Nanoscale stick-slip friction studied with trapped ions

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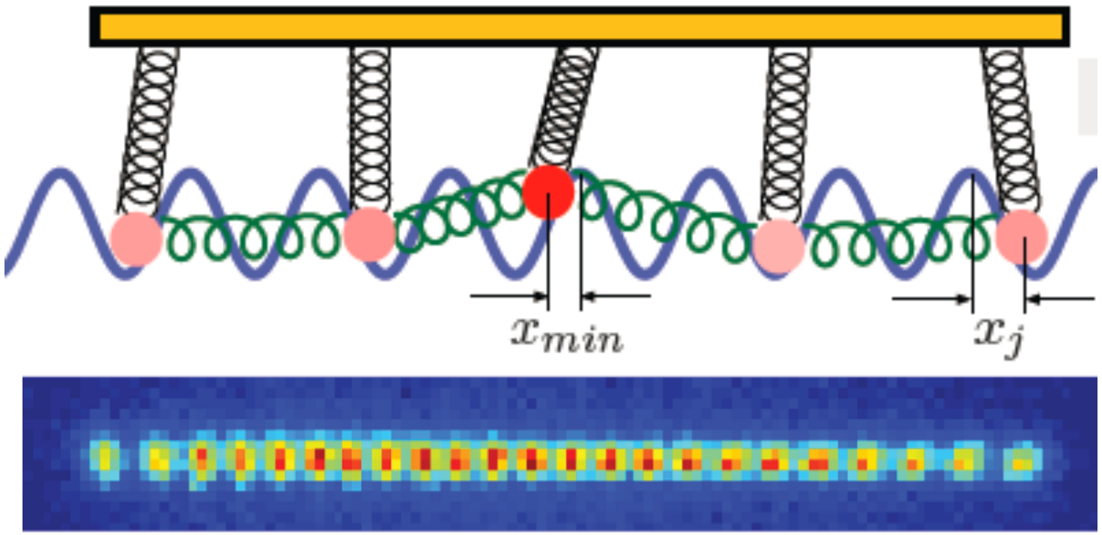

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MIT-Harvard Center for Ultracold Atoms

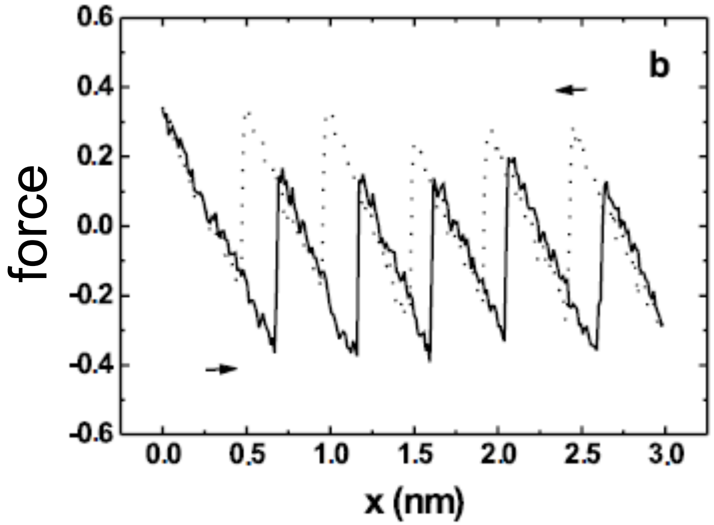
Outline

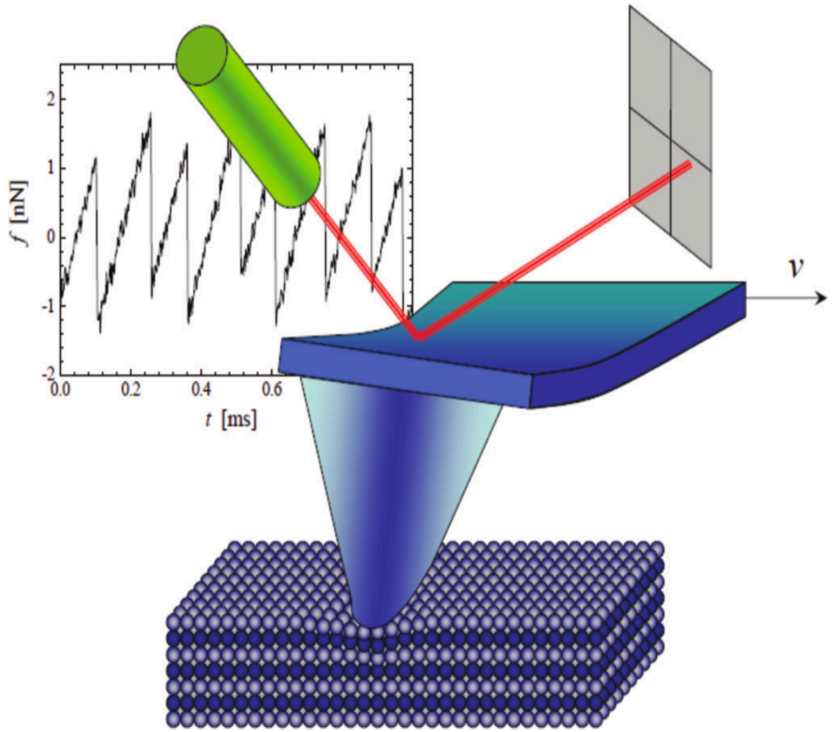
- Ion-trap emulator of friction with cold trapped ions
- Single-asperity, single-atom friction (Prandtl-Tomlinson model 1928)
- Thermolubricity, velocity dependence of friction
- From few- to many-particle friction (Frenkel-Kontorova model 1938)
- Superlubricity and the Aubry transition (Aubry 1983)
- Friction in multistable potentials

Friction at the nanoscale

- Spectacular advances
- Molecular dynamics simulations with thousands of atoms at the surface layer.
- Atomic force microscopy friction can measure atomic-scale friction.

A. Socoliuc, R. Bennewitz, E. Gnecco, and E. Meyer, PRL **92**, 134301 (2004).





Ion-crystal friction emulator

Pioneering theoretical proposals by Shepelyansky, Vanossi & Tosatti, Haeffner and others

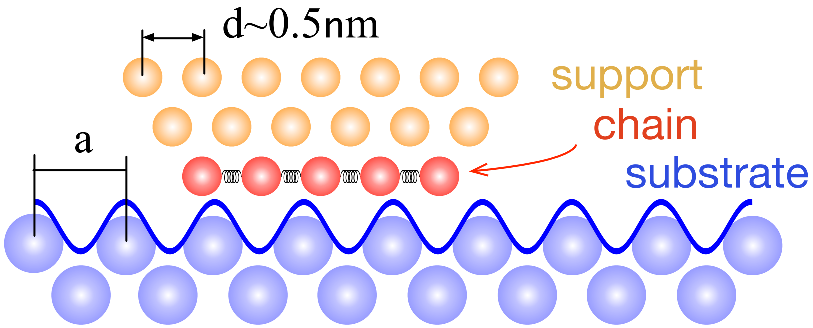
I. Garcıa-Mata, O. V. Zhirov, D. L. Shepelyansky, Eur. Phys. J. D **41**, 325 (2006).

A. Benassi, A. Vanossi, E. Tosatti, Nat. Commun. **2**, 236 (2011).

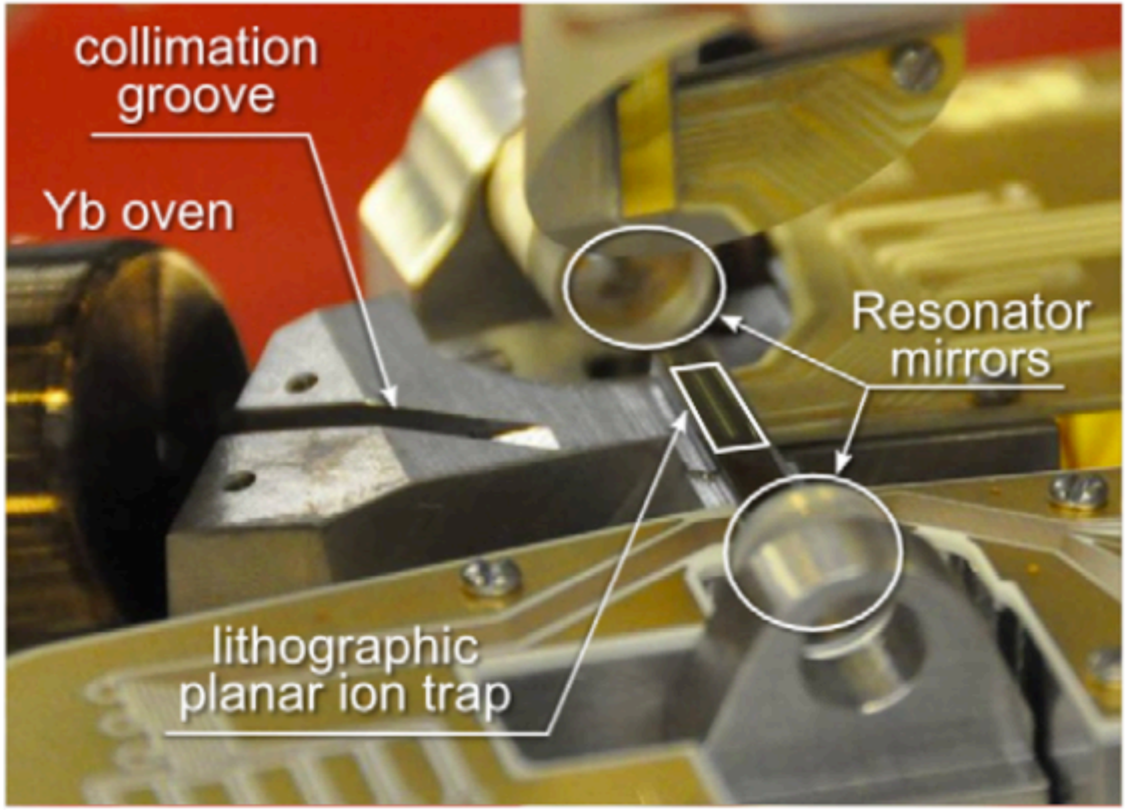
D. Mandelli, A. Vanossi, E. Tosatti, Phys. Rev. B **87**, 195418 (2013).

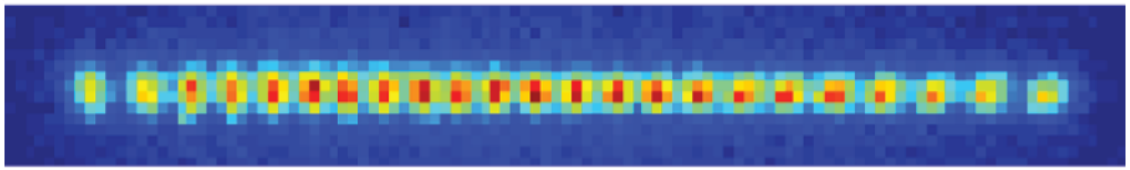
T. Pruttivarasin, M. Ramm, I. Talukdar, A. Kreuter, H. Haeffner, New J. Phys. **13**, 075012 (2011).

Our ion friction system



Our ion friction system



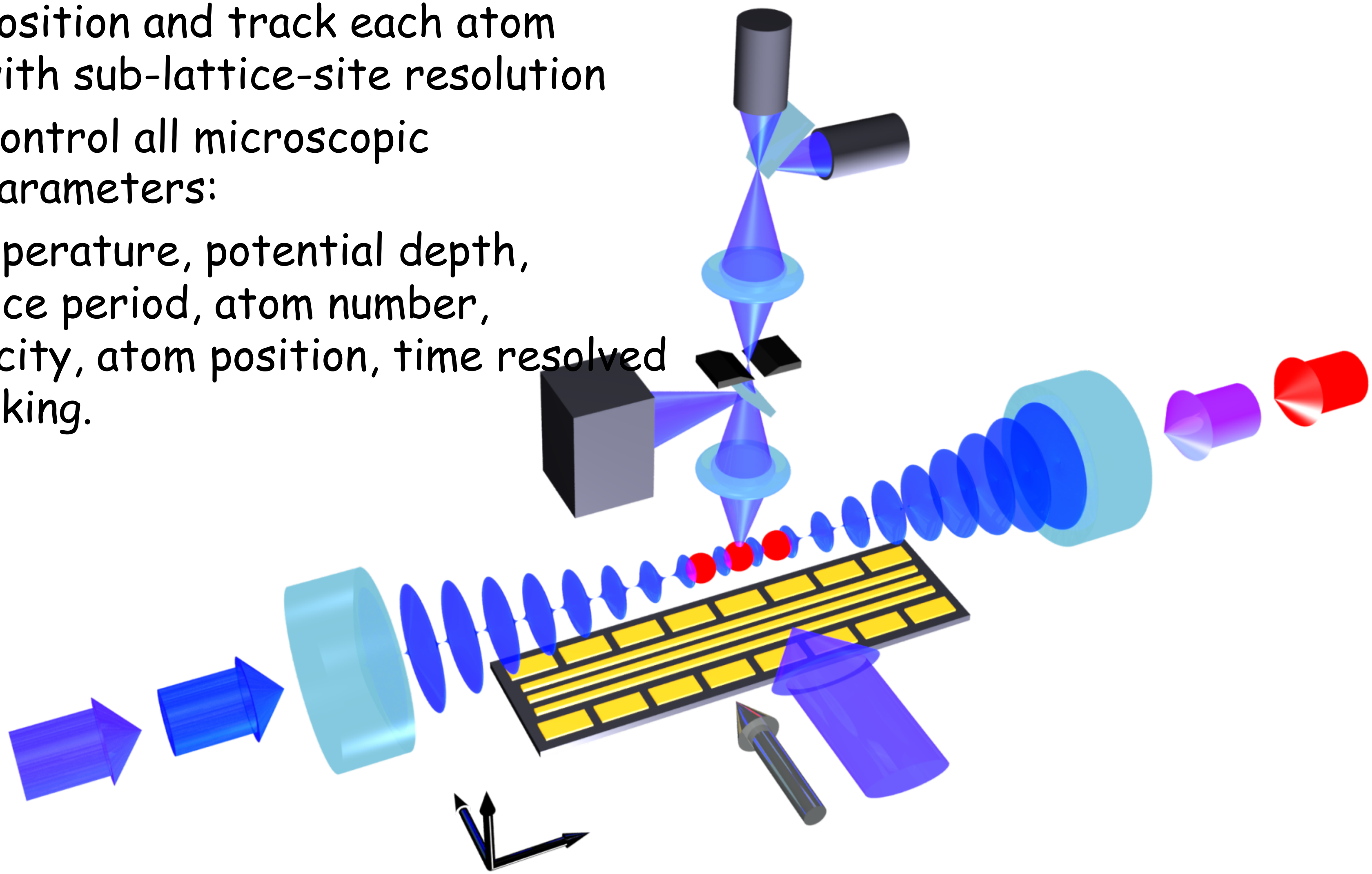


Karpa, Bylinskii, Gangloff, Cetina, & Vuletic, Suppression of Ion Transport due to Long-Lived Subwavelength Localization by an Optical Lattice. PRL **111**, 163002 (2013).

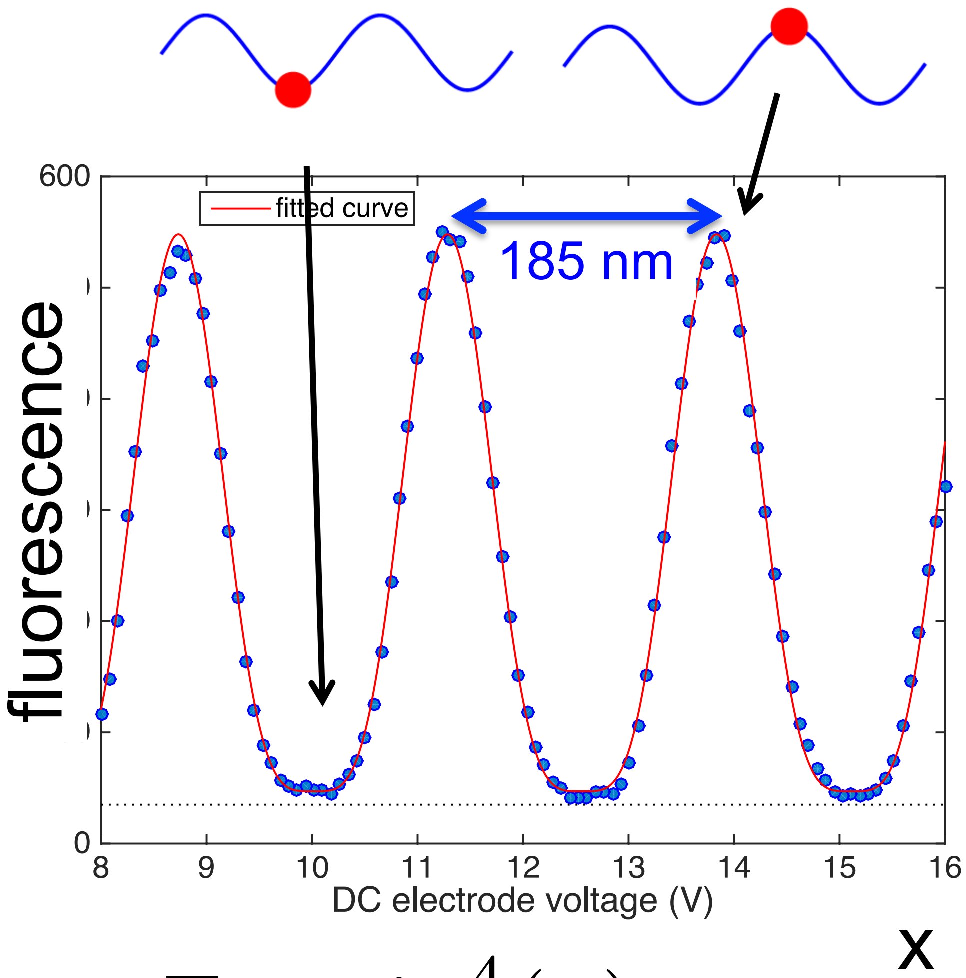
Ion crystal friction emulator

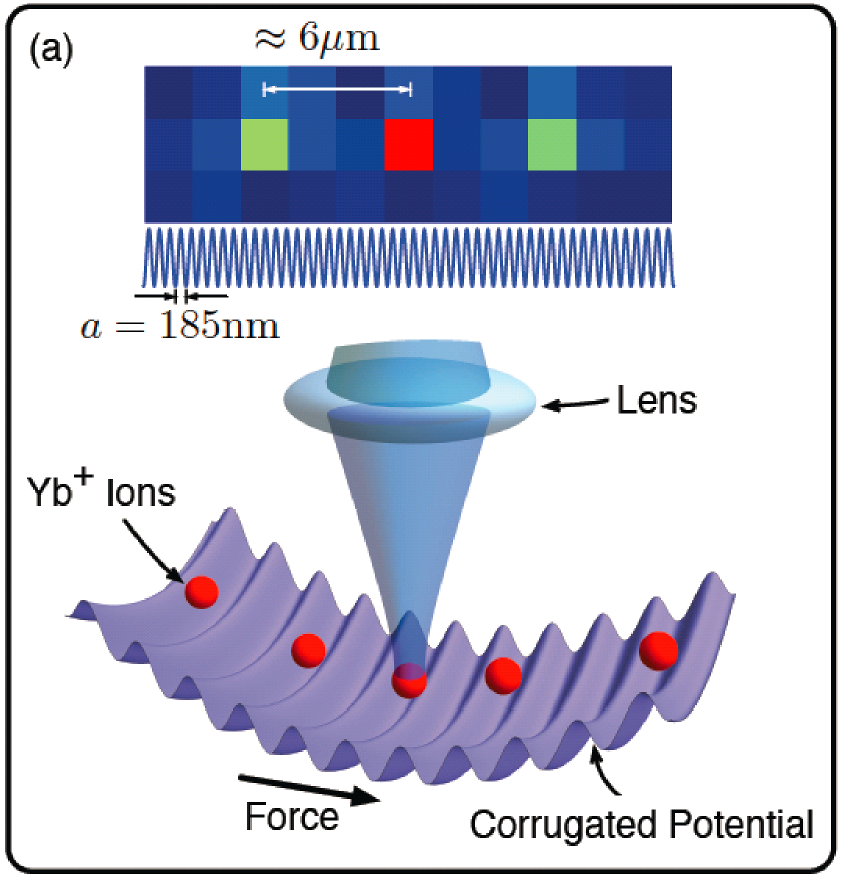
- Position and track each atom with sub-lattice-site resolution
- Control all microscopic parameters:

Temperature, potential depth, lattice period, atom number, velocity, atom position, time resolved tracking.



Subwavelength position tracking

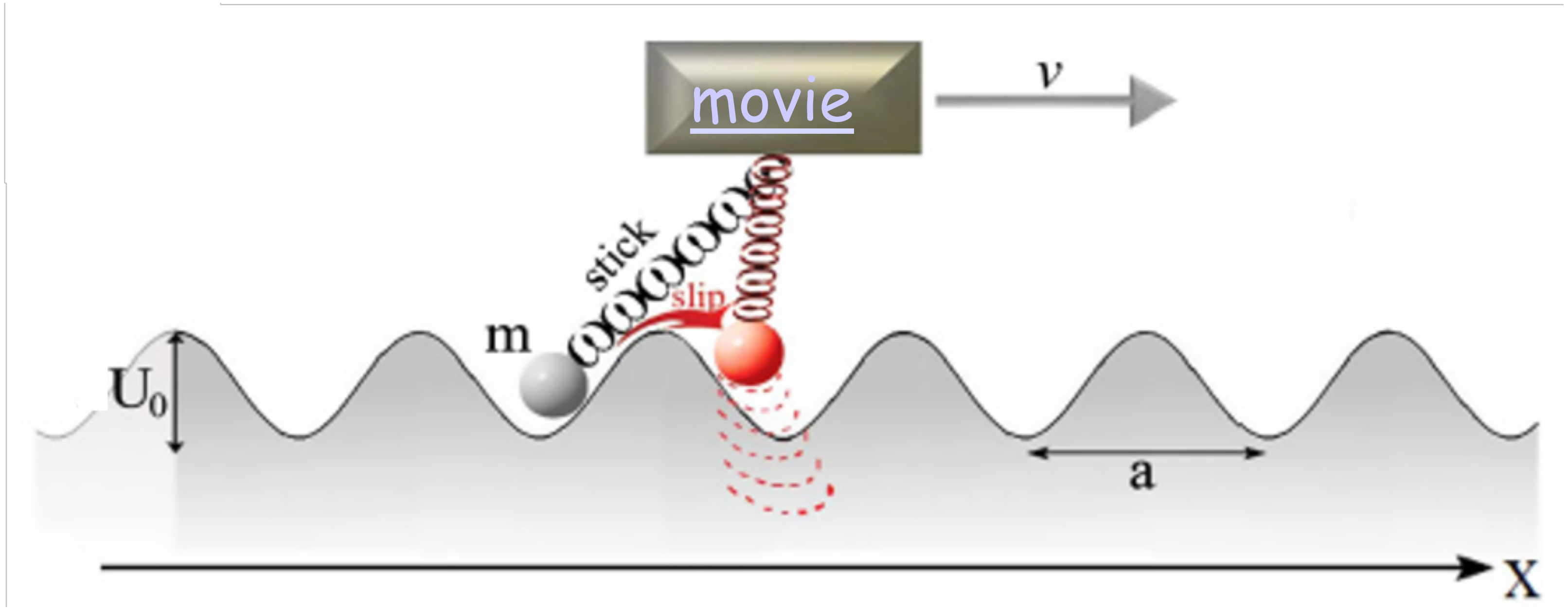




$$F \propto \sin^4(x)$$

Single-particle friction: Prandtl-Tomlinson model

Single-particle model for nanofriction

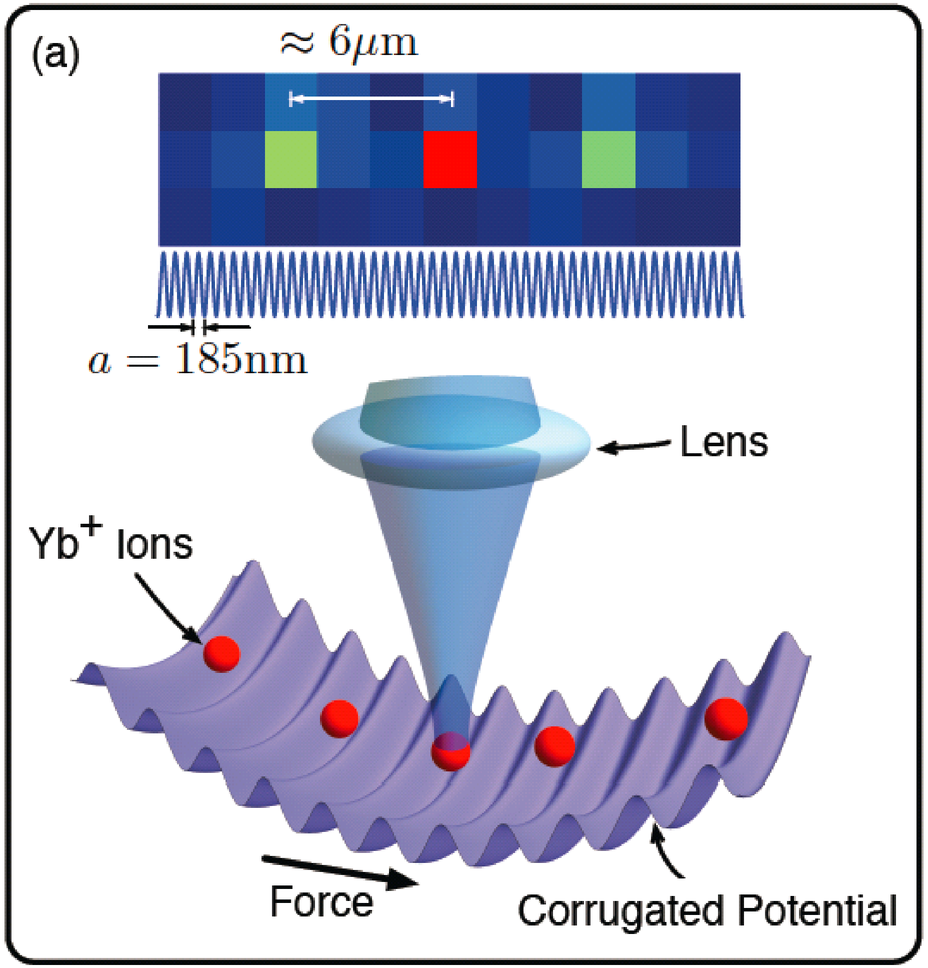


Stick-slip friction

L. Prandtl, Z. Angew. Math. Mech. **8**, 85 (1928);

G. A. Tomlinson, Philos. Mag. **7**, 905 (1929).

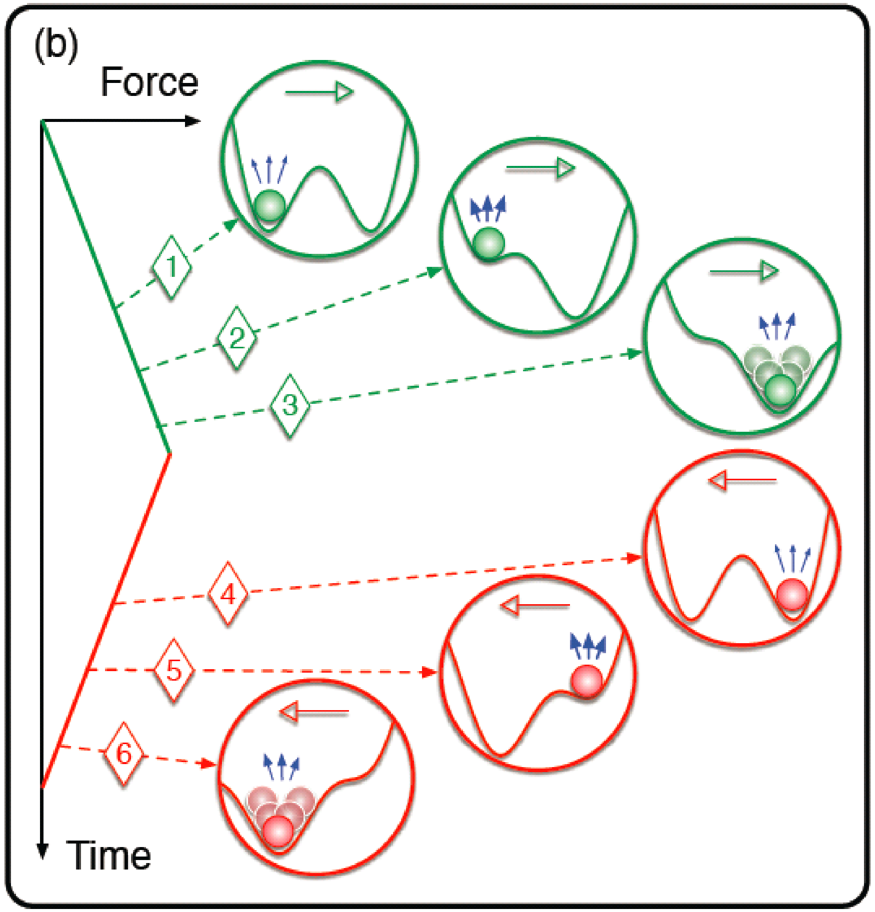
Stick-slip friction with ions in optical lattice

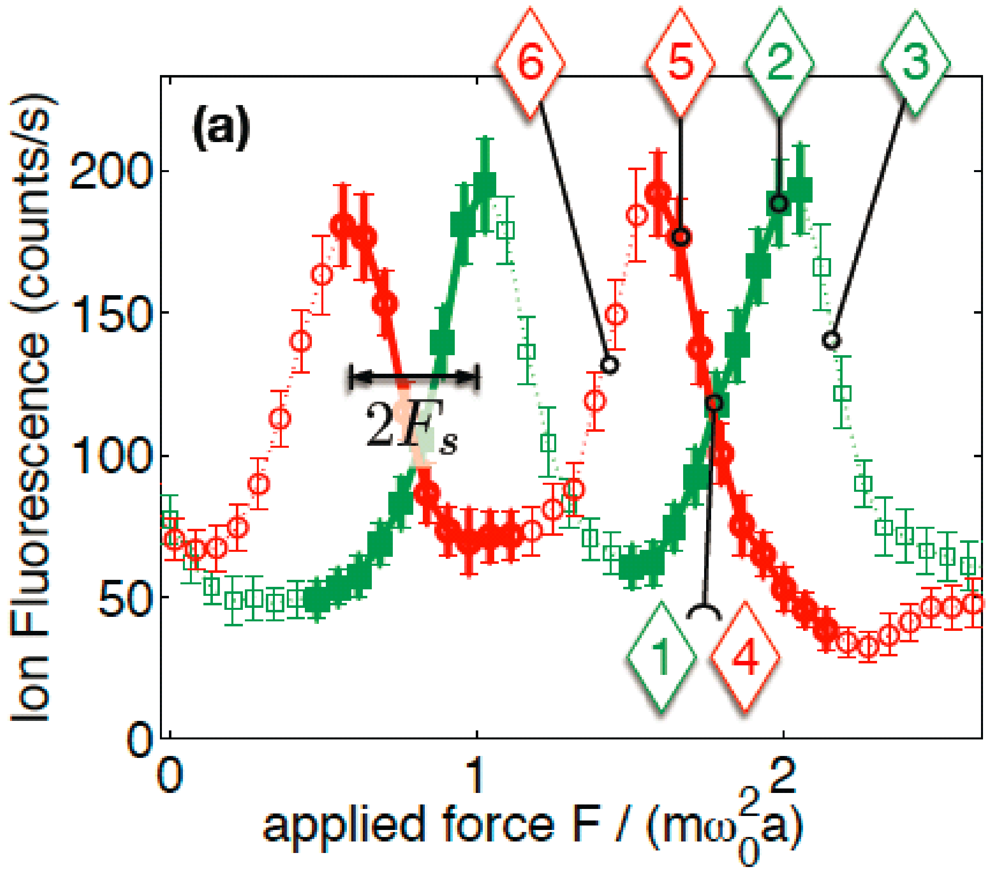


- Ion imaging with 3 μm resolution (sufficient to resolve neighboring ions)
- Sub-lattice site resolution via position dependent ion fluorescence (~20 nm for 100ms integration time, lattice spacing 185 nm)

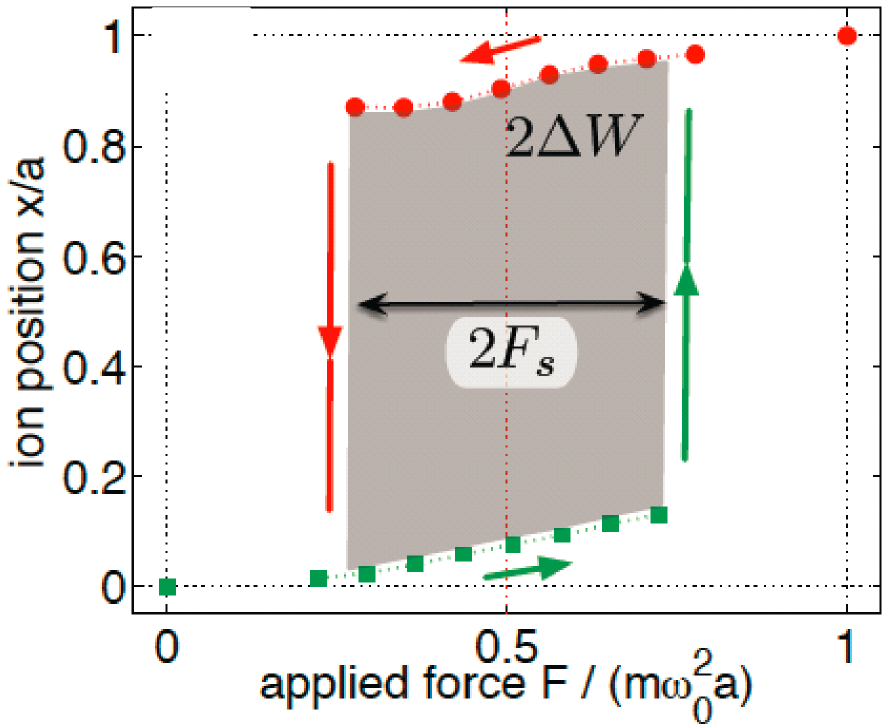
Time- and lattice-site-resolved single-ion detection

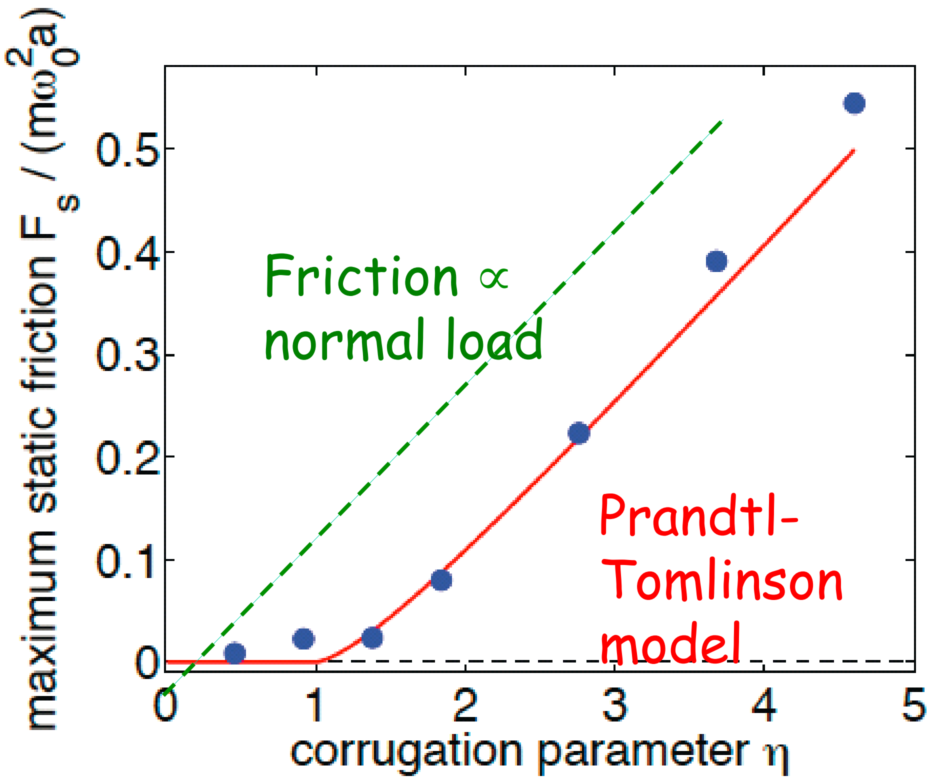
Hysteresis loop measures friction





Friction measurement with single atom





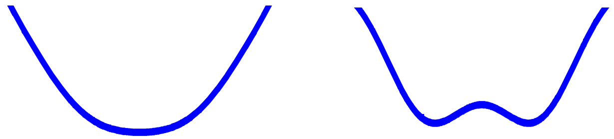
Solid line: Prandtl-Tomlinson model

L. Prandtl, Z. Angew. Math. Mech. **8**, 85 (1928);

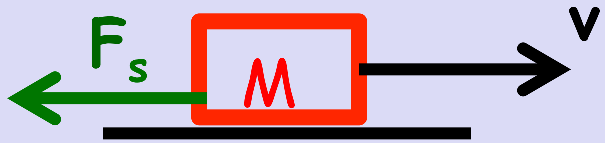
G. A. Tomlinson, Philos. Mag. **7**, 905 (1929).

A. Bylinskii, D. Gangloff, and V. Vuletić, Science **348**, 1115 (2015).

$=(\omega\downarrow latt /a$

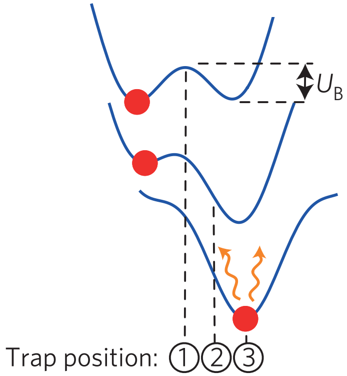


Dependence of friction on velocity



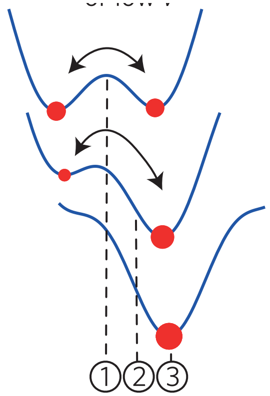
Velocity tuning of friction

Low T

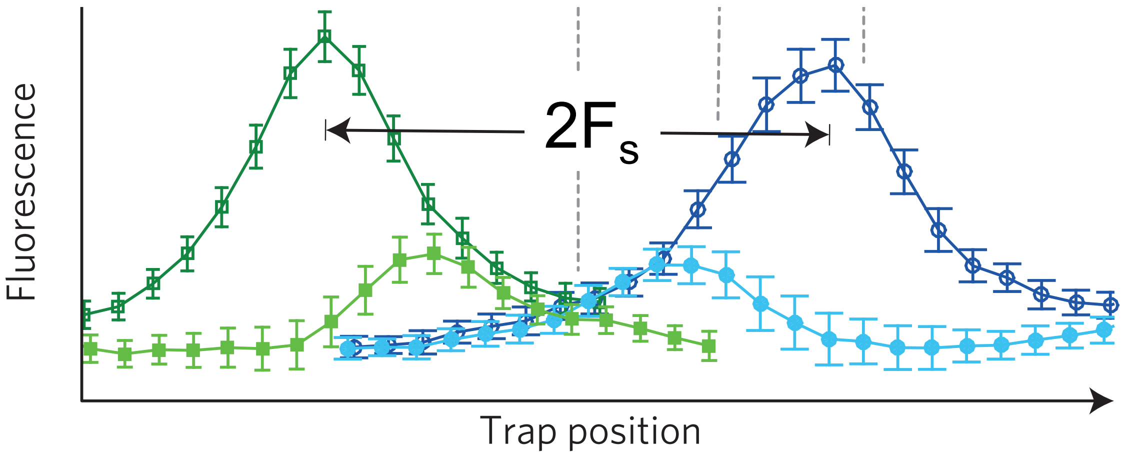


Low temperature or high velocity:
Non-equilibrium, atom stuck in metastable state

High T



High temperature or low velocity:
Near equilibrium, Boltzmann factors



Friction is reduced by temperature. How much depends on velocity

Jinesh, Krylov, Valk, Dienwiebel, & Frenken, Phys. Rev. B **78**, 155440 (2008).

Thermolubricity

Thermal activation reduces friction force as ion follows global potential minimum.

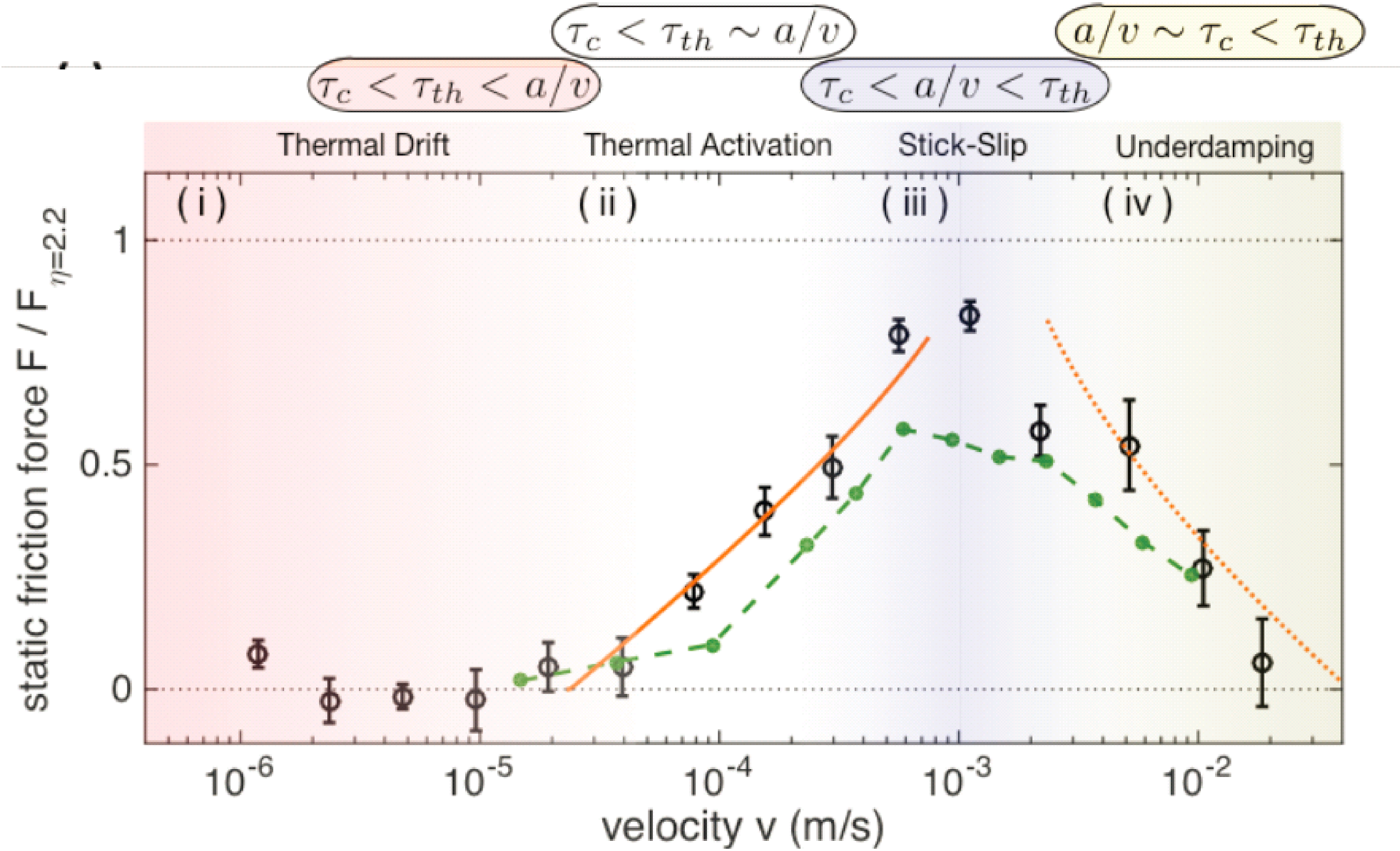
movie

Experiment and theory in real friction:

Speed Dependence of Atomic Stick-Slip Friction in Optimally Matched Experiments and Molecular Dynamics Simulations

Li, Dong, Perez, Martini, and Carpick, Phys. Rev. Lett. **106**, 126101

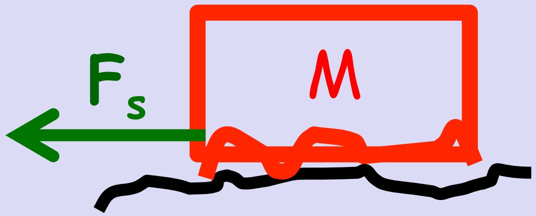
Four velocity regimes of friction



D. Gangloff, A. Bylinskii, I. Counts, W. Jhe, and V. Vuletić, Nat. Phys. **11**, 915 (2015).

Dependence of friction on surface:

Structural friction

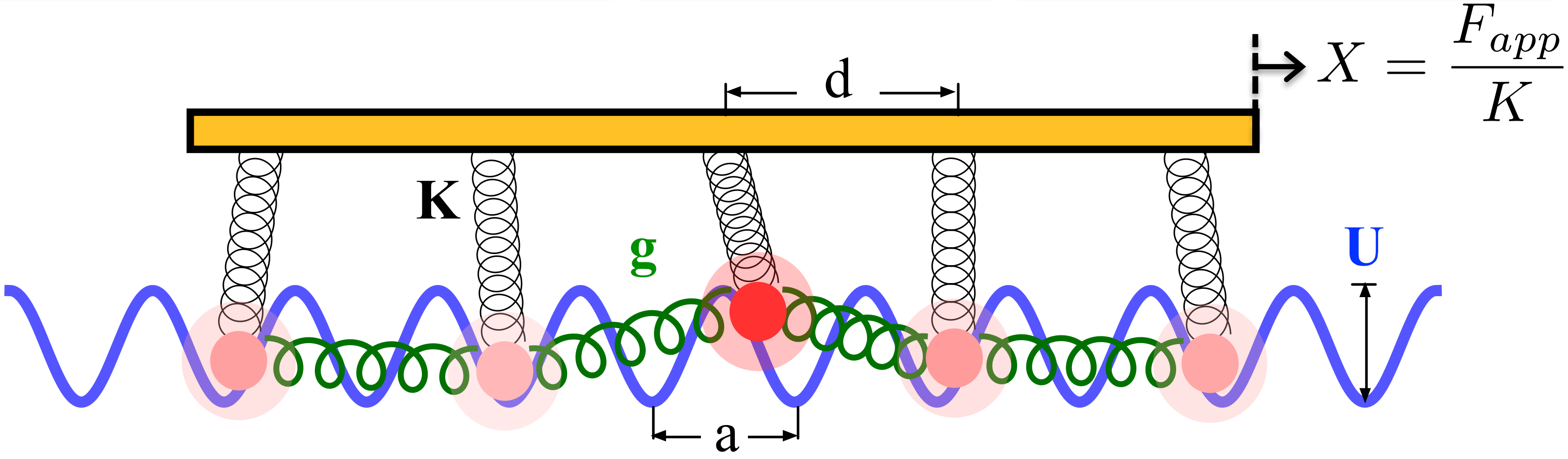


Many-particle model of friction

$$\eta = \frac{2\pi^2}{a^2} U/K = \omega_L^2/\omega_0^2$$

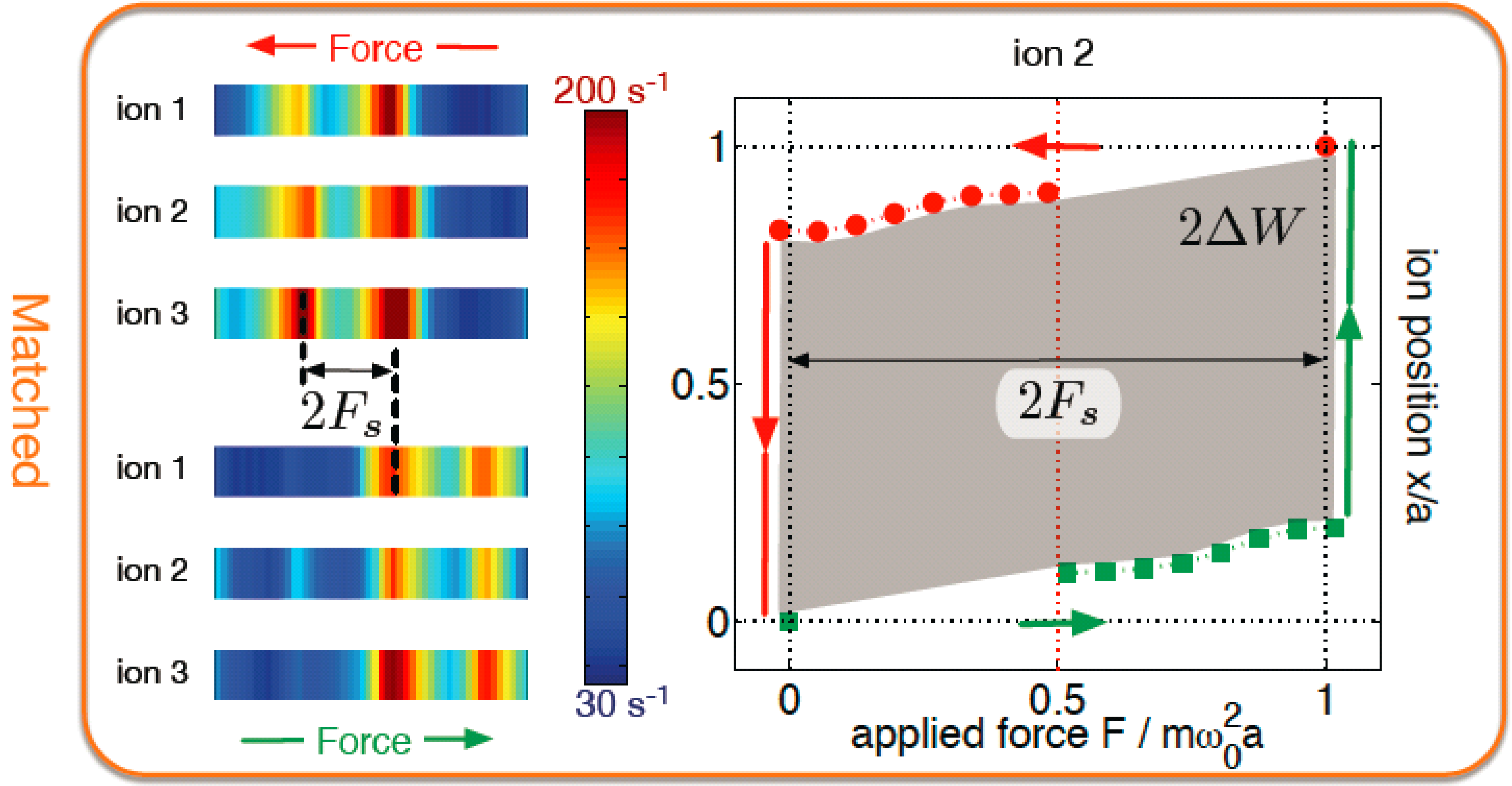
$$g/K$$

$$\frac{d}{a} \pmod 1$$



Prandtl-Tomlinson (1928) + Frenkel-Kontorova (1938)

Friction with several ions: matched case

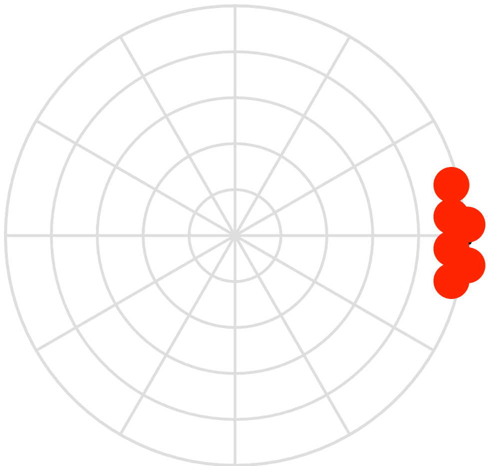


Same as single-ion friction for each ion: large friction.
All ions slip simultaneously.

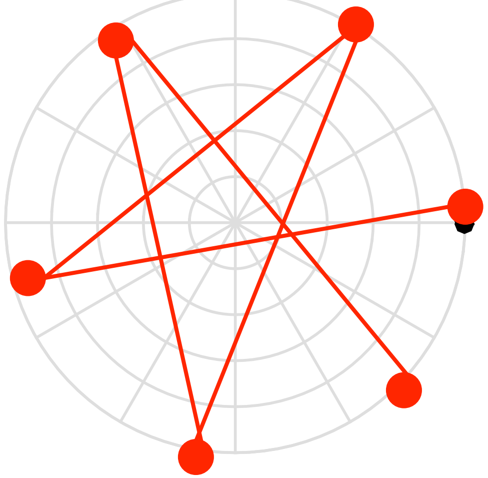
movie

Matched and mismatched configurations

Matched q=1



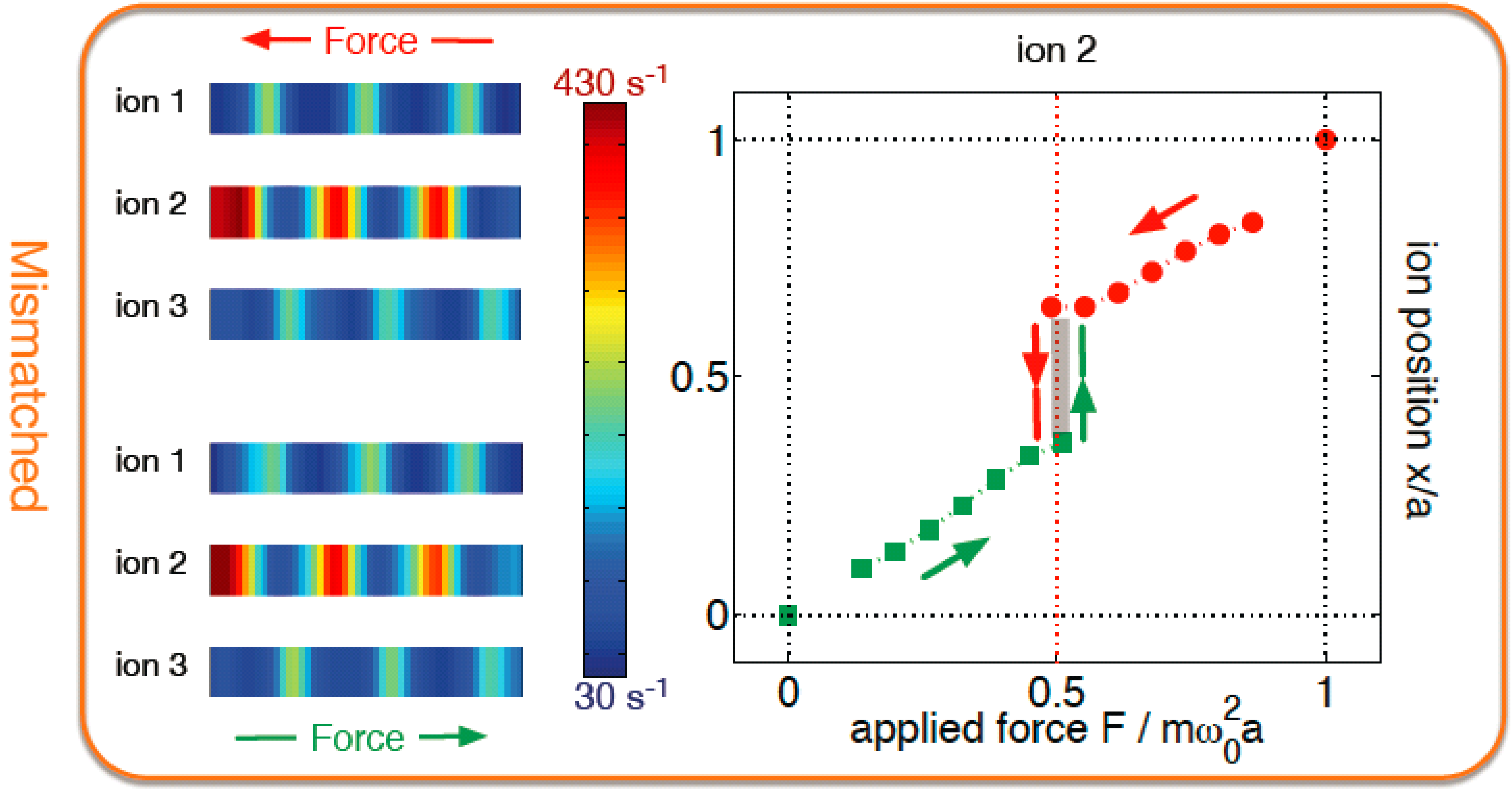
Mismatched q=1



$q \equiv \sum_i \sin(2\pi x_{i,0} + \phi)$ Matching parameter

Shown is phase of unperturbed ion position relative to optical lattice.

Friction with several ions: mismatched

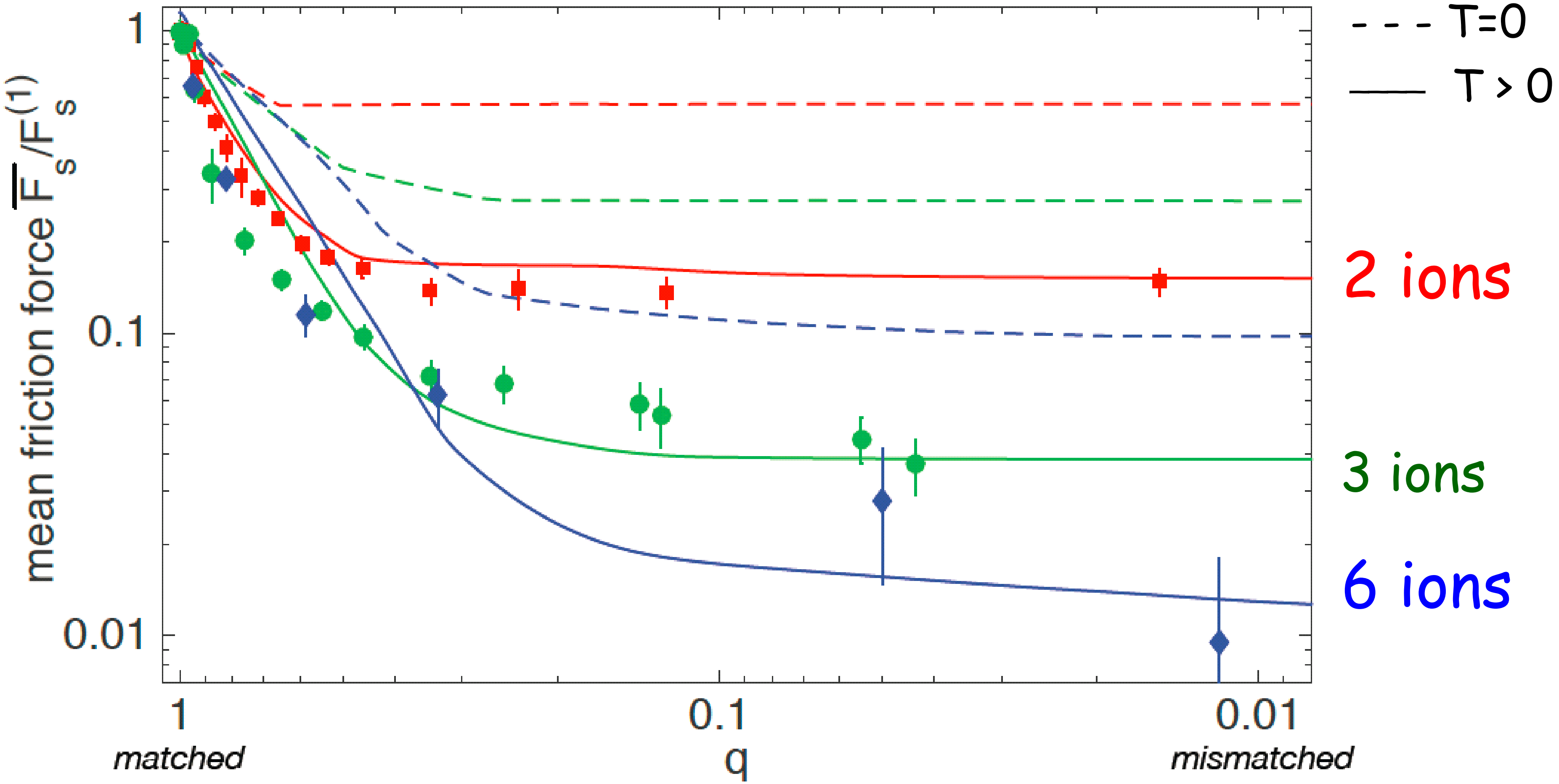


Nearly vanishing friction: Superlubricity.

A. Bylinskii, D. Gangloff, and V. Vuletić, Science **348**, 1115-1118 (2015).

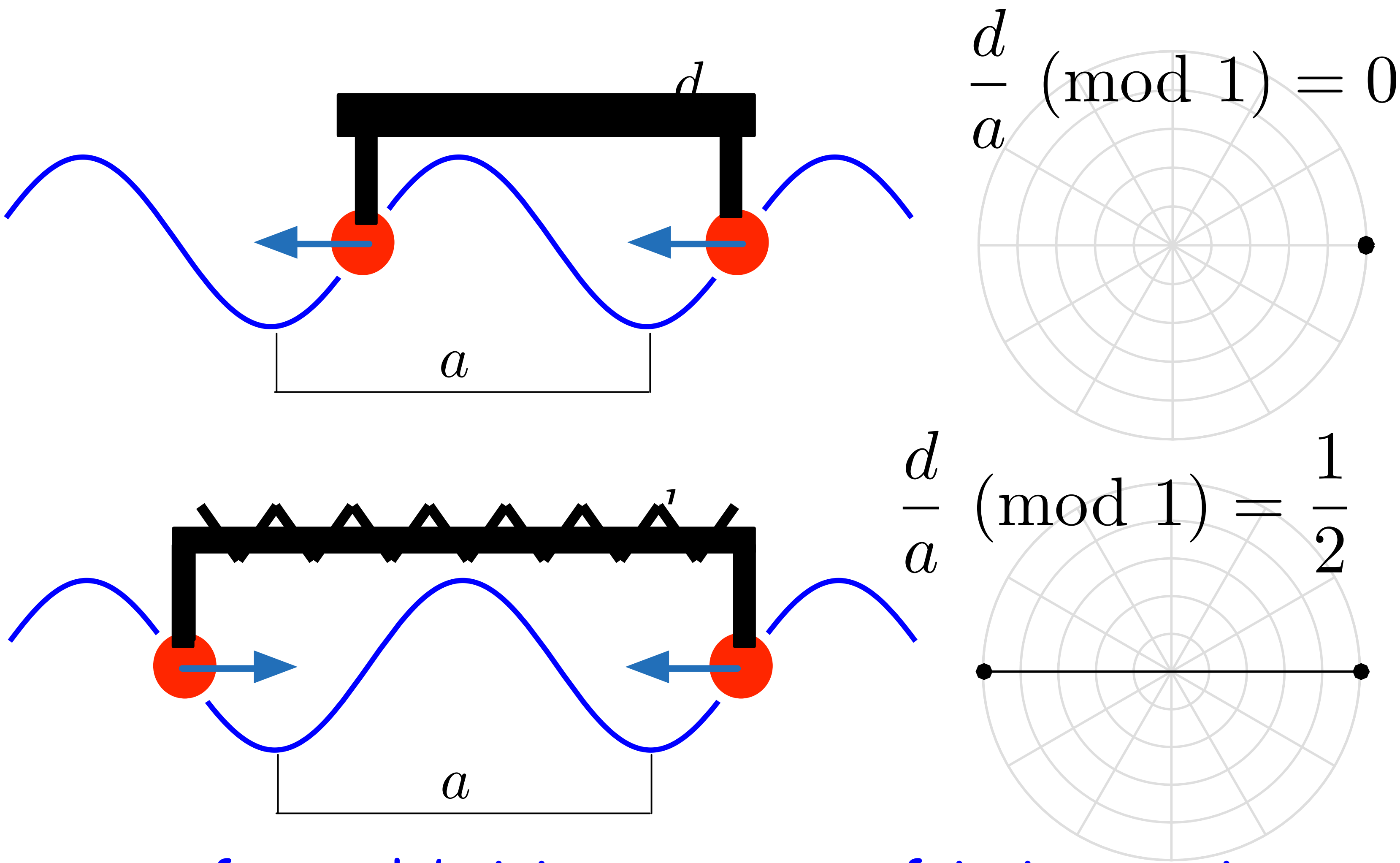
movie

Transition from matched to mismatched regime



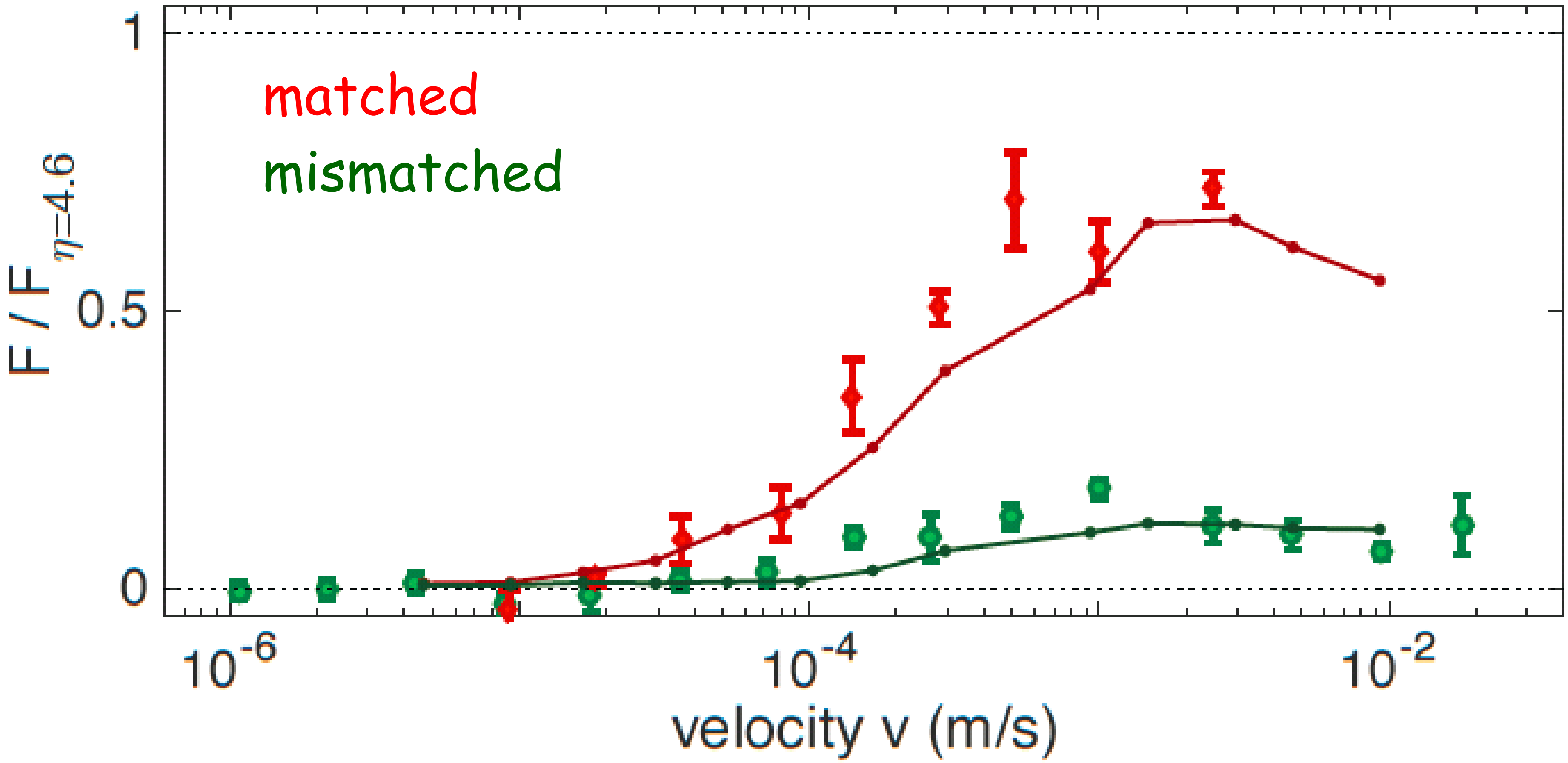
A. Bylinskii, D. Gangloff, and V. Vuletić, Science **348**, 1115 (2015).

Matched vs. mismatched chains



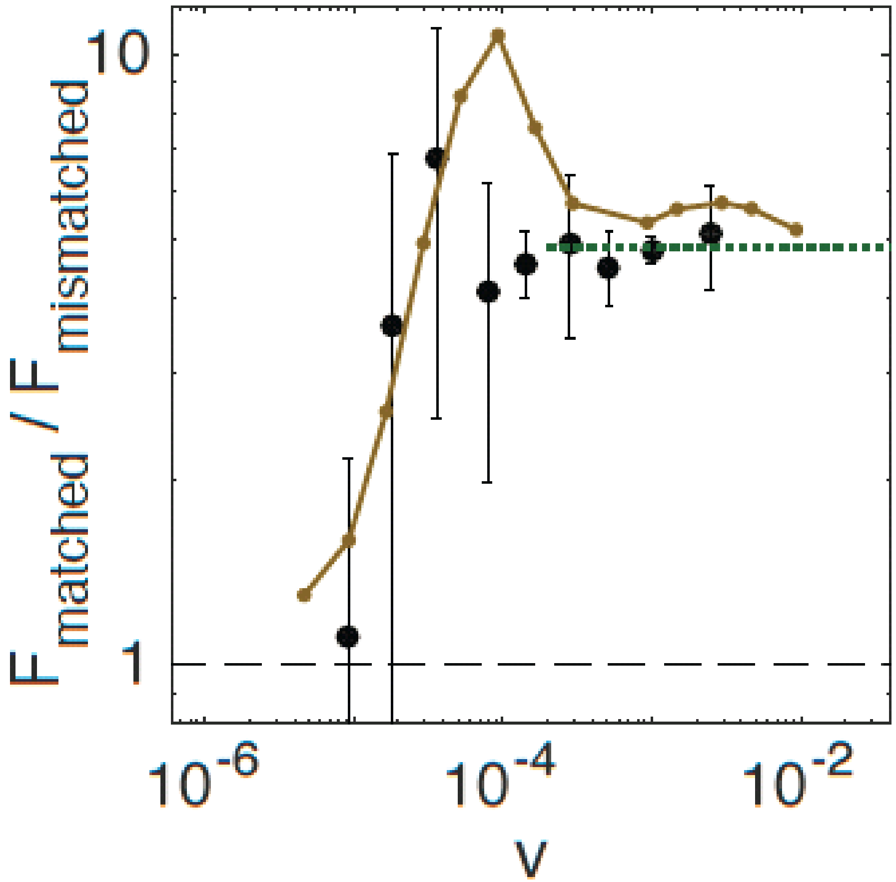
Essence of superlubricity: near-zero friction persists for finite spring constant.

Matched and mismatched friction for two ions

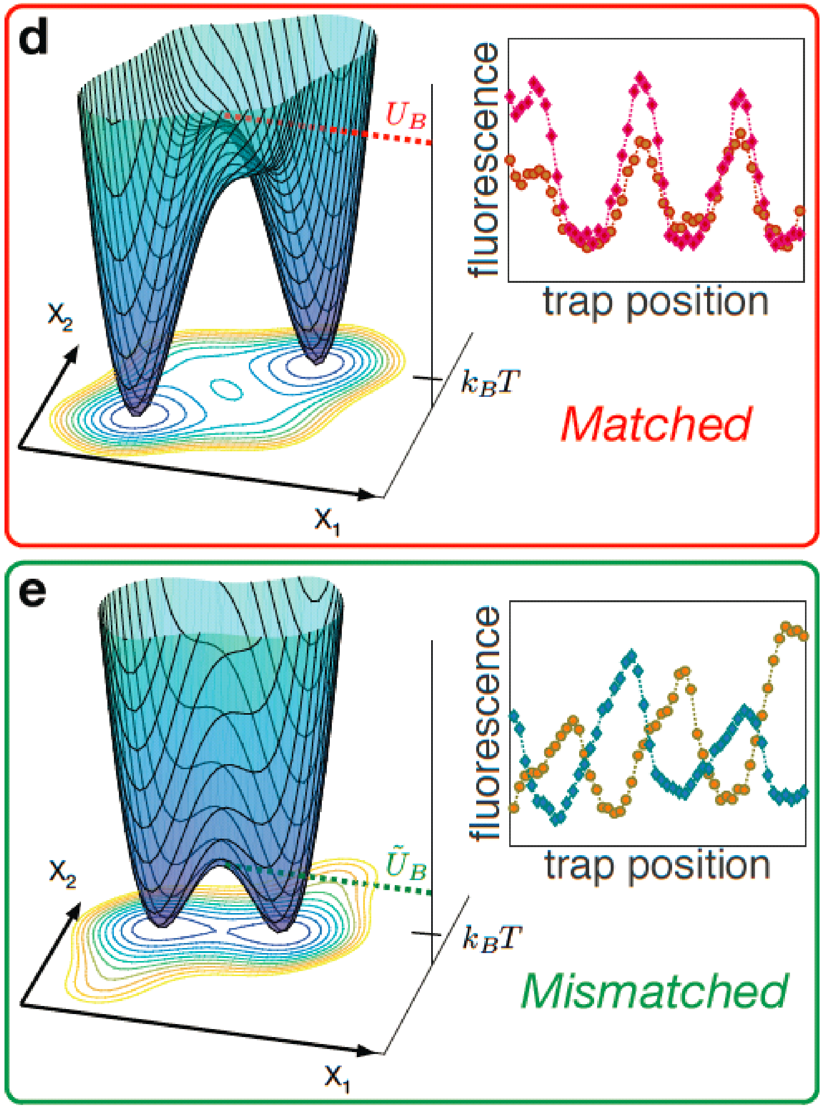


D. Gangloff, A. Bylinskii, I. Counts, W. Jhe, and V. Vuletić, Nature Physics (2015).

Two-ion matching dependence of friction: "superlubricity"

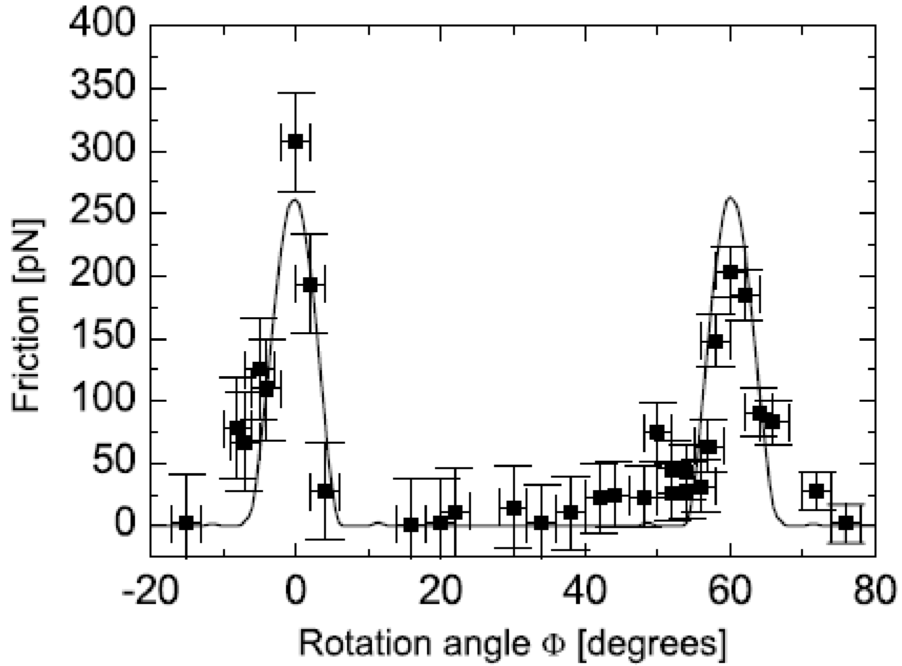


"Superlubricity": K. Shinjo, M. Hirano, Surf. Sci. 283, 473 (1993).

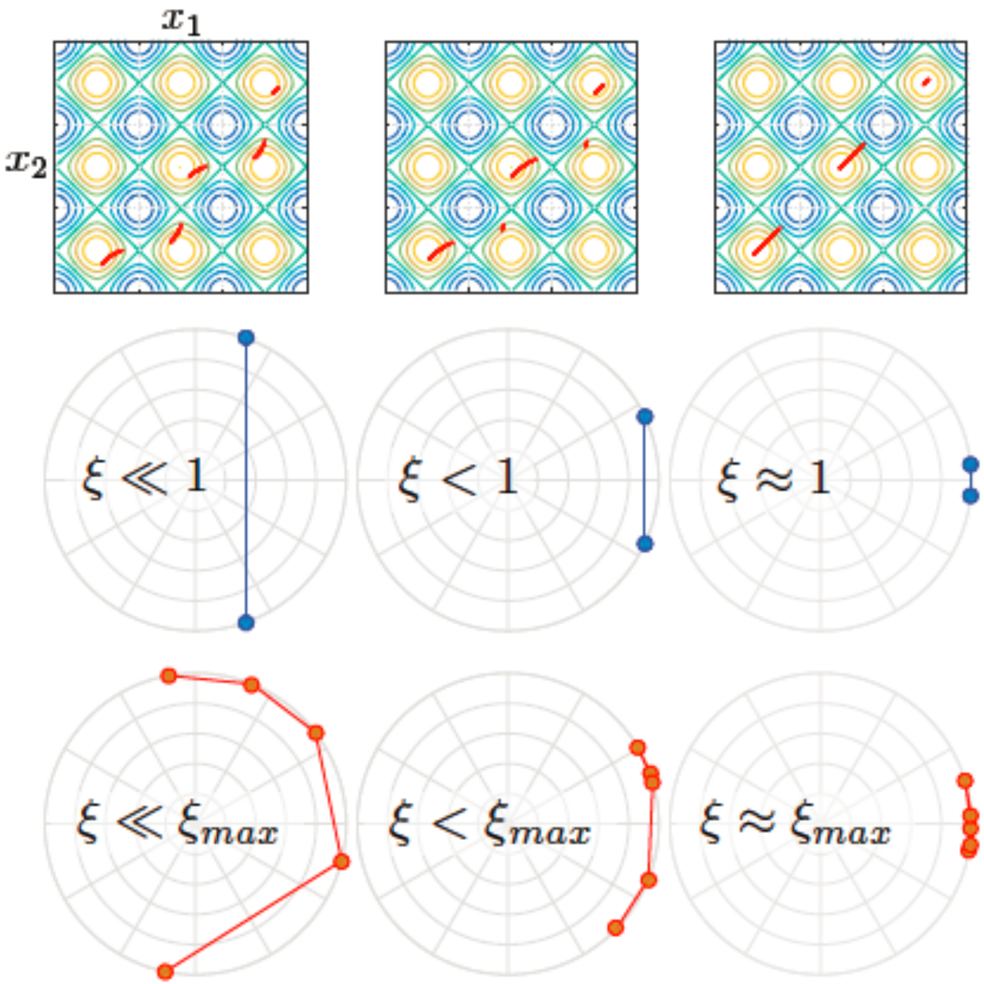


Superlubricity in real friction

- Dienwiebel, M. et al. Superlubricity of graphite. Phys. Rev. Lett. **92**, 126101 (2004).



Transport via kinks: synchrony



Peierls-Nabarro potential for two ions

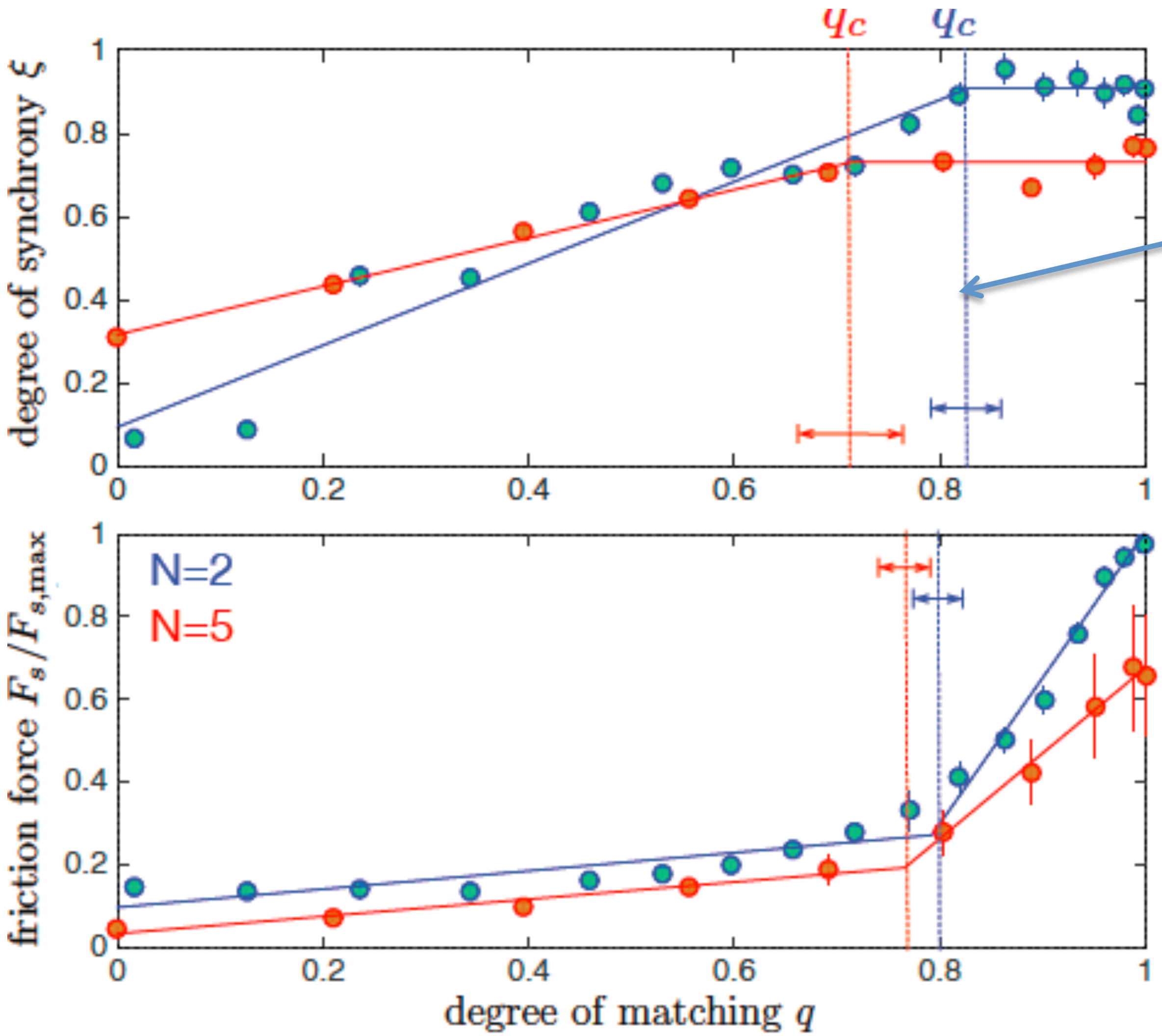
Polar plot representation of slipping times (2 ions)

Polar plot representation of slipping times (5 ions)

$$\xi = 1 - \frac{N}{N-1} \sum_{j=1}^{N-1} \left(\left| X_{j,s} - X_{j+1,s} \right| / a \right) \bmod (1)$$

Synchrony

Transport via kinks: synchrony



commensurate-
incommensurate
transition

commensurate

Transport via kinks

Weak dependence of friction on matching

incommensurate

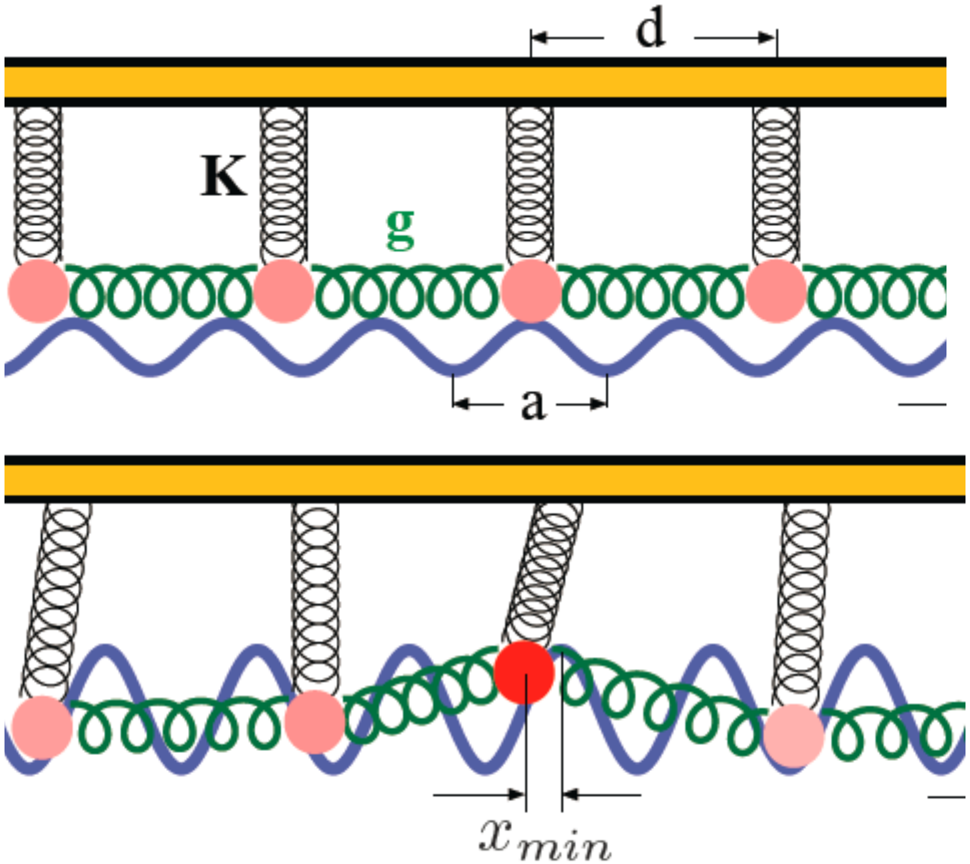
Synchronous transport

Strong dependence on matching

Nanofriction and Aubry transition

Static Aubry transition

Infinite chain



Maximally incommensurate d/a mod 1 = Golden Ratio

What happens as periodic corrugating potential is increased?

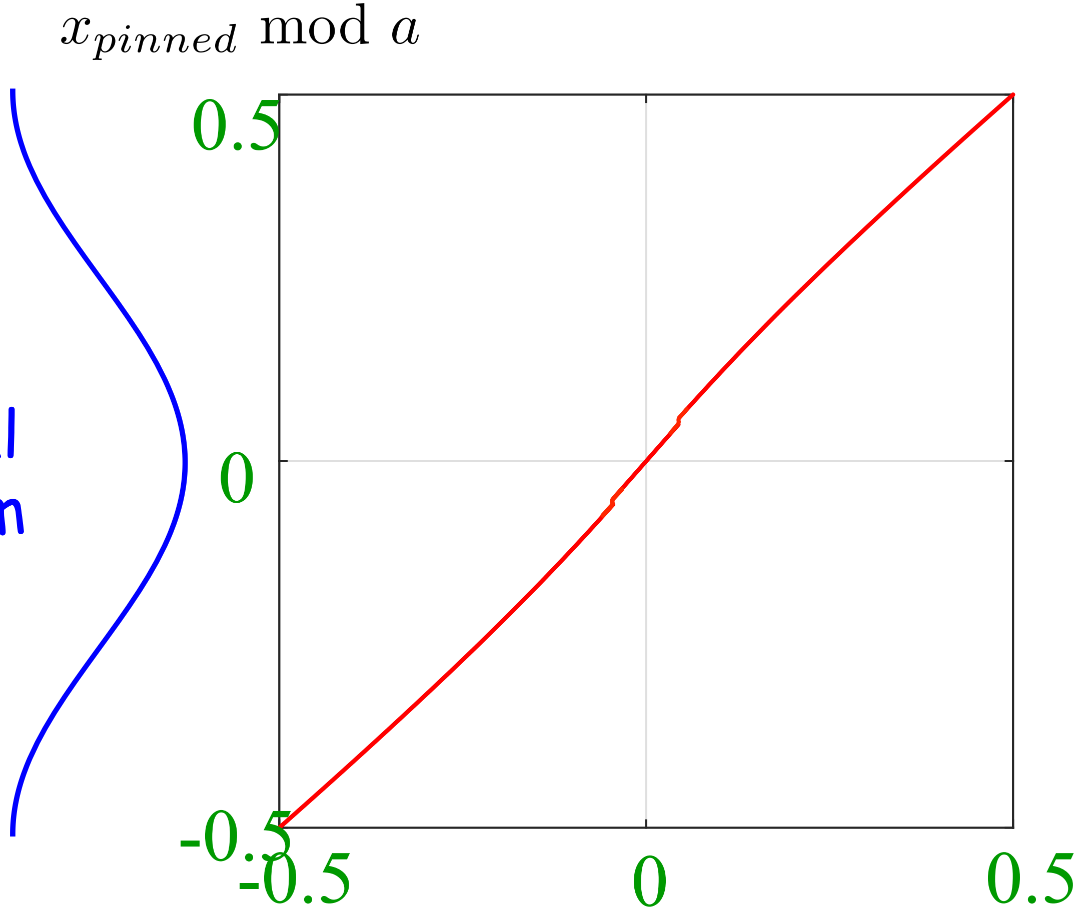
Atoms suddenly localize in periodic potential at some criticial potential depth.

Aubry, S. Exact models with a complete devil's staircase. Journal of Physics C: Solid State Physics **16**, 2497 (1983).

Aubry, S. & Le Daeron, P. The discrete Frenkel-Kontorova model and its extensions. Physica D: Nonlinear Phenomena **8**, 381–422 (1983).

Analyticity breaking

Potential maximum

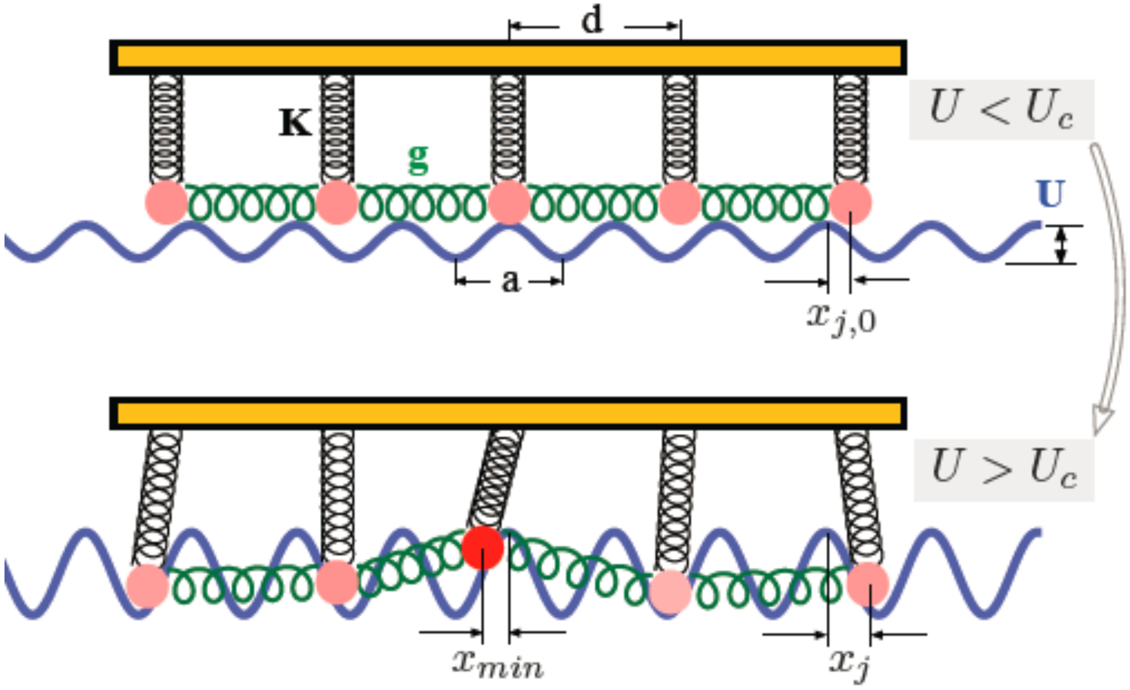


$$U < U_c$$

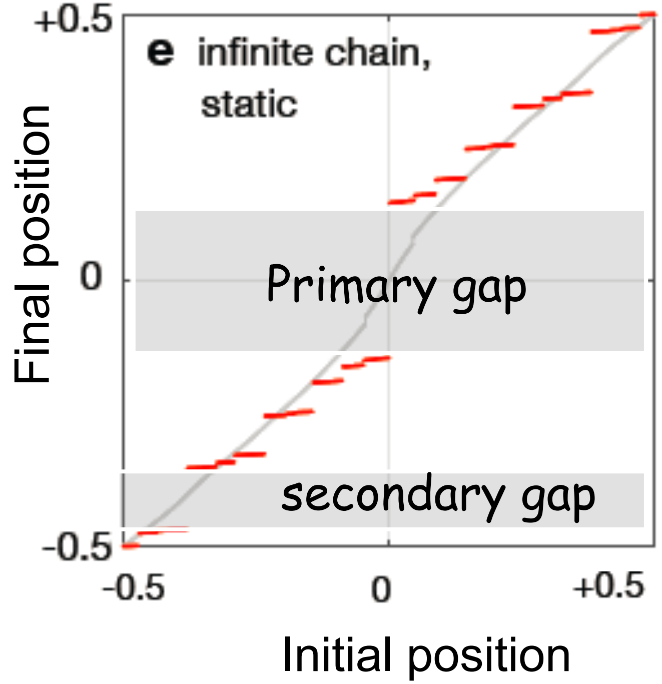
Fractal structure: gaps in position space on every scale

Aubry, S. Exact models with a complete devil's staircase. Journal of Physics C: Solid State Physics **16**, 2497 (1983).

Aubry transition



Position relative to lattice

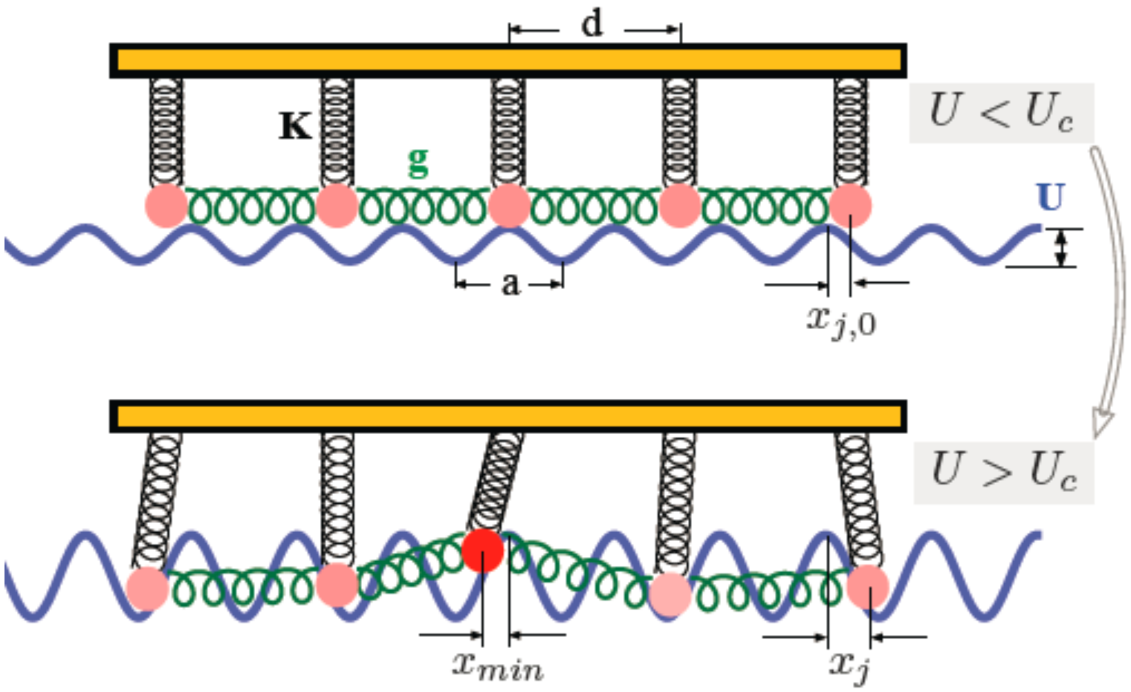


Aubry transition: smooth distribution of positions (for infinite chain) breaks up into fractal distribution.

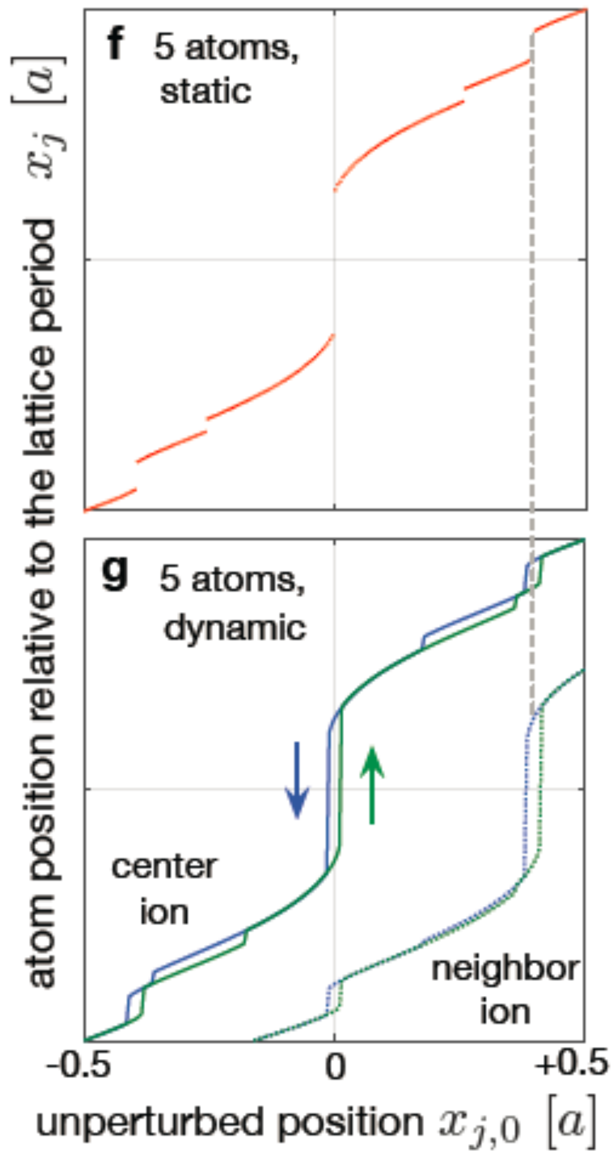
Highest critical potential for (d/a) mod 1 =(1+√5)/2

(Golden Ratio)

Finite Aubry transition



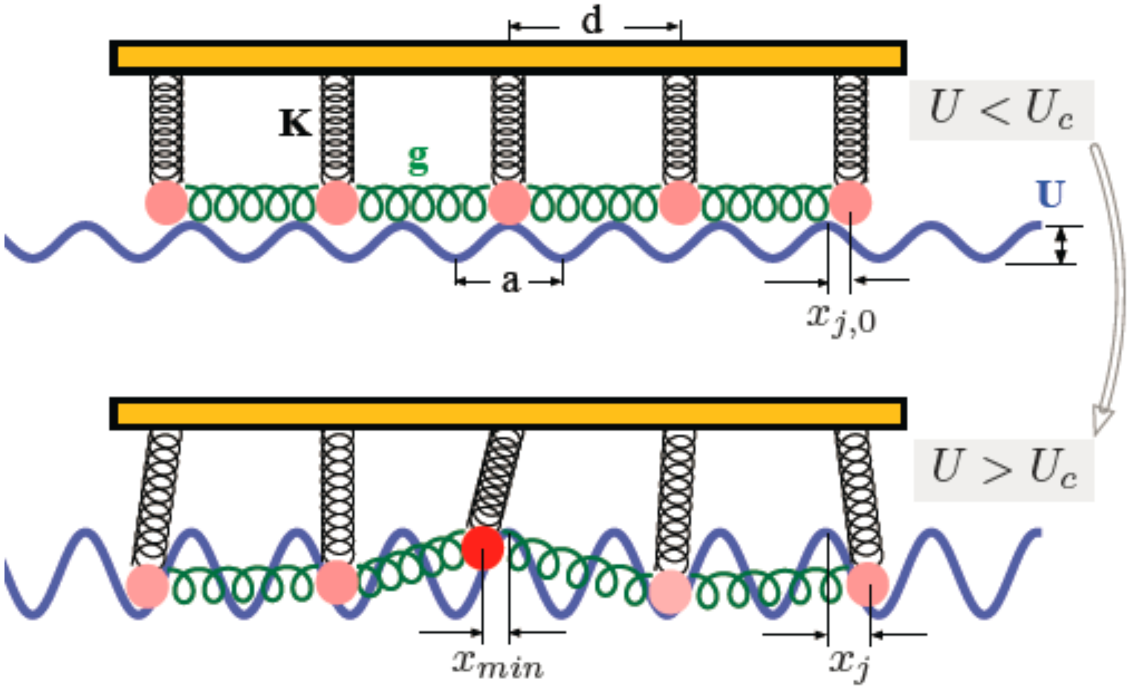
Position relative to lattice

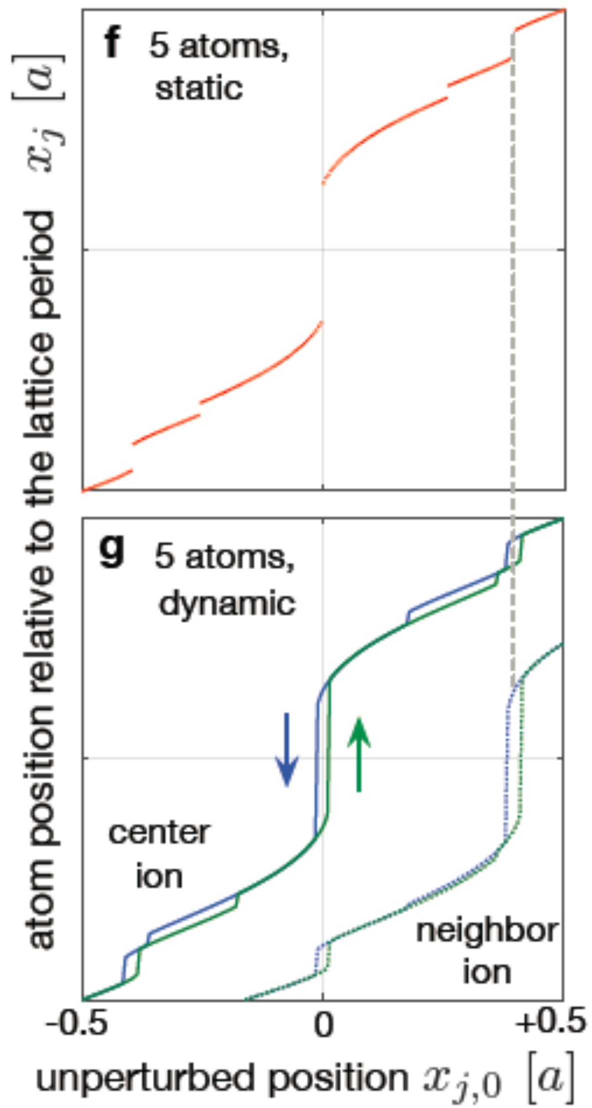


Gaps correspond to bistable hysteresis loops in friction.

Aubry sliding-to-pinned analycity breaking transition is transition from superlubricity to stick-slip friction.

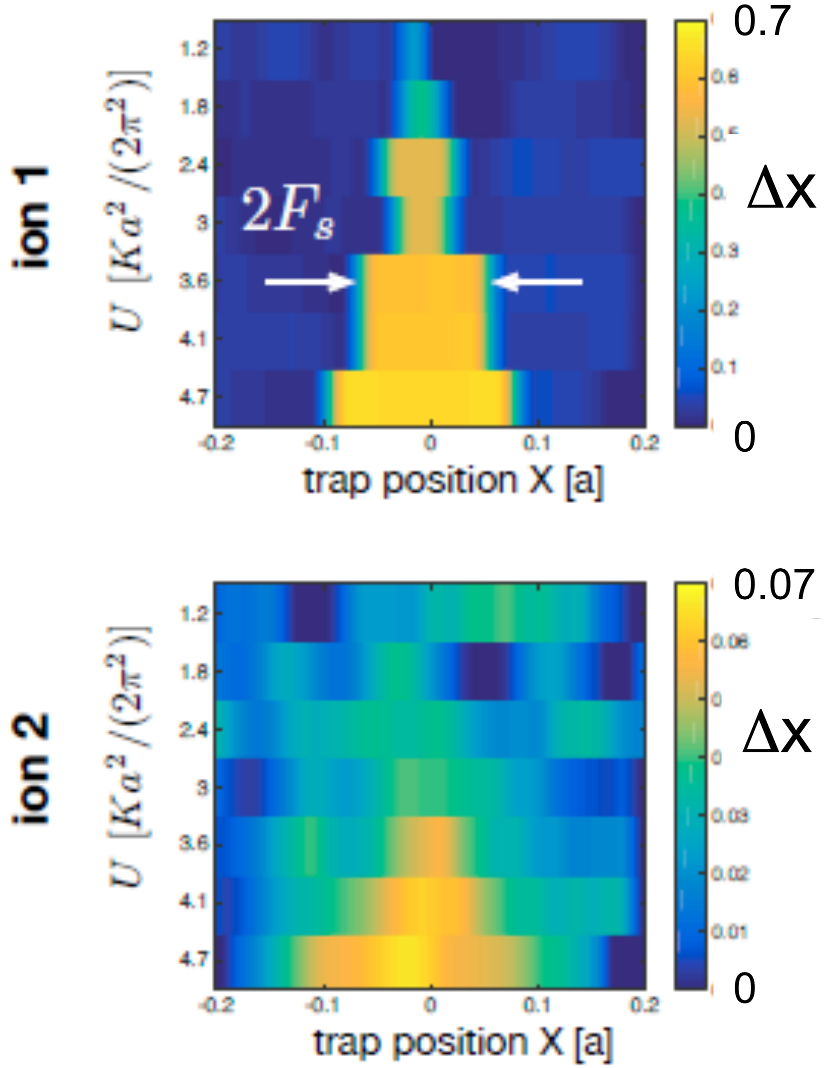
Aubry transition in finite chain

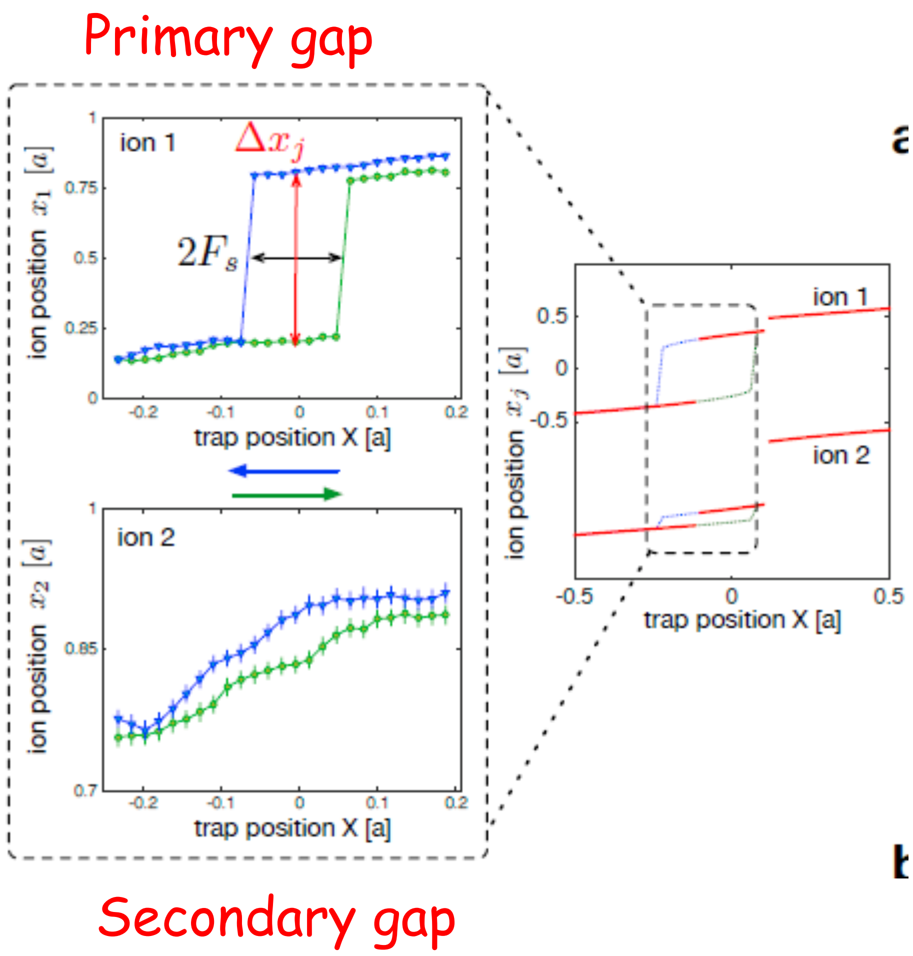




Primary gap for one ion (avoiding potential maximum) corresponds to secondary gap for next ion.

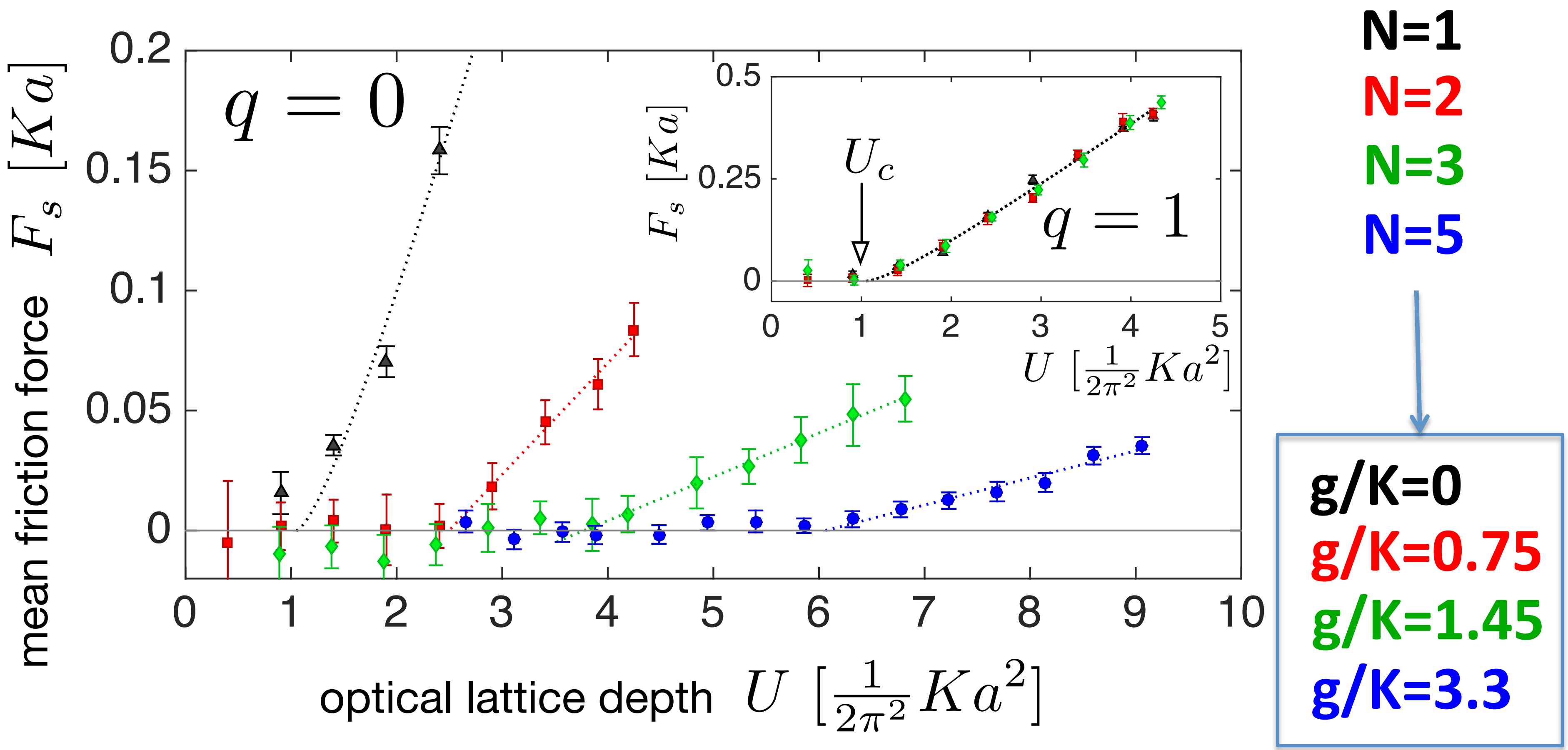
Observation of primary and secondary gaps in three-ion chain



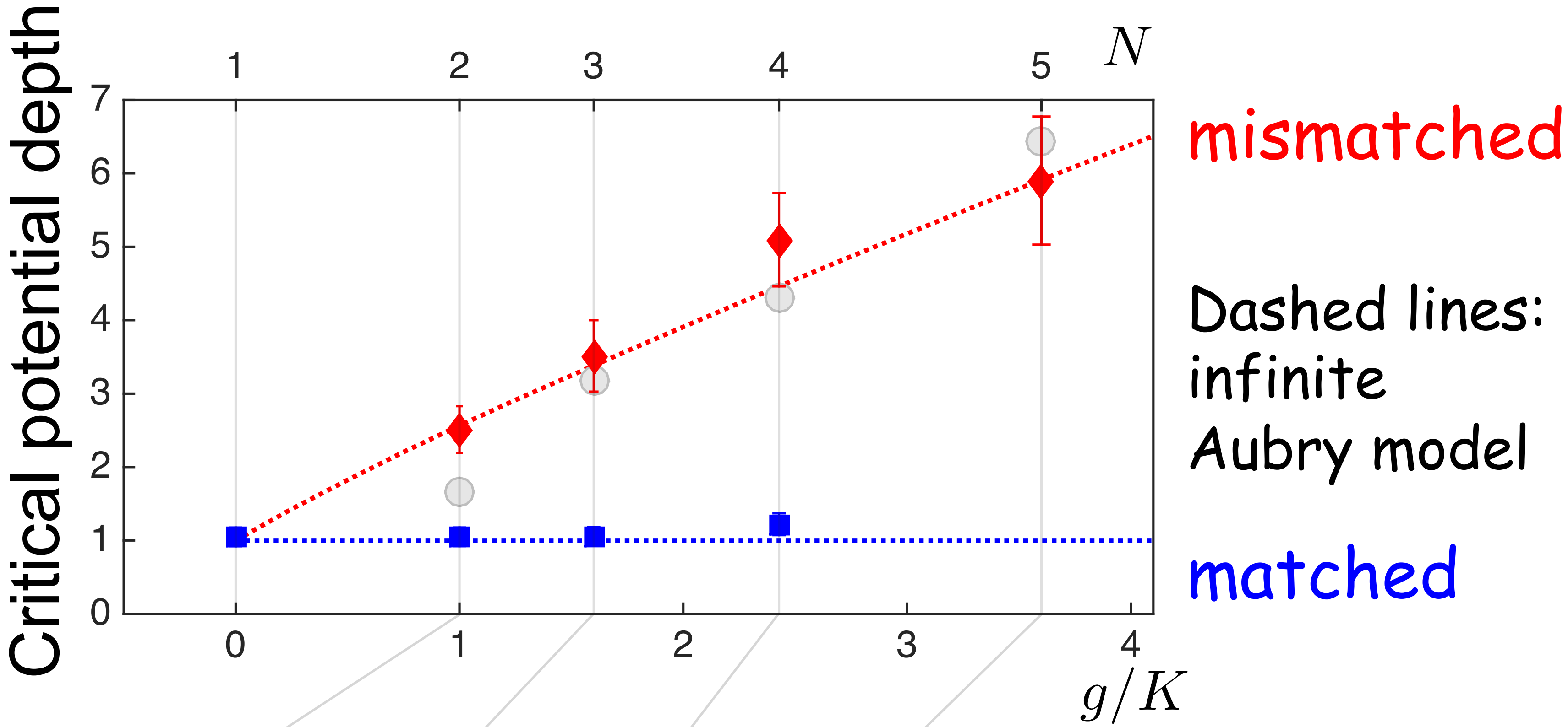


A. Bylinskii, D. Gangloff, I. Counts, V. Vuletic, Nat. Mat. (2016).

Interactions widen sliding phase



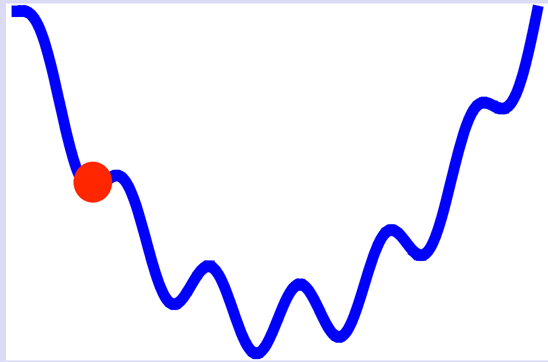
Agreement with Aubry model



More is different – Phil Anderson

More is not that many

Multislip friction
(Friction in multistable potentials)



Multislip Friction with a Single Ion. I. Counts, D. Gangloff, A. Bylinskii, J. Hur, R. Islam, and V. Vuletić, to appear in Physical Review Letters, arXiv:1705.00716 (2017).

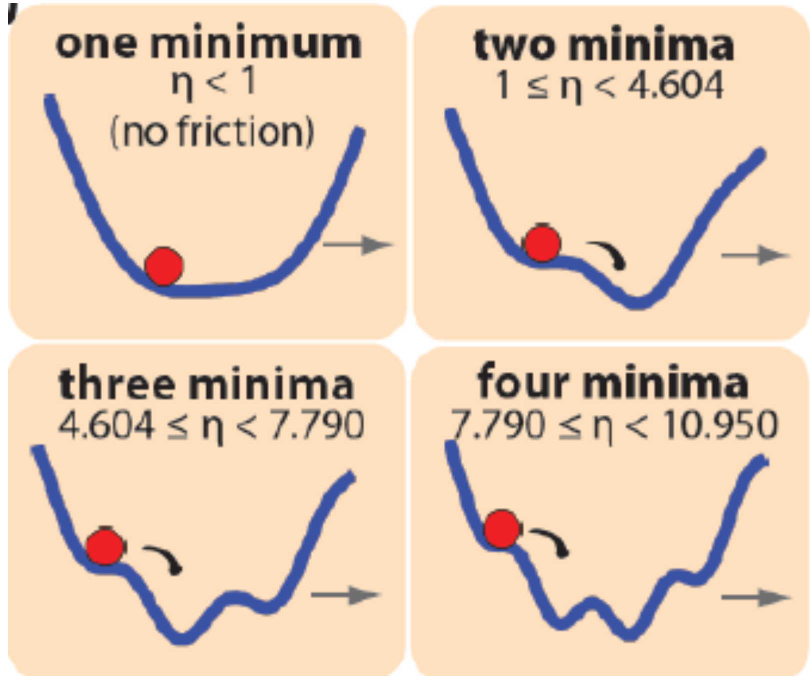
Multislip friction

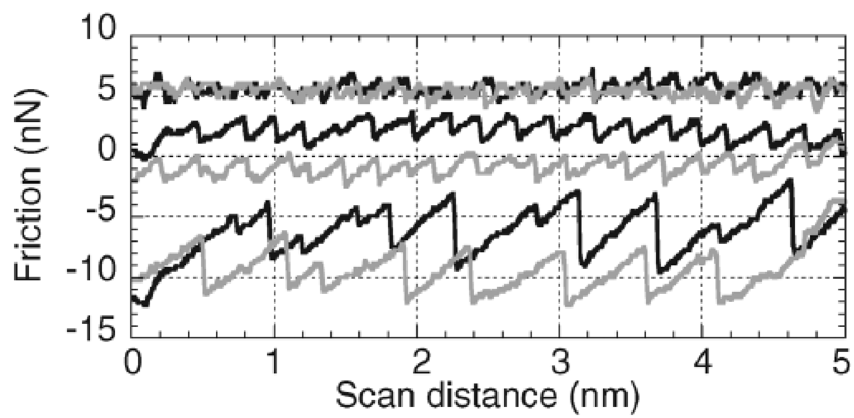
Increasing the lattice depth creates a potential with multiple minima.

Prandtl-Tomlinson corrugation parameter η is ratio of periodic potential depth to spring constant of harmonic trap.

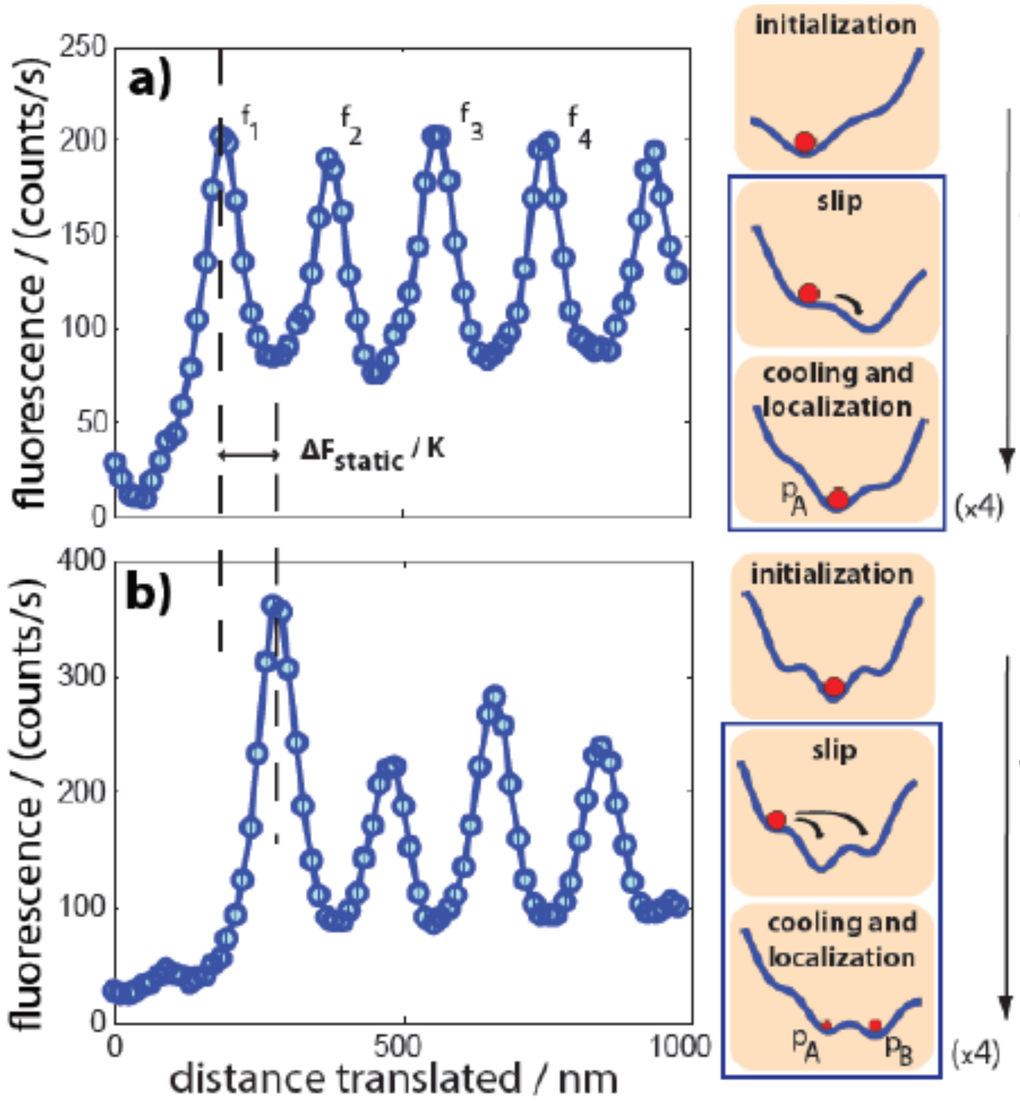
In real friction:

Medyanik, Liu, Sung, & Carpick, Phys. Rev. Lett. **97**, 136106 (2006).





Experimental signature of multislip regime

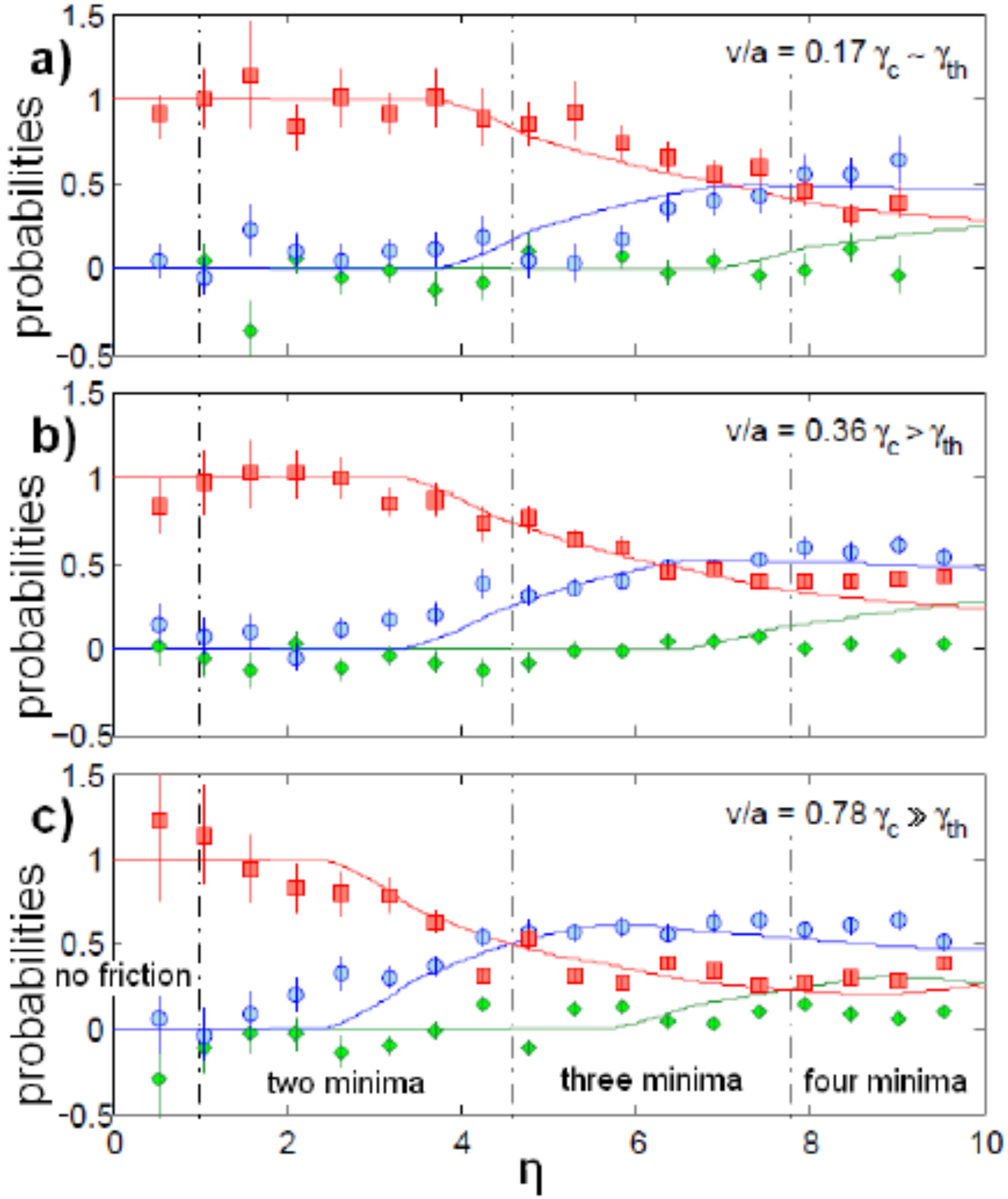


The distribution of peak heights can be used to extract slip probabilities to different minima.

First slip happens always (system prepared in global minimum).

Second peak appears only if system slipped to next minimum A, etc.

Extracting slip probabilities to different minima



next minimum A

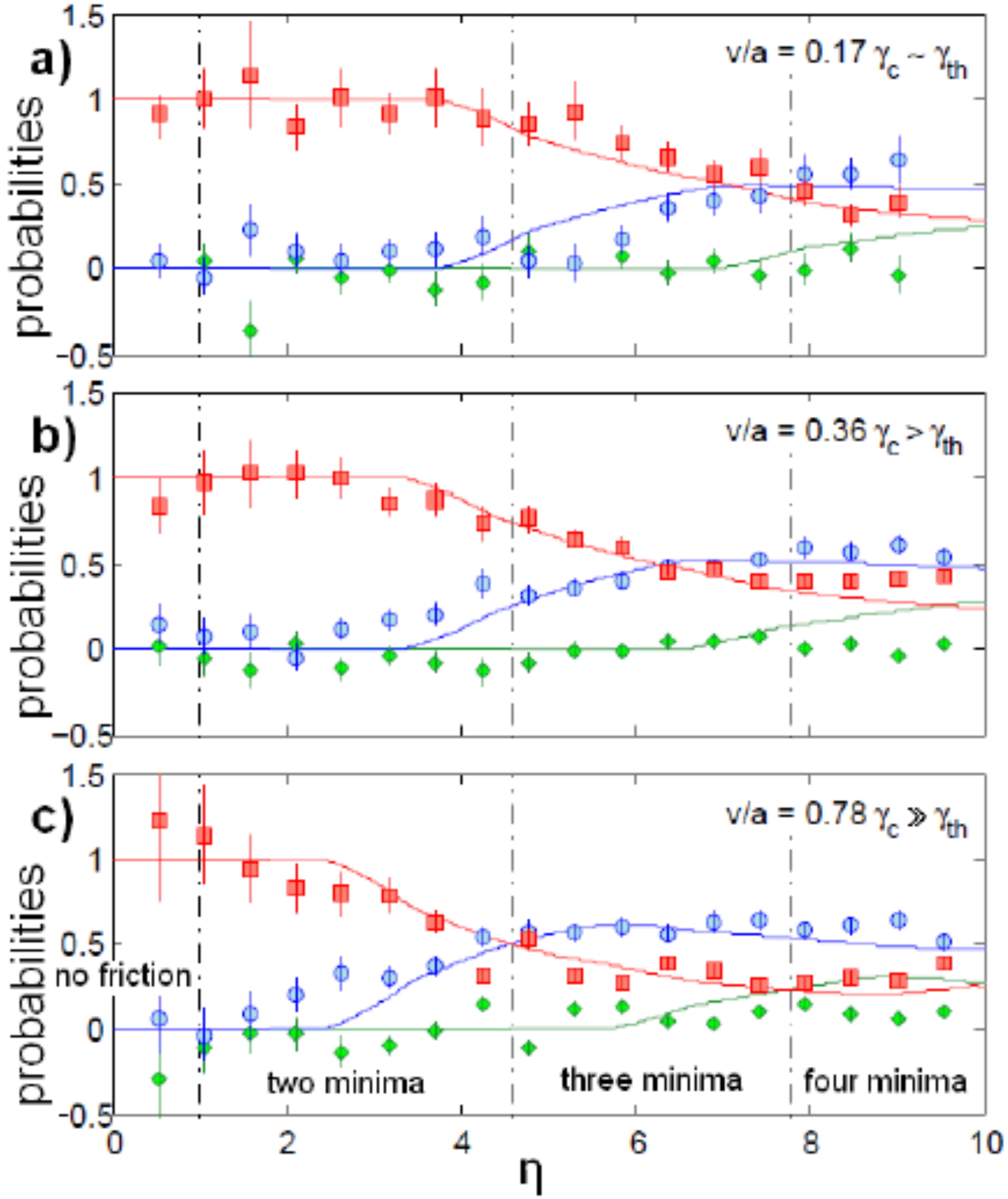
second next minimum B

third minimum C

For large transport speed, localization in distant minimum observed before possible statically:

Finite rethermalization time, additional minima open up before particle thermalizes.

Extracting slip probabilities to different minima



next minimum *A*

second next minimum B

third minimum *C*

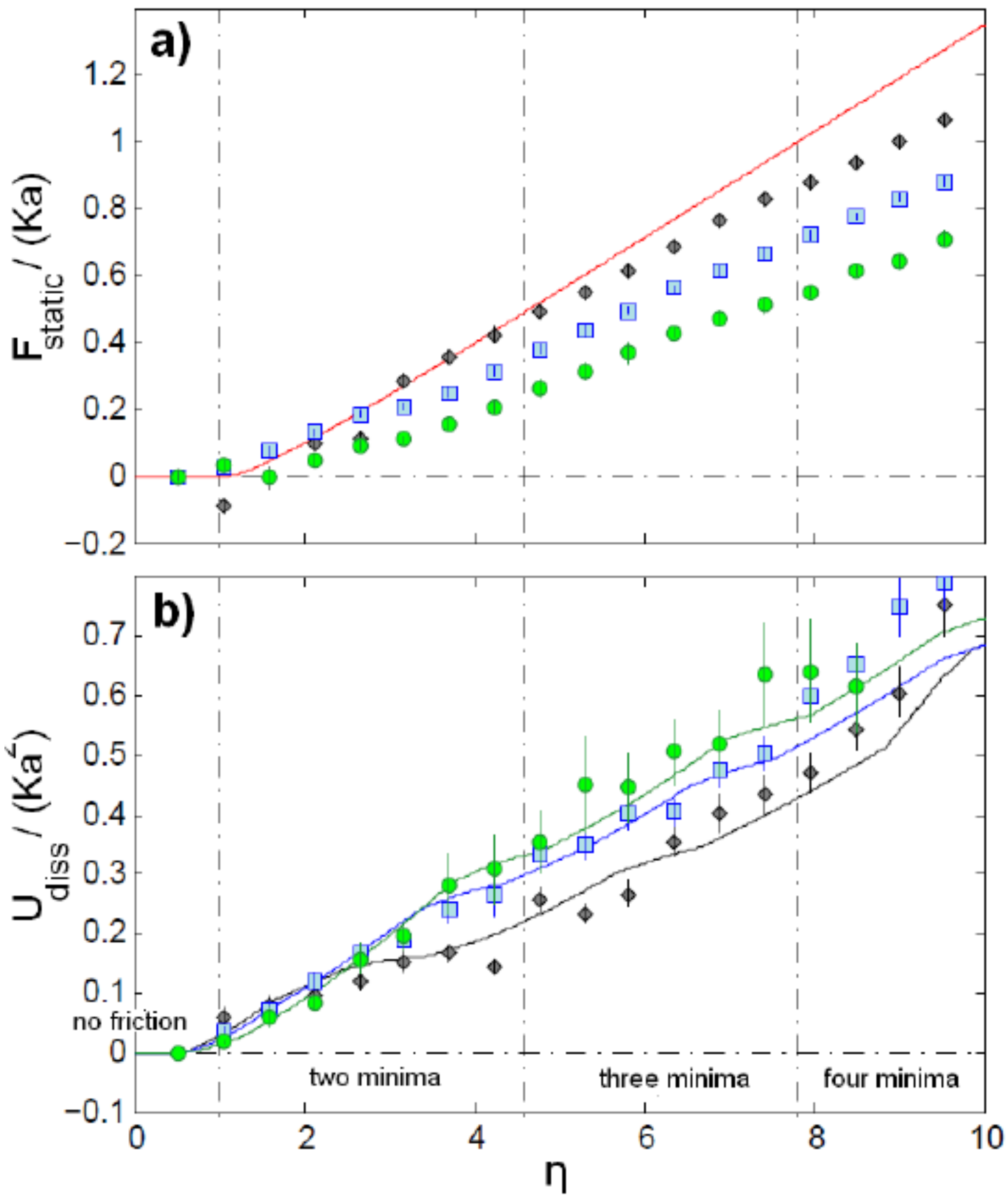
Solid lines: quasistatic Boltzmann model.

$$p_i \propto \exp(-\frac{V_i(\tau)}{k_B T(\tau)})$$

Potential evolves due to trap motion while particle cools down exponentially.

τ is fit parameter for the ion to localize in potential.

Friction force and dissipation in multislip regime

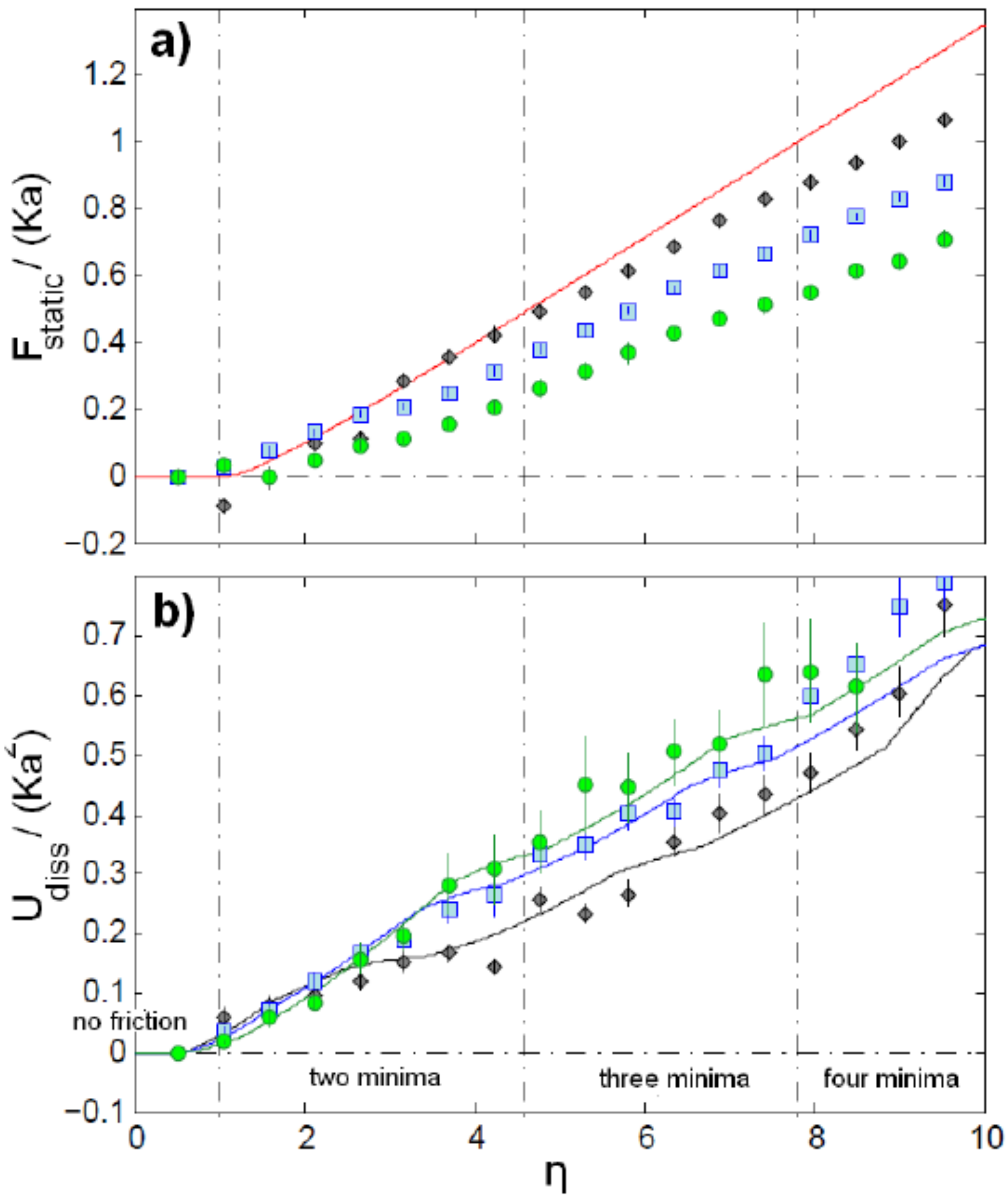


Friction and dissipation are hardly affected by transition to multistable potentials.

Solid line: Prandtl-Tomlinson model

Points: experimental data

Friction force and dissipation in multislip regime



Prandtl-Tomlinson model

$v/a = 0.78\ \gamma_c$ fast

$v/a = 0.36\ \gamma_c$ medium

$v/a = 0.17\ \gamma_c$ slow

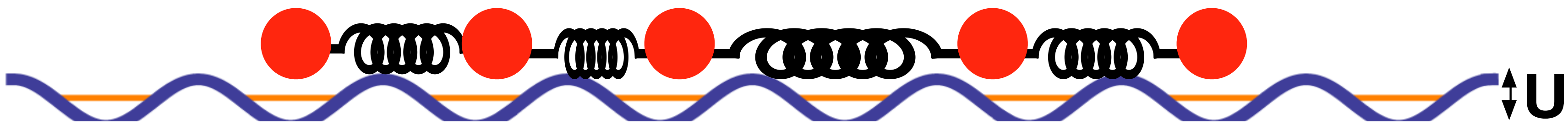
Thermal hopping reduces friction.

Dissipated energy if slip happens.

Localization in distant potential slightly reduces dissipated energy.

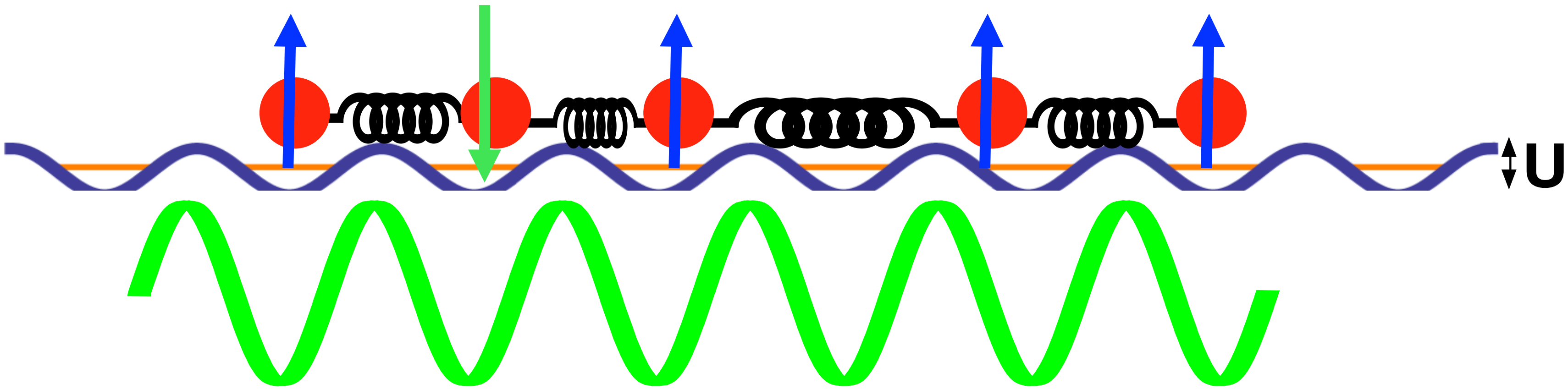
What's next?

Quantum friction?



Competition between kinetic energy (delocalization through tunneling) and interaction energy (leading to localization). Quantum friction? Quantum Aubry transition?

Outlook: simulating impurities



Add spin degrees of freedom

Different spin state can experience attractive potential of different depth: simulate impurity with chemical bond to surface or deeper trapping potential.

Conclusion

- Simulator for one-dimensional stick-slip friction with ion chains with atom-by-atom control and observation.
- Stick-slip friction, superlubricity, and thermolubricity.
- Close connection between the static Aubry transition and the dynamic superlubricity transition.
- Future: Quantum friction? Friction with impurities? Friction in two-dimensional systems?