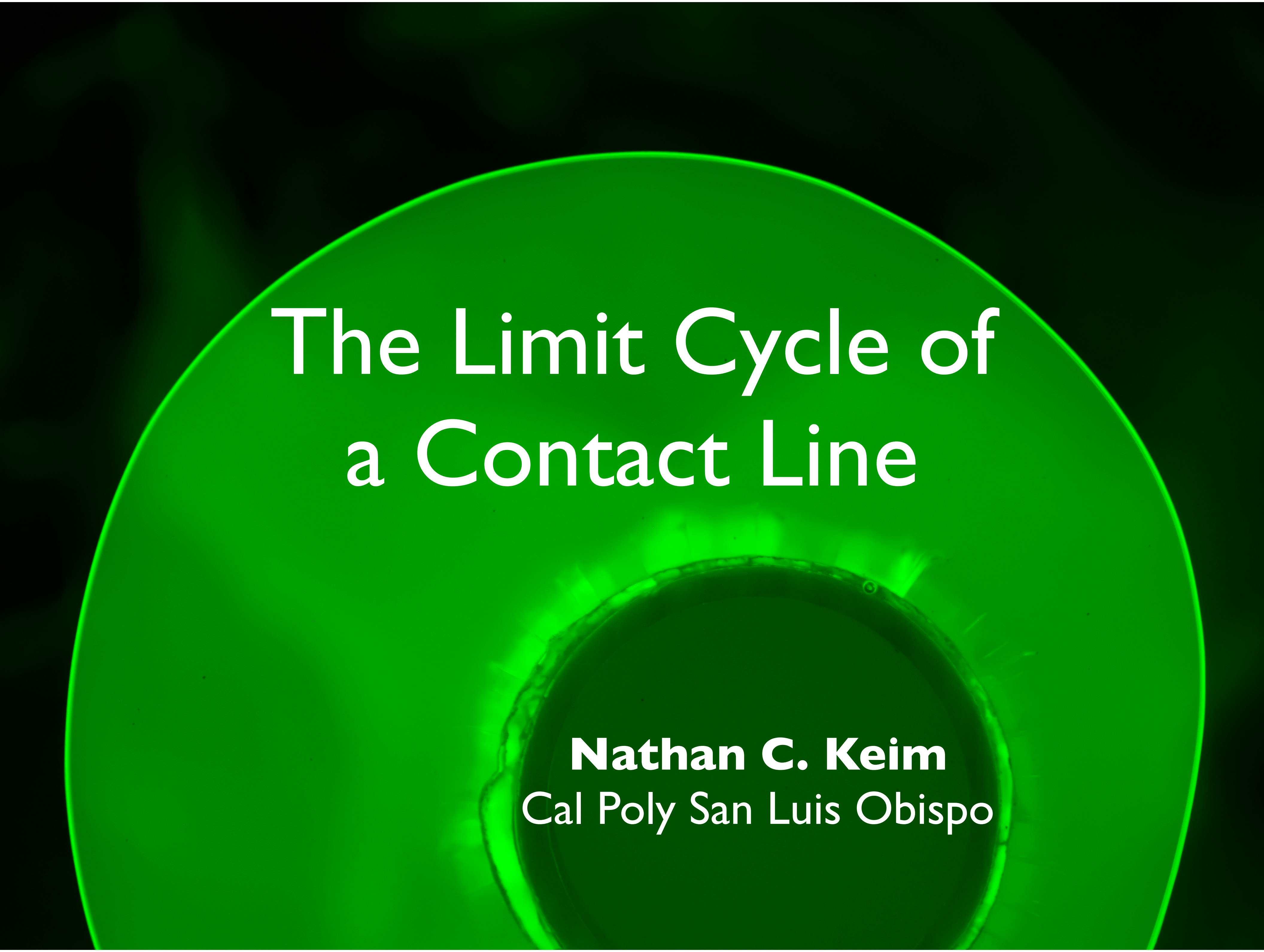
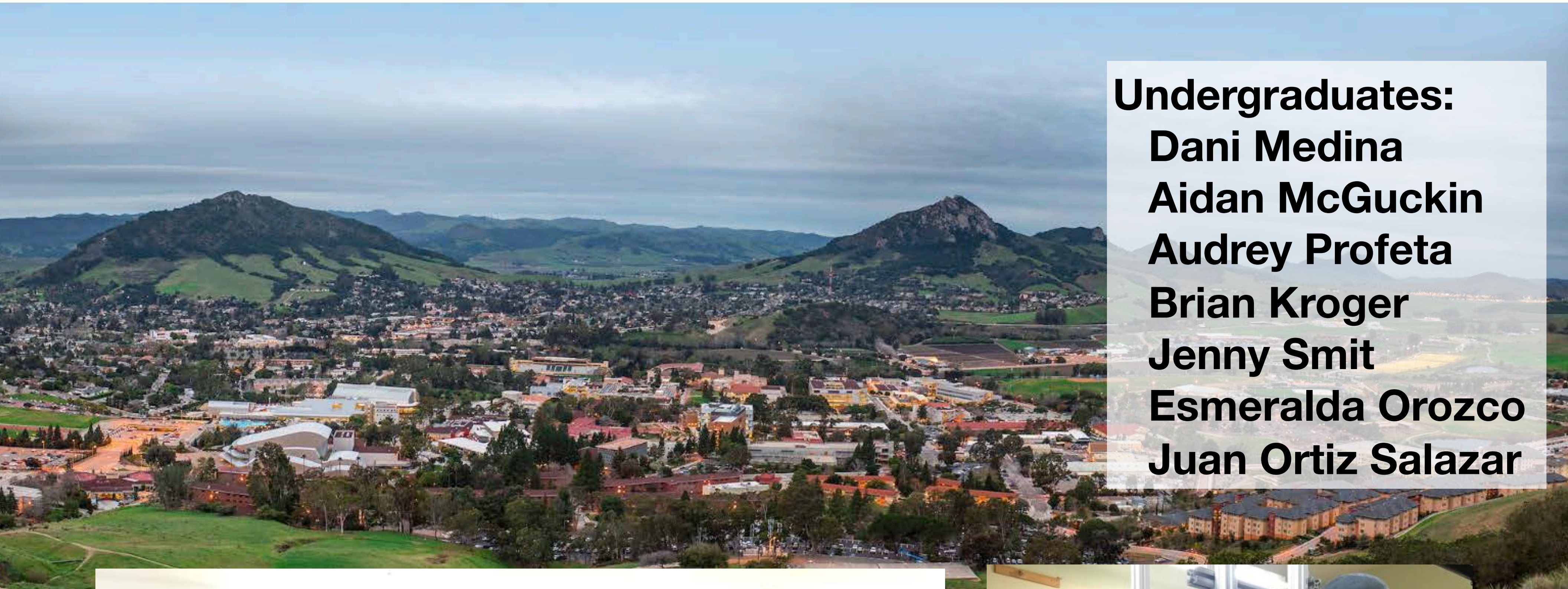


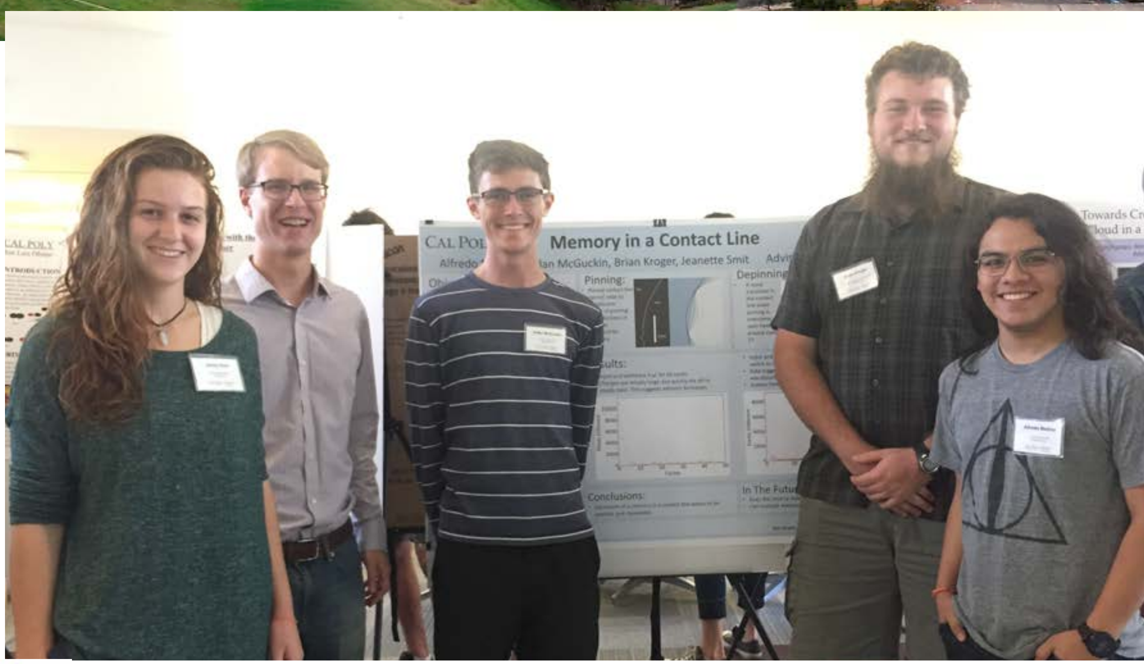
# The Limit Cycle of a Contact Line

**Nathan C. Keim**
Cal Poly San Luis Obispo



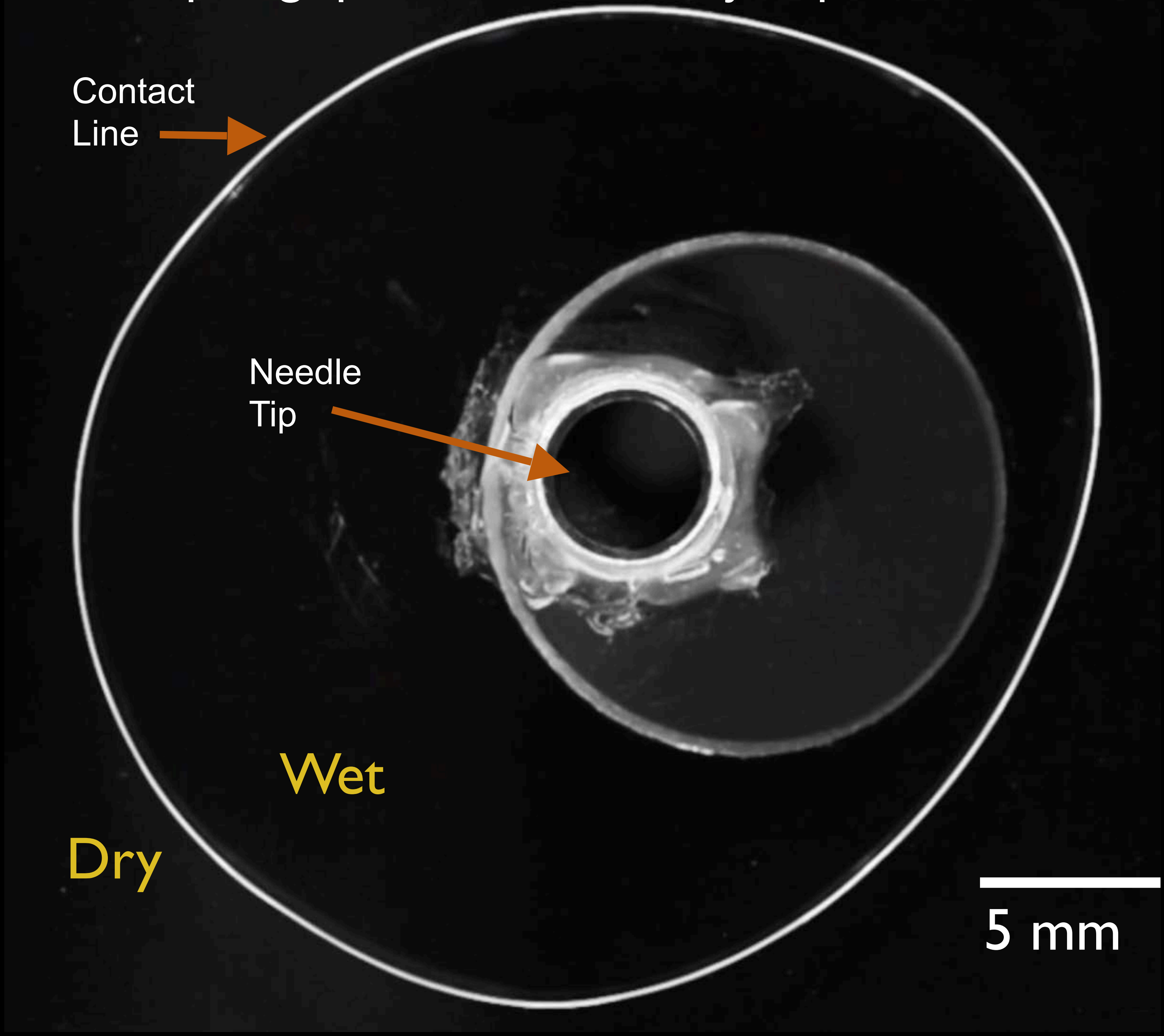
**Undergraduates:**

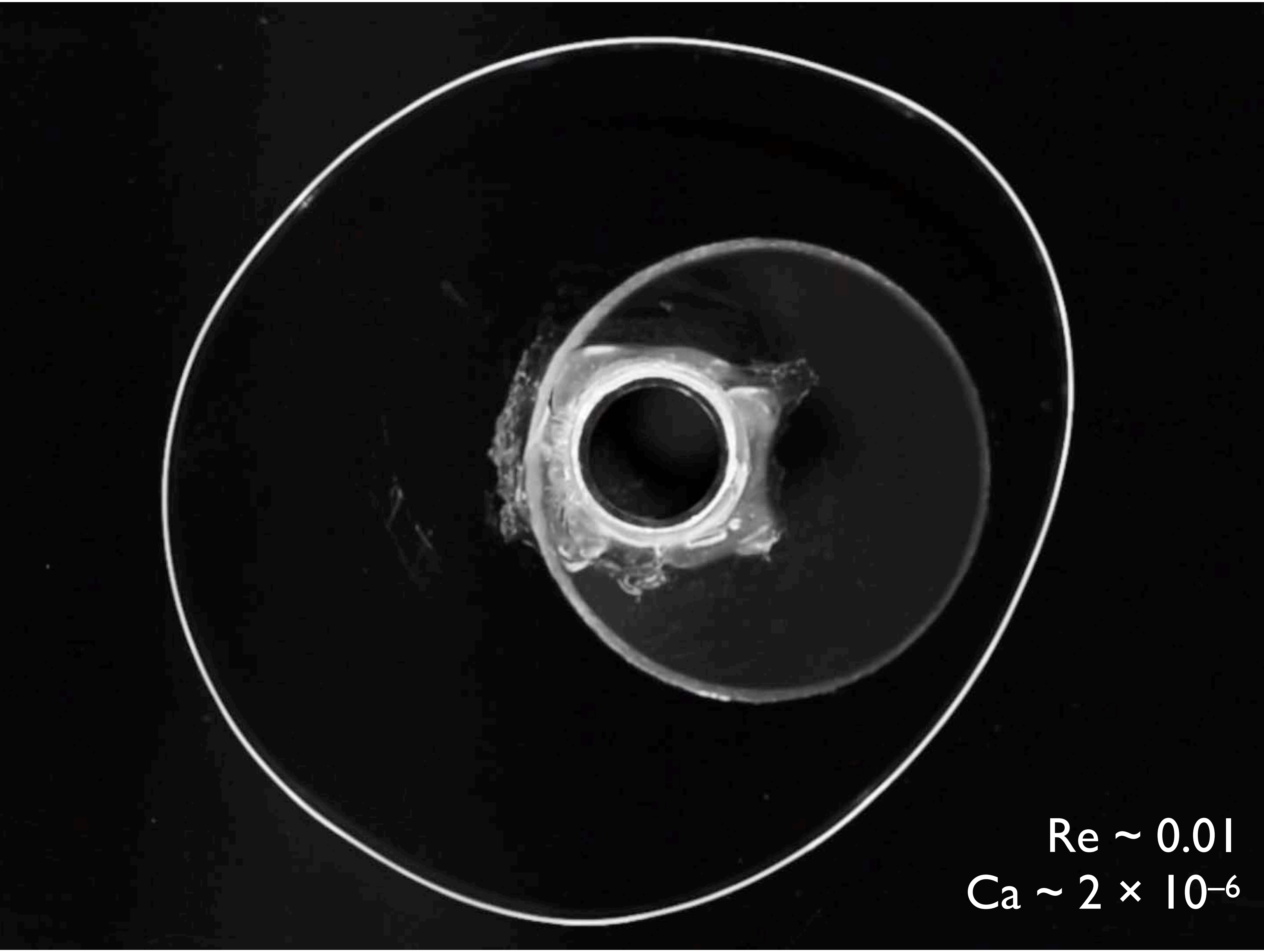
- Dani Medina
- Aidan McGuckin
- Audrey Profeta
- Brian Kroger
- Jenny Smit
- Esmeralda Orozco
- Juan Ortiz Salazar



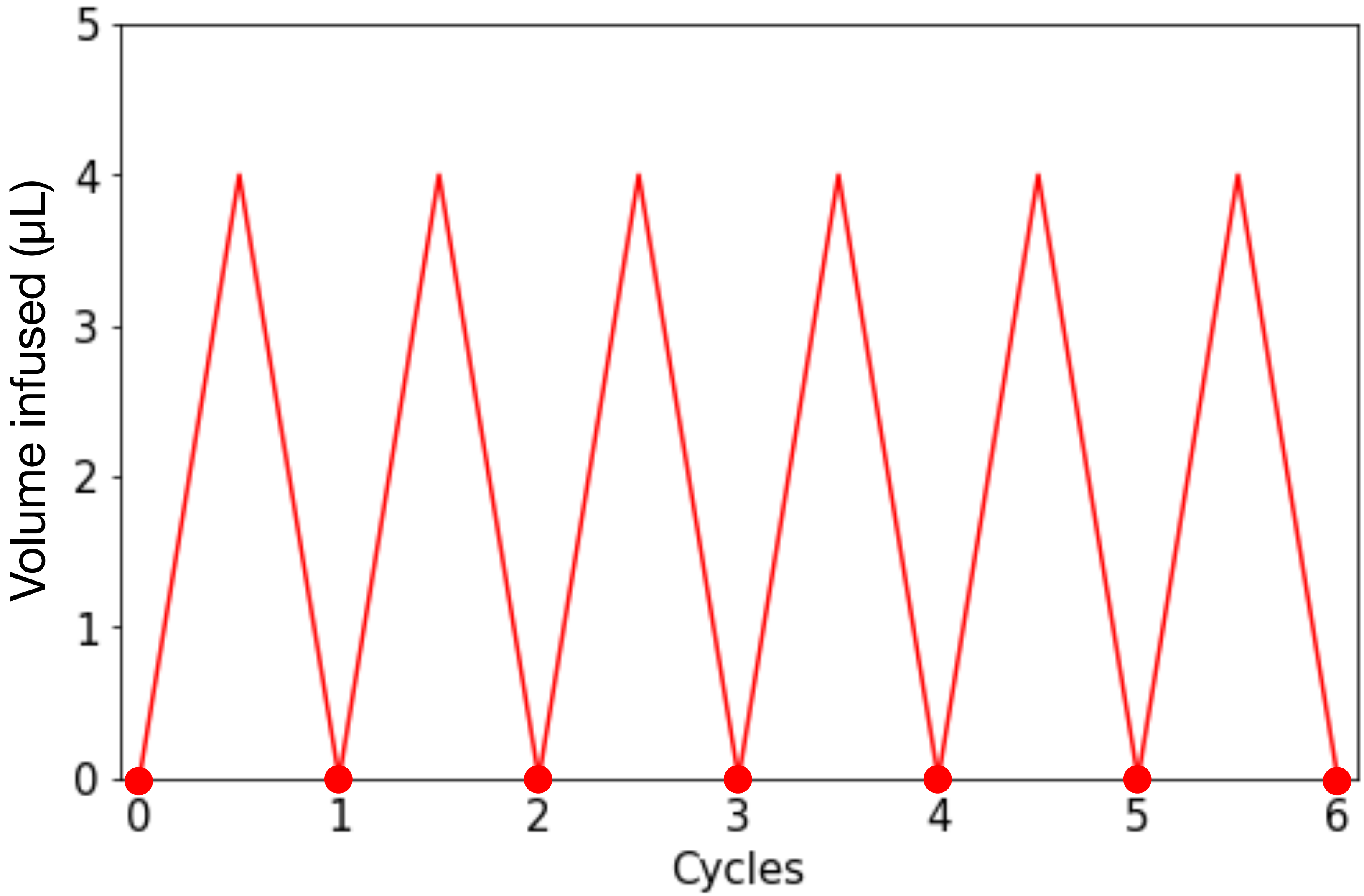

NSF DMR-1708870;
CSU RSCA Grant; CSU LSAMP; Bill & Linda Frost Fund

# Water in 500 µm gap between 2 acrylic plates



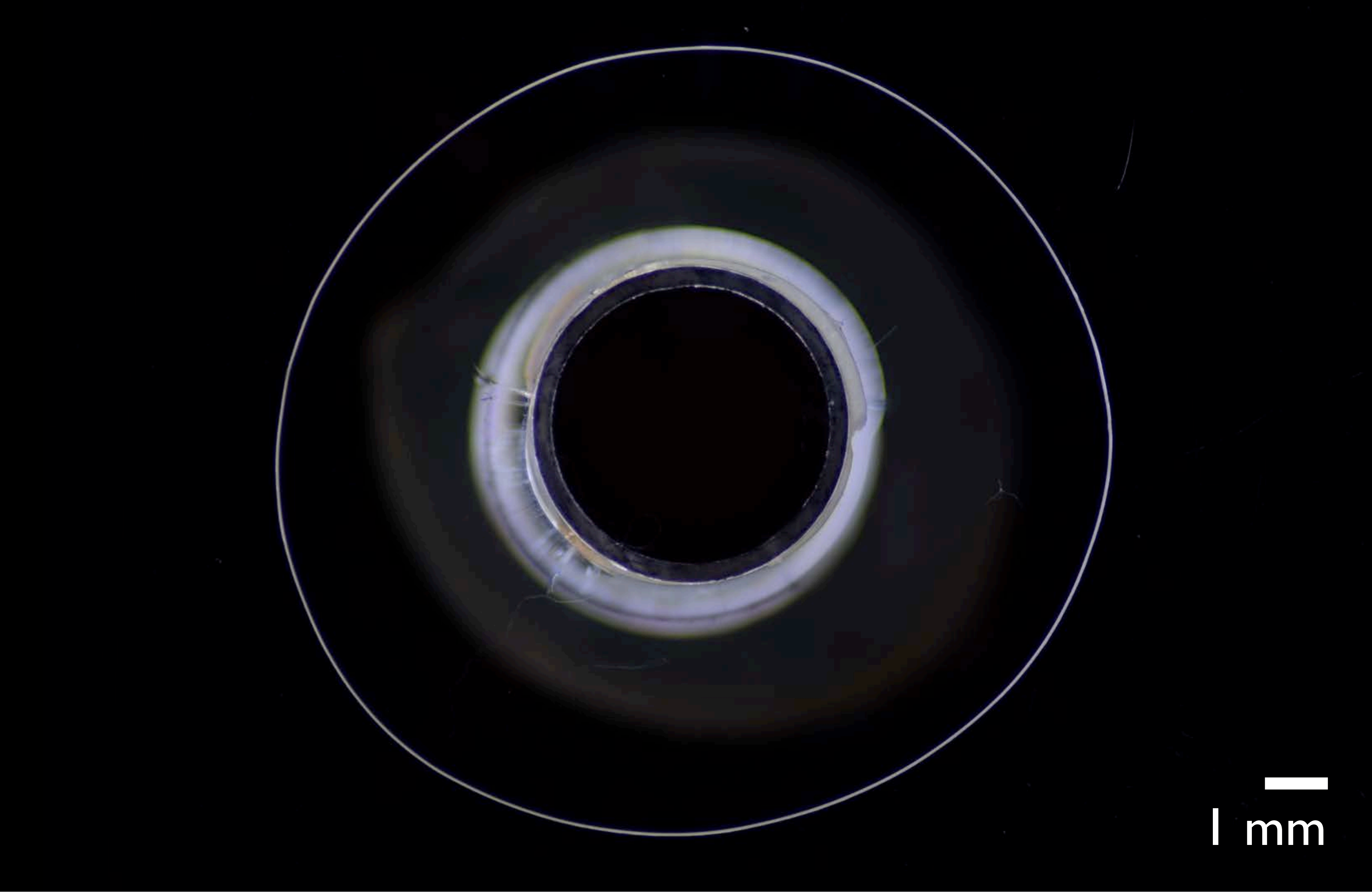

Re ~ 0.01
Ca ~ 2 × 10–6

# Stroboscopic Imaging

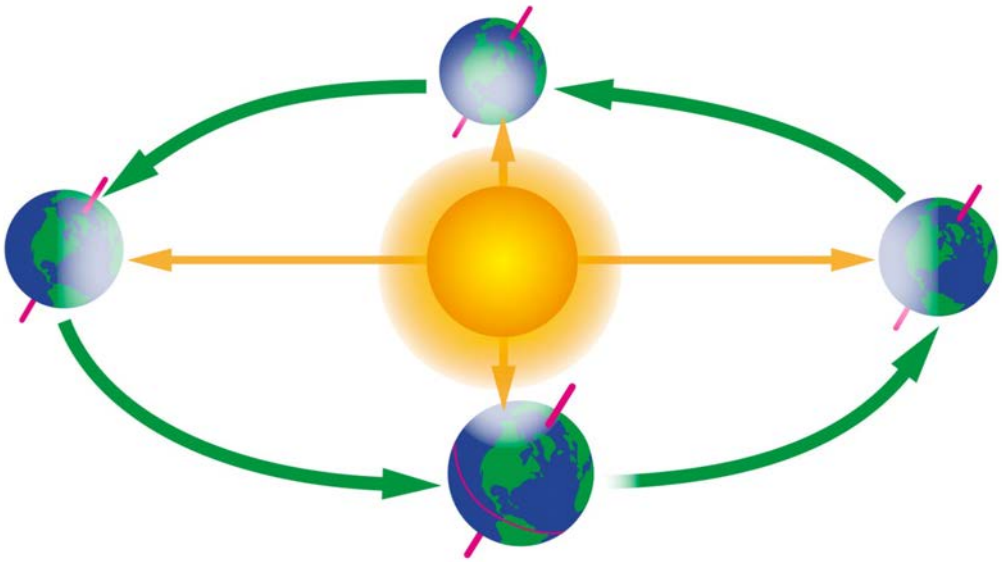



Pictures taken at the red circles

# One frame per cycle



# Cyclic driving is ubiquitous



DK Find Out, Granor

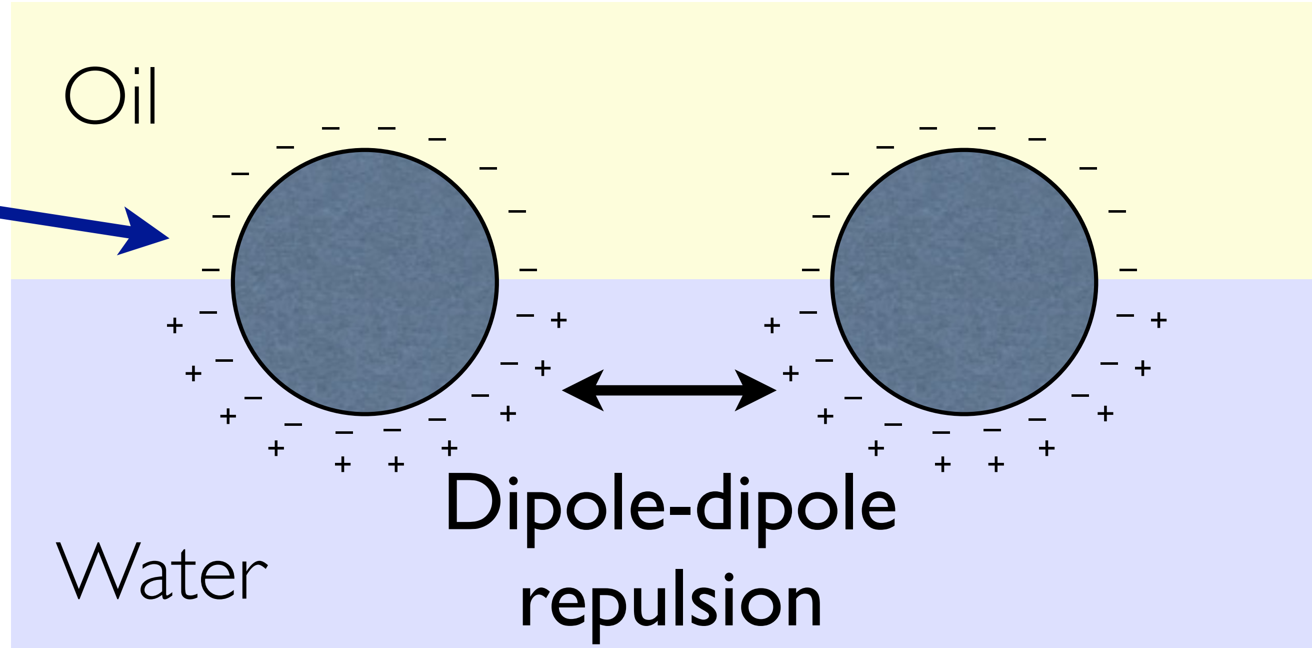
- Can change systems that don’t relax
- Can form memories
- Can reveal new behaviors & prompt new questions

Use amorphous solids to develop these ideas

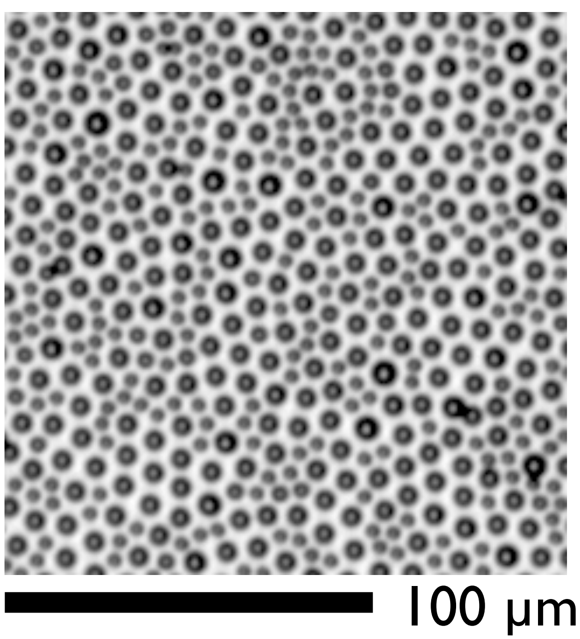
Keim & Nagel *PRL* 2011
Keim & Arratia *PRL* 2014
Keim *et al.* in preparation

# 2D Amorphous Solid

Polystyrene microspheres 3.8, 5.8 µm




Aveyard, Clint, Nees, & Paunov. *Langmuir* (2000)
Masschaele *et al.*, *Phys. Rev. Lett.* (2010)



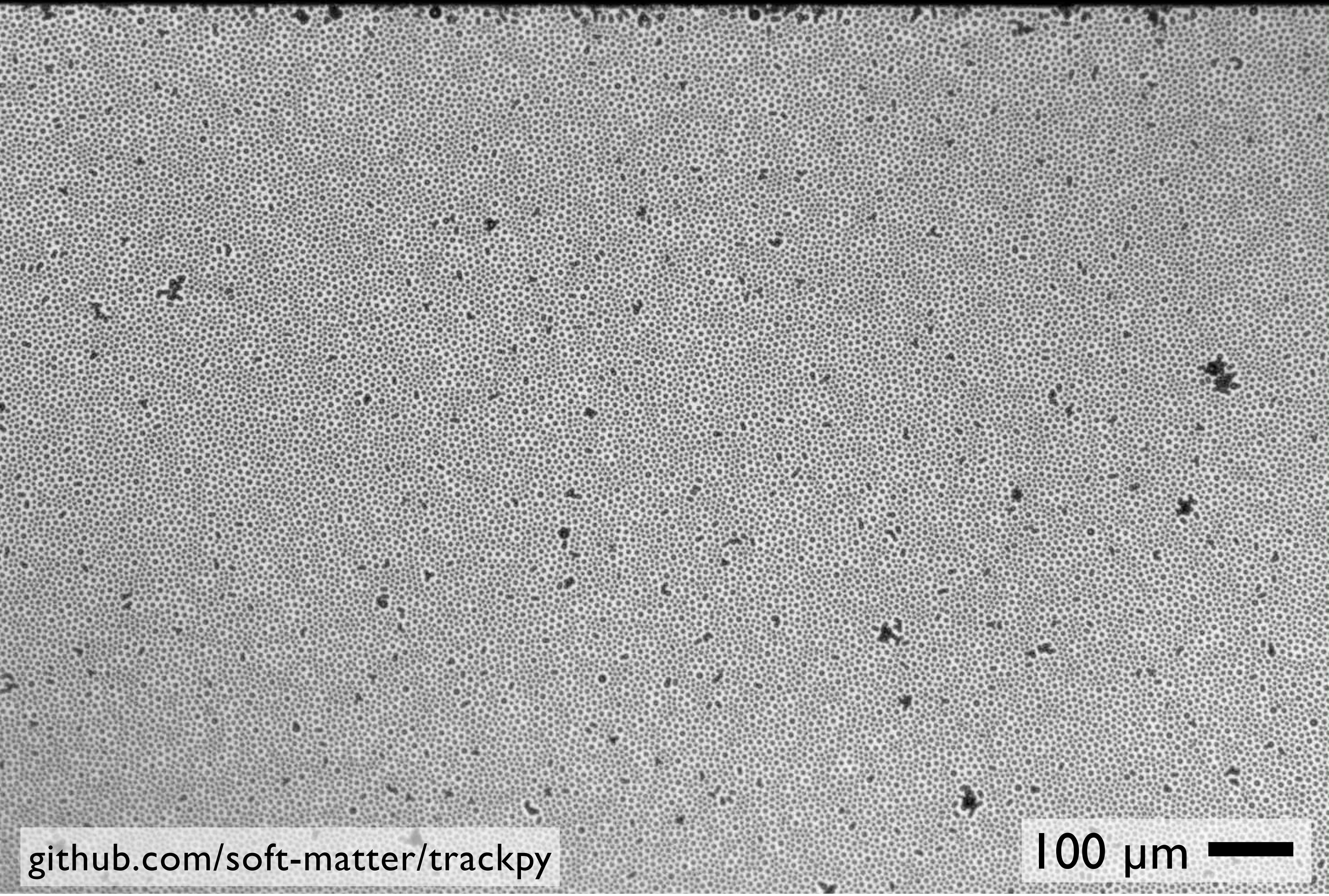

Long-range repulsion
→ Mechanically over-constrained (jammed)

Particles *not touching*

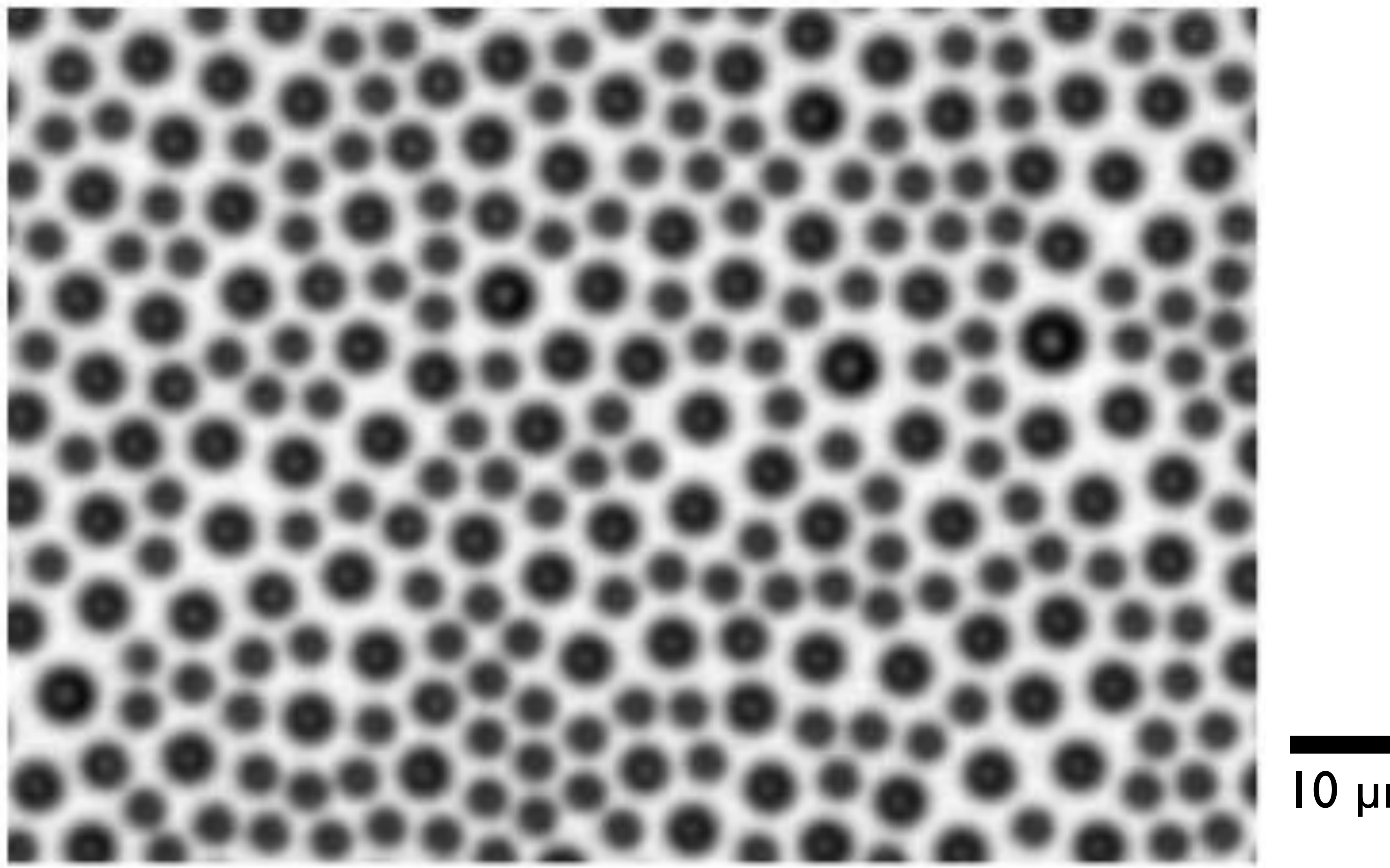
Negligible thermal motion

Keim & Arratia, *Soft Matter* 2013

Shear at 0.05 Hz     Strain amplitude 0.055



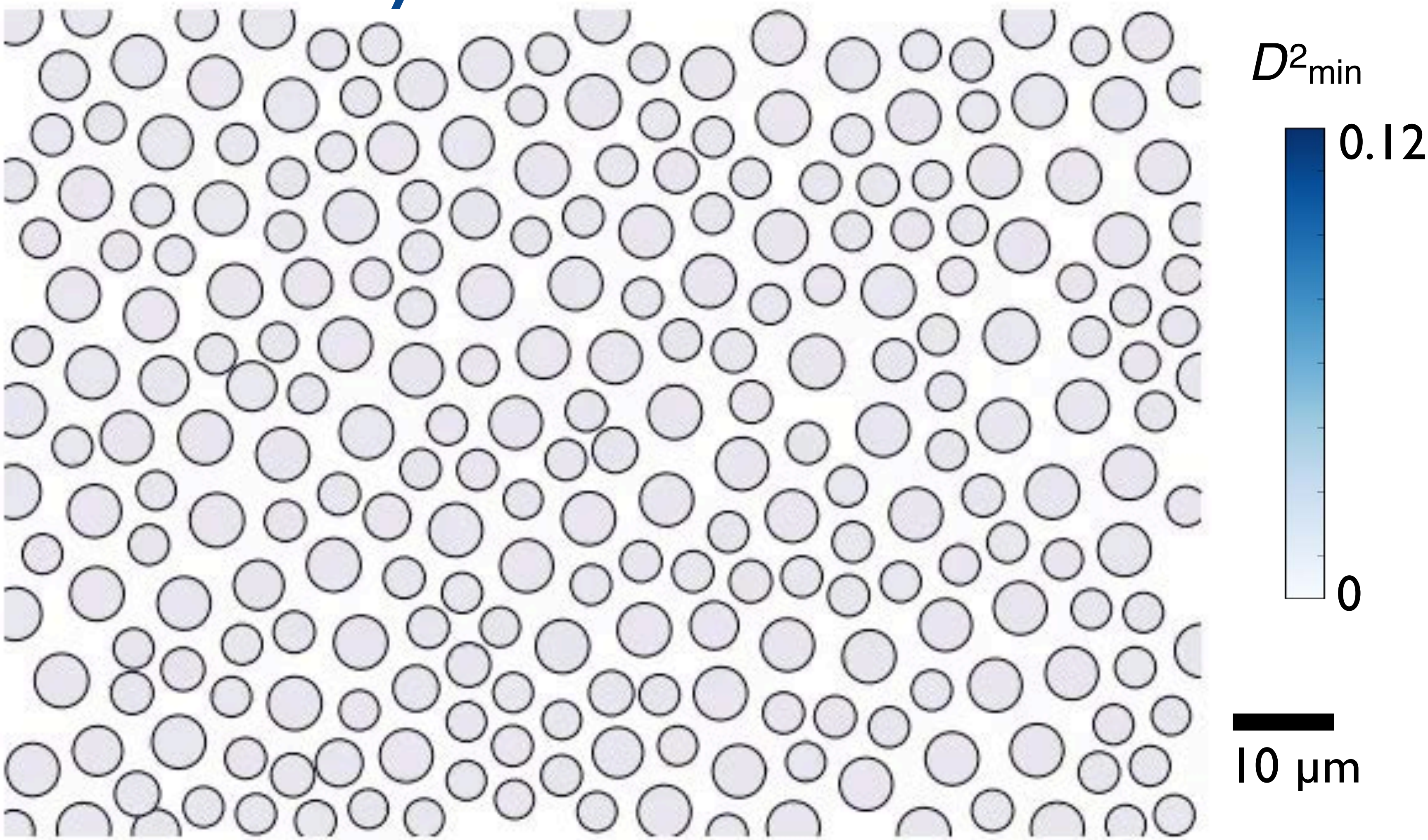
# Find rearrangements




Falk & Langer *Ann Rev CMP* 2011, Keim & Arratia, *PRL* 2014; *Soft Matter* 2015

# Find rearrangements

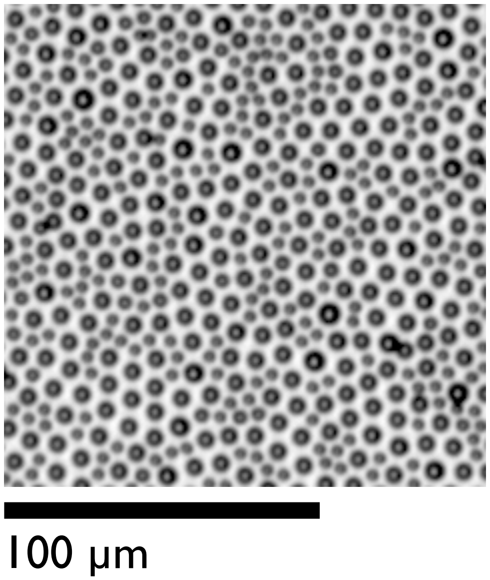
## $D^2_{min}$ = locally non-affine

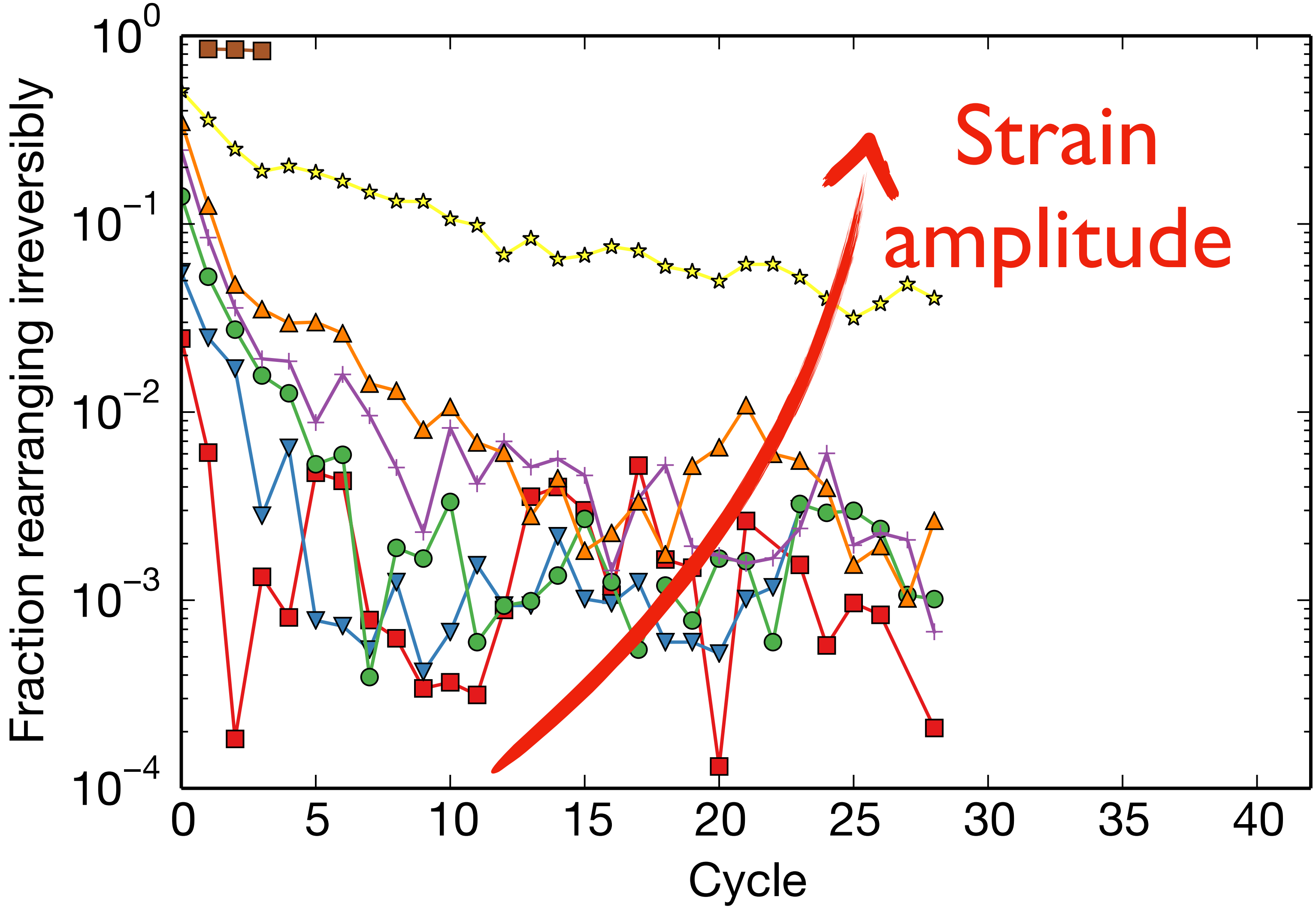



github.com/nkeim/philatracks

Falk & Langer *Ann Rev CMP* 2011, Keim & Arratia, *PRL* 2014; *Soft Matter* 2015

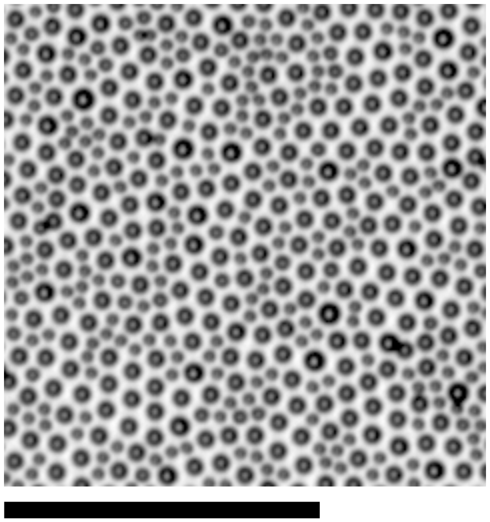
# Self-Organization in Jammed Solid



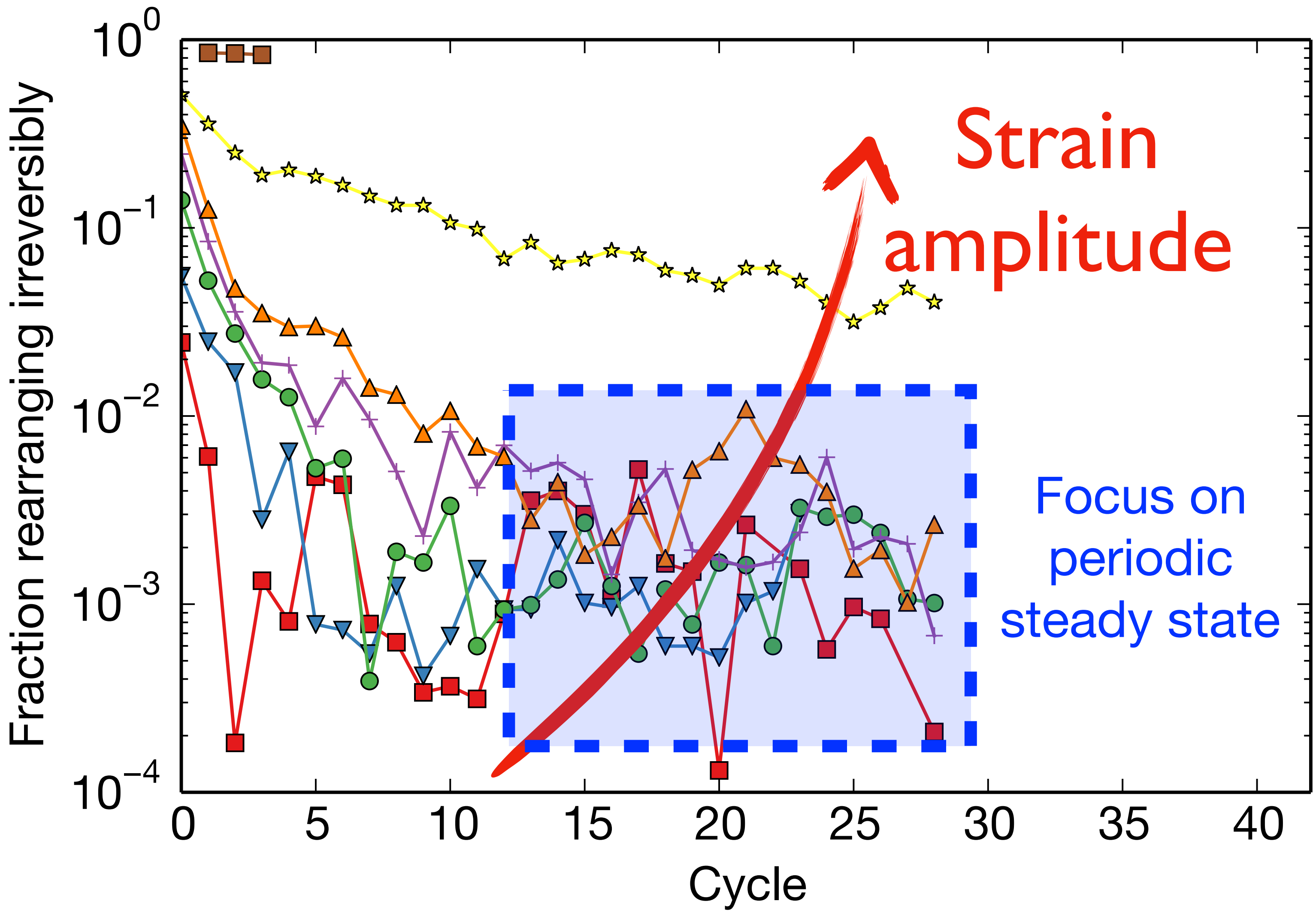




Keim & Arratia, *Soft Matter* (2015)

# Self-Organization in Jammed Solid

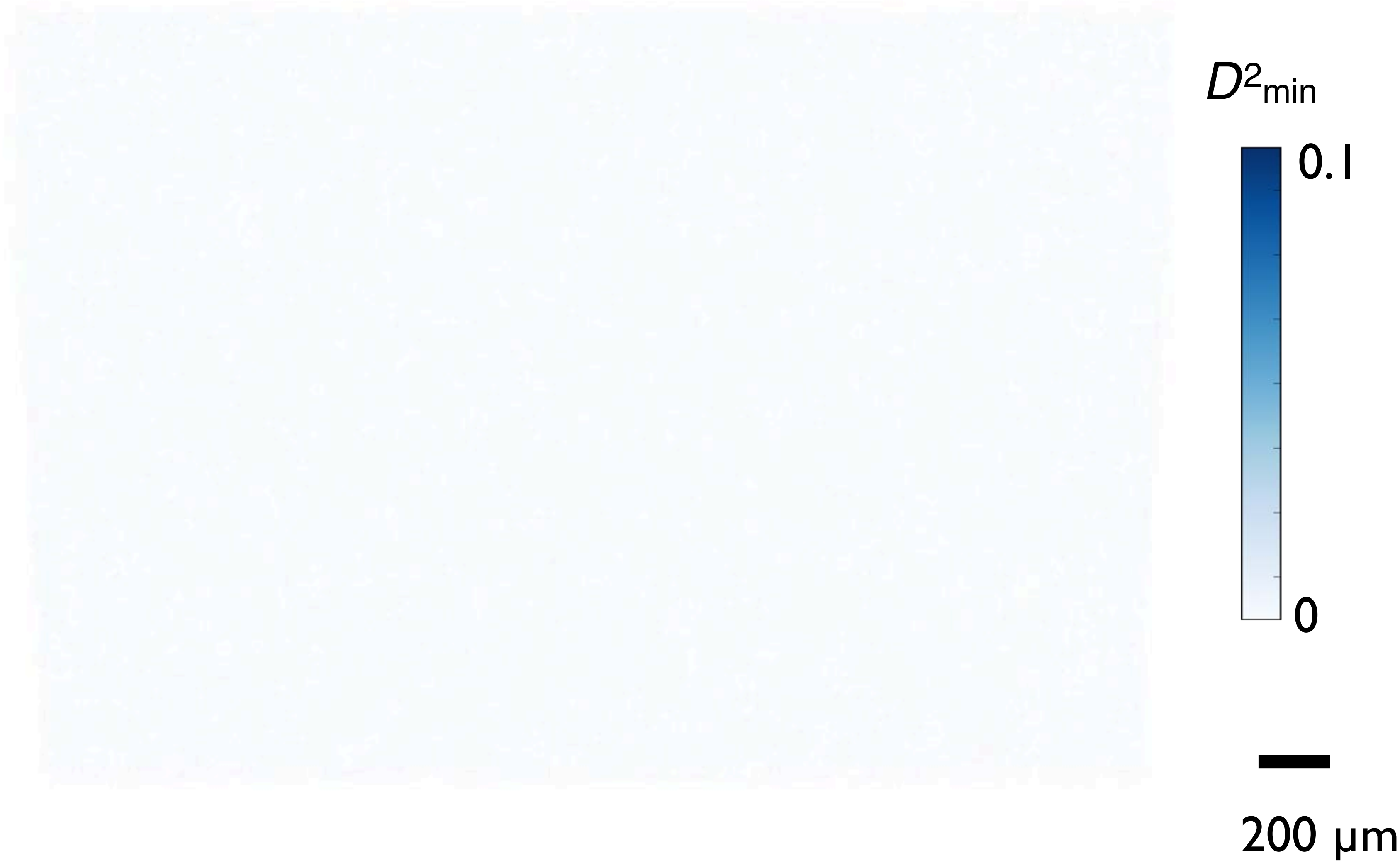


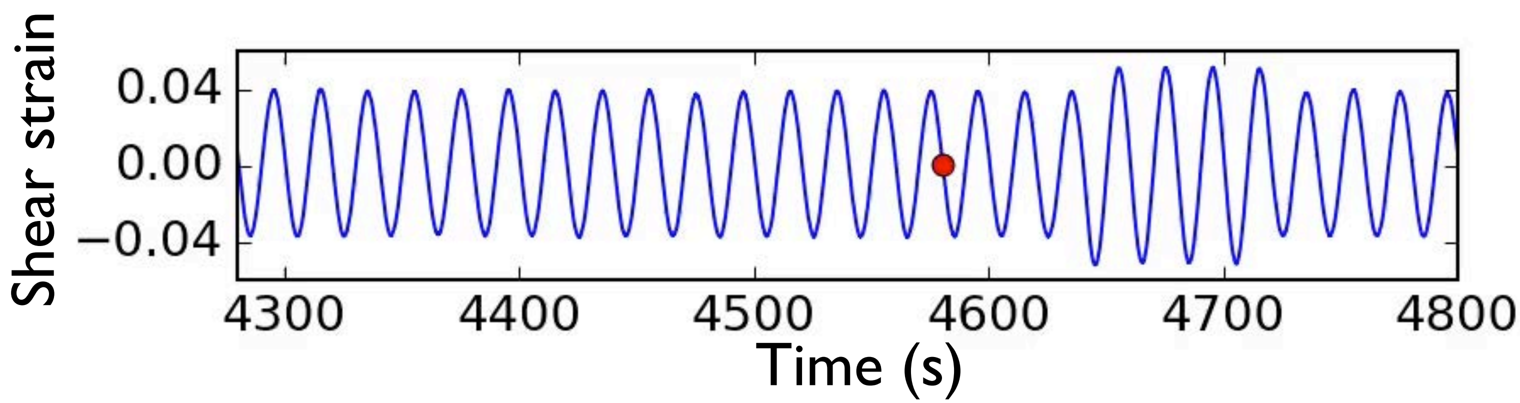
100 μm




Keim & Arratia, *Soft Matter* (2015)

# Steady State = repeating rearrangements



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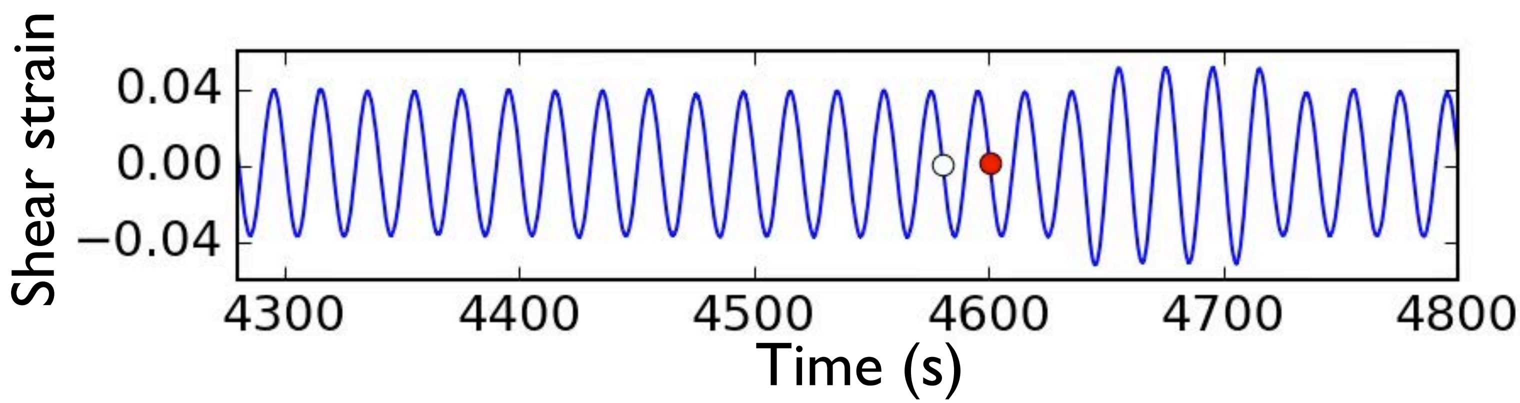
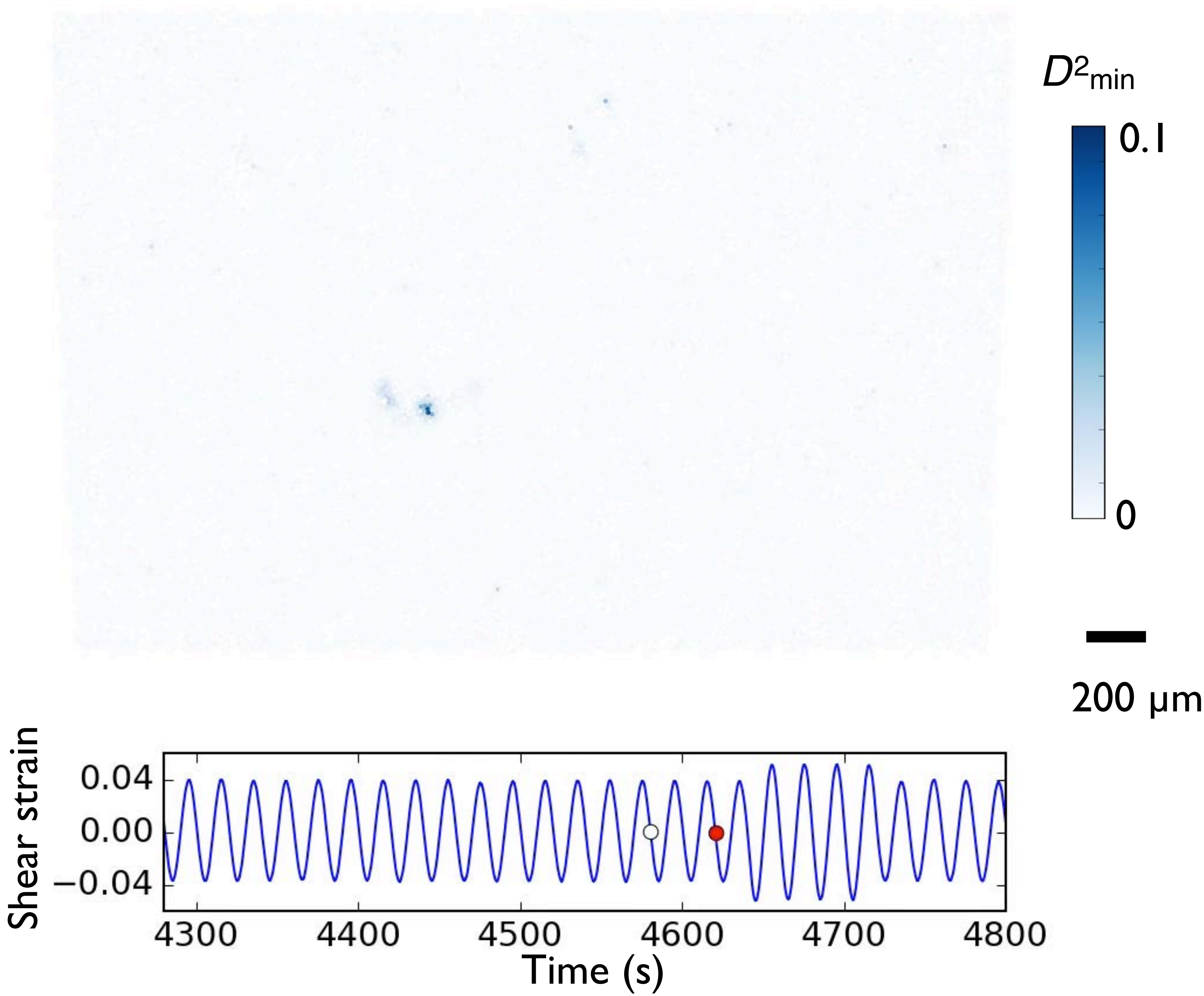
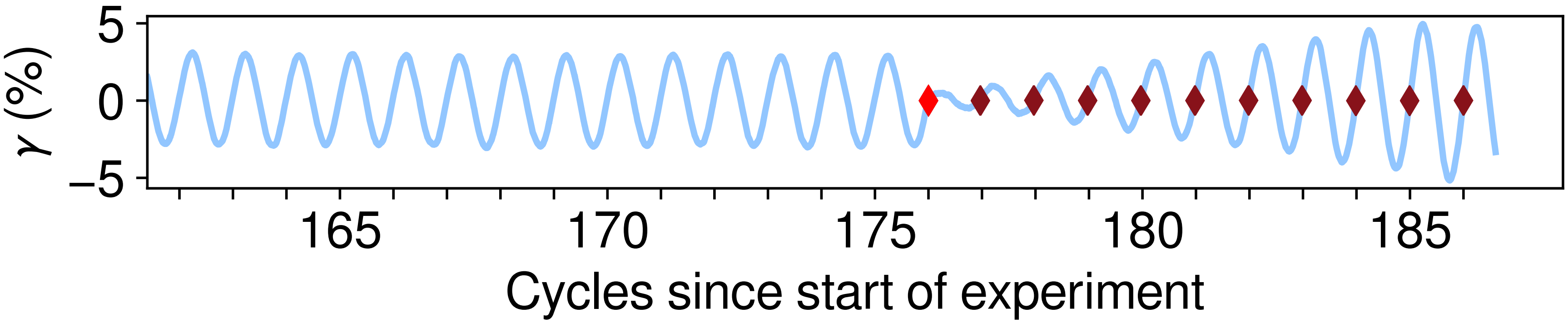


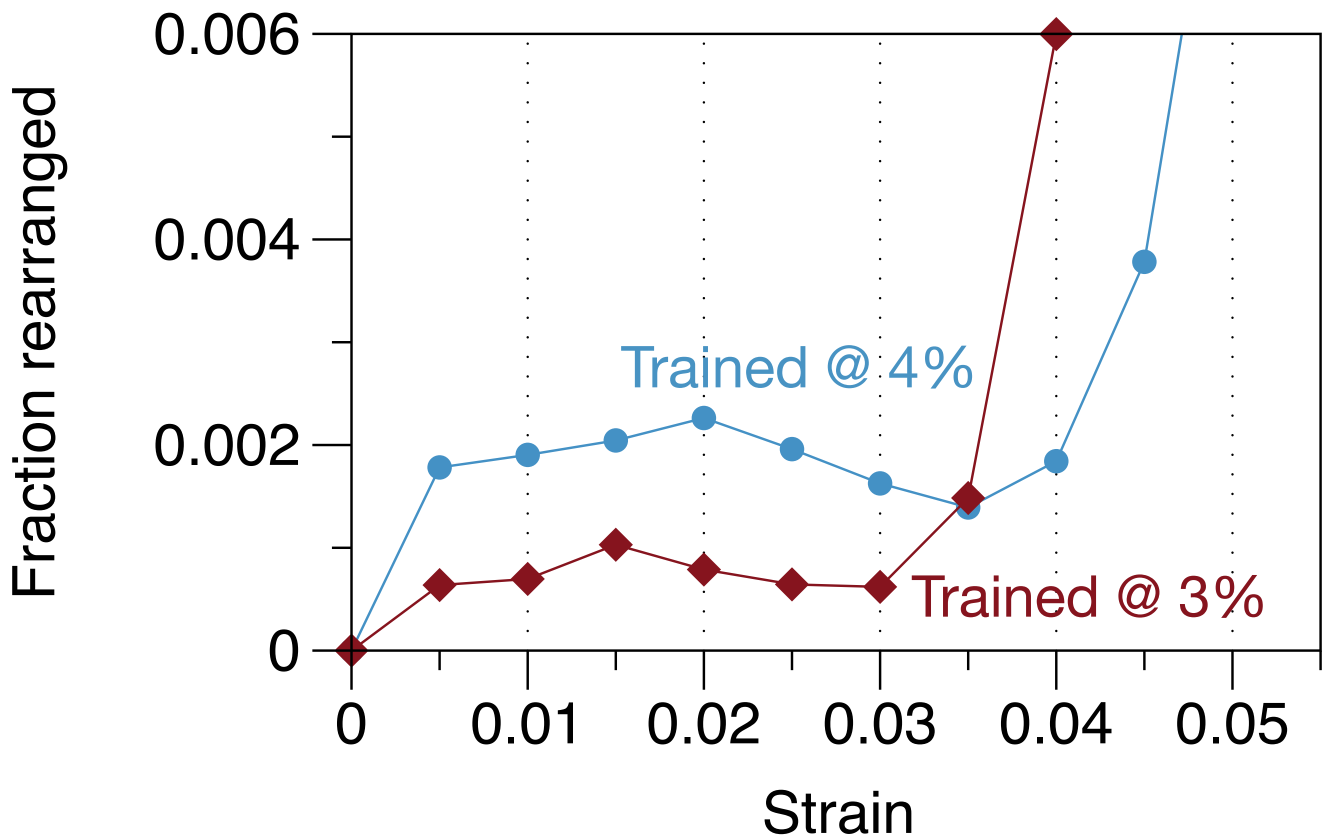
# Steady State = repeating rearrangements



# Reading out a memory

## Compare trained state w/ each snapshot



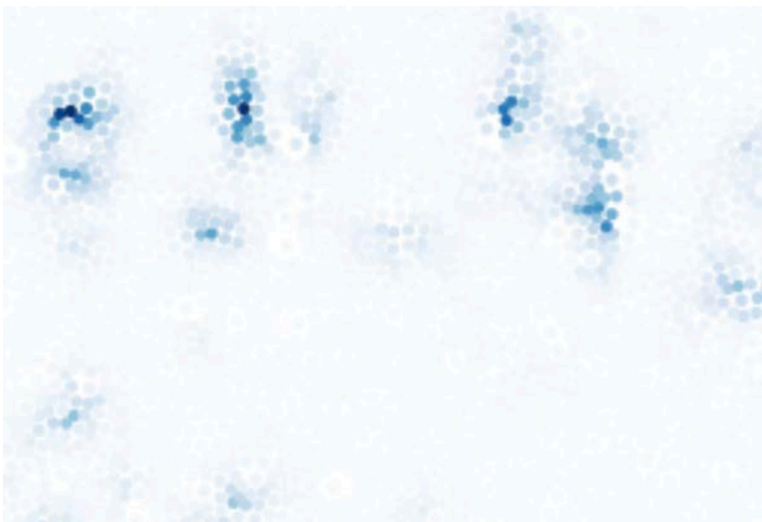

Steady state encodes strain that prepared it

Fiocco *et al.* PRL 2014
Keim *et al.* in preparation

# Results

Kinetics of rearrangements consistent with **return-point memory**

Arises from hysteretic subsystems + cooperative interactions

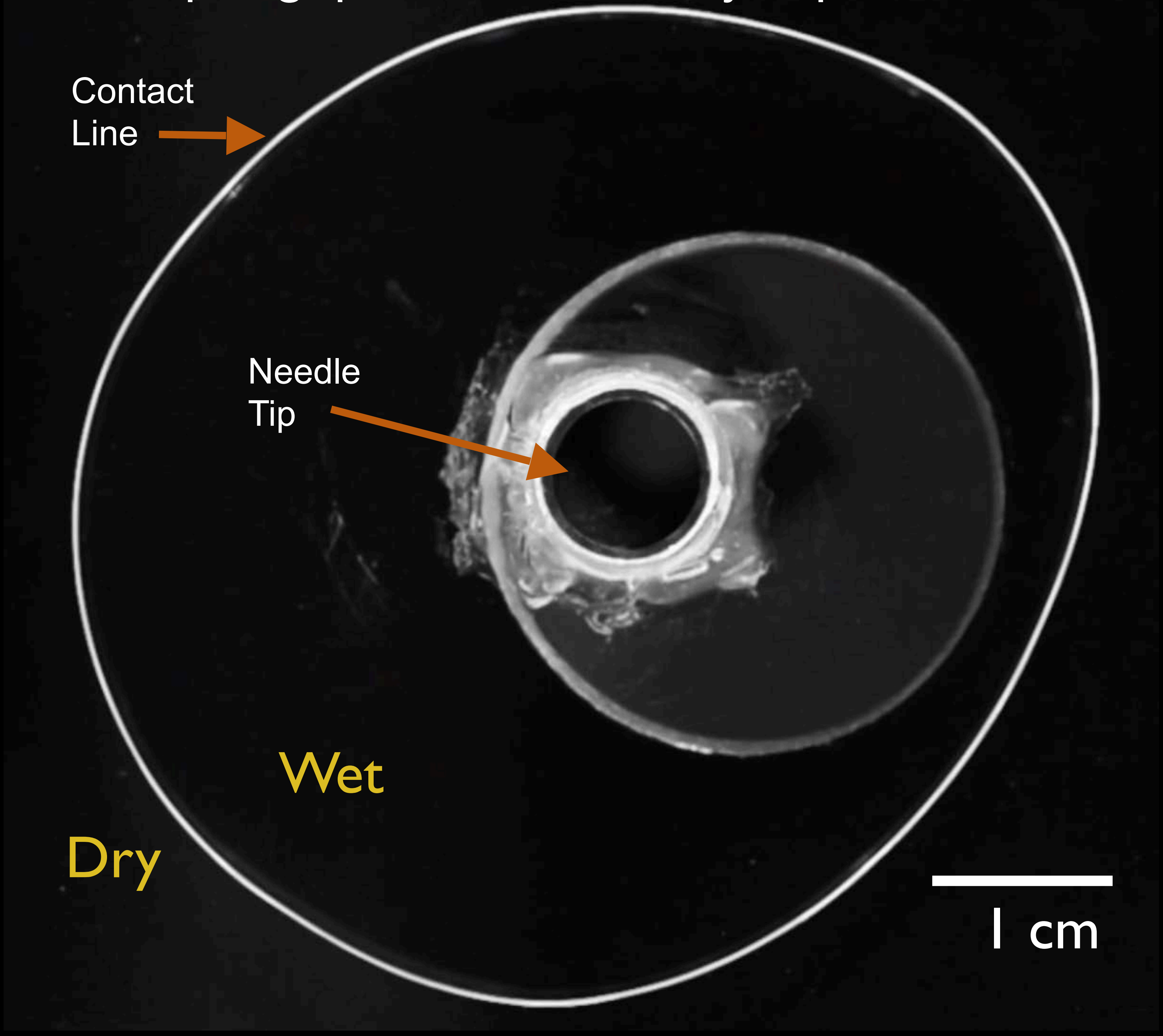


Large strain amplitude ➔ Too many subsystems + interactions
➔ Depinning ➔ No periodic steady state

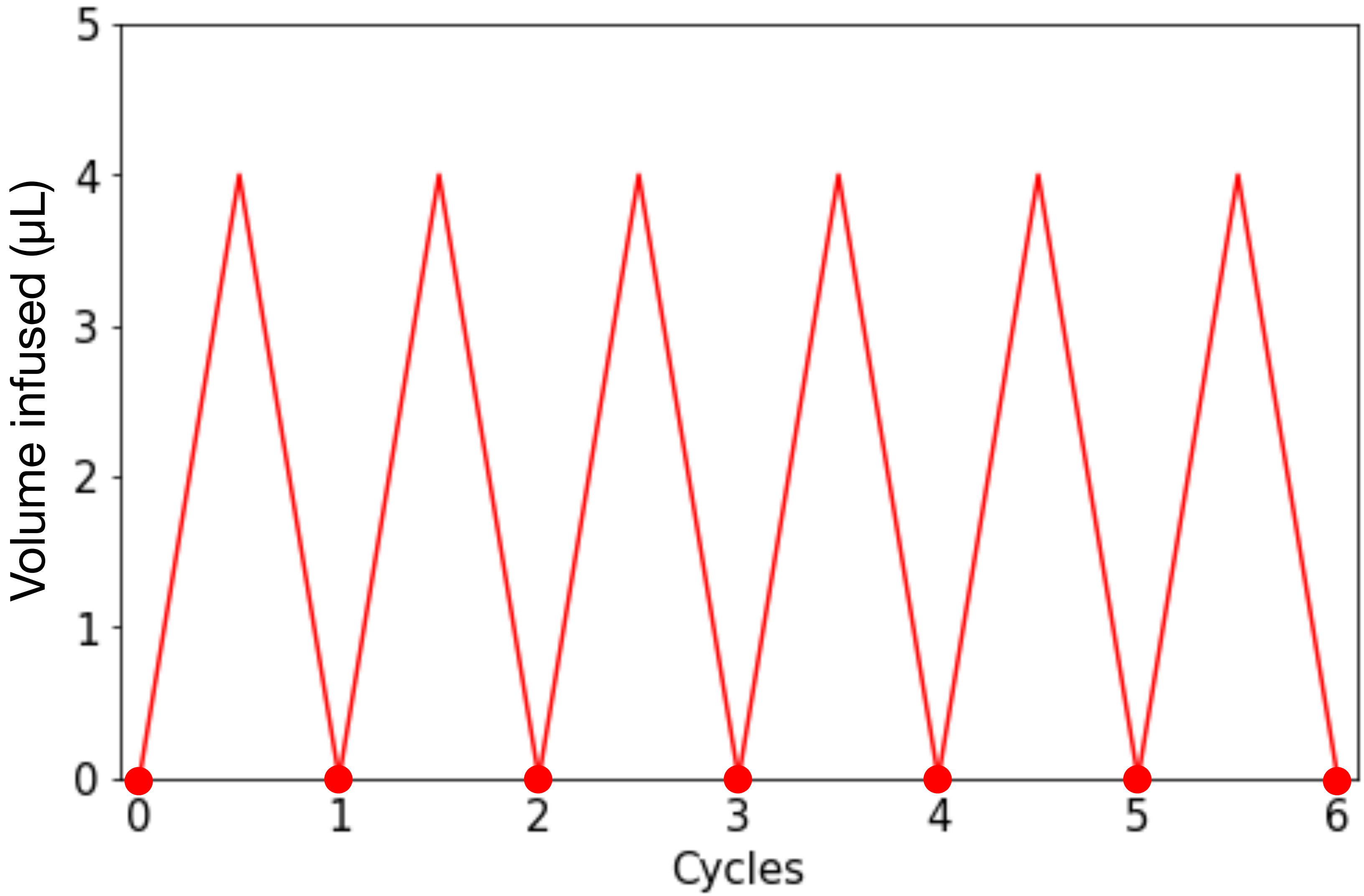
Are these ideas relevant to contact line?

Keim *et al.*, in preparation
Regev *et al. Nat Comms* (2015)

# Water in 500 μm gap between 2 acrylic plates

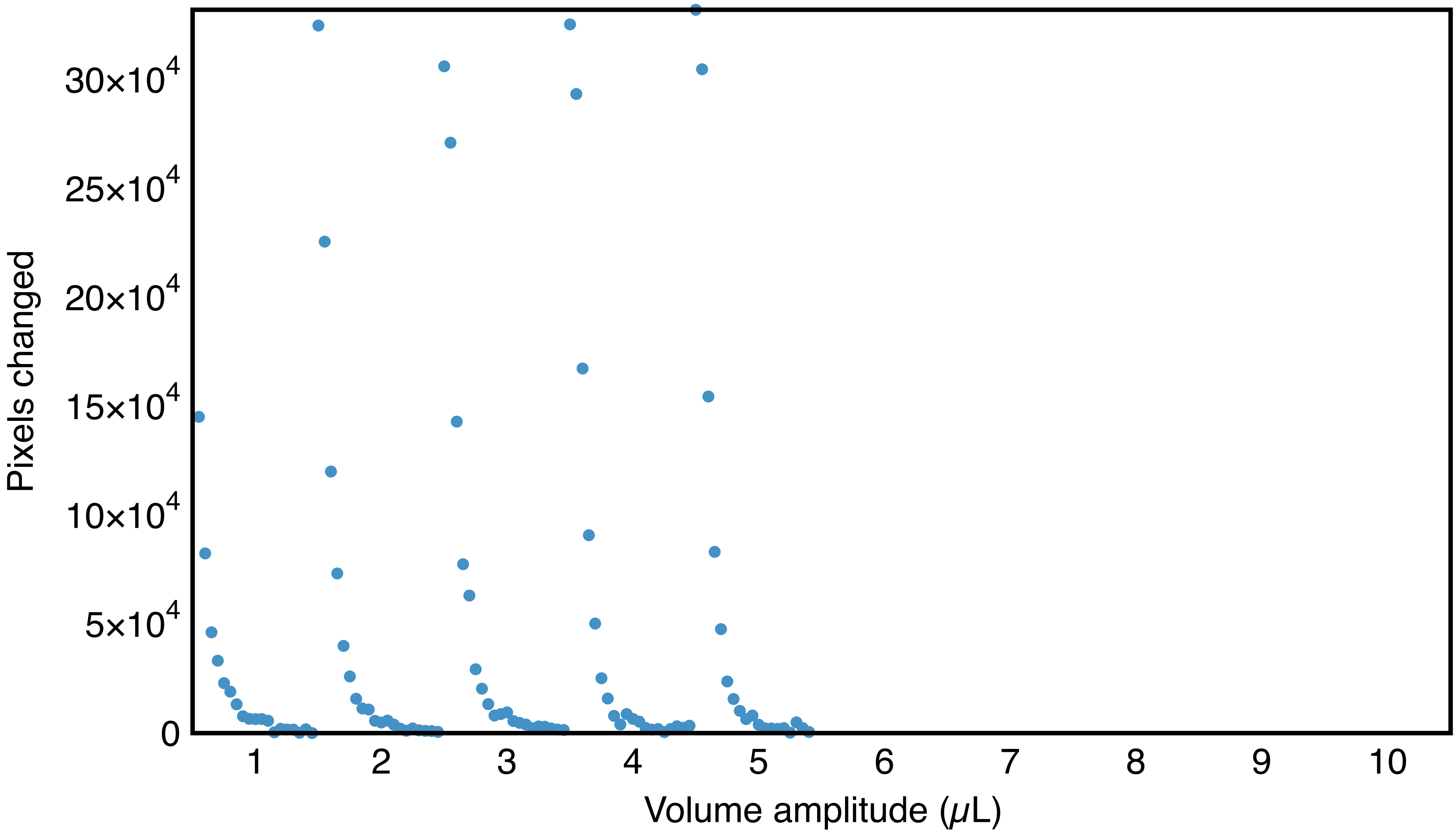


# Stroboscopic Imaging

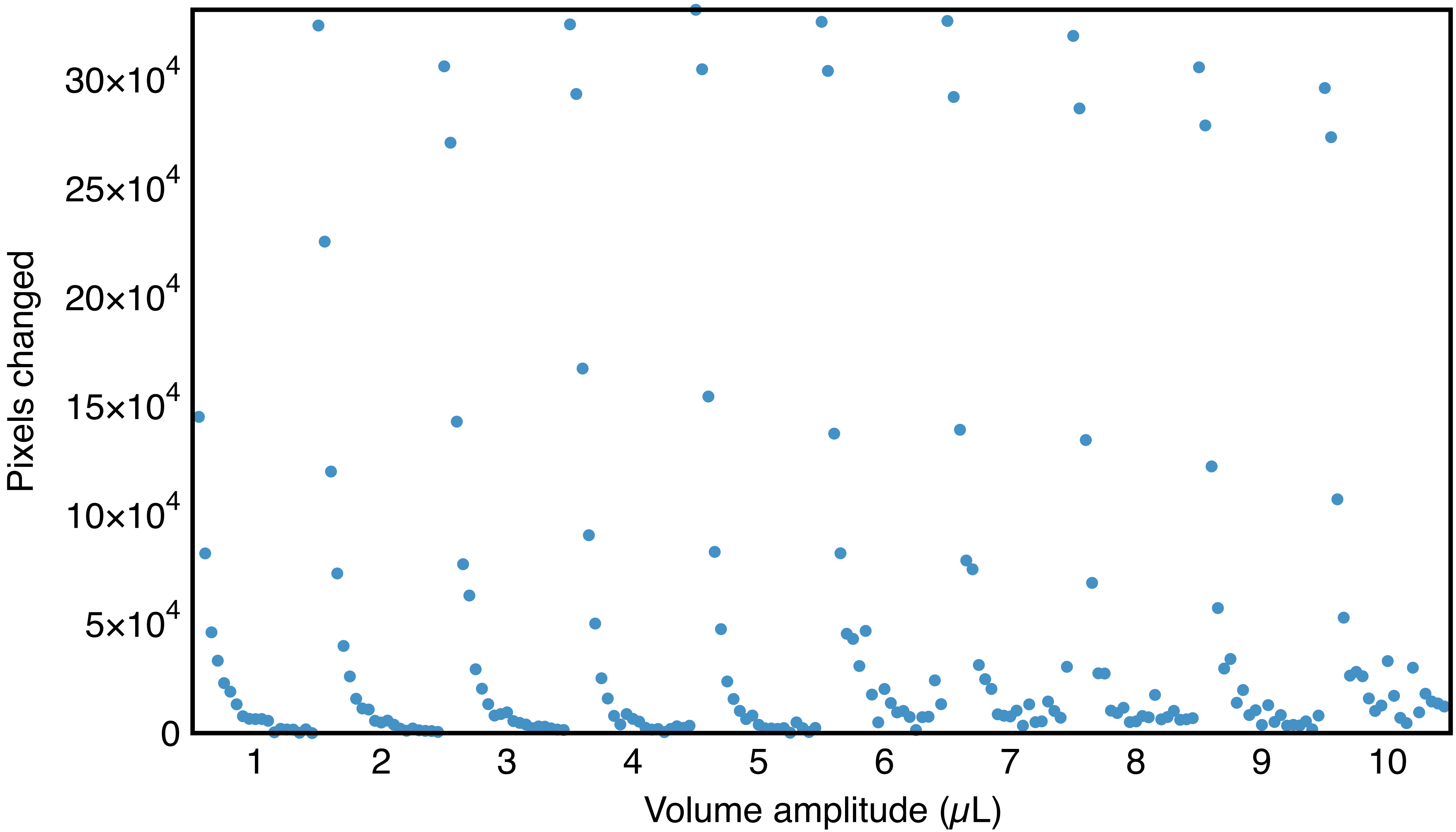



Pictures taken at the red circles

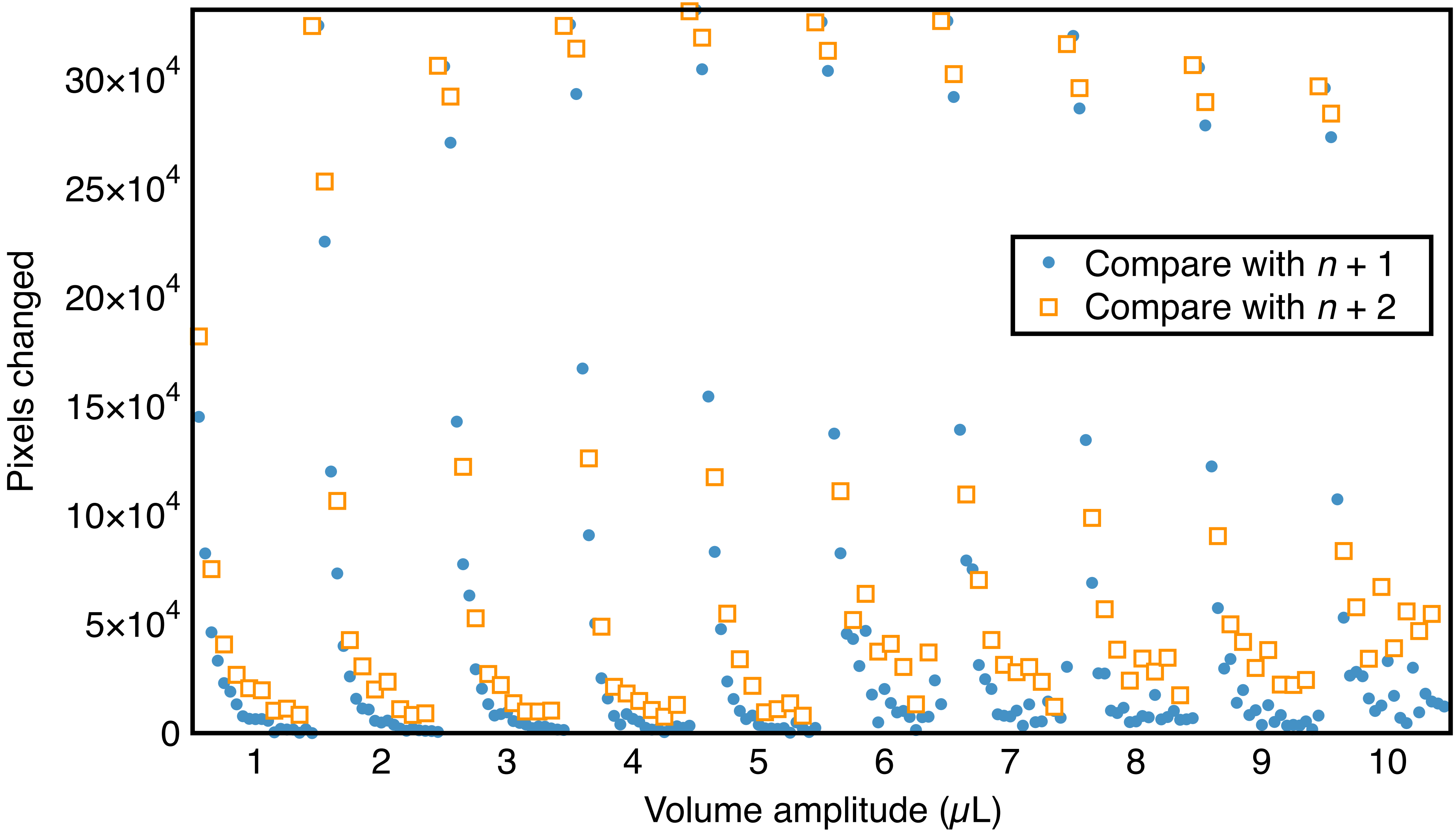
# Approach to steady state



# Transition from Periodic to Fluctuating

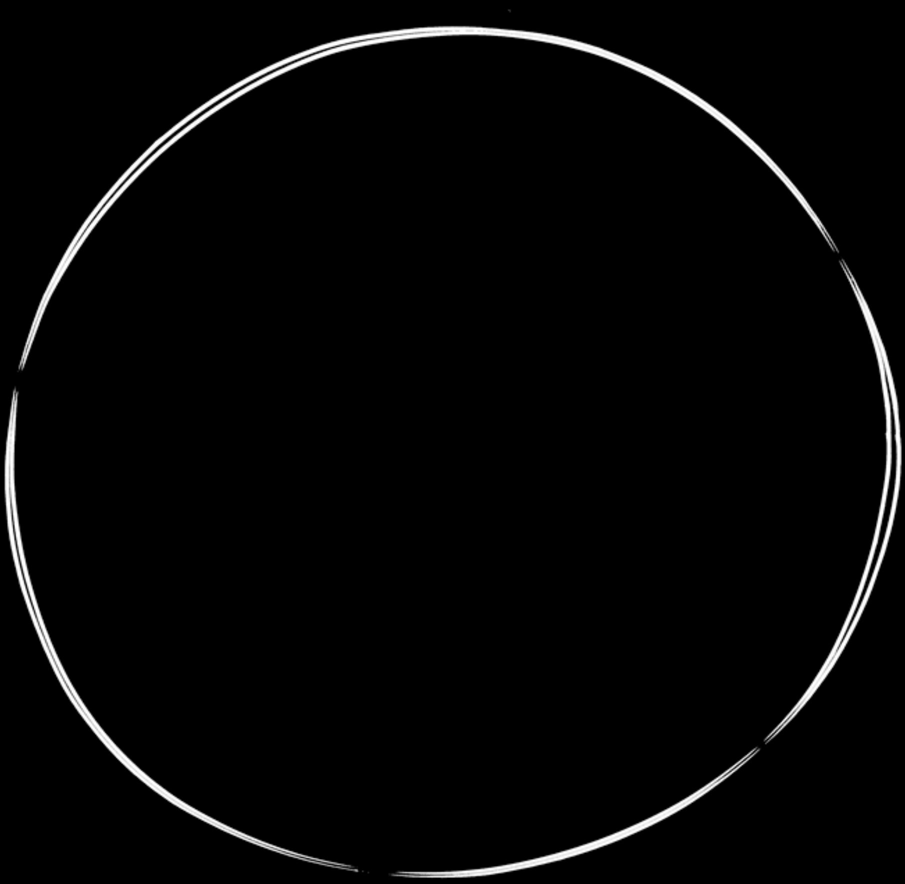


# Transition from Periodic to Fluctuating

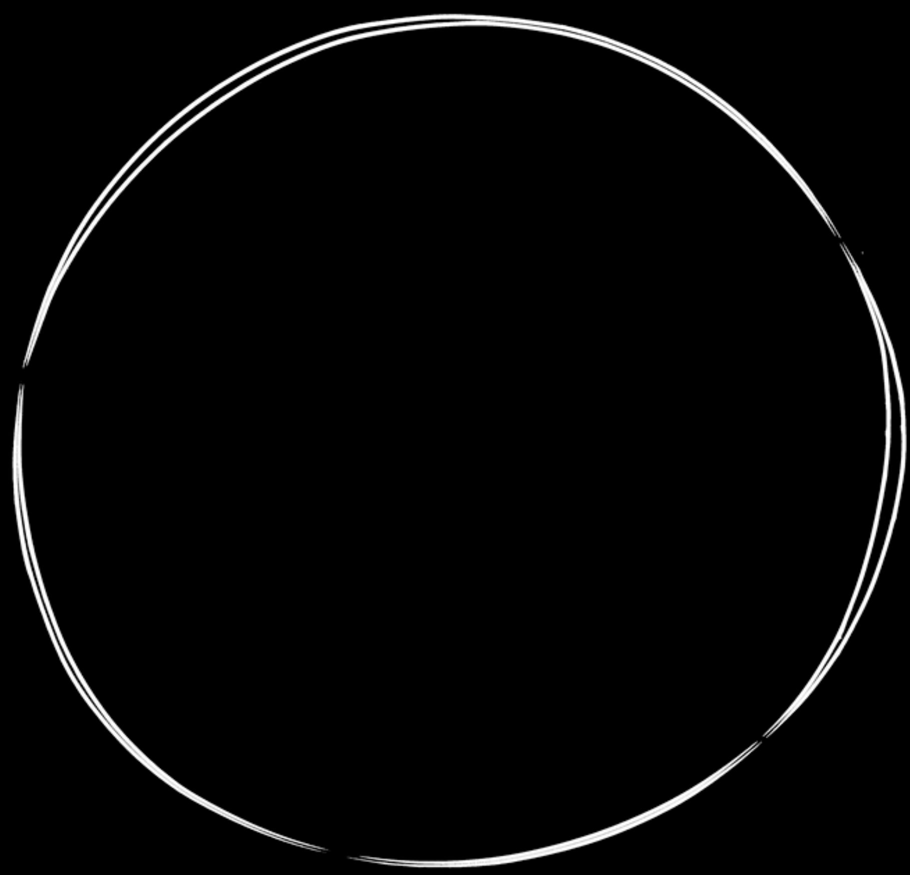


# Binary difference images show transition

5 µL amplitude

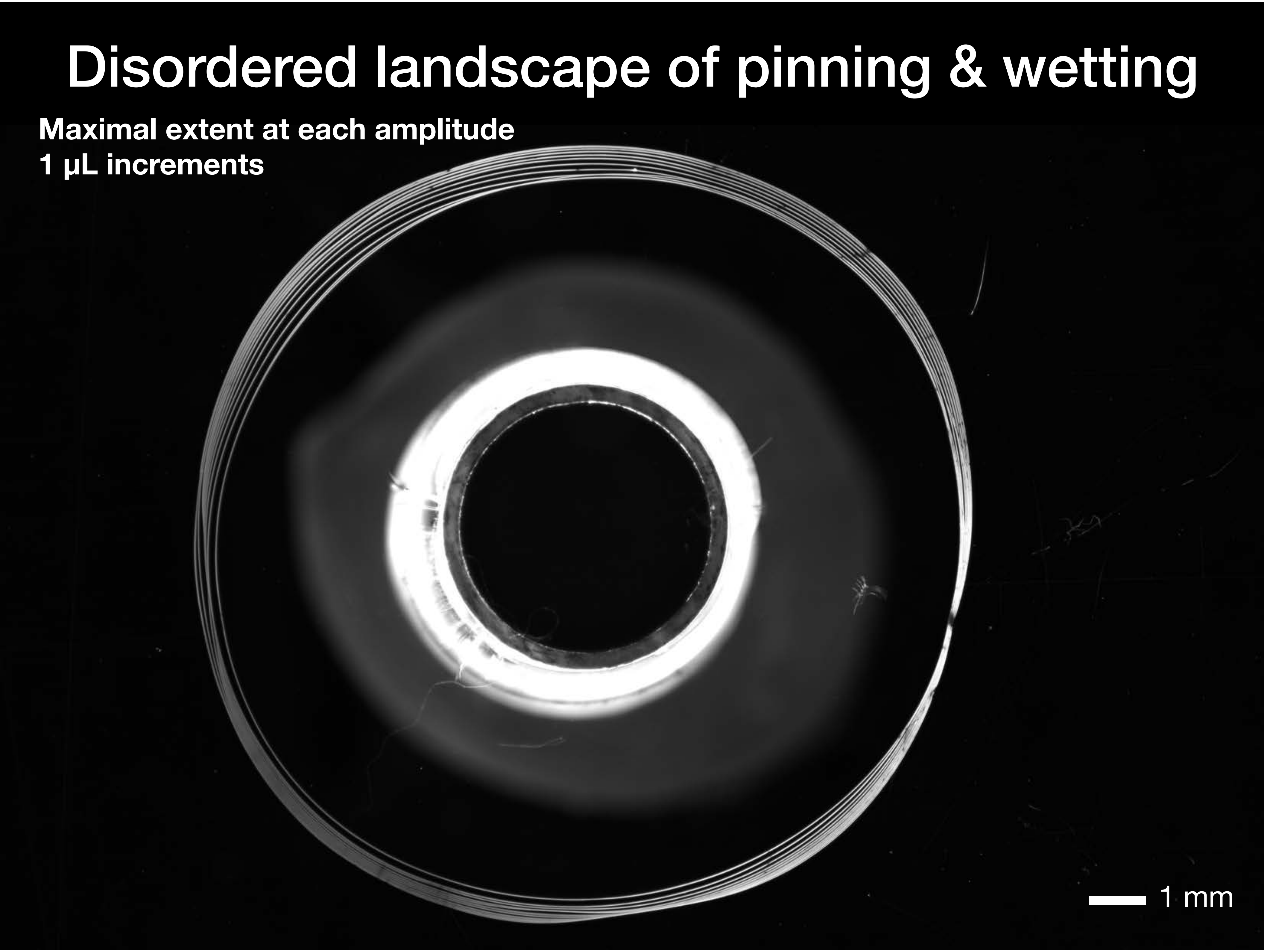


6 µL amplitude



# Disordered landscape of pinning & wetting

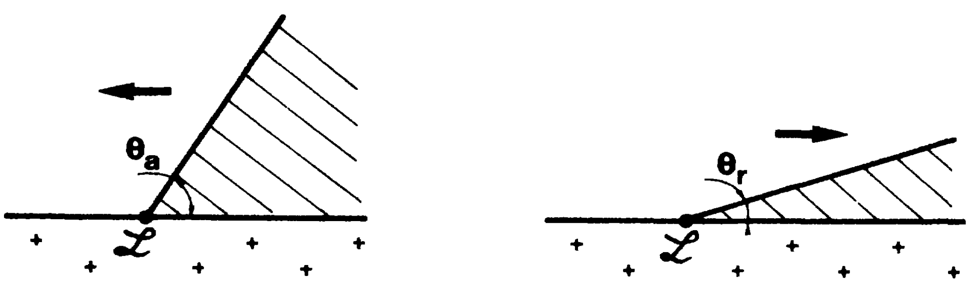
**Maximal extent at each amplitude**
**1 μL increments**

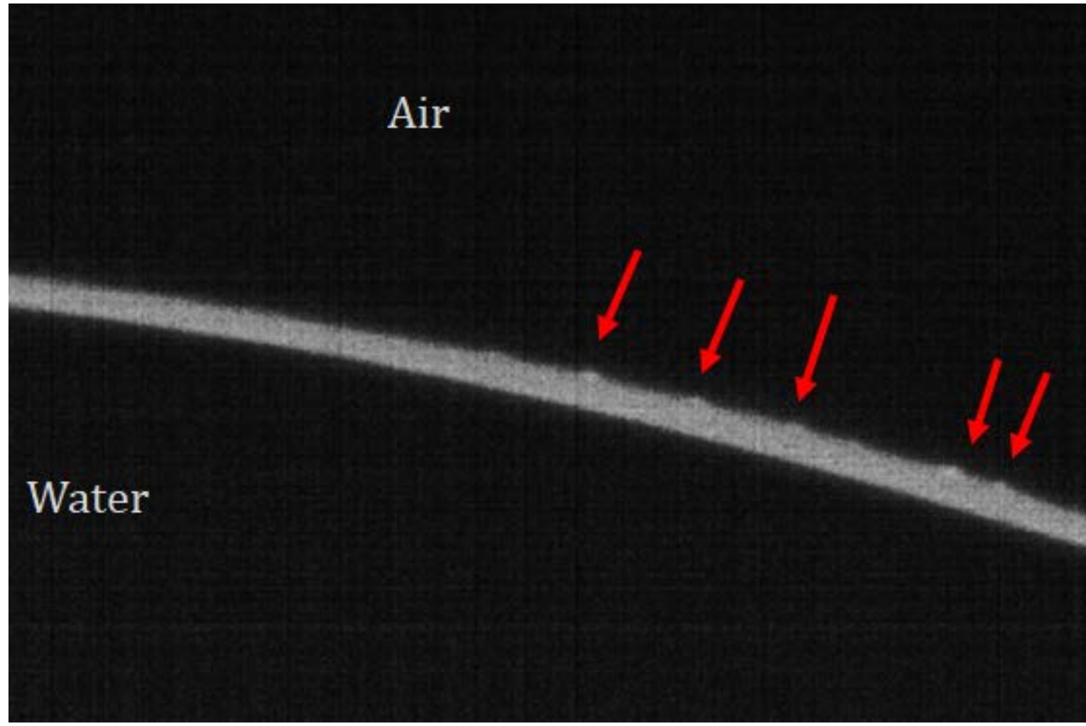


# Contact line is rich in hysteresis

- Metastable; disordered substrate

- Hysteretic subsystems →






- Cooperative interactions

de Gennes, *Rev. Mod. Phys.* (1985)

# What happens during training? An hypothesis.

*Below* critical amplitude,

1. **Pinning:** Below critical amplitude, discrete jumps mean system is trapped in finite set of states
2. **Self-organized limit cycle:** Each piece of the contact line stops changing when its motion becomes periodic.

Coppersmith, *Phys. Rev. A* (1987)
Regev *et al.*, *Nat. Comms.* (2015)
Keim & Arratia, *PRL* (2014)

# What happens during training? An hypothesis.

*Below* critical amplitude,

1. **Pinning:** Below critical amplitude, discrete jumps mean system is trapped in finite set of states
2. **Self-organized limit cycle:** Each piece of the contact line stops changing when its motion becomes periodic.

*Above* critical amplitude,

– Jumps encourage more jumps, depinning large regions

– System "flows" among many more states
➔ Never periodic.

Coppersmith, *Phys. Rev. A* (1987)
Regev *et al.*, *Nat. Comms.* (2015)
Keim & Arratia, *PRL* (2014)

# Memory?

# Conclusions

- Contact line motion has self-organized limit cycles, memory
  - "Depinning physics" at its most literal.
- Could comparison w/ other systems tell us about microscopic physics?

Thanks: Tom Bensky, Andrew Cantino, Sid Nagel, Joey Paulsen, Kevin Thompson
Supported by NSF DMR-1708870 and PHY-1748958, the Bill and Linda Frost Fund, CSU LSAMP, and CSU RSCA.