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Friction and thermolubrication: thermal fluctuations and 'universal' behaviour

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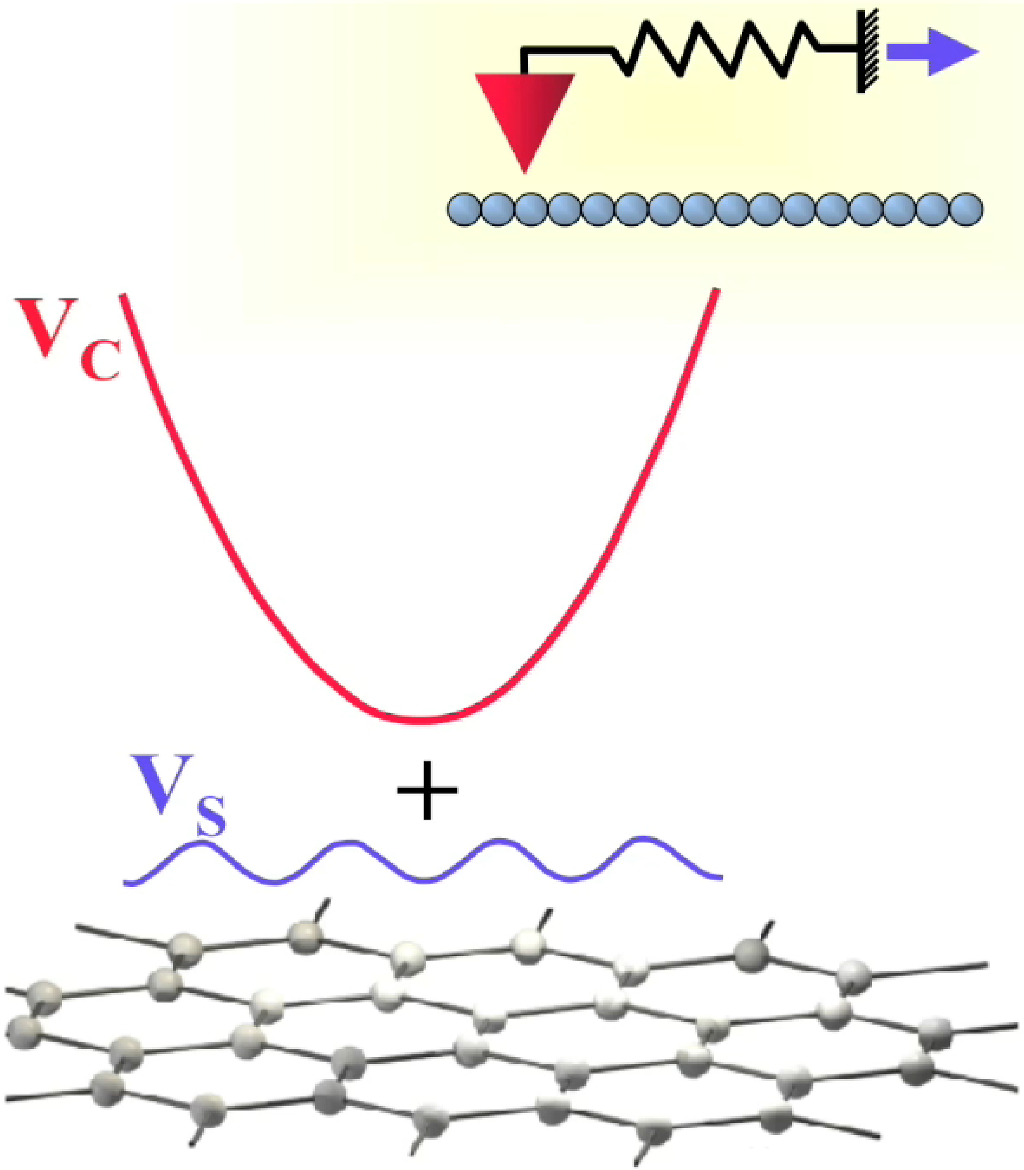
Friction and Thermolubrication
fluctuations and 'universal' behavior

Joost Frenken & Sergey Krylov
Kamerlingh Onnes Laboratory, Leiden University, Netherlands

- Friction force microscopy
- Atomic stick-slip: **superlubricity** and **thermolubricity**
- Role of contact flexibility: *surprising!*
- *'Zoo'* of friction regimes…

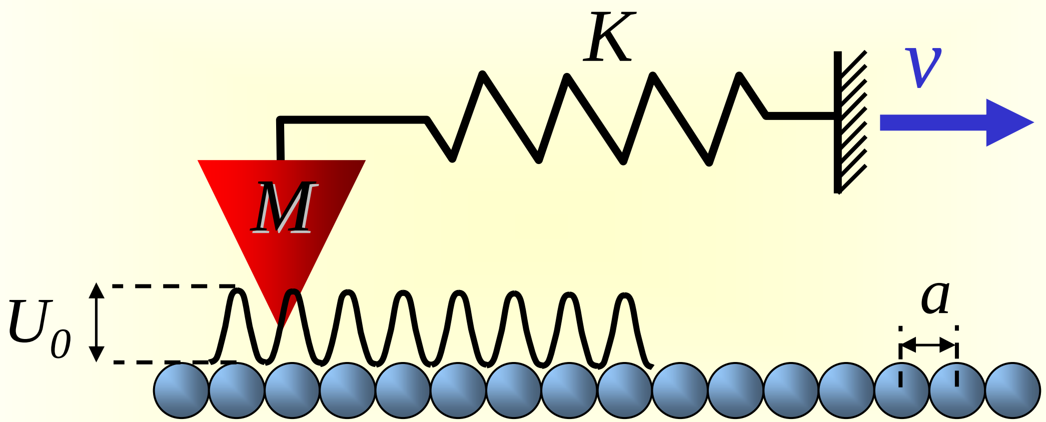
FOM NWO stw nano ned LPM ESRF Smart mix

Prandtl - Tomlinson model (1929/1928)

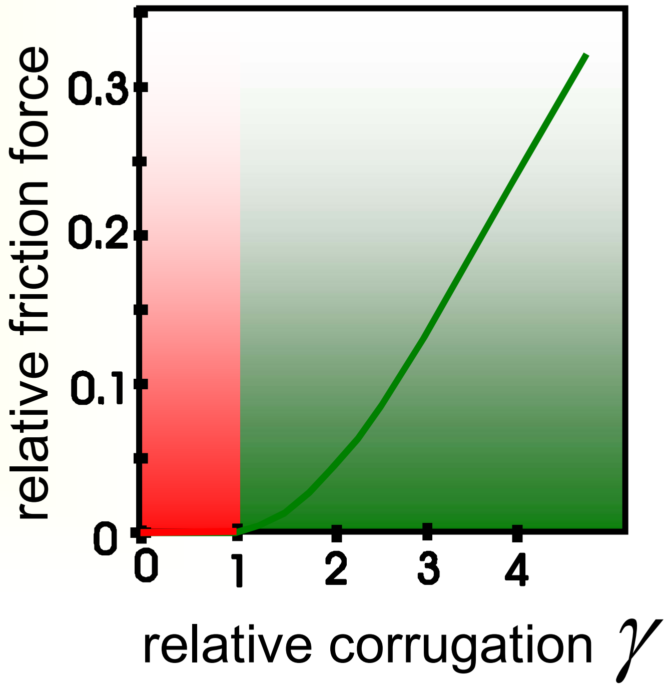


movie

Prandtl - Tomlinson model (1929/1928)



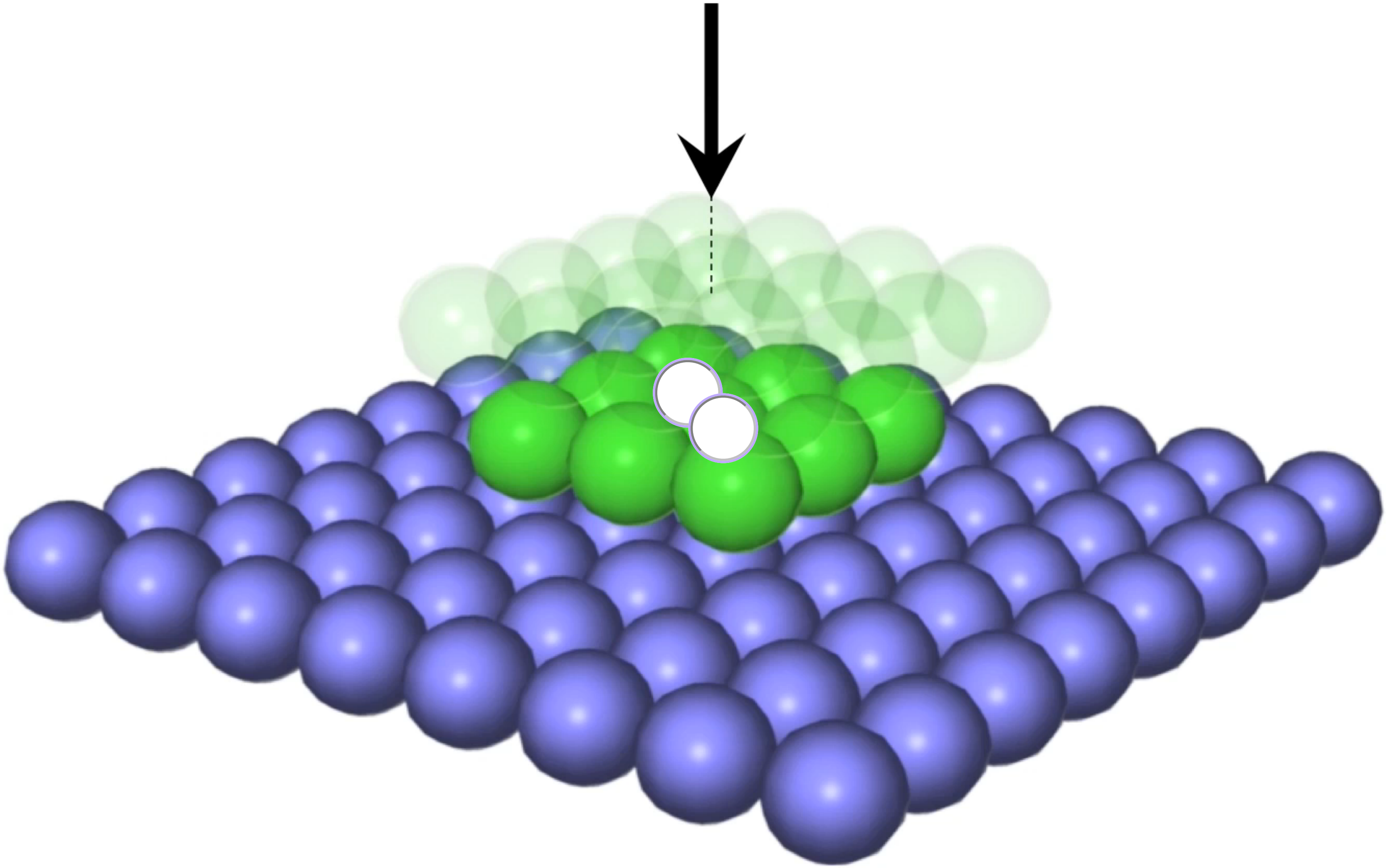
friction parameter : $\gamma \equiv 2\pi^2 \dfrac{U_0}{Ka^2}$



Two regimes:

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

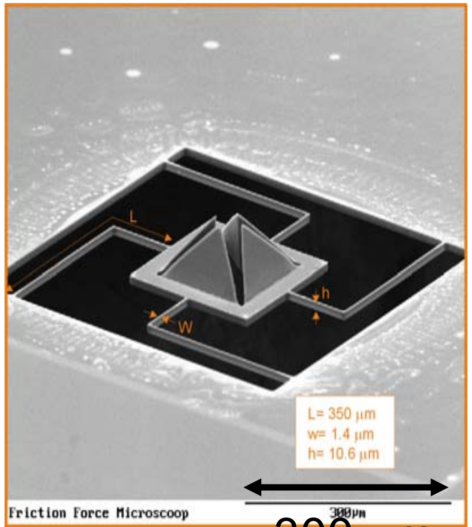
How to lower U_0: *'Superlubricity'*



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

movie

Special friction-sensor: Tribolever™

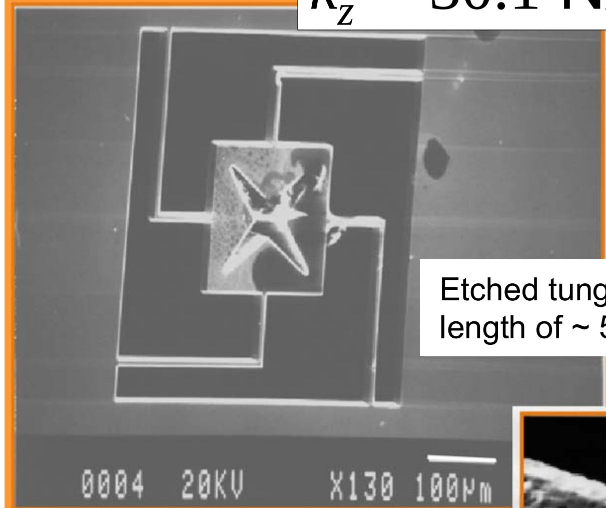


300 µm

sensor

$k_x = k_y = 6.5$ N/m

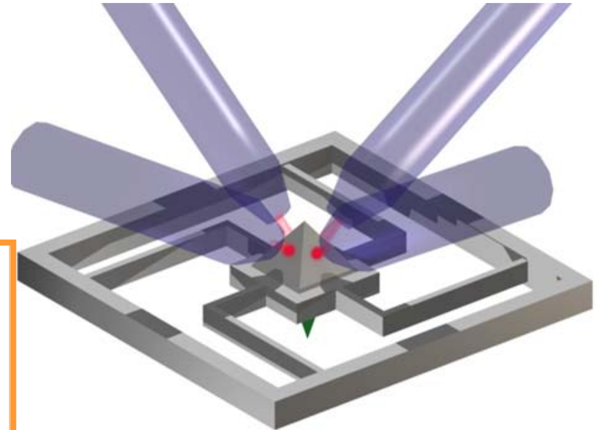
$k_z = 30.1$ N/m



Etched tungsten tip
length of ~ 50 µm

A scanning metal tip (e.g.
W or Au) is placed in the
central hole of the cantilever

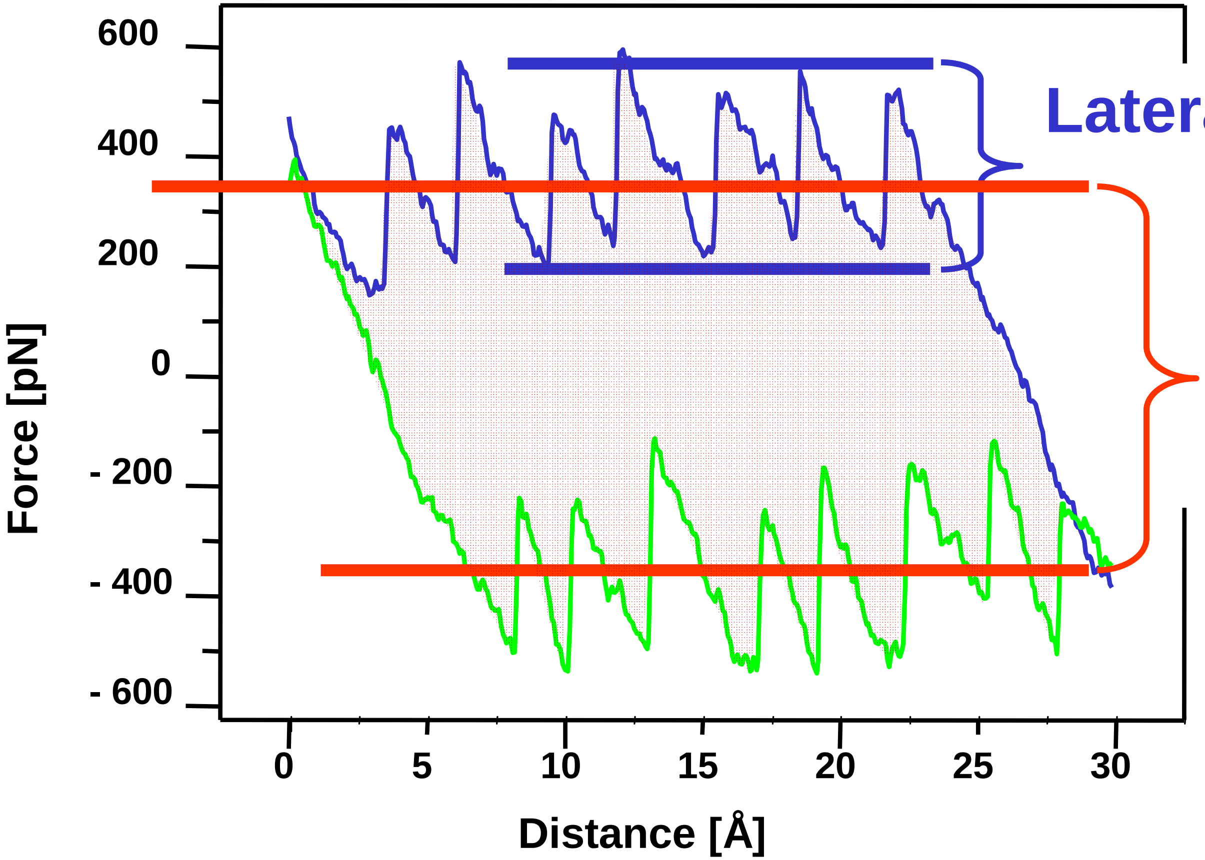
4-fiber
interferometer



T. Zijlstra *et al.*, *Sensors and Actuators A: Physical* **84** (2000) 18
M. Dienwiebel *et al.*, *Rev. Sci. Instrum.* **76** (2005) 043704

Lateral forces and dissipation

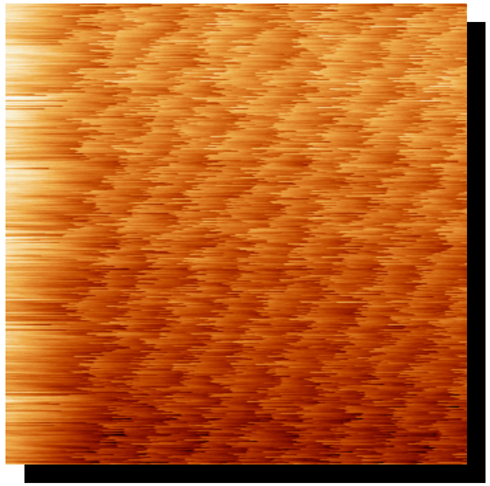
W-tip on graphite (HOPG) surface; $F_N = 35.8$ nN



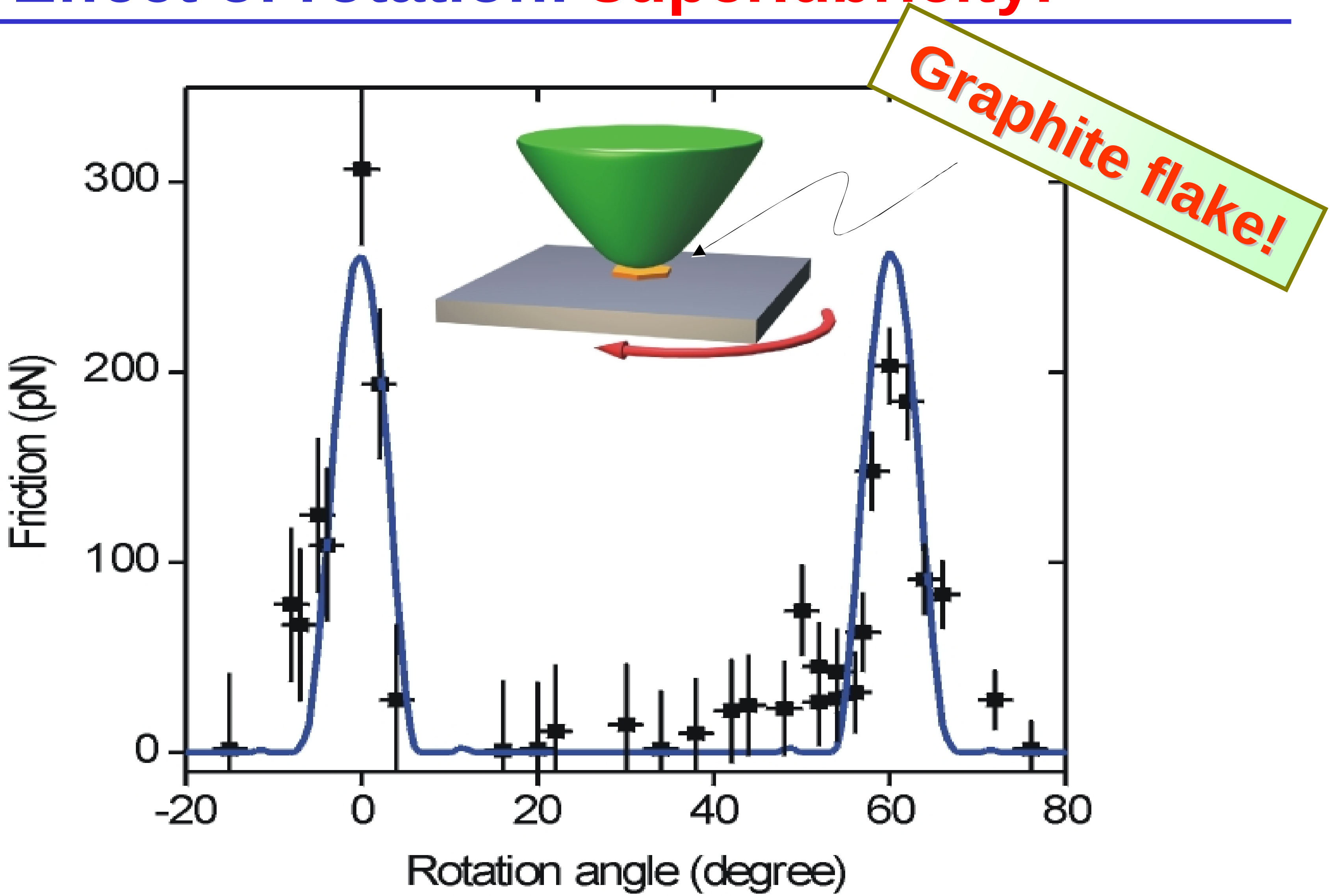
Lateral force variations: atomic stick-slip

Energy dissipation: friction

"friction force loop"

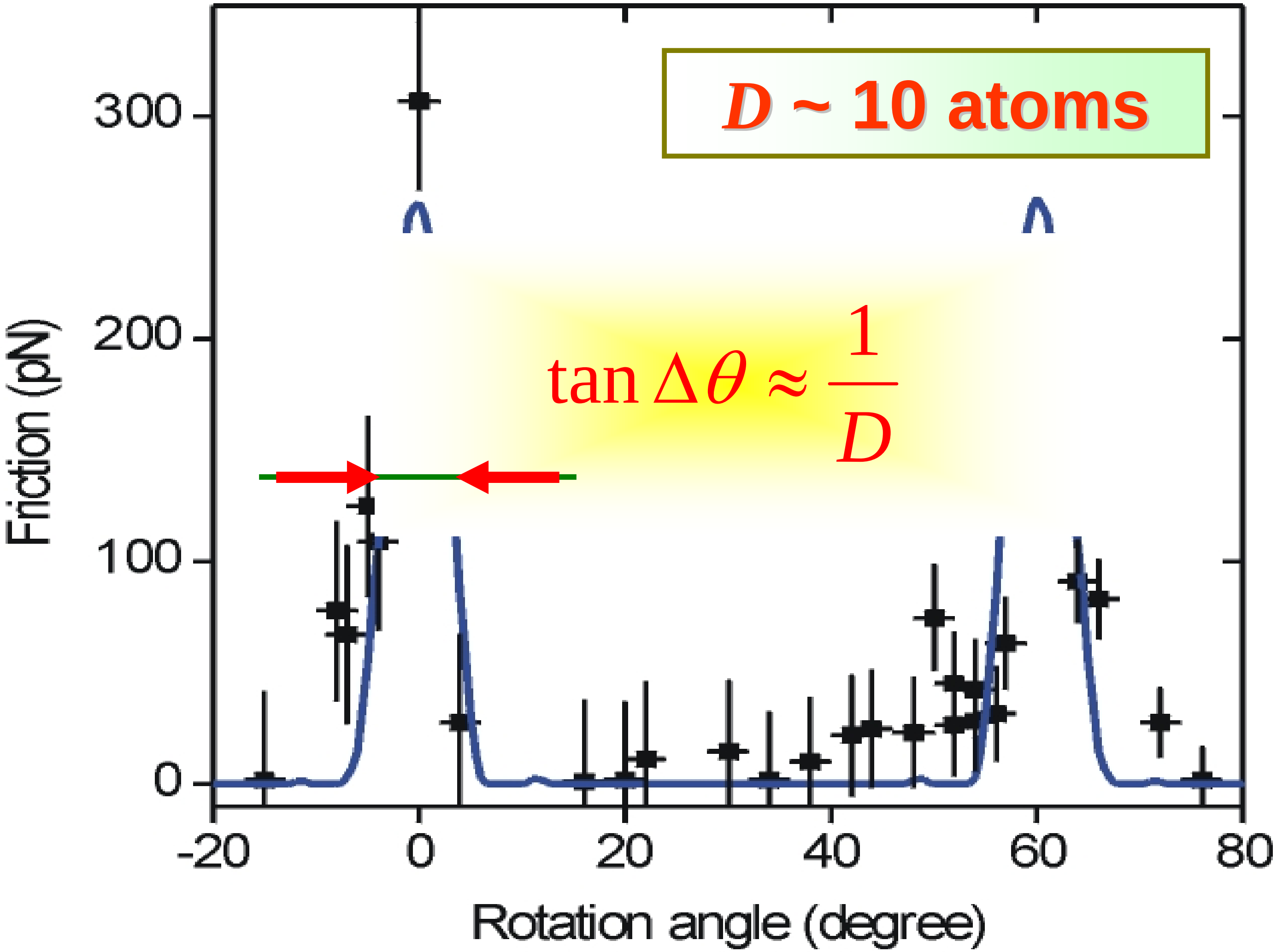


Effect of rotation: superlubricity!



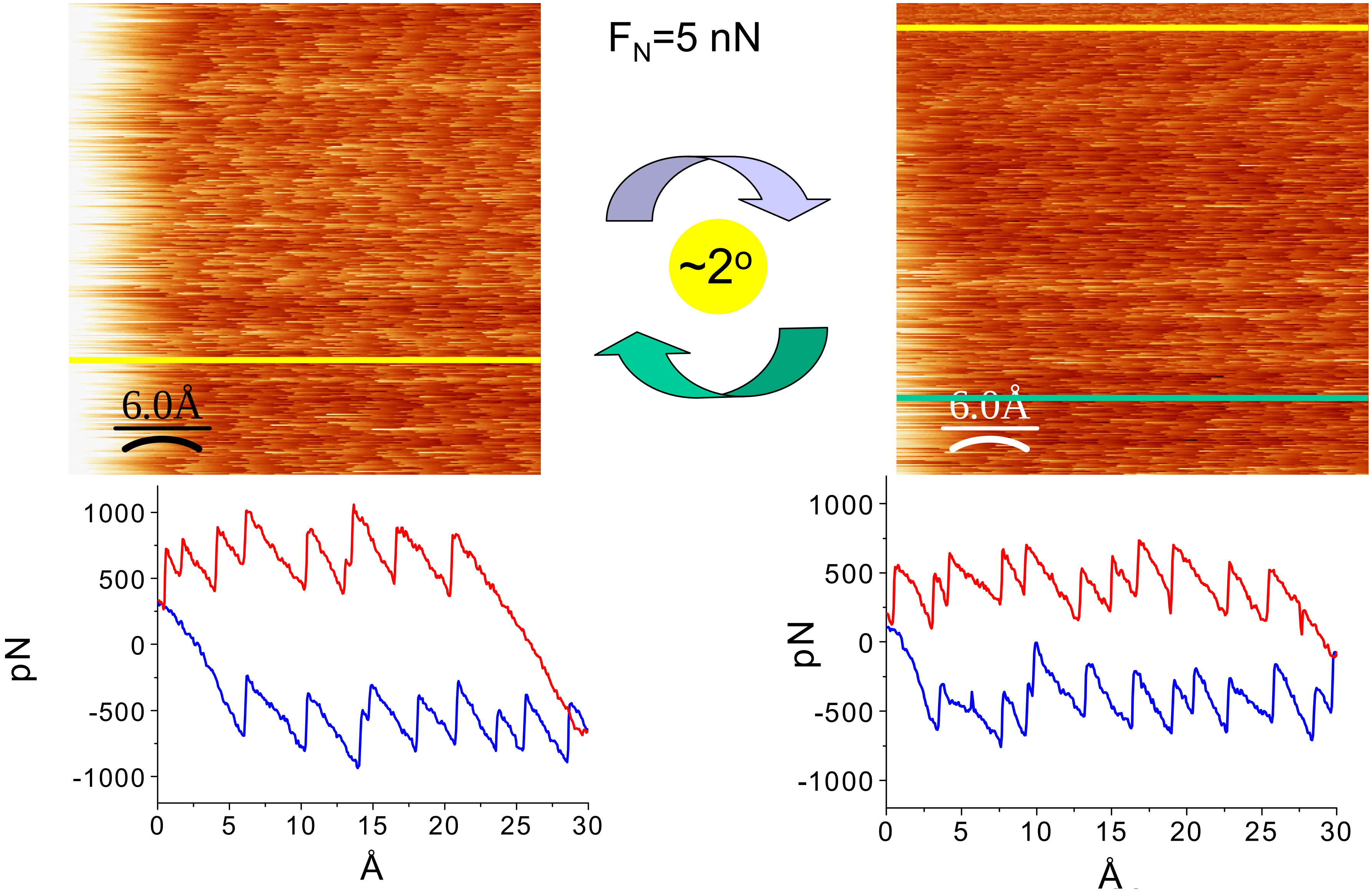
Dienwiebel et al., *PRL* **92** (2004) 126101

Width of the peak: flake diameter



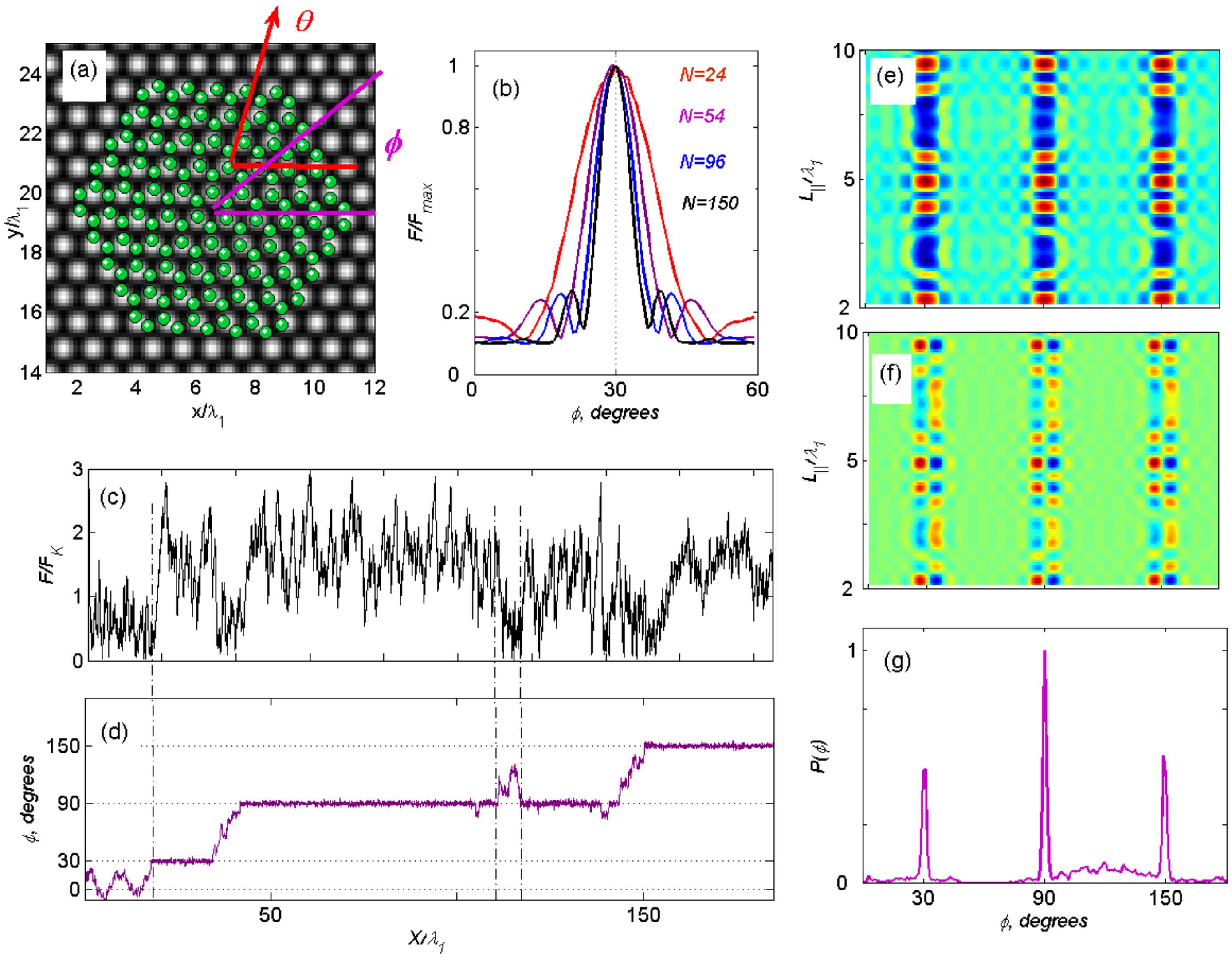
Dienwiebel et al., *PRL* **92** (2004) 126101

‘Loose’ flake



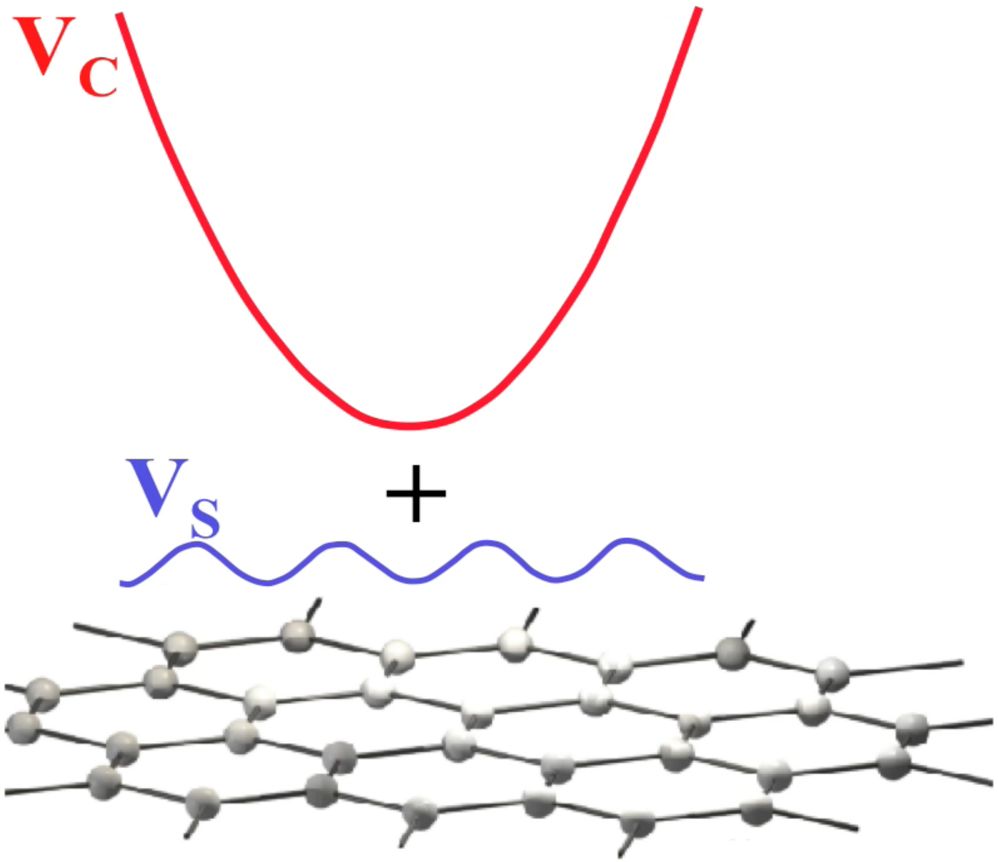
6.0Å
F_N=5 nN
~2°
6.0Å
1000
500
0
-500
-1000
pN
0
5
10
15
20
25
30
Å
1000
500
0
-500
-1000
pN
0
5
10
15
20
25
30
Å

Effect of torque on freely rotating flake



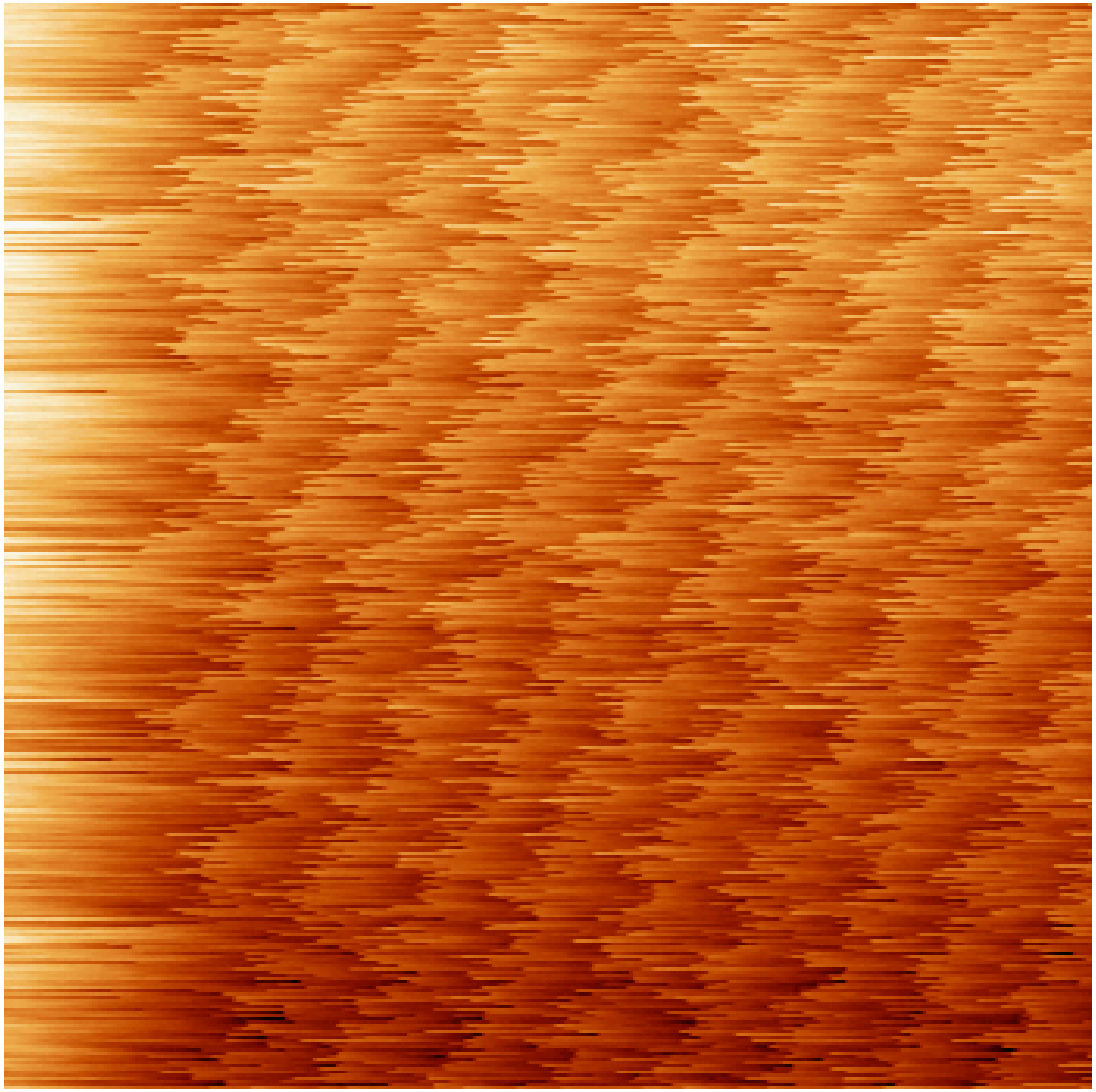
Fillipov *et al.*, *Phys.Rev.Lett.* **100** (2008)

Thermal excitations!



movie

Thermal noise in the experiment



Simple theory with temperature

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

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

p_i - probability to find the tip in well i

V - scanning velocity

X - support position

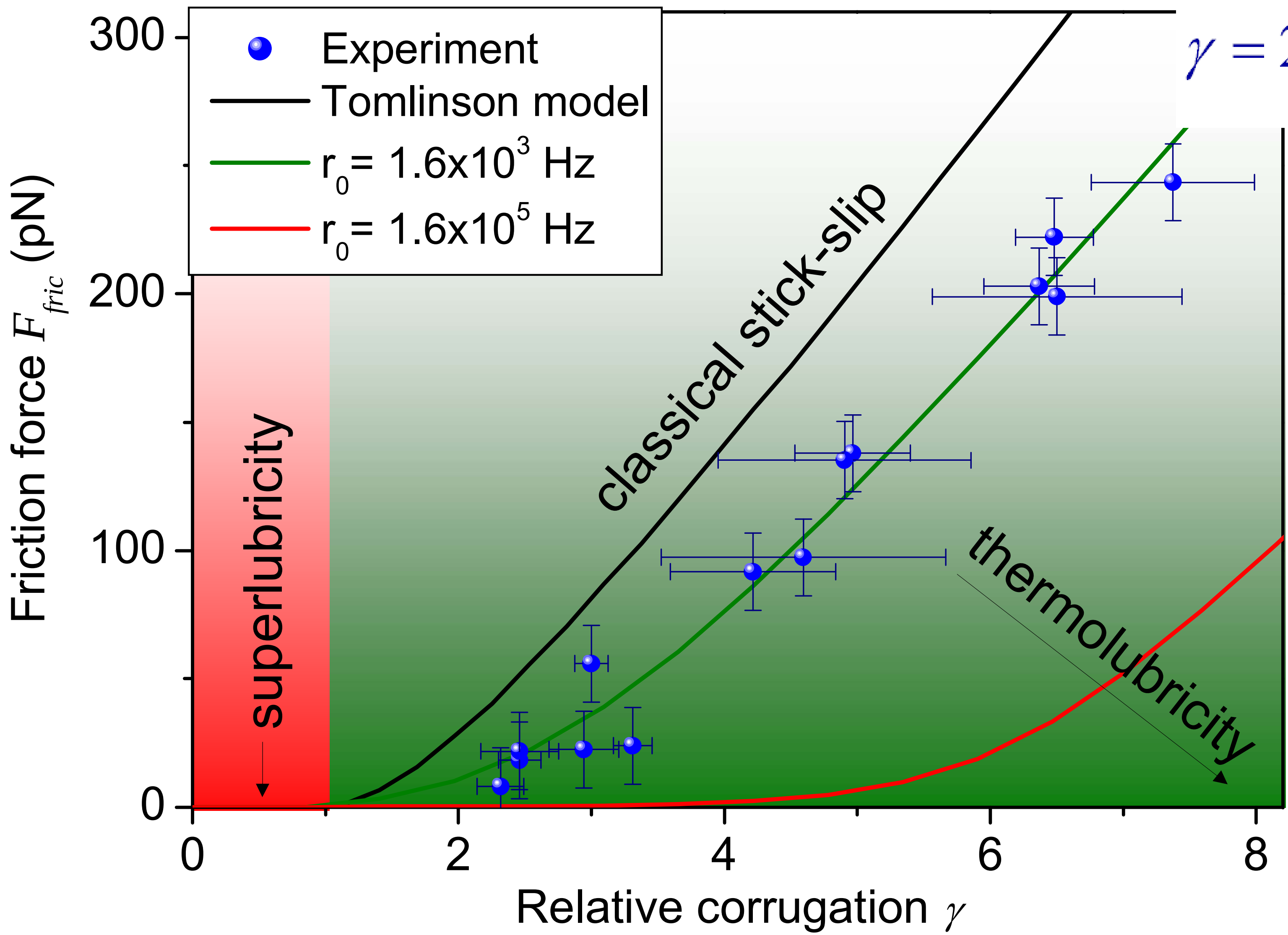
r_i^+ and r_i^- - rates of activated jumps to the right and to the left, resp.

$r_0 = \nu$ (TST)

Potential barriers are known functions of X

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

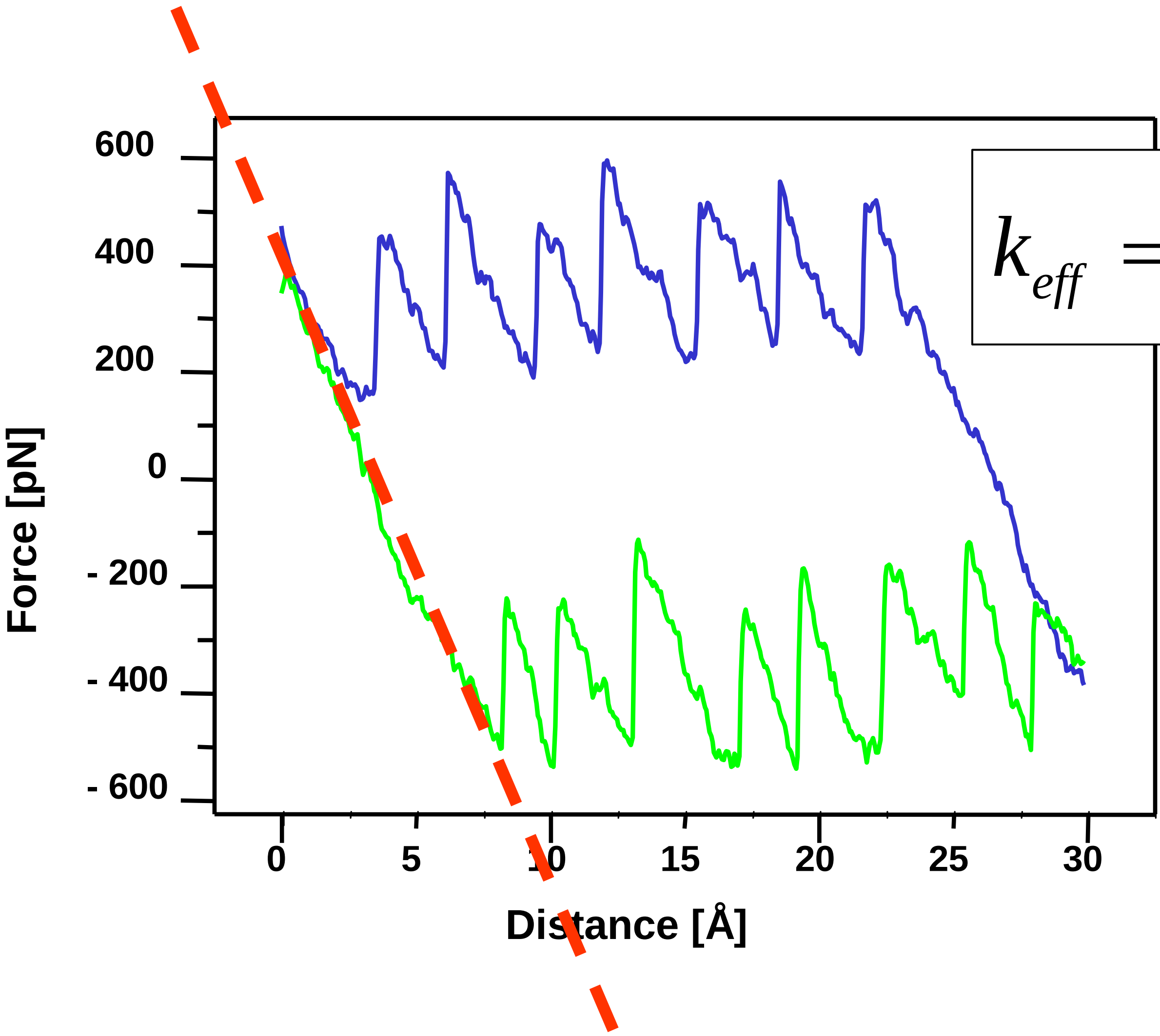
Thermolubricity: theory+experiment



$$\gamma = 2\pi^2 \frac{U_0}{ka^2}$$

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

There's a second spring: the tip

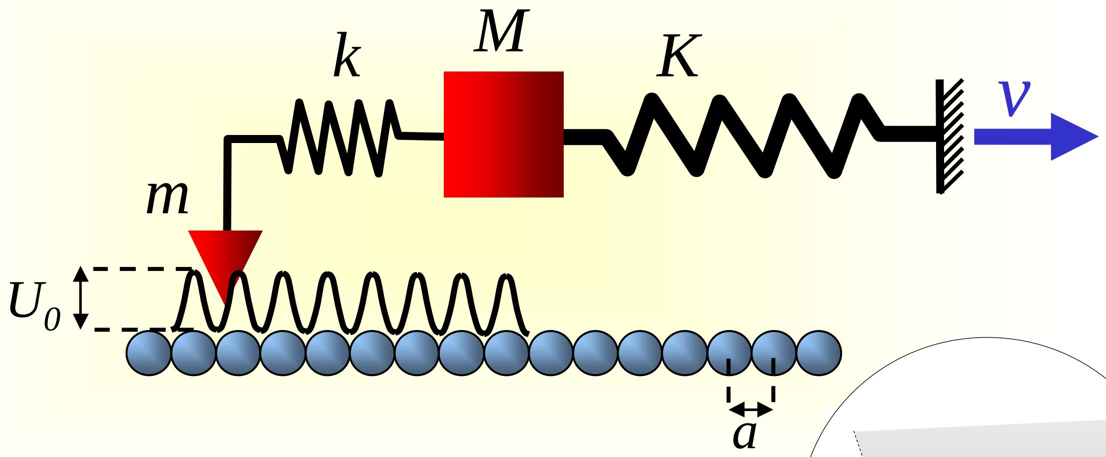


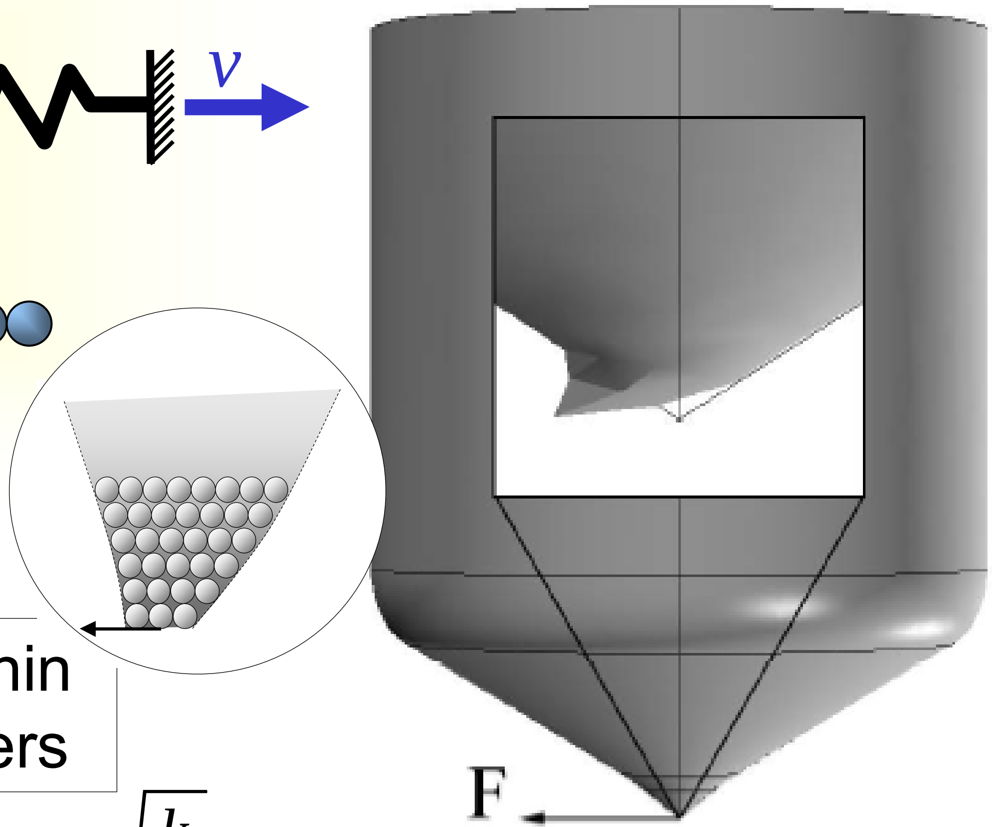
$$k_{eff} = \left(K^{-1} + k^{-1}\right)^{-1}$$

cantilever

tip
(~2 N/m)

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





98% of deformation within the first 100 atomic layers

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

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

cantilever position

tip position

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

Trick: combine Langevin dynamics for M:

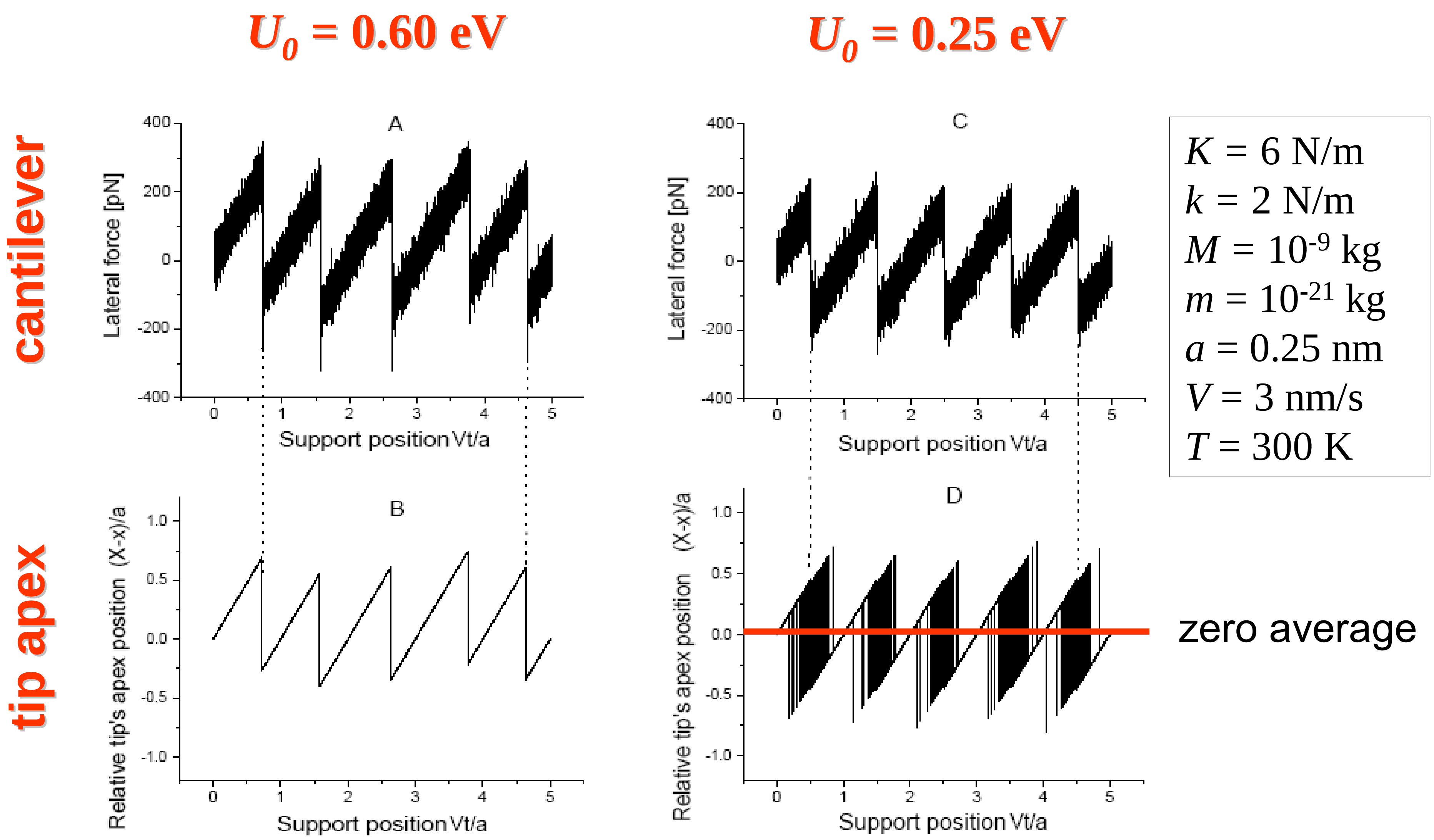
$$M\ddot{X}=-k\left[X-x_i(X)\right]-K(X-Vt)-M\eta\dot{X}+\xi$$

with Monte Carlo dynamics for m:

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

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

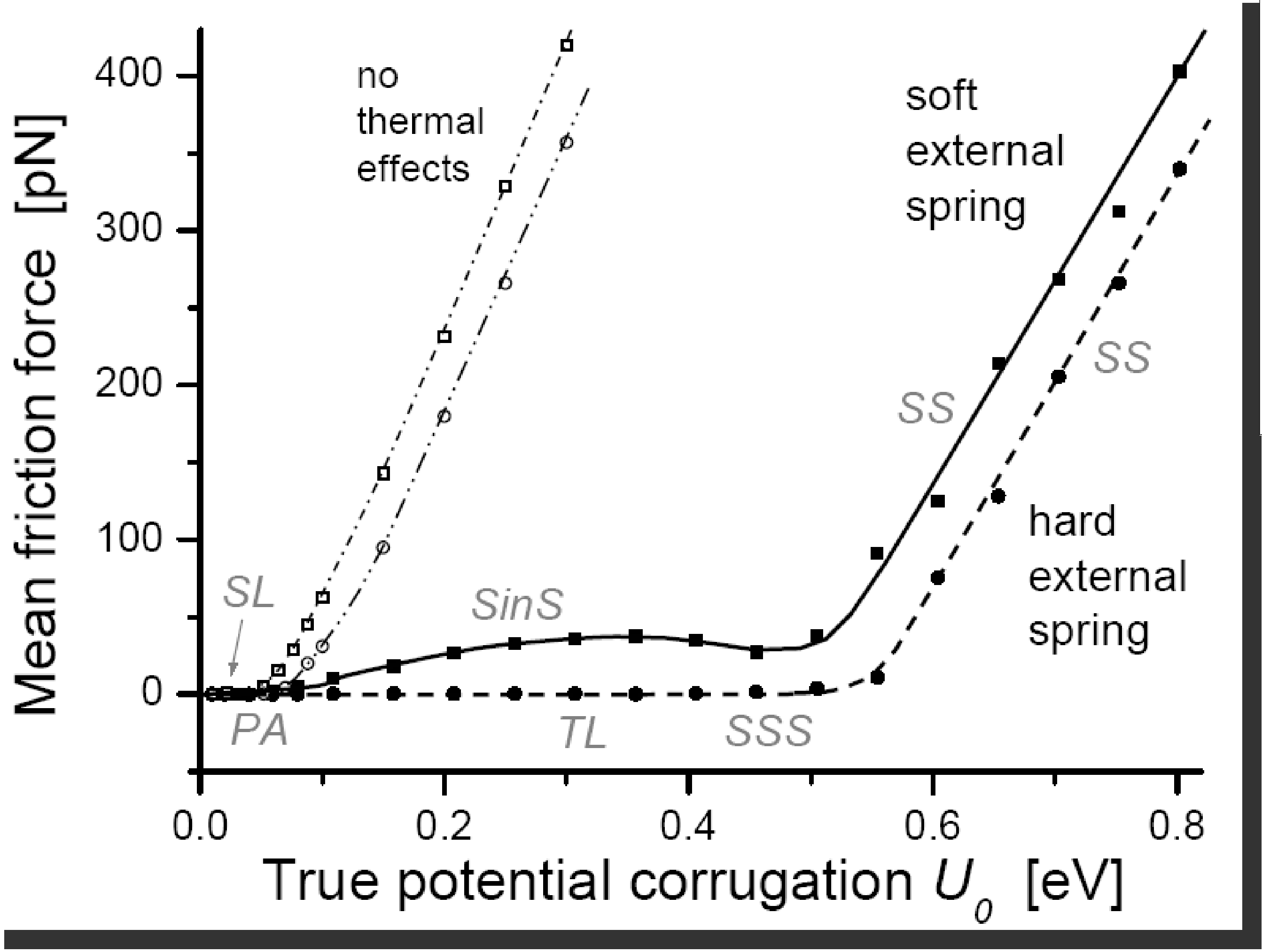
"Stuck – in – slipperiness" regime



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

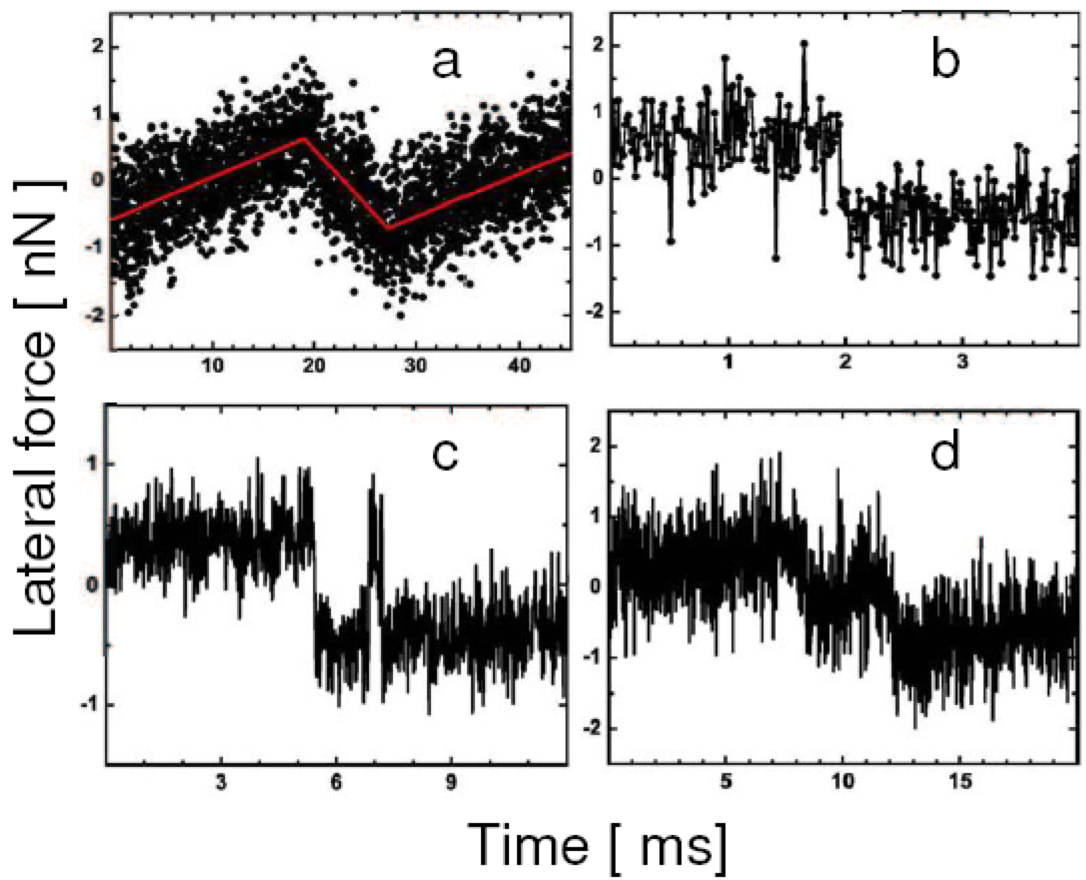
SinS = ‘stuck-in-slipperiness’ regime

SSS = stochastic stick-slip

SS = ordinary stick-slip

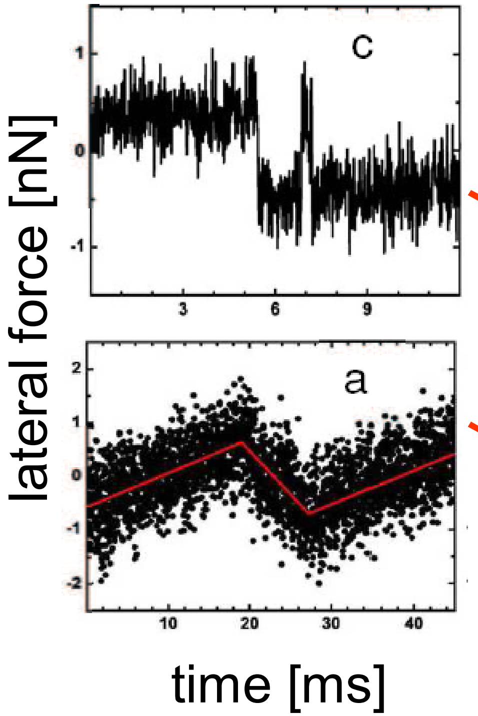
Krylov et al., *New J. Phys.* **9** (2007) 398

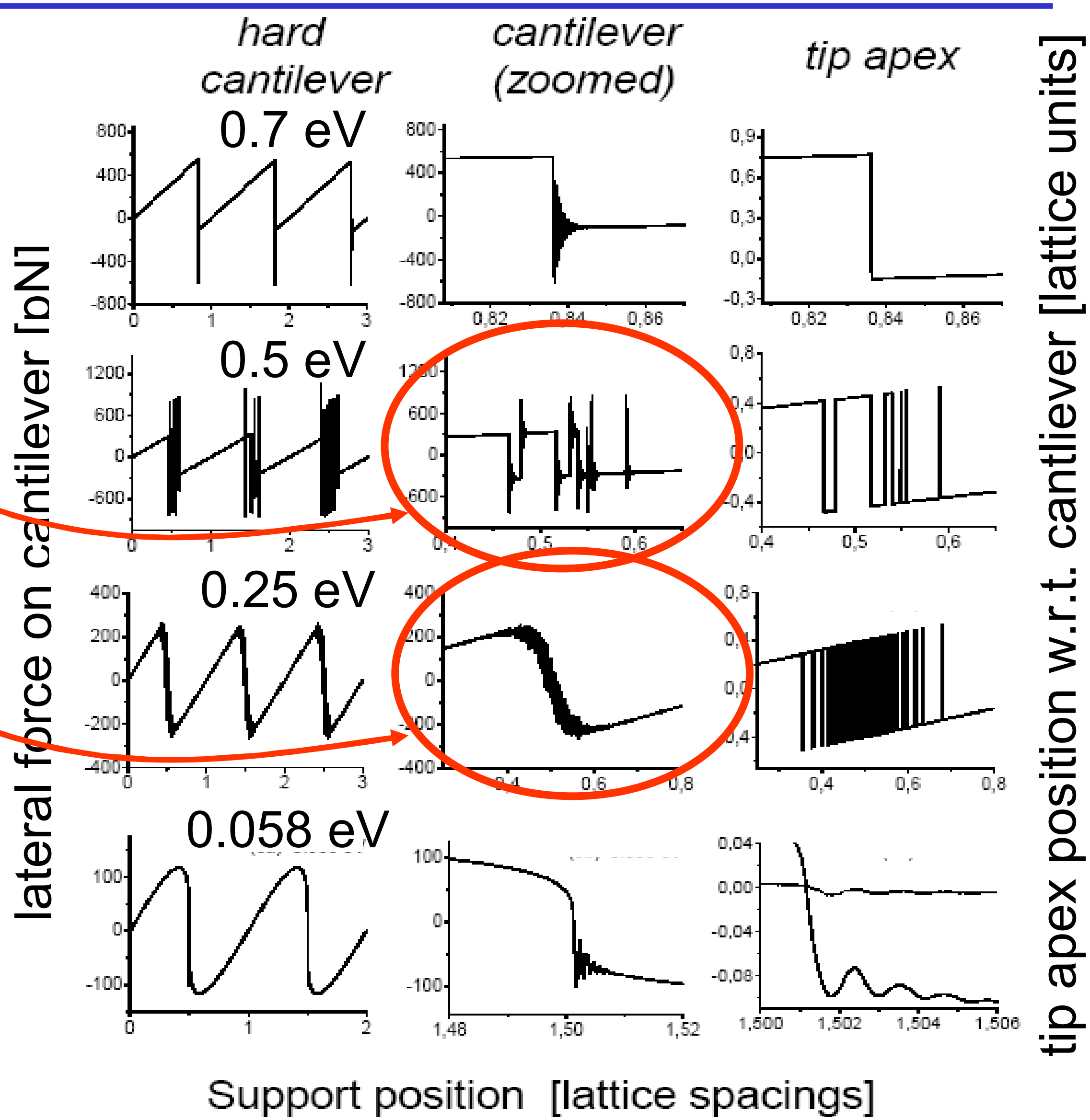
Smoking gun



S. Maier, et al., *Phys. Rev. B* **72** , 245418 (2005)

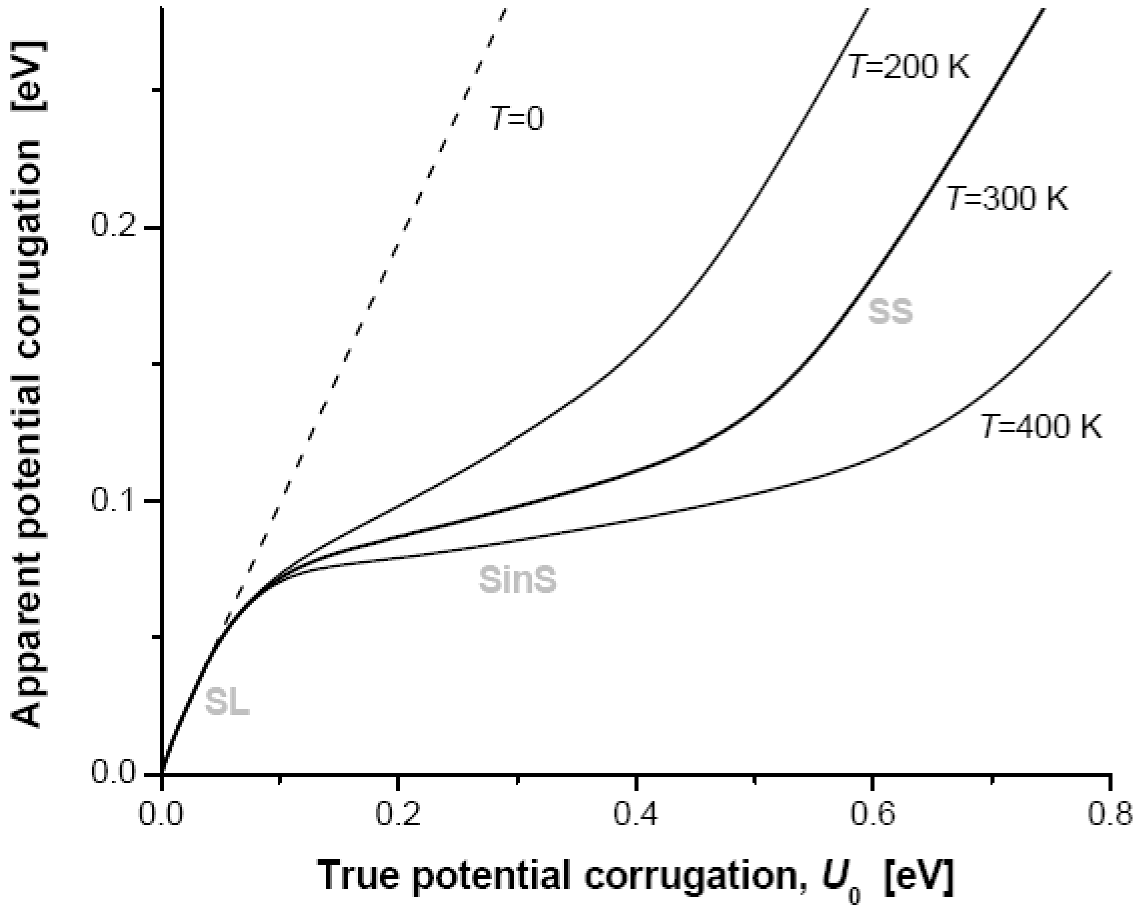
Smoking gun





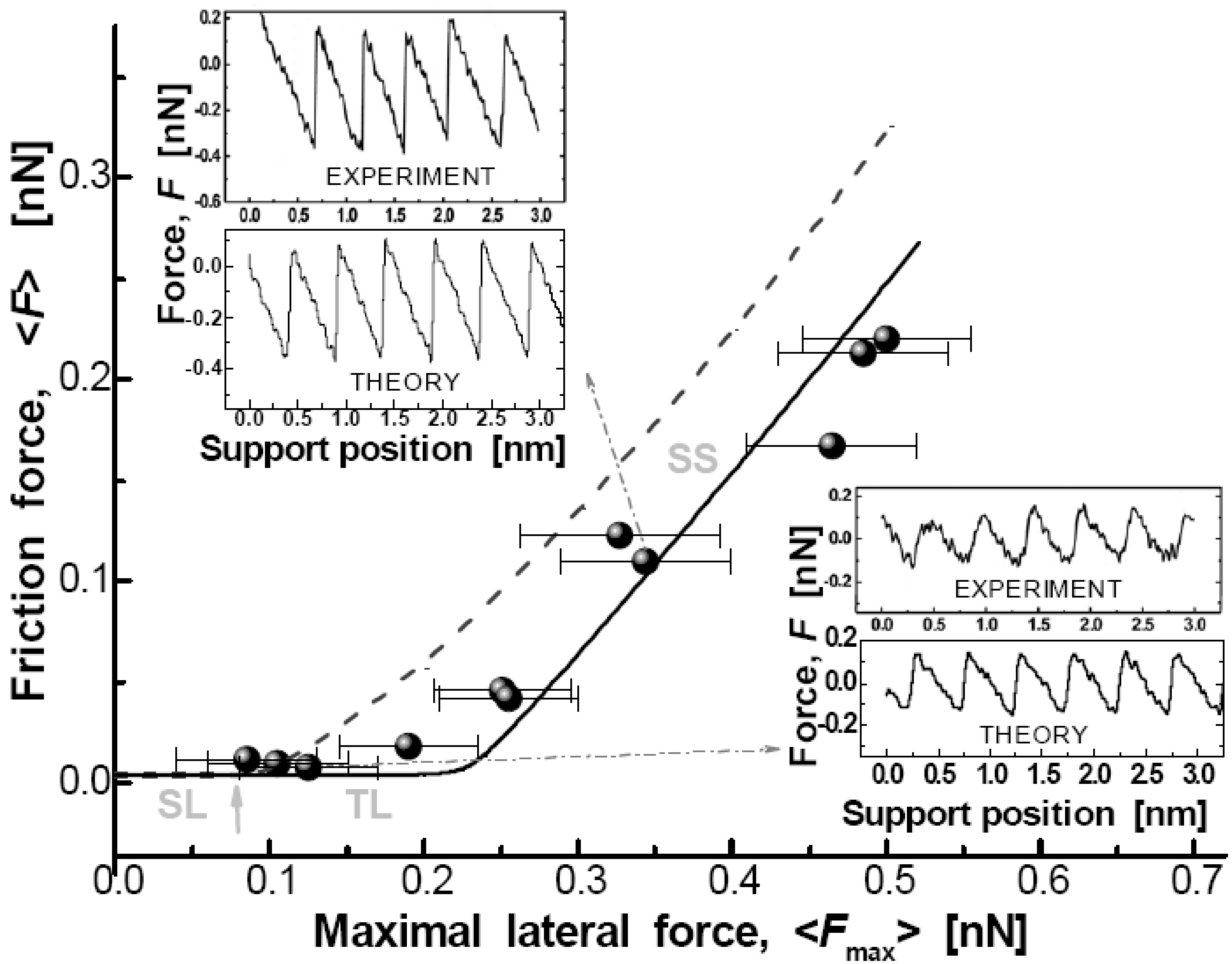
Maier, et al., *PRB* **72** , 245418 (2005)   Krylov et al., *New J. Phys.* **9** (2007) 398

Also dramatic for strong potentials



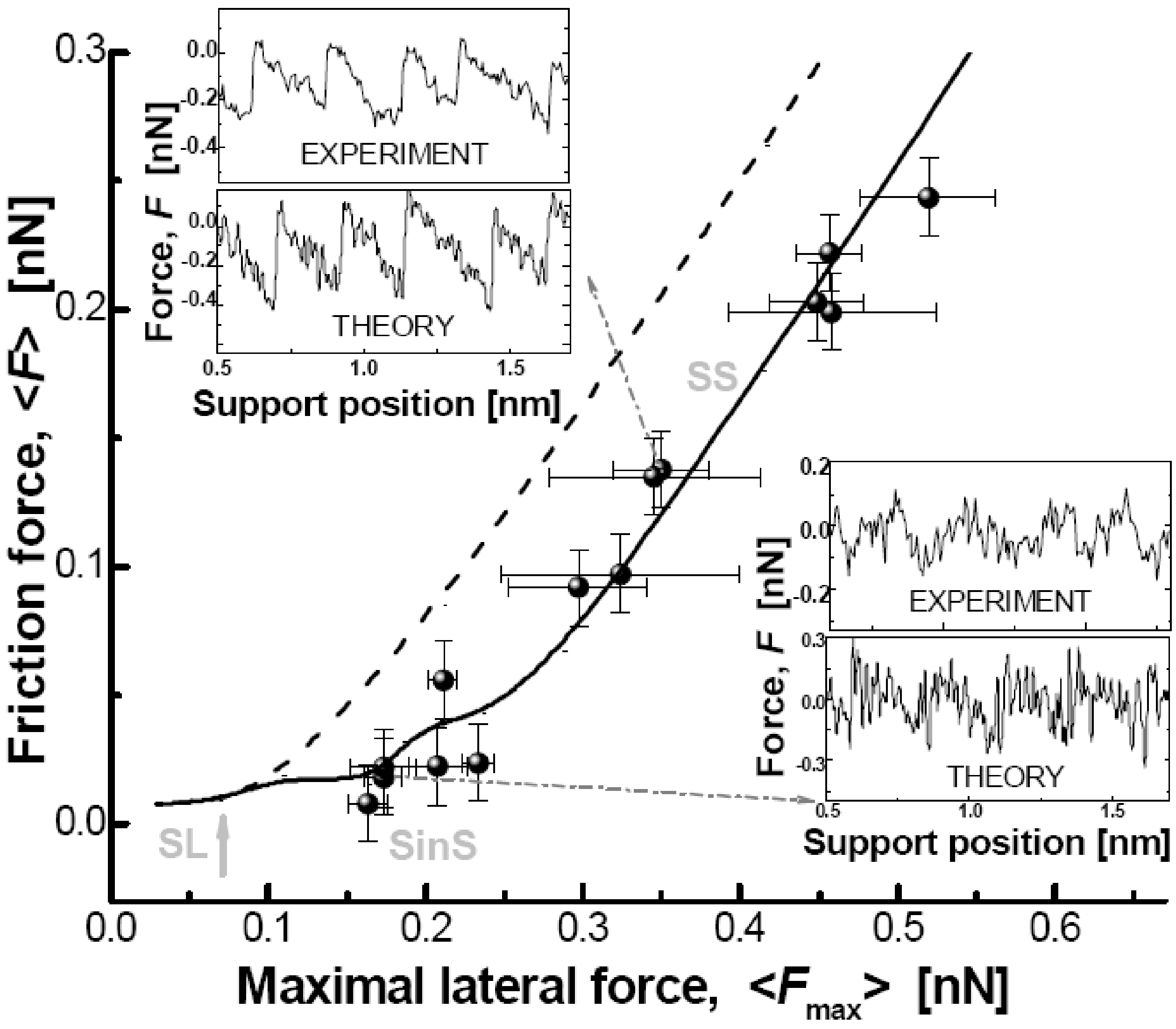
Krylov et al., *to be published*

'Universal' behavior: hard cantilever



data from:A. Socoliuc et al., PRL 92, 134301 (2004) Krylov et al., *to be published*

‘Universal’ behavior: soft cantilever



data from M. Dienwiebel et al., PRL92 , 126101 (2004) Krylov et al., *to be published*

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...
- Many FFM measurements may be affected
- Universal curve(s)

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