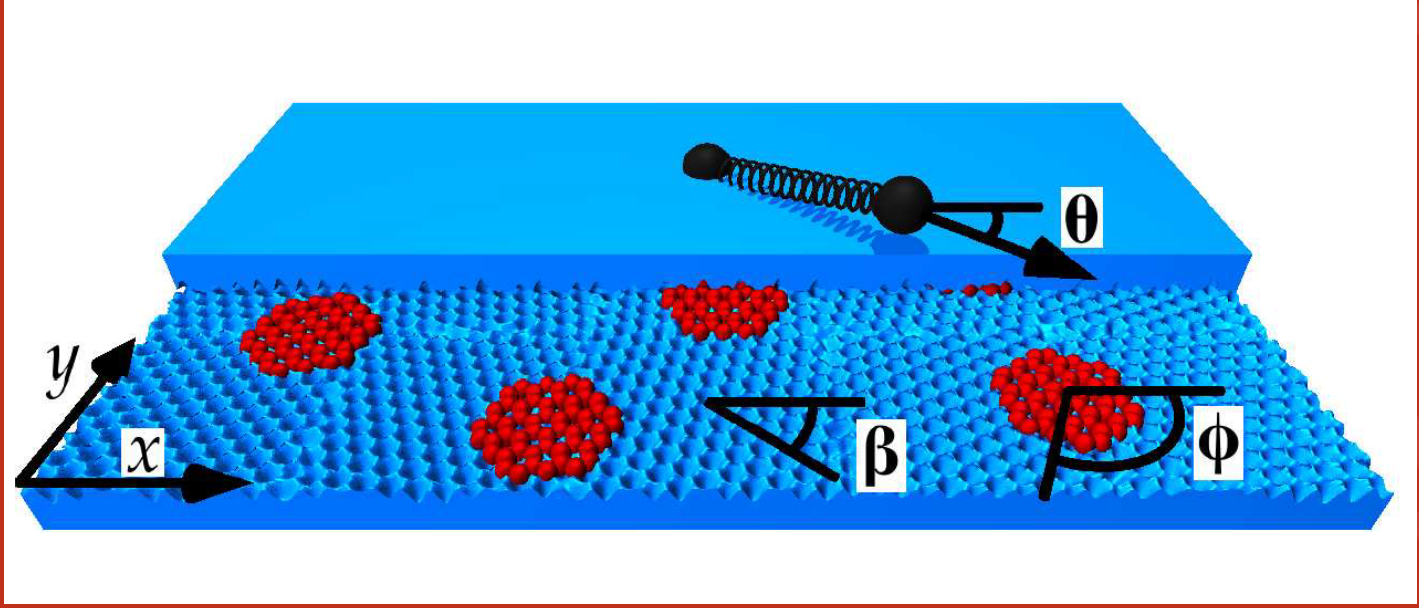
Low friction and rotational dynamics of crystalline flakes in solid lubrication

Astrid S. de Wijn, Annalisa Fasolino, Alexander Filippov and Michael Urbakh

Nijmegen, Donetsk, Tel Aviv



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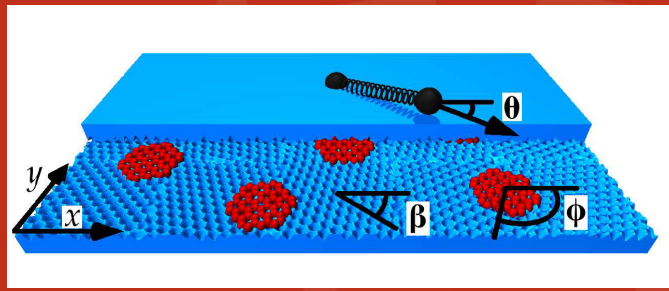
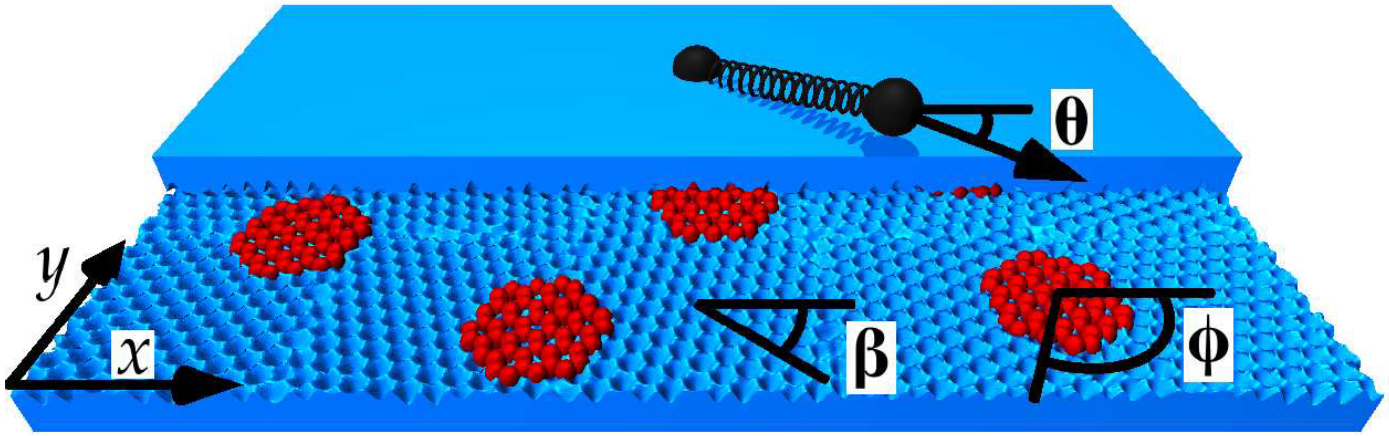
- importance of rotational dynamics
- flakes on a surface
- flakes between plates: model of solid lubrication
- low friction cases
- friction drop at low temperature



Minimal model of lubrication

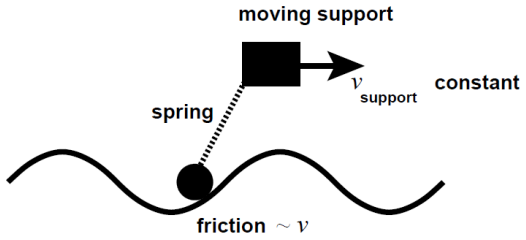
large number of graphene or graphite flakes
between moving graphite plates



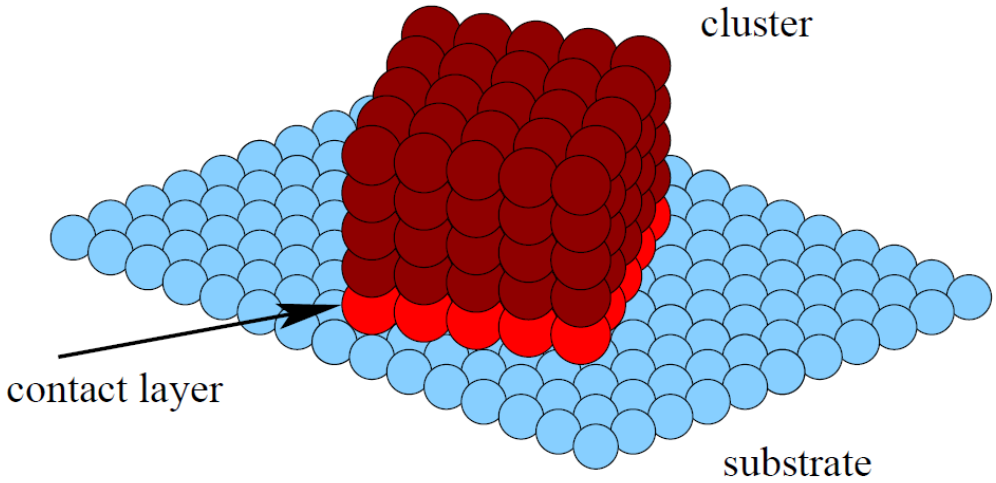
What happens to orientation of lubricant flakes?

Friction of sliding nanoscrystals

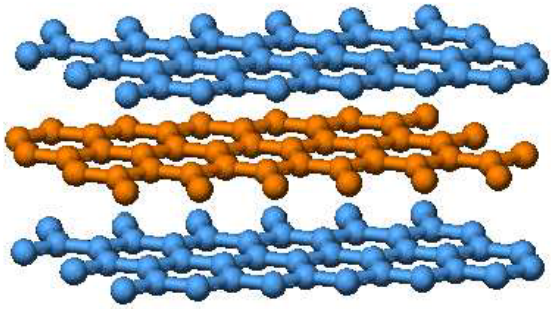
- beyond Tomlinson model

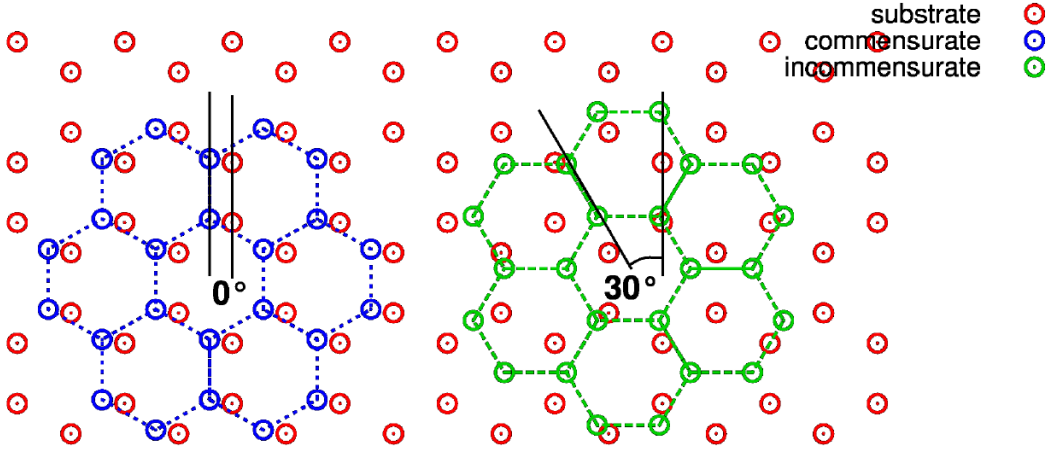


- small extended contact layer
- interaction affected by lattice geometries
- Incommensurability reduces friction : superlubricity



hexagonal symmetry: graphite flakes on a surface





AFM exp. + theory

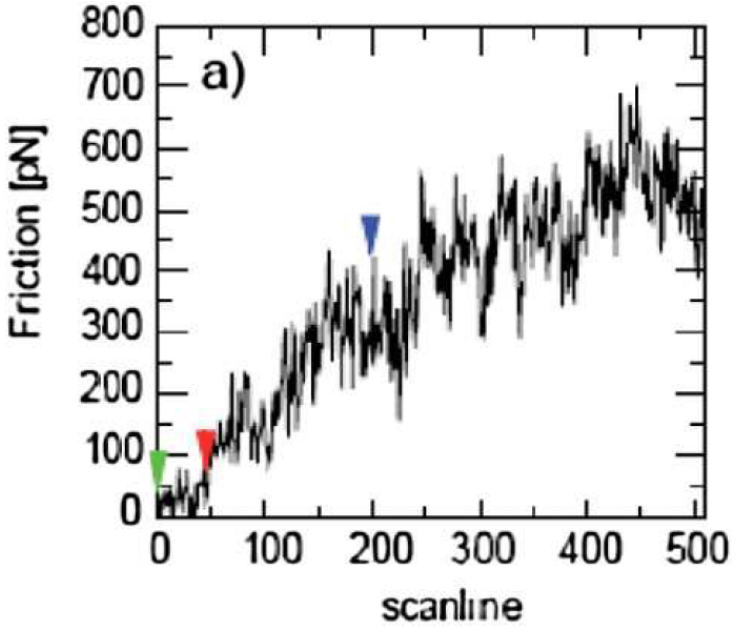
Dienwiebel et al. PRL 2006

Filippov et al. PRL 2008

flake (≈ 100 atoms)

temporary superlubricity

flake rotates from incommensurate to commensurate contact



flake rotation

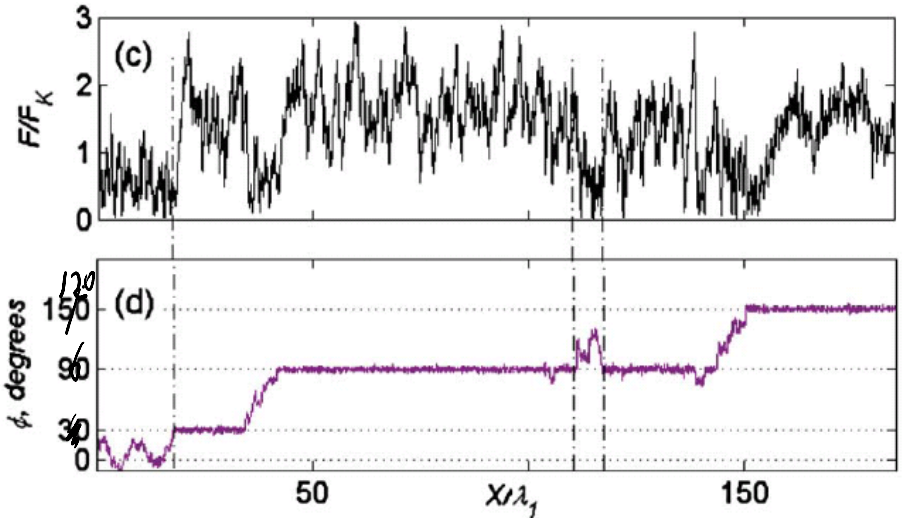
PRL 100, 046102 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

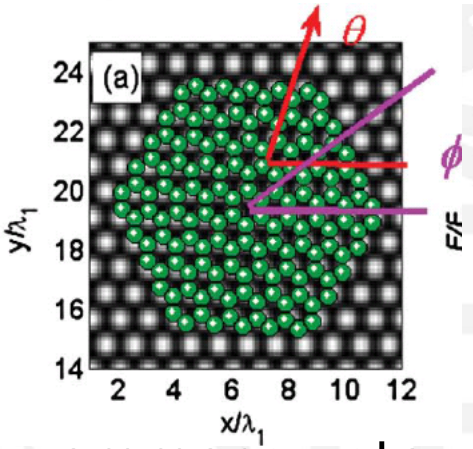
Torque and Twist against Superlubricity

Alexander E. Filippov,[1] Martin Dienwiebel,[2,3] Joost W. M. Frenken,[2] Joseph Klafter,[4] and Michael Urbakh[4]

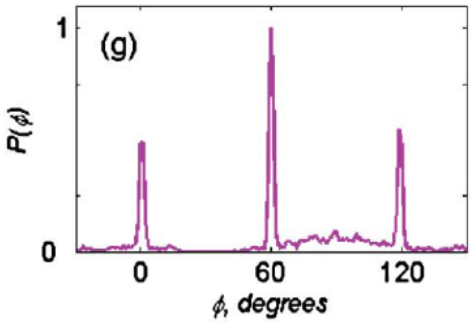
Simulations

- 2D motion V(x,y), hexagonal substrate
- substrate as heat bath: Langevin simulations
- flake driven at v=30 nm/s



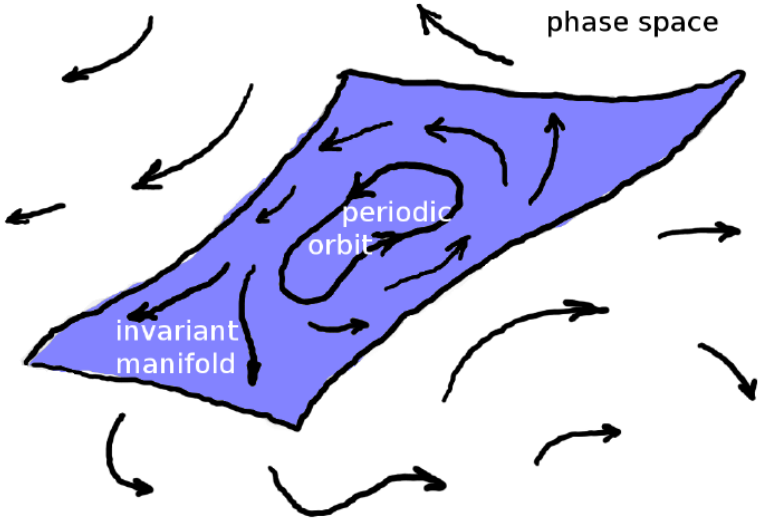


Mostly in commensurate orientation



Finding periodic orbits

dynamical systems theory: periodic orbits lie on invariant manifolds (manifolds in phase space that are mapped onto themselves)



$$v_x = \dot{x} \ ,$$

$$M\dot{v}_x = -\frac{\partial V(x,\phi)}{\partial x} - c(x - v_{st} - x_{s\,0}) - \gamma M v_x \ ,$$

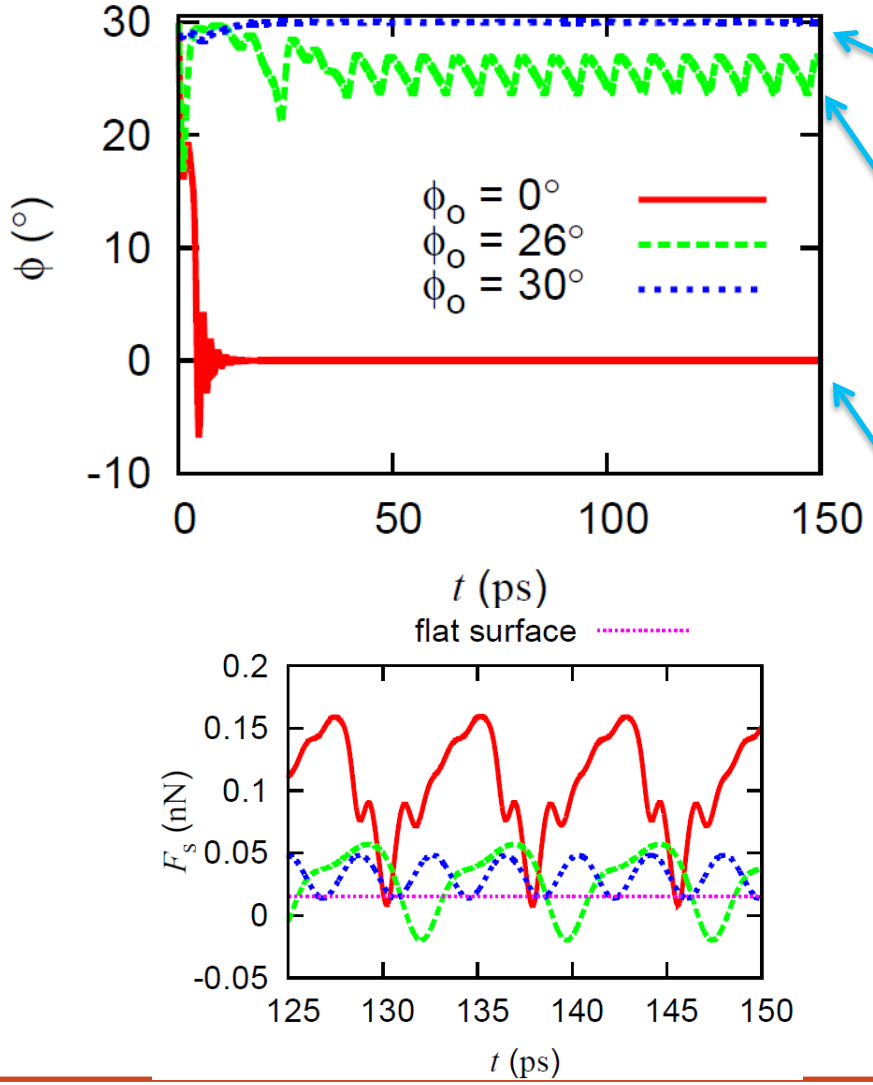
$$\dot{\phi} = \omega \ ,$$

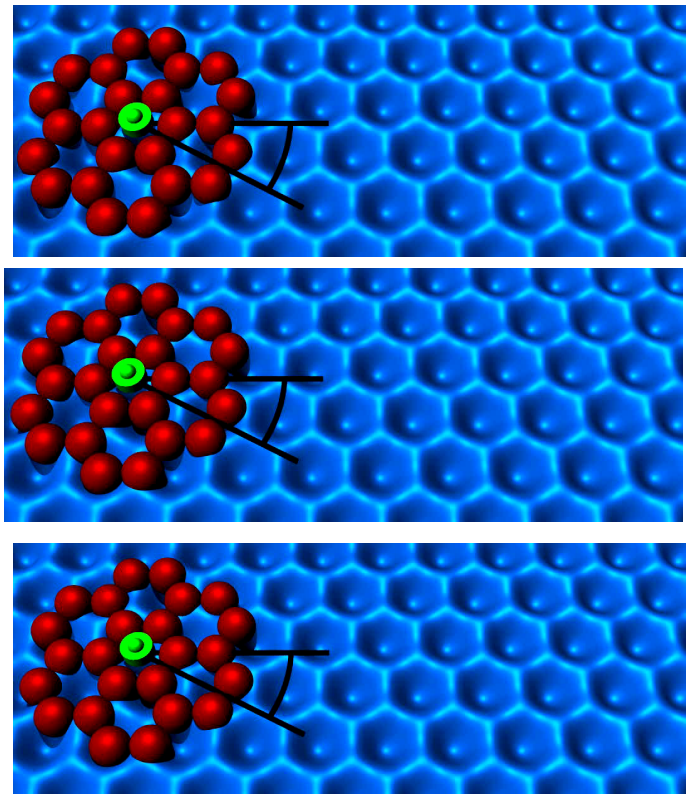
$$I\dot{\omega} = -\frac{\partial V(x,\phi)}{\partial \phi} - \gamma I \omega \ .$$

invariant manifolds are
$\phi = \phi_0,\ \omega = 0$, no torque

A.S. De Wijn, C. Fusco, A. Fasolino Phys. Rev. E **81**, 046105 (2010)

Can superlubricity survive?

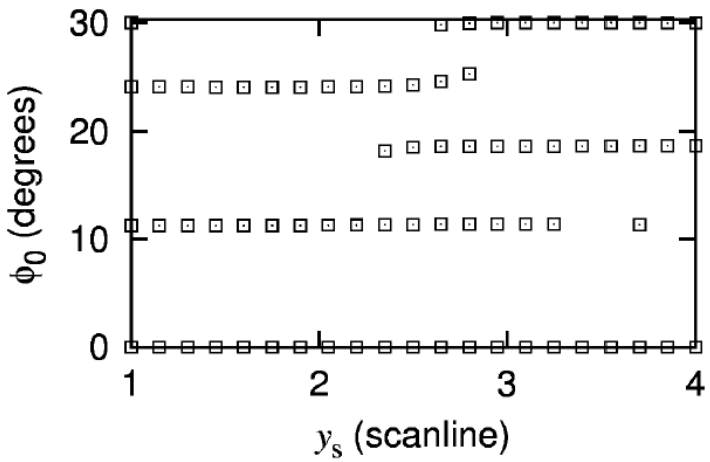


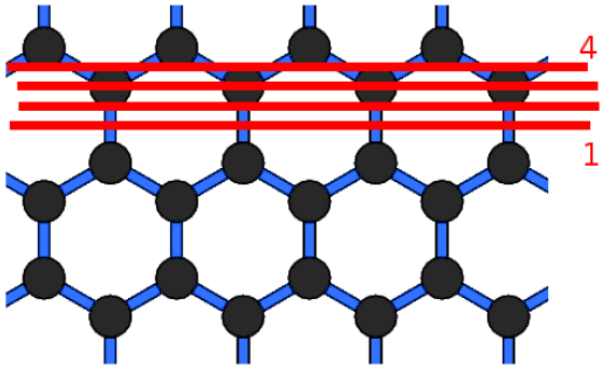


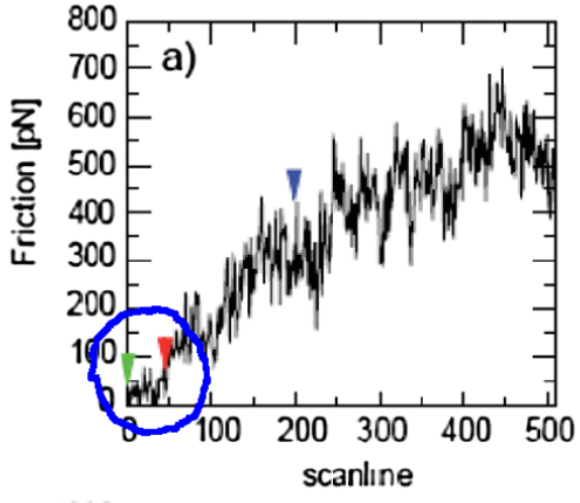
- high friction commensurate
- low friction incommensurate
- approximately constant orientation
  depends on initial conditions
- converges within few lattice periods

Varying scanning line on graphite

bifurcation diagram of 96-atom flake







- decay in experiments ($N \approx 96$) about 40 scan lines
- change of scan line
  $\Rightarrow$ flake forced to rotate
  after scanning 25 to 50 lines

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real life : high friction

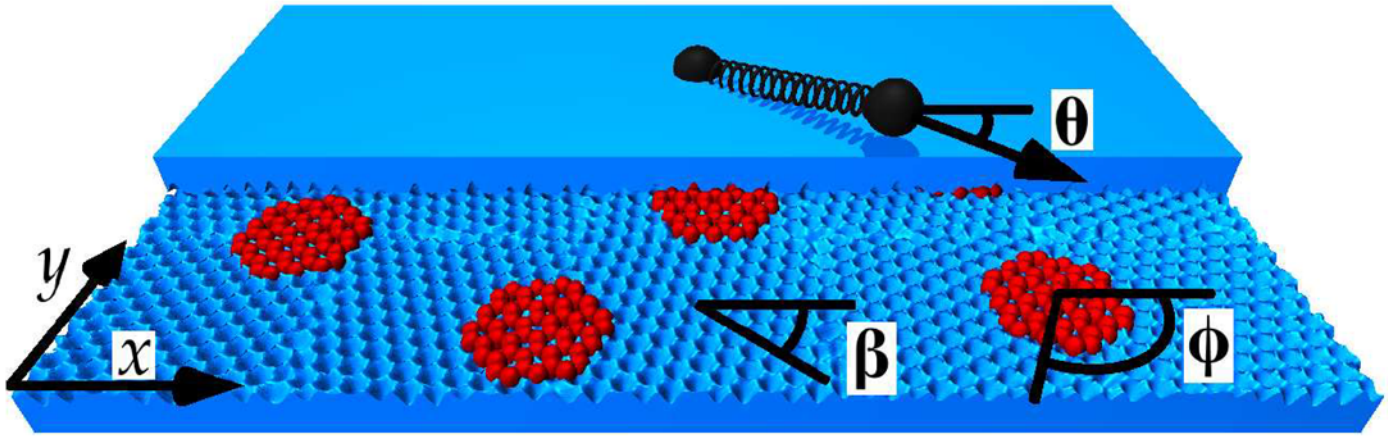
- Periodic incommensurate orbits are not robust against thermal fluctuations particularly for hexagonal lattices and weak potential corrugation

rotations destroy low friction sliding

- Other geometries (square lattices) more promising
  (A.S. de Wijn, A. Fasolino Trib. Lett. 39,91 (2010)

Is there a way to enhance stability of incommensurate low friction sliding?

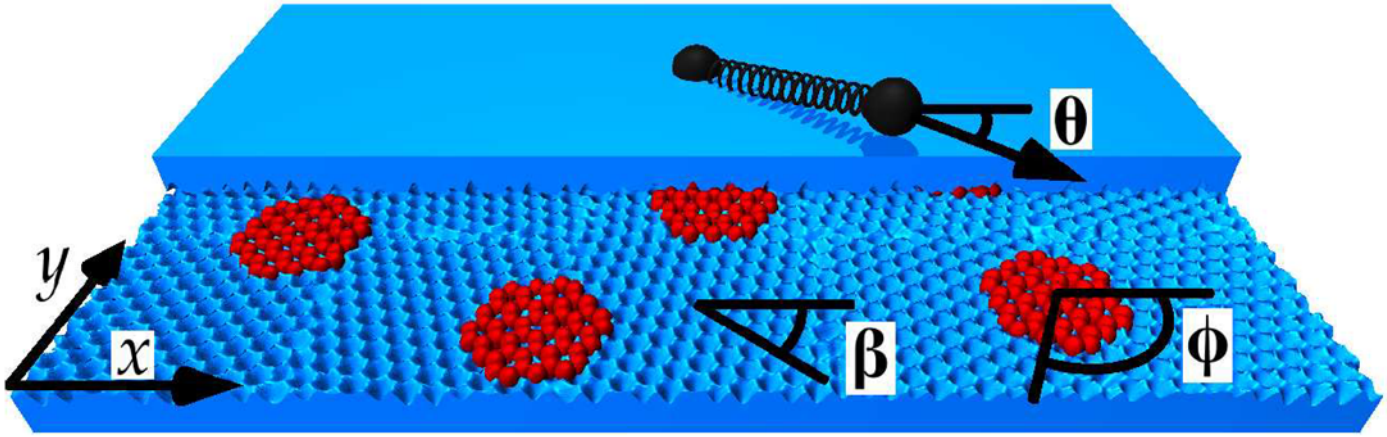
solid lubrication with random domains



mobile flakes between two plates

- unless plates are commensurate flakes cannot be commensurate with both -> low friction
- holds also for plates with random domains
- patched graphene surfaces of large dimensions are currently produced
- patched surfaces could result from wear of flakes that get pinned to the plates

solid lubrication: MD simulations



- top plate driven by support moving at constant velocity
- ensemble of flakes at all initial orientations
- rigid rotating flakes, rigid substrate potential
- Langevin temperature control, variable load

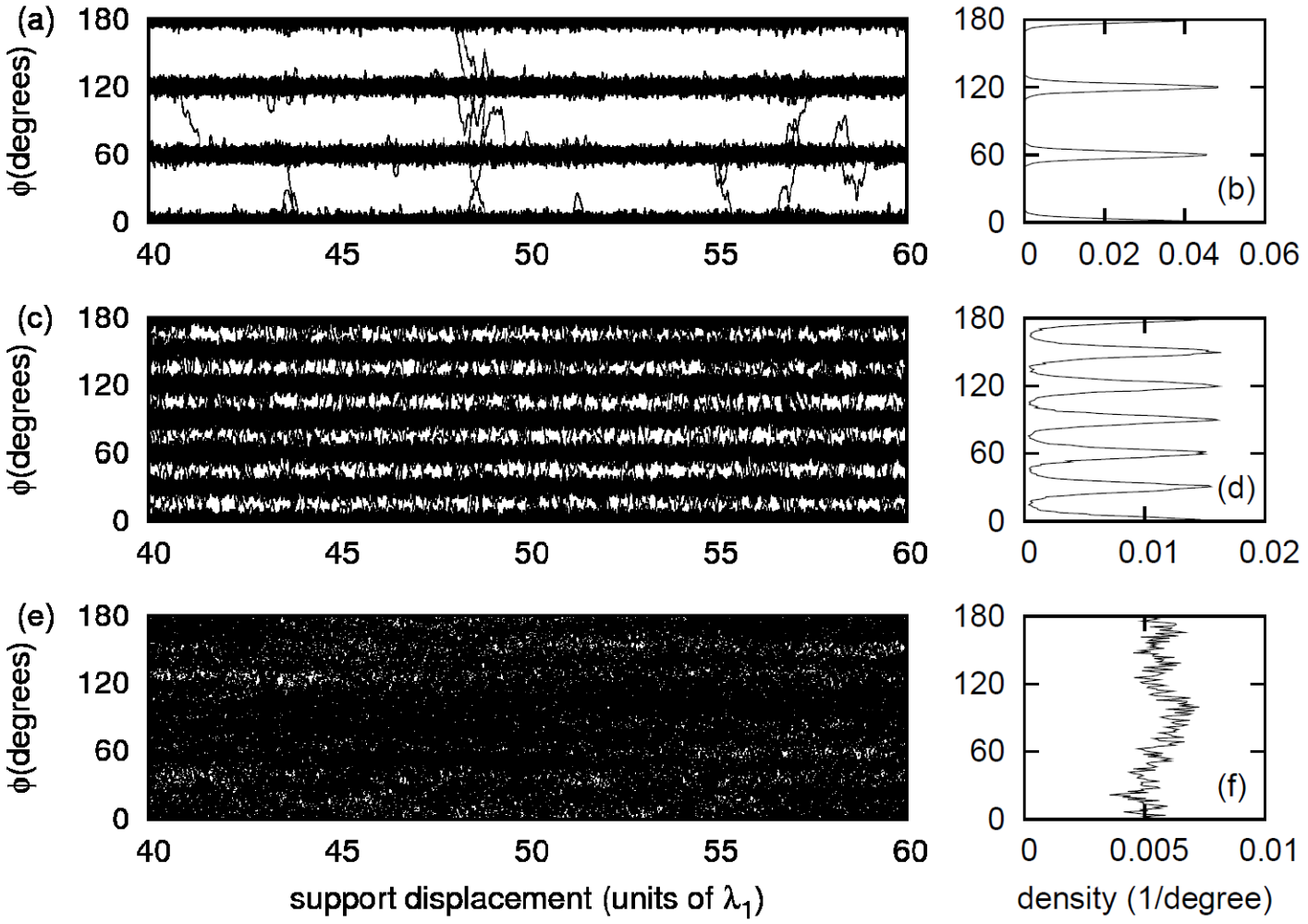
flake orientations

Plates:

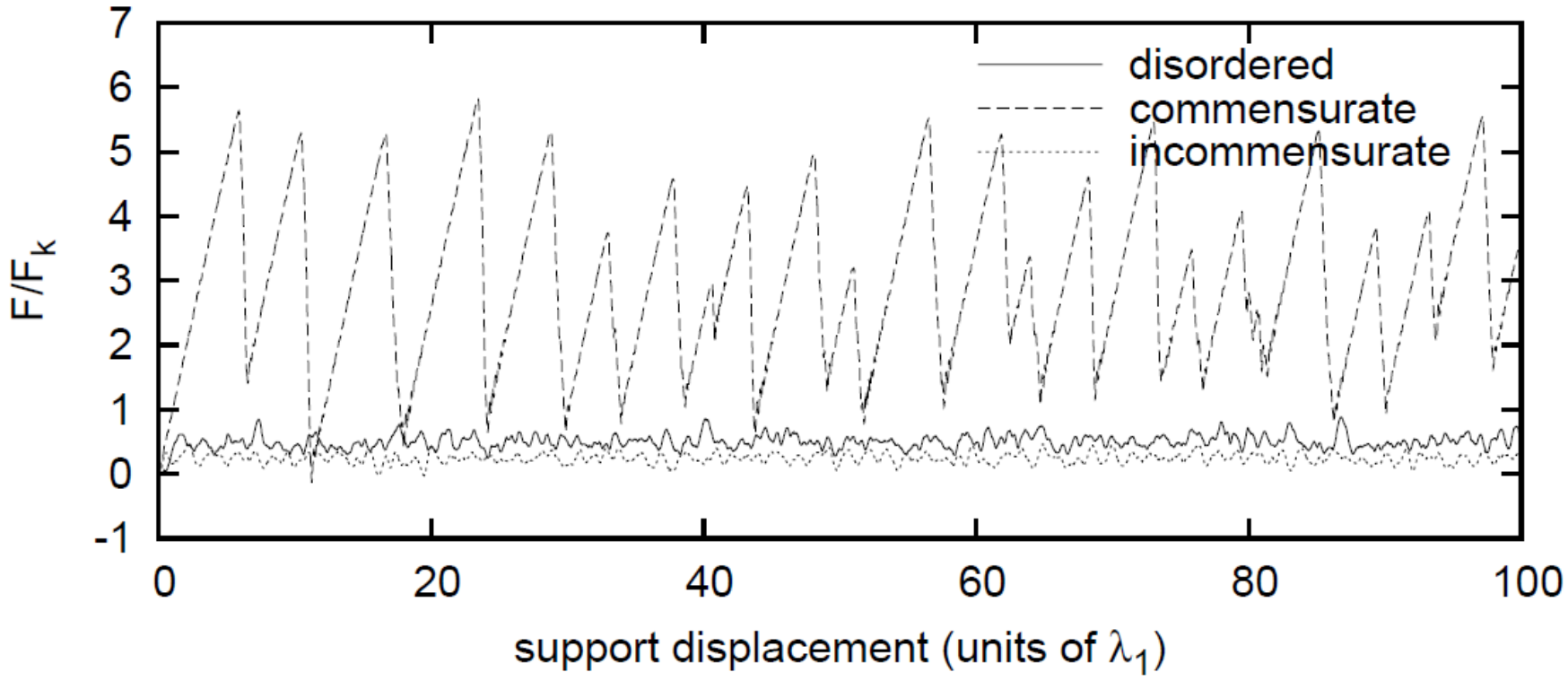
comm.

incomm.

patched

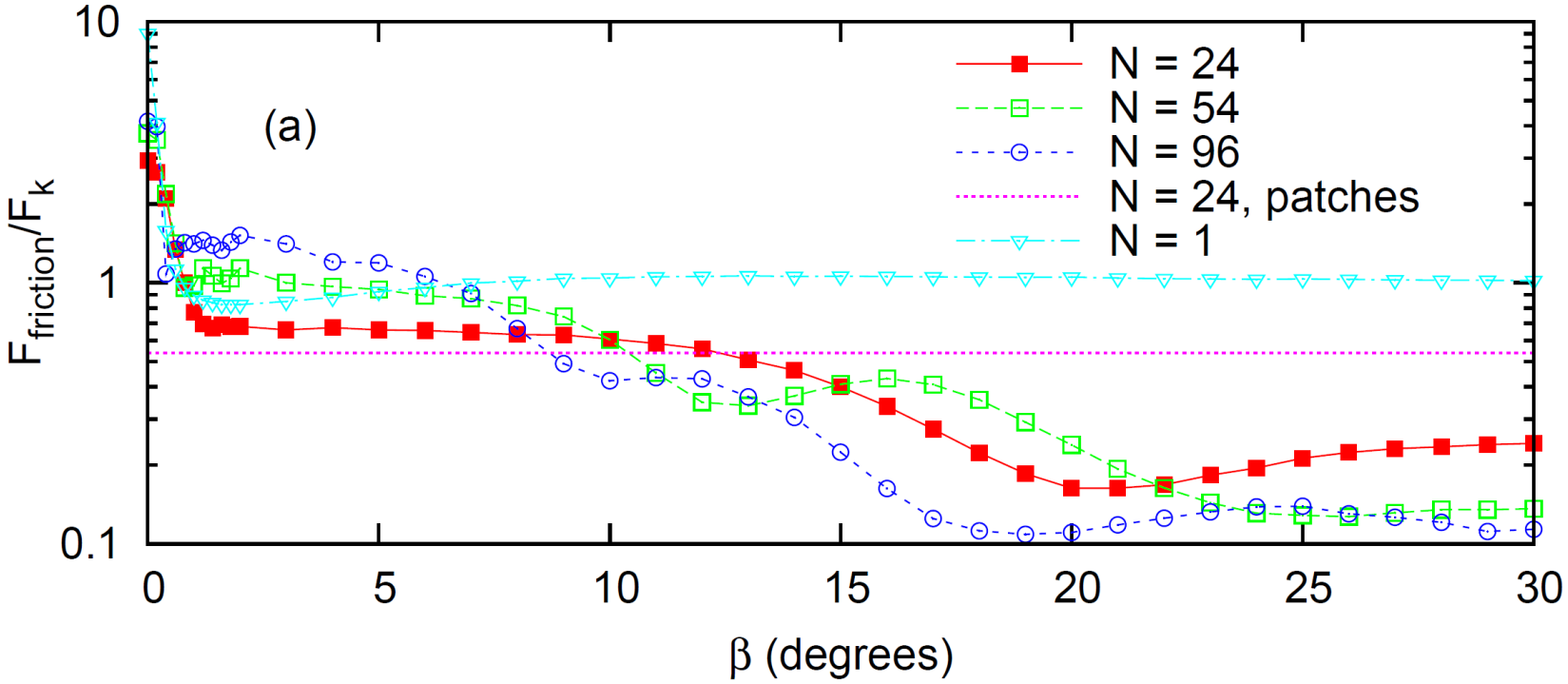


Low friction



- Stick slip (high friction) only for commensurate plates
- Similar friction for infinite incommensurable plates and for plates with domains

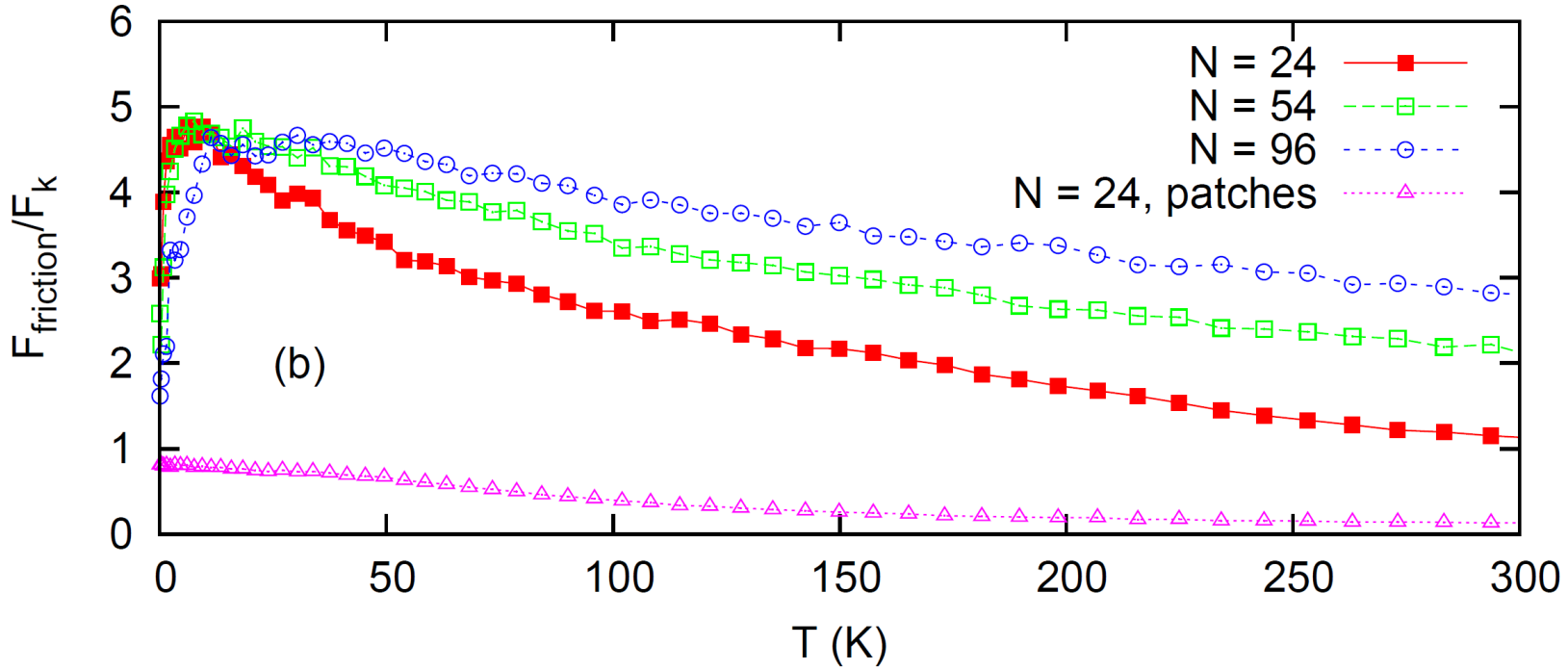
Dependence on relative plate orientation



Comparison of average friction of monodomain plates at an angle β (with rotating flakes in between) with that of patched plates (average orientation)

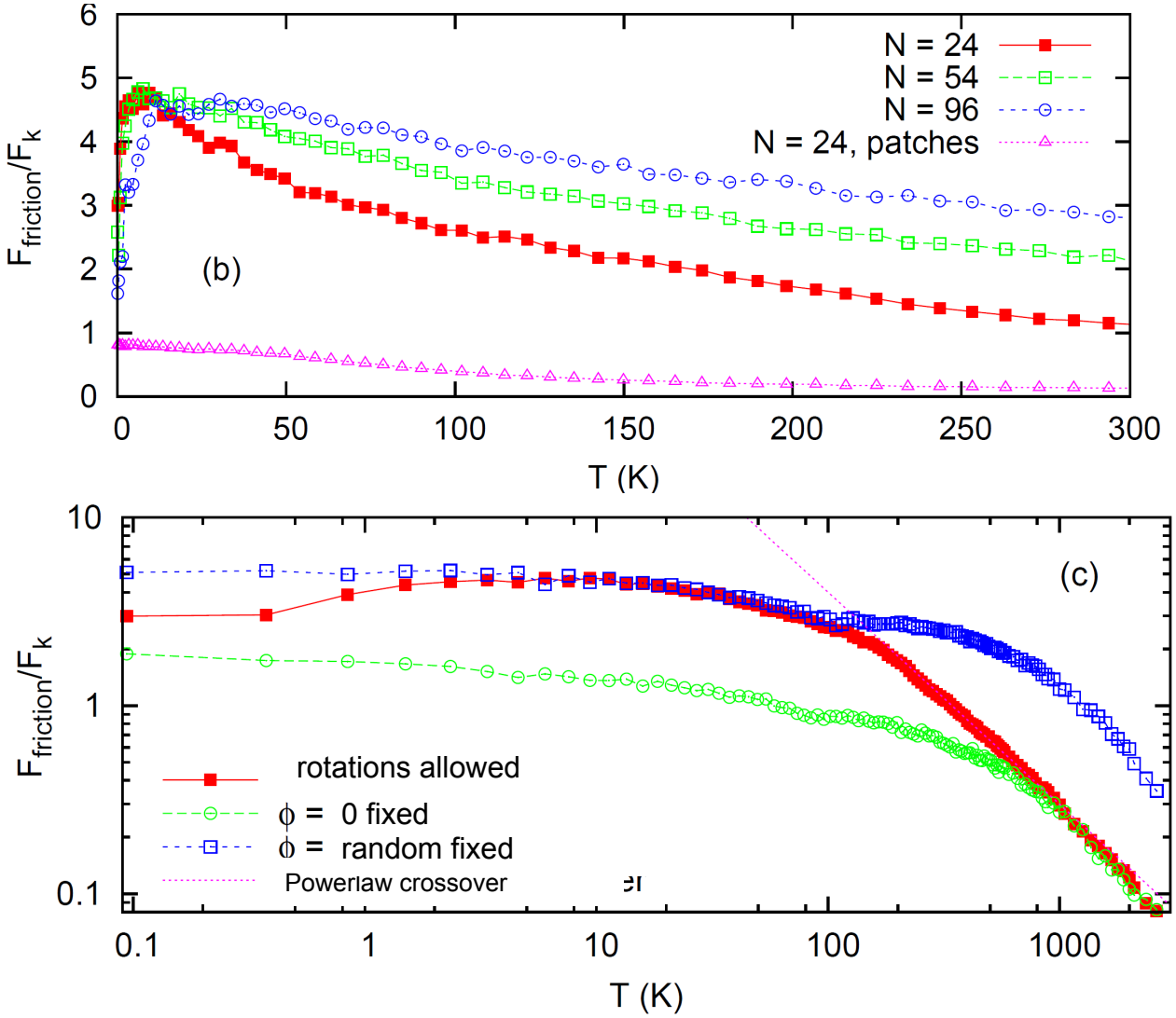
temperature dependence of friction

worst possible case: commensurate plates

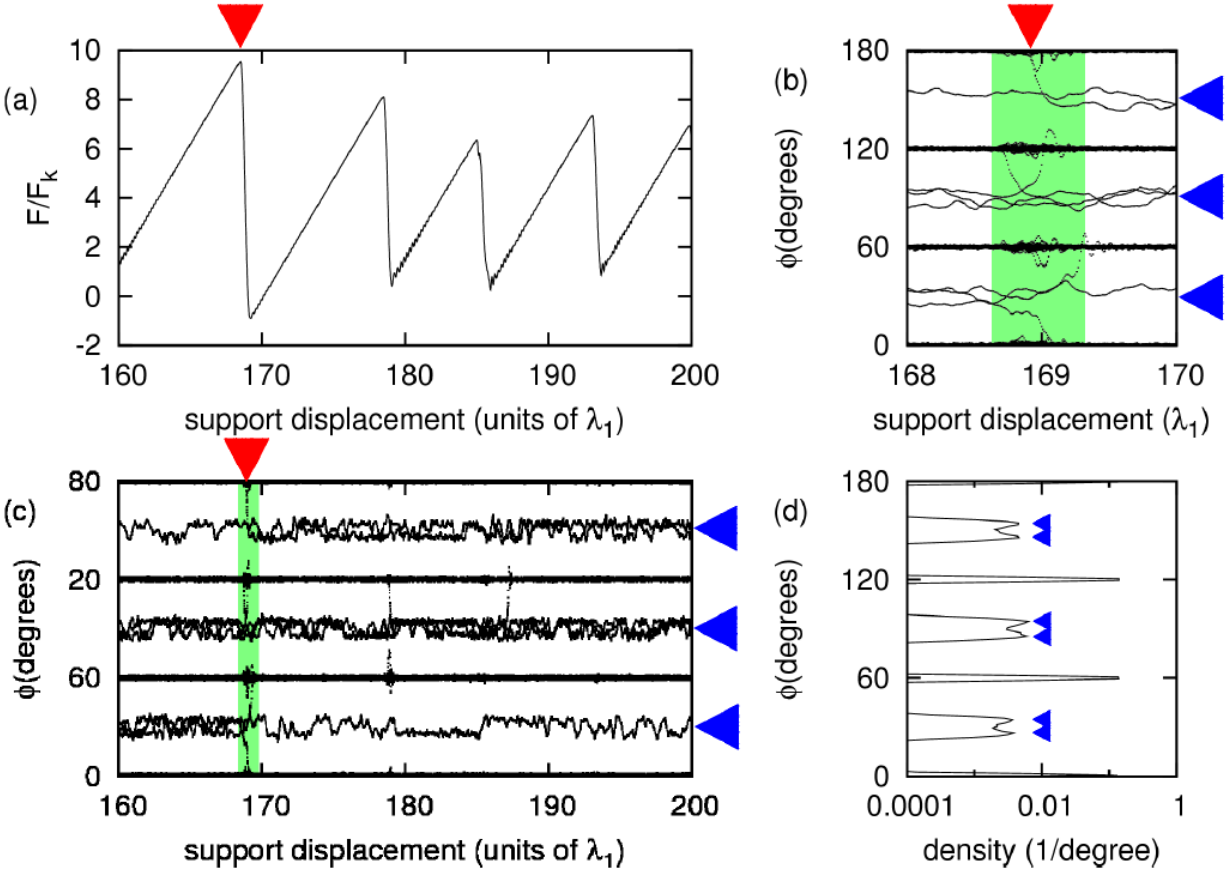


- Tomlinson: friction decrease at high temperature
- but also at low T !

temperature dependence



incommensurate orbits at low T



- energy released during slip
- flakes rotate, activating incommensurate trajectories
- survive at low temperature
- ⇒ low friction
- "low" might be room temperature under the right conditions

summary and conclusion

- model of solid lubrication: many rotating flakes between moving plates
- even if simplified, model include main mechanism for friction of flakes on a single surfaces
- no need for ordered surfaces at incommensurate contact to achieve low friction
- incommensurate orbits can lead to low friction at low temperature also for commensurate plates
- patched graphene surfaces of large dimensions are currently produced
- patched surfaces could result from wear of flakes that get pinned to the plates

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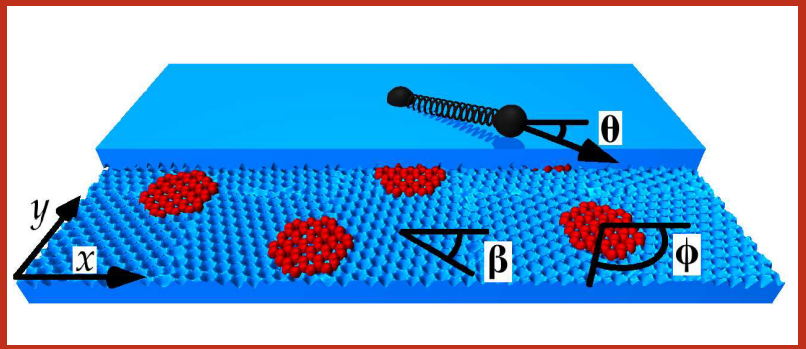

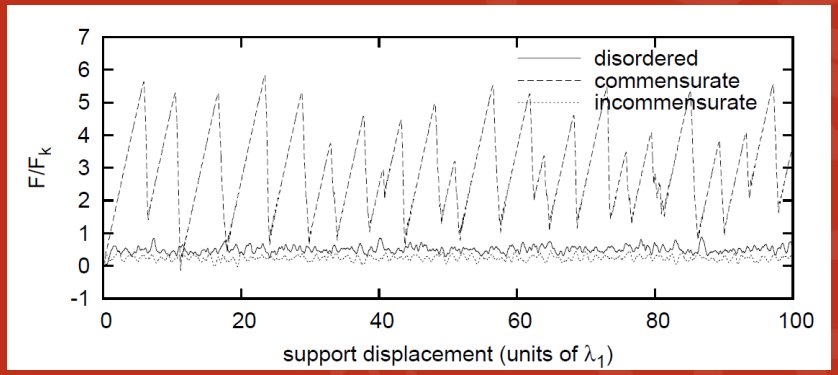

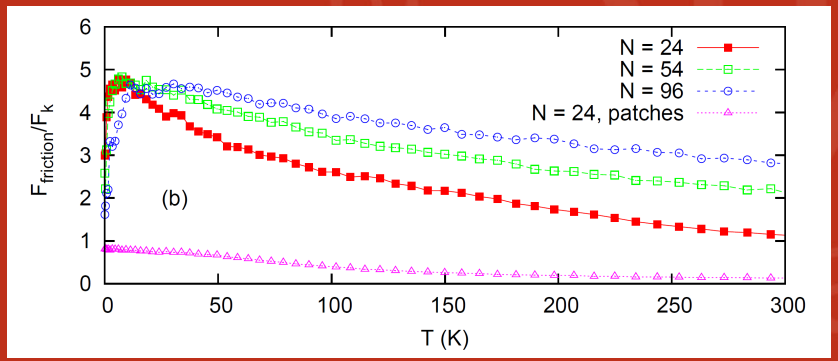

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