm (bottom). Adapted from [56].

Attractive-repulsive instability



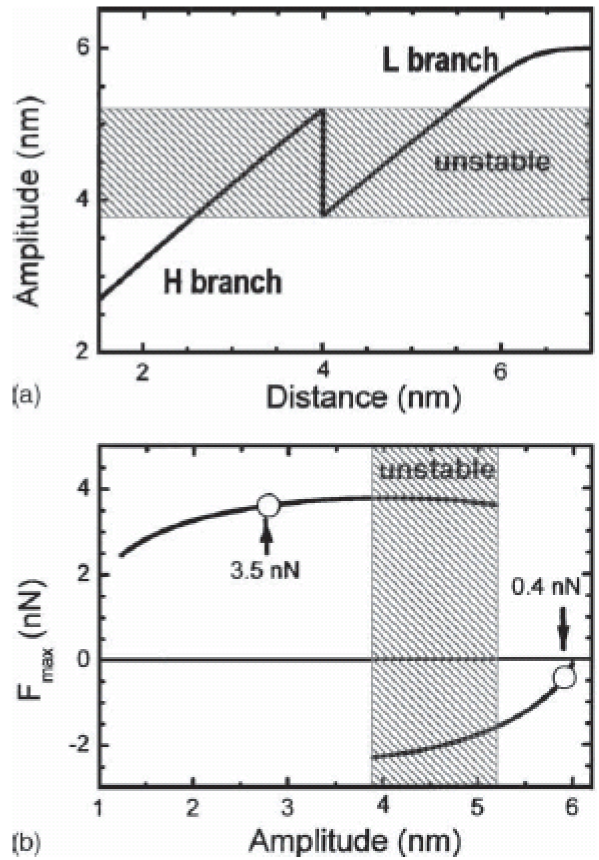


Fig. 12. (A) High-resolution image of a single a-HSA (obtained by operating in an L state). The three fragments and the hinge regions are clearly resolved. (B) Image of the same molecule obtained by operating the instrument in an H state. (C) Image of the molecule in the initial L state after repeated imaging in an H state. The characteristic shape of the molecule has been lost by imaging in an H state. Adapted from [7].

Next time

- Please Read Garcia and Perez in the reader
- VEDA for tuning and dynamic approach curves

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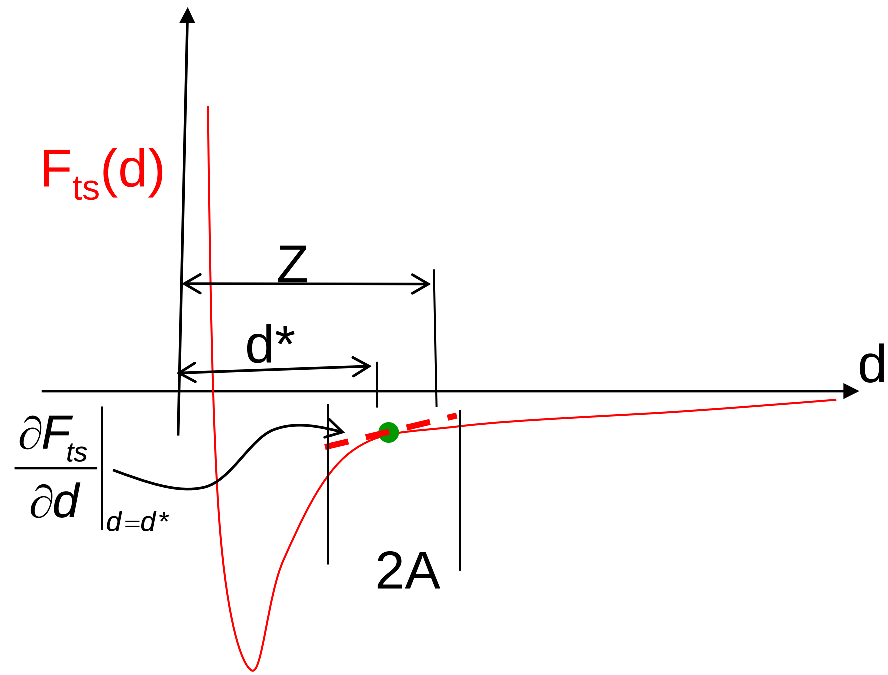

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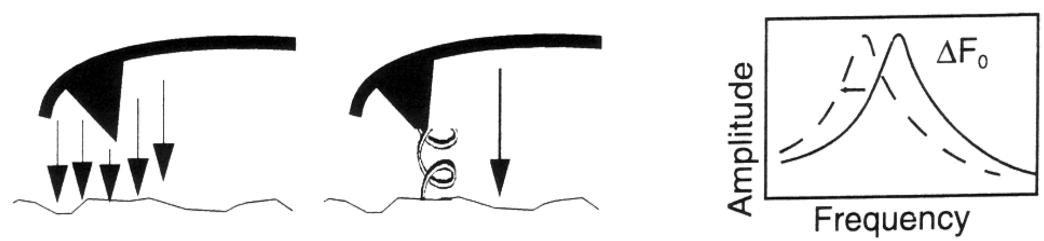

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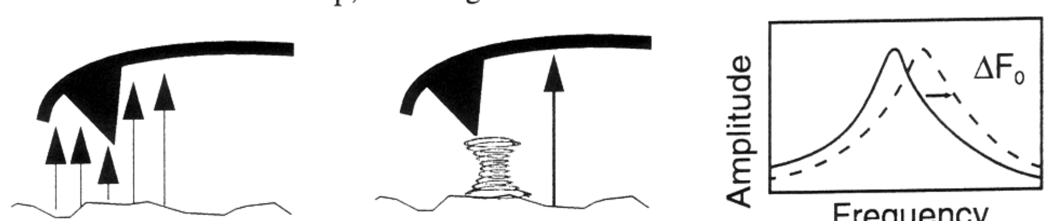

Repulsive gradient equivalent to additional spring in compression attached to tip, increasing the cantilever resonance frequency.

Linear vs. nonlinear tuning response