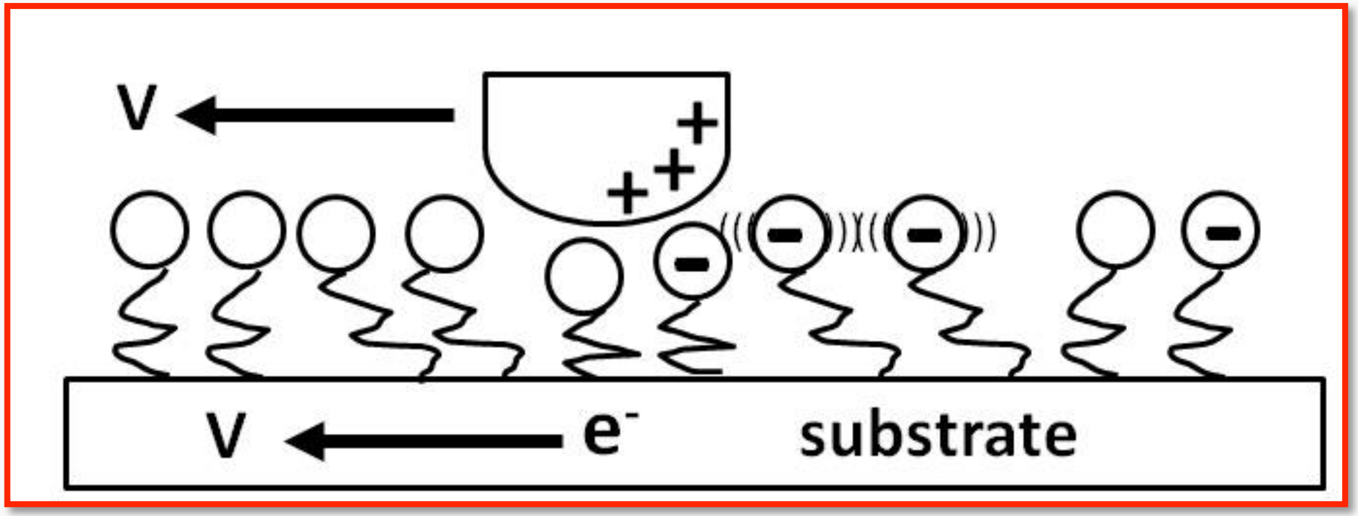
Imagine a world without wear:
Is this a dream or a nightmare?

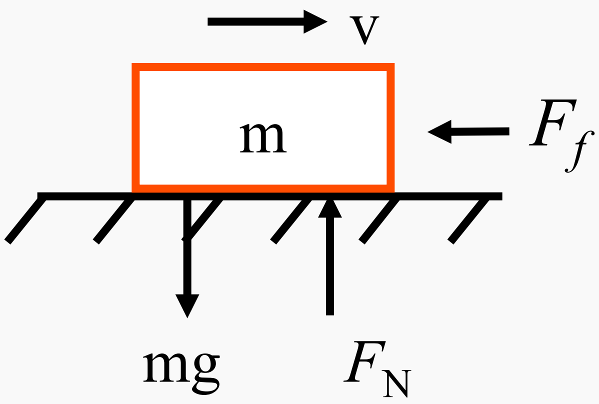
Friction and energy dissipation mechanisms in adsorbed molecules and molecularly thin films:
Are friction,superconductivity and magnetism related?



J. Krim, Advances in Physics, 61, pp. 155-323 (2012)

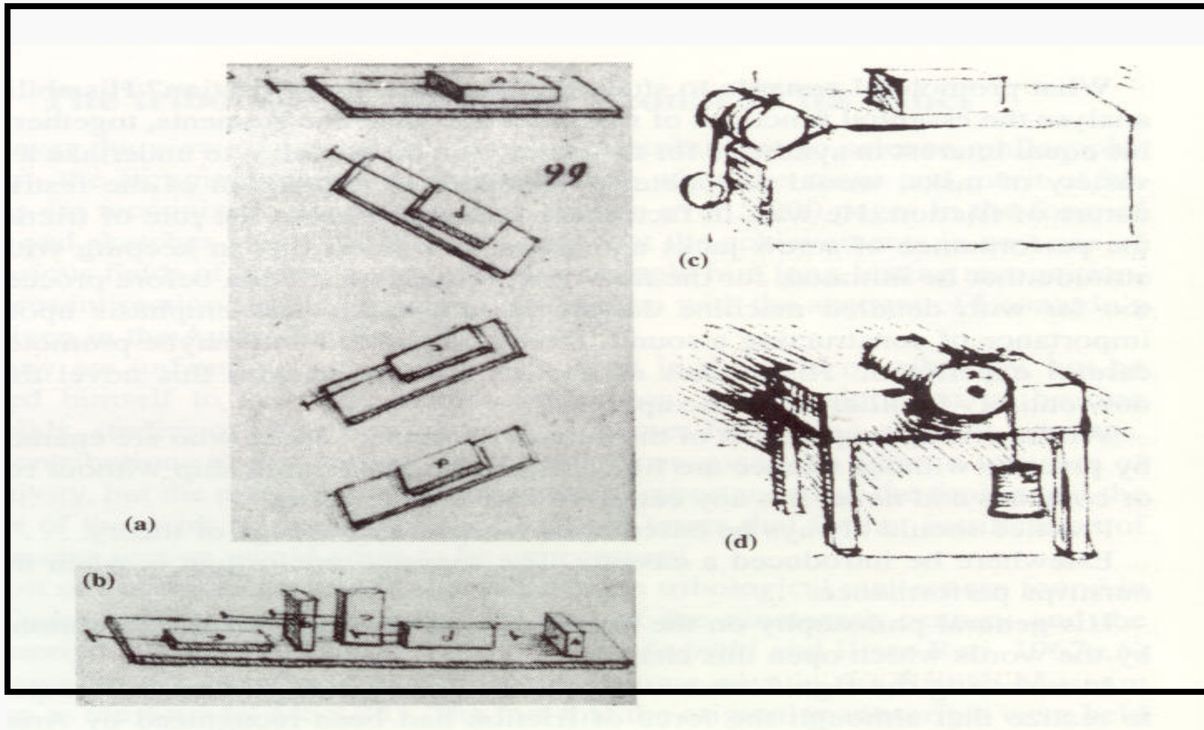
Research supported by NSF DMR

Friction is not new.



$$F_f = \mu F_N$$

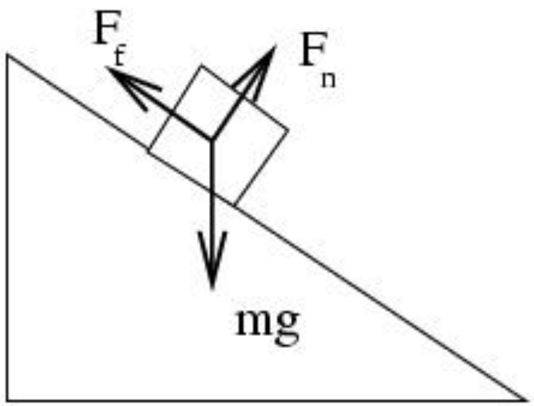
Amontons, 1699



Leonardo da Vinci Codex Atlanticus
Codex Arundel   ca. 1500 $\mu_k = 0.25$

1785 (friction is not fast) Coulomb and static friction

A Friction Analogue: Block on a Plane



At balance:

$$F_n = mg\cos\theta$$

$$F_f = mg\sin\theta$$

At failure (slipping): $F_f = \mu F_n$

$$\tan\theta = \mu$$

ESSAI

Sur une application des règles de Maximis & Minimis *à quelques Problèmes de Statique, relatifs à l'Architecture.*

Par M. COULOMB, Ingénieur du Roi.

INTRODUCTION.

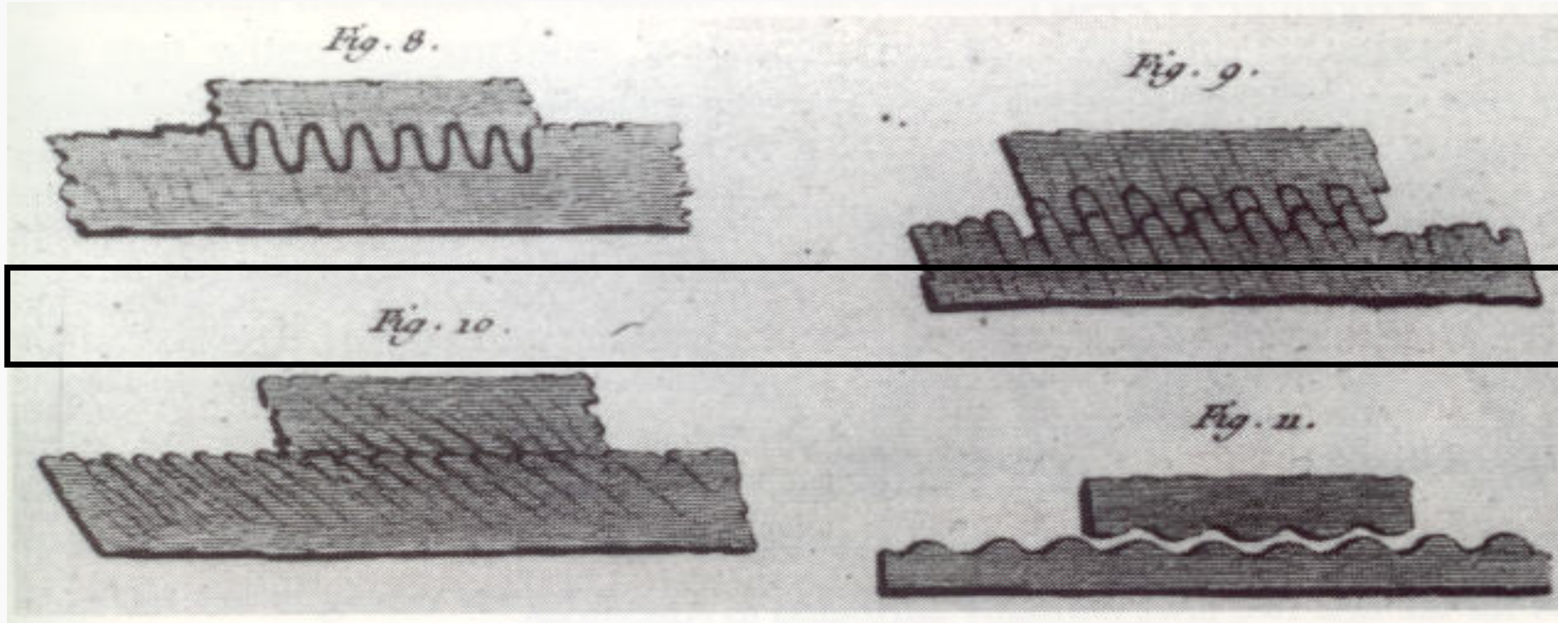
CE Mémoire eſt deſtiné à déterminer, autant que le mélange du Calcul & de la Phyſique peuvent le permettre, l'influence du frottement & de la cohéſion, dans quelques problèmes de Statique. Voici une légère analyſe des différens objets qu'il contient.

Après quelques obſervations préliminaires ſur la cohéſion, & quelques expériences ſur le même objet, l'on détermine la force d'un pilier de maçonnerie; le poids qu'il peut porter, preſſé ſuivant ſa longueur; l'angle ſous lequel il doit ſe rompre. Comme ce problème n'exige que des conſidérations aſſez ſimples, qui ſervent à faire entendre toutes les autres parties de cet Eſſai, tâchons de développer les principes de ſa ſolution.

Si l'on ſuppoſe un pilier de maçonnerie coupé par un plan incliné à l'horizon, en ſorte que les deux parties de ce pilier ſoient unies dans cette ſection, par une cohéſion donnée, tandis que tout le reſte de la maſſe eſt parfaitement ſolide, ou lié par une adhérence infinie; qu'enſuite on charge ce pilier d'un poids: ce poids tendra à faire couler la partie ſupérieure du pilier ſur le plan incliné, par lequel il touche la partie inférieure. Ainſi, dans le cas d'équilibre, la portion de la peſanteur, qui agit parallèlement à la ſection, ſera exactement égale à la cohérence. Si l'on remarque actuellement, dans le cas de l'homogénéité, que l'adhérence du pilier eſt réellement égale

Friction as we know it is a combination of mechanical and electrical effects, in combination with ever present adsorbed films.

file://localhost/Users/Jackie/Desktop/ICSOS/5A40.20.1 (Converted).mov



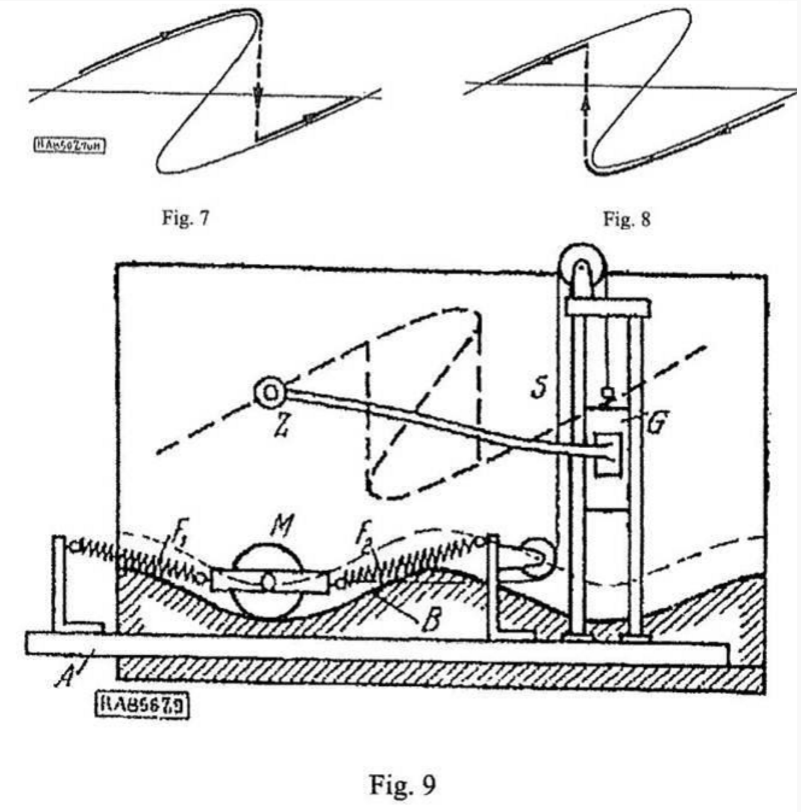
1785: Coulomb: *Théorie des Machines Simple*
Unsuccessful attempt to establish the fundamental origins of friction in terms of surface roughness.
1960's: Surface roughness definitely ruled out, since one molecule thick films changed friction but not roughness.

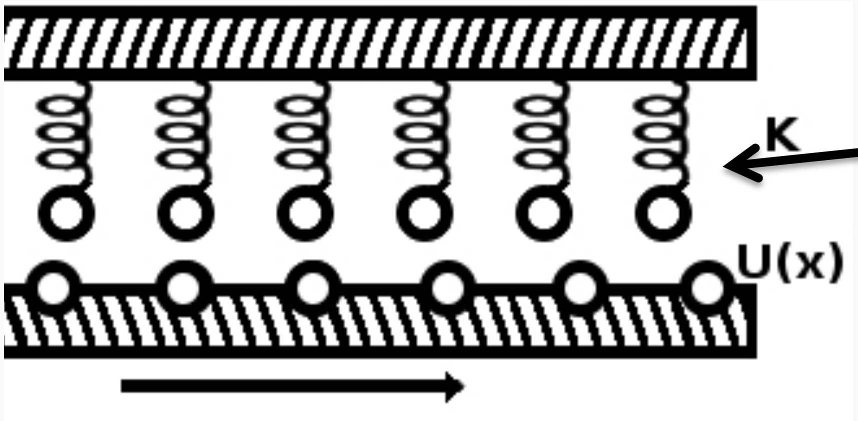
Friction matters: Unpeeled onions have low friction (0.2) and form a weak base. Peeled onions have high friction (1.2) They are difficult to collapse.

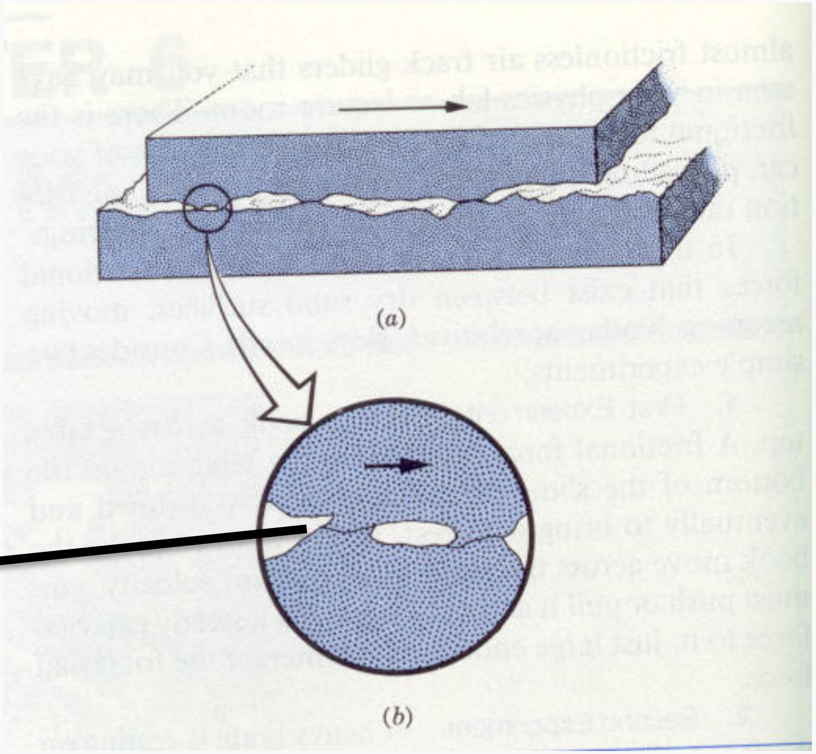
"*Friction, Force Chains and Falling Fruit*",
Krim and R.P. Behringer,
Physics Today, **62,** pp. 66-67 (Sept. 2009)

Coulomb: Smooth and shiny does not necessarily imply slippery. With onions, for example it is quite the opposite….

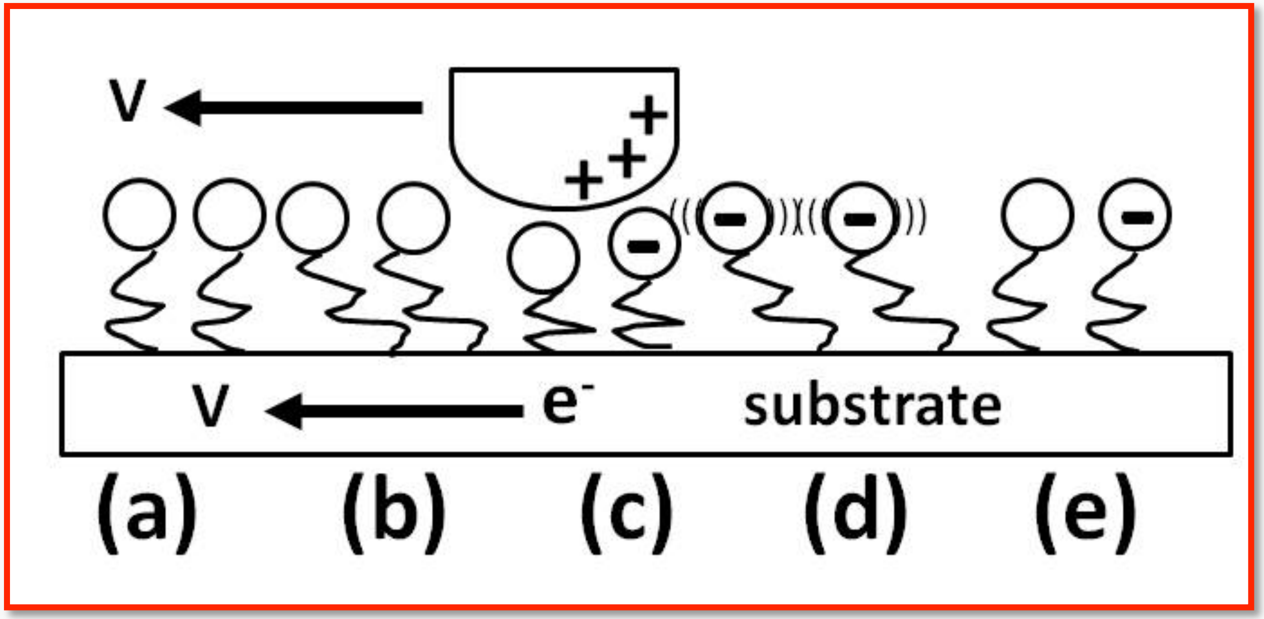
1928: L. Prandtl first principles' prediction of phononic lattice vibration "wear-free" mechanisms for friction





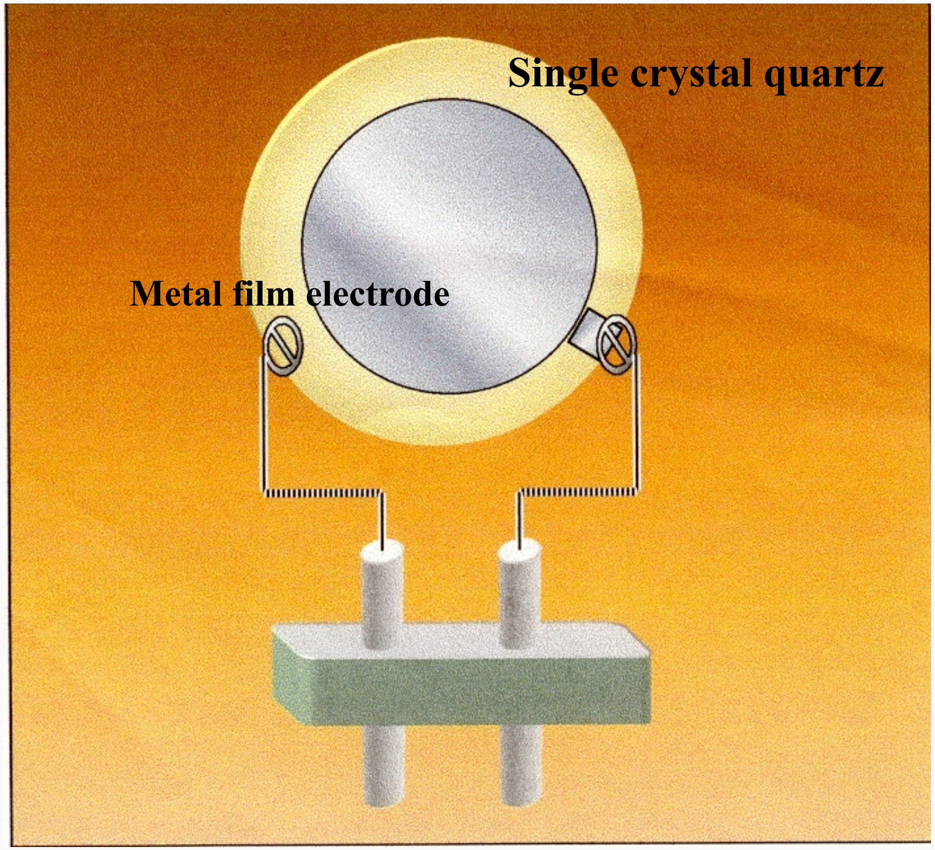


QCM verification of phononic friction mechanisms

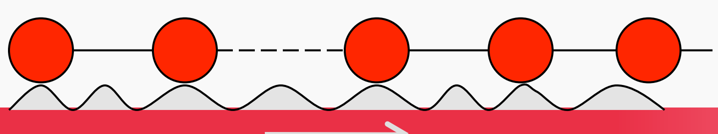


1986-2006 Theory colleagues A. Widom, J.B. Sokoloff, M.O. Robbins, Students, E. Watts, R. Chiarello, C. Mak and T. Coffey

A Quartz Crystal Microbalance (QCM) can probe film sliding friction levels



$$F = \frac{m}{\tau} v$$



We measure frequency and amplitude change of the QCM.

Frequency shift is proportional to mass uptake:

$$\frac{\Delta f}{f^2} = \frac{-2\rho_f t_t}{\rho_q v_q}$$

Sometime Δf can be reduced if there is extreme slippage:

$$\Delta f_{film} = \frac{\Delta f_{mass}}{1+(\omega\tau)^2}$$

The amplitude is related to the quality factor:

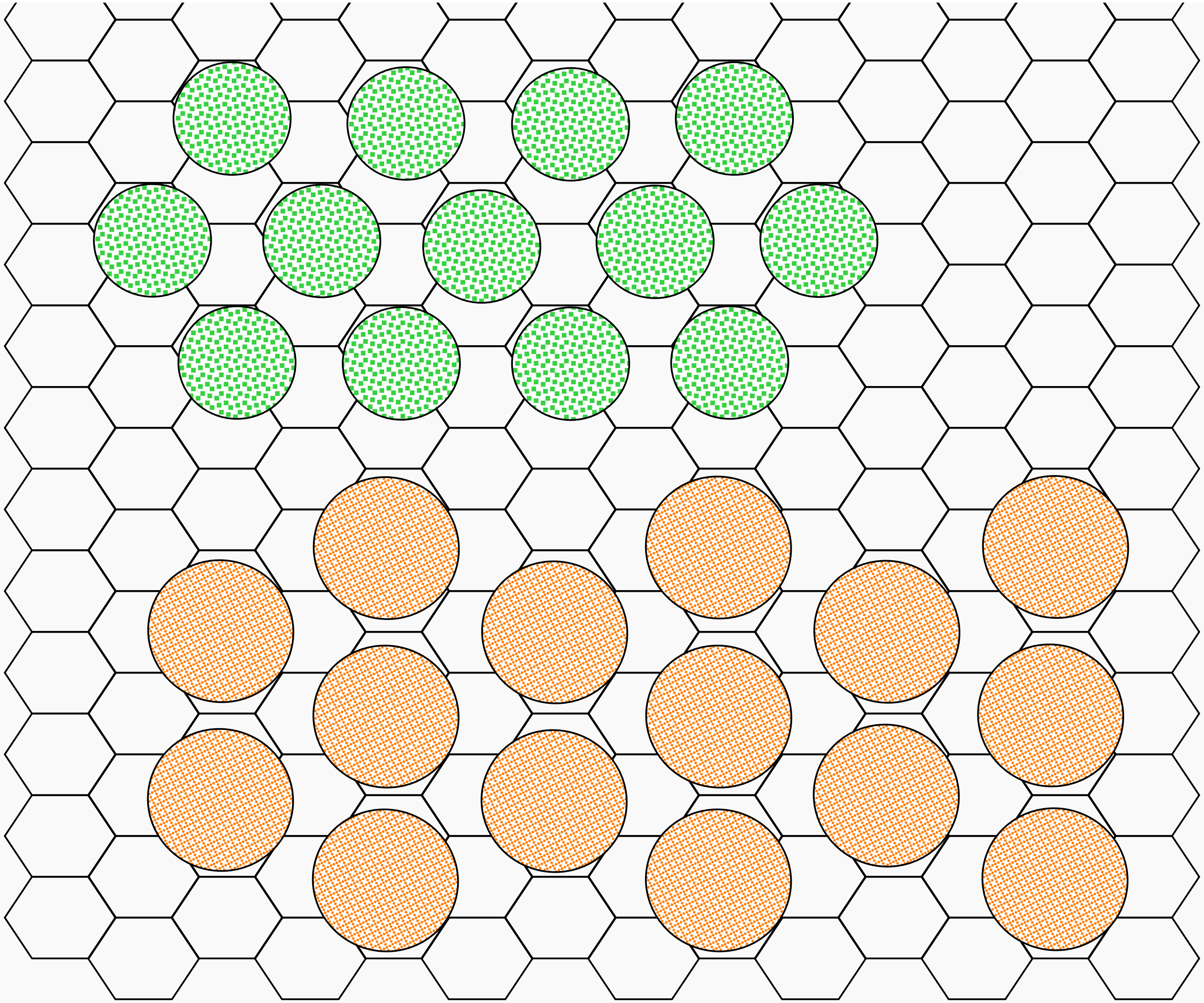
$$\Delta\left(\frac{1}{Q}\right) \propto \Delta\left(\frac{1}{A}\right)$$

We then calculate a slip time:

$$\Delta\left(\frac{1}{Q}\right) = 4\pi\tau\Delta f$$

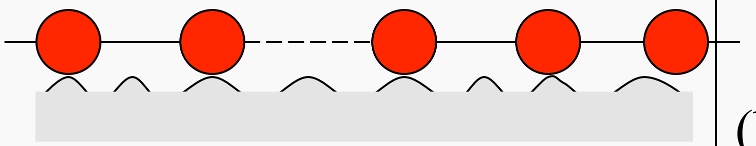
(*Krim and Widom, PRB, v. 38, n.17, 1988*)

Physisorbed layers can form commensurate and incommensurate solids structures: Friction is highly sensitive to commensurability



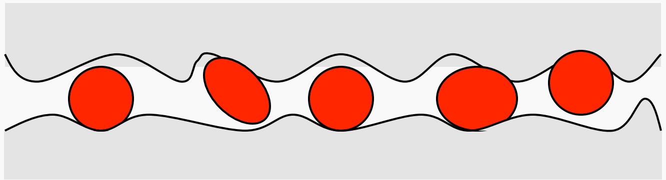
Studies of the sliding friction of adsorbed layers allow fundamental mechanisms of dissipation to be probed, in both contact and non contact geometries.

(a) $$F = \frac{m}{\tau} v$$



(b)

$\mu_s \geq \mu_k$

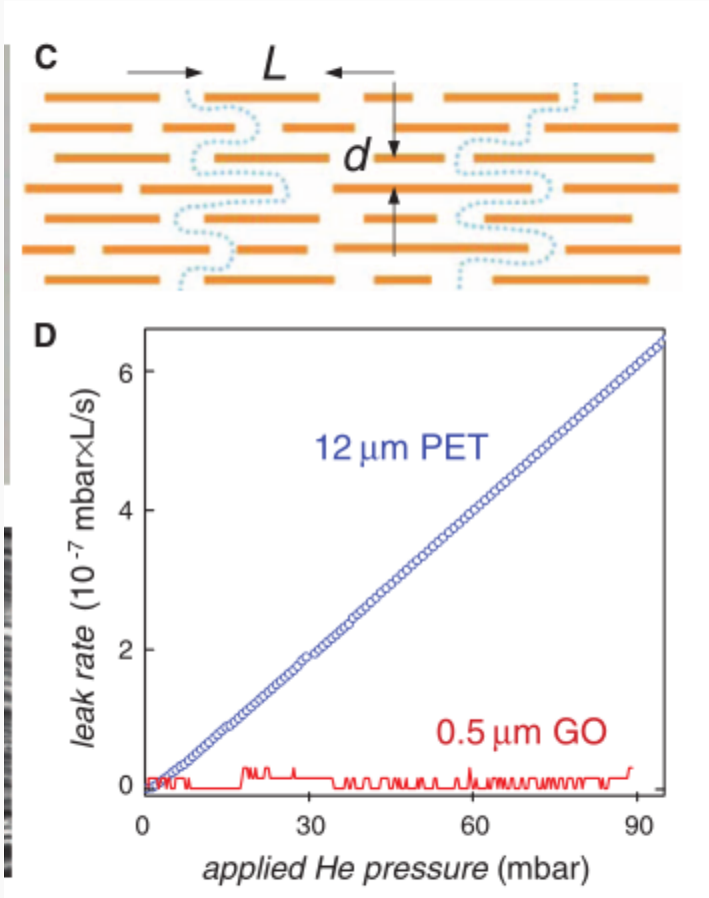


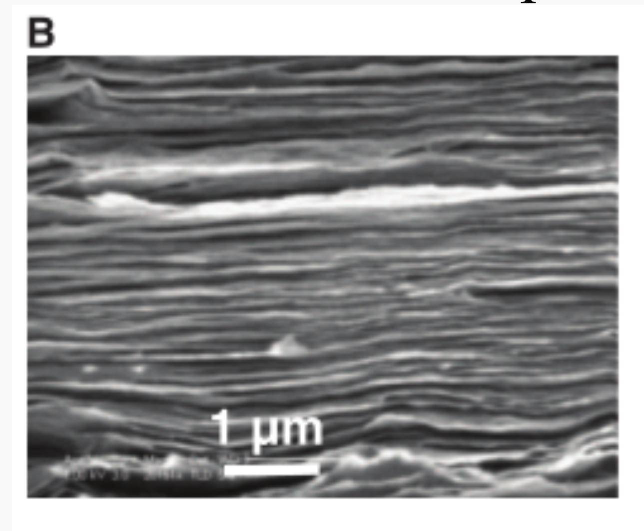
(a) On an open surface, both solid and liquid films slides are characterized by a viscous friction law. (QCM, ``blowoff experiments)

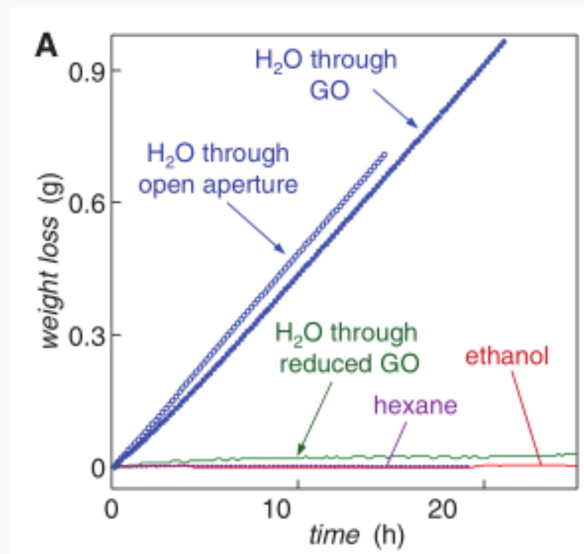
(b) In a confined geometry(SFA, AFM?), static friction and stick-slip phenomena are ever-present and overall friction levels are substantially higher for comparable sliding speeds. This may arise from a mobile particles' pinning of counterface materials?

"realistic contact" is a combination of both (a) and (b); **a film need not be within a contact to change the friction of that contact.**

Water passes through GO with little to no friction: Is it superlubric?







R.R. Nair et al Science 2012 V 335 Page 442

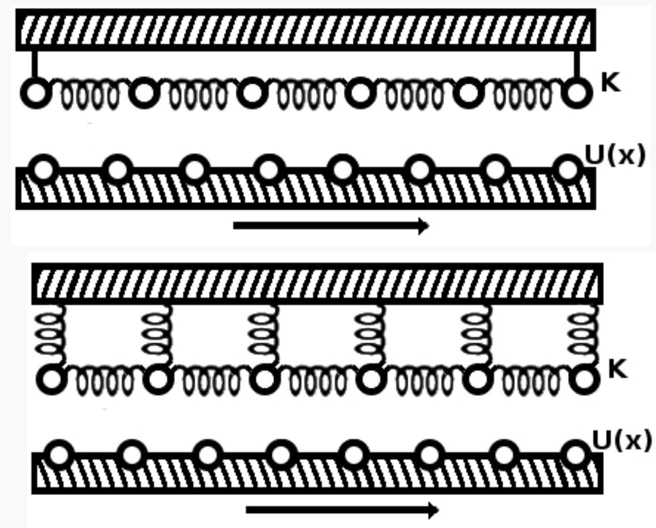
Phononic friction is related to the variation of the adsorbate substrate interaction potential. For constant substrate lattice spacing, Cieplak et al.[1] observed that the sliptime, t varied with corrugation strength, C, as:

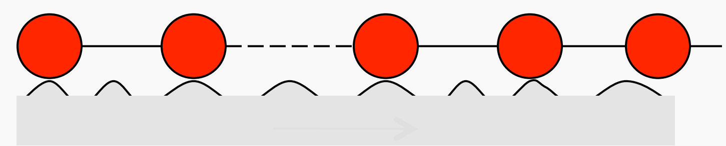
$\tau \sim C^{-2}$

Friction is also related to the damping, $\eta_{=}$, that comes from substrate phonon modes and/or electronic friction.[2] : [3]

$\eta = \eta_{=} + a\, C^2$

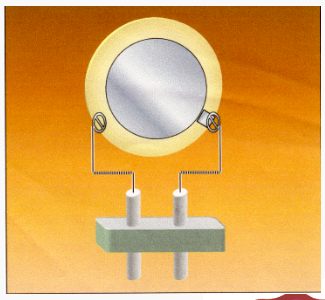
Here, a is a constant.



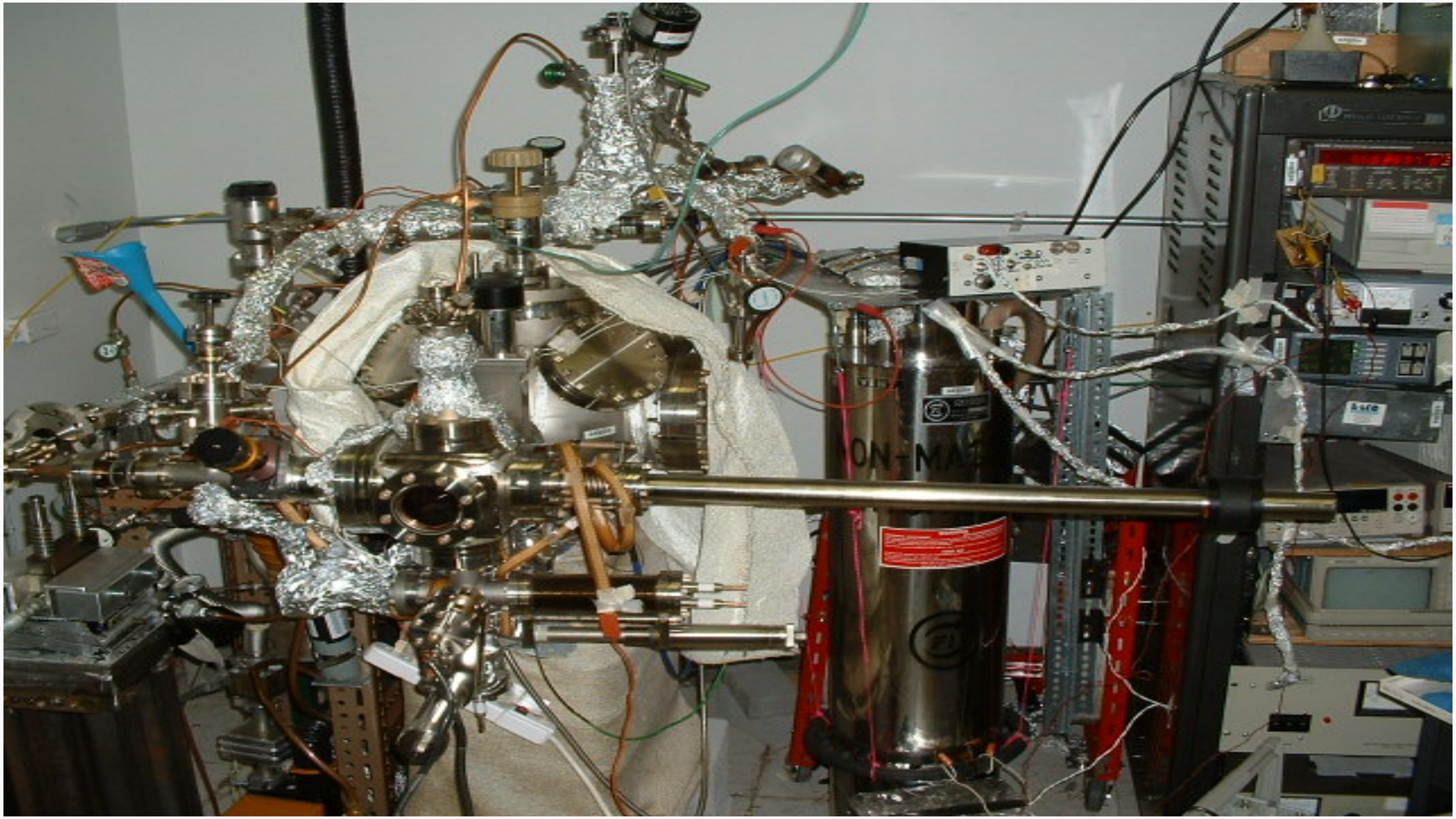


$$F_f = \eta v = (m/\tau) v$$

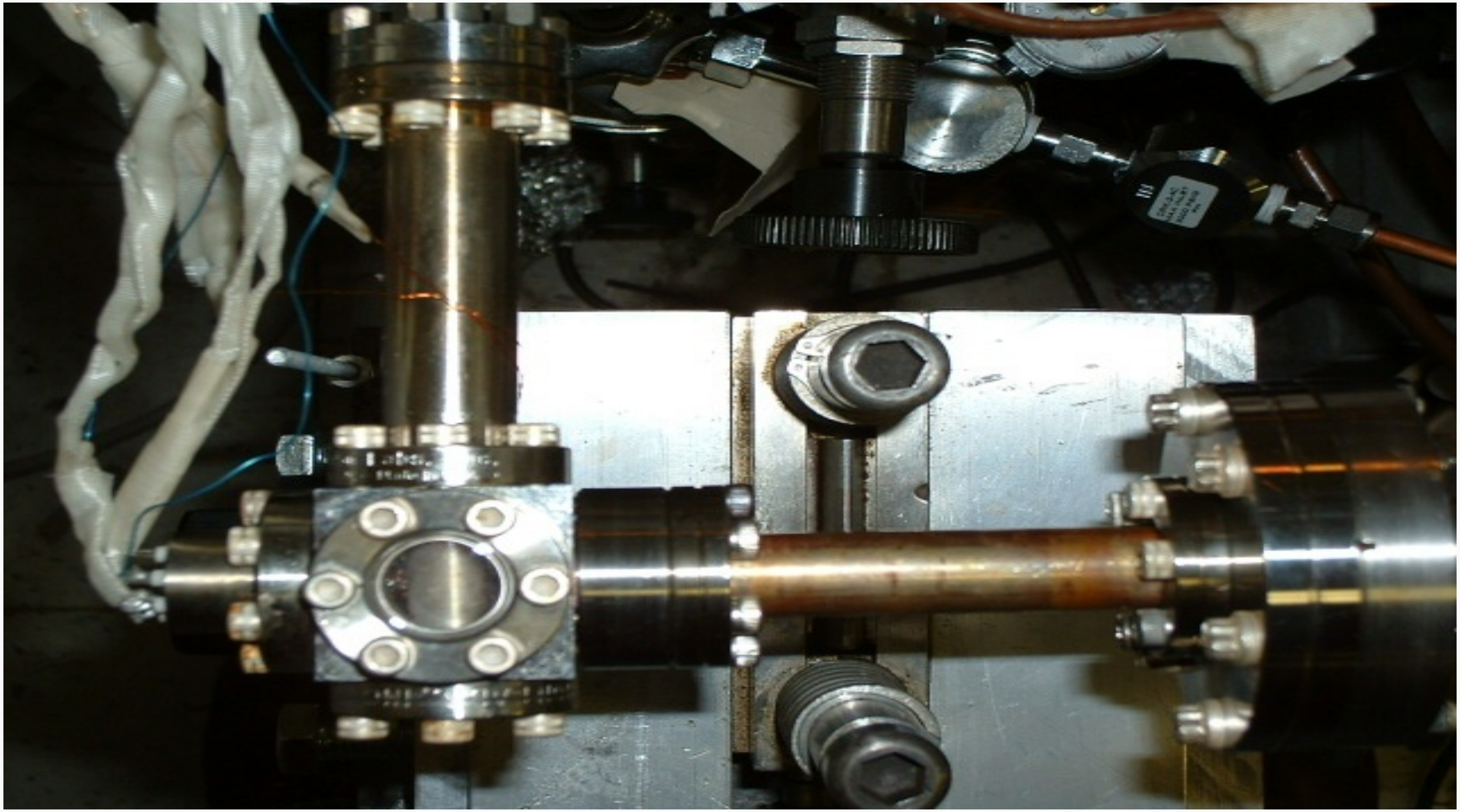
1. Cieplak, Smith, and Robbins, Science 265, 1209 (1994).
2. Persson and Nitzan, Surf. Sci. 367, 261.
3. Robbins and Muser, in Handbook of Modern Tribology.



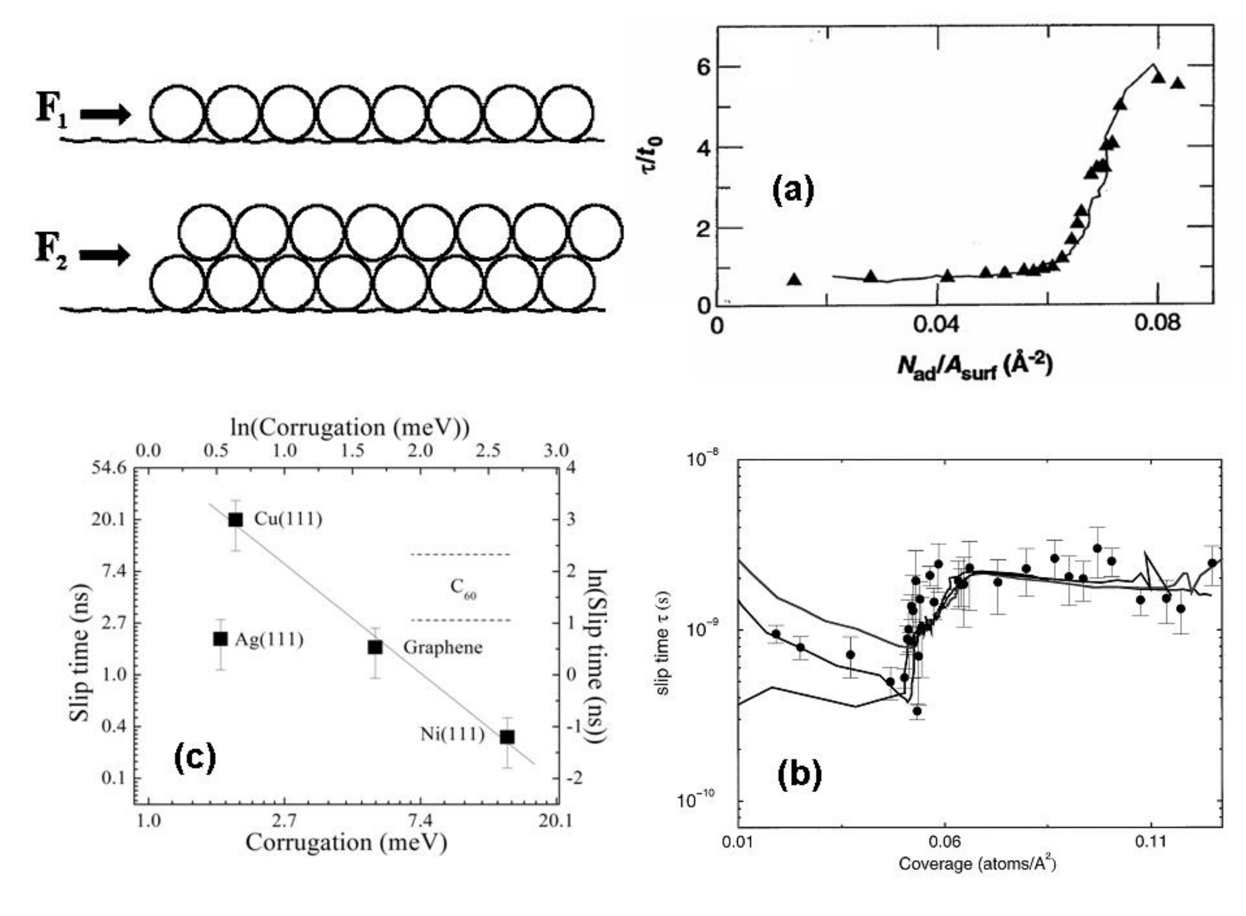
The Experimental System



All samples prepared and measured in situ



QCM confirmations of phononic friction

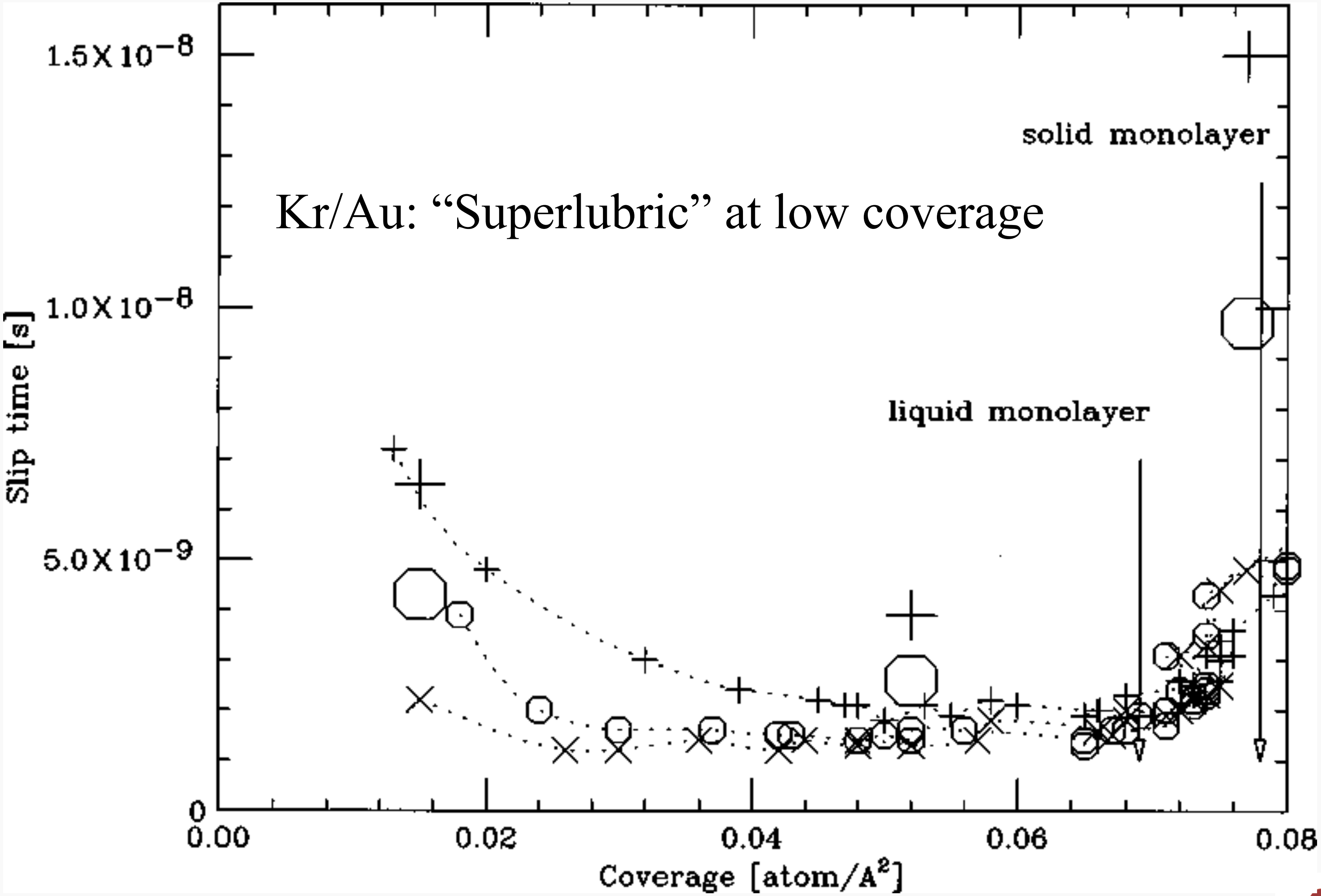


Solid-liquid Transition in a Kr/Au layer Krim, PRL 1991

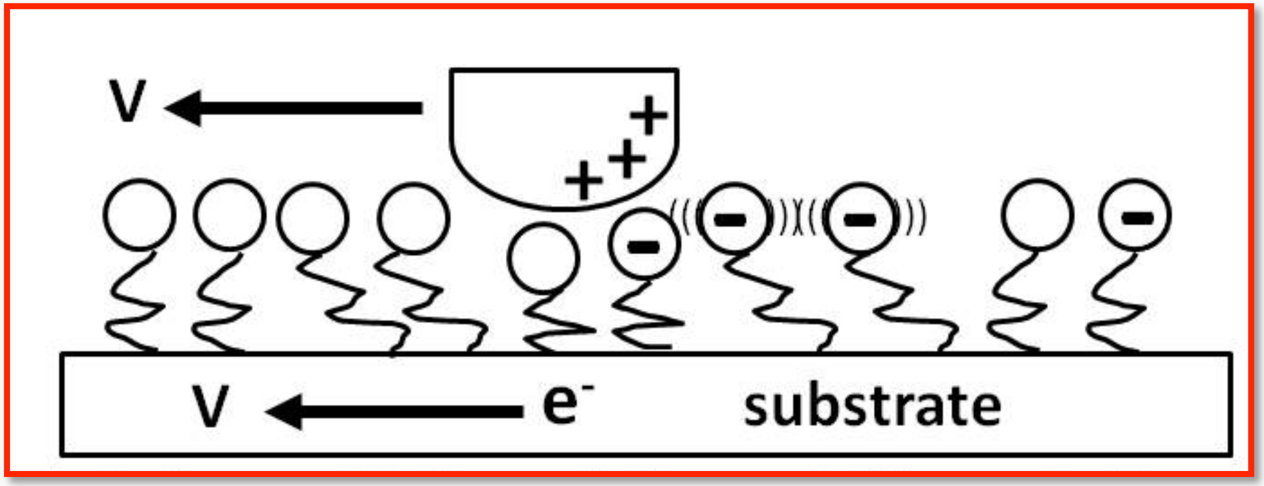
Slip time versus substrate potential corrugation Coffey, PRL 2006

Monolayer to Bilayer in Xe/Ag Daly, PRL 1996

Kr/Au: “Superlubric” at low coverage

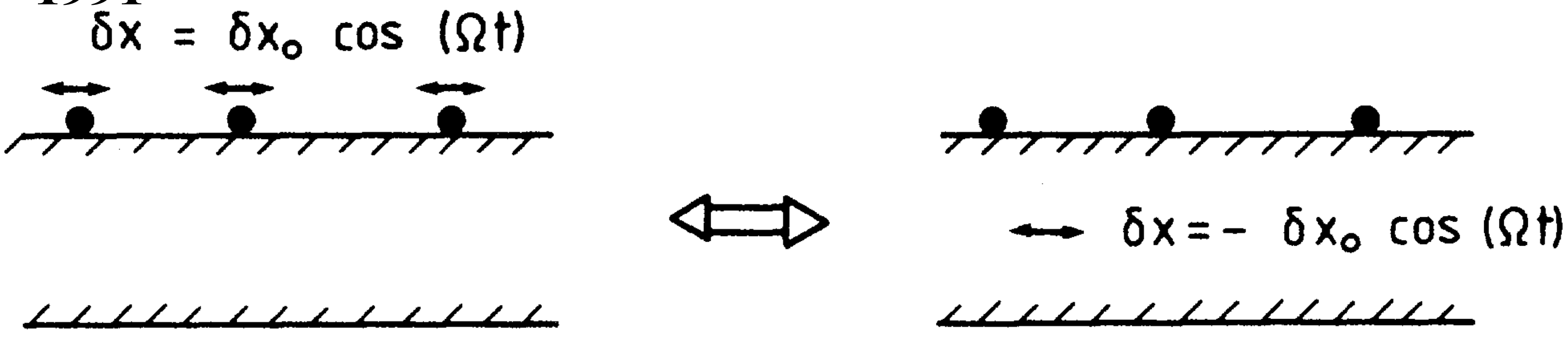


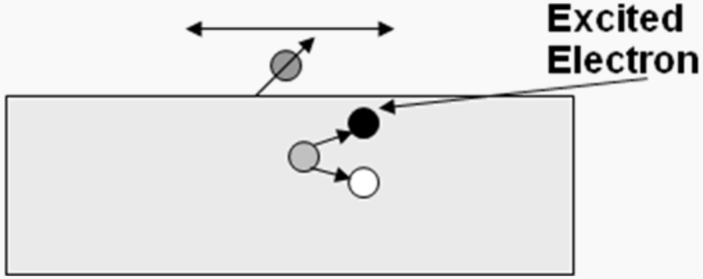
QCM documentation of superconductivity dependent friction.

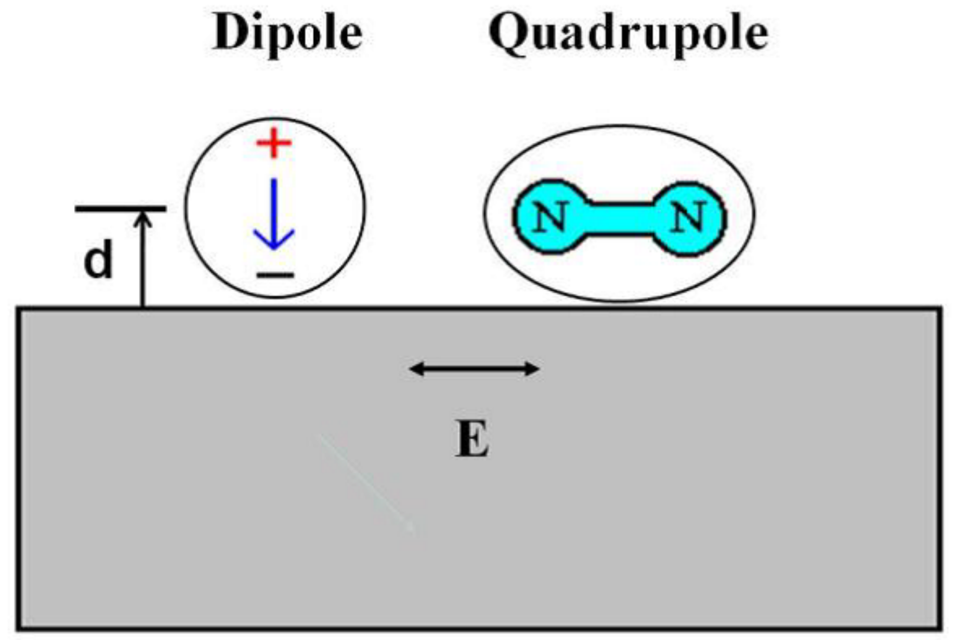


1996-2006 Theory colleagues: B.N. J. Persson, M.O. Robbins, L.W. Bruch, Students: A. Dayo, M. Highland, Postdocs: B. Mason and B. Borovsky

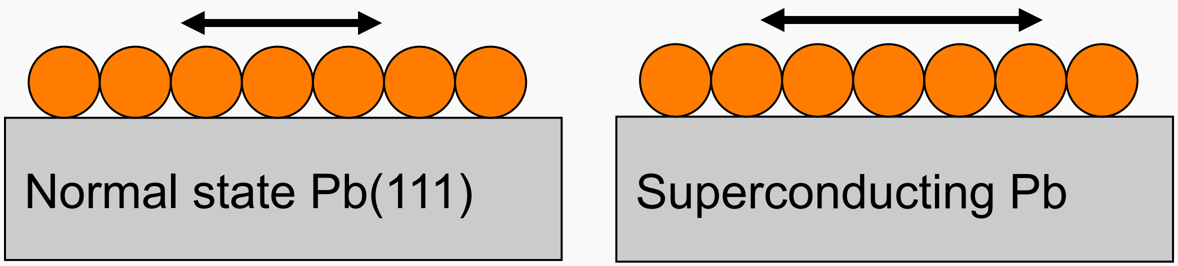
Conduction electron Mechanisms for friction B.N.J. Persson, 1991



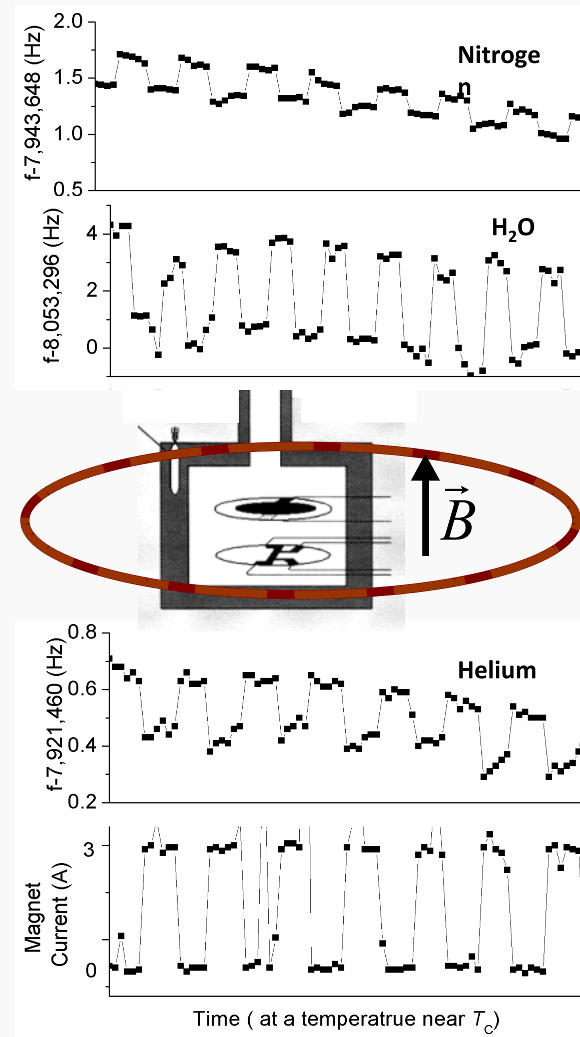




Superconducting materials provide a means to study conduction electron contributions to friction.

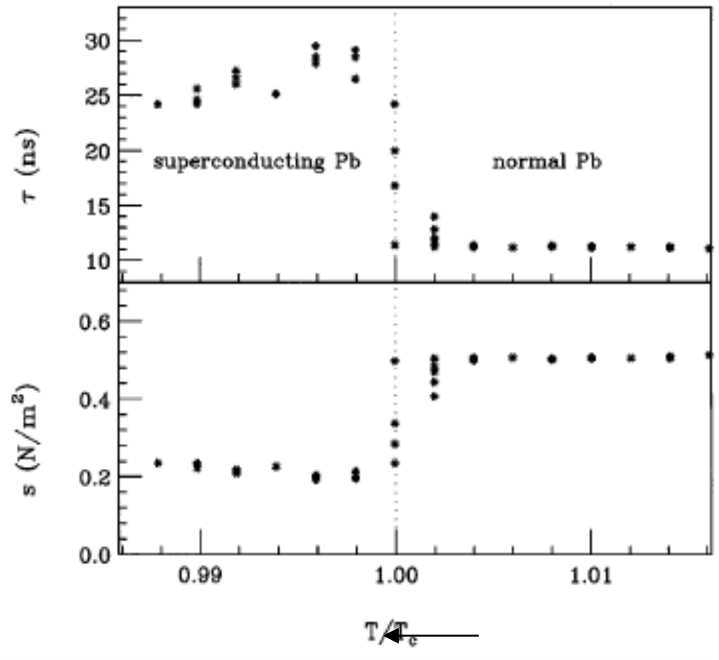


$\text{Friction}_{\text{Normal}} > \text{Friction}_{\text{Superconducting}}$



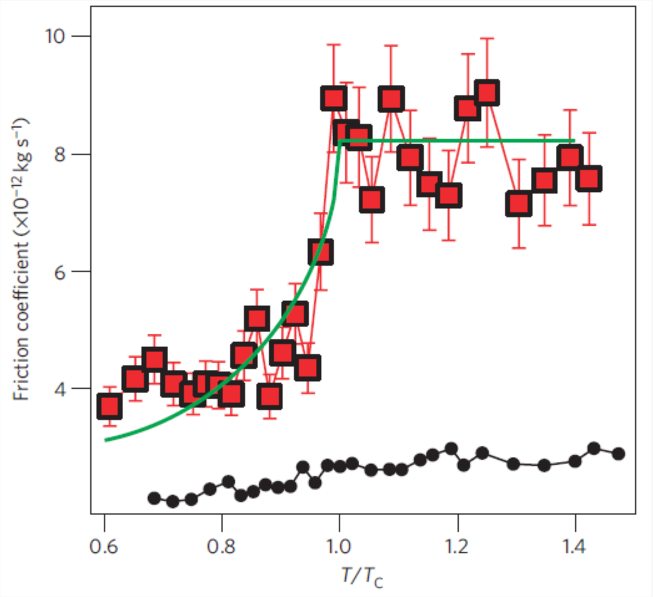
A. Dayo, Alnasrallah, and Krim, PRL (1998); M. Highland and J. Krim, PRL (2006) Superconductivity dependent friction for nitrogen, helium and water on Pb(111)

Phononic friction must be very low in order for conduction electron effects to be observed.



A. Dayo *et al.*, *Phys. Rev. Lett.*, (1998)

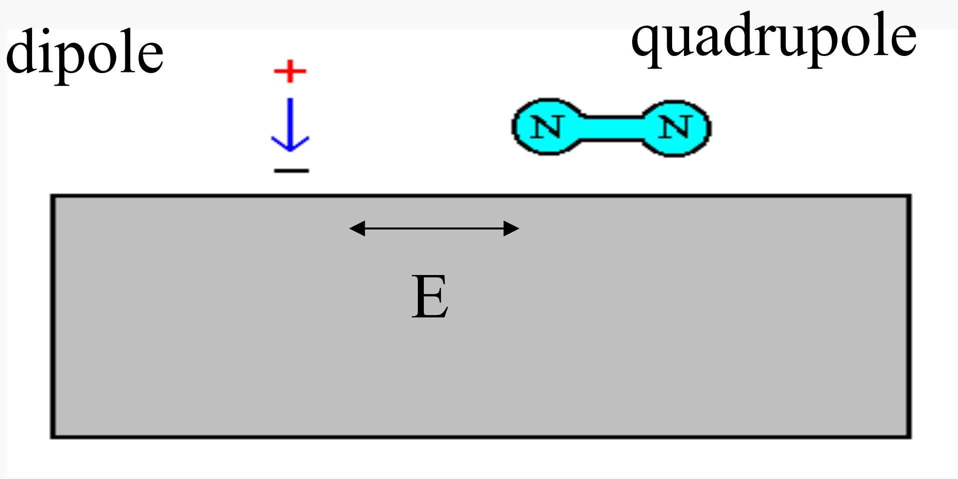
- Quartz microbalance study of nitrogen monolayers sliding on Pb(111)
- Friction dropped in half as the system passed through Tc = 7.2 K.



M. Kisiel *et al.* , Nature Materials (2011)

- Sharp cantilever tip vibrating at 5.3 KHz in close, but noncontacting proximity with Nb.
- Friction dropped in half as the system passed through Tc = 9.2K, compared well with theory.

Bulk Electronic Contributions to Friction



- Quadrupole moments can result in large dissipation, assuming a N_2 herringbone lattice
- **This effect will be much smaller for rare gases and larger for CO**

L. W. Bruch, Phys. Rev. B, 16, 201, (2000).

Comparison of Theory and experiment：

Highland and Krim , PRL 2006 with Bruch, 2000

	Highland data		Theory	
	N_2/Pb ($10^7 s^{-1}$)	He/Pb ($10^7 s^{-1}$)	N_2/Pb ($10^7 s^{-1}$)	Xe/Ag ($10^7 s^{-1}$)
η_{sc}	2.5	0.51	-	-
η_n	5.1	1.3	-	-
$\eta_{n} - \eta_{sc}$	2.6	0.79	5 – 50	0.5

Bruch's Theory (2000)

General expressions for the E-field of adsorbate monolayer

$$E_Z(\vec{r},z)=\sum_{\vec{g}} E(\vec{g},z)\exp(i\vec{g}\cdot\vec{r}) \quad \vec{E}_{parallel}=\sum_{\vec{g}}\left[i\vec{g}/g^2\right]\exp(i\vec{g}\cdot\vec{r})\partial E(\vec{g},z)/\partial z .$$

Microscopic E for the "herringbone" N_2 lattice

$$E(\vec{g},z)=-\frac{\pi\theta}{a_c}\exp(-g[z-z_0])\sum_{\beta=1}^{2}\exp(-i\vec{g}\cdot\rho_\beta)\left[\vec{g}\cdot\hat{i}_\beta\right]^2$$

Timescale for power loss in adsorbed film for quadrupoles

$$\frac{1}{t_d(\hat{A})}=\frac{\theta^2 l}{6M\sigma_0(1-p)}\left(\frac{1}{a_c}\sum_{\vec{g}}(\vec{g}\cdot\hat{A})^2\exp(-2gL_{ov})\times\left|\sum_{\beta=1}^{2}\exp(-i\vec{g}\cdot\vec{\rho}_\beta)\left[\vec{g}\cdot\hat{i}_\beta\right]^2\right|^2\right).$$

t_d=2-20ns in agreement with the results of Dayo et al experiment

Timescale for power loss in adsorbed film of dipoles

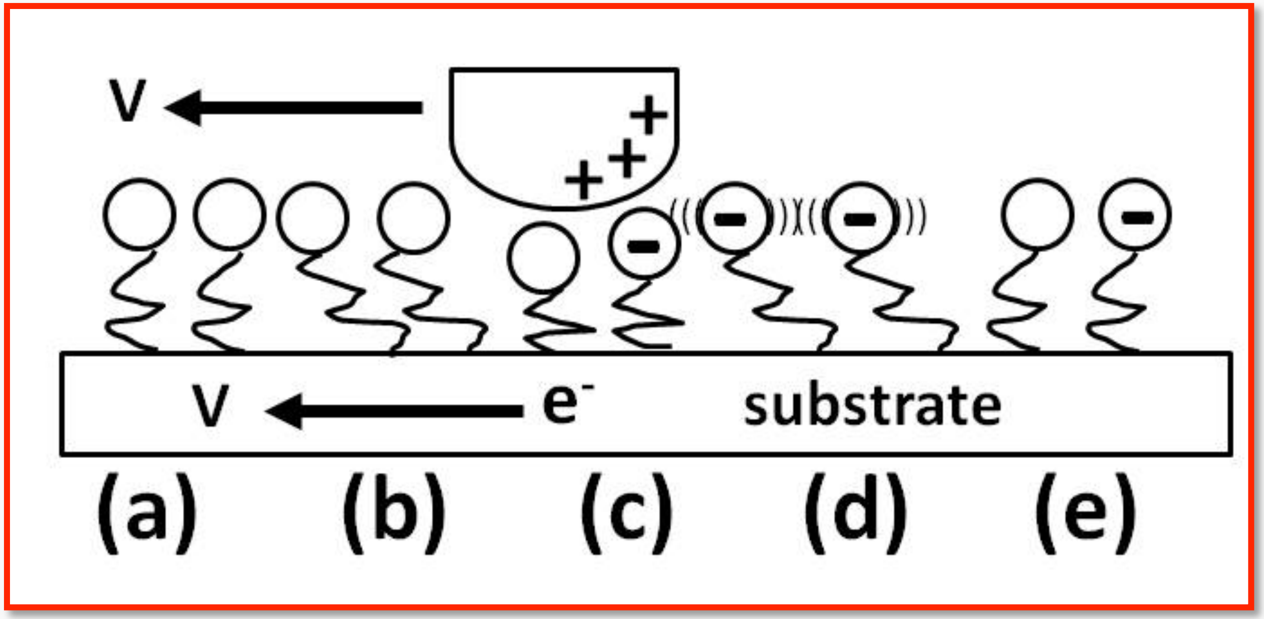
$$\frac{1}{t_d}=\frac{2\mu^2 l}{3Ma_c\sigma_0(1-p)}\sum_{\vec{g}} g^4\exp(-2gL_{ov})$$

Computes t_d for Xe/Ag(111) to be ~200ns

“After all these years of teaching graduate level Jackson E&M, I have finally found something that it is useful for”

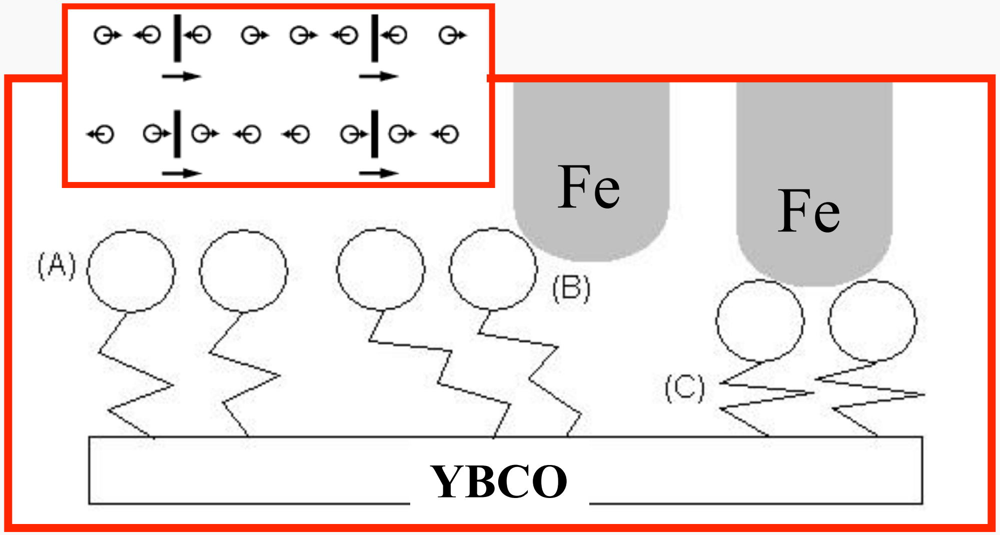
L.W. Bruch, Madison, WI, 2000

AFM study of friction for a high temperature superconductor: magnetic tip sliding on YBCO



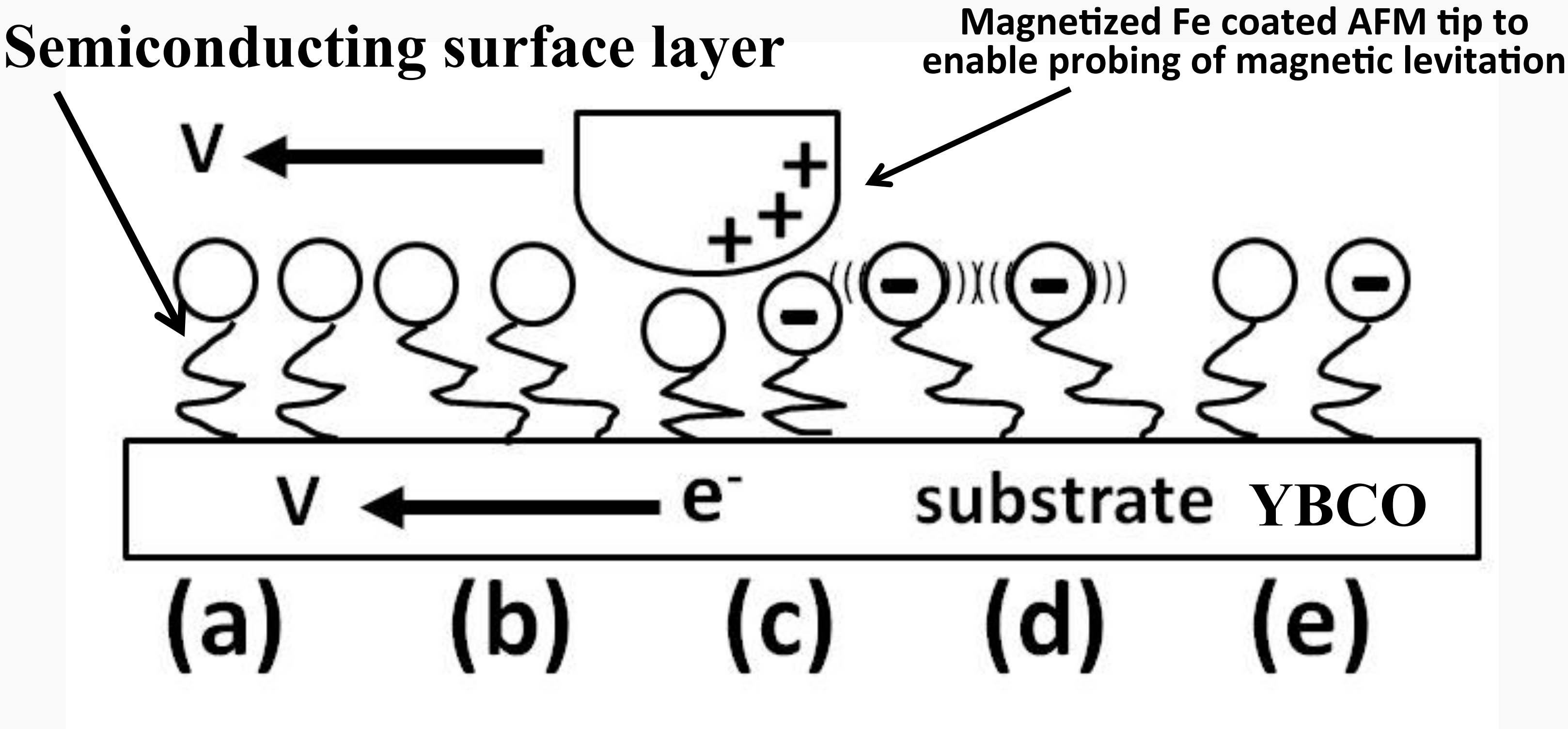
2010-2012: Post-doc I. Altfeder

High temperature supercondutor: an AFM study of Fe/YBCO above and below Tc: Is the friction higher, or lower above and below Tc?

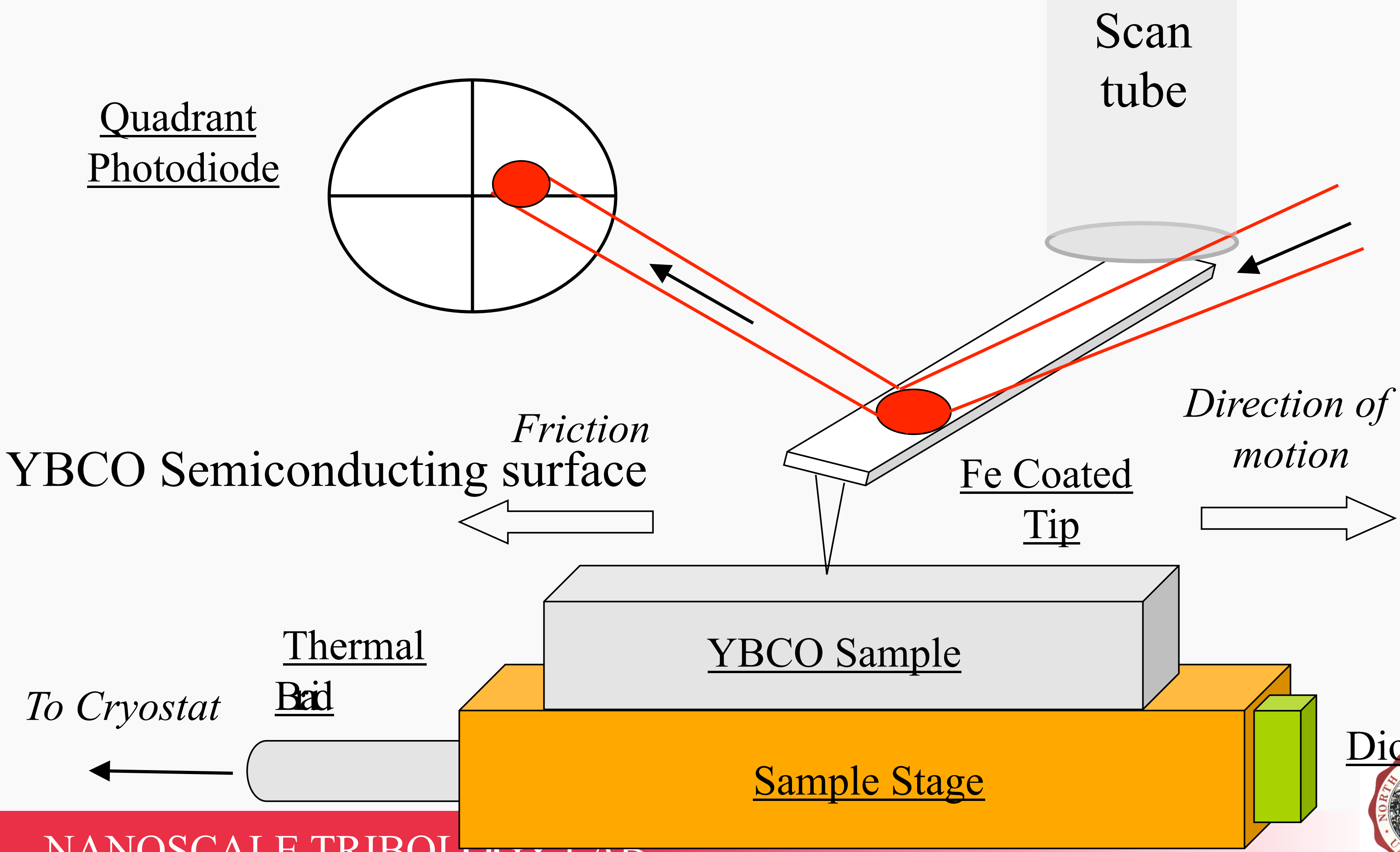


Altfeder I B and Krim J 2012 *J. Appl. Phys.* 111 094916 (2012)

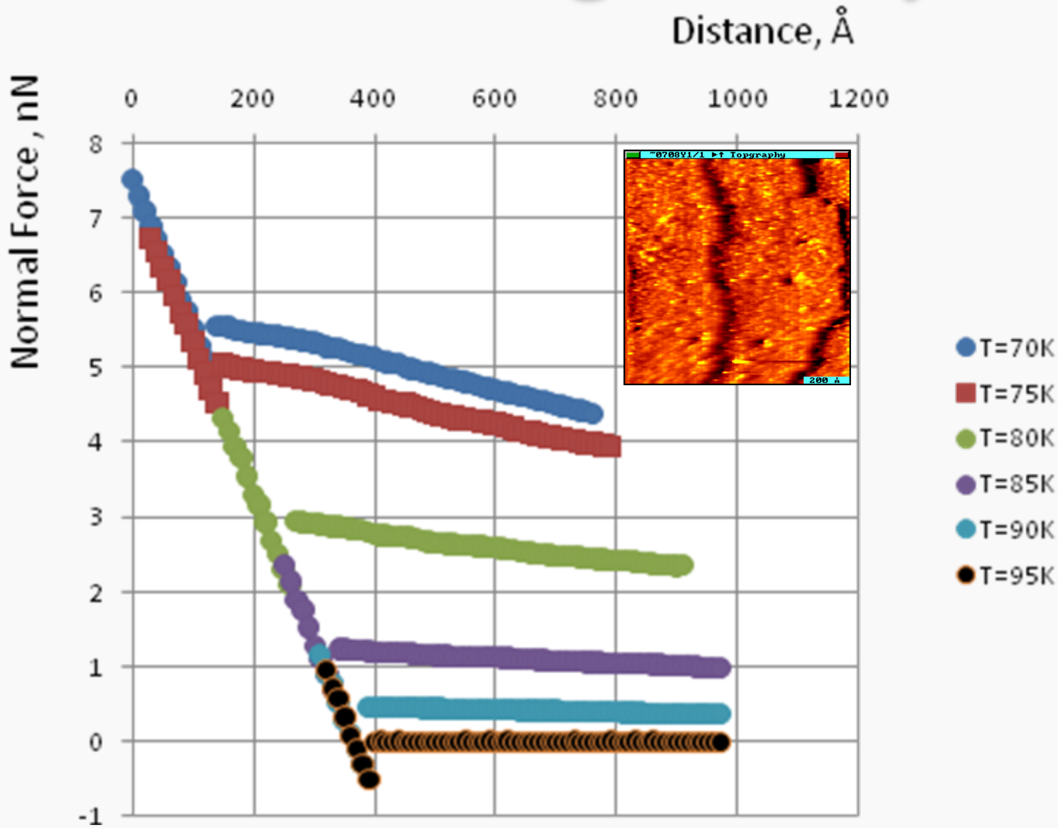
Our experiment: AFM in sliding contact with YBCO above and below Tc= 92.5K

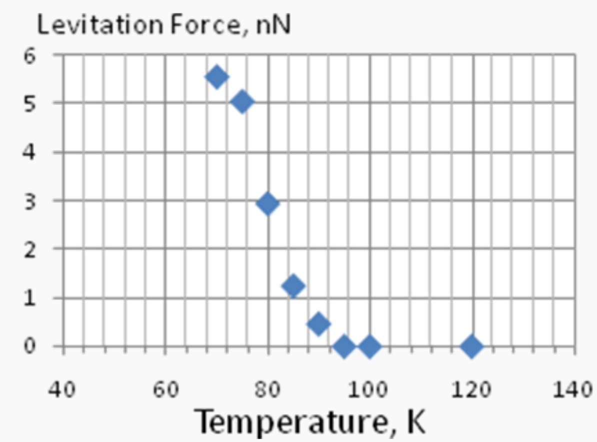


Our experiment: All work performed in Ultra-high vacuum.



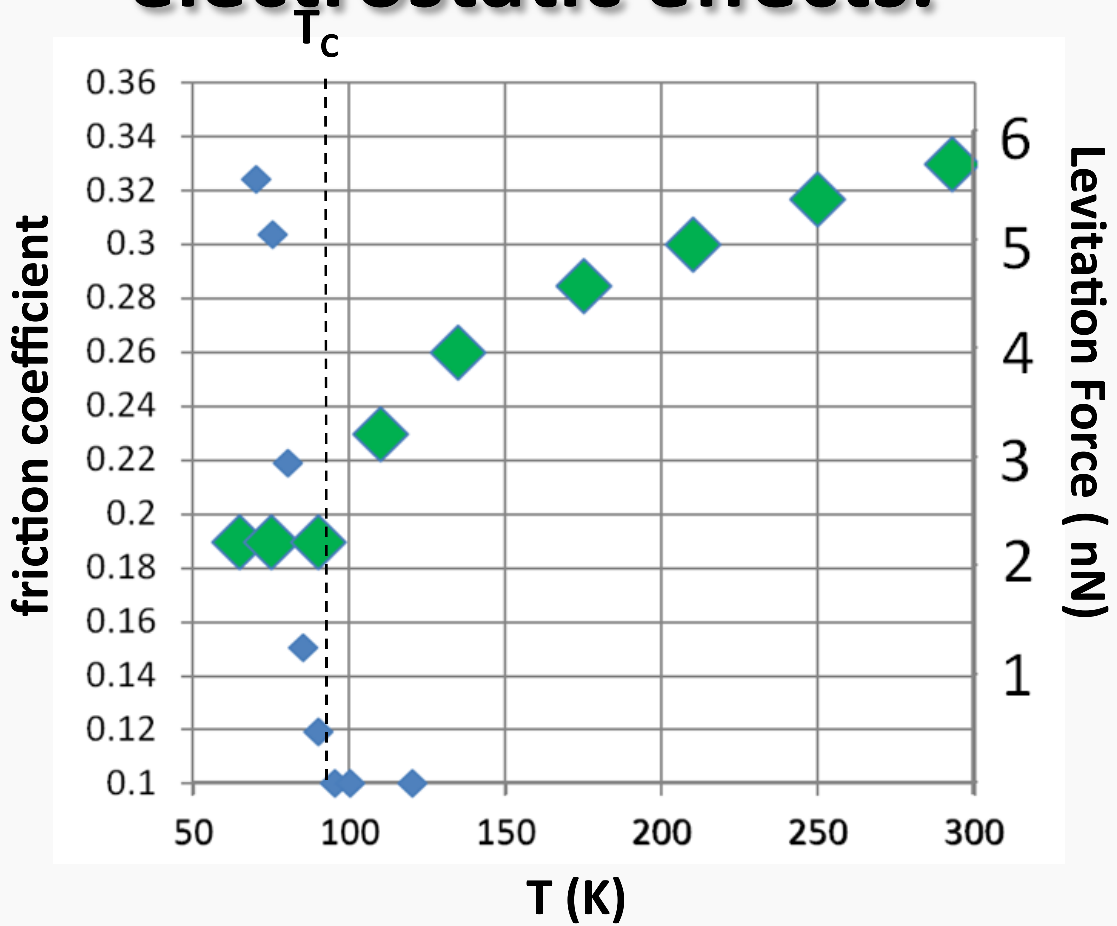
Sample image and levitation forces: Contact heating destroyed superconductivity





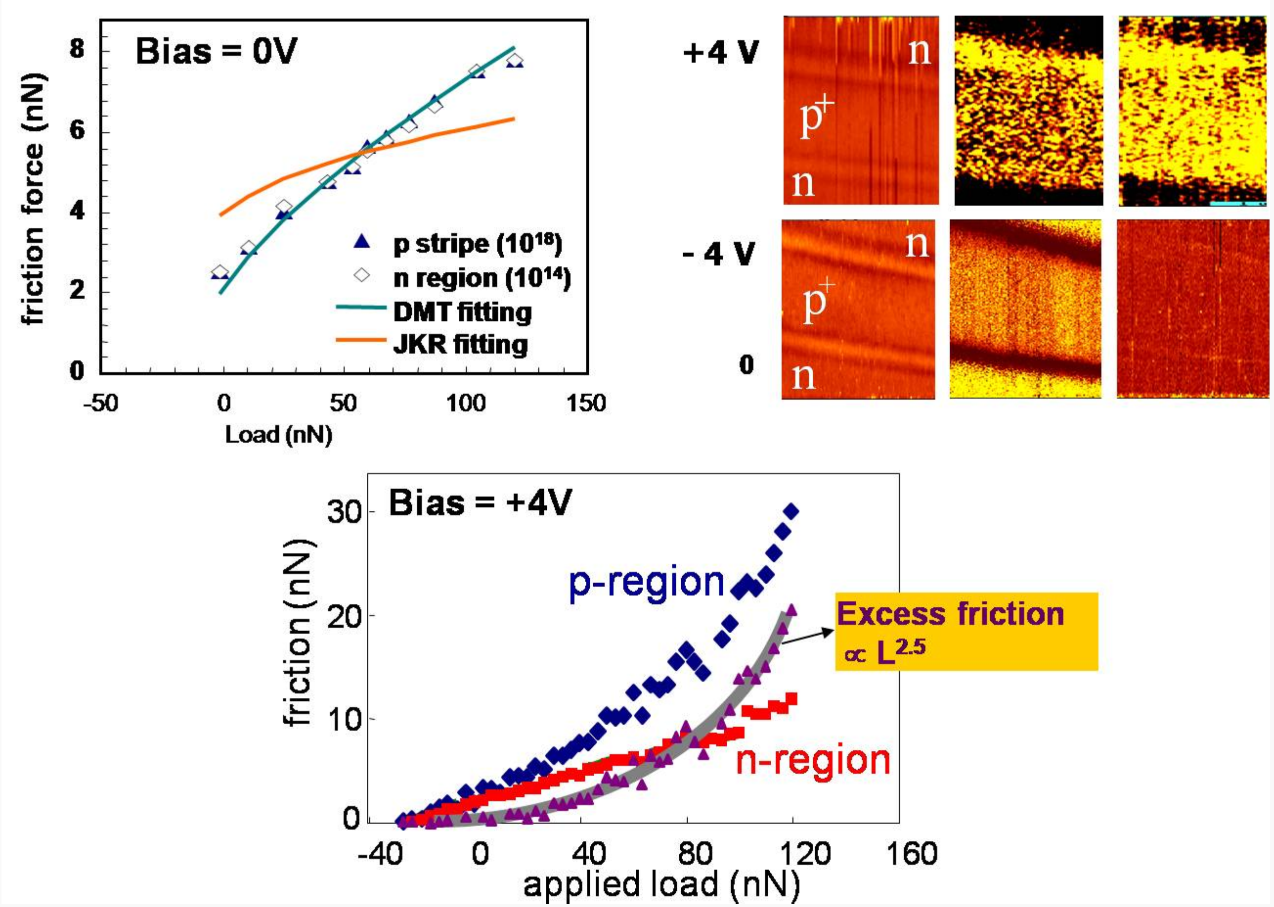
Consistent with prior reports:
H.J. Hug et al., Physica B, 194-196 (1994)

Results: Data can only be explained by electrostatic effects.



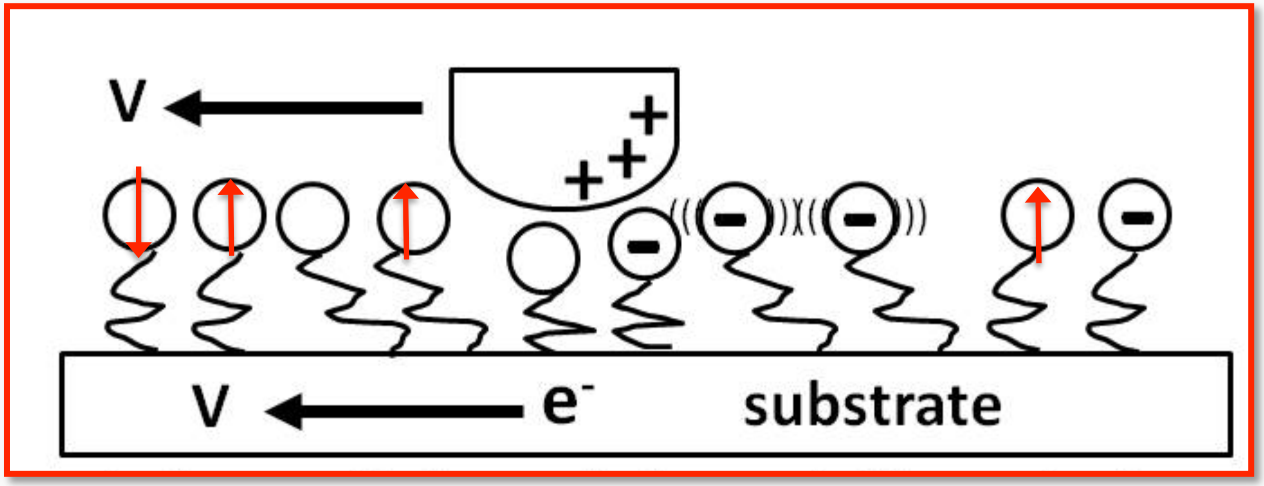
Change in friction at Tc not linked to levitation or to contact heating.

Electrostatic effects are generally inferred by process of elimination particularly by M. Salmeron & coworkers



Park, JY, Qi, YB, Ogletree, DF, et al. (2007), "*Influence of Carrier Density on the Friction Properties of Silicon Pn Junctions,*" Phys. Rev. B 76 (6), 064108. Ogletree, DF, Park, JY, Salmeron, M, Thiel, PA (2006), "*Electronic Control of Friction in Silicon pn Junctions*," Science 313 (5784), pp. 186.

Tuning Friction with an external magnetic field.



2013-present: Zack Fredricks and Keeley Stevens.

"Highland Mystery":

- The changing magnetic field reduced the frictional force.
  - Diamagnetic and paramagnetic films display different behavior
- *"Spin Friction Observed on the Atomic Scale",* B. Wolter, Y. Yoshida, A. Kubetzka, S.-W. Hla, K. von Bergmann and R. Wiesendanger, Phys. Rev. Lett. **109**, art#116102 (2012)

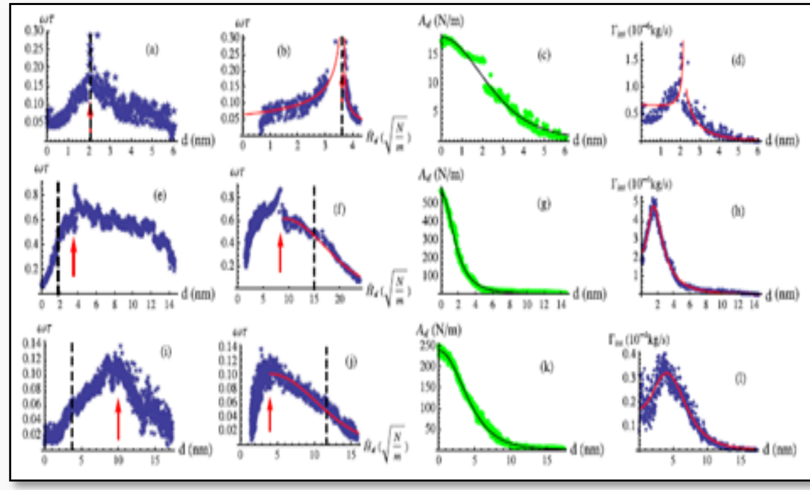
Lijnis Nelemans, High Field Magnet Laboratory

	No Magnet		Cycled Magnet		Theory	
	N_2/Pb (10^7 s^{-1})	He/Pb (10^7 s^{-1})	N_2/Pb (10^7 s^{-1})	He/Pb (10^7 s^{-1})	N_2/Pb (10^7 s^{-1})	Xe/Ag (10^7 s^{-1})
η_{SC}	2.5	0.51	0.084	0.065	...	...
η_n	5.1	1.3	0.714	1.14	...	...
$\eta_n - \eta_{SC}$	2.6	0.79	0.63	1.08	5–50	0.5

Highland & Krim PRL 96 2006

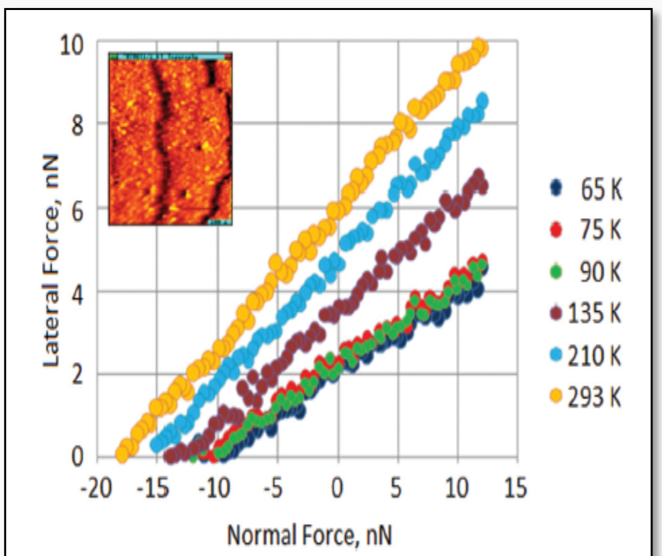
She, J-H *et al. Phys. Rev. Lett.* 108, 136101 (2012)

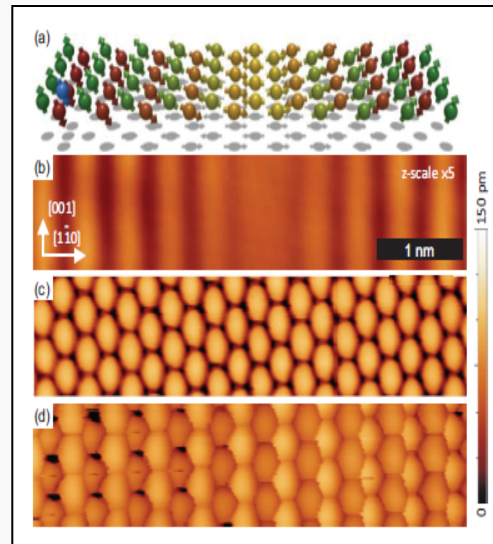
- Spin-spin coupling between defects in substrate and cantilever tip as origin of NCF



Wolter B, *et al. Phys. Rev. Lett.* 109, 116102 (2012)

- Use SP-STM to manipulate single magnetic atom (Co) over magnetic template
- Spin friction force variations





Altfeder I B and Krim J 2012 *J. Appl. Phys.* 111 094916 (2012)

- Static electrical mechanisms

Our experiment: oxygen/Ni(111)

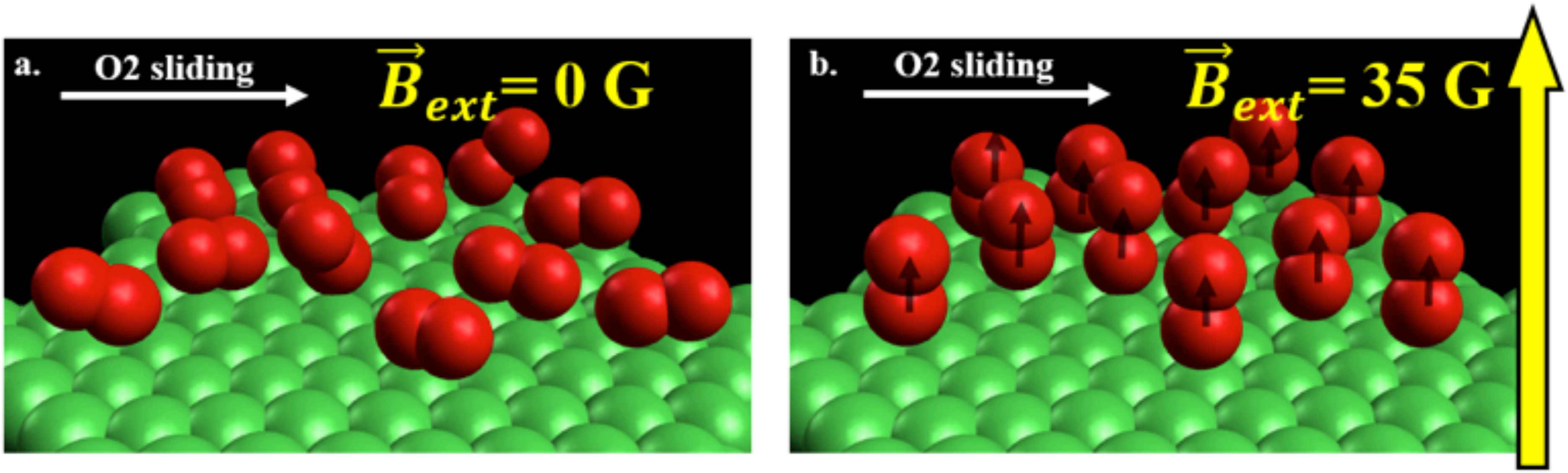
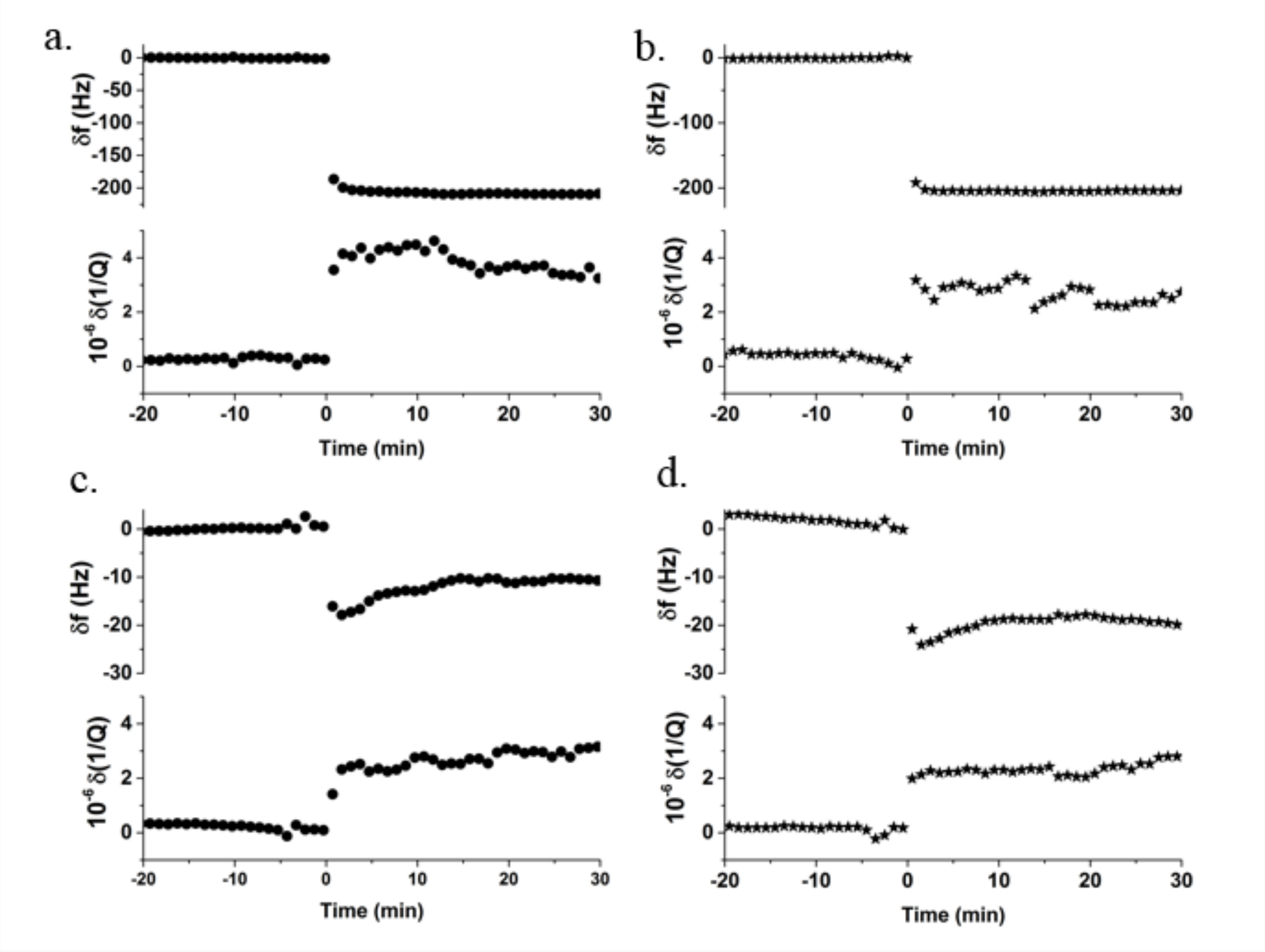
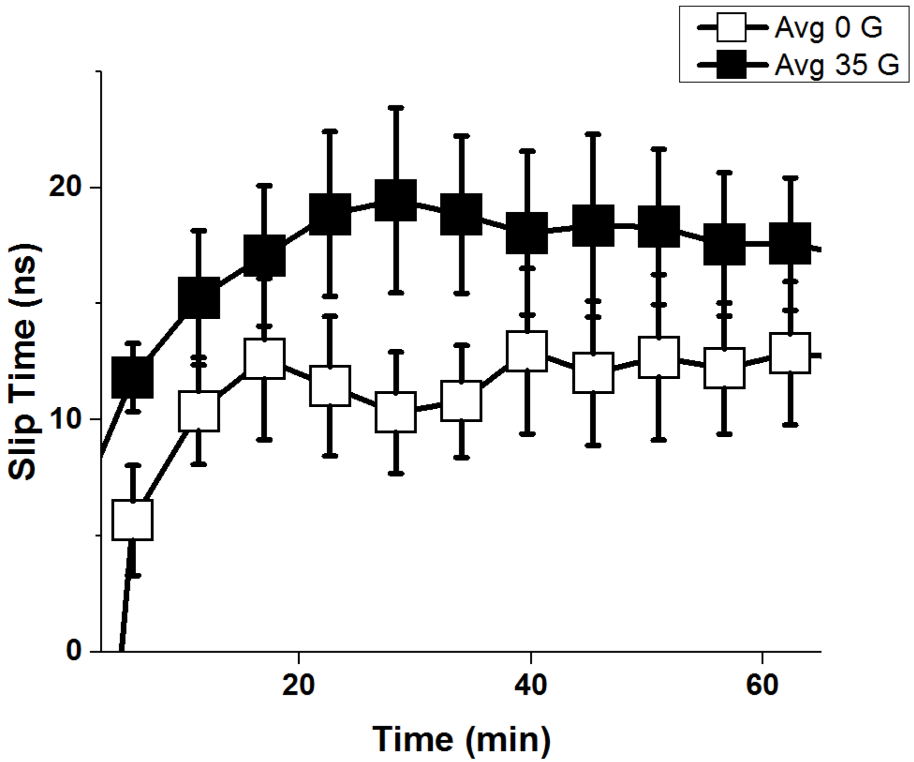


Figure 1. Model of magnetically tunable friction process. (a) Liquid O2 thin film sliding on Ni(111) surface in absence of field. When the film is grown in presence of external field (b), the O2 spin moments align in preference towards the field, altering intramolecular interactions and resulting in increased film viscosity and decreased damping.

Raw data for thick and thin films in presence and absence of field

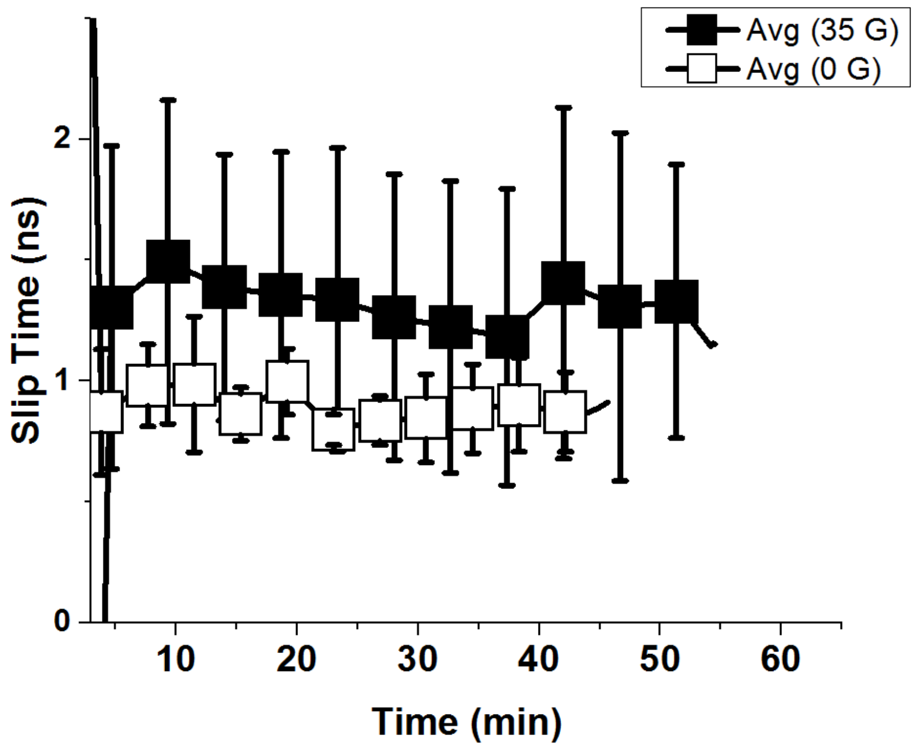


B field reduces friction



One monolayer

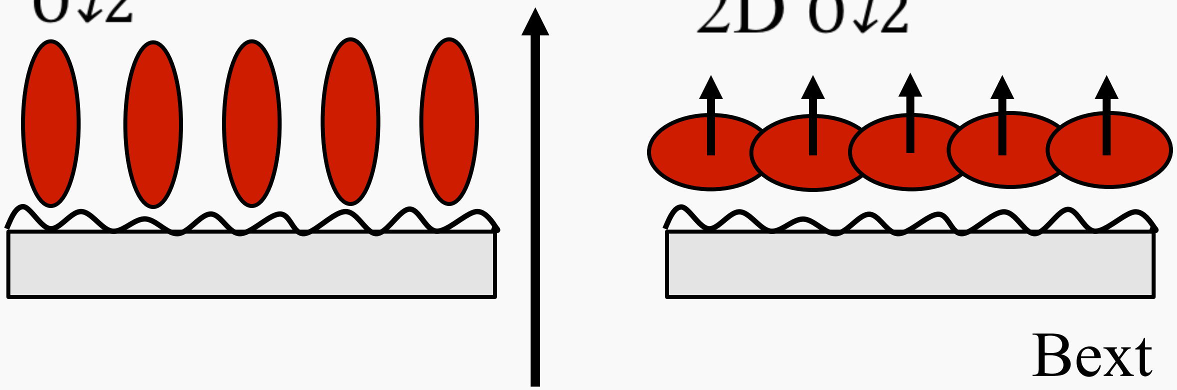
Ten monolayers

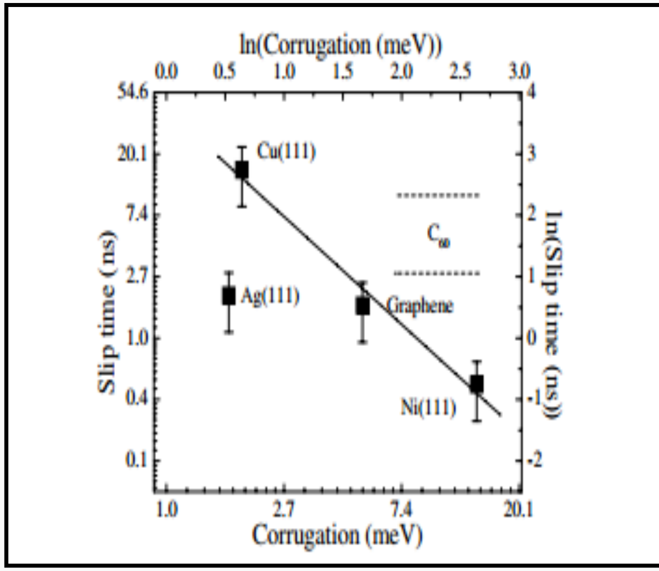


Corrugation affects friction

ζ-phase solid 2D 0↓2

δ-phase solid 2D 0↓2





Coffey & Krim
PRL 95 2005

Sliding friction directly proportional to energy corrugation amplitude squared

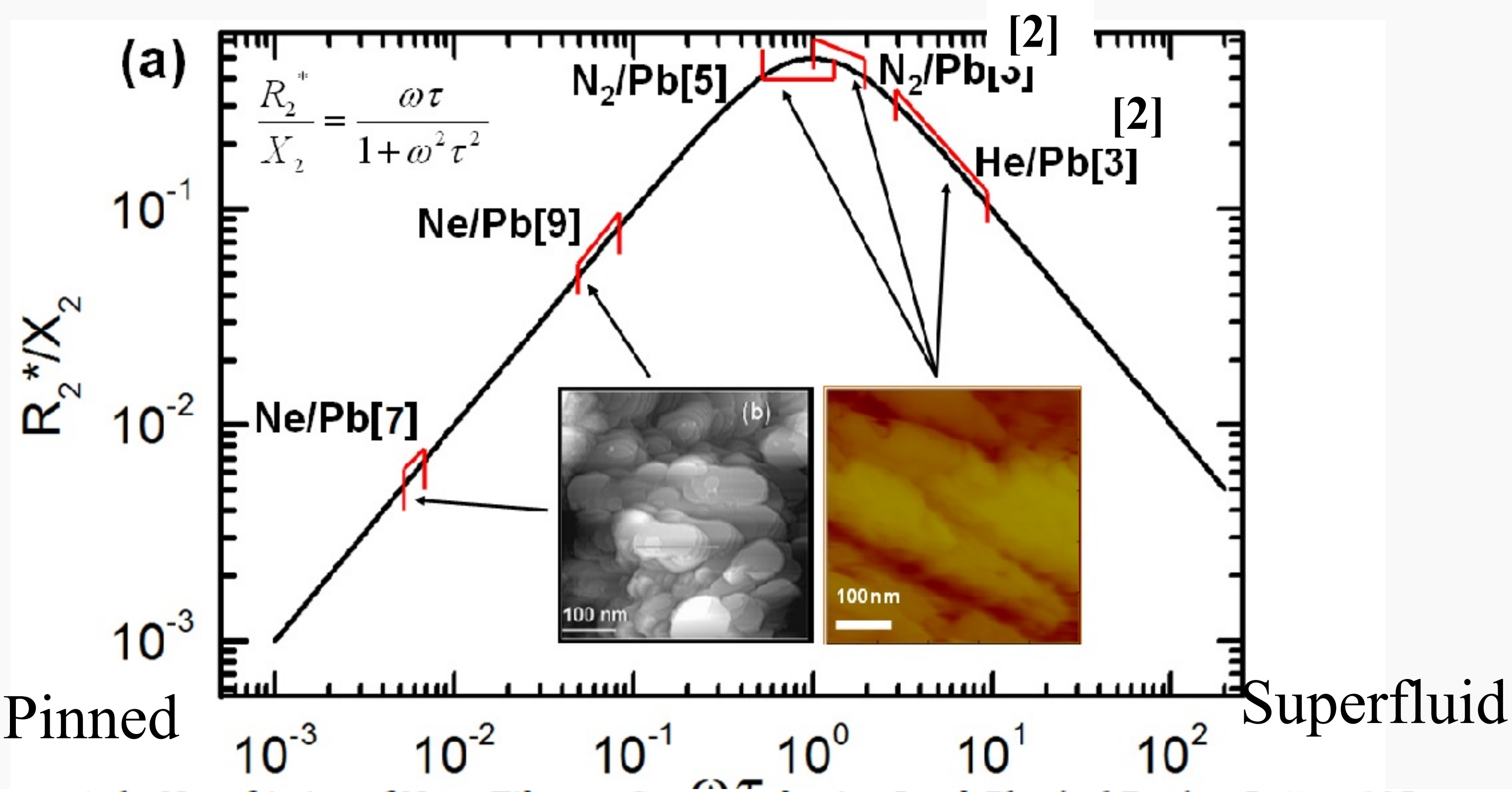
Summary

- We have observed experimental manifestations of 3 forms of wearless friction: phononic, and conduction electronic and electrostatic friction.
- The experimental values for phononic and conduction electronic contributions are consistent with first principles' theory, without fitting.
- Friction measurements are sensitive to the surface phase of a material, and its conductivity: Fixed charges indicative of insulating phases.
- We have observed secondary effects of the impact of magnetic fields on friction.

Let’s go No Wear

Let’s go NOW!

Superconductivity-dependent friction "discrepancies" arise from large variations in the phononic friction contributions associated with different surface topologies. Pierno et al [1] did not have sufficient resolution to detect the low electronic friction levels reported in Refs. [2] and [5]. K. Steven and J. Krim, Tribology letters, in prep.



[1] M. Pierno et al., *Nanofriction of Neon Films on Superconducting Lead*. Physical Review Letters **105**, 016102 (2010)

[2] M. Highland and J. Krim, *Superconductivity Dependent Friction of Water, Nitrogen, and Superheated He Films Adsorbed on Pb(111)*. Physical Review Letters **96**, 226107 (2006); Note Figure 2(b) is for nitrogen adsorption on Pb.

[3] M. Kisiel et al., *Suppression of electronic friction on Nb films in the superconducting state*. Nature Materials **10**, 119-122 (2011).

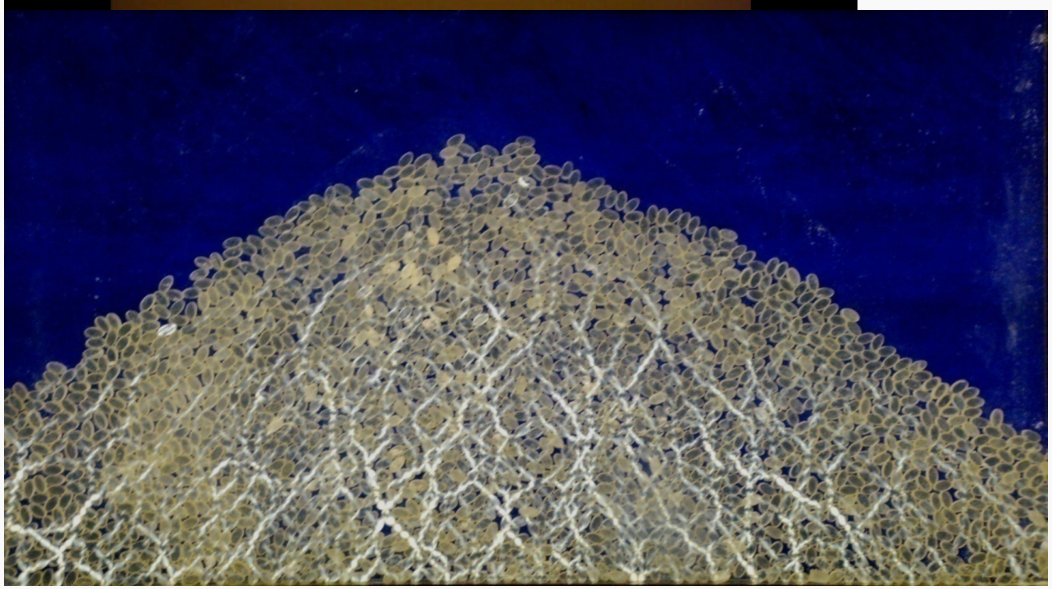
[4] J. Krim and A. Widom, *Damping of a crystal oscillator by an adsorbed monolayer and its relation to interfacial viscosity*. Physical Review B **38**, 17 12184-12189(1988).

[5] A. Dayo et al., *Superconductivity Dependent Sliding Friction*, Physical Review Letters **80**, 8 1690-1693 (1998).

[6] Y. Braiman et al., *Tuning friction with noise and disorder*, Physical Review E **59**, 5 R4737-R4740 (1999).

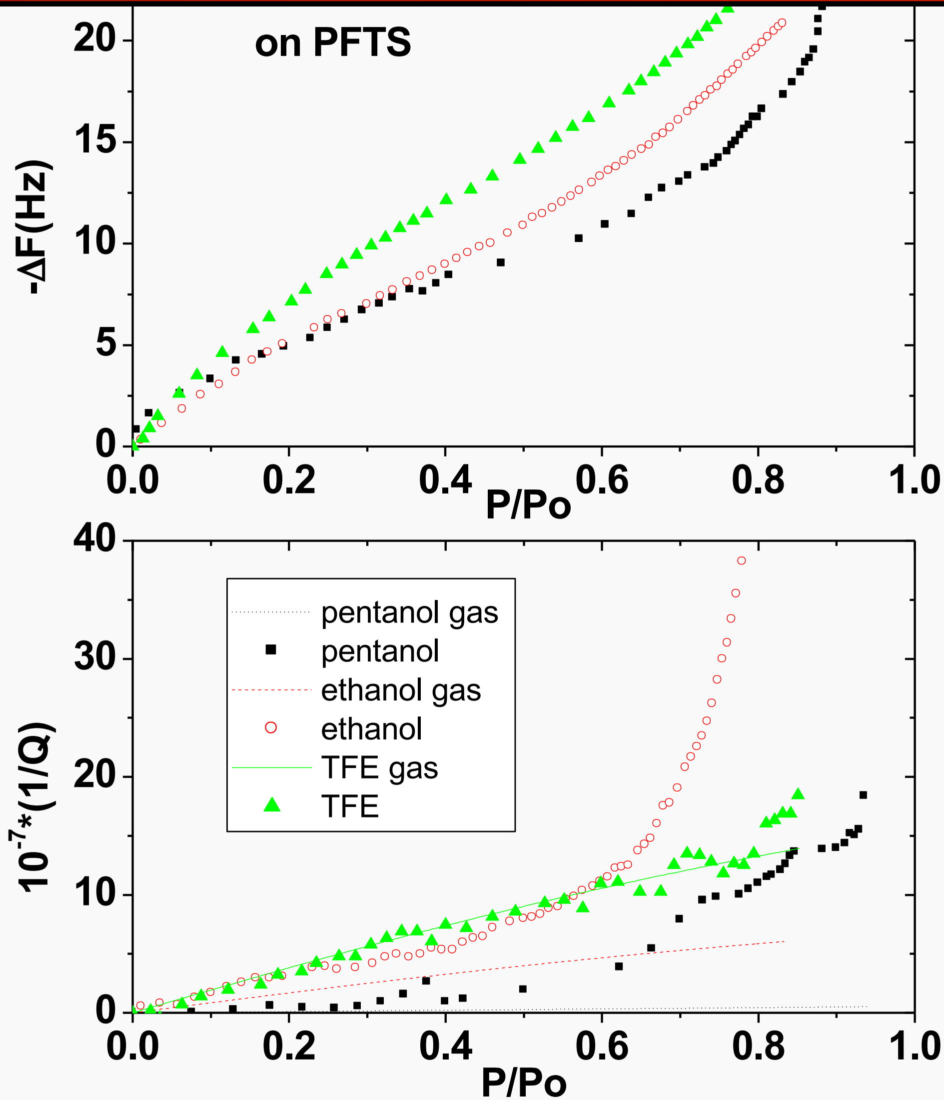
[7] L. Bruschi et al., *Structural Depinning of Ne Monolayers on Pb at T < 6.5 K*. Physical Review Letters **96**, 216101 (2006).

Friction, Force Chains and Falling Fruit



Jacqueline Krim and Robert Behringer, Physics Today, 2009

Nanoscale Sliding friction and diffusion coefficients as coverage increases: Note that differing lubrication mechanisms are possible



Ethanol/PFTS always slips

Pentanol/PFTS slips
for coverages above on monolayer.

Triflouroethanol/PFTS
never slips

B.P. Miller and J. Krim, J. Low. Temp. Phys., **157** (2009)