Tribology of Colloidal Systems

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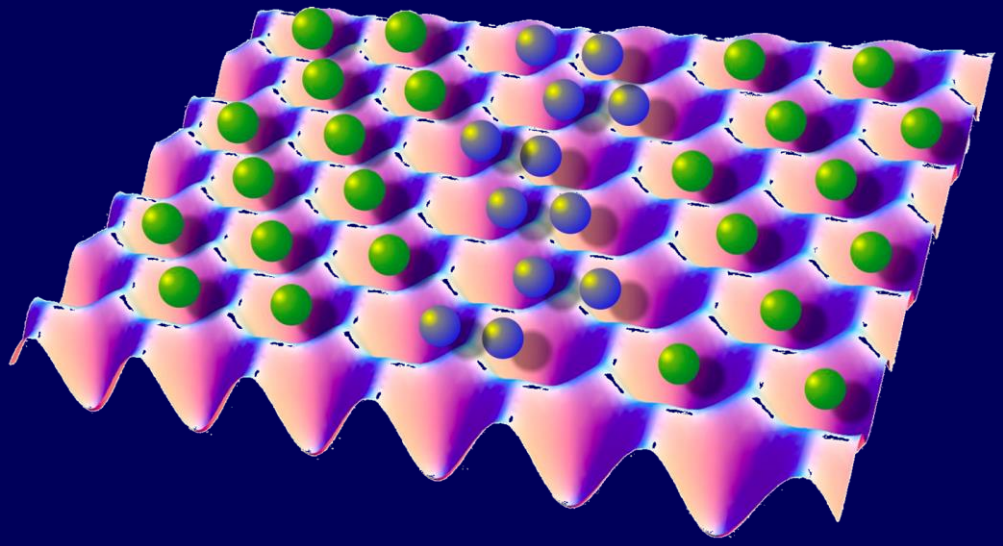
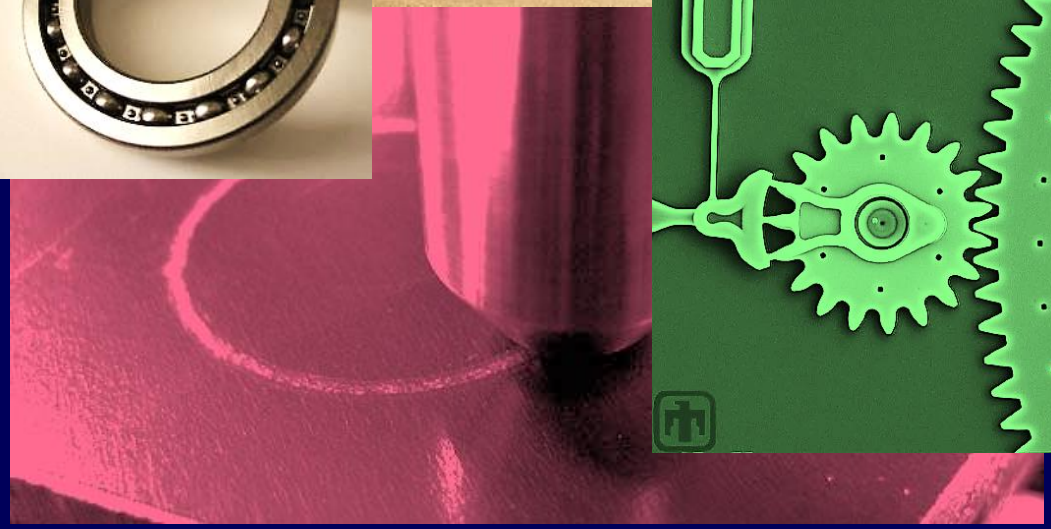
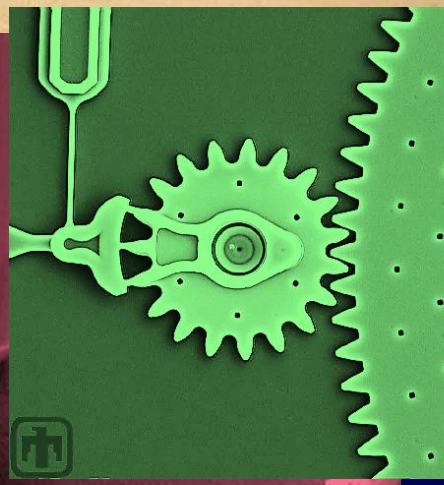


Friction *(the evil of motion)*

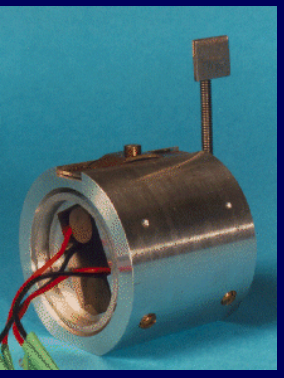
- *energy losses*
- *wear*
- *plastic/elastic deformation*
- *indentation*
- *crack propagation*

avoiding friction ...





but frequently ...



Controlling friction !

Outline

I. Friction: an old problem

II. Colloidal monolayers on periodic substrate potentials

III. Observation of kinks & antikinks

IV. Friction on surfaces with quasiperiodic order

V. Directional locking & dynamical ordering

V. Conclusions & Outlook

History of (dry) friction

Leonardo Da Vinci (1452-1519)

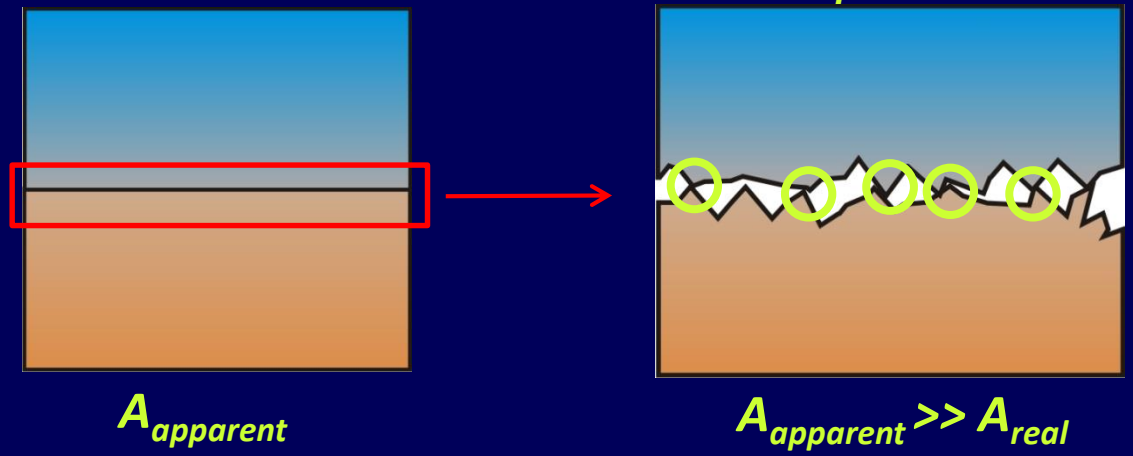
1. Friction force proportional to load
2. Friction independent of velocity
3. Friction independent of the areas in contact

Guillaume Amontons (1663-1705)

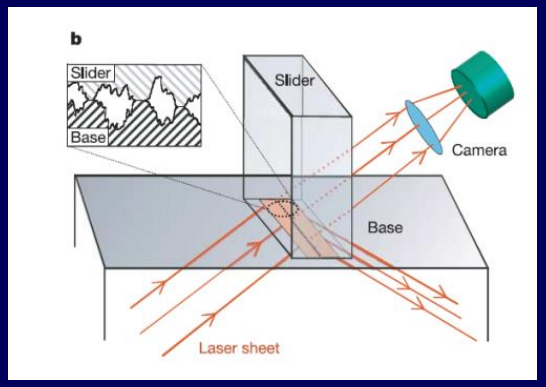
$$F_{friction} = \mu F_{load}$$ (Amontons - Coulomb)

Real contact area

Bowden and Tabor (1950)



elastic/plastic deformation of asperities by F_{load}



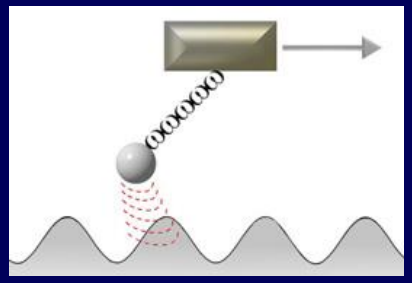
Rubinstein et al. Nature ***430****, 1005 (2004).*

$$A_{real} \propto F_{load}$$
$$F_{friction} \propto A_{real}$$

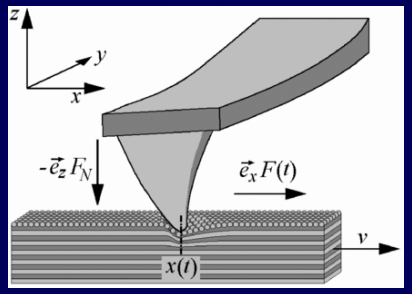
$$F_{friction} = \mu F_{load}$$ ✓

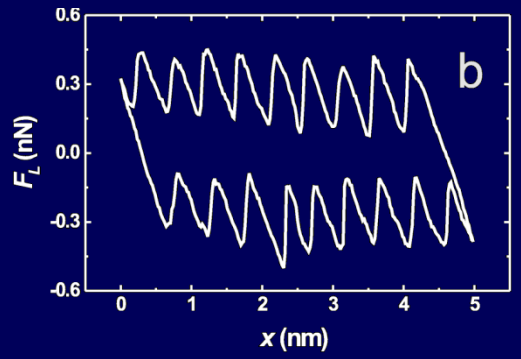
Towards Small Length-scales: Nanotribology

Tomlinson model



Stick-slip motion

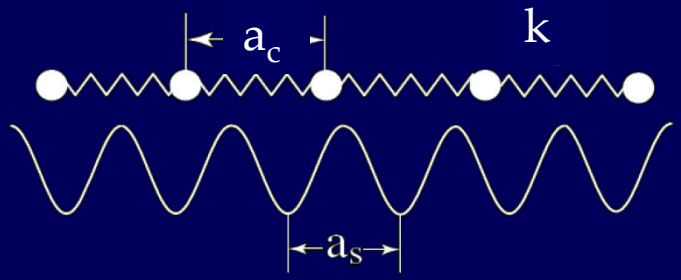




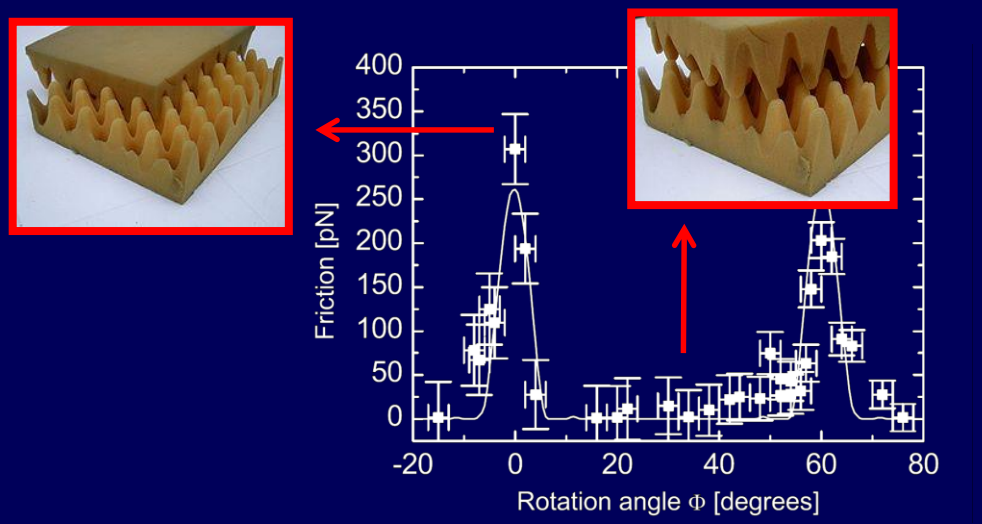
Gnecco et al. PRL **84**, *1172* (2000)

interface

Frenkel Kontorova model



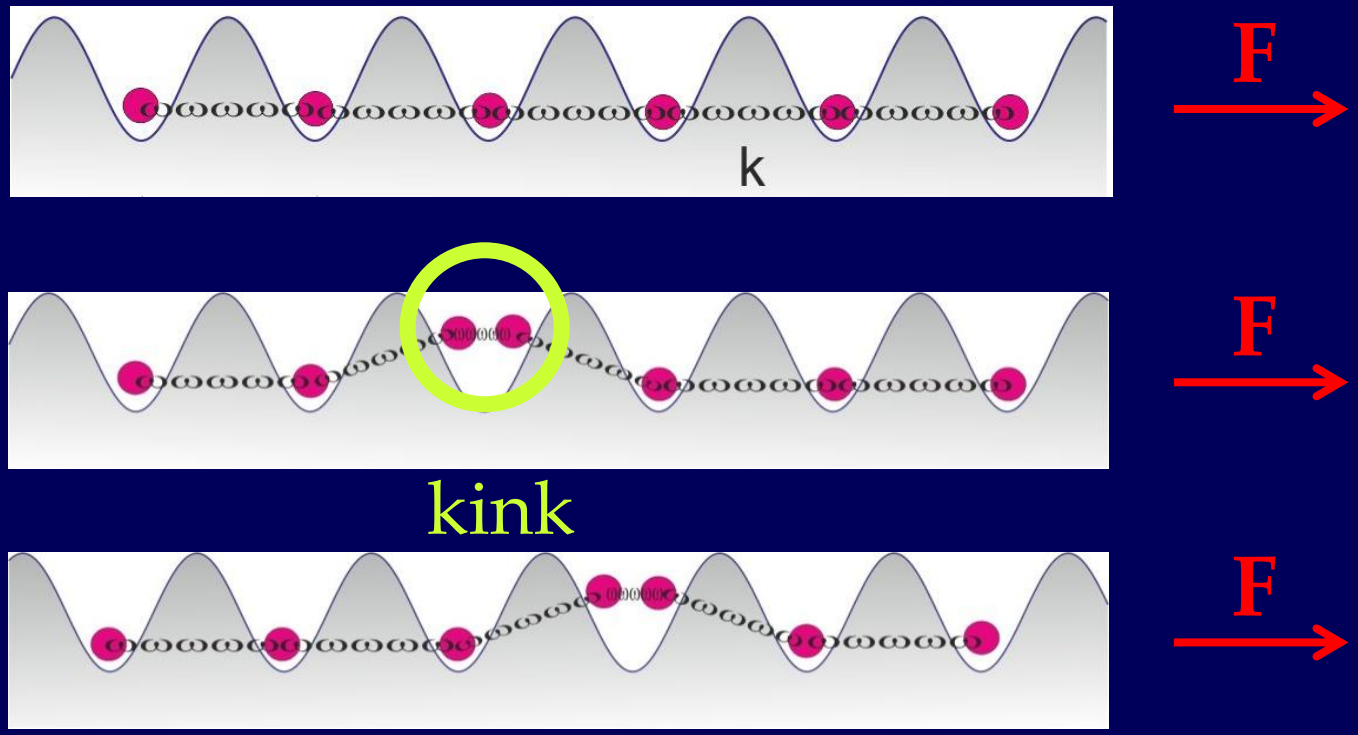
commensurability a_c/a_s determines frictional properties



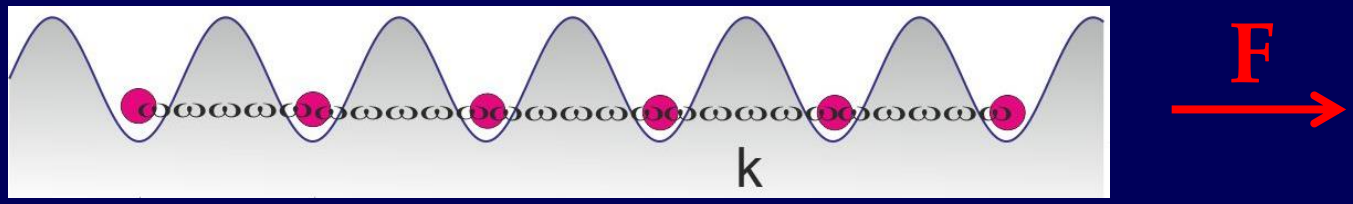
Dienwiebel *et al. PRL.* ***92, 126101 (2004)***

Mass Transport within the FK-Model

Frenkel, Kontorova, Physik. Z. Sowietunion **13** (1938) , Kontorova, Frenkel, Zh. Eksp. Teor. Fiz., **8** (1938)



Experimental Realization of FK-Model



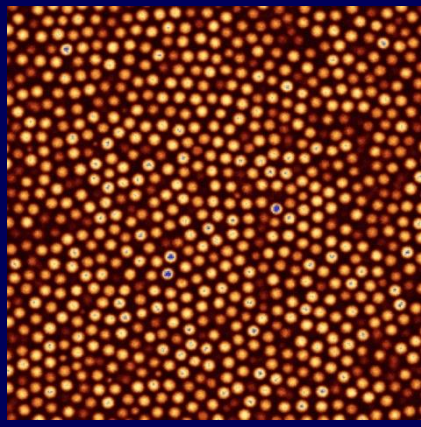
Atoms $\rightarrow$ Colloids

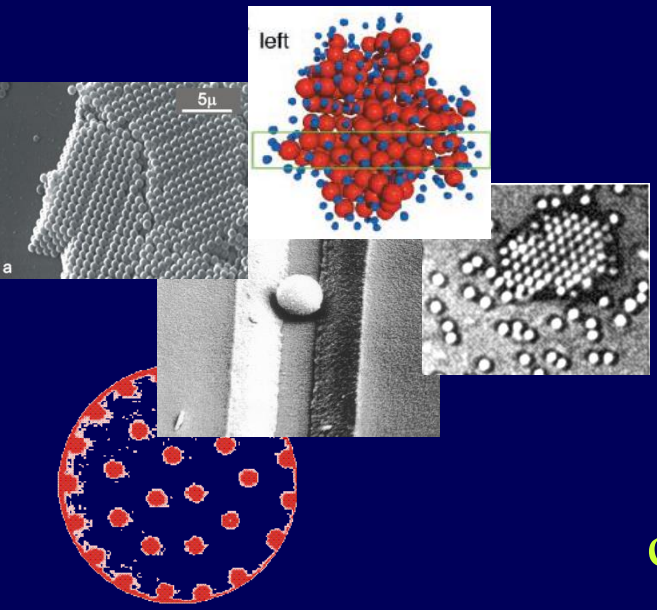
Atomic surface $\rightarrow$ Optical field

From atomic to μm length scales

Colloids: = Solid particles ranging between 10 nm and 10 μm dispersed in liquids

- overdamped motion: → **slow**
- very small elastic constants $\approx \frac{k_B T}{a^3}$ → **soft**
- typical length scales ≈ visible light: → **seeable**





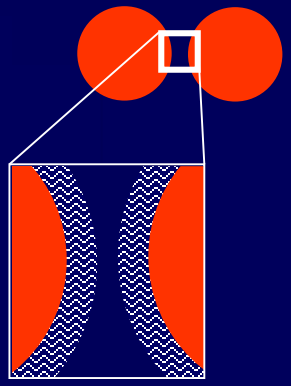
Atoms $u(r)_{atom}$ ≡ Colloids $u(r)_{colloid}$

- Phase transitions
- Nucleation phenomena
- Glass formation
- Diffusion through pores
- Hexatic order (e.g. graphene)

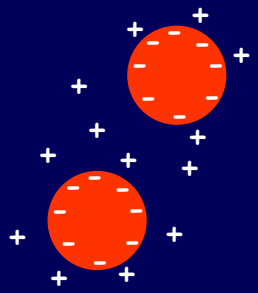
colloids as model systems

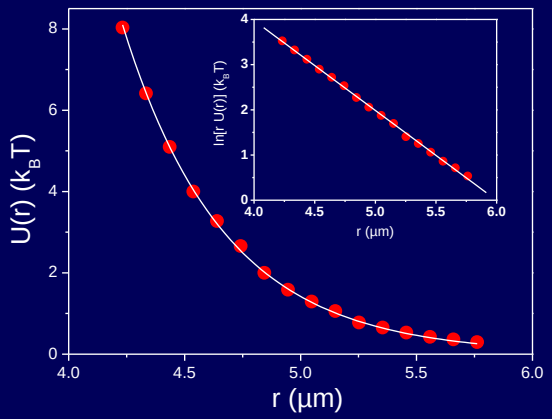
Tunable Pair Interactions

steric



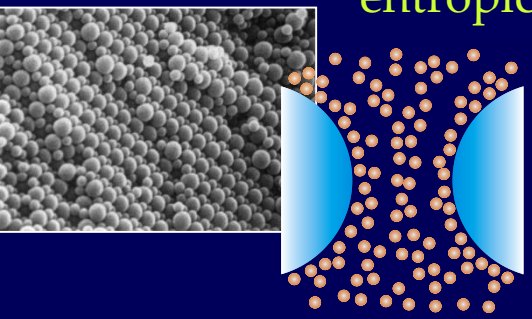
electrostatic





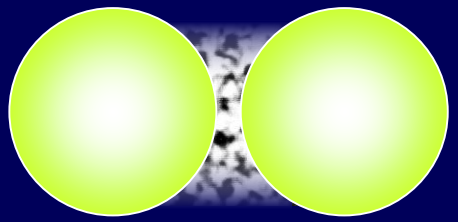
*Brunner, Dobnikar, v. Grünberg, Bechinger, PRL **92**, 078301 (2004).*

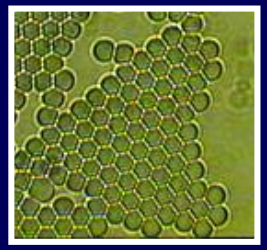
entropic



Helden, Roth, Koenderink, Leiderer, Bechinger, PRL **90, 48301 (2003).**

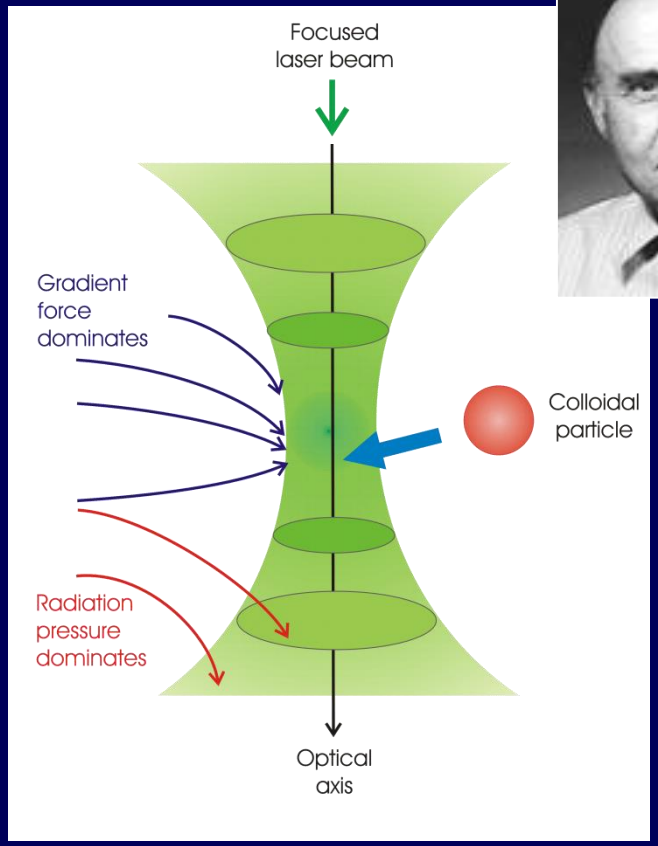
Critical Casimir

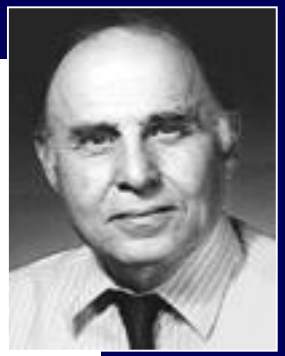


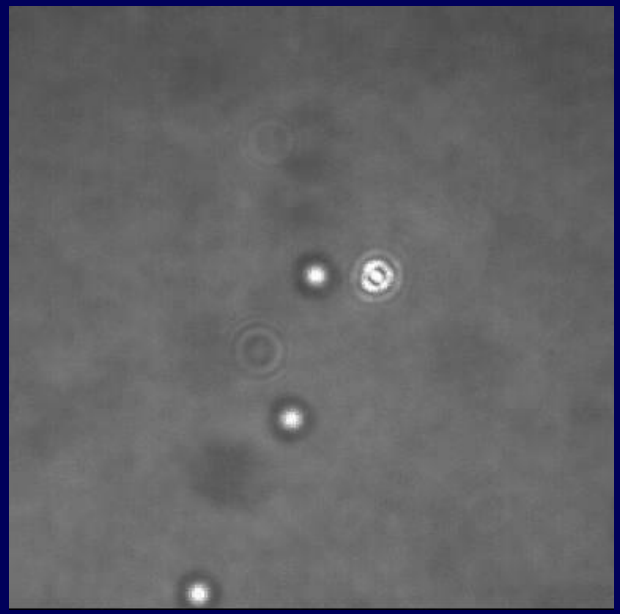


Hertlein, Helden, Gambassi, S. Dietrich, Bechinger, Nature **451, 172 (2008).**

Optical Tweezers



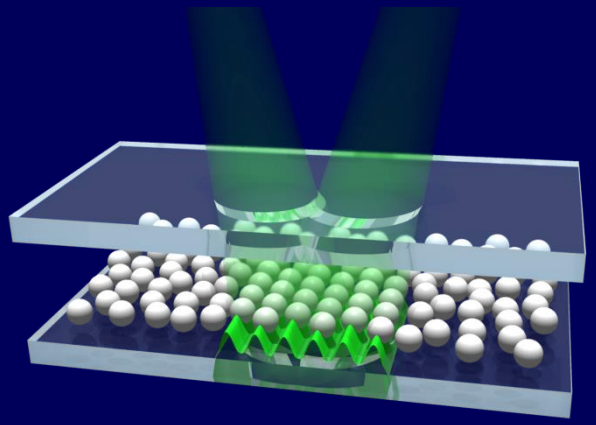


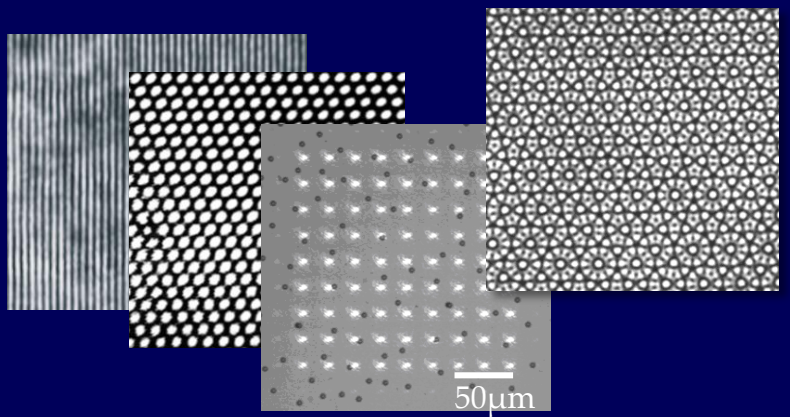


A. Ashkin, Acceleration and trapping of particles by radiation pressure, Phys. Rev. Lett. ***24****, 156 (1970)*

Extended Optical Potentials

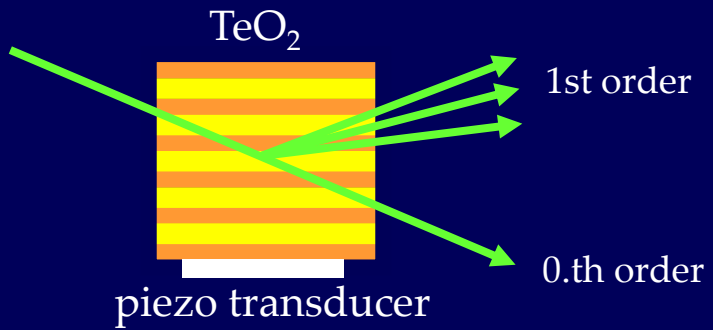
- Interfering laser beams

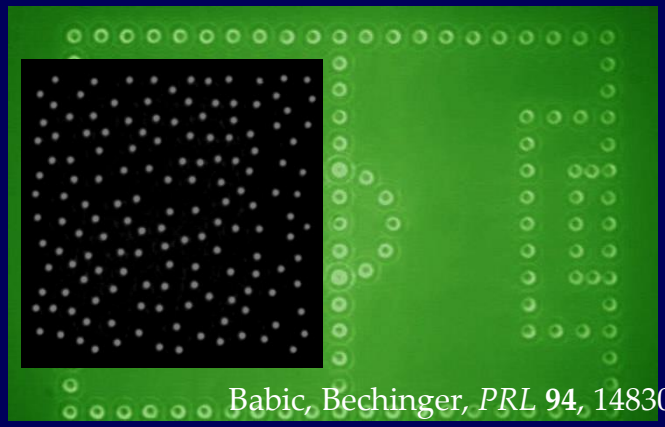




Mikhael, Roth, Helden, Bechinger *Nature* ***454, 501 (2008).***
.Baumgartl, Zvyagolskaya, Bechinger, PRL 99, 205503 (2007).

- AOD (time sharing)



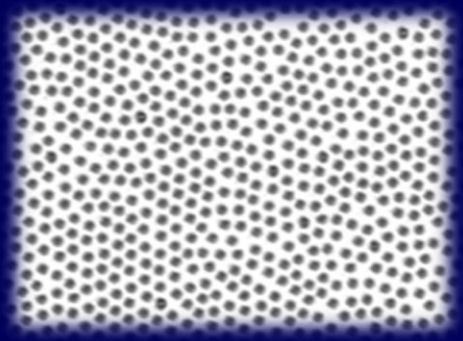


Babic, Bechinger, *PRL* **94**, 148303 (2005).

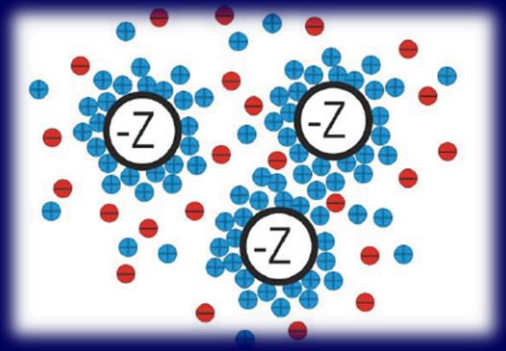
→ *in situ* adjustable strength and geometry of substrate potential

Experimental procedure

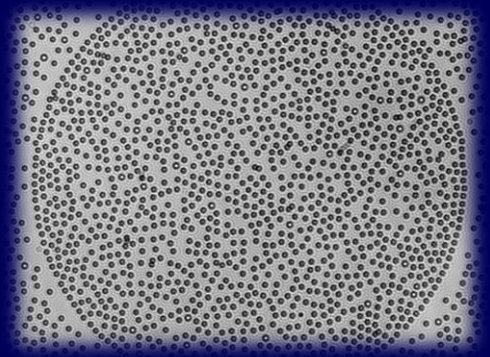
❶ colloidal suspension



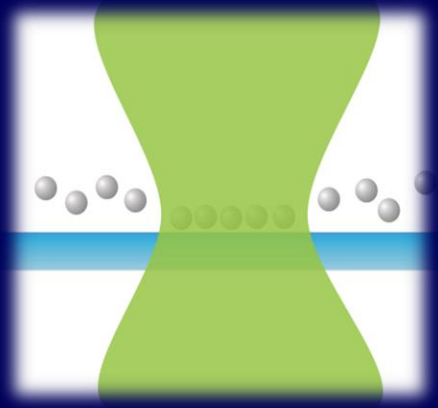
❷ tuning the interaction



❸ adjust particle density

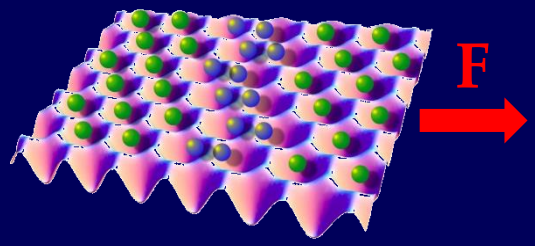


❹ confinement to 2D

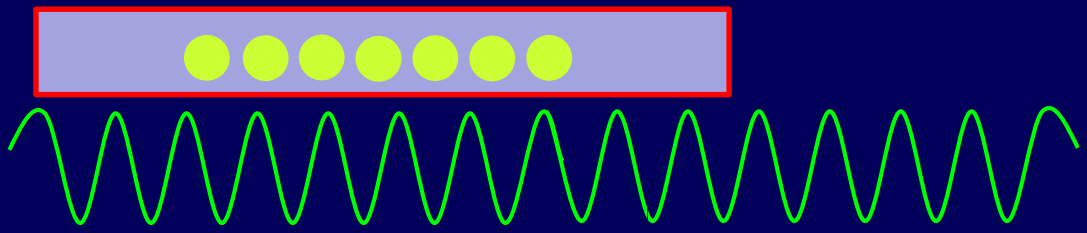


❺ optical substrate potential

❻ lateral driving force



Lateral driving forces



direct optical access to interface !

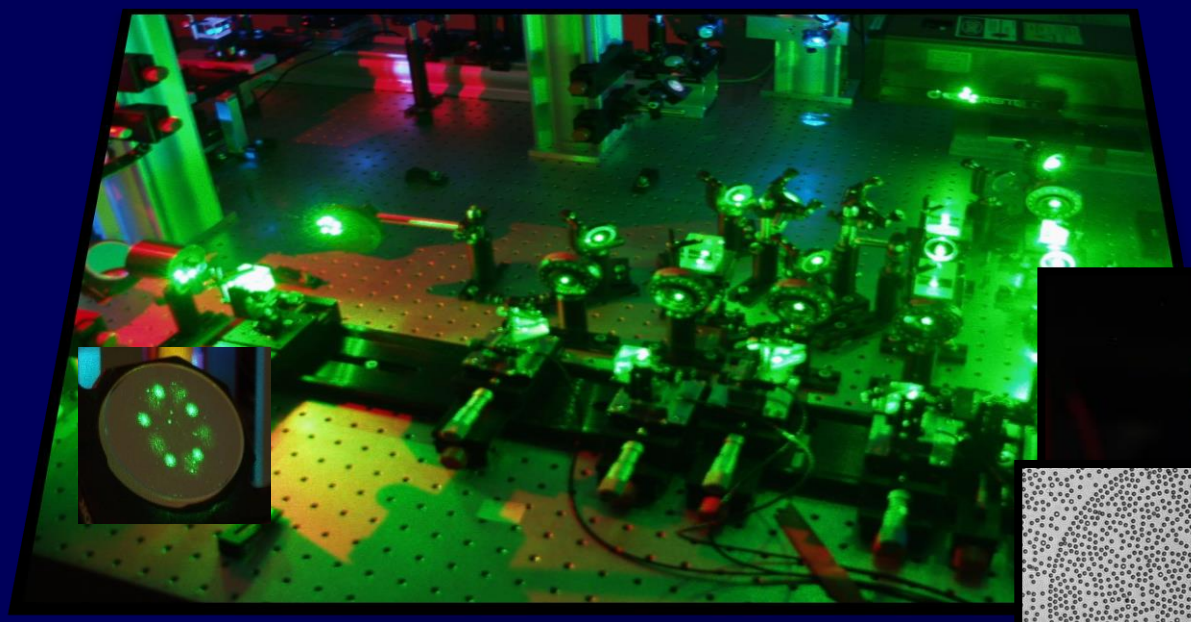
translation of sample cell with velocity $\vec{u}$

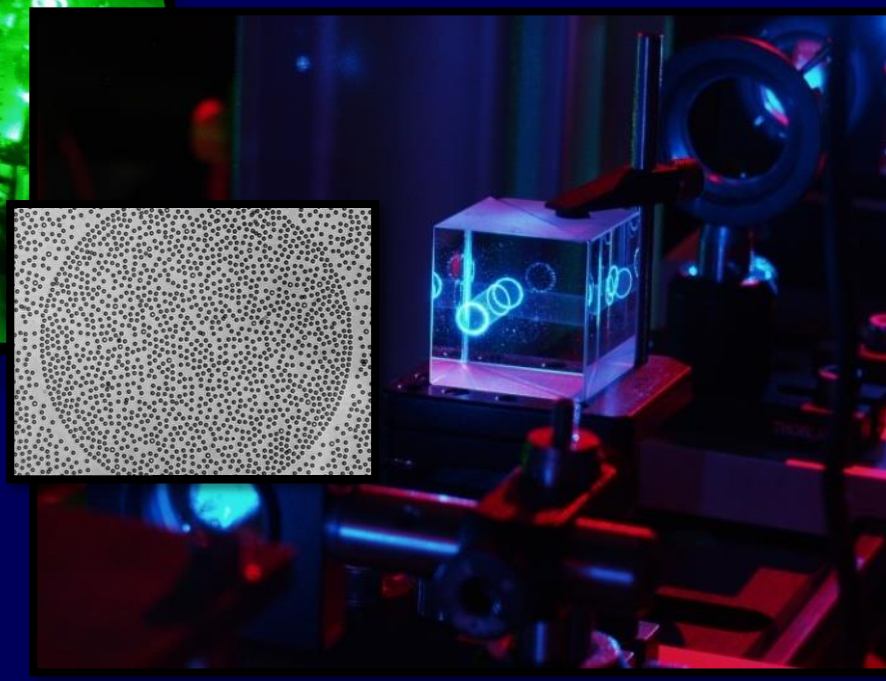
$$\vec{F} \approx 6\pi\eta a\vec{u}$$

influence of wall and other particles: $\gamma_{eff} = \frac{k_B T}{D_{eff}}$

Bohlein, Bechinger, *Phys. Rev. Lett.* ***109, 058301 (2012)***

Experimental Setup

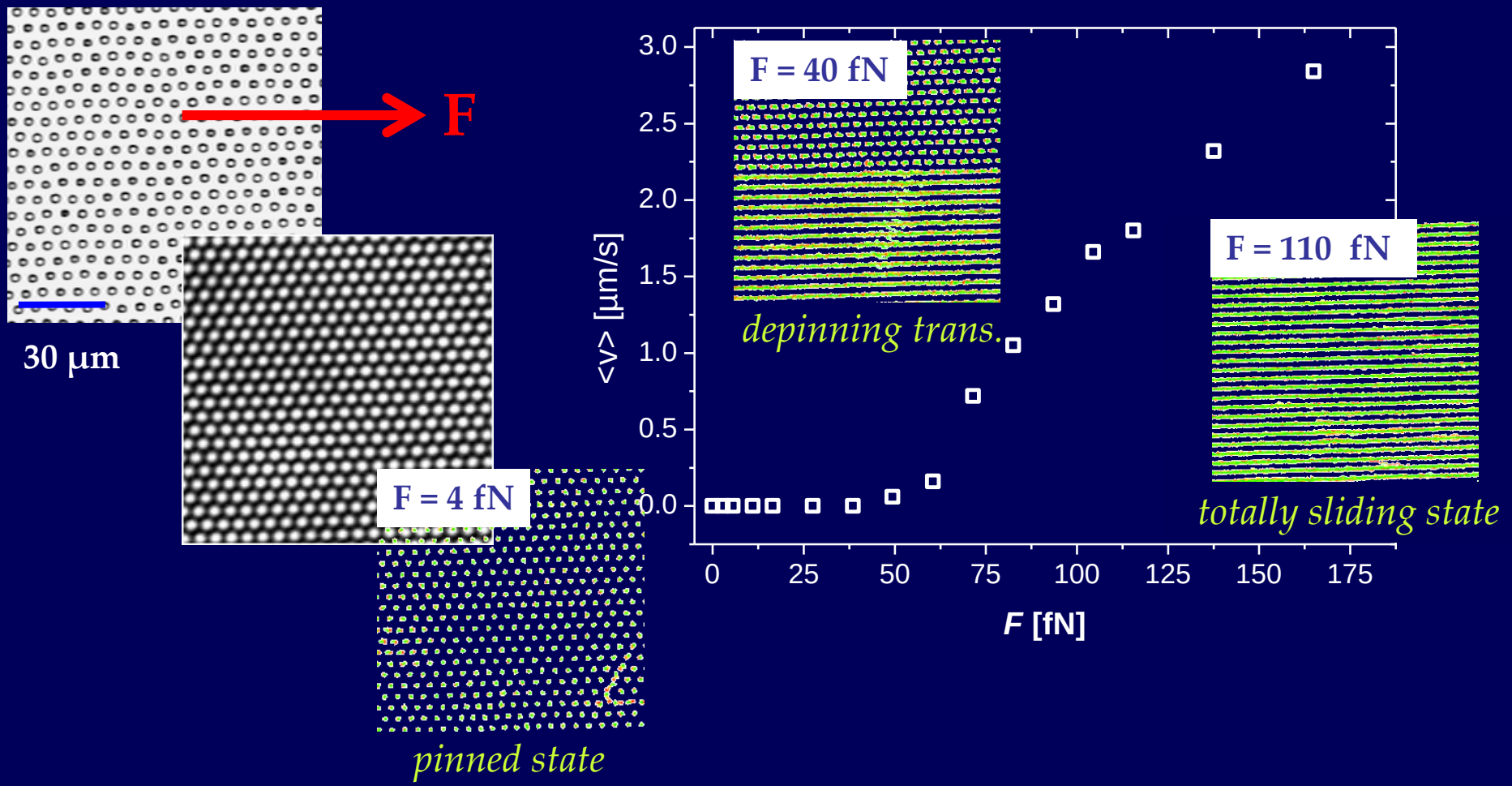




- Substrate potential 18W, λ = 532 nm
- Optical Fence: 7W, λ = 488 nm
- 2D confinement: 1064 nm
- Control of polarization and phases

Friction at commensurate surfaces

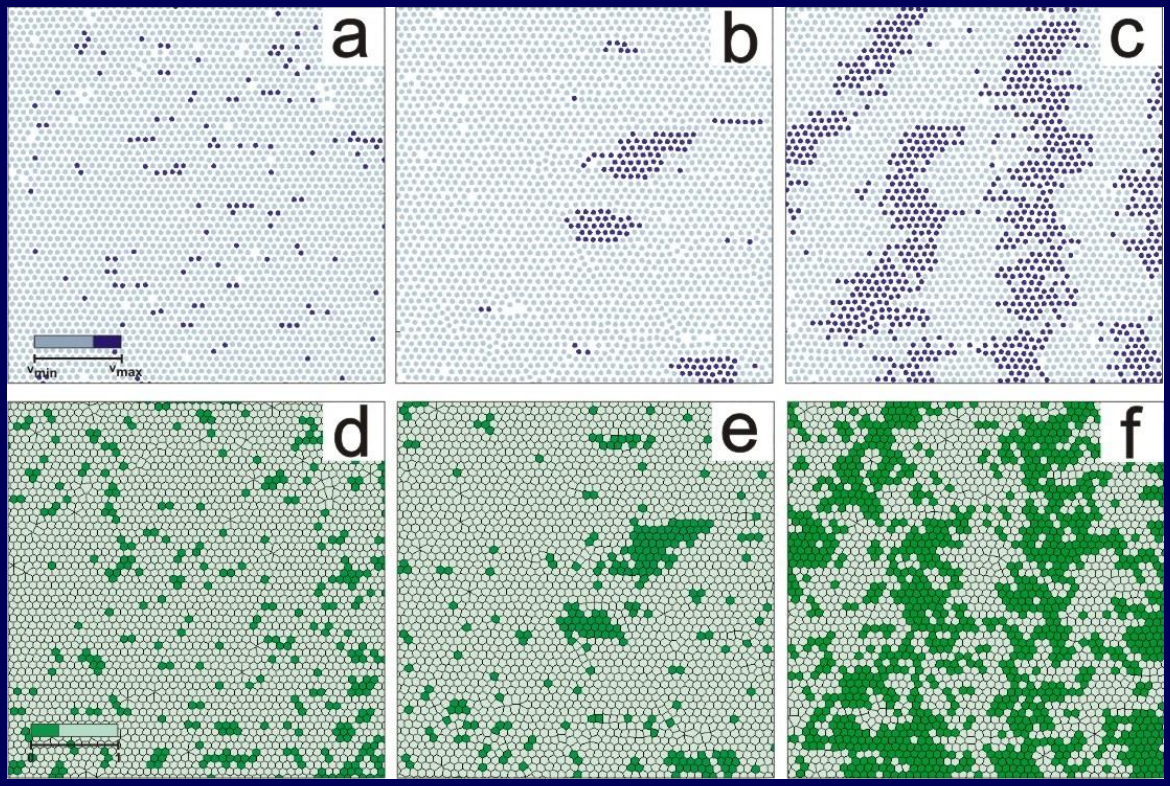
$a_c = a_s = 5.7\mu m$



Particle Motion

F= 0 fN F= 49 fN F= 82 fN

velocities



voronoi cell area

fast particles @ lattice compressions

Bohlein, Mikhael & Bechinger, *Nature Materials* ***11, 126 (2012).***

Particle Motion

F= 0 fN F= 49 fN F= 82 fN

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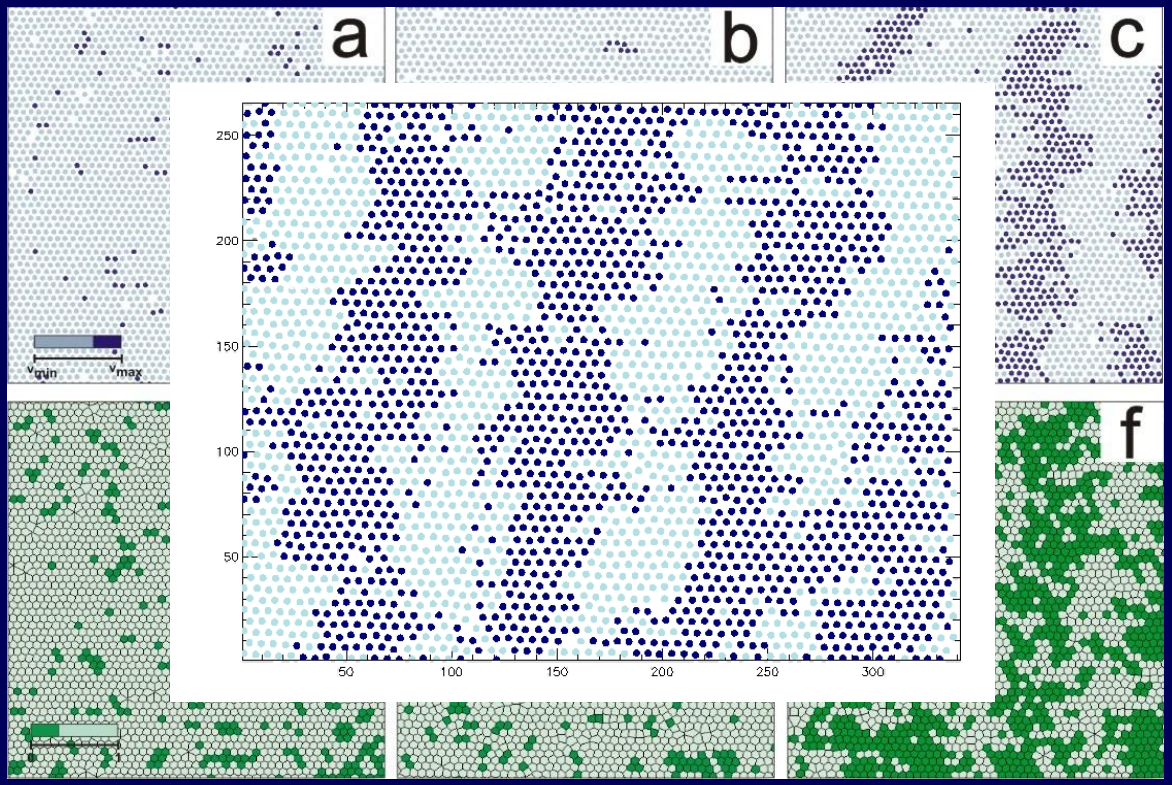
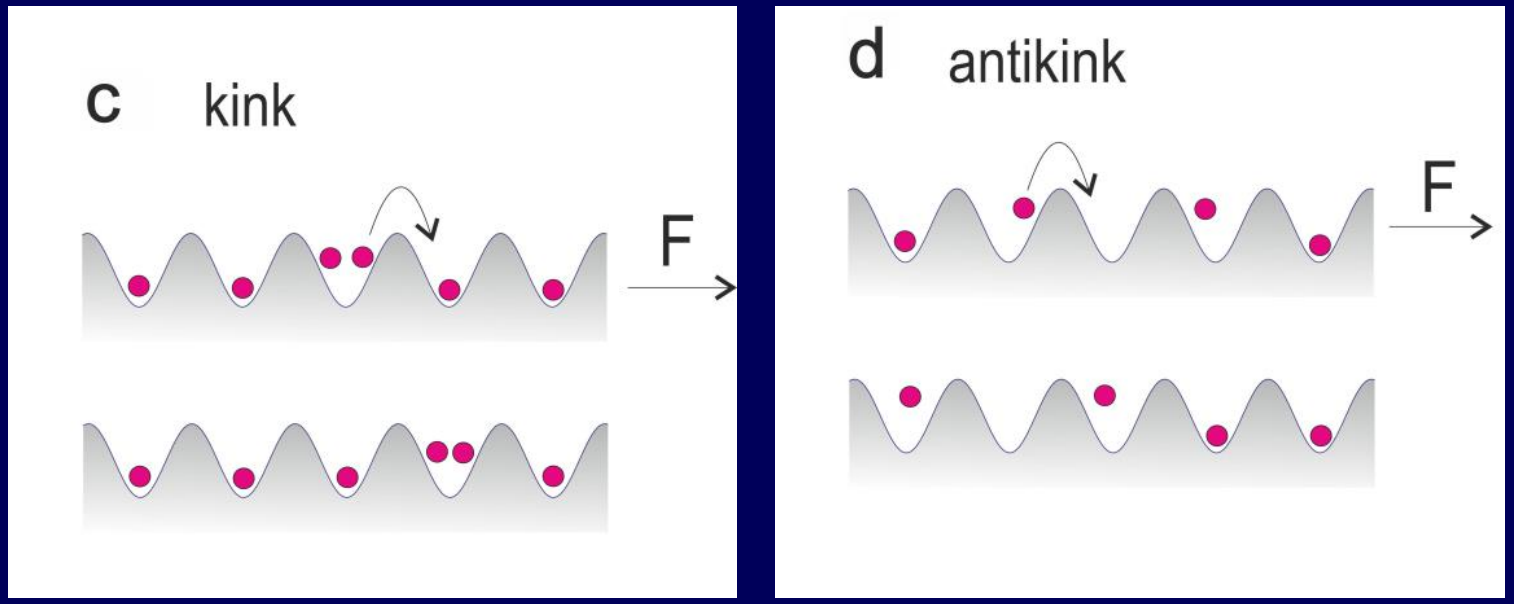


fast particles @ lattice compressions

Bohlein, Mikhael & Bechinger, *Nature Materials* ***11, 126 (2012).***

Frenkel-Kontorova Model

Vanossi et al J.Phys.: Condens. Matter 19 (2007)



kinks & antikinks provide mechanism for efficient mass transport at small length scales

Incommensurate Conditions

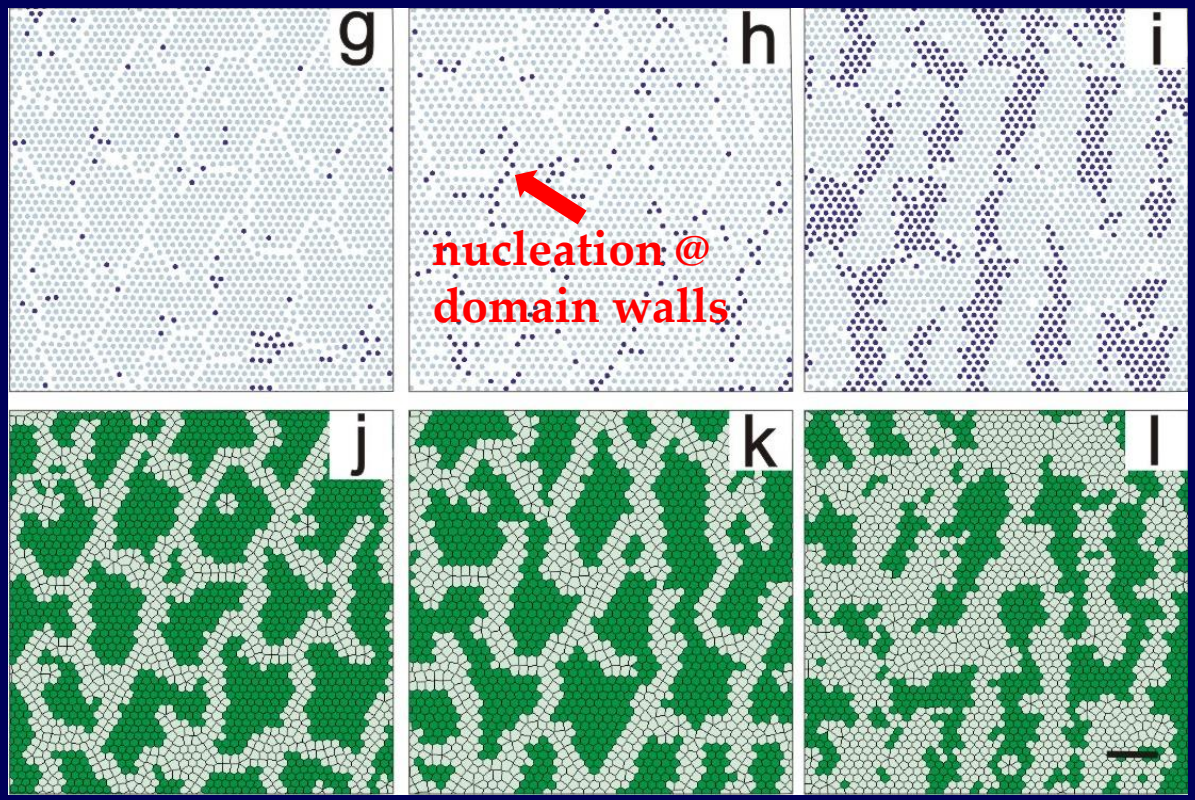
$a_c = 5.7\mu m > a_s = 5.2\mu m$

Domain formation: Brune, Giovannini, Bromann, Kern, Nature **394,** 451-453 (1998).
Bleil, Grünberg, Dobnikar, Bechinger *EPL 73, 450-456 (2006).*

F= 0 fN F= 19 fN F= 82 fN

velocities

voronoi cell area



fast particles @ lattice expansions !

Incommensurate Conditions

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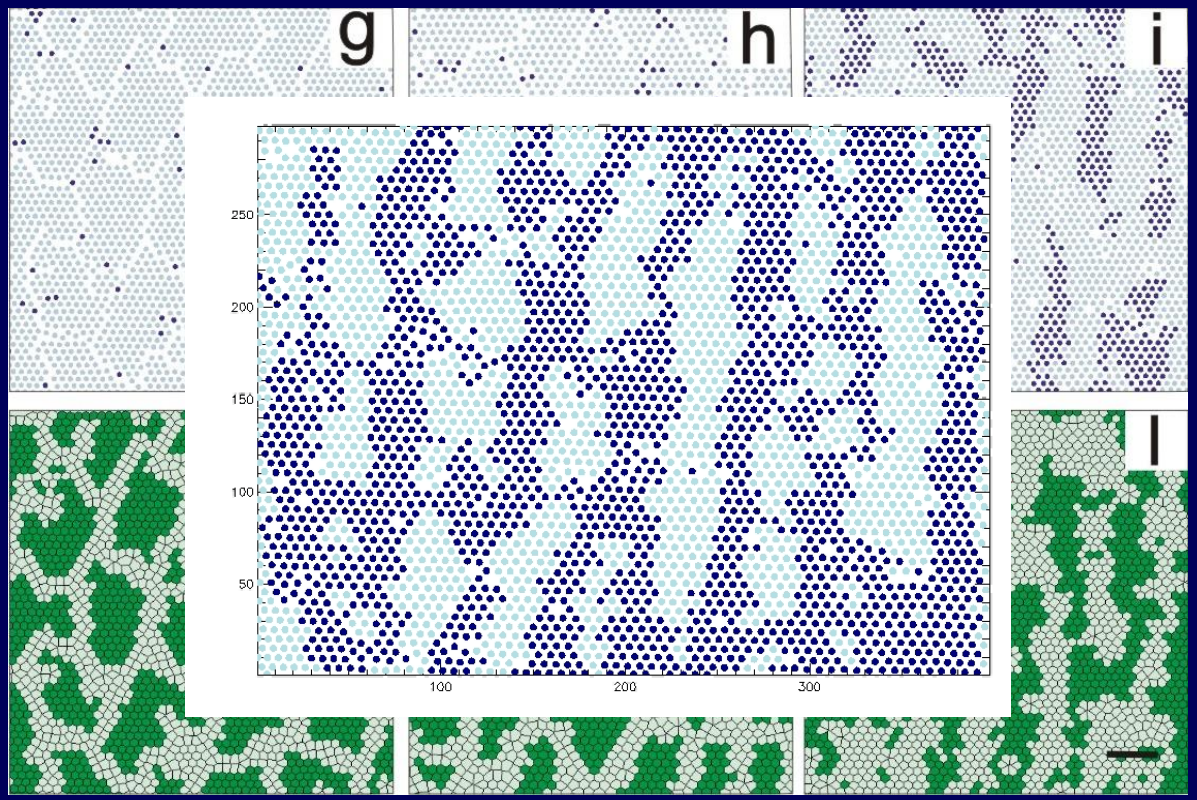
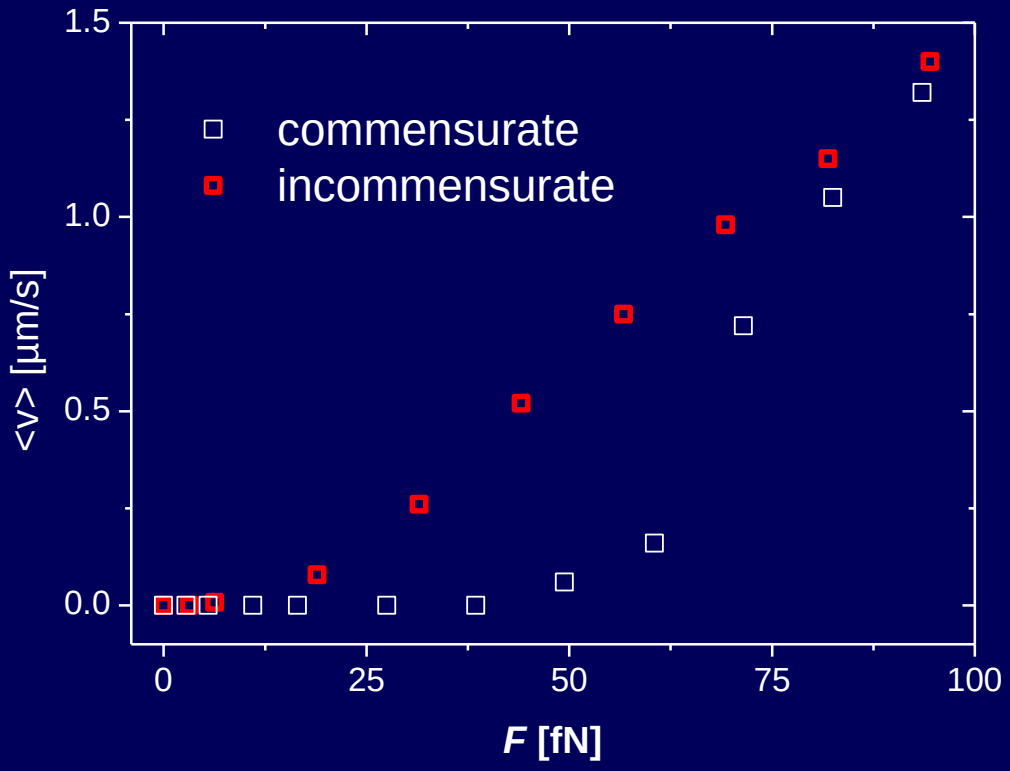


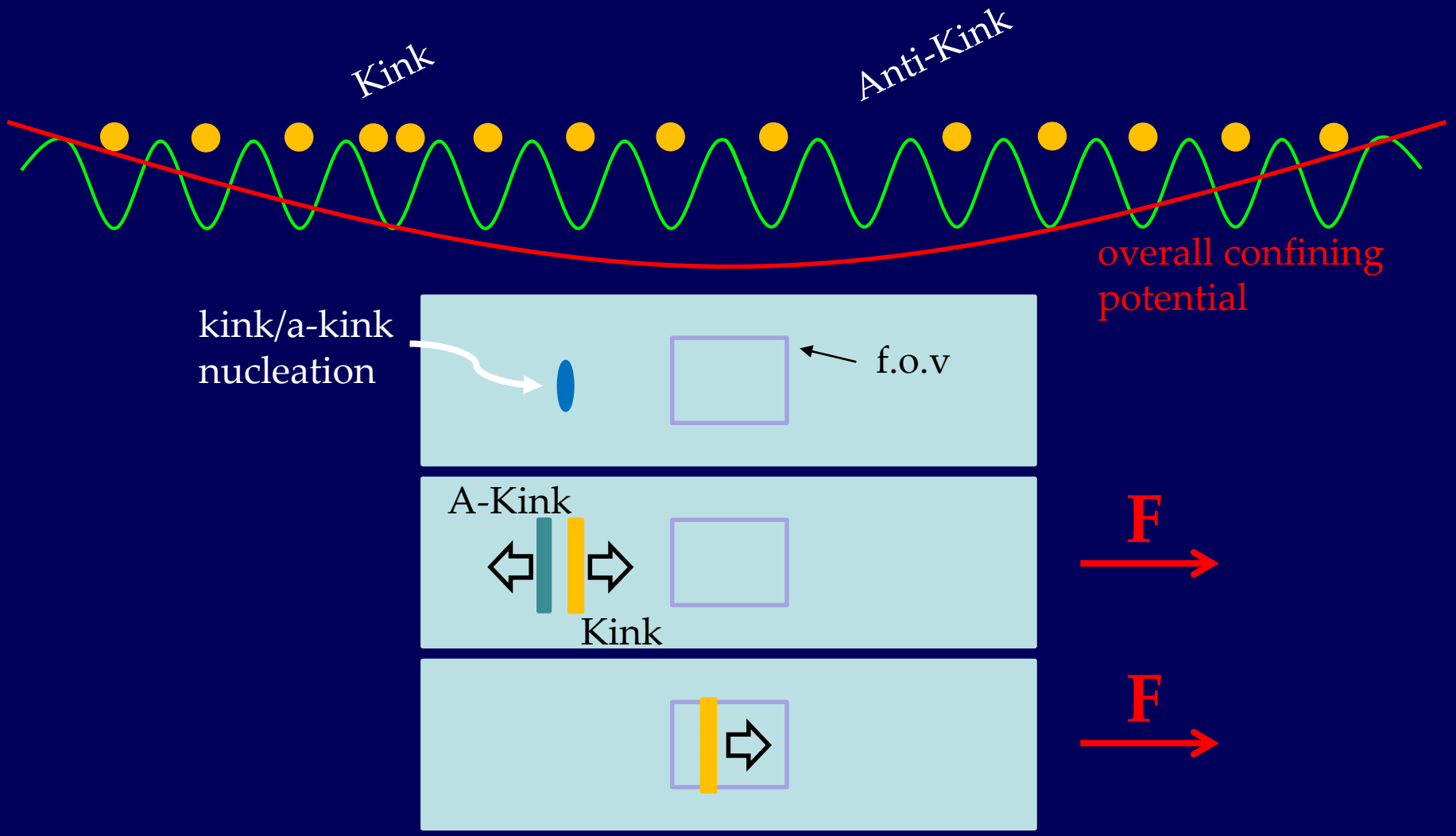
fast particles @ lattice expansions !

Commensurate vs. Incommensurate



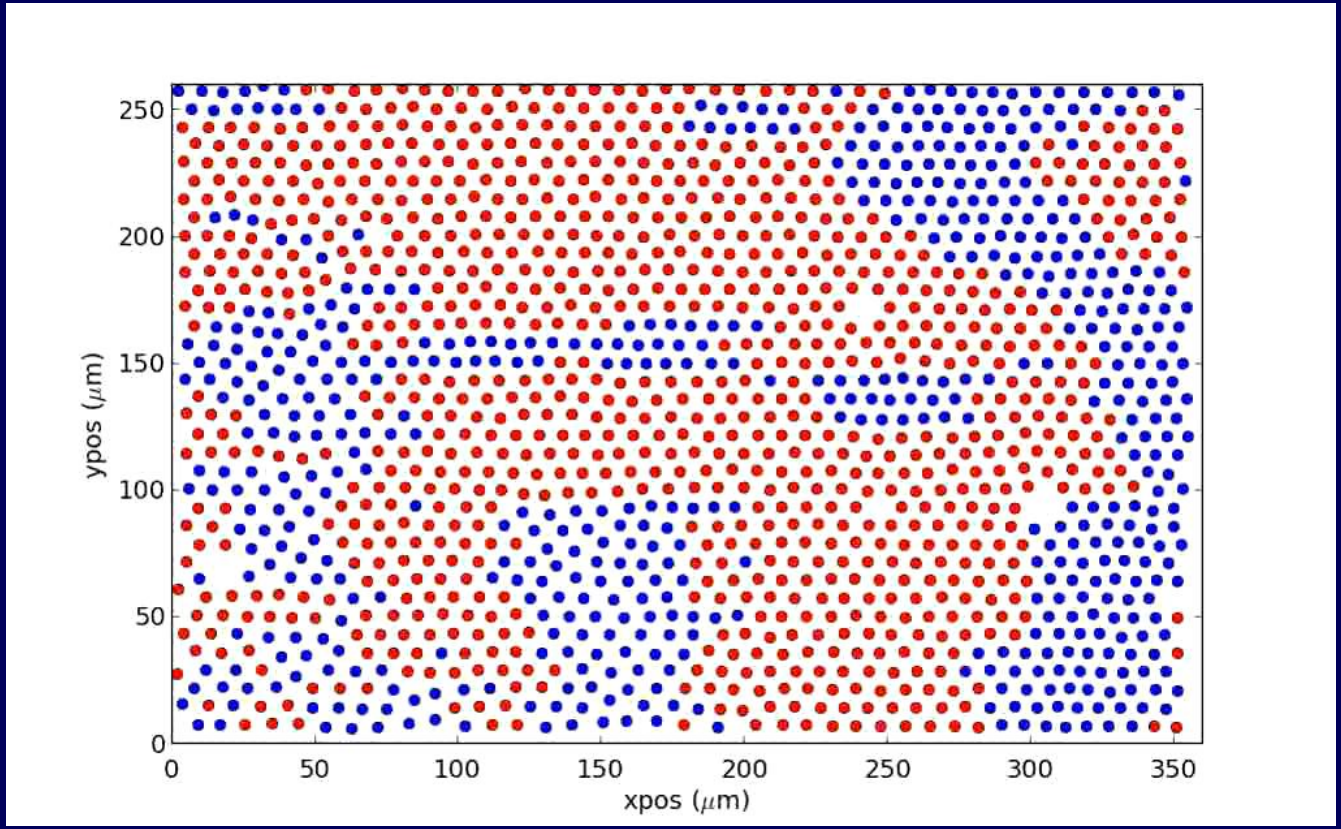
Reduced static friction due to enhanced antikink formation
(nucleated at domain walls)

Why only kinks at commensurate conditions ?

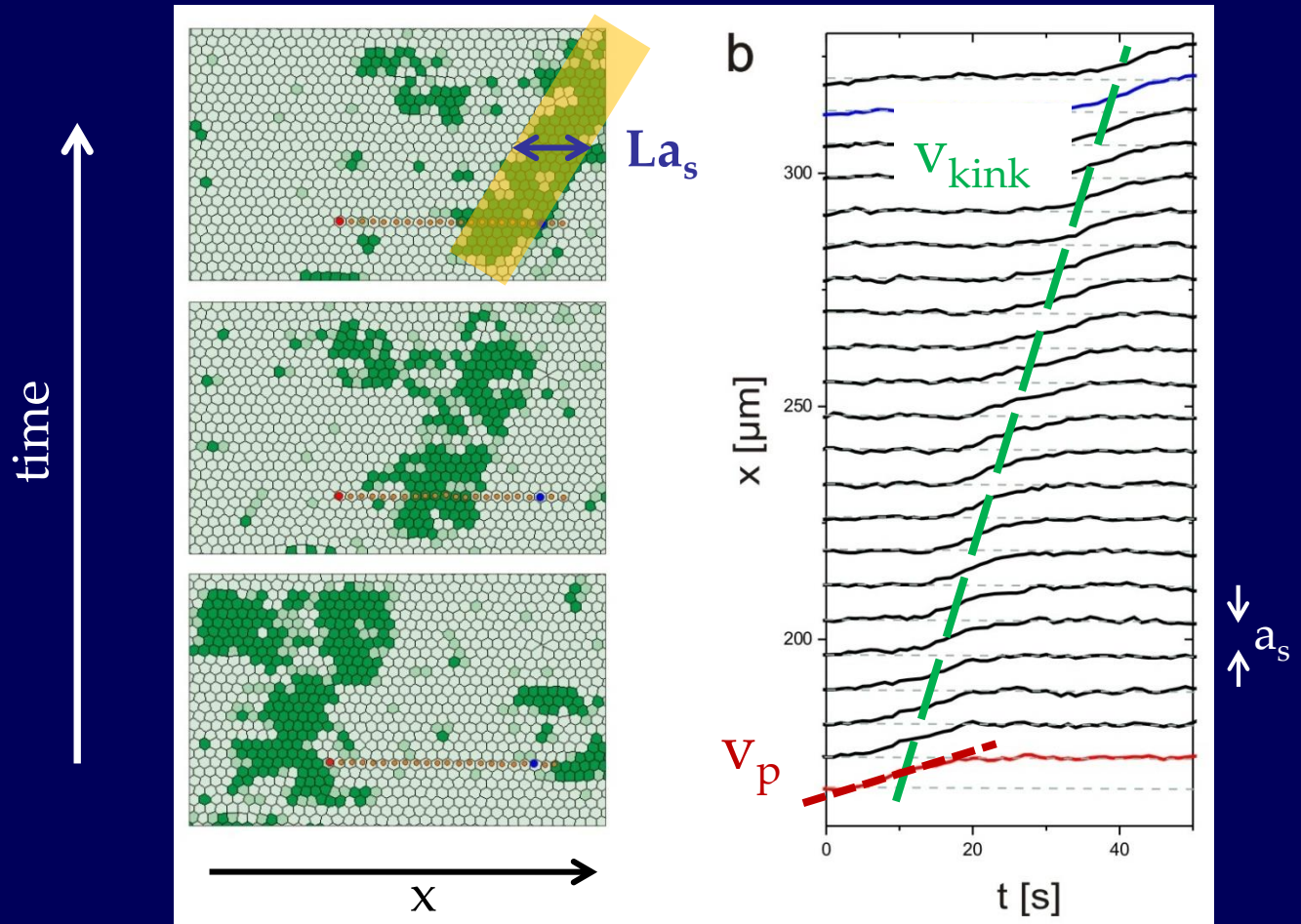


Vanossi, Manini, Tosatti, *PNAS, 16429 (2012).*

Annihilation of kinks & antikinks

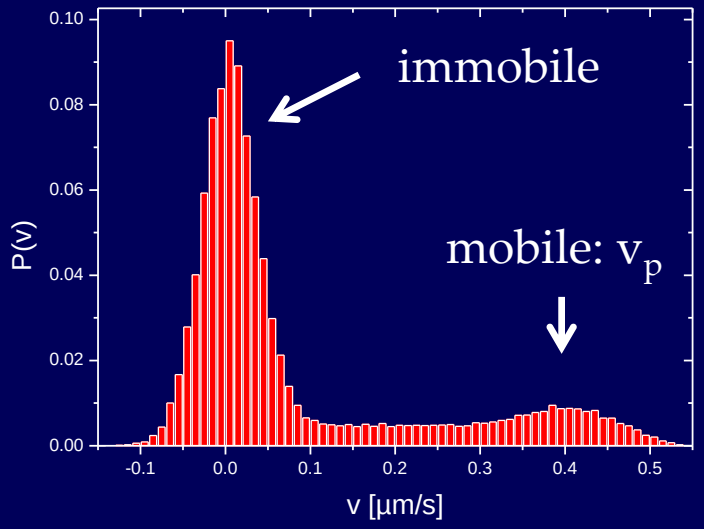


Kink motion



$$v_{kink} = v_p \cdot L$$

Quantitative Comparison



1 dim. model

$$\langle v \rangle = v_p \cdot \underbrace{L \cdot n_{kink}}_{\text{number of mobile particles}} \cdot \frac{1}{N} = v_{kink} \cdot \frac{n_{kink}}{N}$$

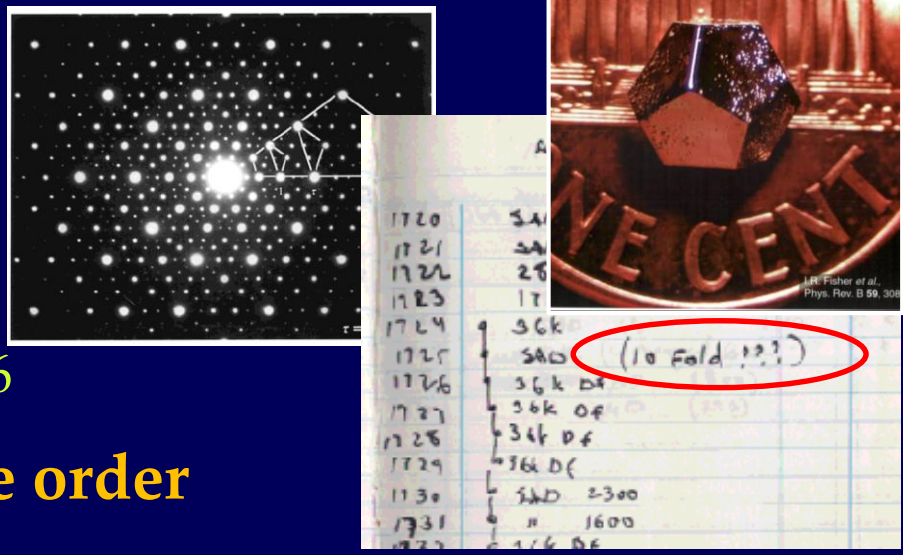
Commensurate (a = s = 5.7 μm)				
F [fN]	n_{kink}	v_{kink} [μm/s]	$v_{kink} \cdot n_{kink} / N$ [μm/s]	<v> [μm/s]
120	4.2 ± 0.4	29.2 ± 1.4	1.75 ± 0.19	1.76
145	4.2 ± 0.4	37.5 ± 2.3	2.24 ± 0.26	2.2
195	4.2 ± 0.4	48.0 ± 3.8	2.87 ± 0.36	3.1
Incommensurate (a > s = 5.2 μm)				
F [fN]	$n_{antikink}$	$v_{antikink}$ [μm/s]	$v_{antikink} \cdot n_{antikink} / N$ [μm/s]	<v> [μm/s]
120	8.5 ± 1.2	15.8 ± 0.8	1.92 ± 0.28	1.84
145	8.5 ± 1.2	17.6 ± 1.0	2.14 ± 0.33	2.25
195	8.5 ± 1.2	28.3 ± 2.1	3.43 ± 0.55	3.1

(anti) kinks dominate friction at small length scales

Quasicrystals

other rotational symmetries than 2,3,4,6

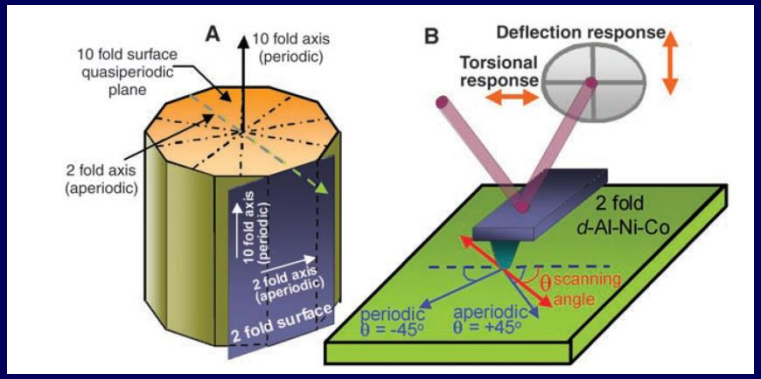
aperiodic but perfect long-range order

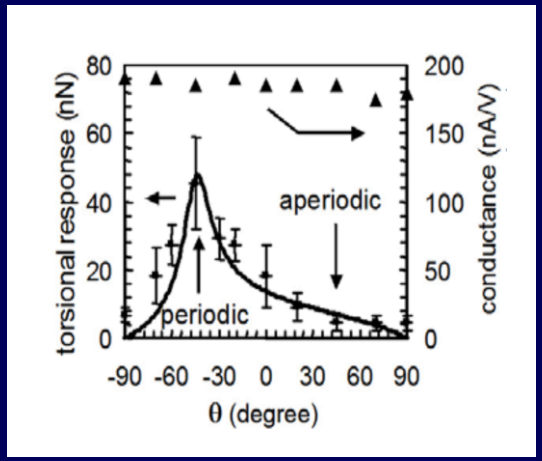


Dan Shechtman, Nobel price 2010

Bulk: unusual electrical, optical, mechanical properties

Surface: catalytic, low corrosion & low friction, small wear

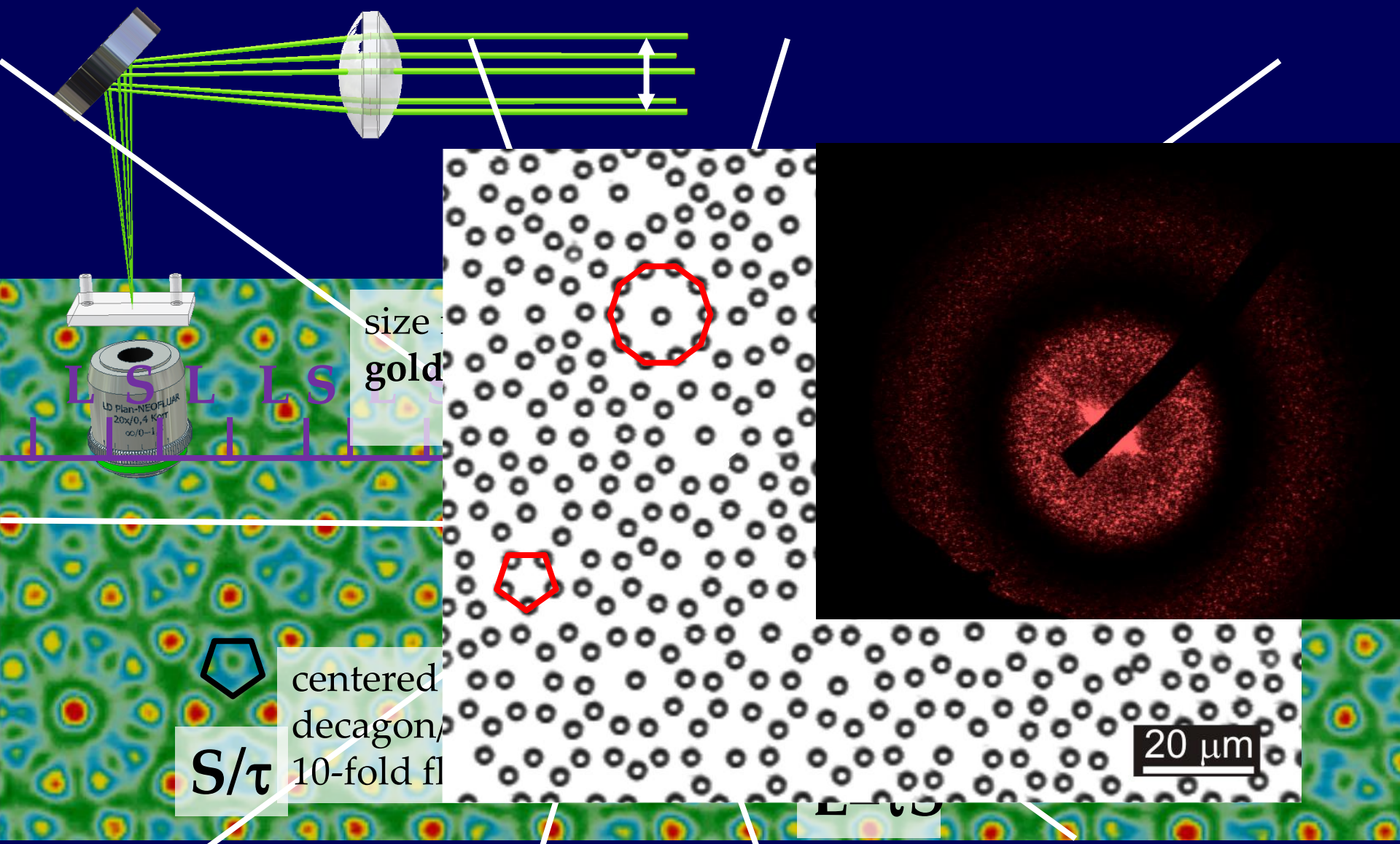




Al-Ni-Co

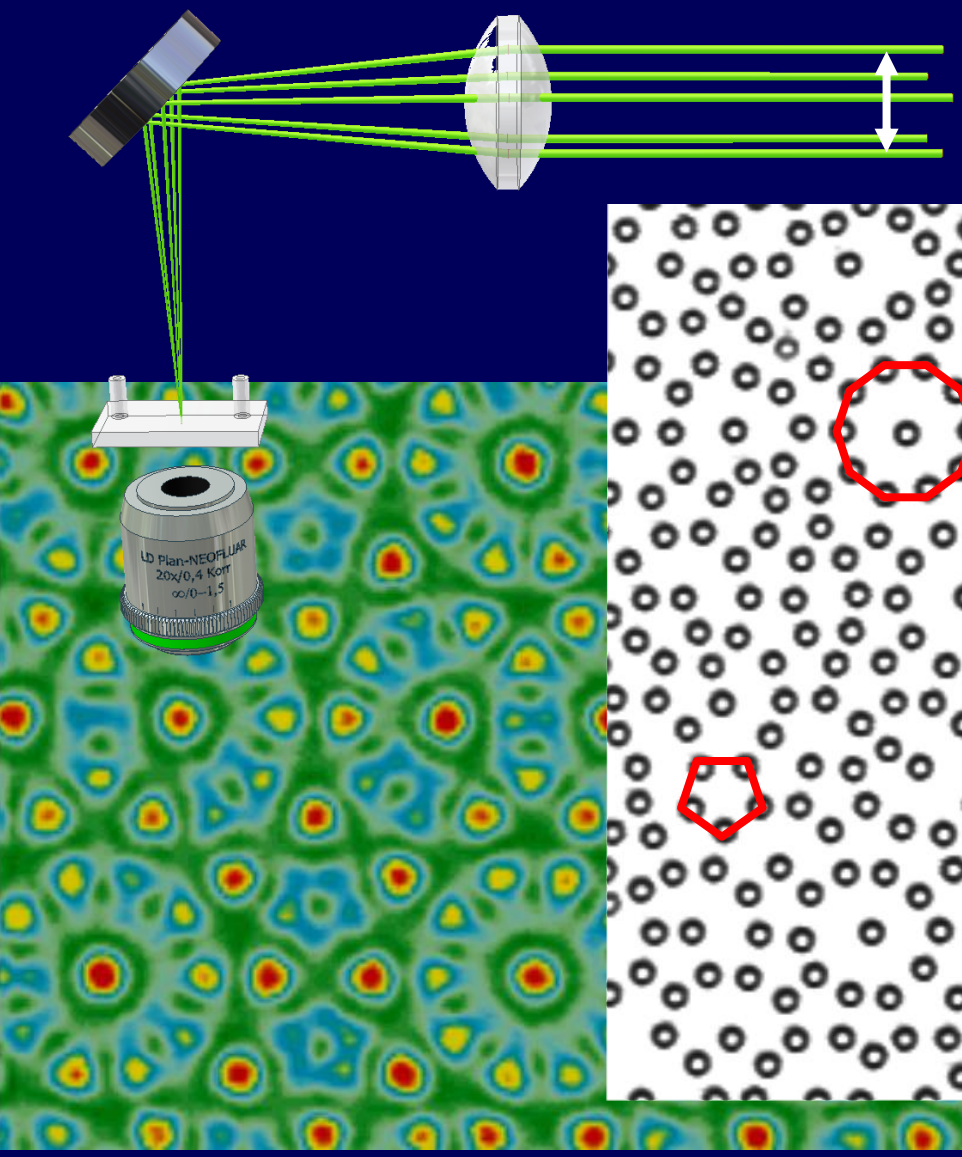
Park, Ogletree, Salmeron, Ribeiro, Canfiled, Jenks, Thiel Science, ***309*** *1354 (2005)*

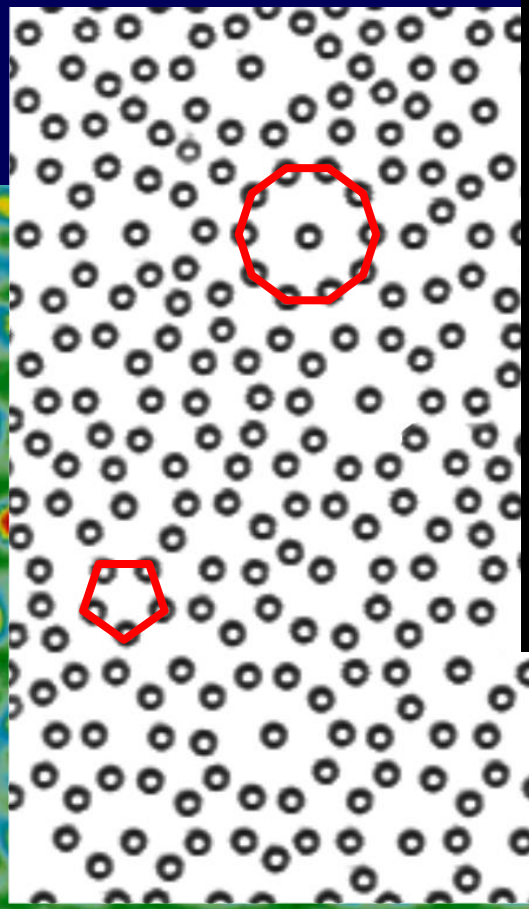
Quasiperiodic Light Fields

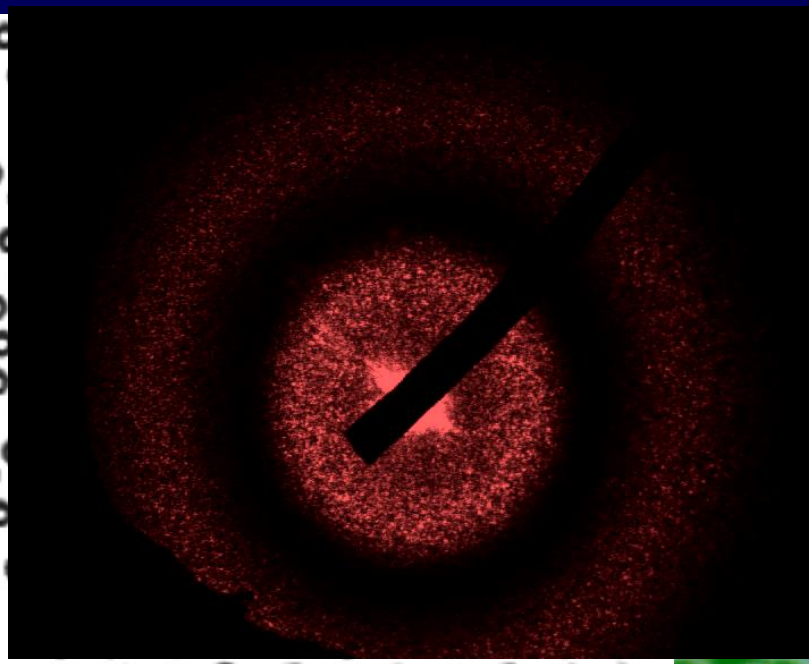


Mikhael, Schmiedeberg, Rausch, Roth, Stark, Bechinger, PNAS **107, 7214 (2010).**

Quasiperiodic Light Fields



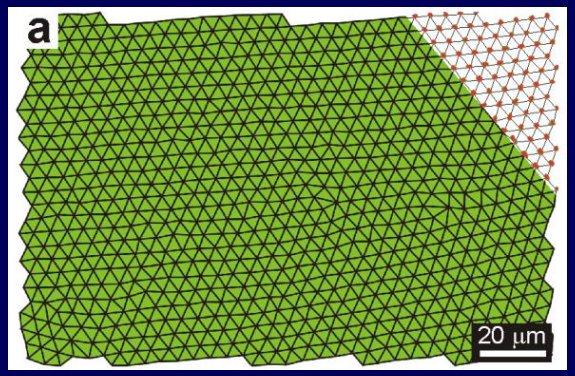


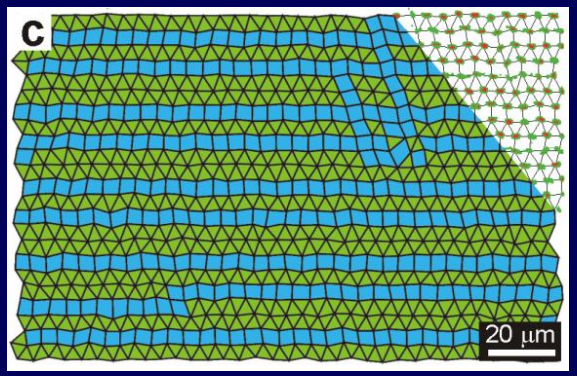


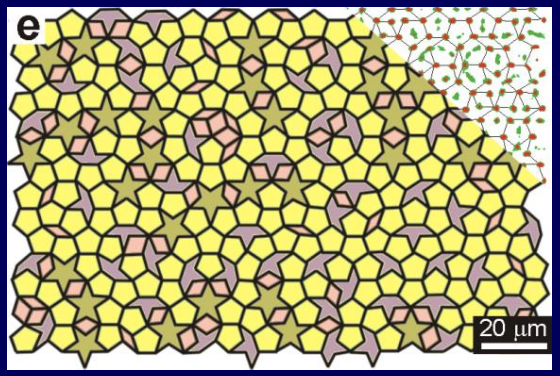
Mikhael, Schmiedeberg, Rausch, Roth, Stark, Bechinger, PNAS **107, 7214 (2010).**

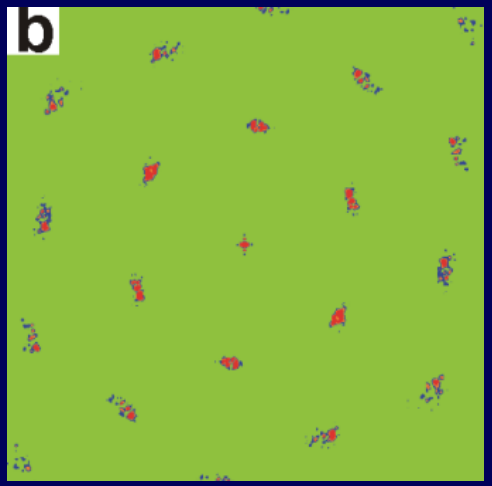
Increasing Substrate Interaction

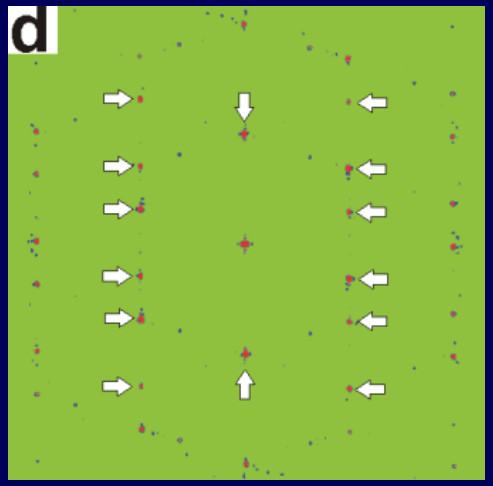
rel. particle substrate interaction →

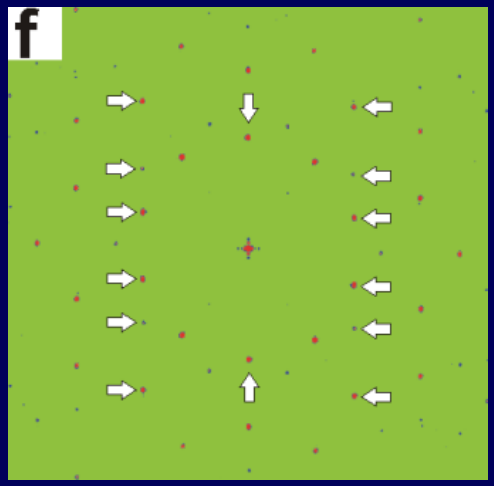








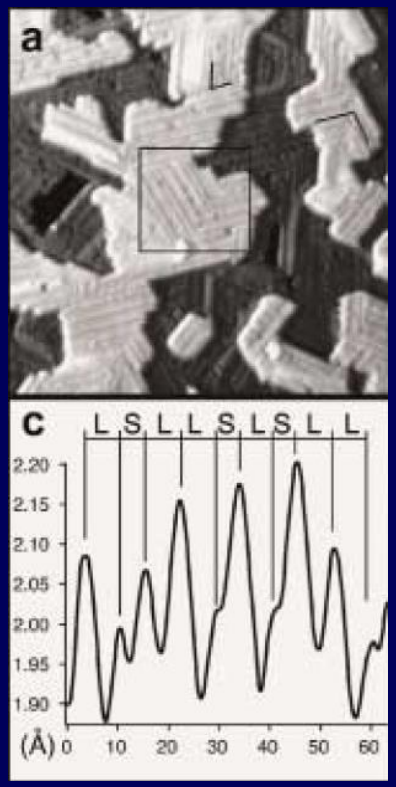


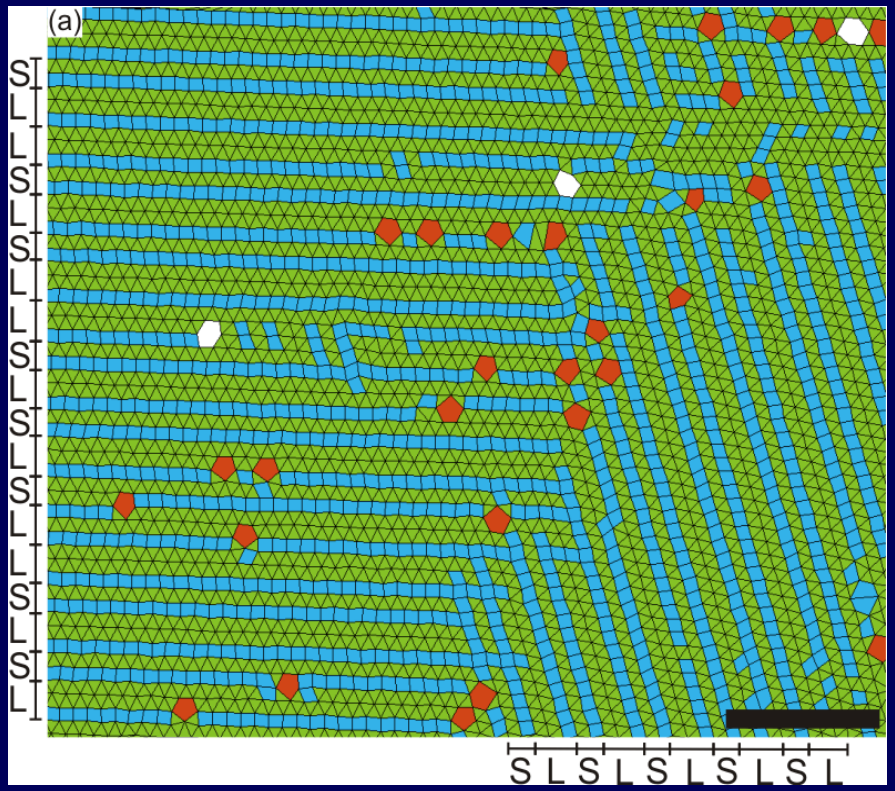


$\Phi = 0.0465\,\mu m^{-2}$

Mikhael, Roth, Helden, Bechinger, Nature **454**, 501 (2008)

Cu Films on *i*-Al_{70}-Pd_{21}-Mn_9

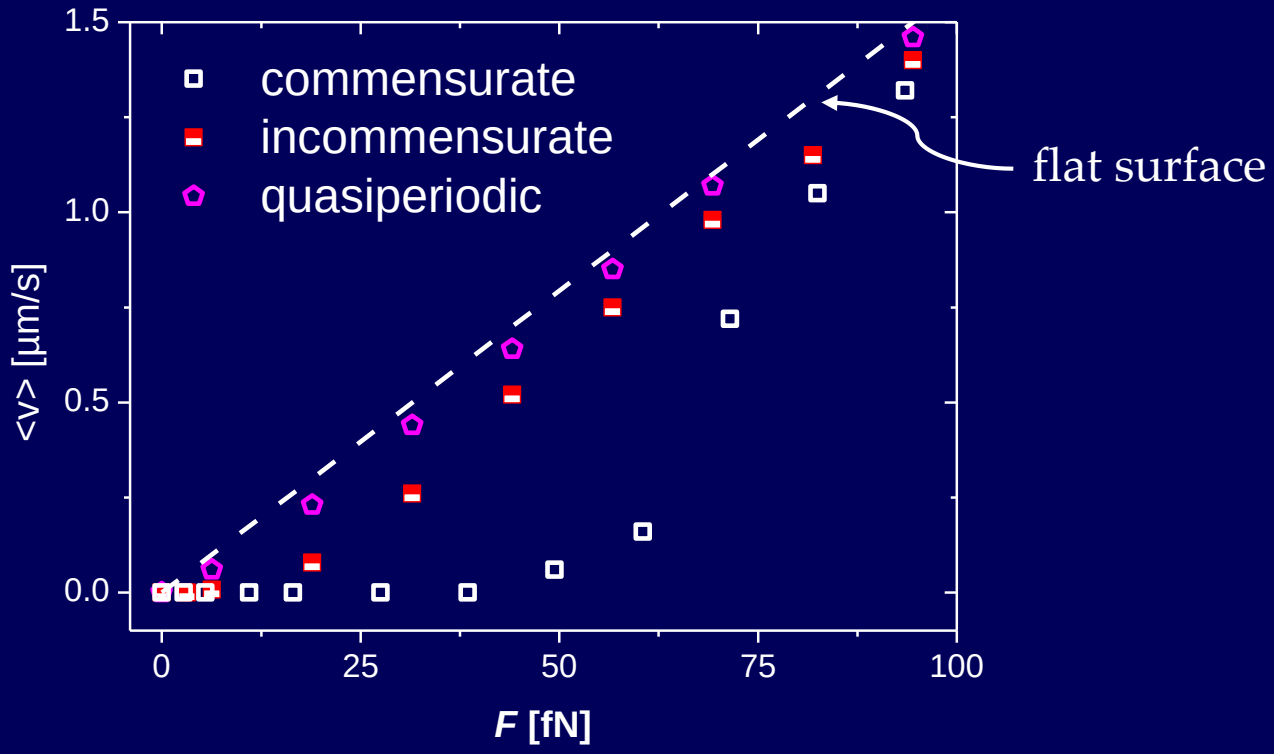




Ledieu, Reid, Smerdon, Diehl, Lograsso, Ross, McGrath PRL 13, 92 (2004)

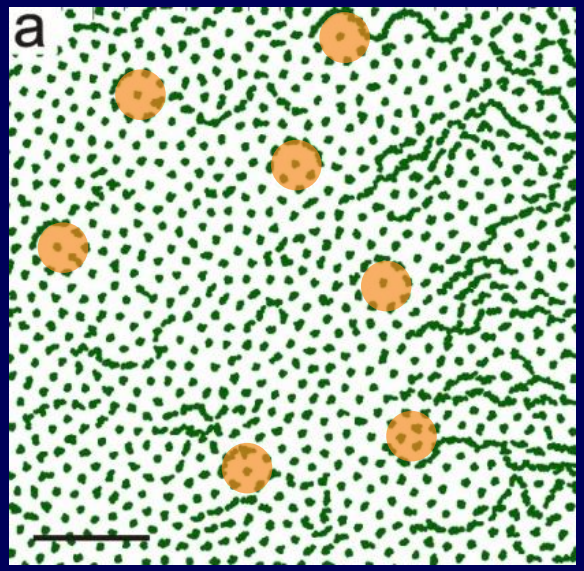
⟹ Fibonacci sequence of Cu rows but <u>no atomic resolution within rows</u>

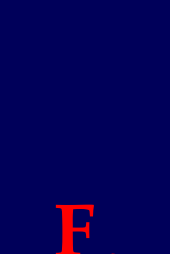
Friction on QC substrates

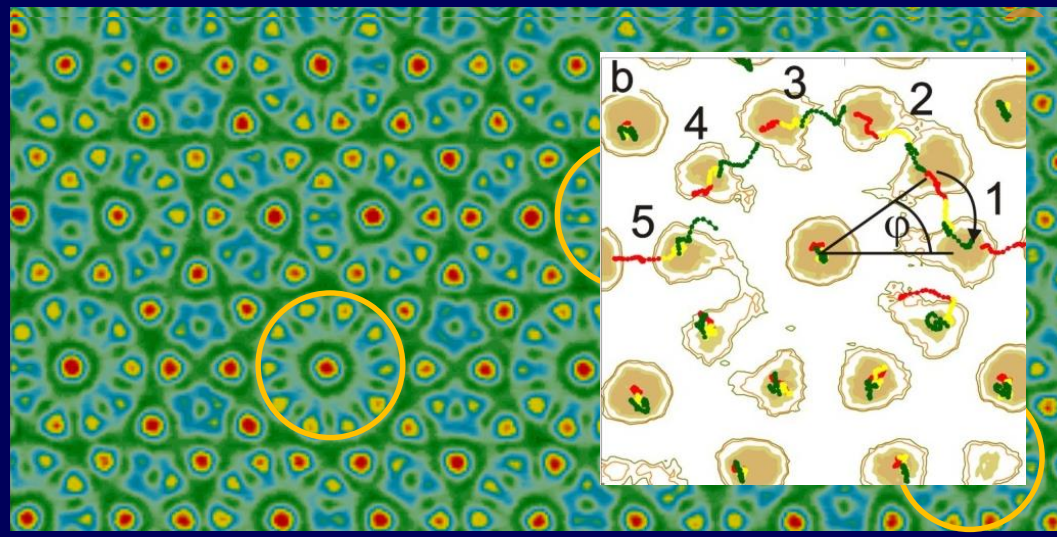


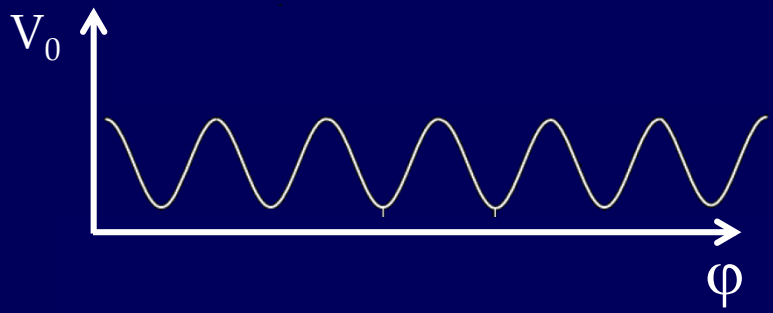
Vanishing static friction: superlubric sliding

Friction mechanism on QC surfaces?





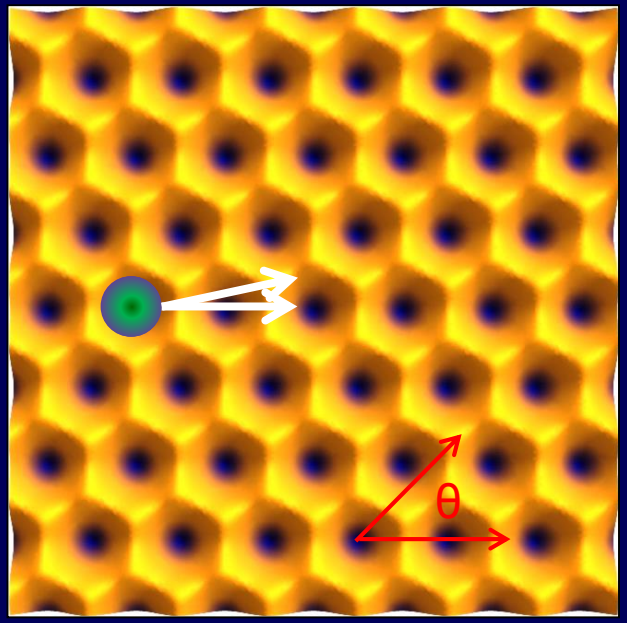


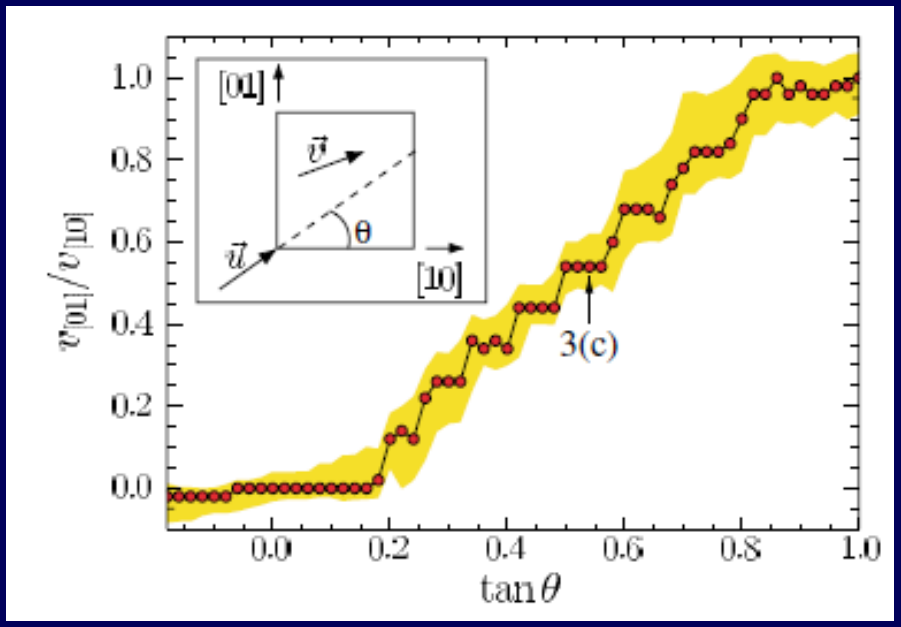


local kinks on QC surfaces at HSS
high density of HSS → small friction

Bohlein, Mikhael & Bechinger, *Nature Materials* ***11, 126 (2012).***

Variation of Pulling Direction: Directional Locking





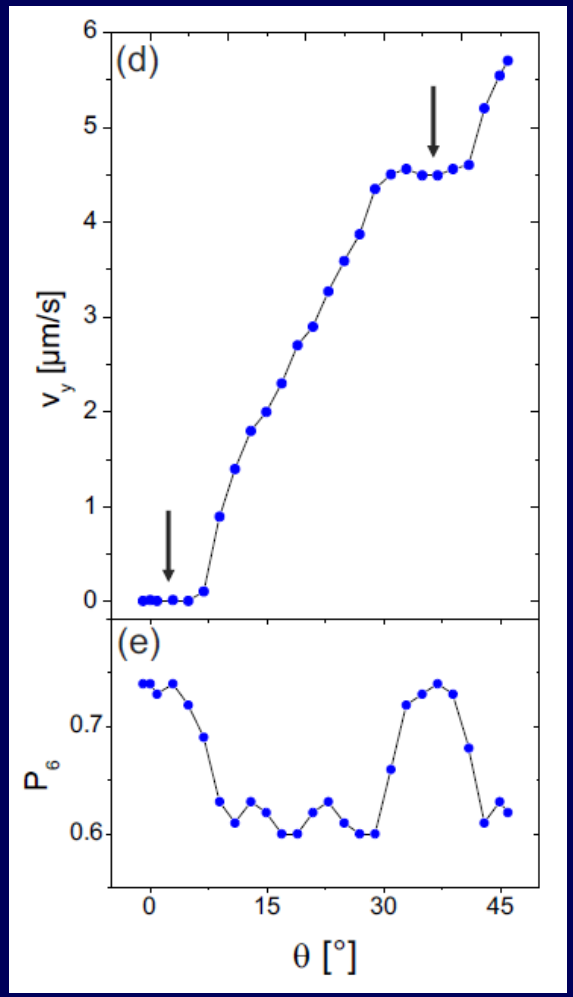
Korda et al, PRL **82** (1999)

- atom migration on crystalline lattices
- flux flow in type II superconductors

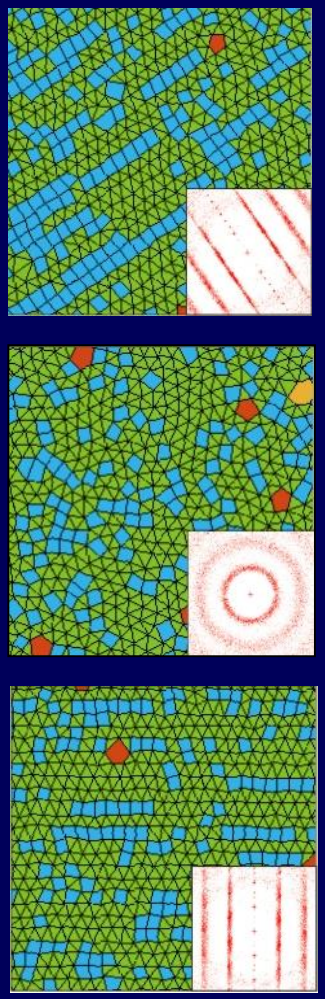
Directional locking on quasiperiodic surfaces ?
Influence of particle – particle interactions ?

Directional Locking on QC surfaces

colloidal liquid on QC surface



Bohlein, Bechinger, PRL **109, 058301 (2012).**



36° **Smectic**

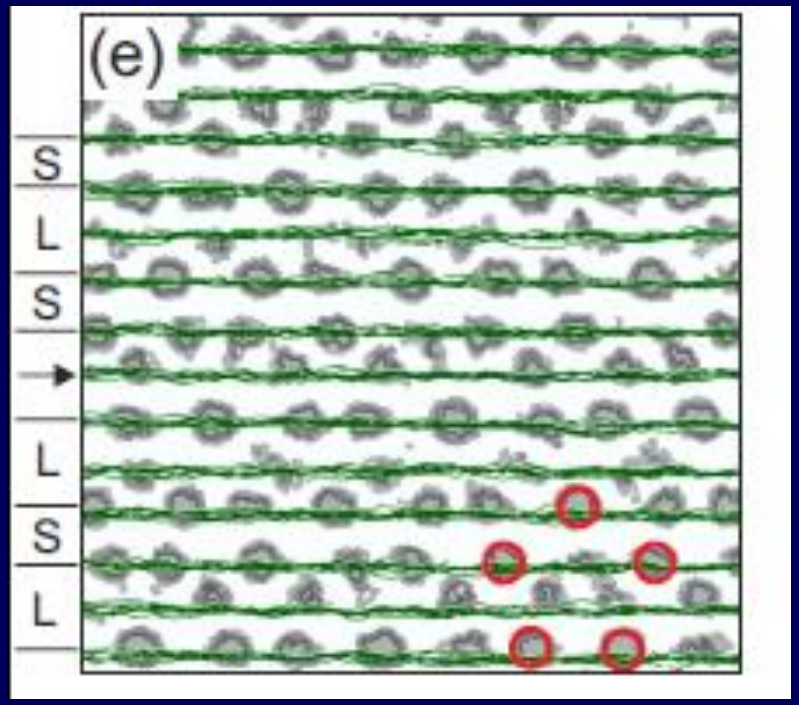
20° **Disordered**

0° **Smectic**

Dynamical ordering !

Reichhardt et al. PRL **106**, 060603 (2011)

Origin of Dynamical Ordering

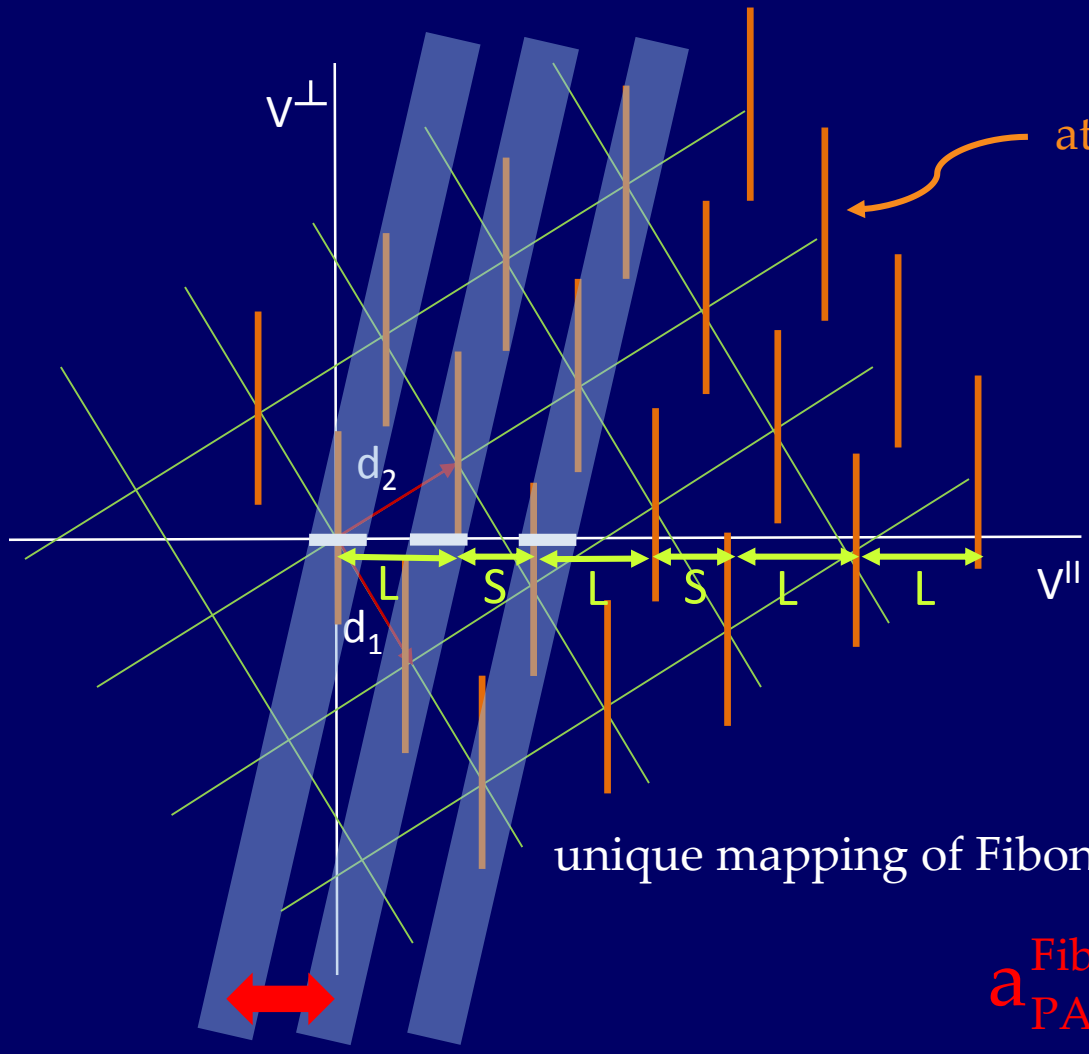


equidistant line spacing !!!!

Link between periodic and quasiperiodic order ?

Periodic average structures (PAS)

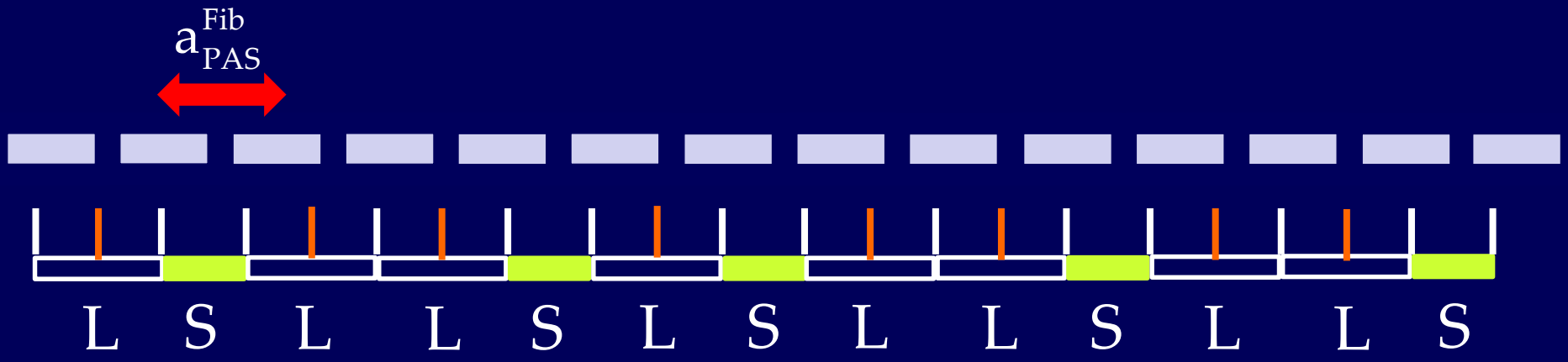
Steurer, Haibach, *Acta Crystallographica A* ***55, 48 (1999)***



unique mapping of Fibonacci sequence to periodic structure

$$a_{PAS}^{Fib} = (3-\tau)S$$

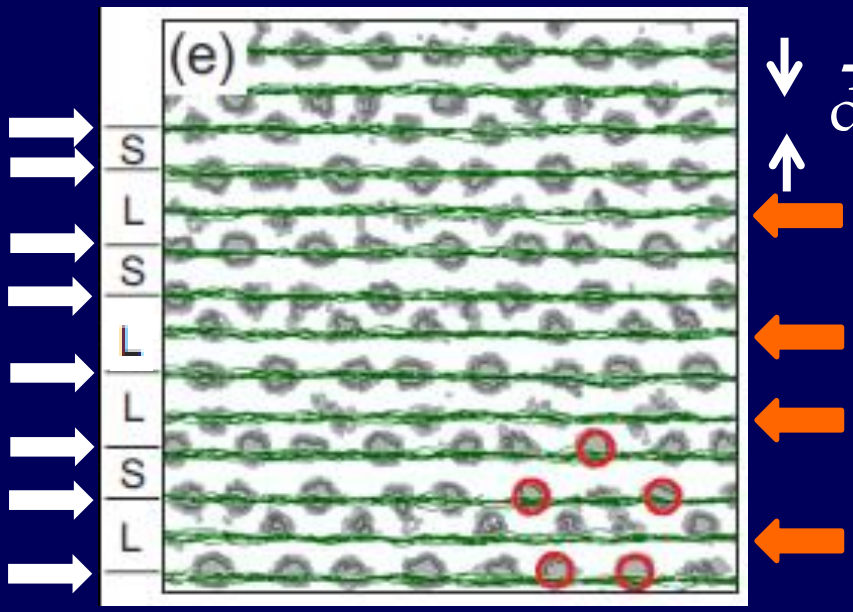
Periodic average structures (PAS)



$$a_{PAS}^{Fib} = (3-\tau)S$$

$$a_{PAS}^{mod} = (3-\tau)\frac{S}{\tau}$$

Driving-force induced PAS



$\bar{d} = 6.4\mu m = a_{PAS}^{mod}$

Fibonacci lines

Interstitial lines

Dynamically ordered phase = periodic average structure

Summary

- *Experimental realization of the FK-model at mesoscopic length scales*
- *Direct observation of kinks/antikinks*
- *Kinks/antikinks not limited to periodic surfaces → quasiperiodic order*
- *Sliding can enhance order in ML: Dynamically ordered states, PAS*

Outlook

- *dependence of friction force on contact size/shape*
- *short vs. long-ranged particle interactions (width & shape of kinks)*
- *Aubry transition (superlubric sliding state)*
- *creeping*

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