SHAKE, RATTLE and SLIP
thermal excitations in atomic-scale friction

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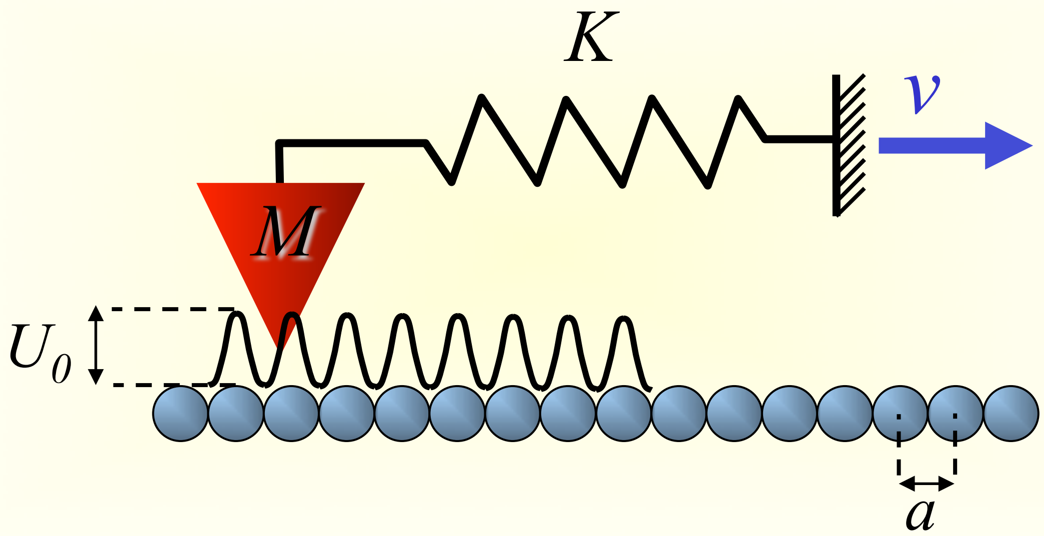
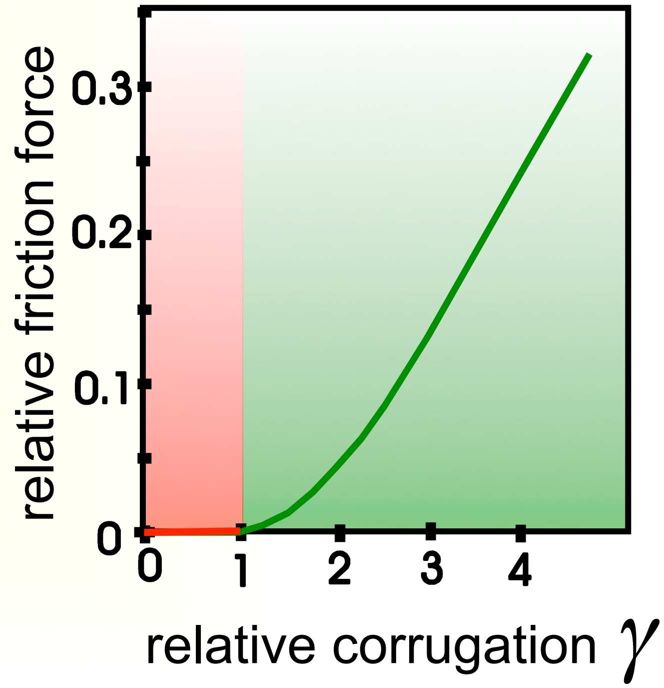
- Atomic stick-slip: superlubricity and **thermolubricity**
- Role of contact flexibility: *dominant!*
- Many friction regimes
- Temperature dependence

Prandtl - Tomlinson model (1929/1928)



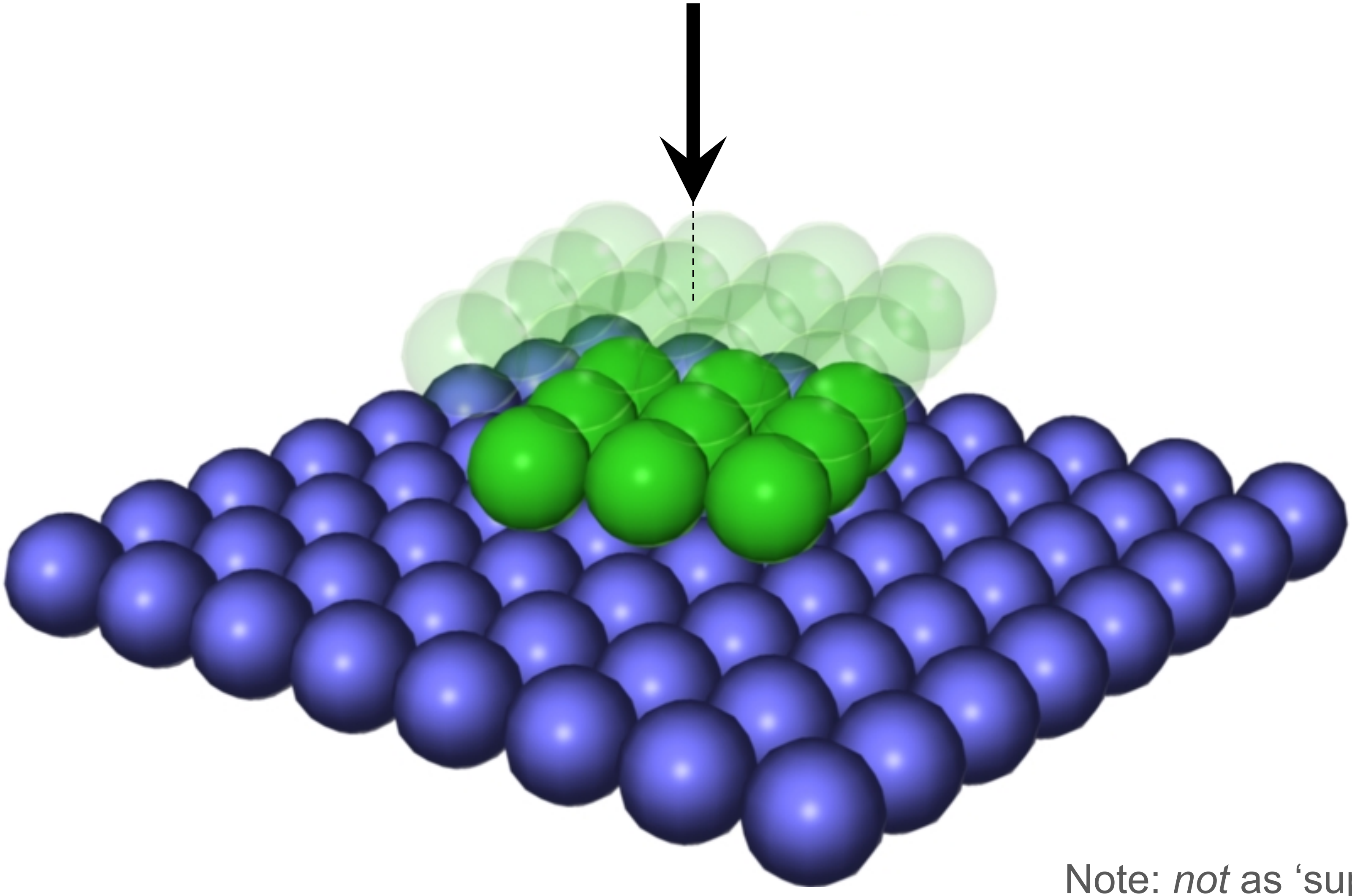


friction parameter : $\gamma = 2\pi^2 \frac{U_0}{Ka^2}$

Two regimes:

$\gamma > 1$	dissipative stick-slip motion	$\langle F \rangle \neq 0$
$\gamma < 1$	reversible motion "superlubricity"	$\langle F \rangle = 0$

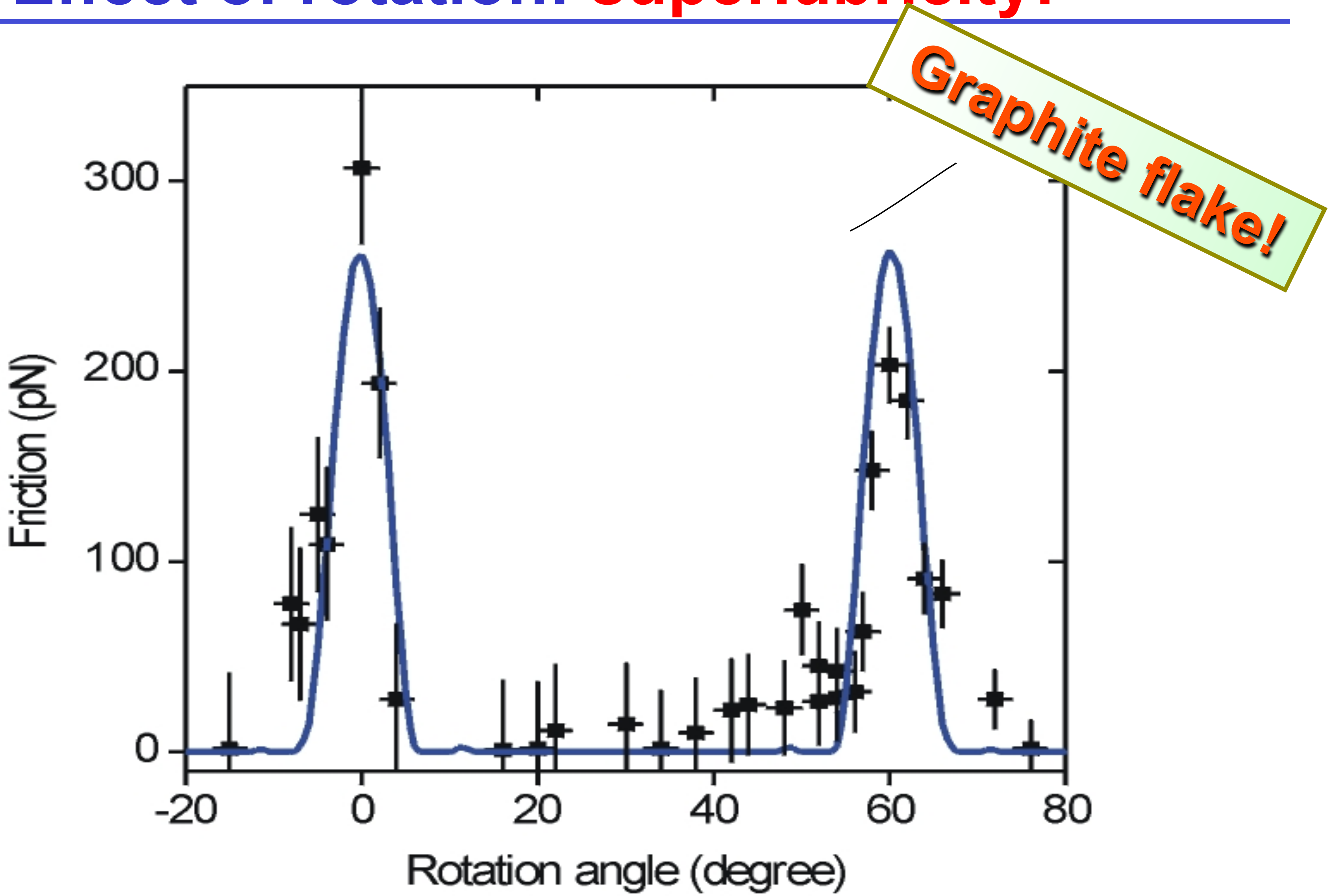
Orientational lubricity: *'Superlubricity'*



Hirano & Shinjo et al. (1990, 1993, 1997)

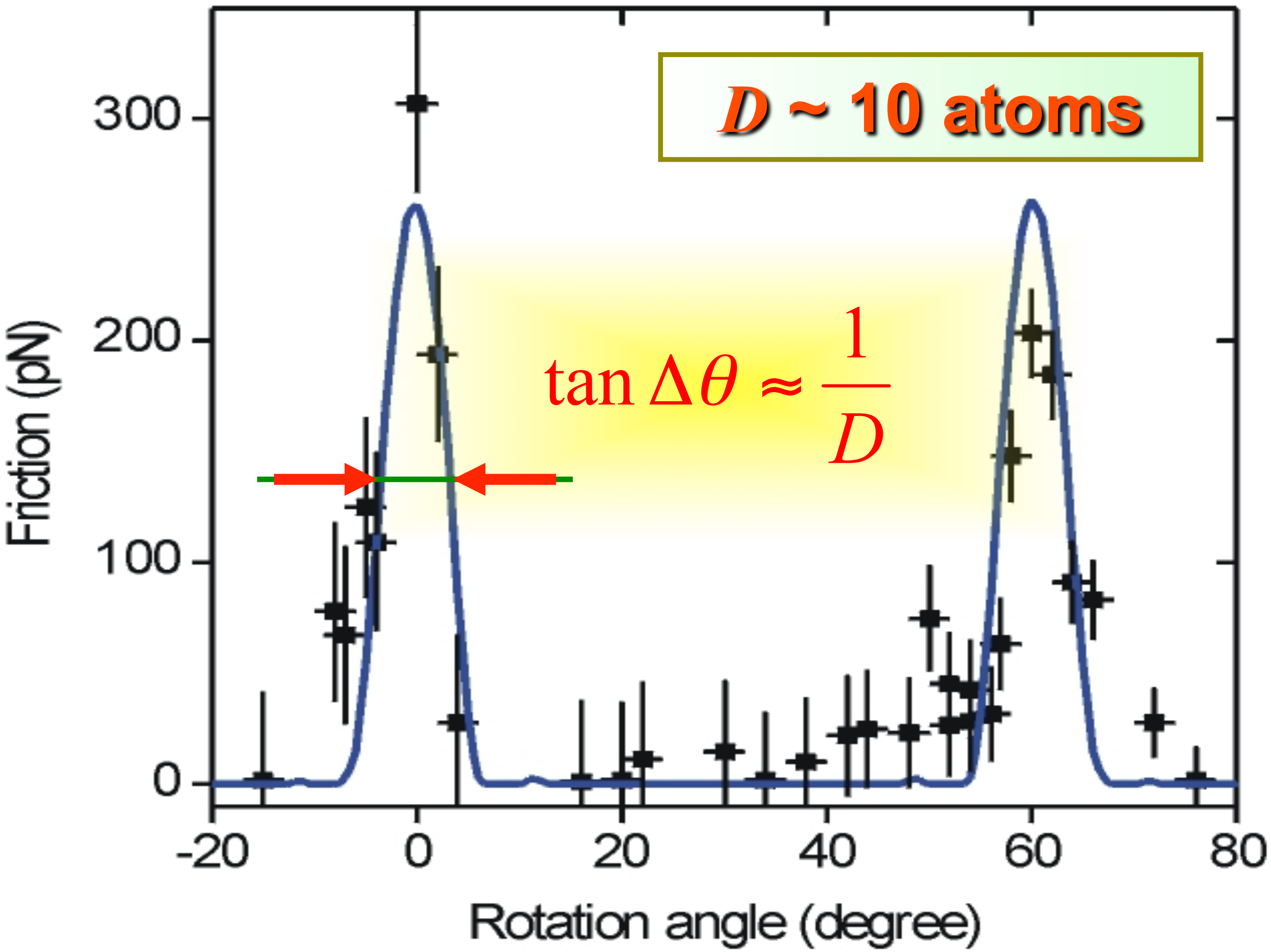
Note: *not* as 'super' as superconductivity or superfluidity

Effect of rotation: superlubricity!



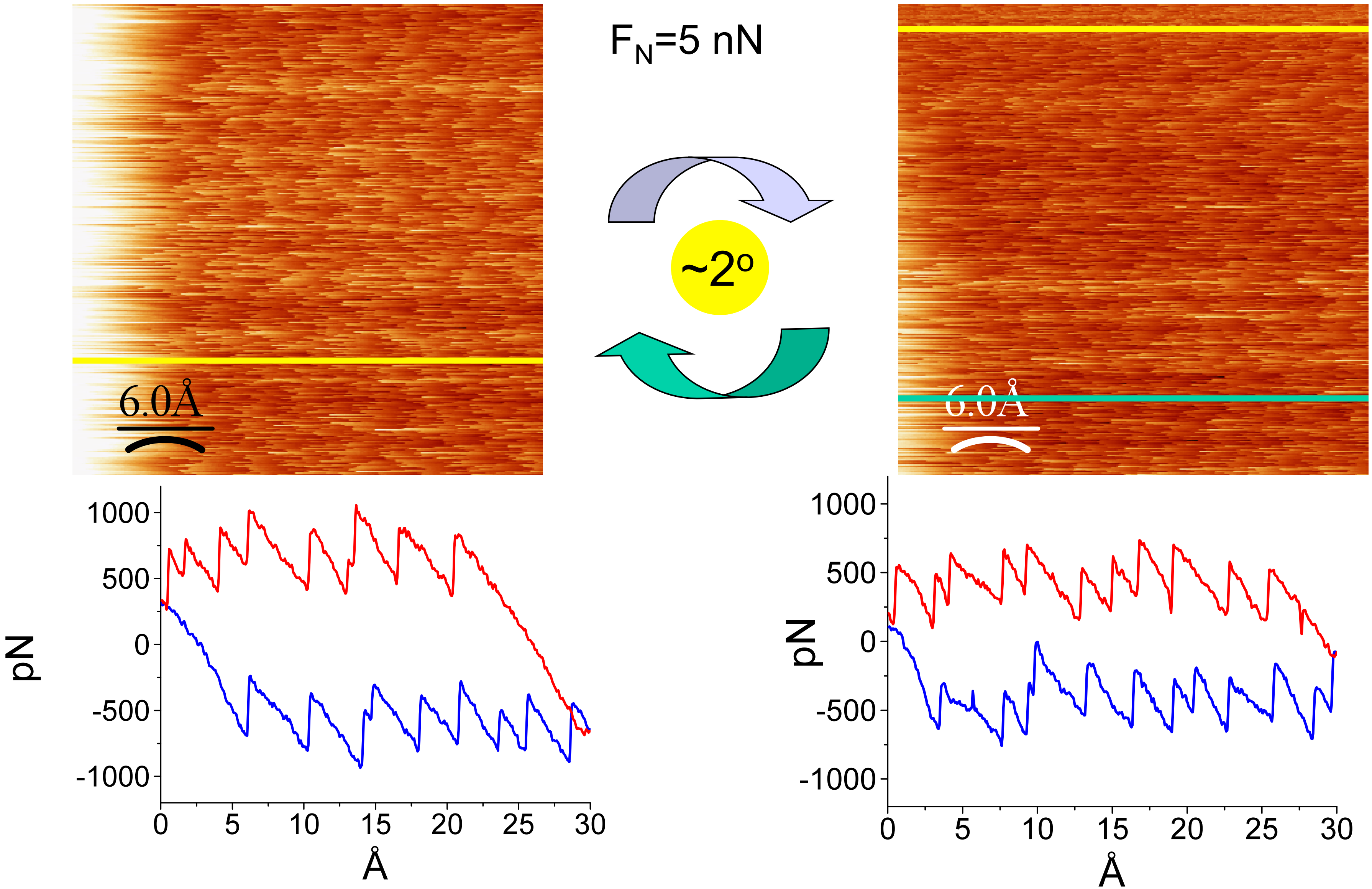
Dienwiebel et al., *PRL* **92** (2004) 126101

Width of the peak: flake diameter



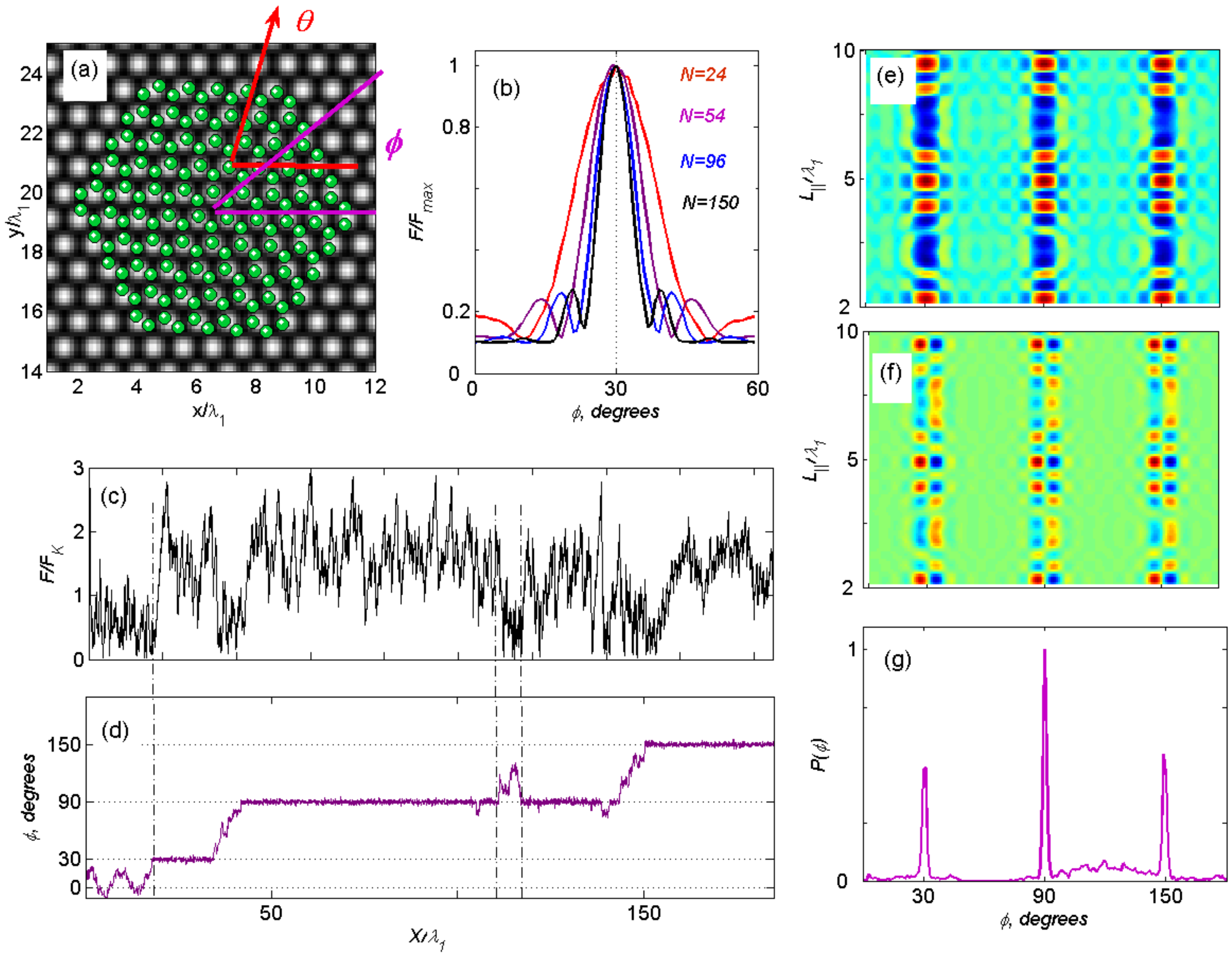
Dienwiebel et al., *PRL* **92** (2004) 126101

‘Loose’ flake



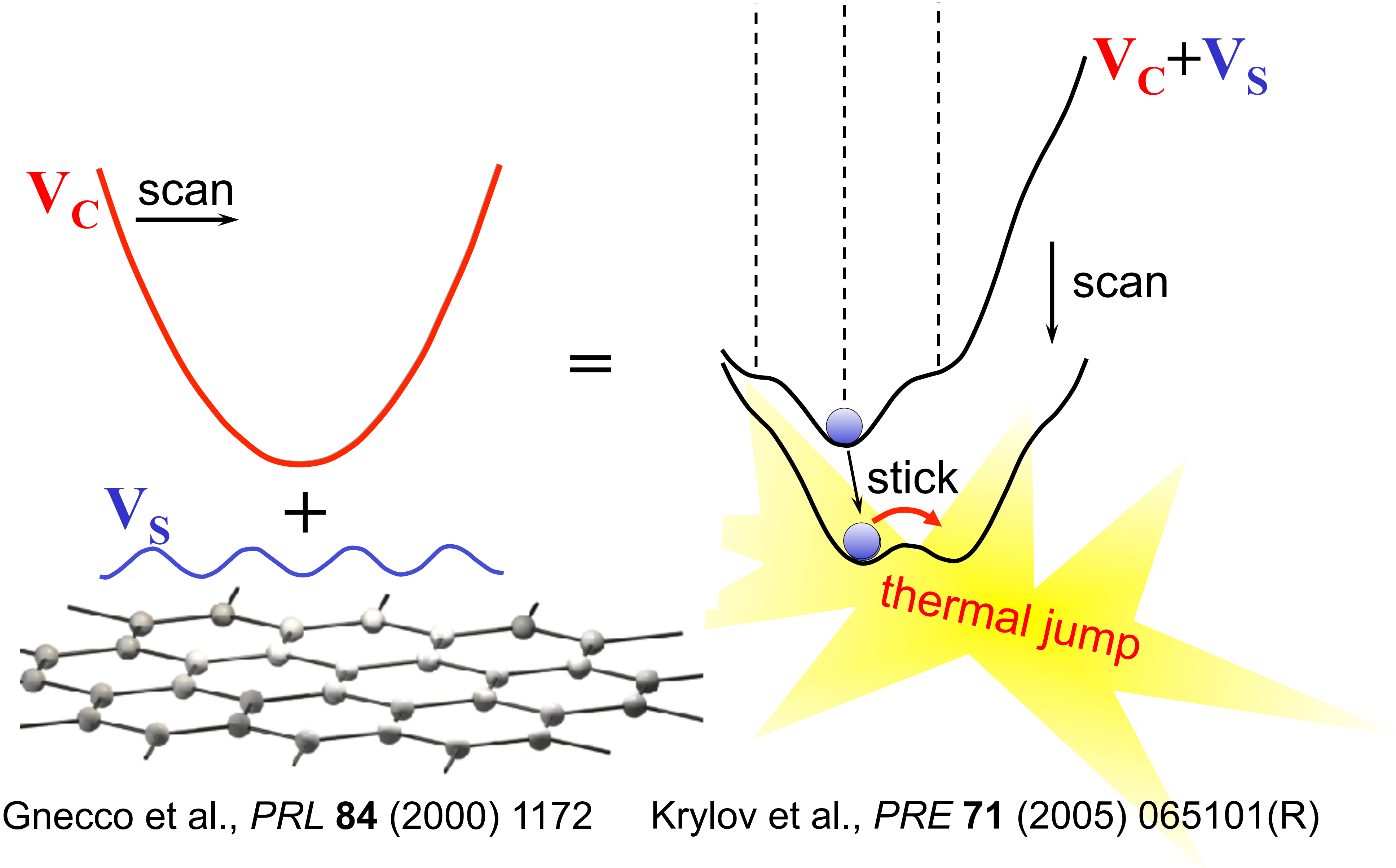
6.0Å
F$_N$=5 nN
~2°
6.0Å
1000
500
0
-500
-1000
pN
0 5 10 15 20 25 30
Å
1000
500
0
-500
-1000
pN
0 5 10 15 20 25 30
Å

Effect of torque on freely rotating flake



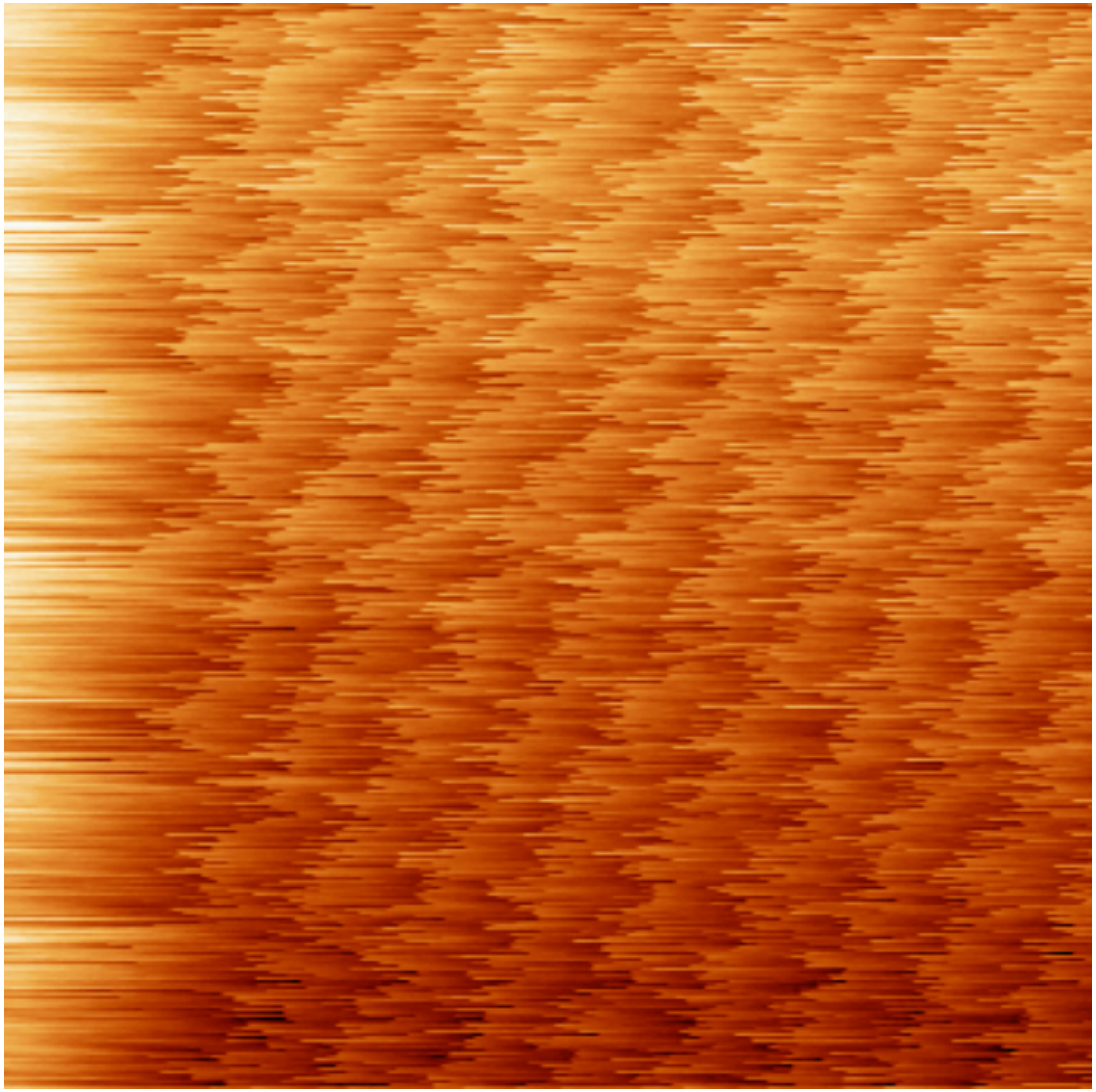
Fillipov *et al.*, *Phys.Rev.Lett.* **100** (2008)

Thermal excitations!



Gnecco et al., *PRL* **84** (2000) 1172 Krylov et al., *PRE* **71** (2005) 065101(R)

Thermal noise in the experiment



Simple theory with temperature

$$V\frac{dp_i}{dX} = -\left(r_i^+ + r_i^-\right)p_i + r_{i-1}^+ p_{i-1} + r_{i+1}^- p_{i+1}$$

$$i = 2, 3, 4, \ldots, i_{\max}$$

$$r_i^\pm = r_0 \exp\left(-\frac{U_i^\pm}{k_B T}\right)$$

$r_0 = \nu$ (TST)

$U_i^\pm(X)$

$\nu(X)$

p_i - probability to find the tip in well i

V - scanning velocity

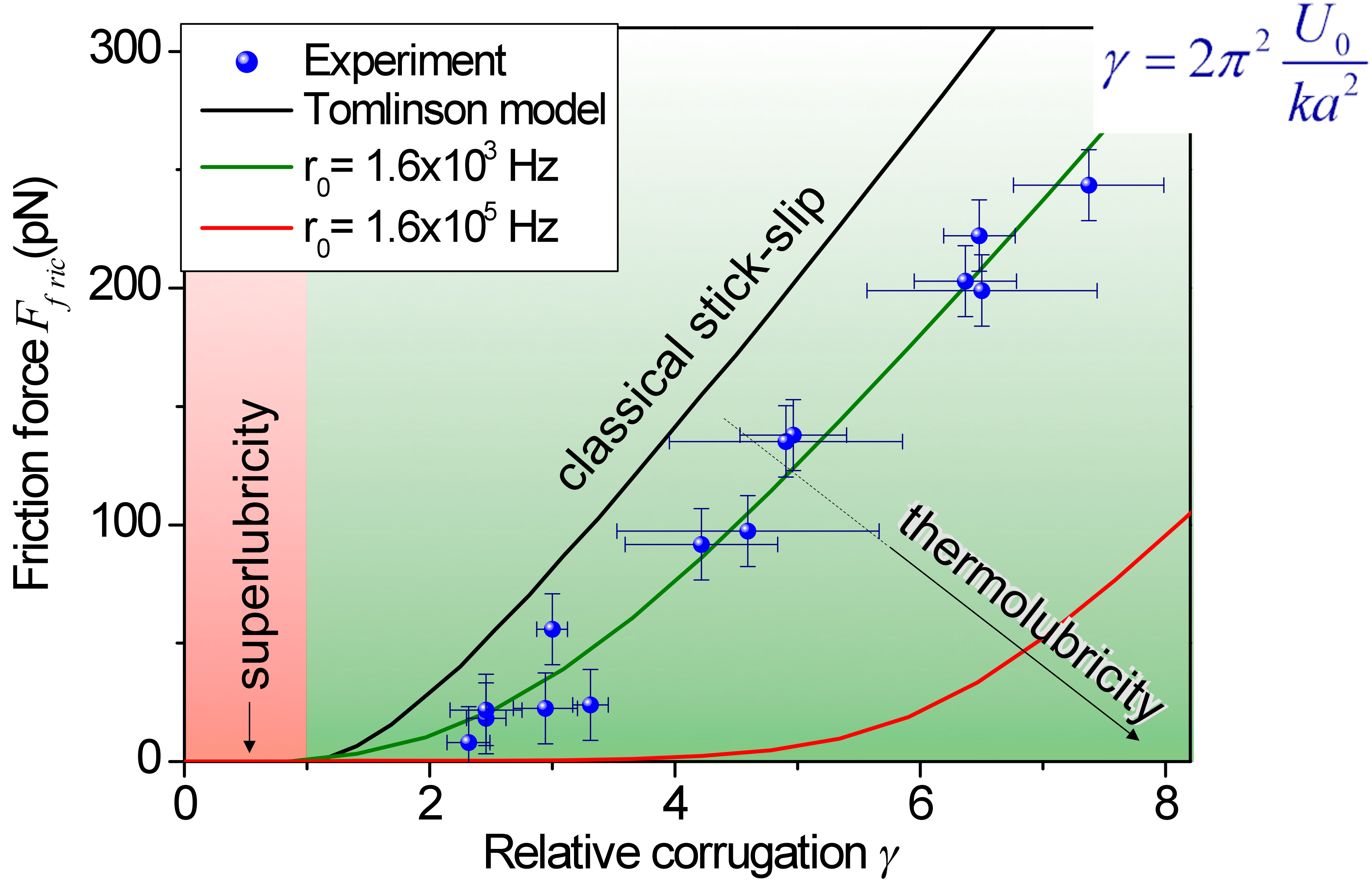
X - support position

r_i^+ and r_i^- - rates of activated jumps to the right and to the left, resp.

Potential barriers are known functions of X

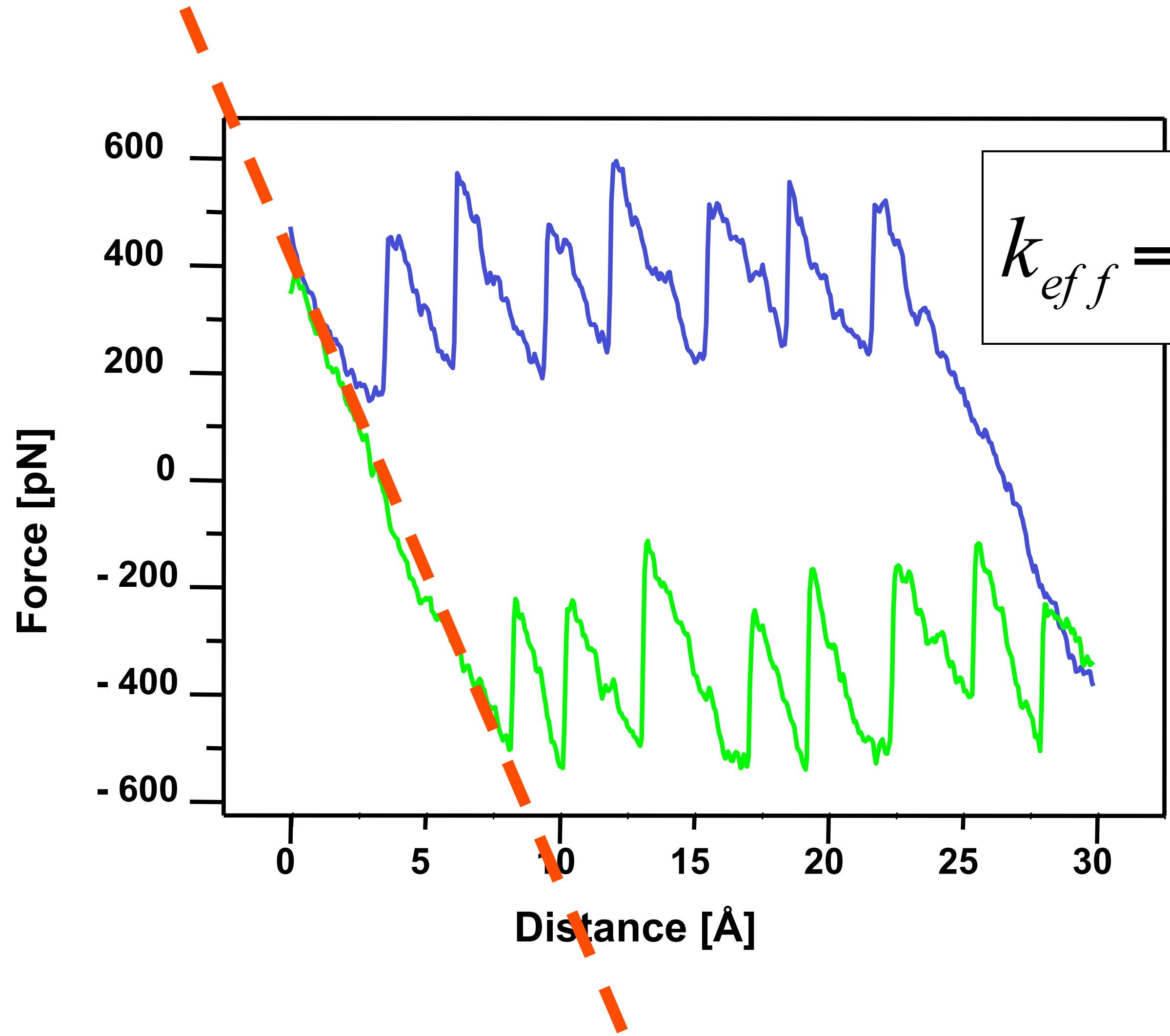
S.Yu. Krylov et al., *Phys. Rev.* E **71**, 065101(R) (2005)

Thermolubricity



S.Yu. Krylov et al., *Phys. Rev.* E **71**, 065101(R) (2005)

There's a second spring: the tip

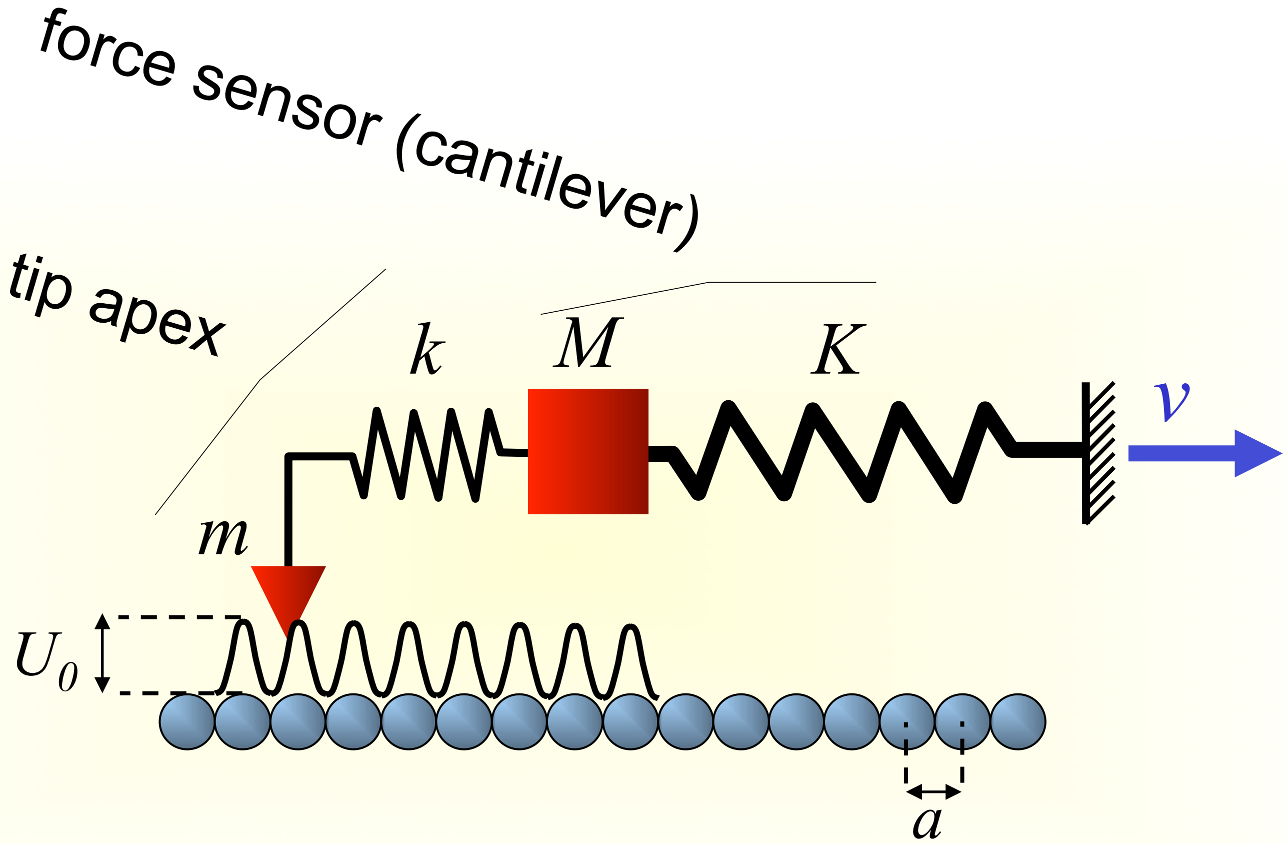


$$k_{eff} = \left(K^{-1} + k^{-1}\right)^{-1}$$

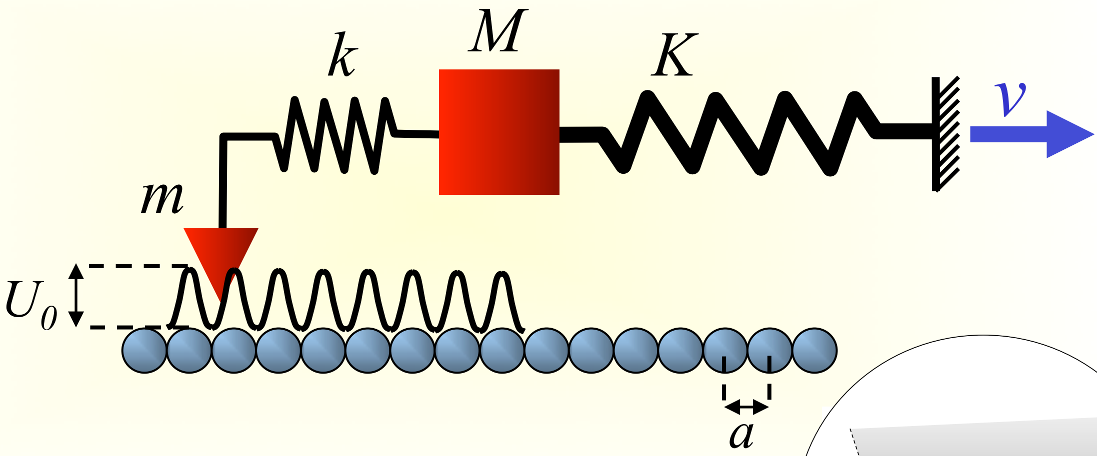
cantilever

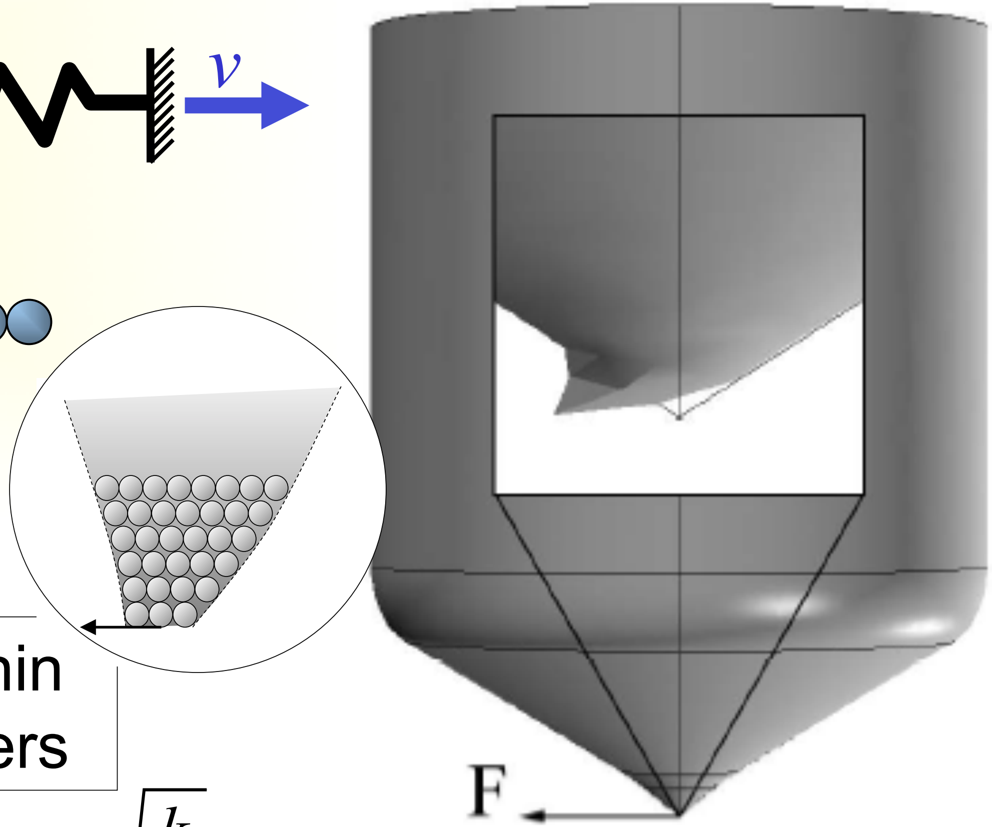
tip
(~2 N/m)

There's a second spring: the tip



There's a second spring: the tip .... apex





98% of deformation within the first 100 atomic layers

$m \leftrightarrow$ $\lesssim 10^5$ atoms $\Rightarrow$ $\omega_{tip} = \sqrt{\frac{k}{m}} > 1\ \mathrm{GHz}$

D. Abel et al., *Phys. Rev. Lett.* **99**, 166102 (2007)

S.Yu. Krylov et al., *Phys. Rev. Lett.* **97**, 166103 (2006)

Two–mass–two–spring model

Total potential:

$$U(X,x,t) = \frac{K}{2}(Vt - X)^2 + \frac{k}{2}(X - x)^2 + U_s(x)$$

support position (Vt) · cantilever position (X) · tip position (x)

Problem: ultra-slow motion of M and ultra-fast motion of m

Trick: combine Langevin dynamics for M:

$$M\ddot{X} = -k\left[X - x_i(X)\right] - K(X - Vt) - M\eta\dot{X} + \xi$$

with Monte Carlo dynamics for m:

$$r_{ij} = r_0 \exp\left(-U_{ij}/k_B T\right)$$

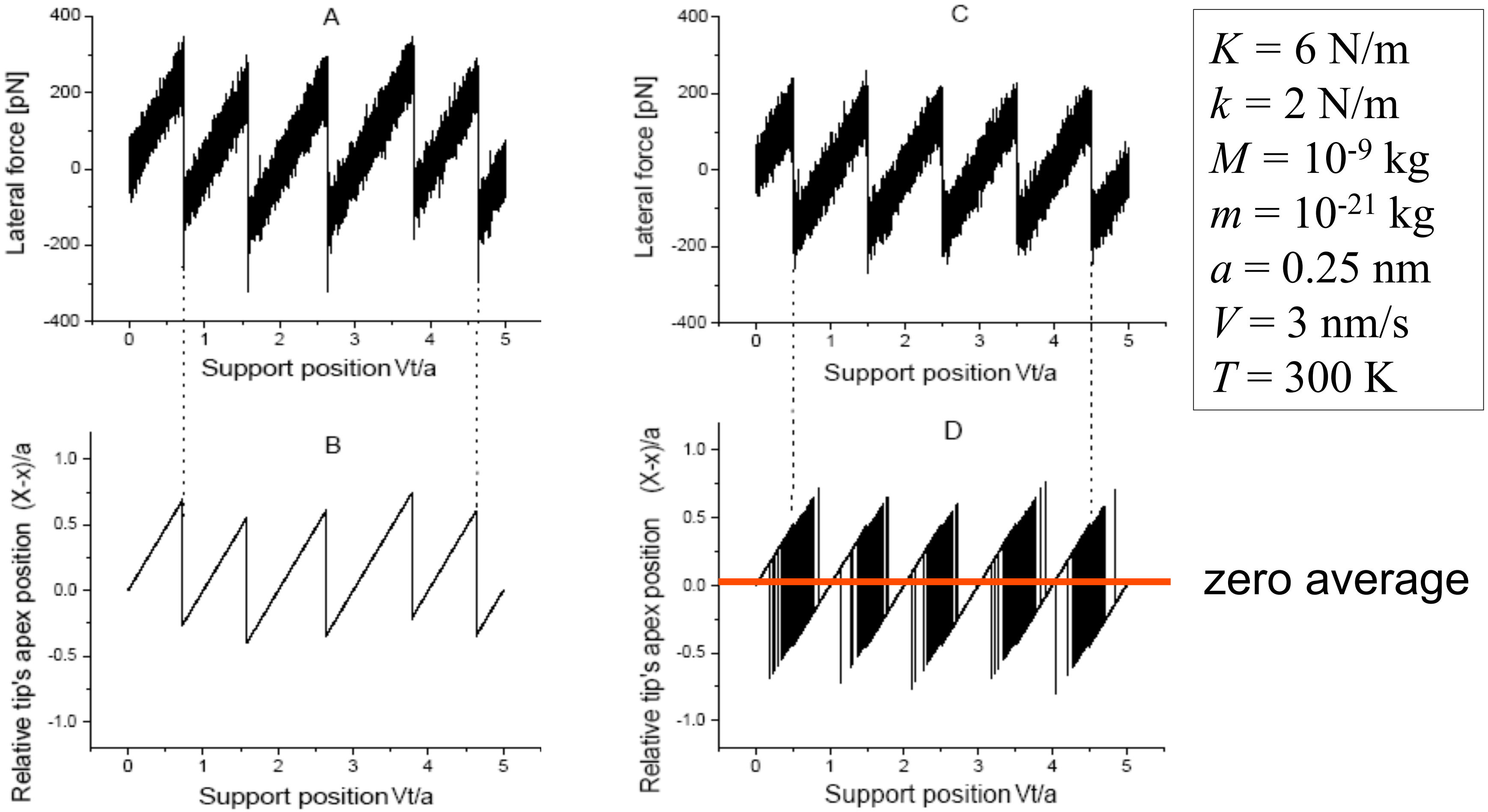
D. Abel et al., *Phys. Rev. Lett.* **99**, 166102 (2007)

“Stuck – in – slipperiness” regime

$U_0 = 0.60$ eV $\quad\quad$ $U_0 = 0.25$ eV

cantilever

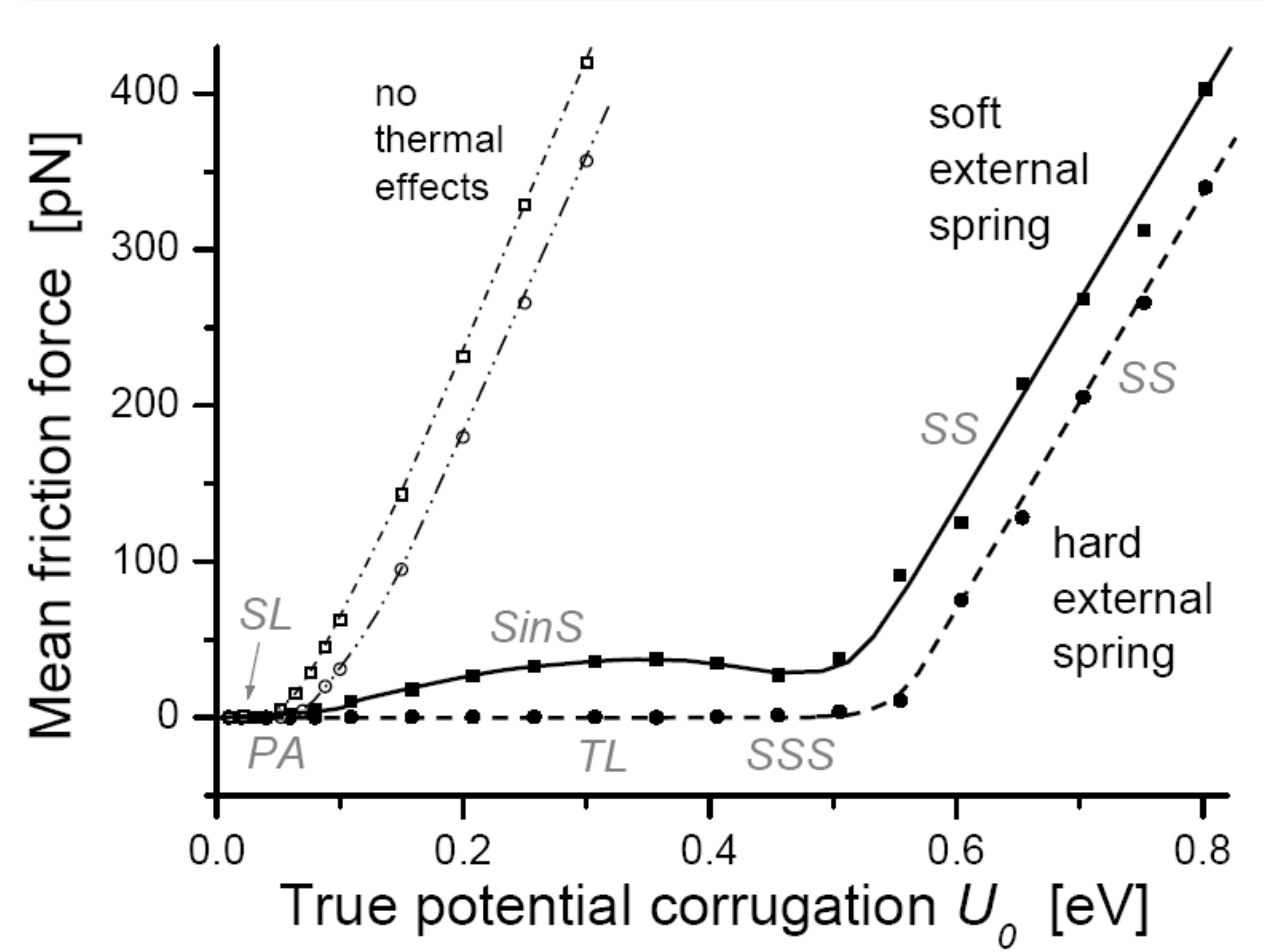
tip apex



$K = 6$ N/m
$k = 2$ N/m
$M = 10^{-9}$ kg
$m = 10^{-21}$ kg
$a = 0.25$ nm
$V = 3$ nm/s
$T = 300$ K

Krylov et al., *New J. Phys.* **9** (2007) 398

‘Zoo’ of regimes in FFM experiments



SL= superlubricity

PA = ‘passive apex’ regime

TL = thermolubricity

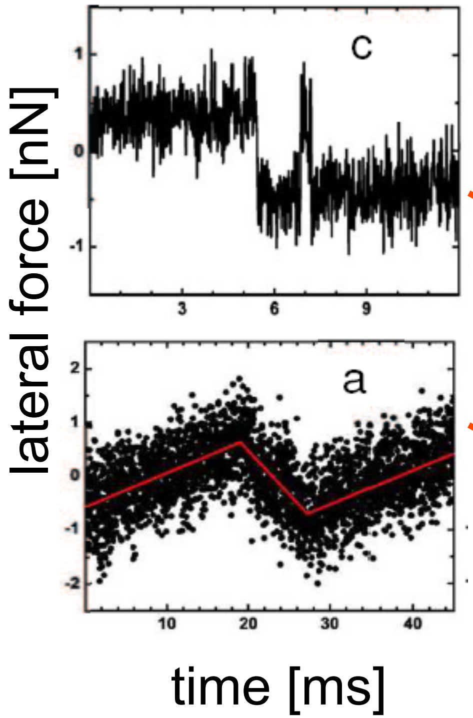
SinS = ‘stuck-in-slipperiness’ regime

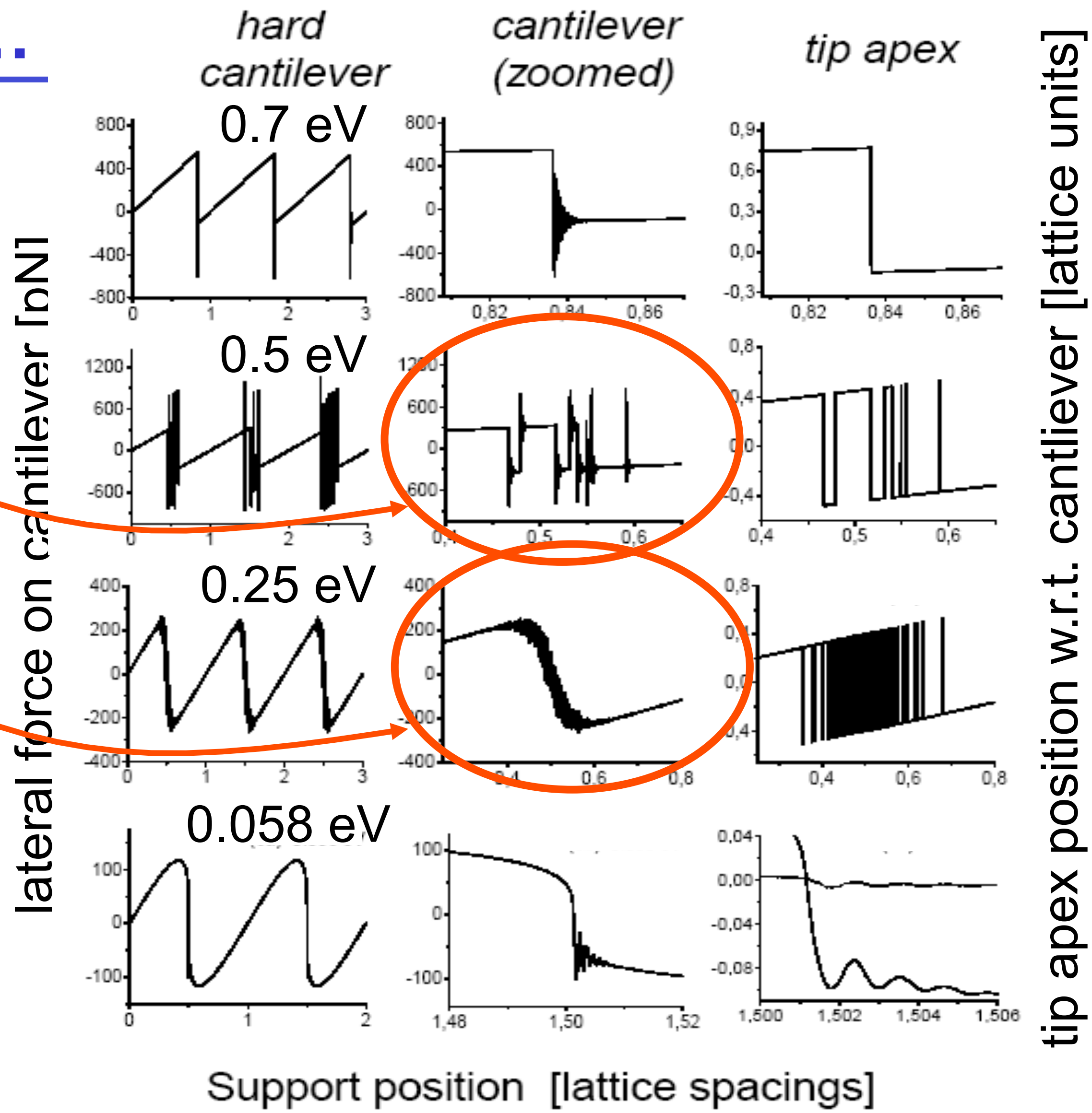
SSS = stochastic stick-slip

SS = ordinary stick-slip

Krylov et al., *New J. Phys.* **9** (2007) 398

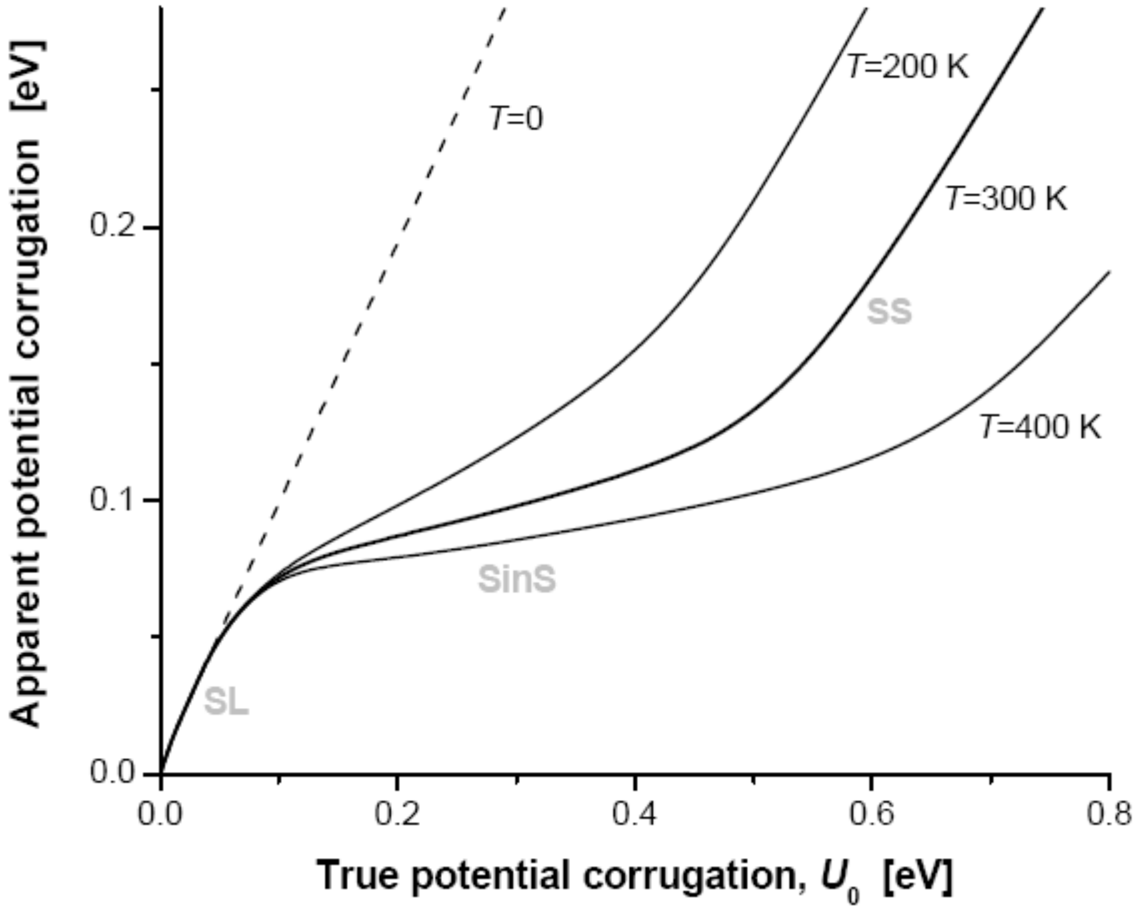
Indirect signs…





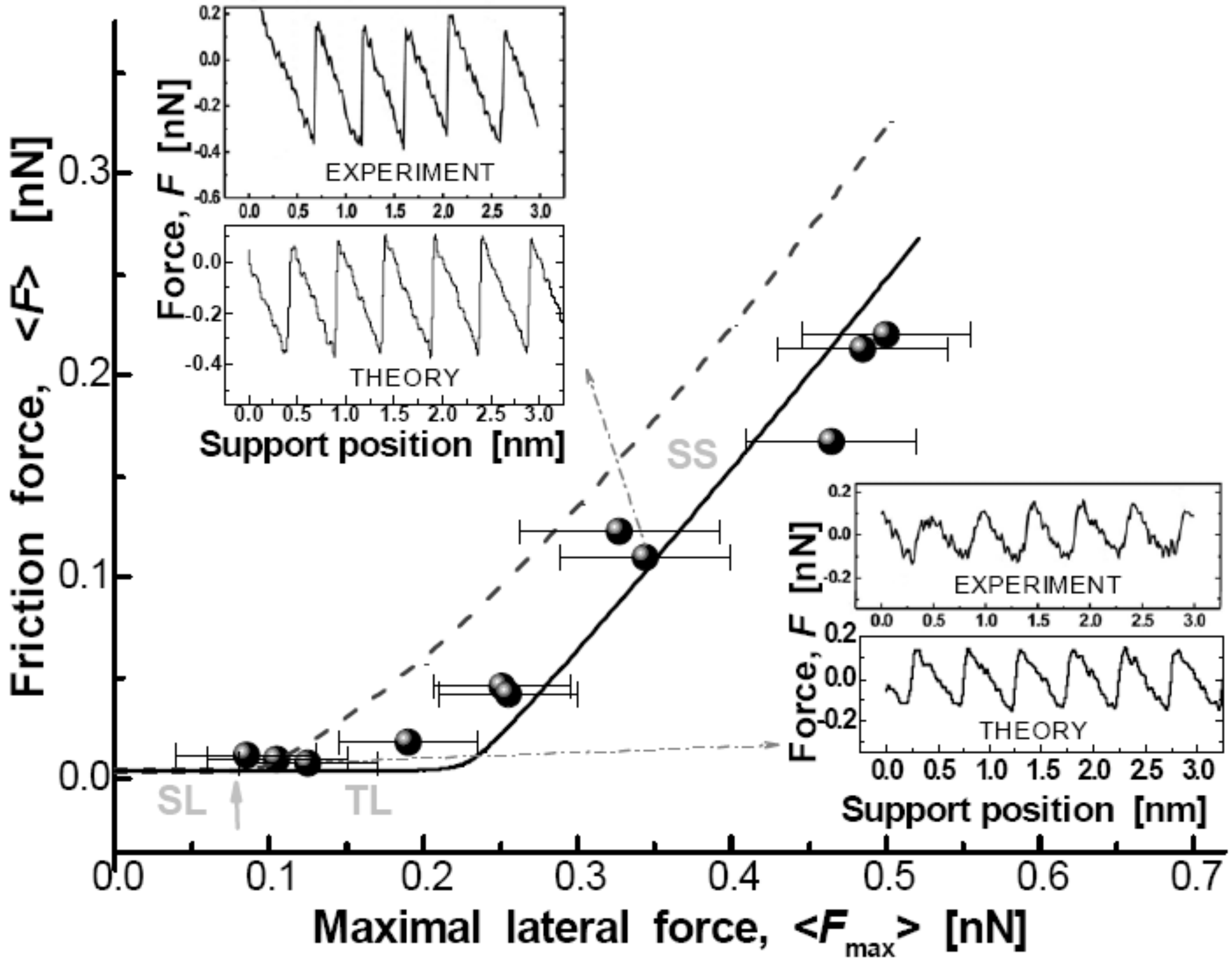
Maier, et al., *PRB* **72** , 245418 (2005)   Krylov et al., *New J. Phys.* **9** (2007) 398

Thermal effects are also dramatic for strong potentials



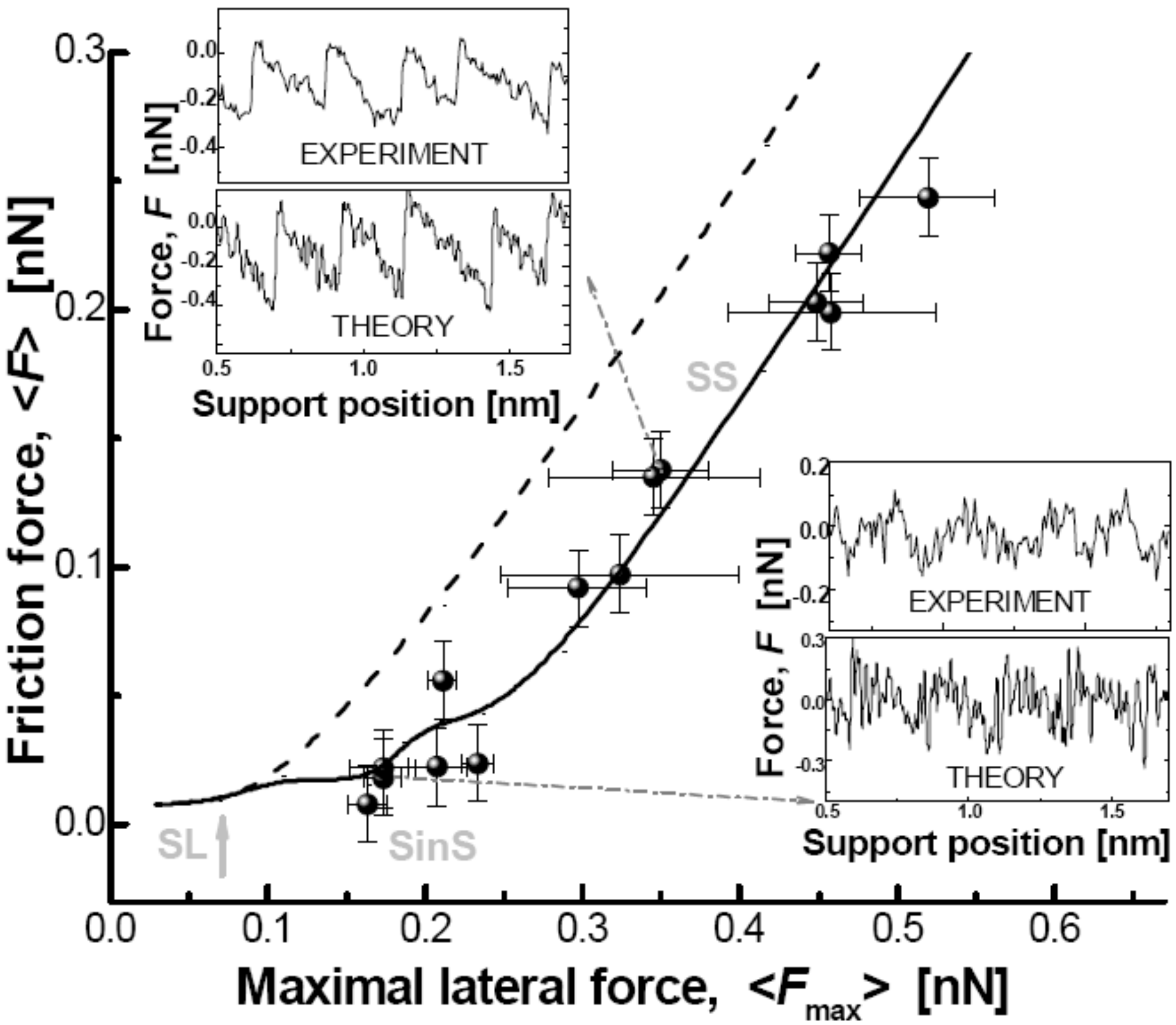
Krylov et al., *PR B* **80**, 235435 (2009)

‘Universal’ behavior: hard cantilever



data: Socoliuc et al., PRL **92**, 134301 (2004)   Krylov et al., *PR B* **80**, 235435 (2009)

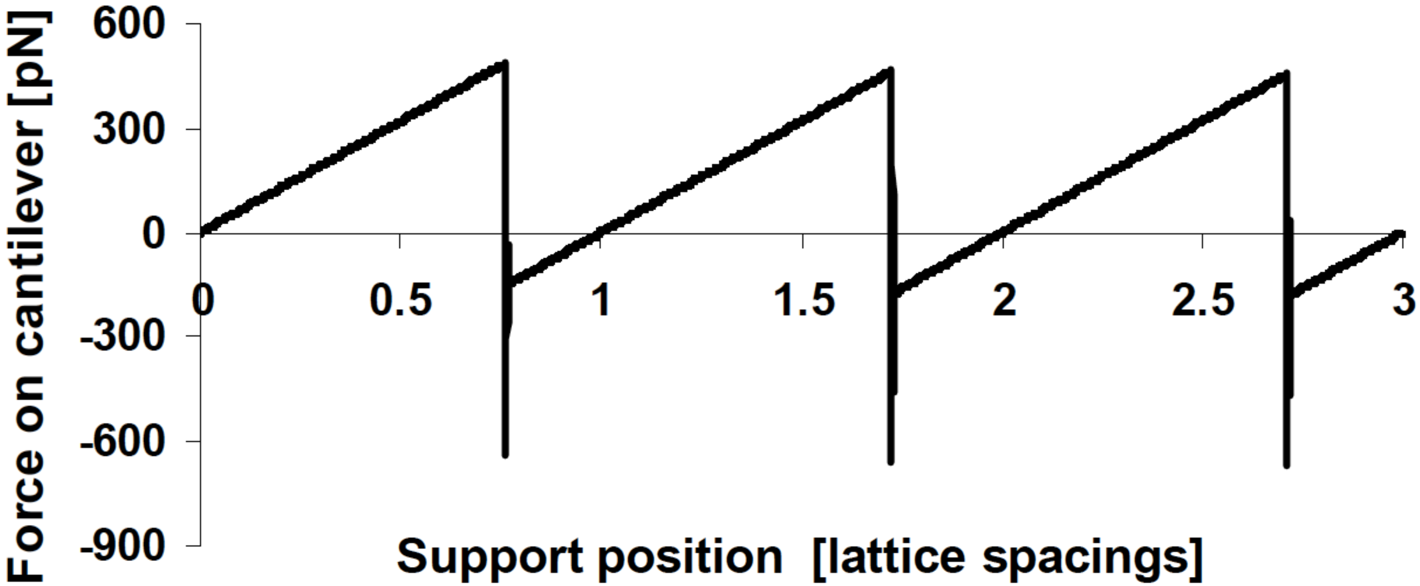
‘Universal’ behavior: soft cantilever



data: Dienwiebel et al., *PRL* **92**, 126101 (2004)   Krylov et al., *PR B* **80**, 235435 (2009)

Temperature dependence of sliding character

T = 200 K



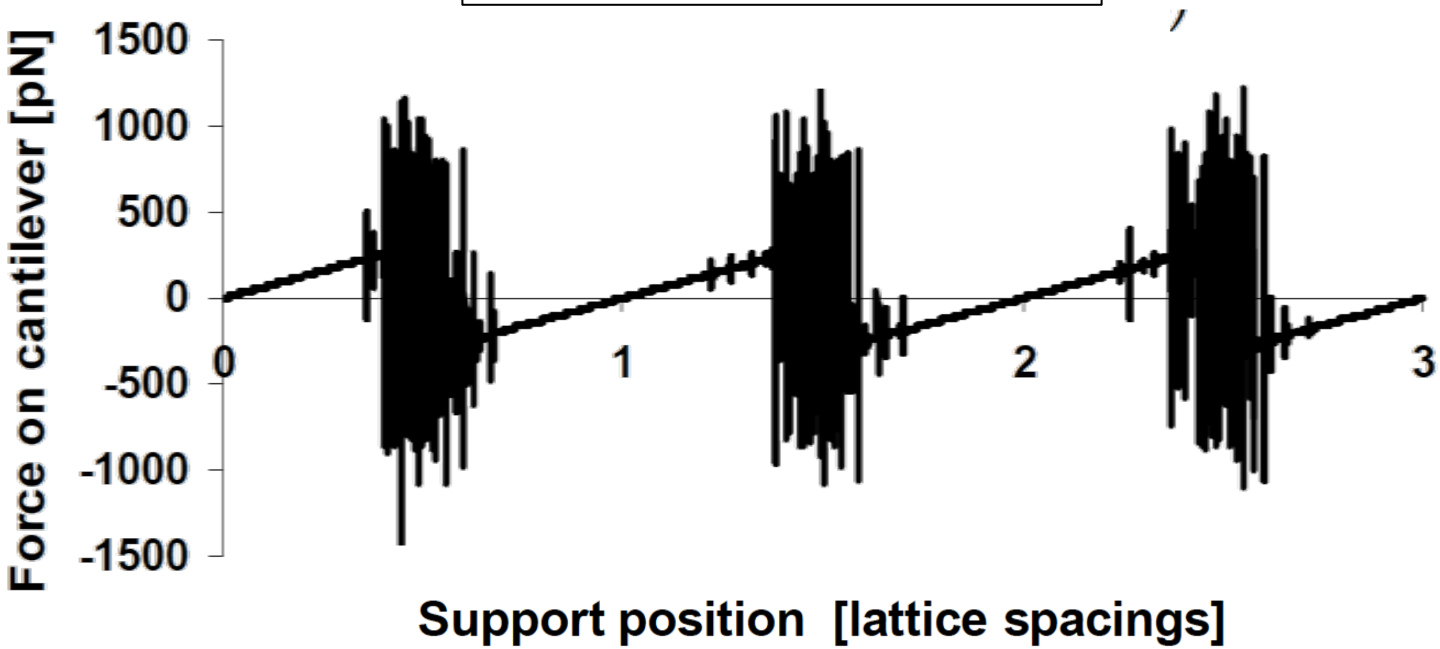
K = 60 N/m
k = 2 N/m
$M = 10^{-9}$ kg
$m = 10^{-21}$ kg
a = 0.25 nm
V = 3 nm/s
U_0 = 0.5 eV

ordinary stick-slip

Krylov et al., *JPCM* **20**, 354003 (2008)

Temperature dependence of sliding character

T = 350 K

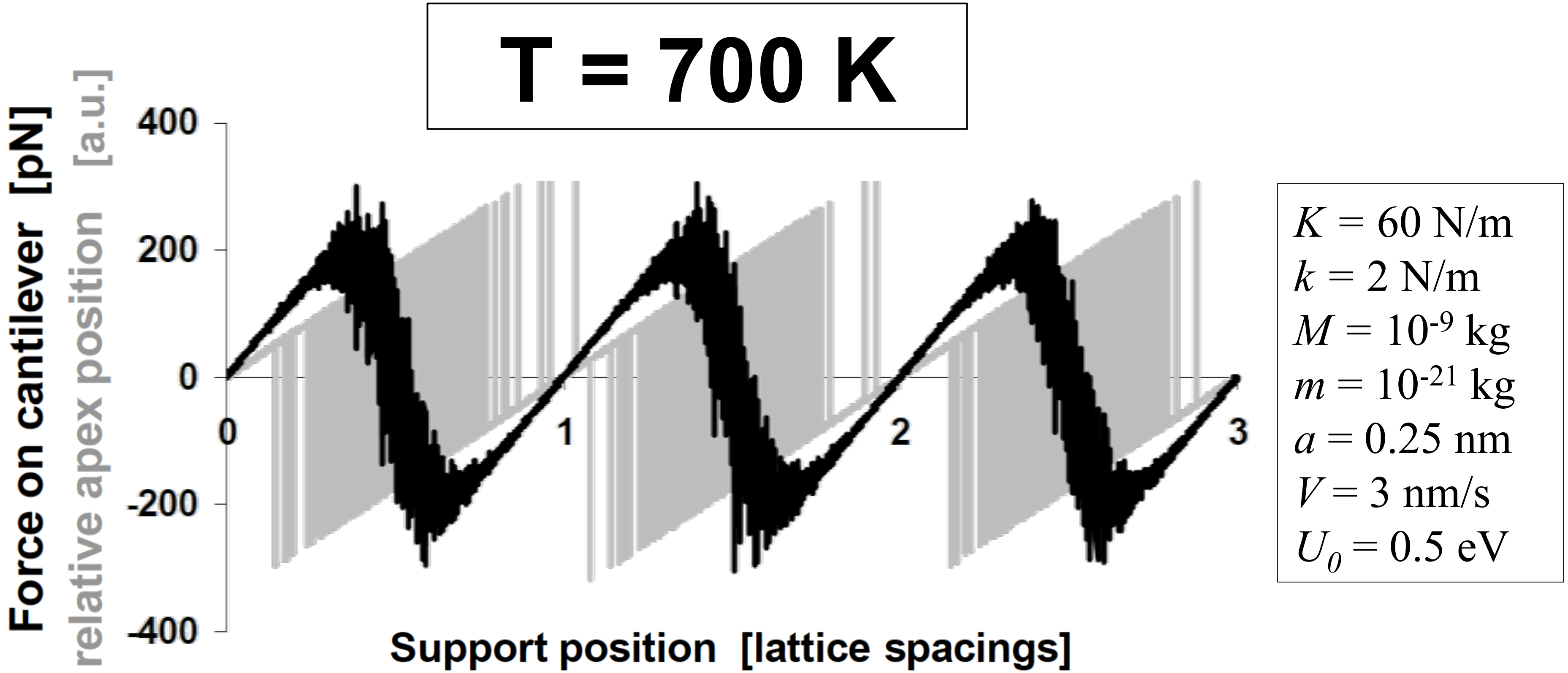


K = 60 N/m
k = 2 N/m
$M = 10^{-9}$ kg
$m = 10^{-21}$ kg
a = 0.25 nm
V = 3 nm/s
U_0 = 0.5 eV

stochastic stick-slip

Krylov et al., *JPCM* **20**, 354003 (2008)

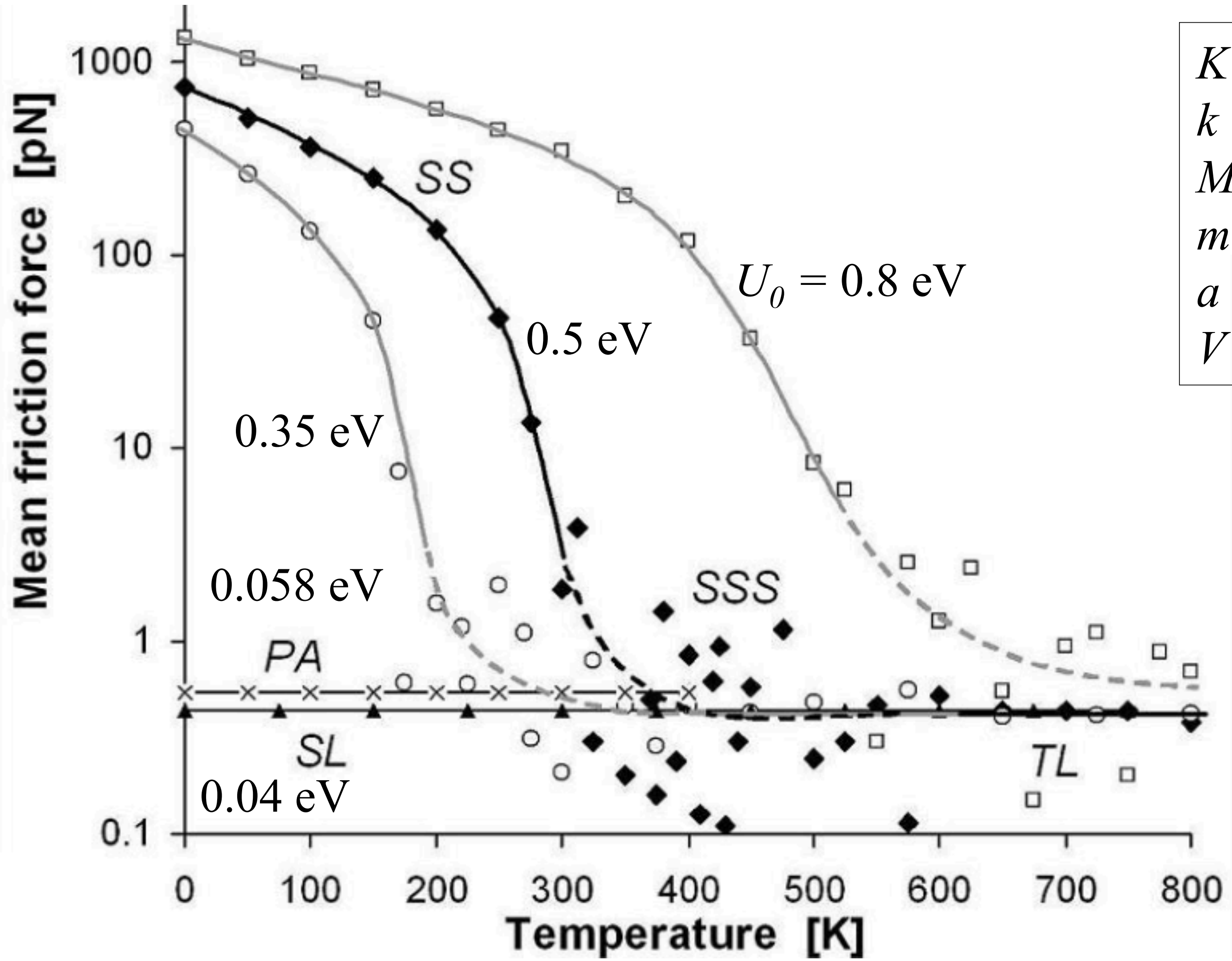
Temperature dependence of sliding character



thermolubricity

Krylov et al., *JPCM* **20**, 354003 (2008)

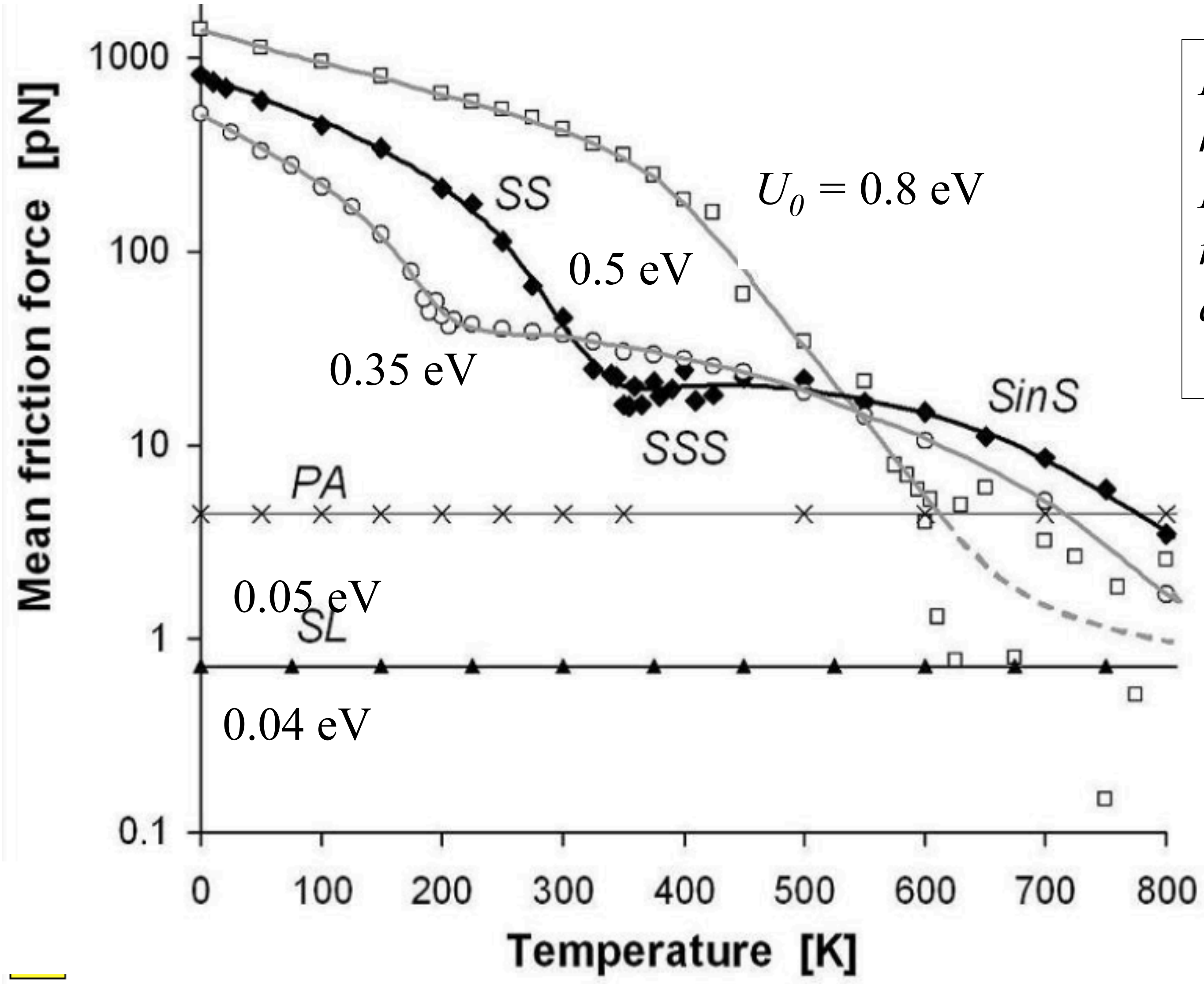
Temperature dependence: hard cantilever



K = 60 N/m
k = 3 N/m
$M = 10^{-9}$ kg
$m = 10^{-20}$ kg
a = 0.25 nm
V = 10 nm/s

Krylov et al., *JPCM* **20**, 354003 (2008)

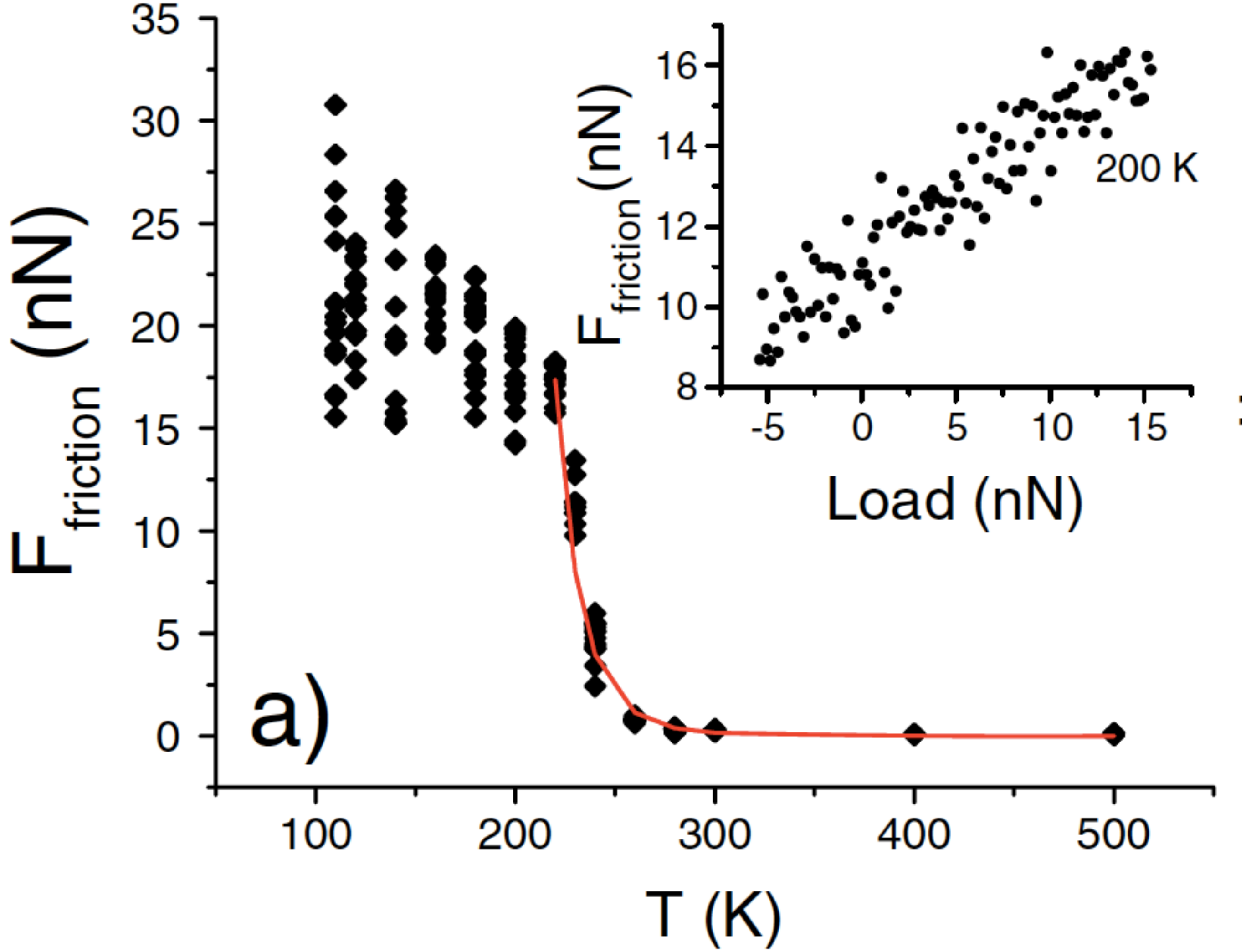
Temperature dependence: soft cantilever



K = 6 N/m
k = 3 N/m
$M = 10^{-9}$ kg
$m = 10^{-20}$ kg
a = 0.25 nm
V = 10 nm/s

Krylov et al., *JPCM* **20**, 354003 (2008)

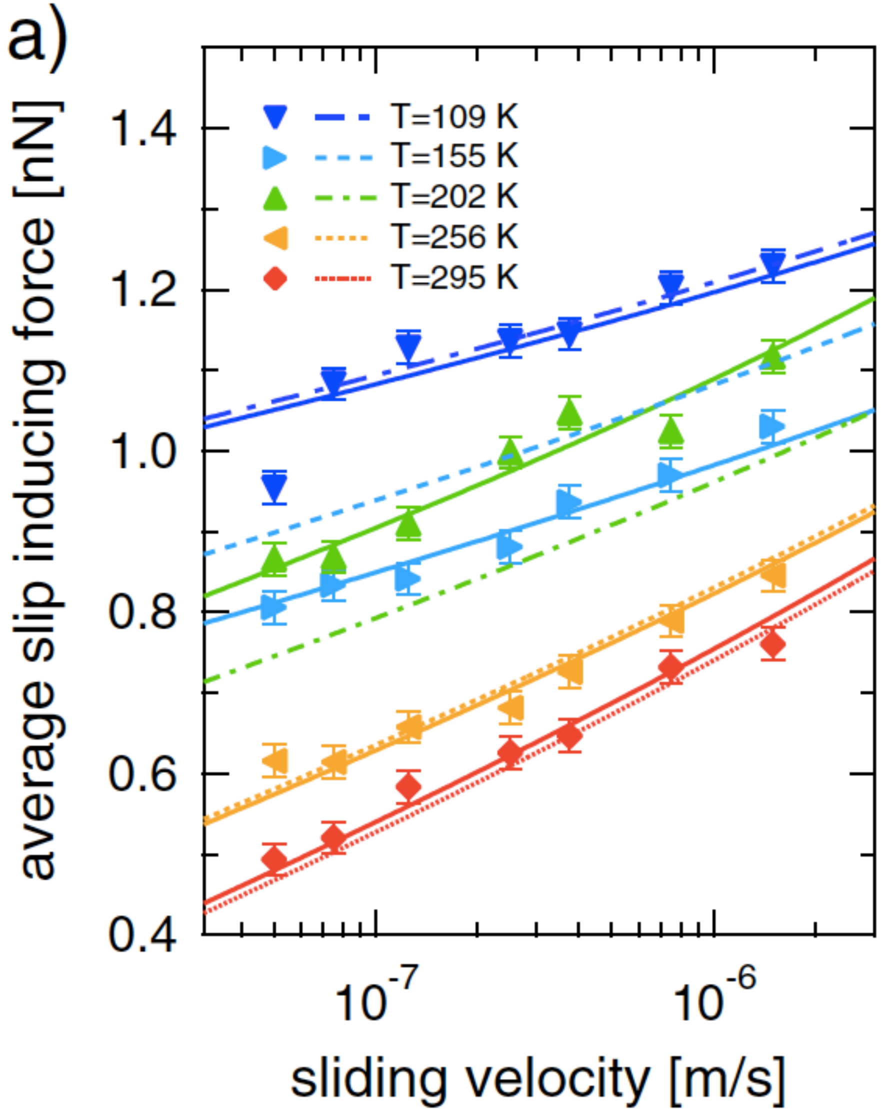
Experimental temperature dependences



Si_3N_4 tip on basal plane MoS_2

Zhao et al., *PRL* **102**, 186102 (2009)

Experimental temperature dependences



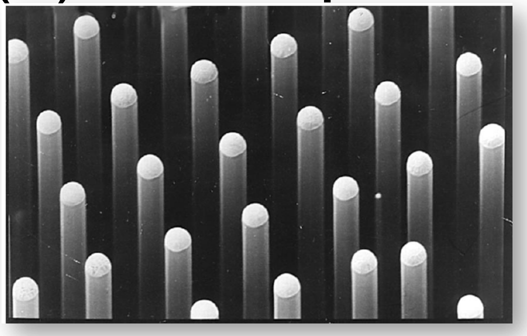
graphite

Janssen et al., *PRL **104**, 256101 (2010)*

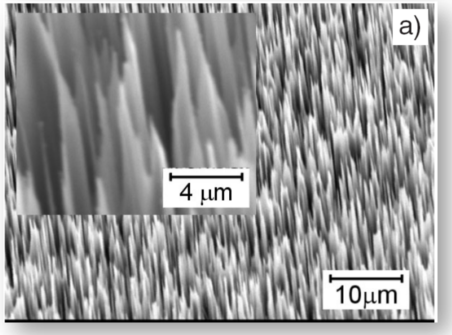
Outlook: scaling up thermolube?

- ***No:*** **larger contacts have larger stiffness…**
- ***Yes (maybe):*** **if we play tricks**

(1) multi-tip interfaces



silicon whiskers formed by vapor-liquid-solid growth



silicon 'nanograss' formed by anisotropic etching

(2) graphene-covered surfaces

Outlook: towards 'perfect' graphene

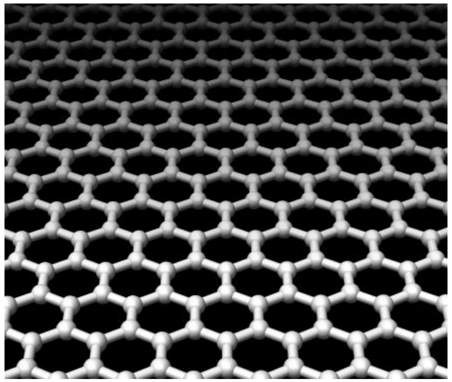
High-temperature STM movie

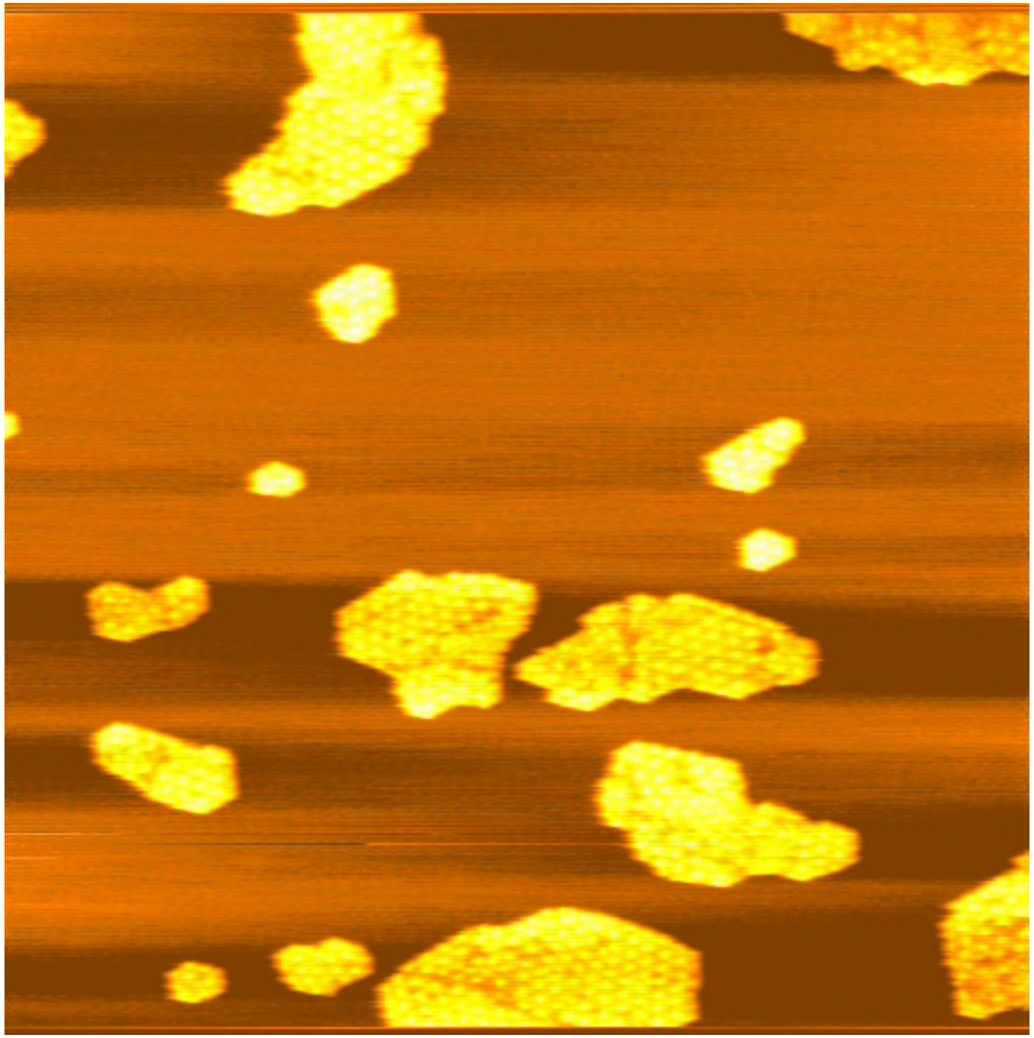
G. Dong et al., *to be publ.*

[similar study of *h*-BN:

PRL **104**, 096102 (2010)]

RT ⇒ 975K.
Rh(111) surface,
exposed to C_2H_4
$3 \times 10^{-9} \rightarrow 1 \times 10^{-8}$ mbar

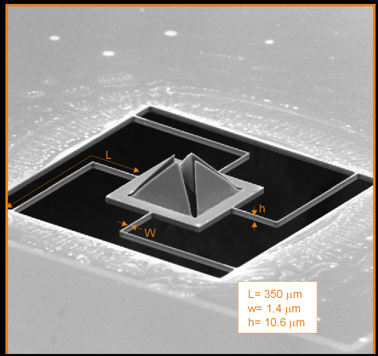


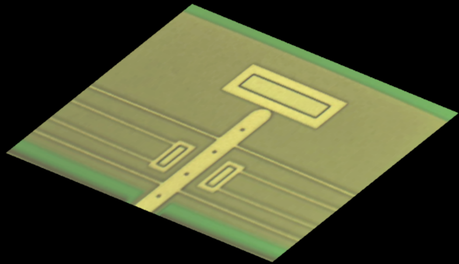


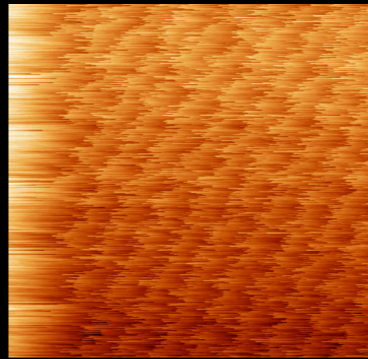
Summary

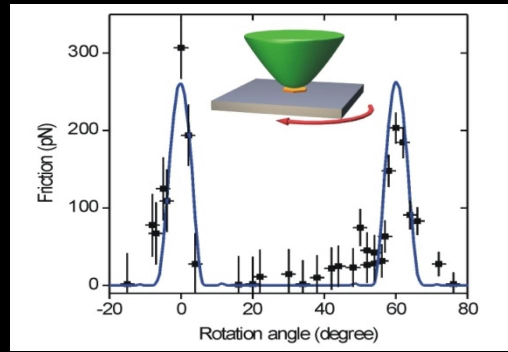
- **Proper FFM description: *two springs* with two very *different masses* and *time scales* plus *thermal excitations***
- **'Zoo' of friction regimes**
- **Measuring 'stick-slip' doesn't guarantee that the contact performs stick-slip...**
- **Non-trivial temperature dependence**
- **Many FFM measurements may be affected**

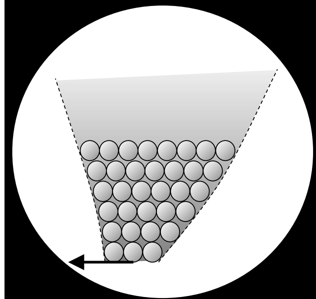
Collaborators: Sergey Krylov (Inst. Phys. Chem., Moscow), Daniel Abel, Hugo Valk, Joshua Dijksman











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