Memory: Fast and Slow

Nathan C. Keim

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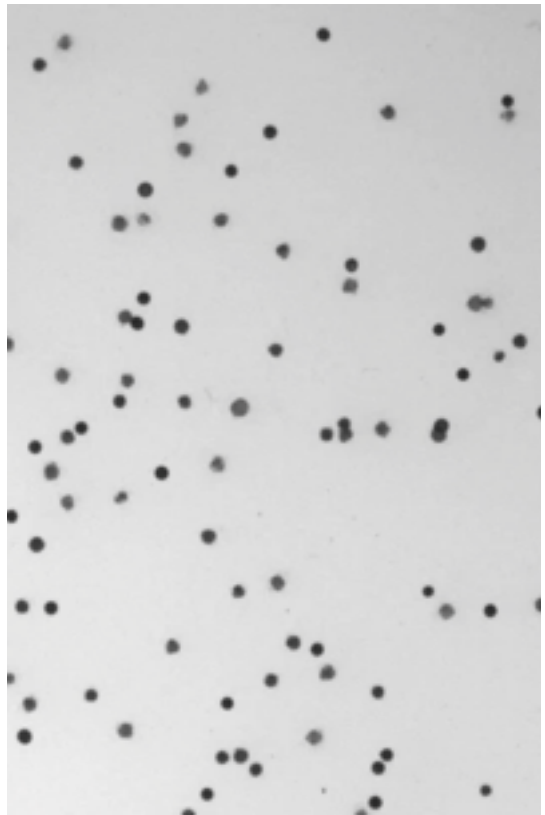
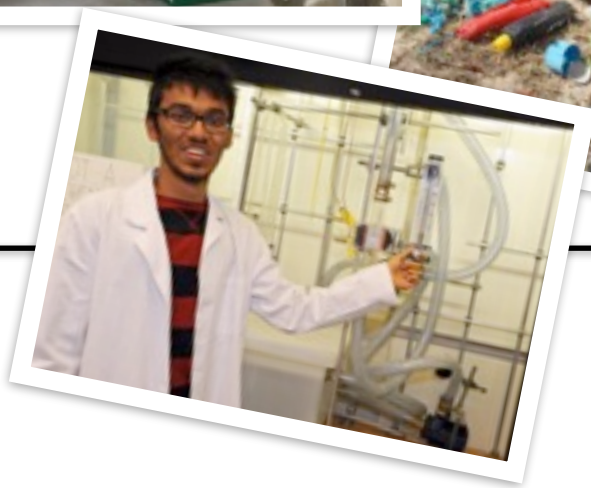
CAL POLY
SAN LUIS OBISPO





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- Focus on pre-service teachers
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Memory

Add information to system → Recover it later

Language for

- Dependence on initial conditions, history
- Nature of a system/material

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- Dependence on initial conditions, history
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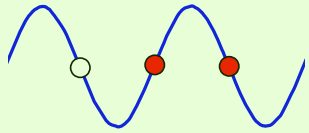
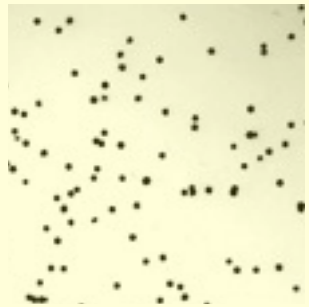
Requirements for material

- Many degrees of freedom
- Changed by external driving (“learning”)
- Can’t relax to equilibrium

Outline



Cyclic driving



Suspensions

Singularities

“Slow”

- Cyclic driving is ubiquitous
- Systems can change/learn *gradually*, over many cycles of driving

Granor

zaui/Scott Catron

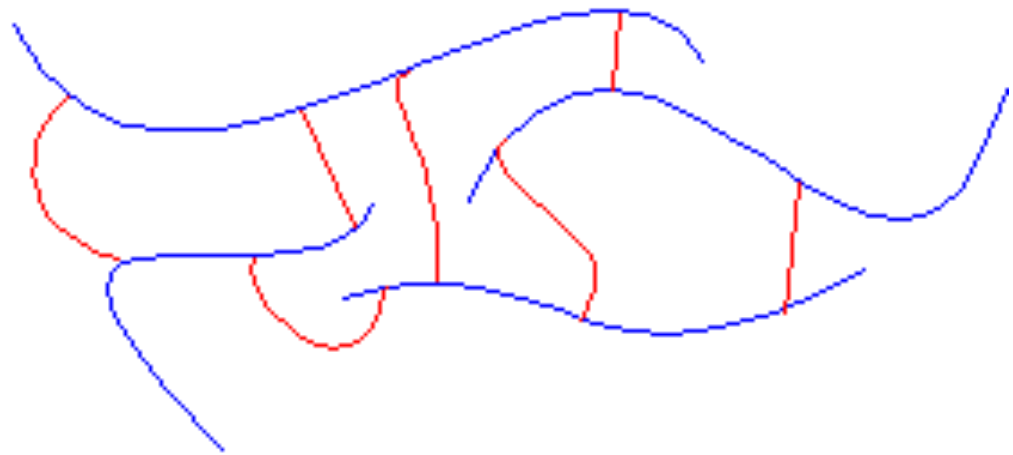
“Slow”

- Cyclic driving is ubiquitous
- Systems can change/learn *gradually*, over many cycles of driving
- Many cycles required to “learn”
  → chance to form multiple memories

How does cyclic driving change a system gradually?

Structure of Rubber

Polymer molecules



Crosslinked rubber

Crosslinks are weaker than original molecules

What happens after *repeated* stretching?

What happens after *repeated* stretching?

1. The rubber changes on the first cycle only
2. The rubber changes over many cycles
3. The rubber warms up but is otherwise unchanged
4. Things do not end well for the rubber

What happens after *repeated* bending?

What happens after *repeated* bending?

1. The metal changes on the first cycle only
2. The metal changes over many cycles
3. The metal warms up but is otherwise unchanged
4. Things do not end well for the metal

Experiment

Bend your wire cyclically!

This side:
Bend to **90°** and
back **twice**

This side:
Bend to **45°**,
then **90°** and back

How many cycles before failure?

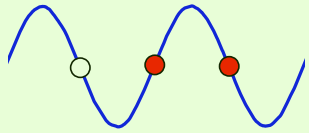
What happens after *repeated* crumpling?

1. The sheet will keep reusing the creases I made the first time
2. Eventually I will stop making new creases
3. Crumping a sheet *always* makes new creases

Crumpling a Sheet:
A steady state*

**approximately*

Outline



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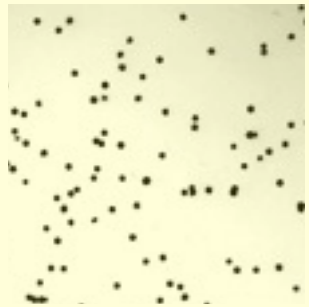

Suspensions

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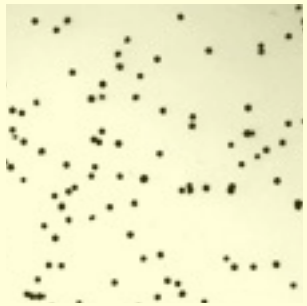


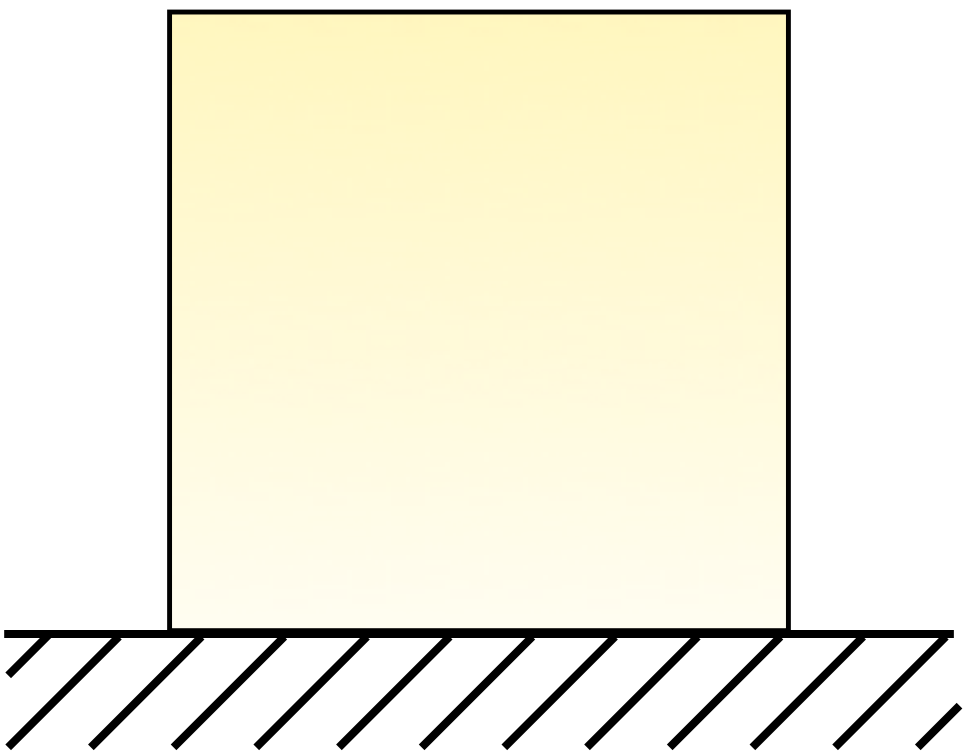
Suspensions

With Sidney Nagel,
Joseph Paulsen
(Chicago, Syracuse)

Funding: **NSF Chicago MRSEC**

Shear and shear strain

Take any material…



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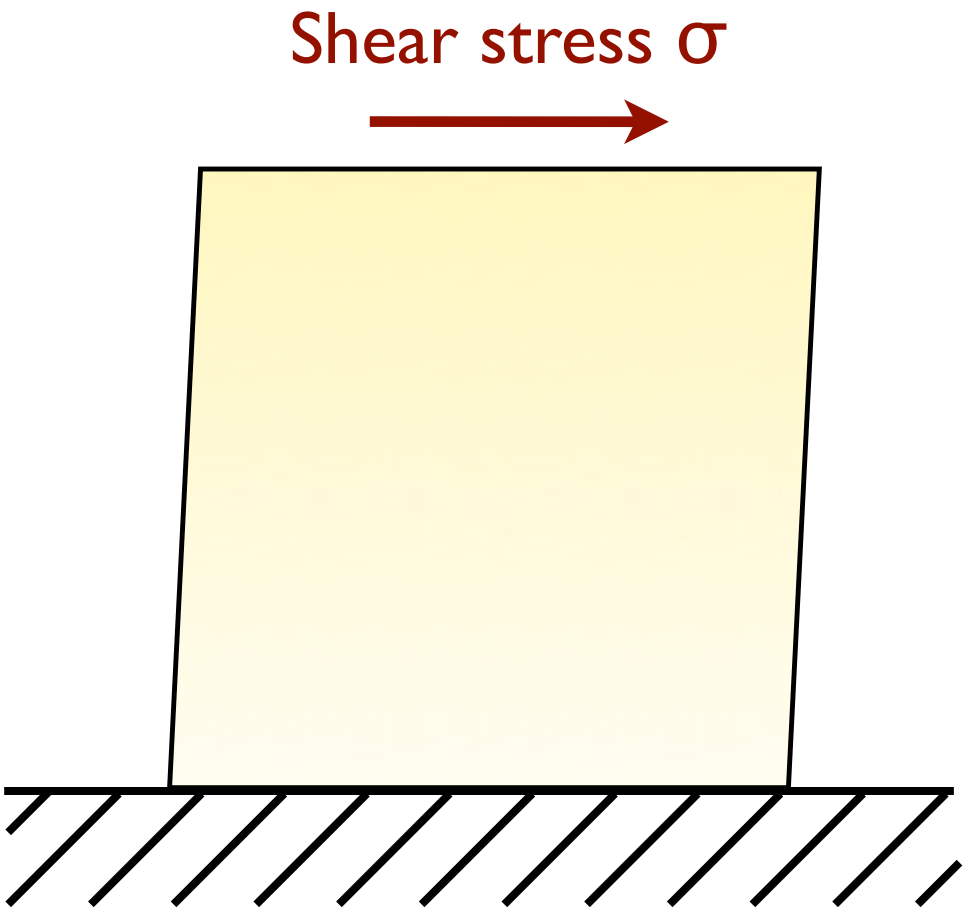

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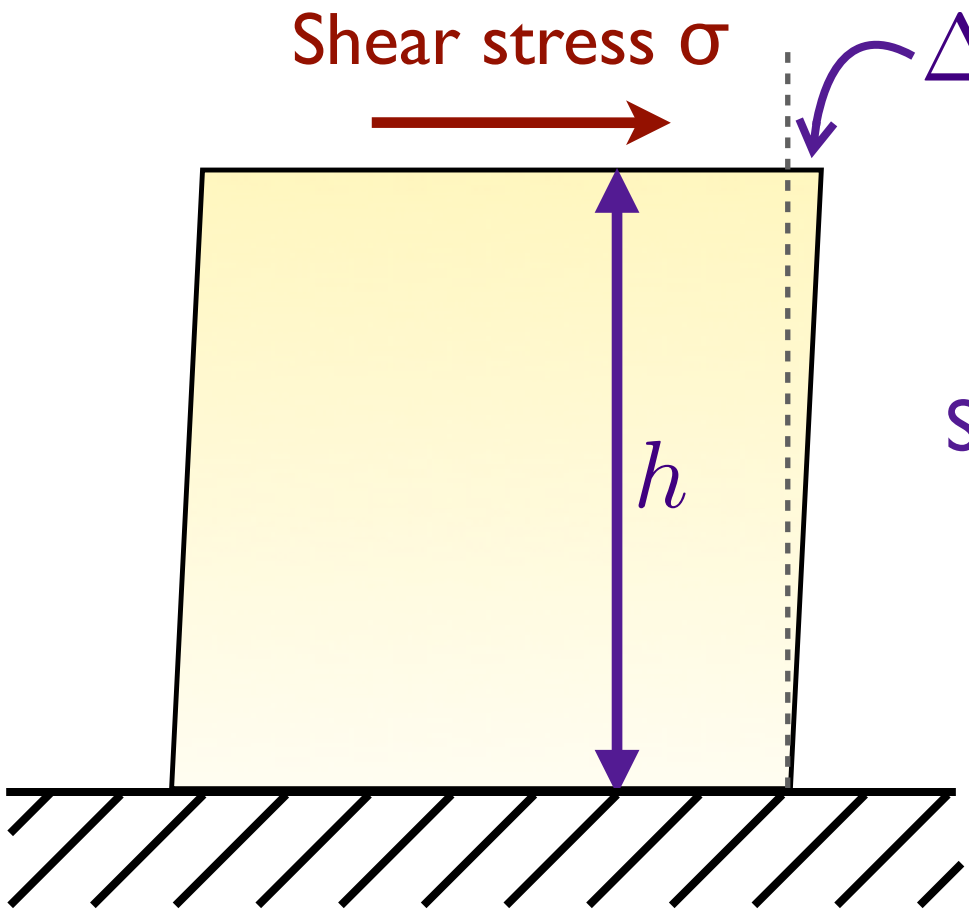

Strain:

$$\gamma = \frac{\Delta x}{h}$$

Oscillatory (or cyclic) shear

$$\gamma = \gamma_0 \sin \omega t$$

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Cyclically sheared suspensions

Acrylic beads in viscous liquid
Diffusion negligible

Bead diameter: 0.6 mm

Pine, Gollub, Brady, Leshansky, *Nature* 2005

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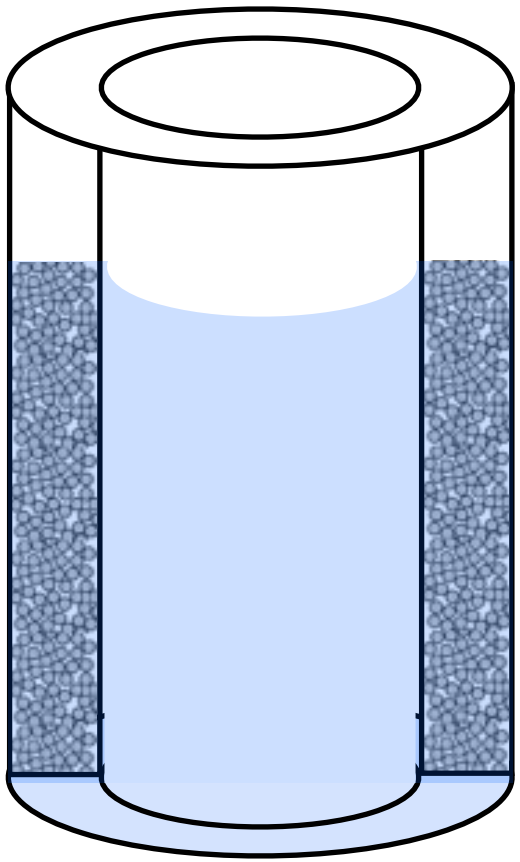

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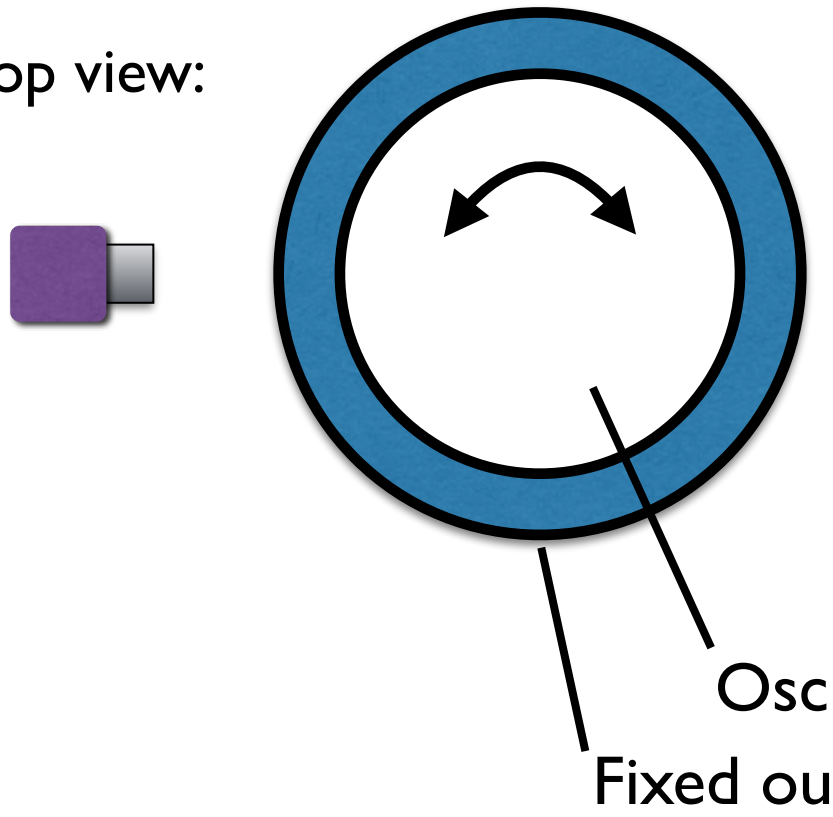

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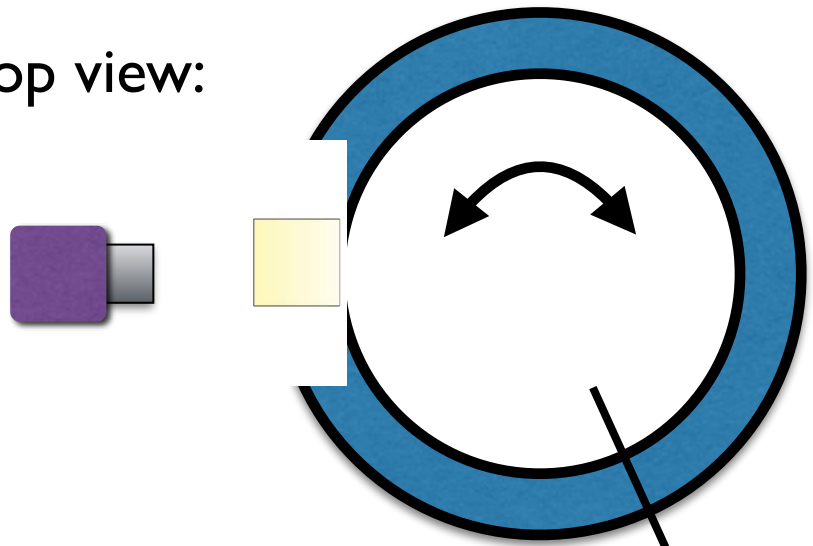

Oscillating inner cylinder

Fixed outer cylinder

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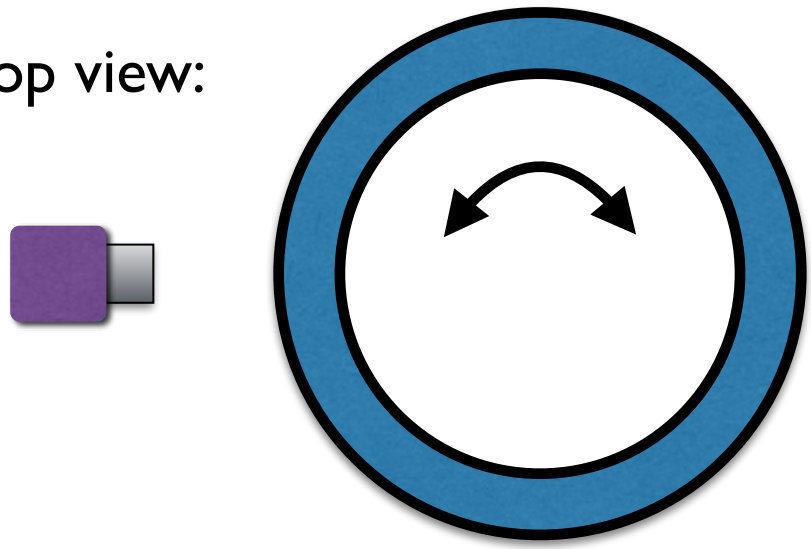

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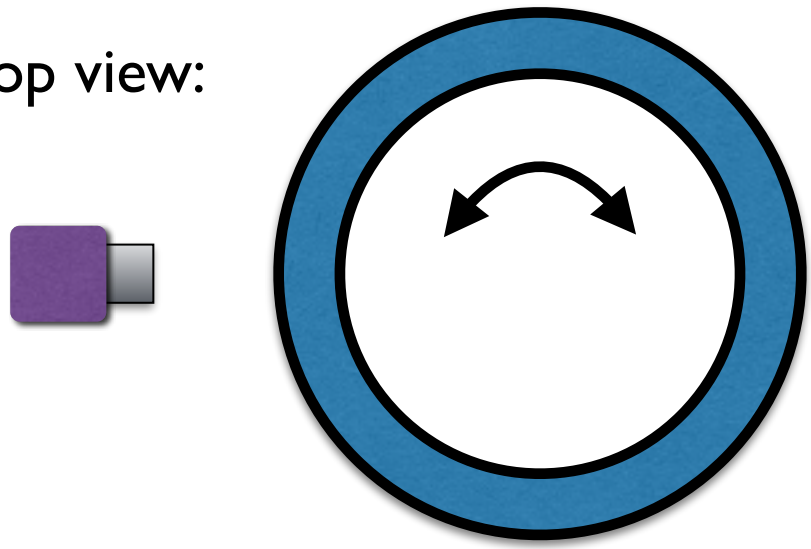

30% particles by volume
(99.5% are transparent)

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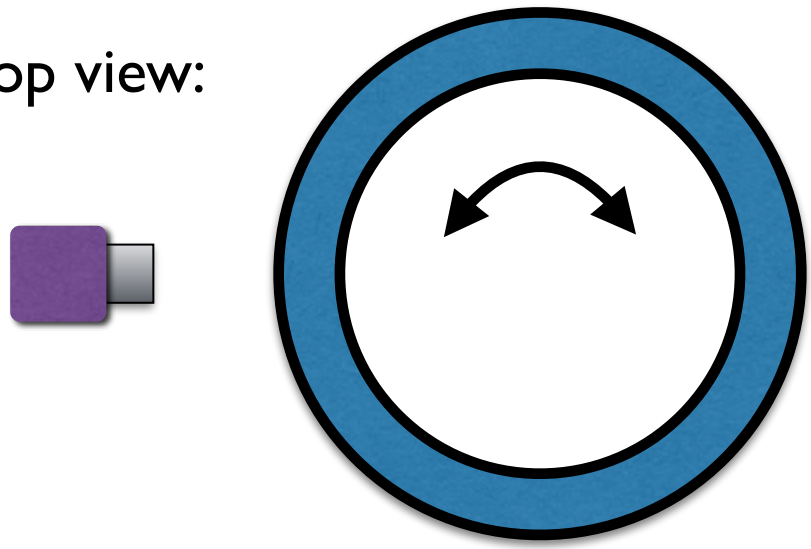

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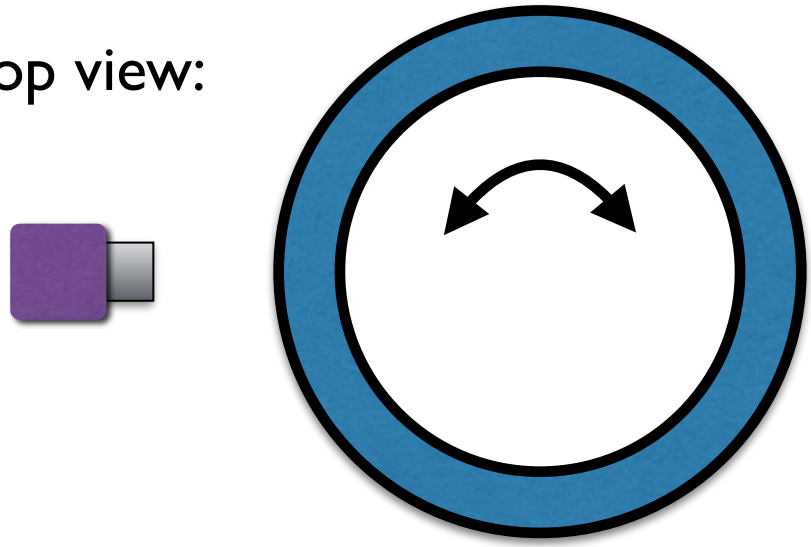

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Image once per cycle →

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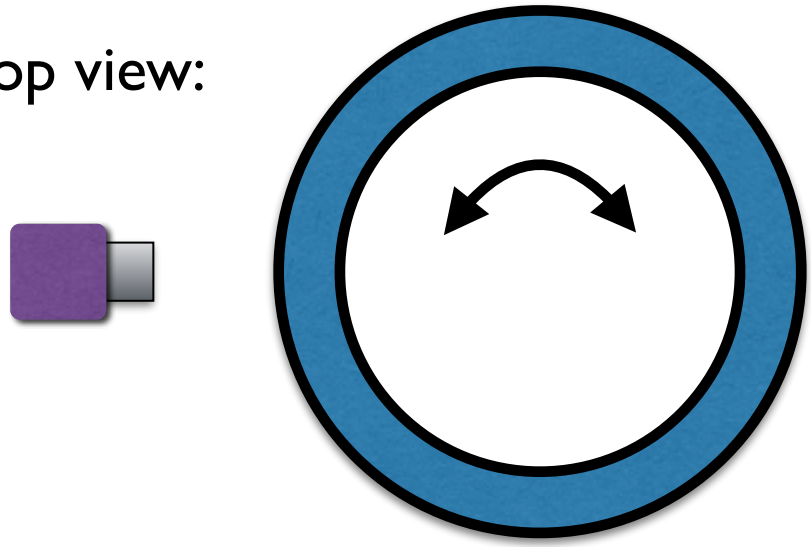

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Why are the particles agitated?

Simple model that works:

1. Shear box with particles in it
2. If particles collide during shear, move them
3. Repeat

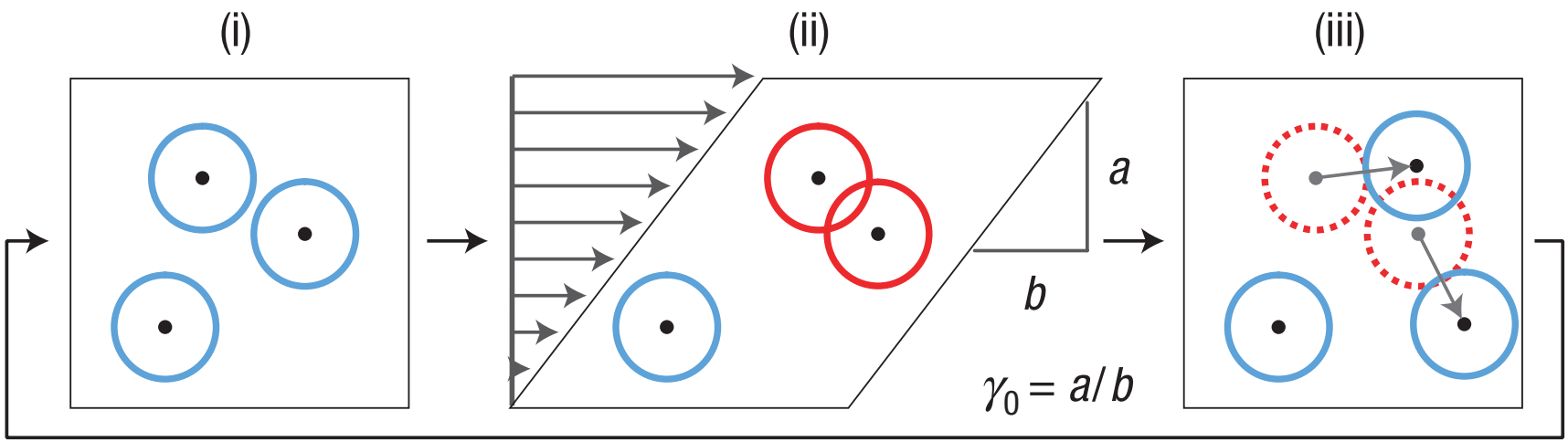

Diagram from Corté, Chaikin, Gollub, Pine, *Nature Phys.* 2008

Sheared Suspension Experiment

Image once per cycle →

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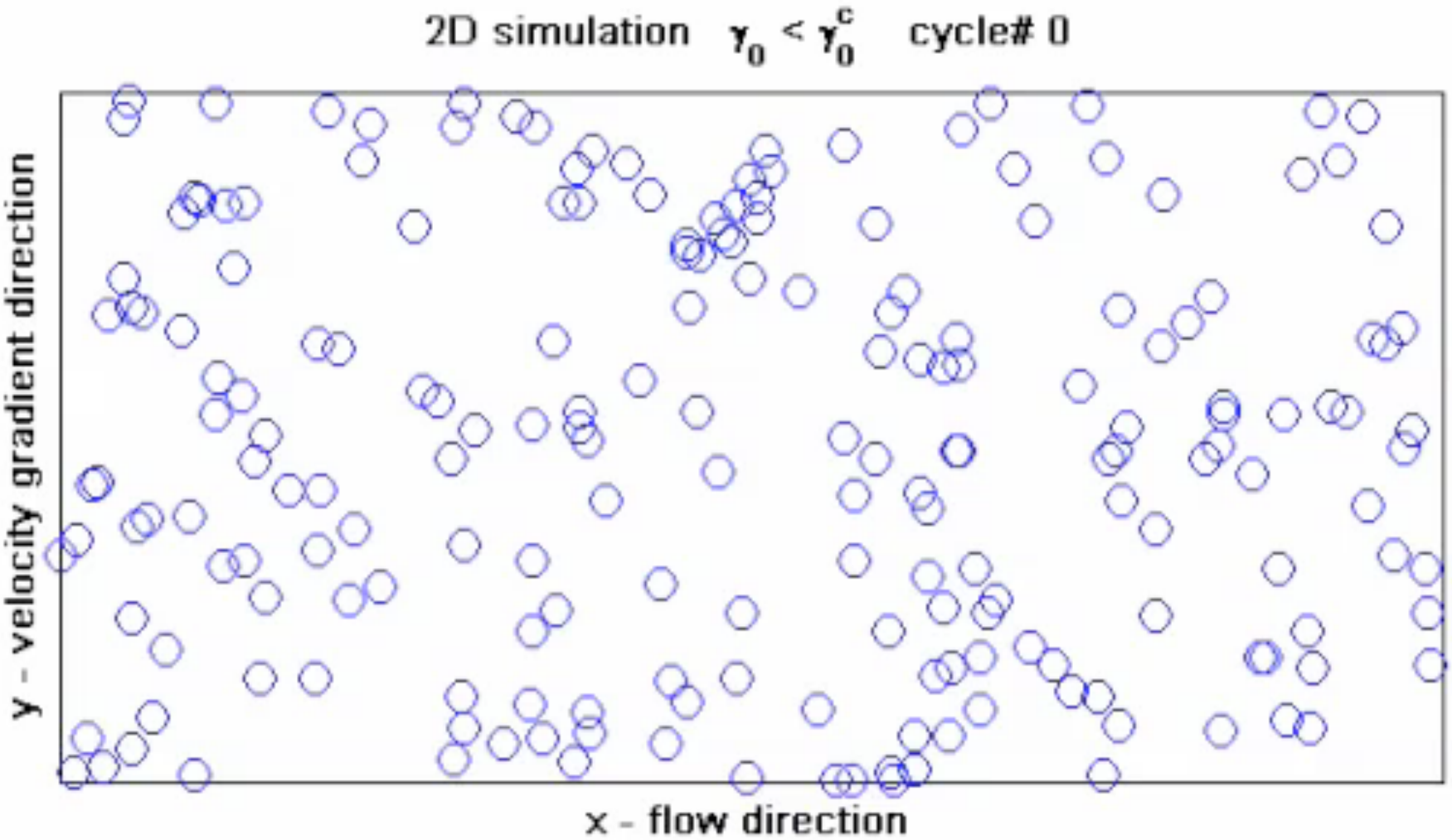
Stroboscopic video of particle positions

Corté, Chaikin, Gollub & Pine, 2008

"Train" with oscillatory shear, constant amplitude



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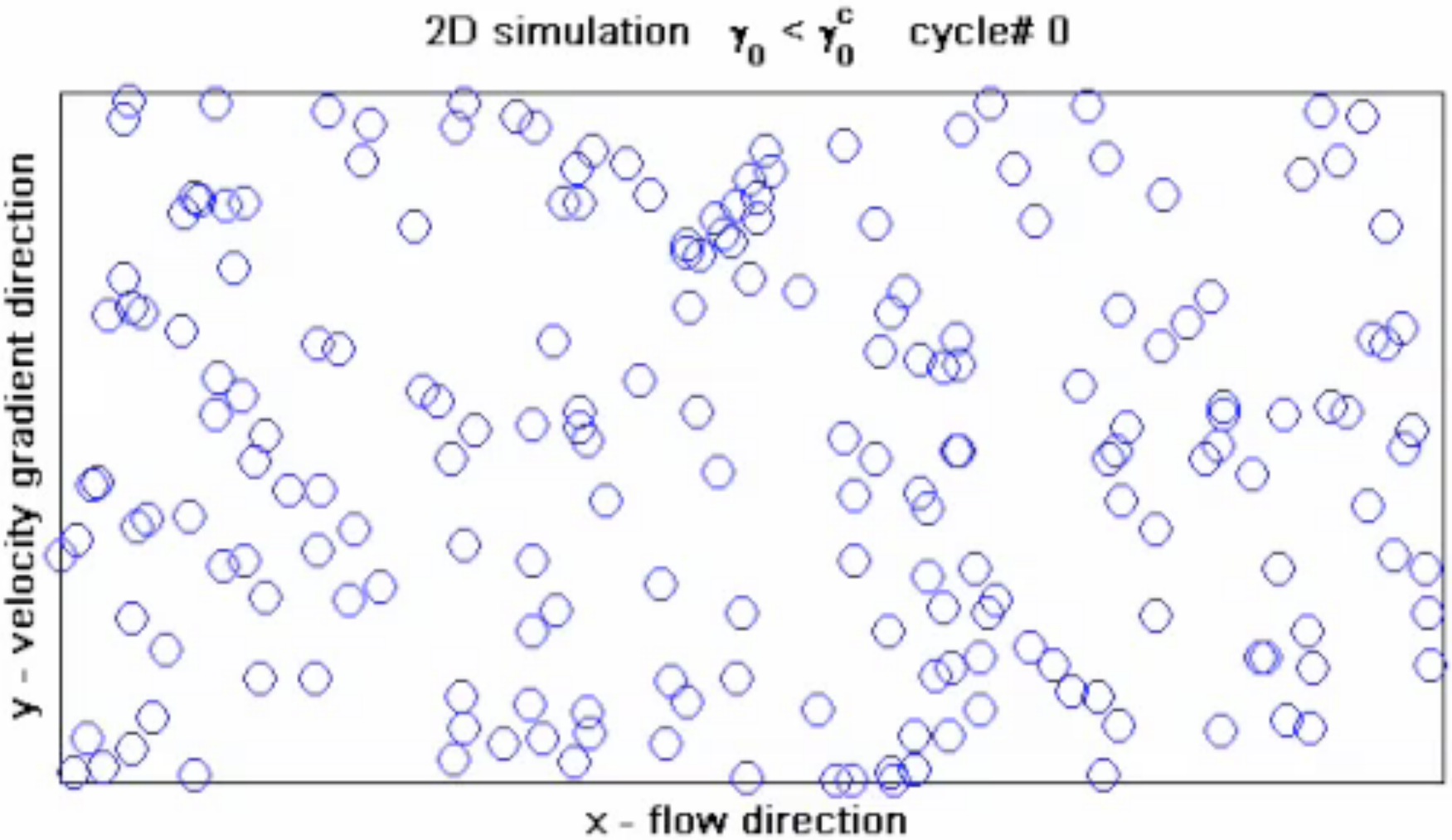
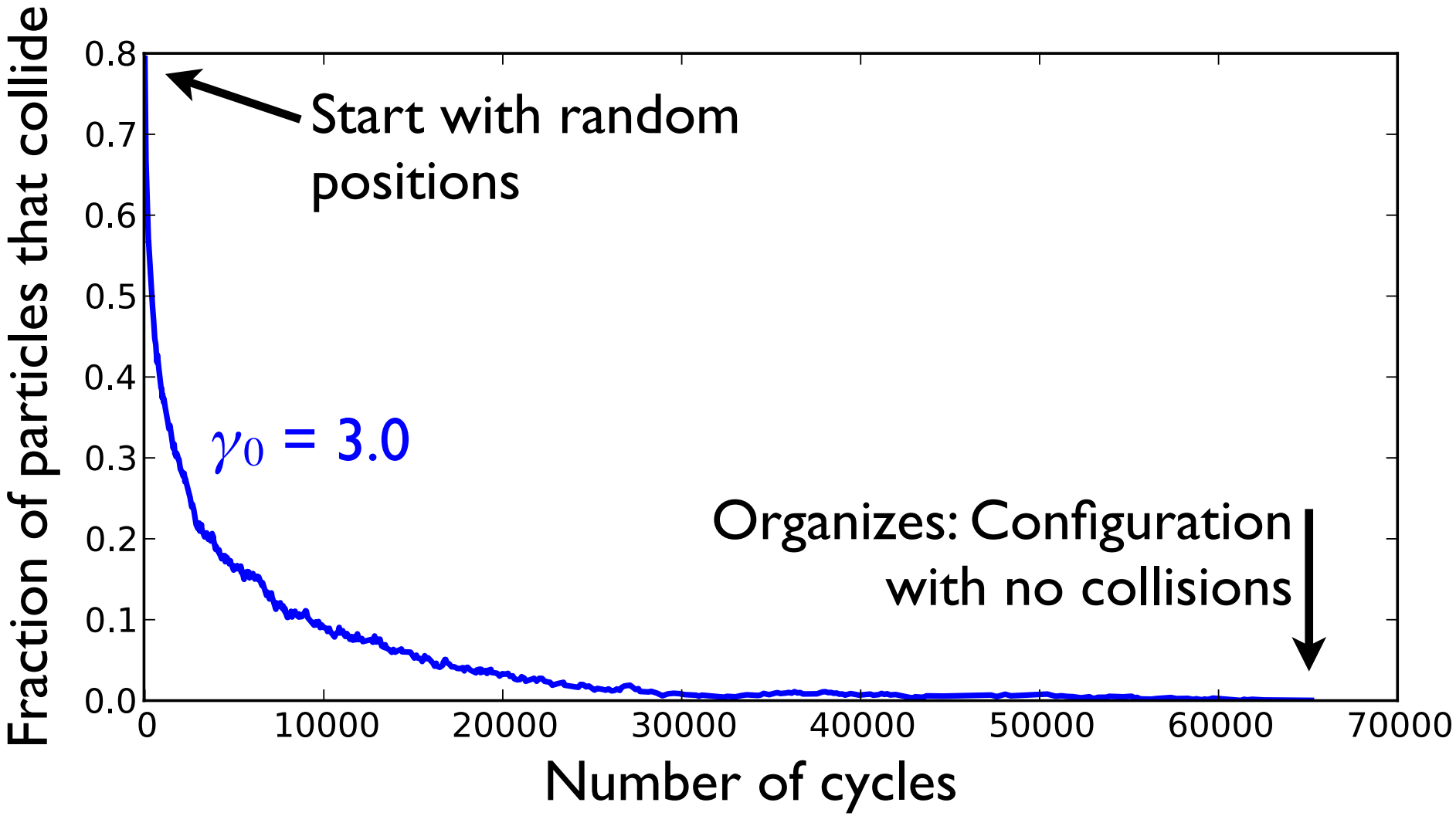


"Learning" in sheared particles

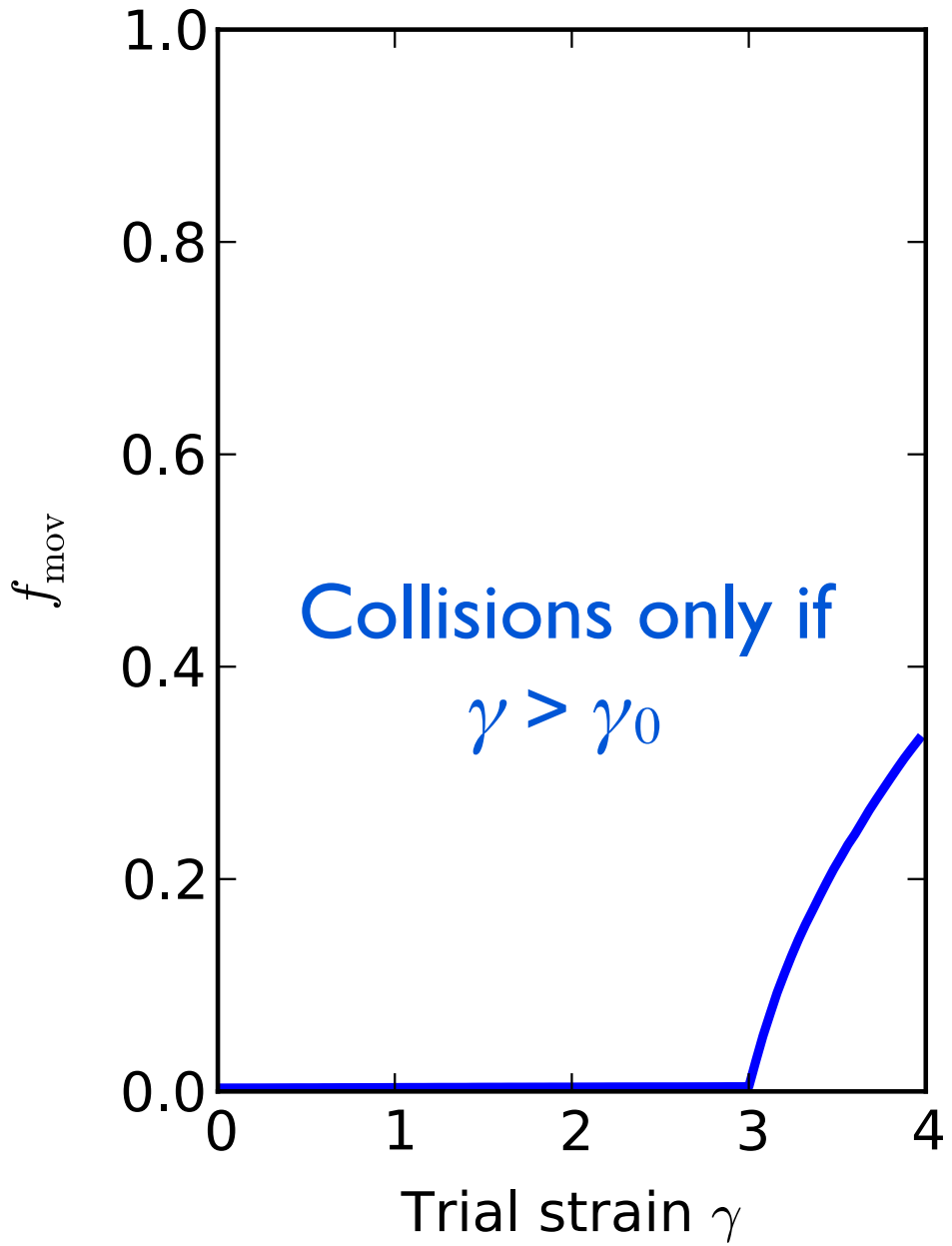


Same behavior as in experiment

Organization ➔ Memory

- System remembers the strain amplitude γ_0 that was applied repeatedly

- To read out γ_0: ramp up γ until particles begin to move



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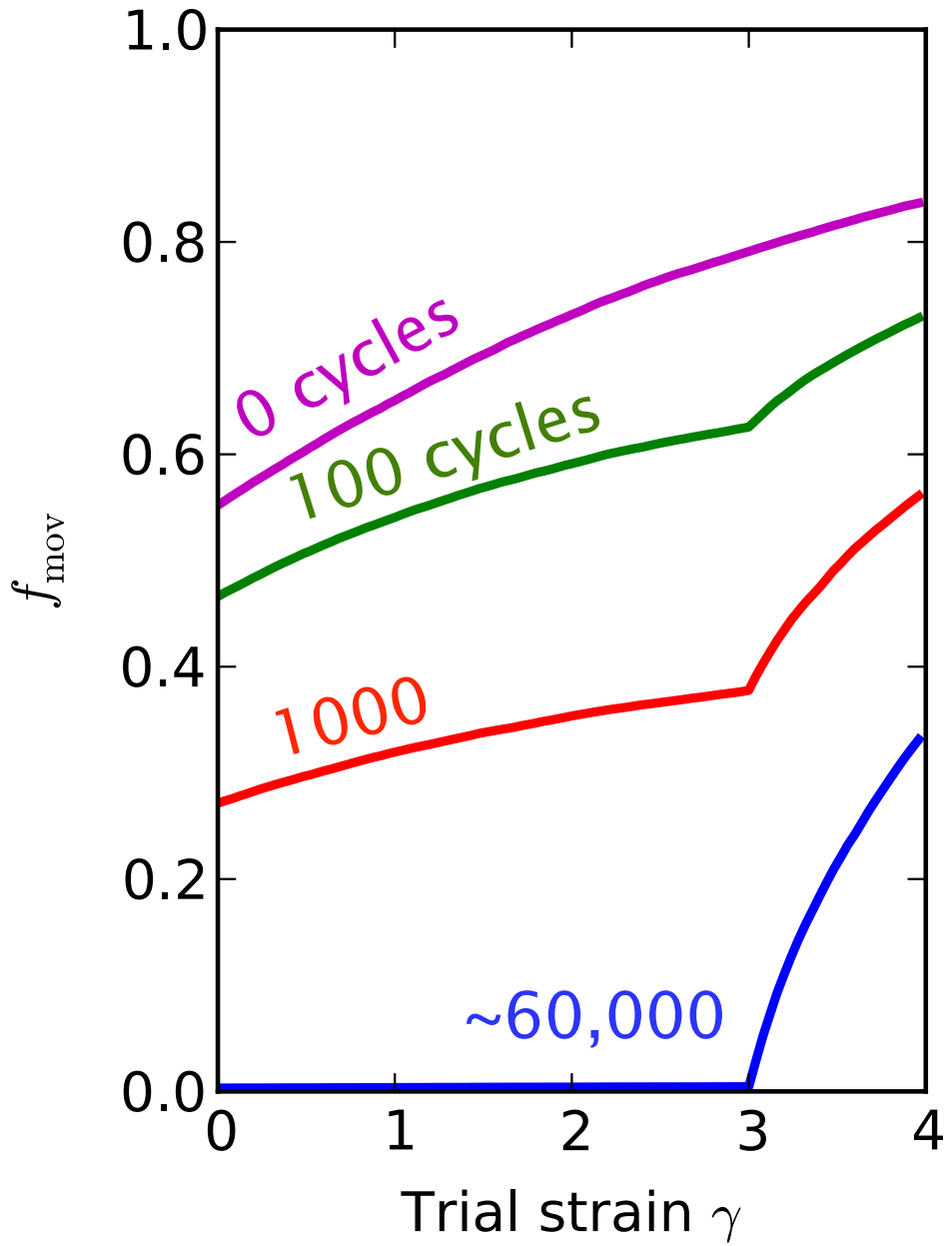
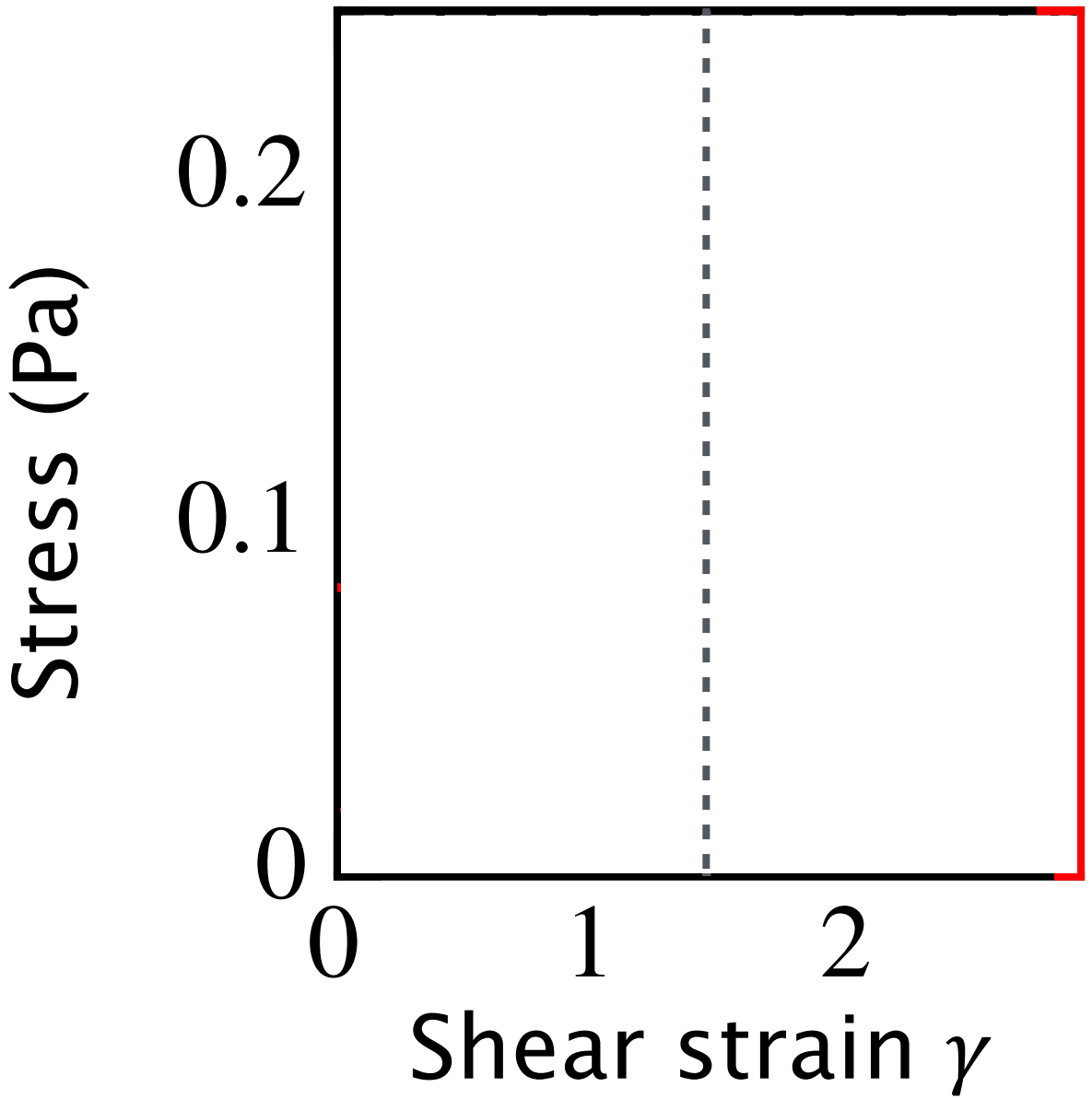


Train with 10 cycles of $\gamma_0 = 1.44$

Read out:



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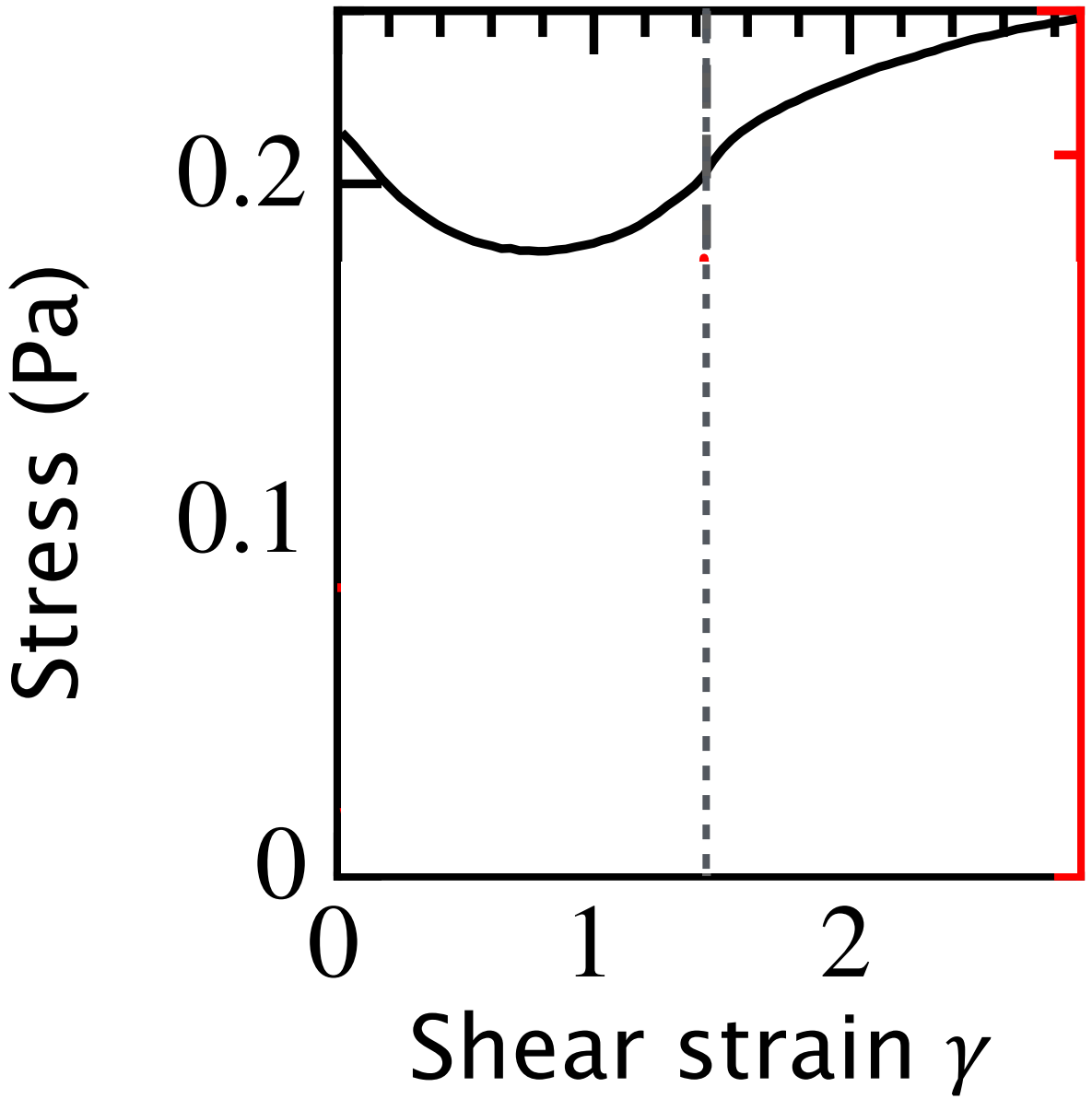

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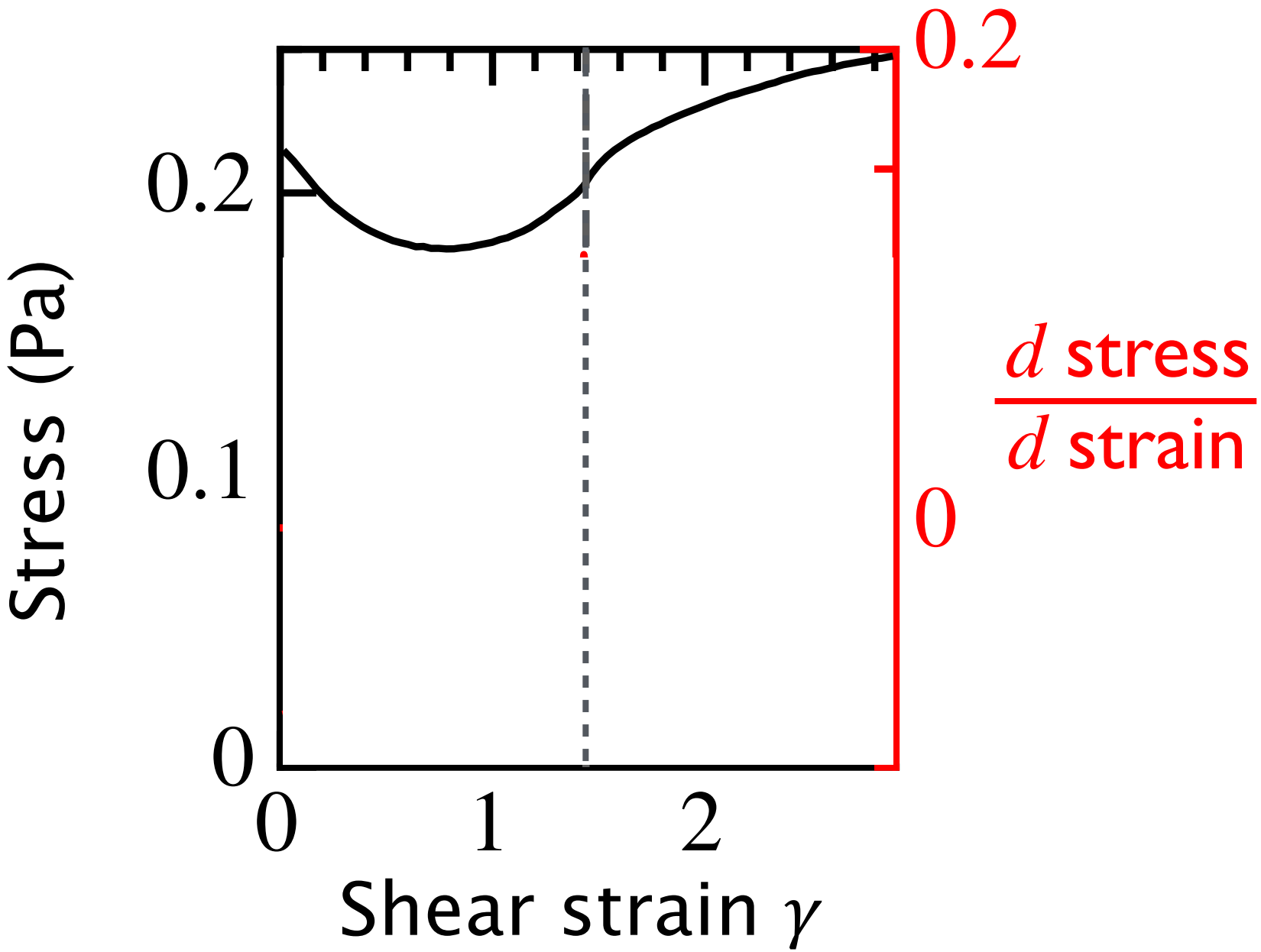

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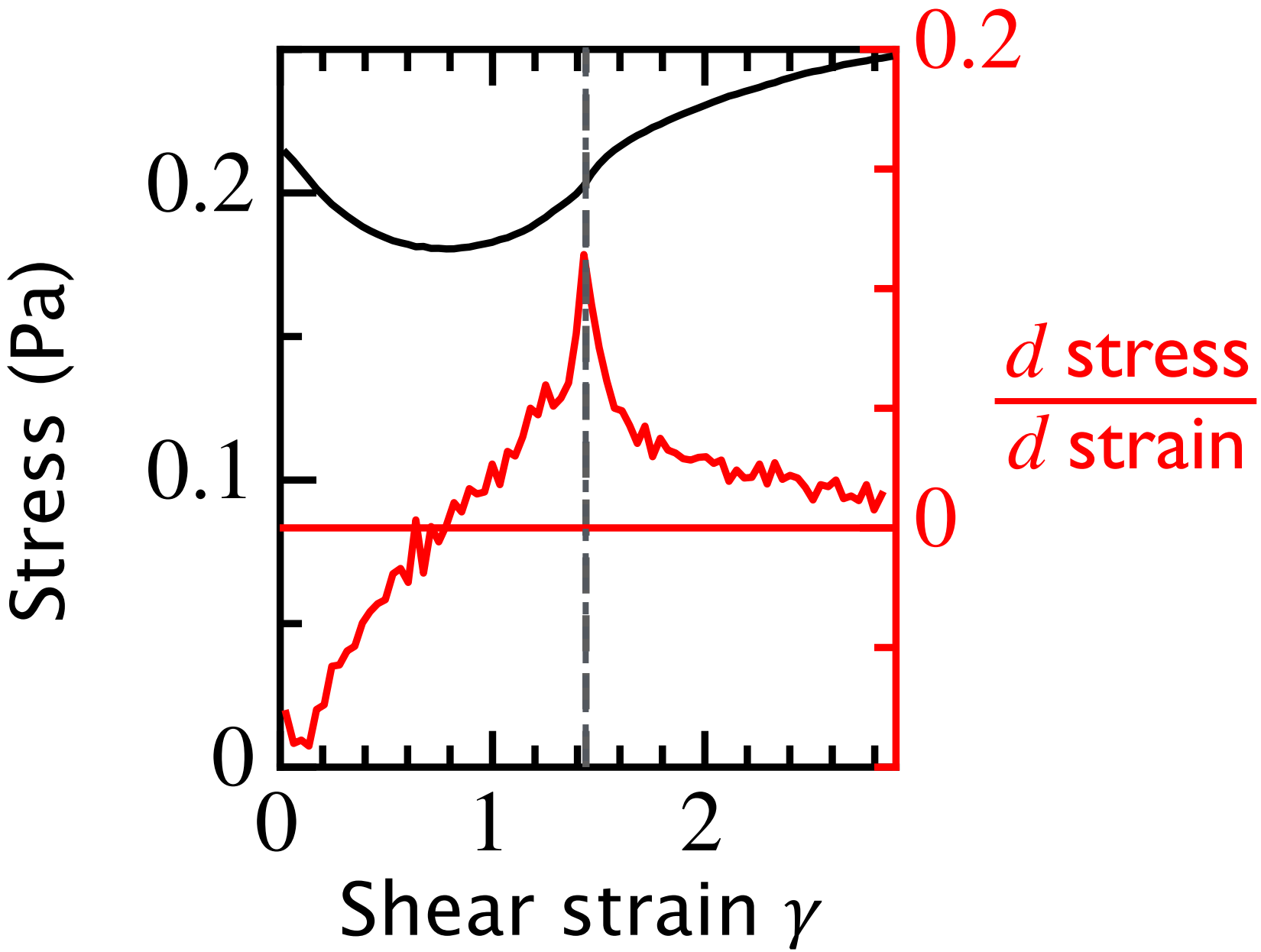
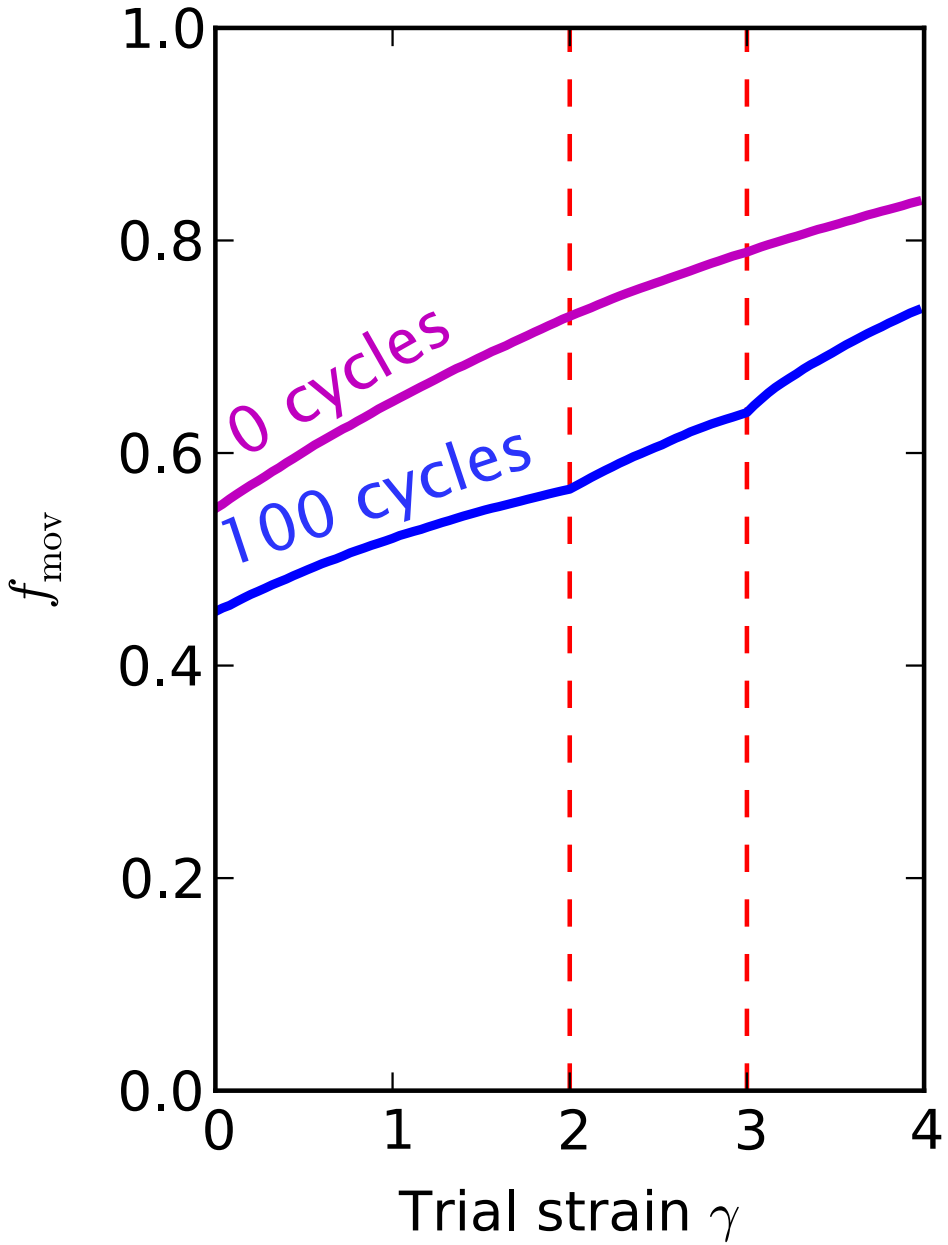


Multiple memories?

Multiple memories

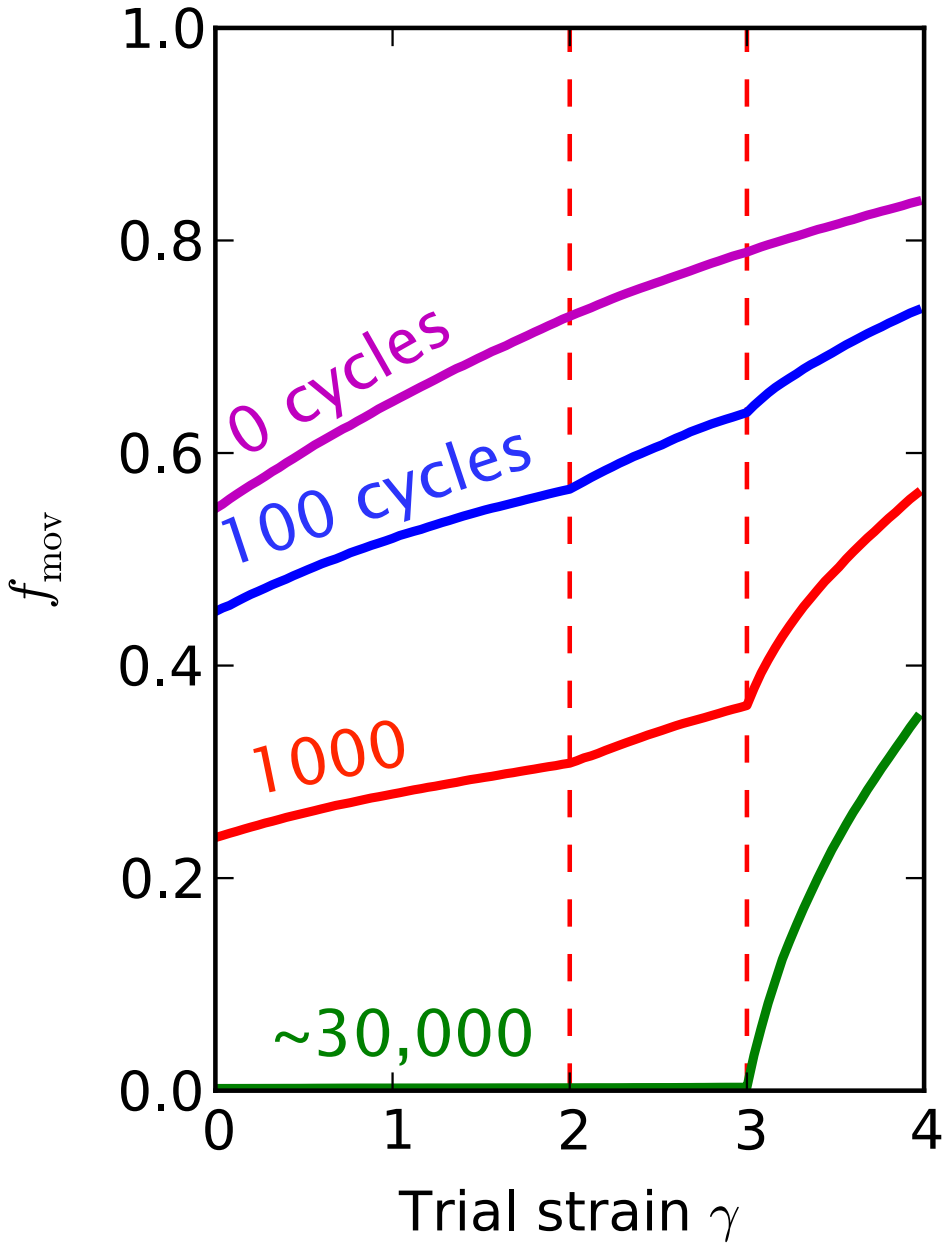
- Apply pattern
  3, 2, 2, 2, 2, 2, **3**, 2, 2, 2, 2, 2, …



Keim & Nagel, PRL *2011*

Multiple memories

- Apply pattern
  3, 2, 2, 2, 2, 2, **3**, 2, 2, 2, 2, 2, …
- When learning is complete, only highest value remains!



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Two memories

Strain amplitudes 1.6, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, repeat…

Paulsen, Keim, Nagel, *PRL* 2014

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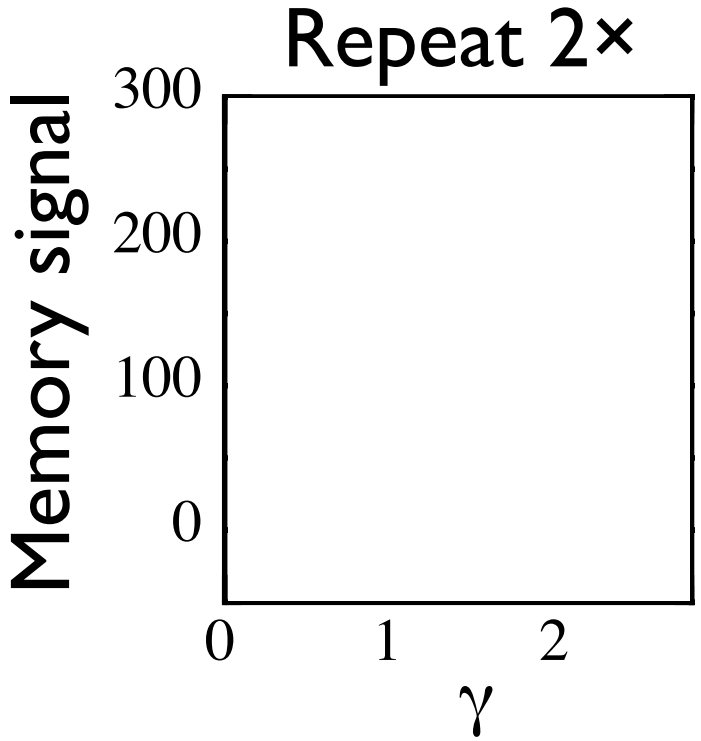

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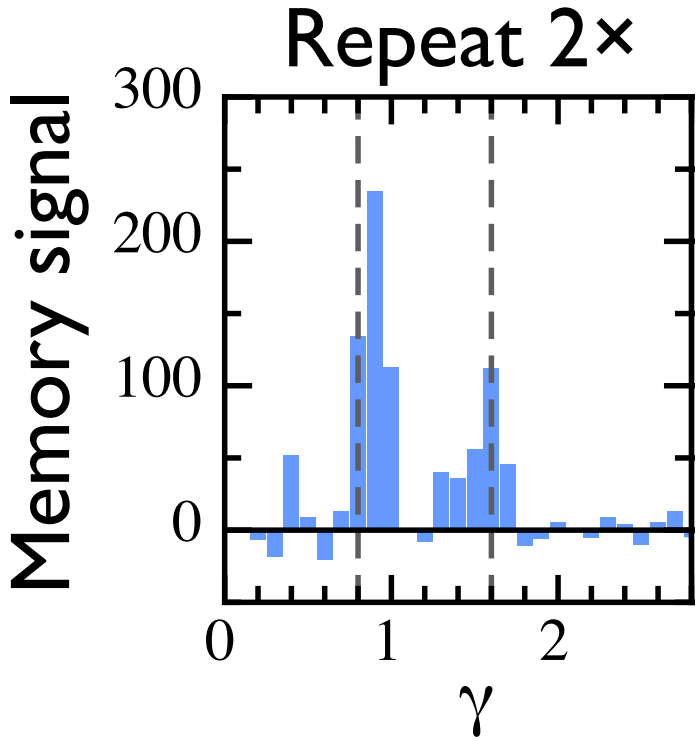

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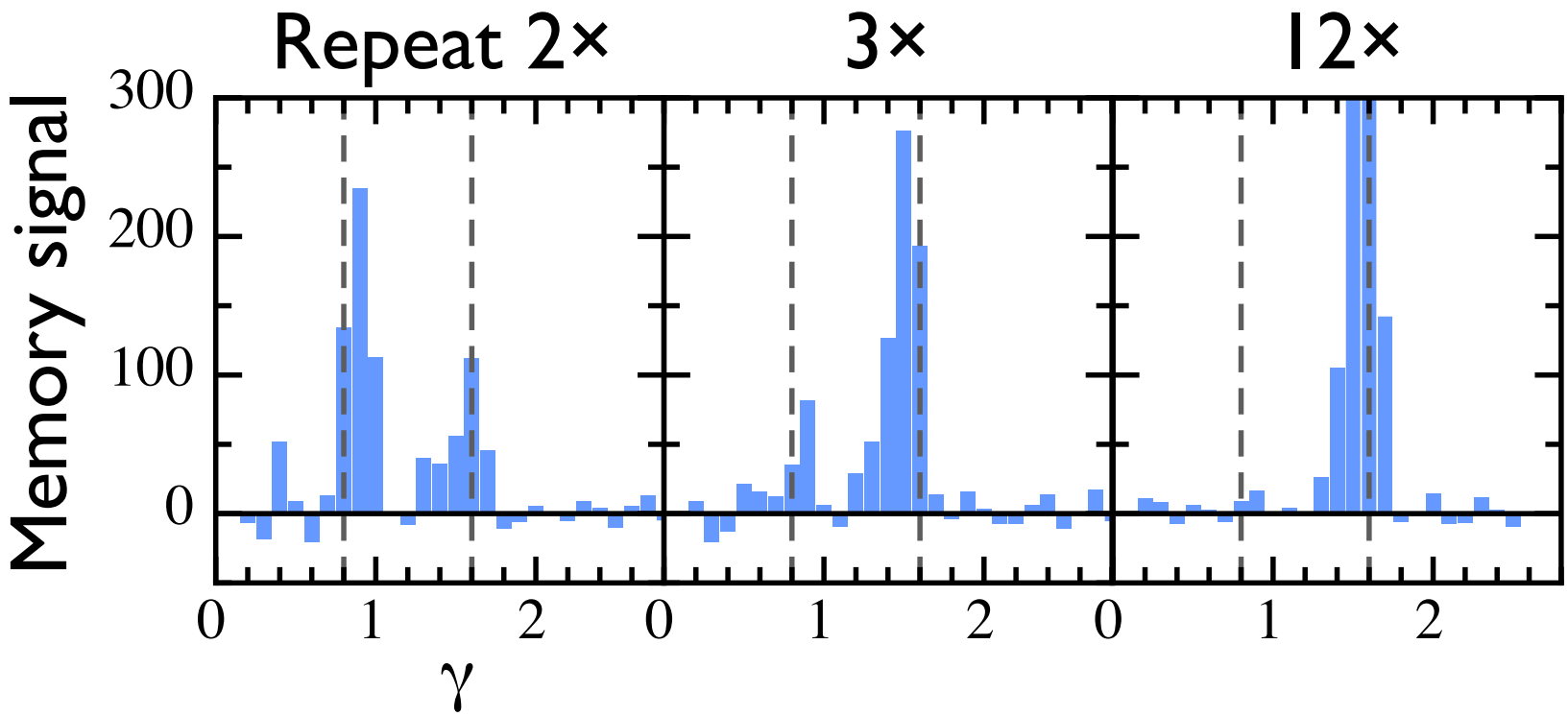

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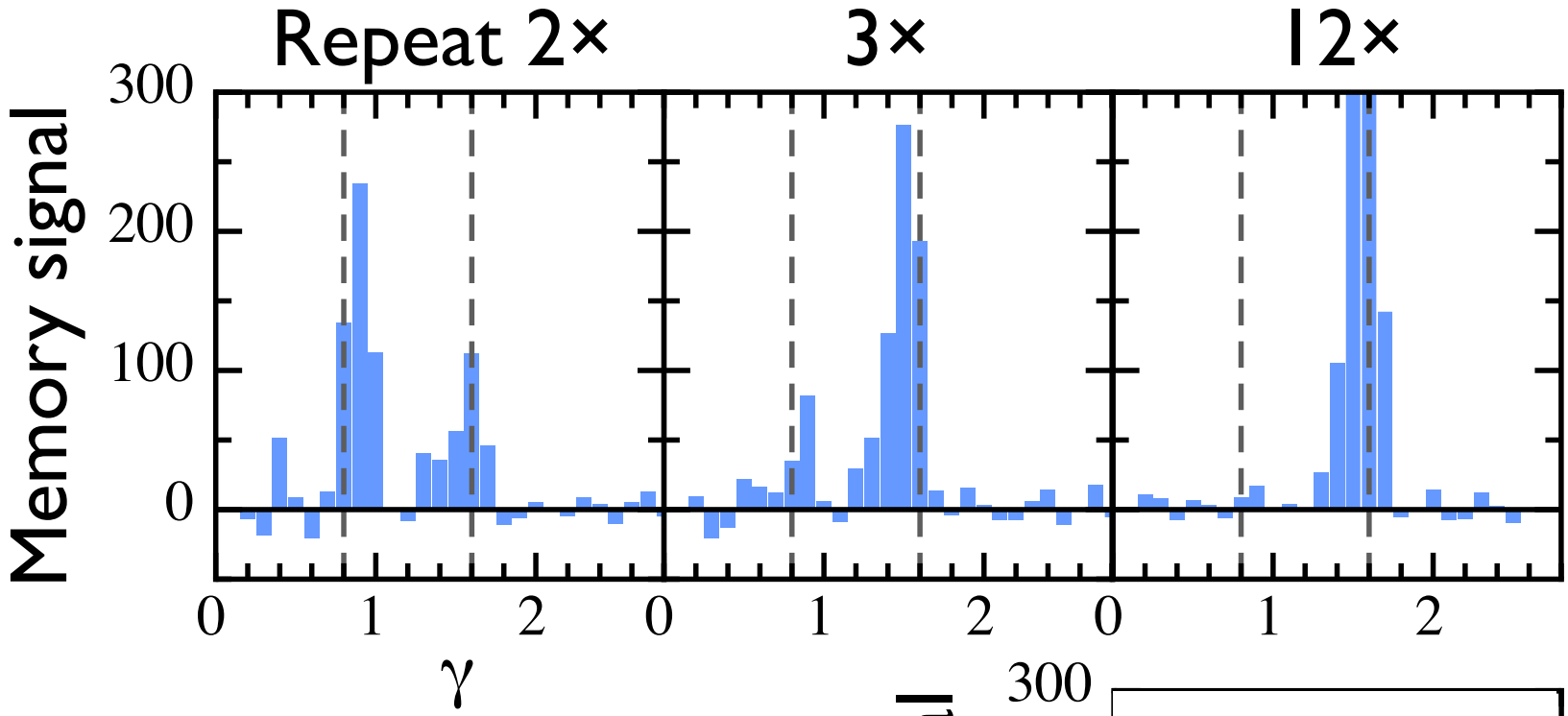
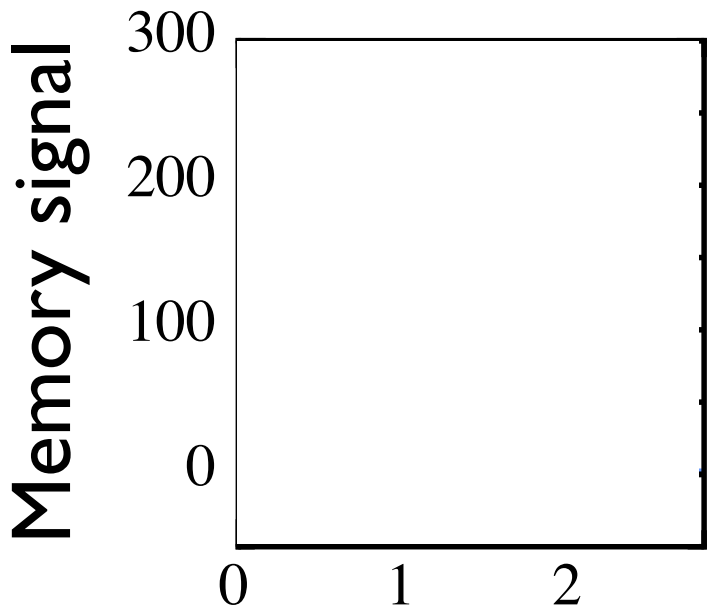


Add noise
(Wait 8 minutes
between cycles)



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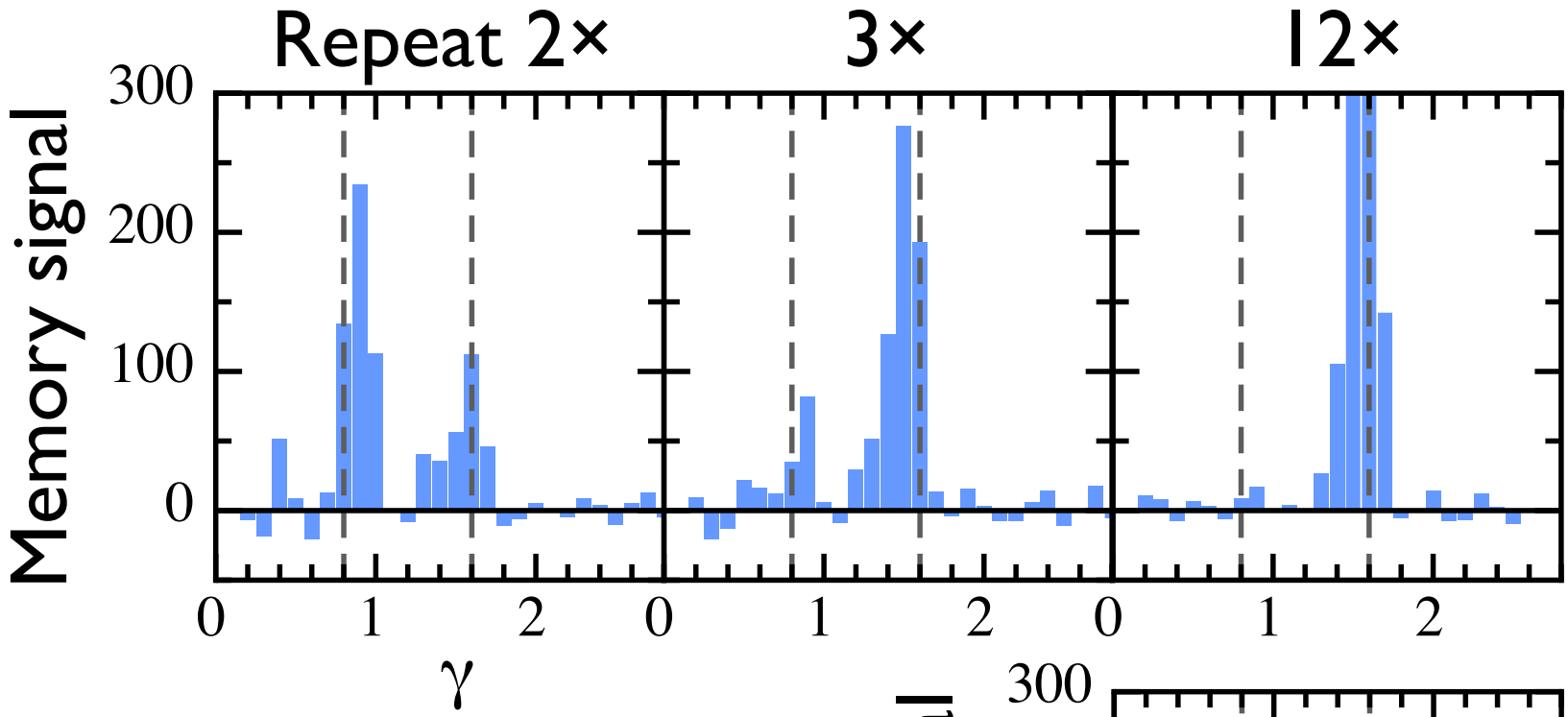

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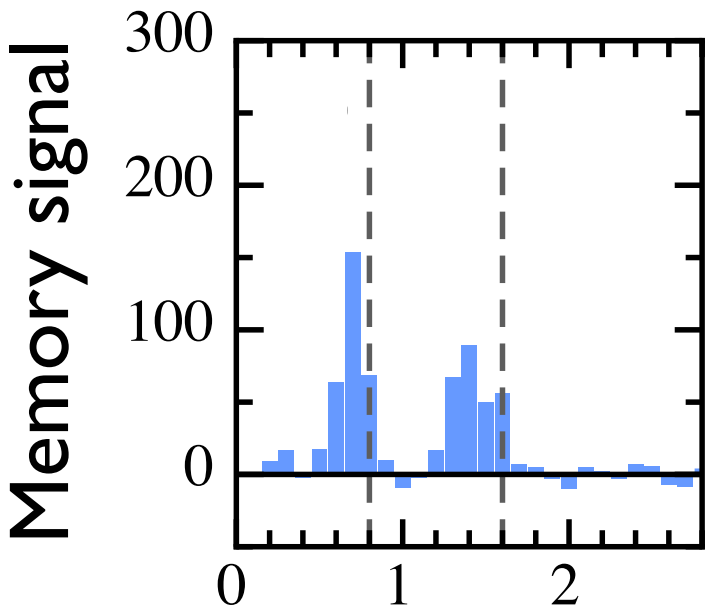

Paulsen, Keim, Nagel, *PRL* 2014

Memory in Sheared Suspensions

- Can learn multiple values of strain
- After many cycles, forgets all but largest
- Noise helps it remember!

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  Coppersmith, S. N. *et al. Phys. Rev. Lett.* 1997

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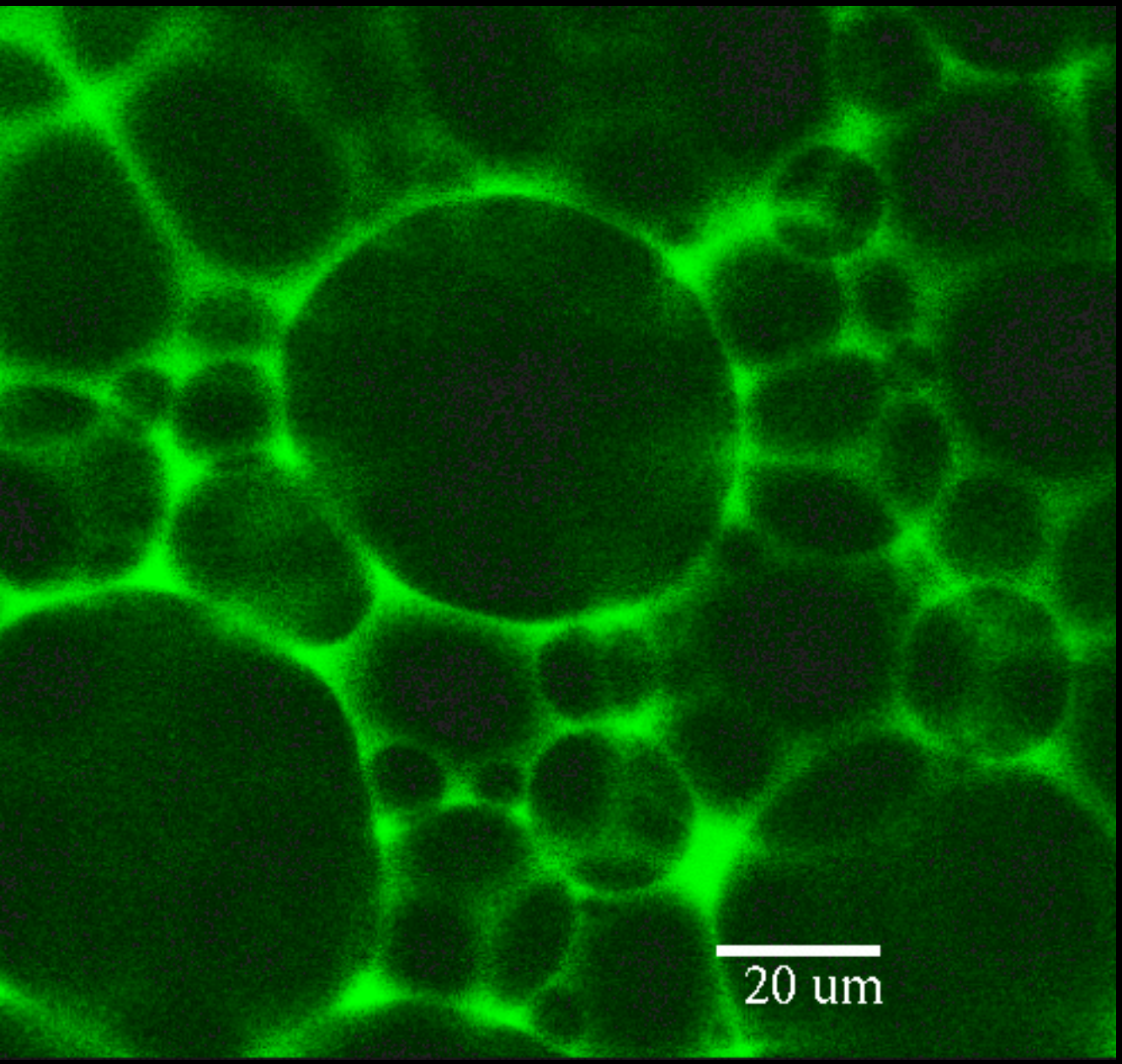
- Other materials?

Mayonnaise

- many degrees of freedom
- changed by driving (soft)
- non-equilibrium



Weeks Lab, Emory U.

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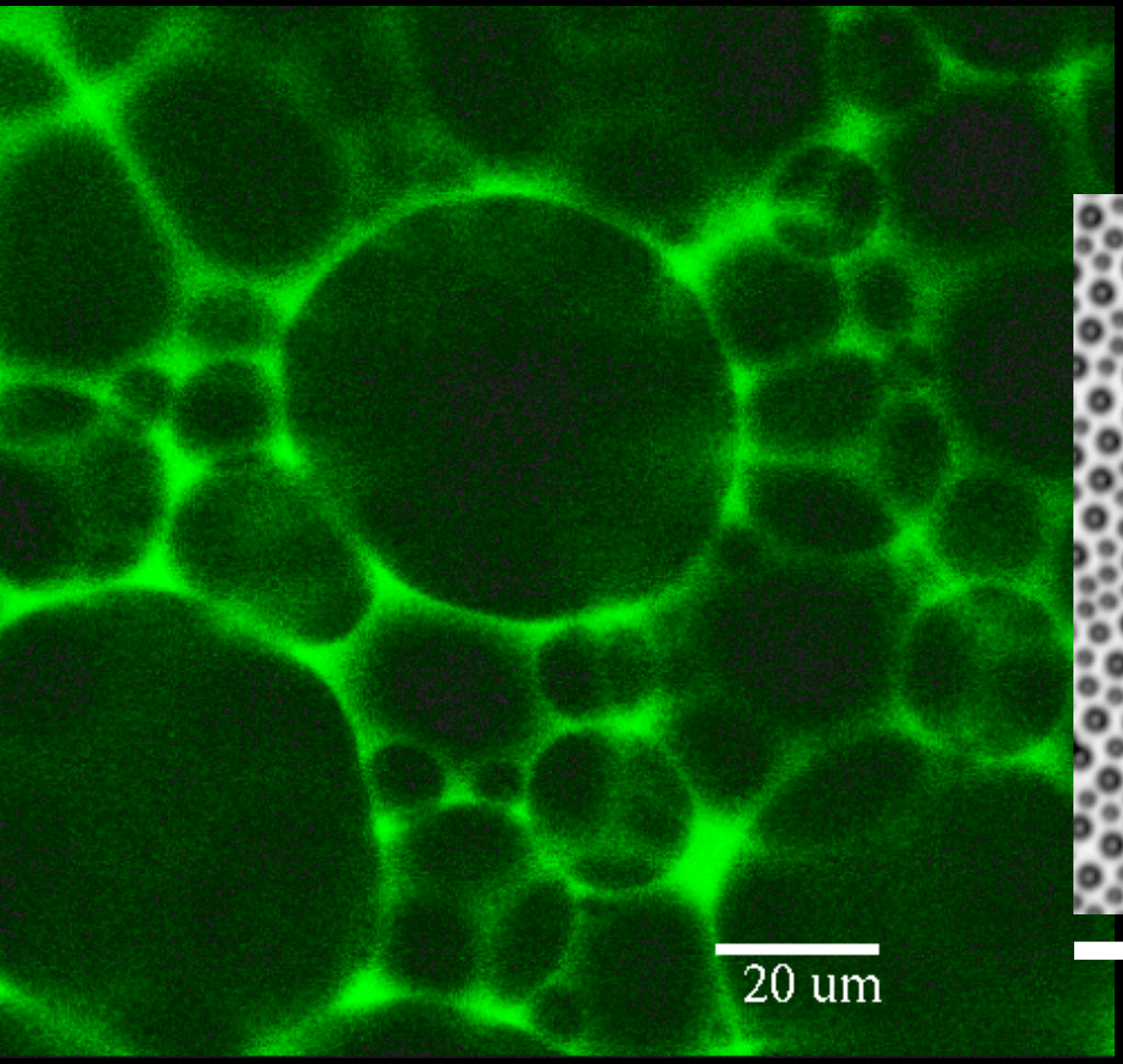
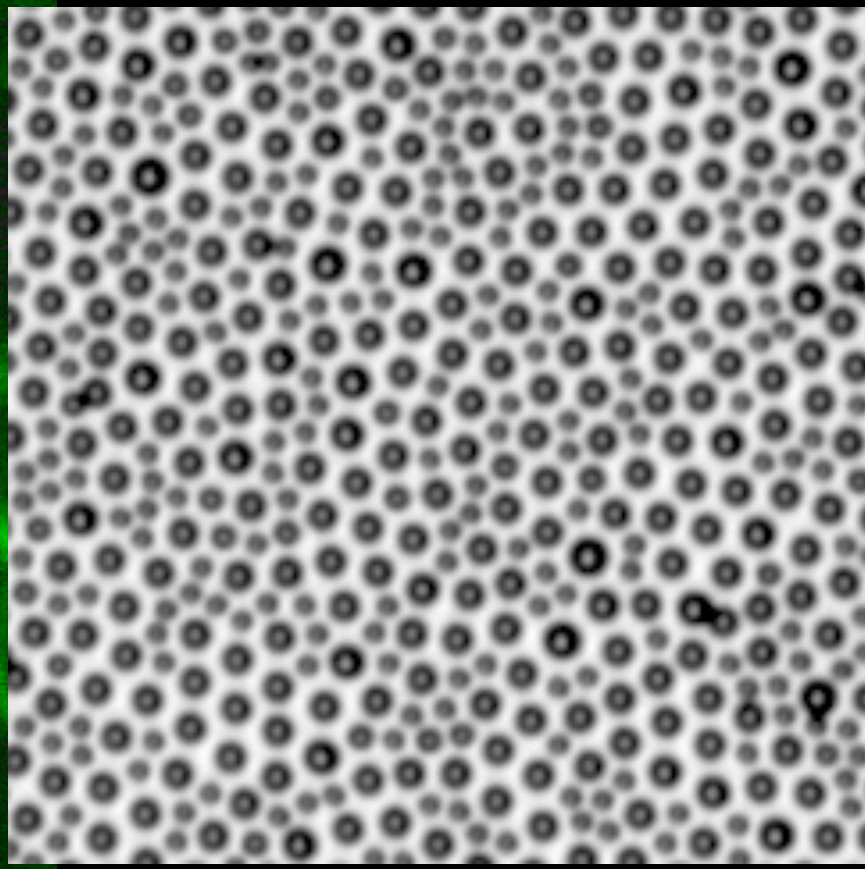


"2D mayonnaise"
at Cal Poly



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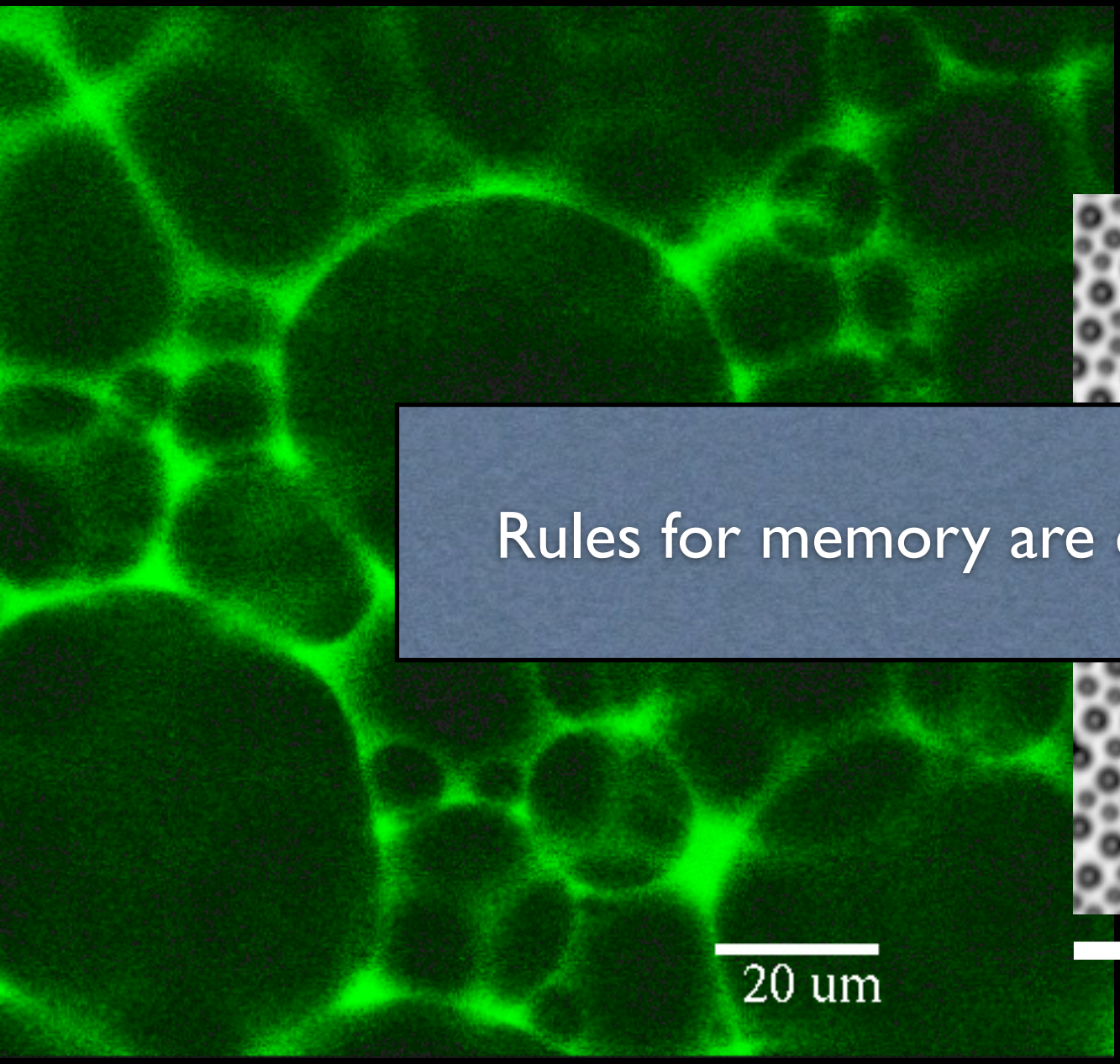

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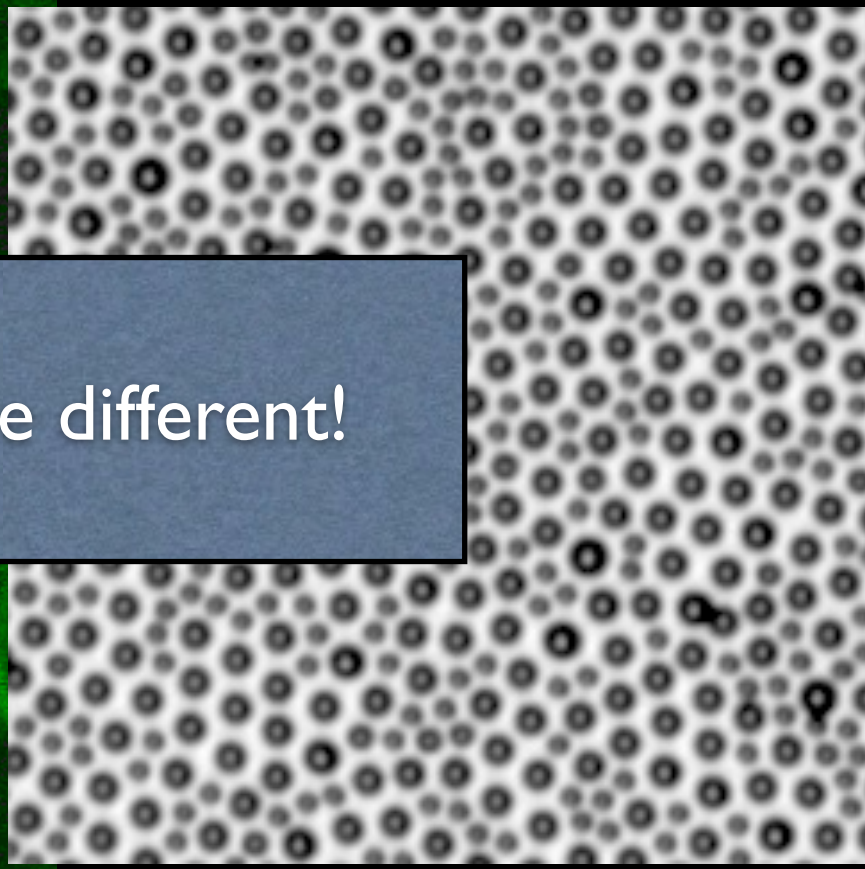
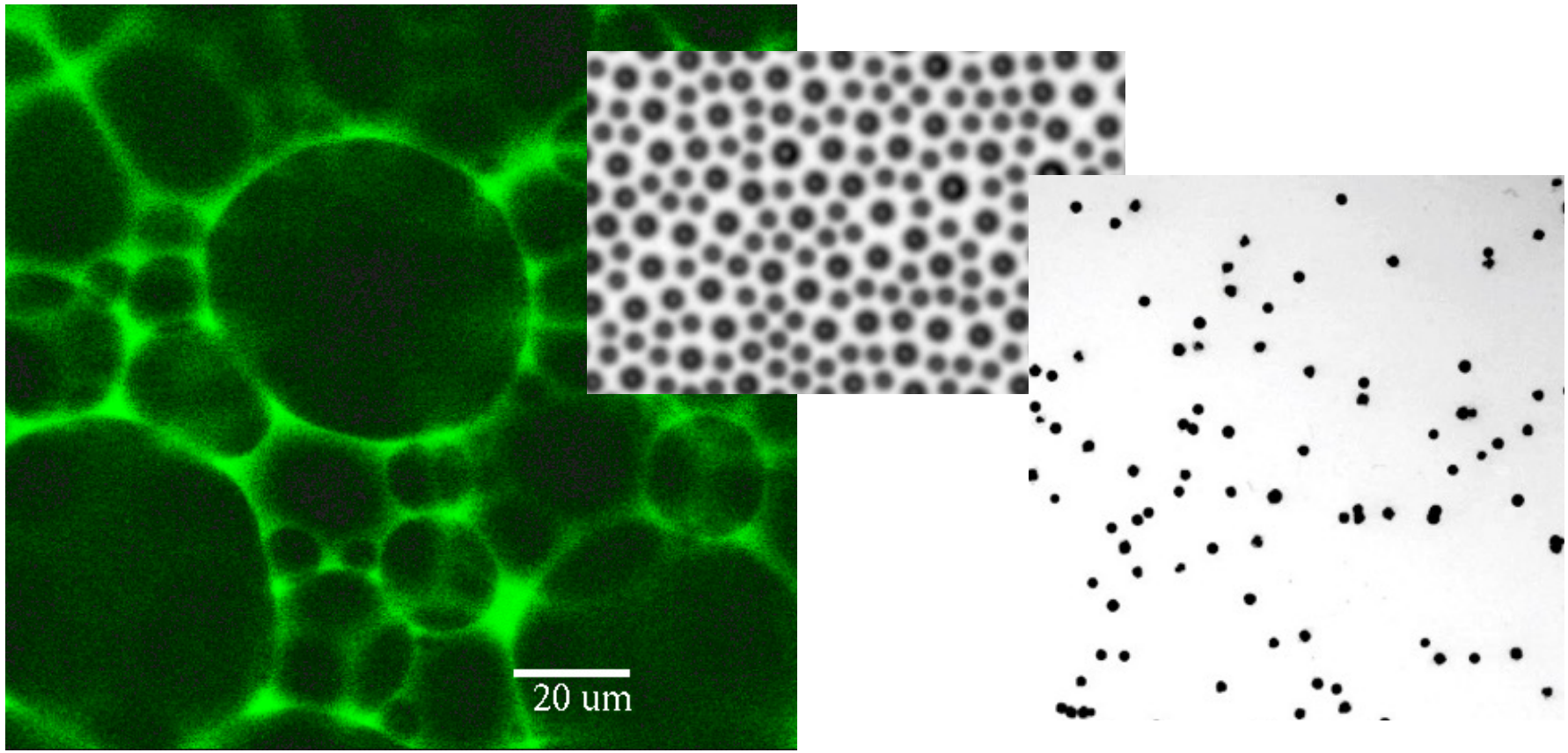


Rules for memory are different!

Weeks Lab, Emory U.

What's needed for memory?

Materials that don't relax to equilibrium



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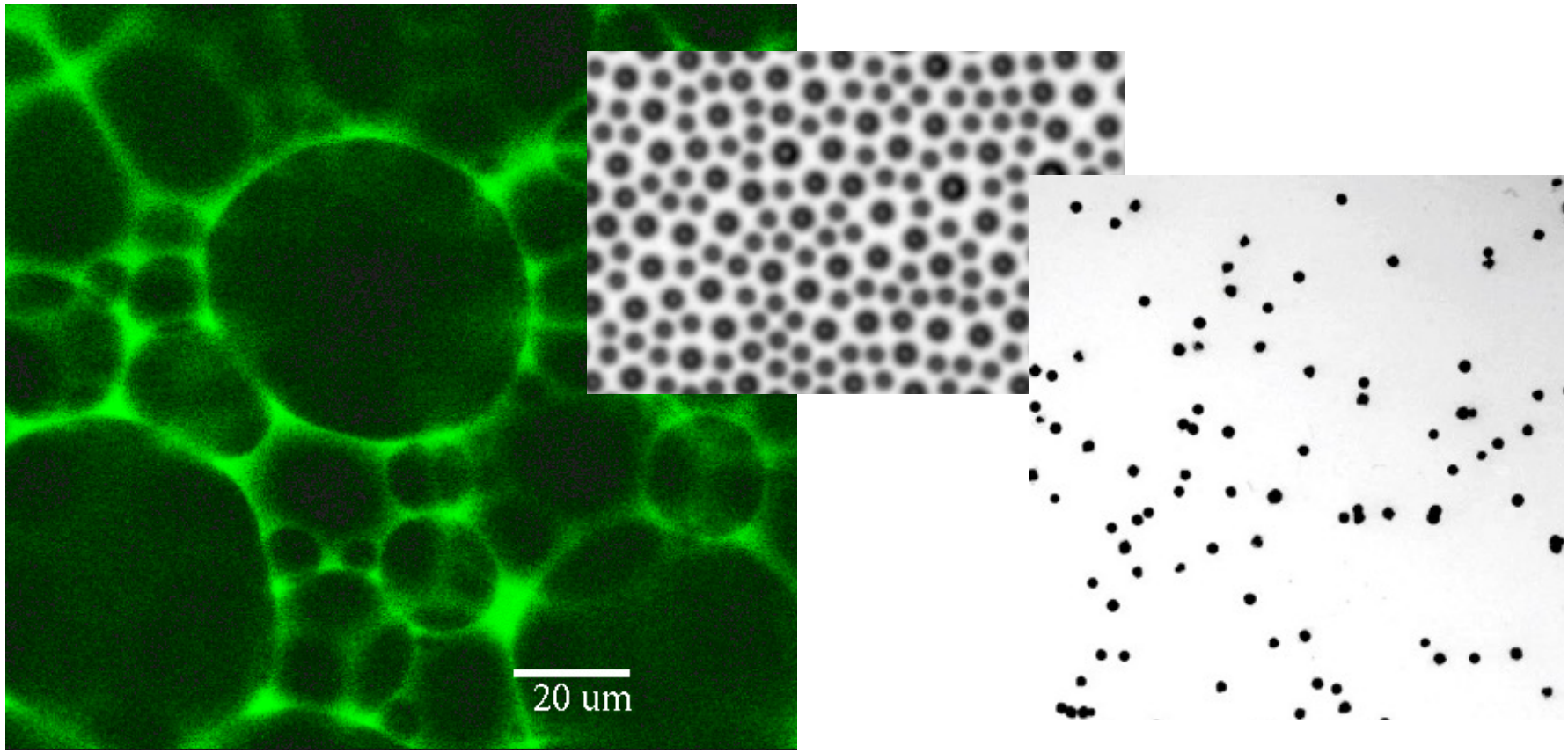
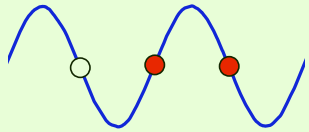
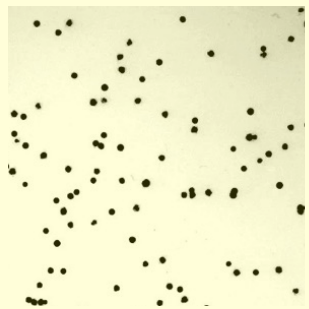


Air and water?

Outline



Cyclic driving



Suspensions

Singularities

Singularities

With: Sidney Nagel *(experiment)*,
Wendy Zhang, Laura Schmidt,
Lipeng Lai *(theory)*

Funding: NSF Chicago MRSEC; Keck Foundation; DOE


240 frames/sec


240 frames/sec

Water pinching off from a nozzle

22,000 frames/sec
Michelle Driscoll

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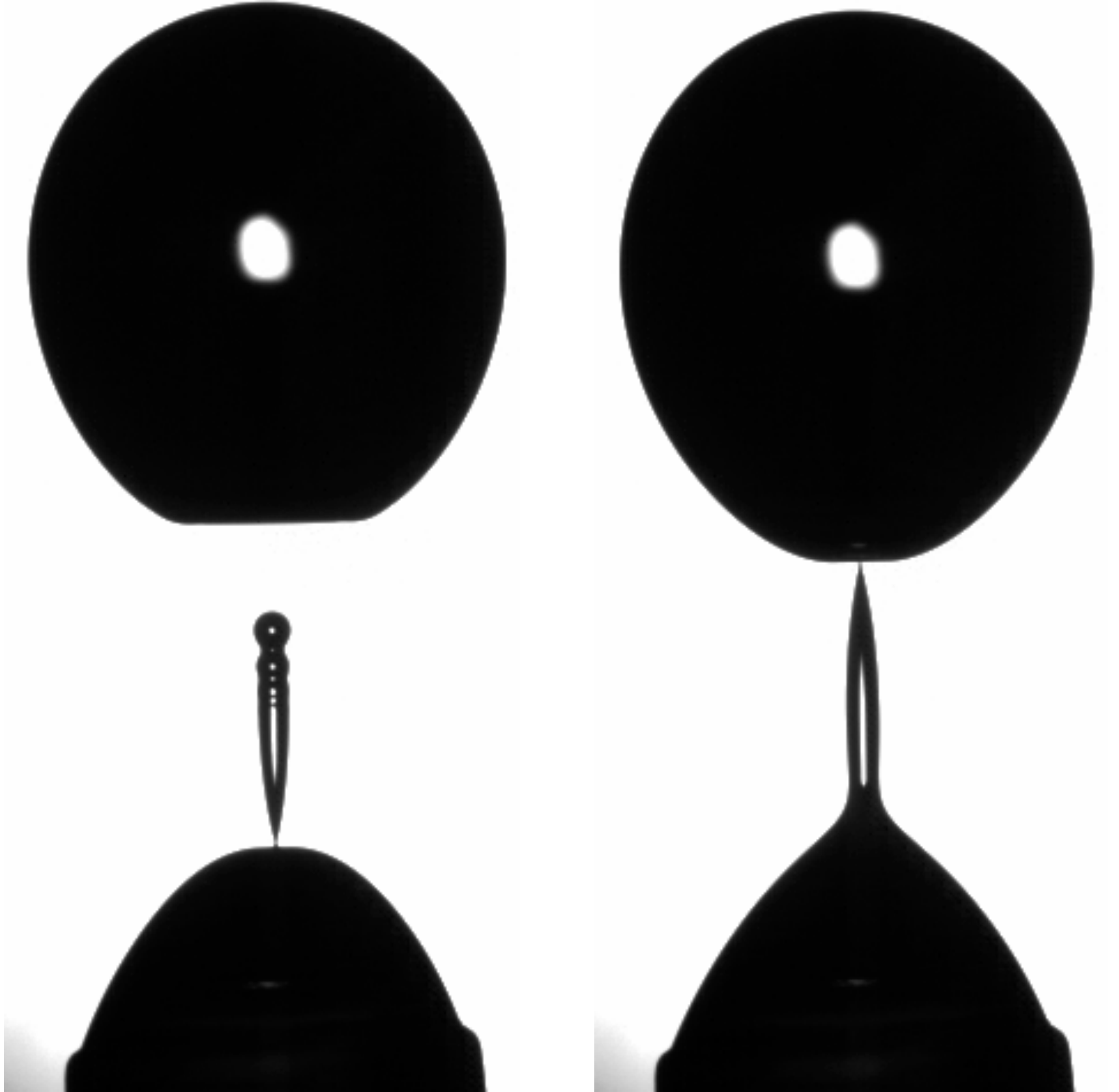
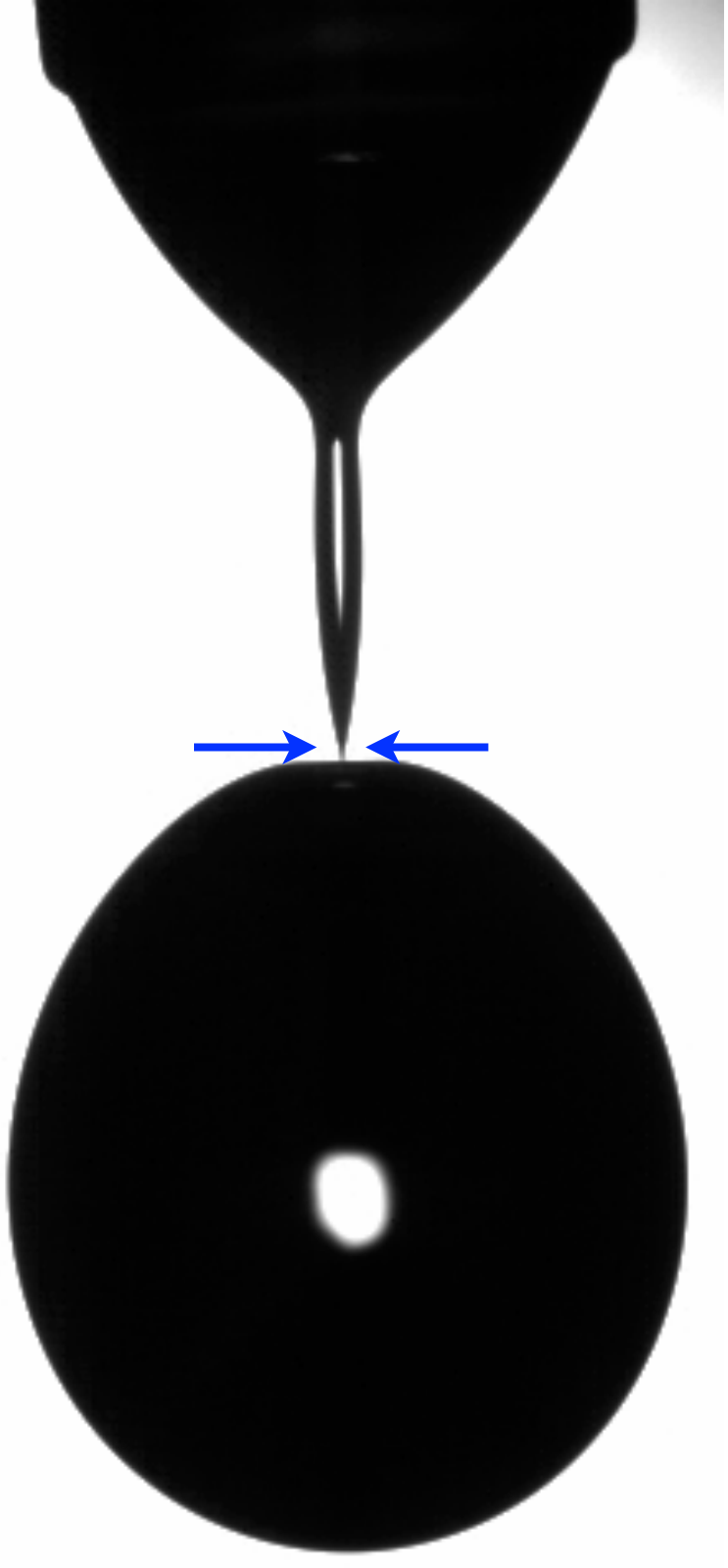
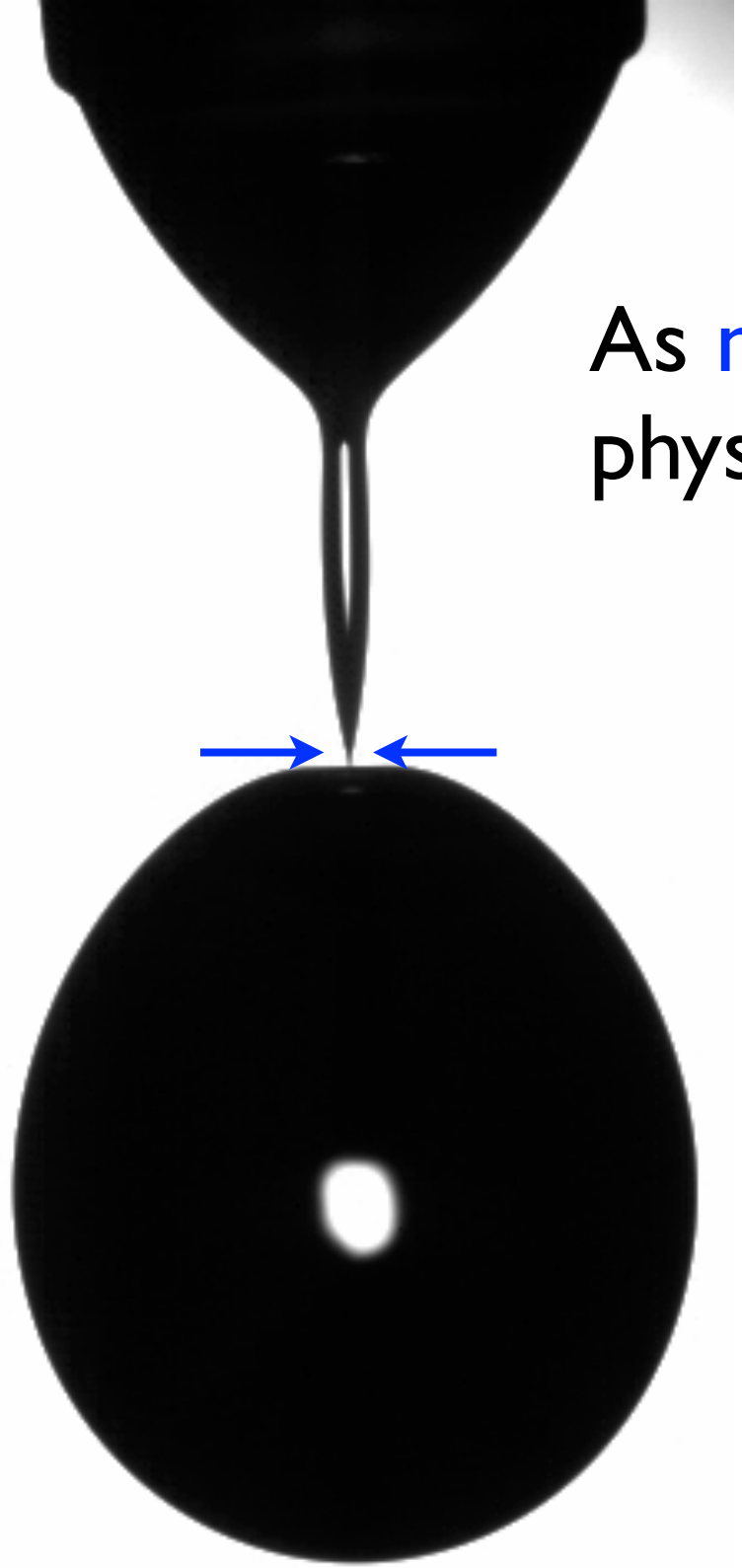


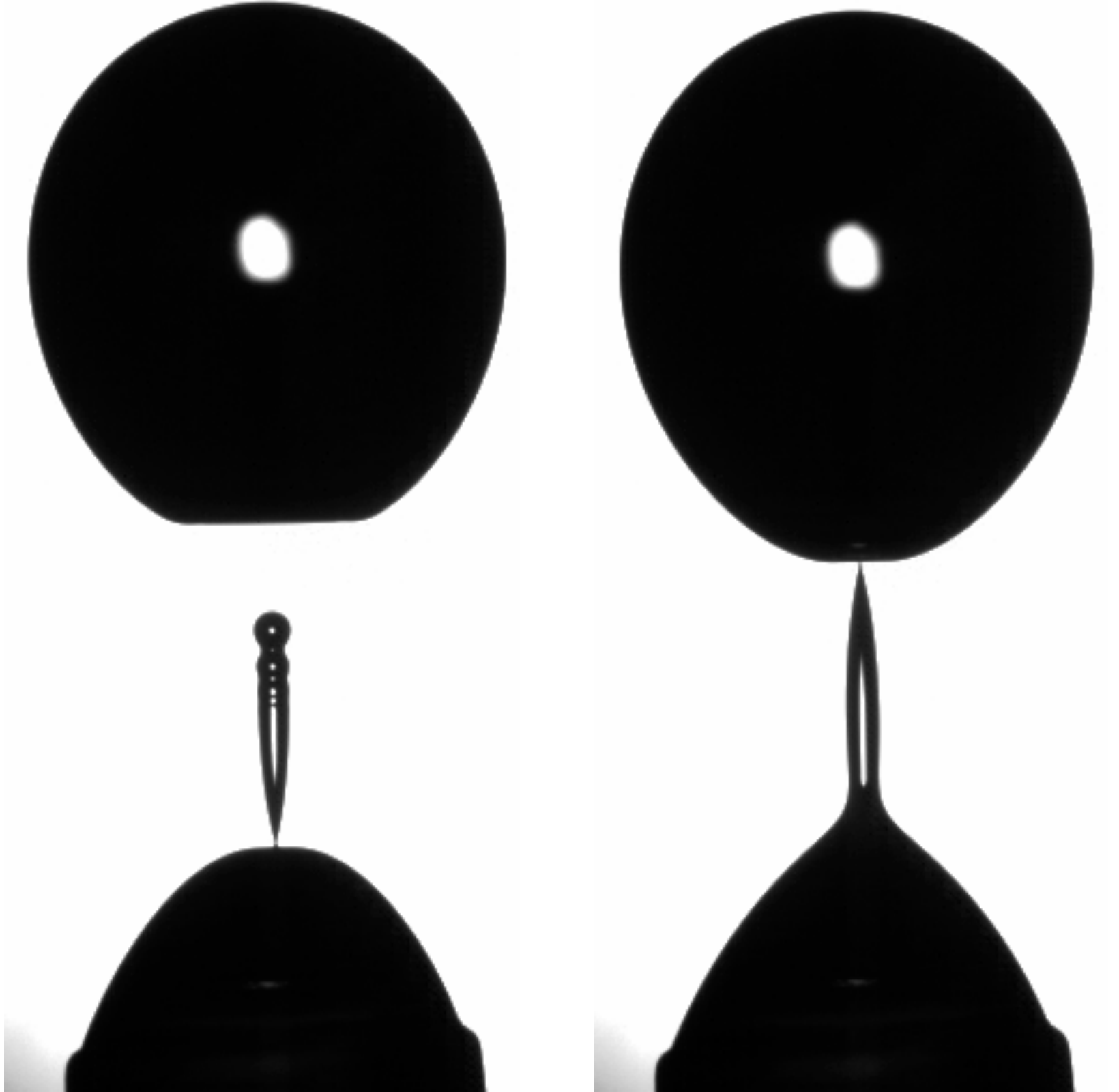


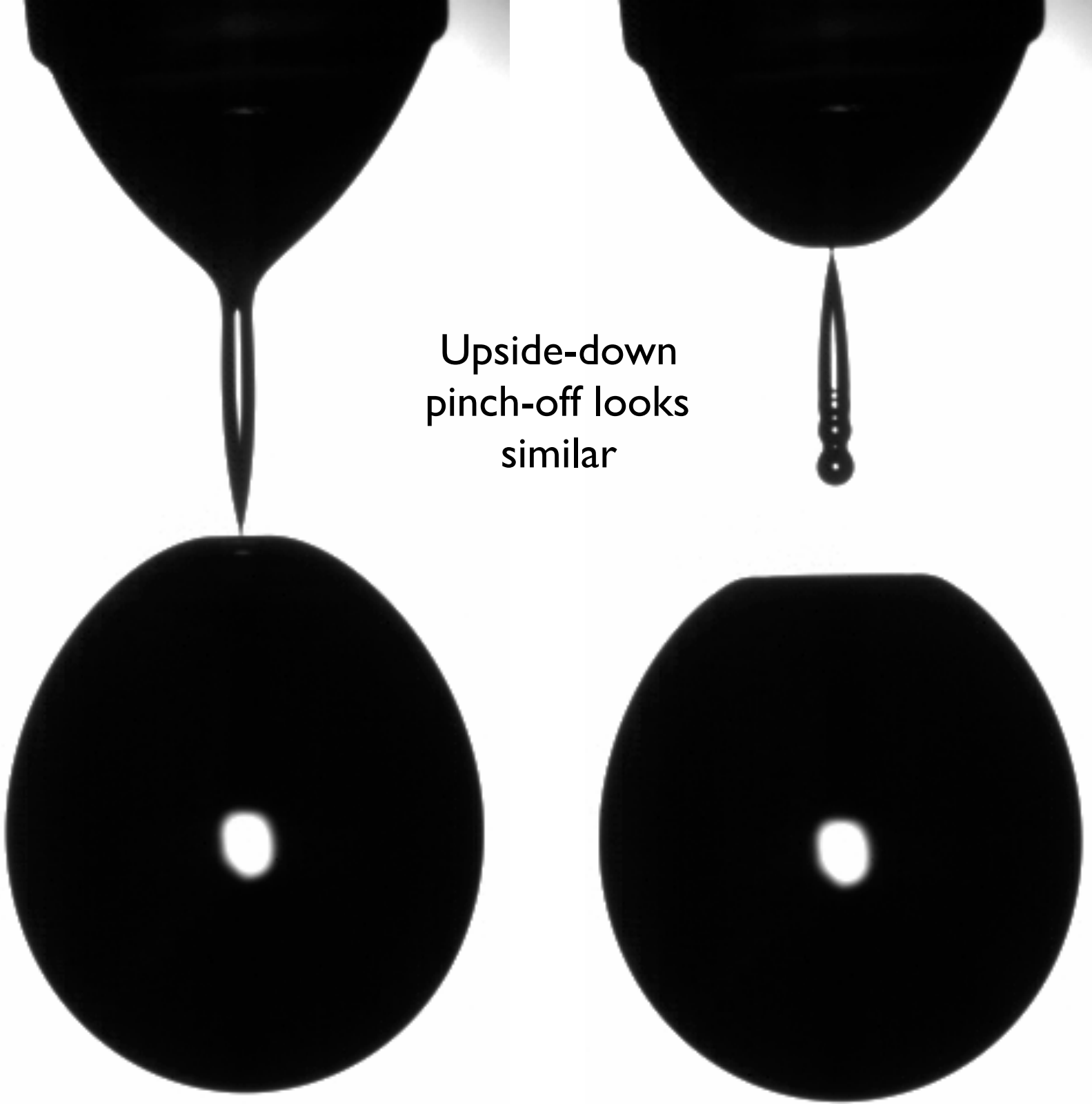


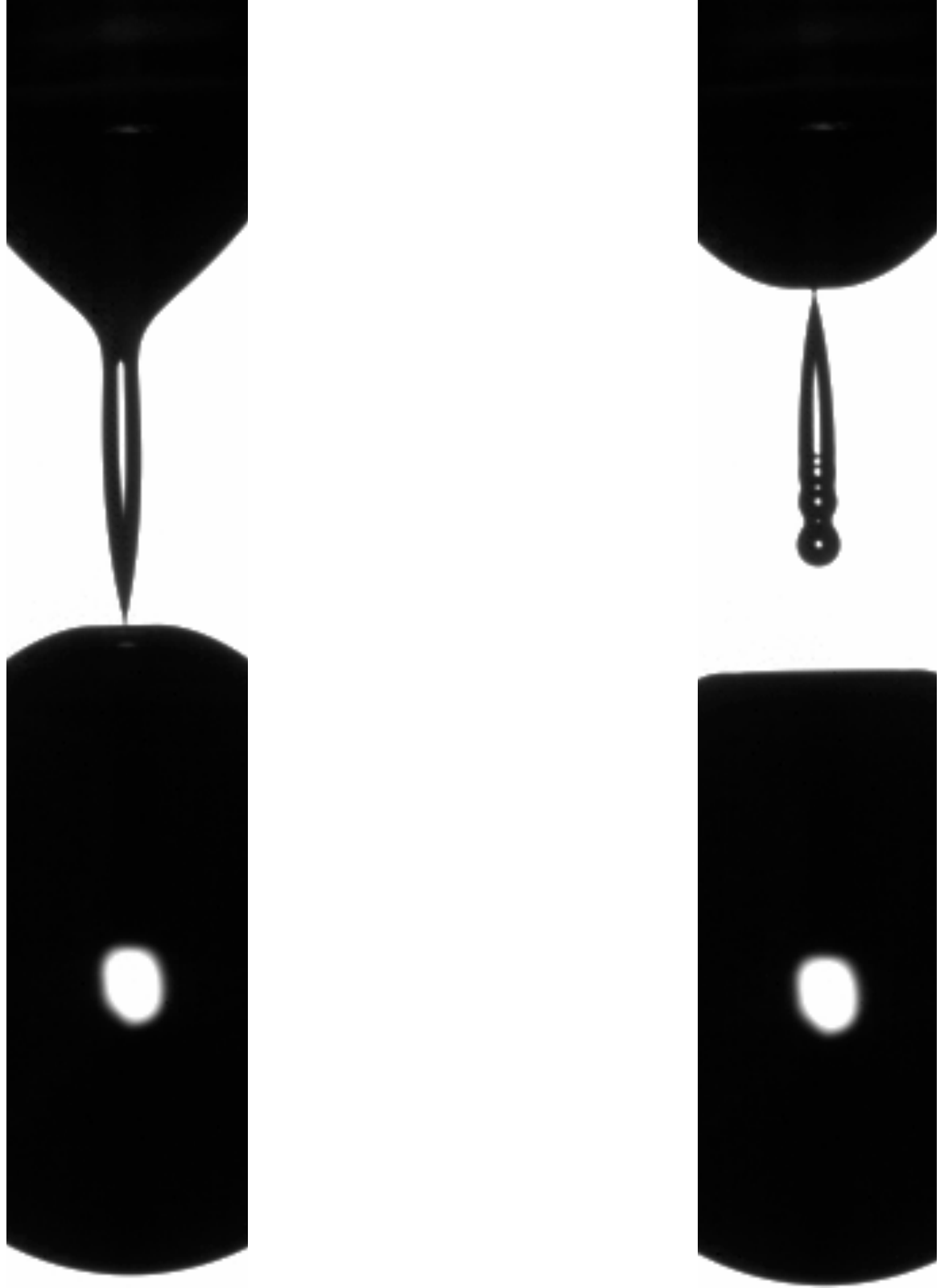
As neck radius → 0,
physical quantities diverge:

- Curvature ~ $\frac{1}{R}$
- Surface tension pressure ~ $\frac{\sigma}{R}$
- Fluid velocity

Singularity




Upside-down
pinch-off looks
similar



Why are these the same?

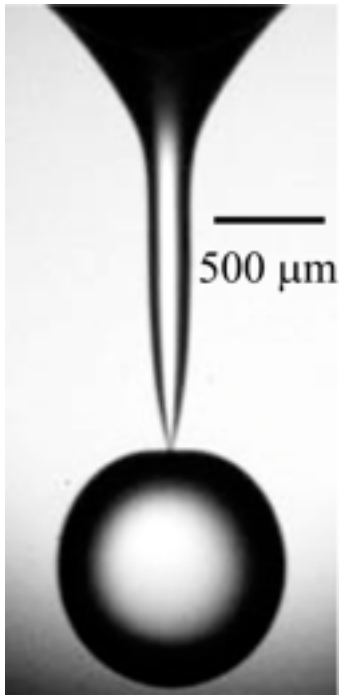
Universality

- Initial, boundary conditions irrelevant near singularity
- Separation of scales
  - Initial conditions stay on large length scales
  - Singularities create, control small scales

Universality

- Initial, boundary conditions irrelevant near singularity
- Separation of scales
  - Initial conditions stay on large length scales
  - Singularities create, control small scales
- Holds generally for pinch-offs

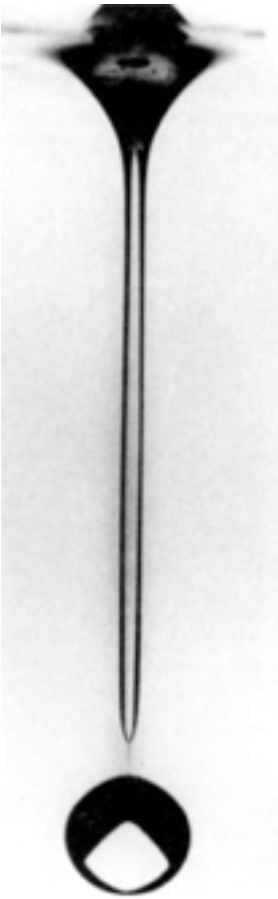
Water in Air
Chen *et al.*



Superfluid He
Burton *et al.*

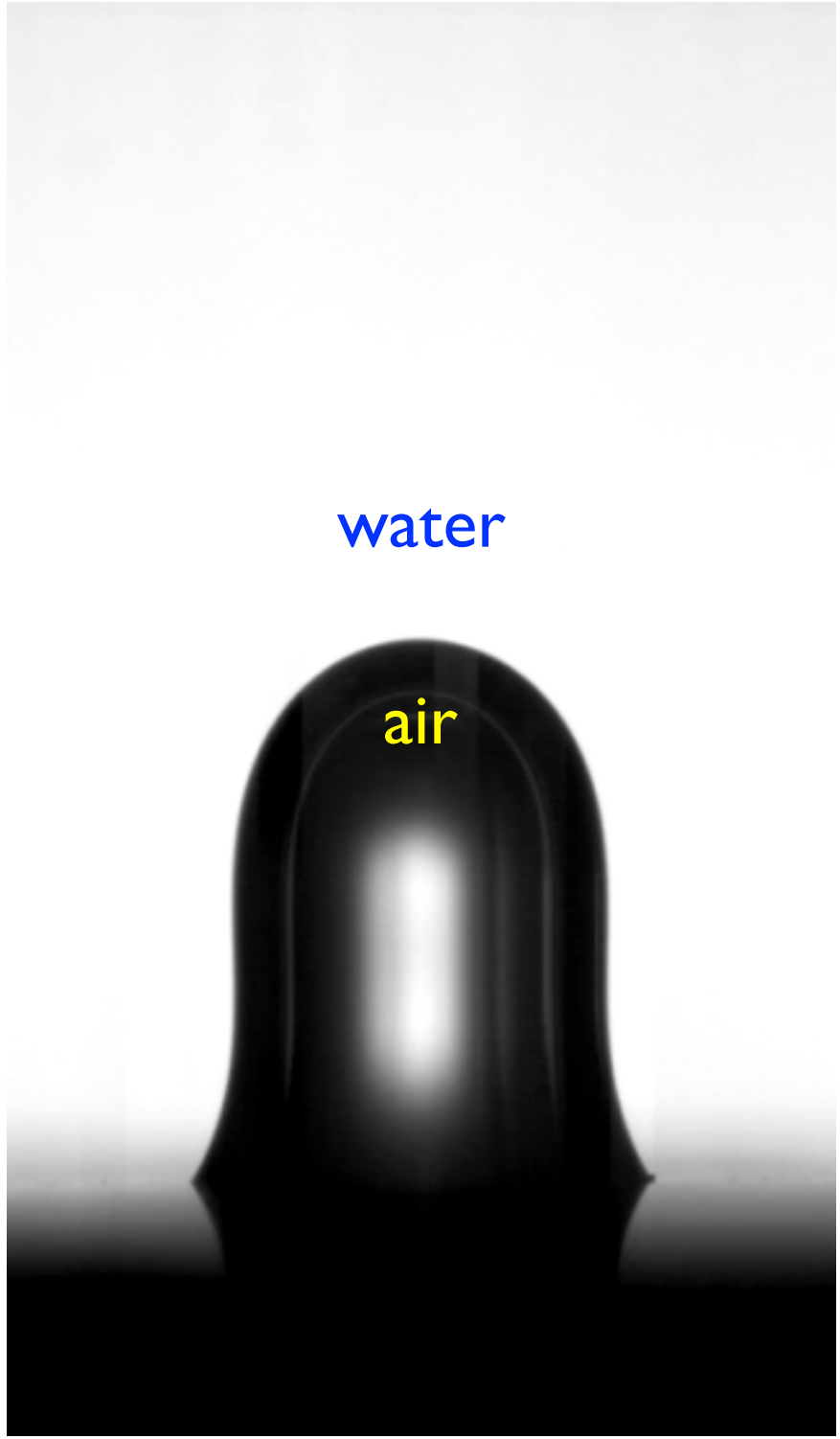
High-pressure
Xe in Water
Burton *et al.*

Viscous liq's
Cohen *et al.*



Glycerin in Air
Shi *et al.*

Air pinch-off in water



2 mm

5000 frames/s

Air pinch-off in water

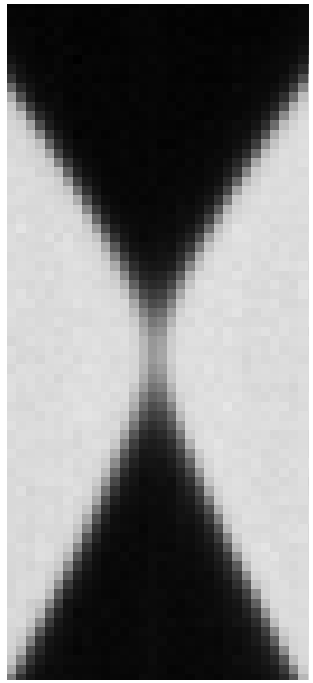
2 mm

5000 frames/s

Air pinch-off in water

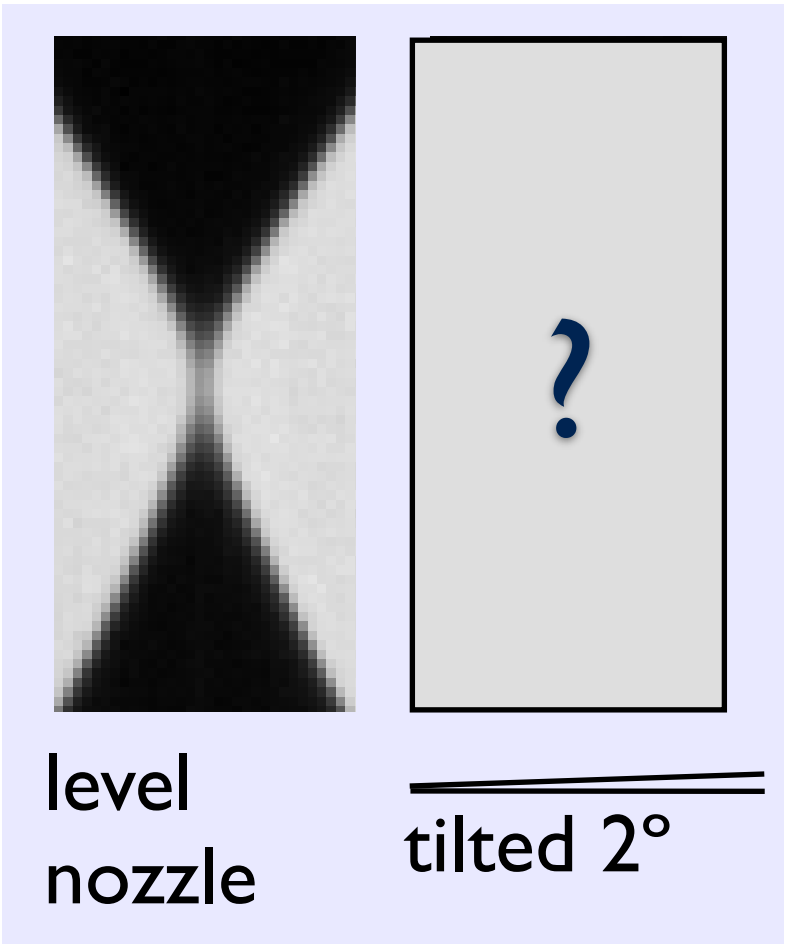
2 mm

5000 frames/s



Keim *et al.*, *PRL* 2006

Tilting the nozzle



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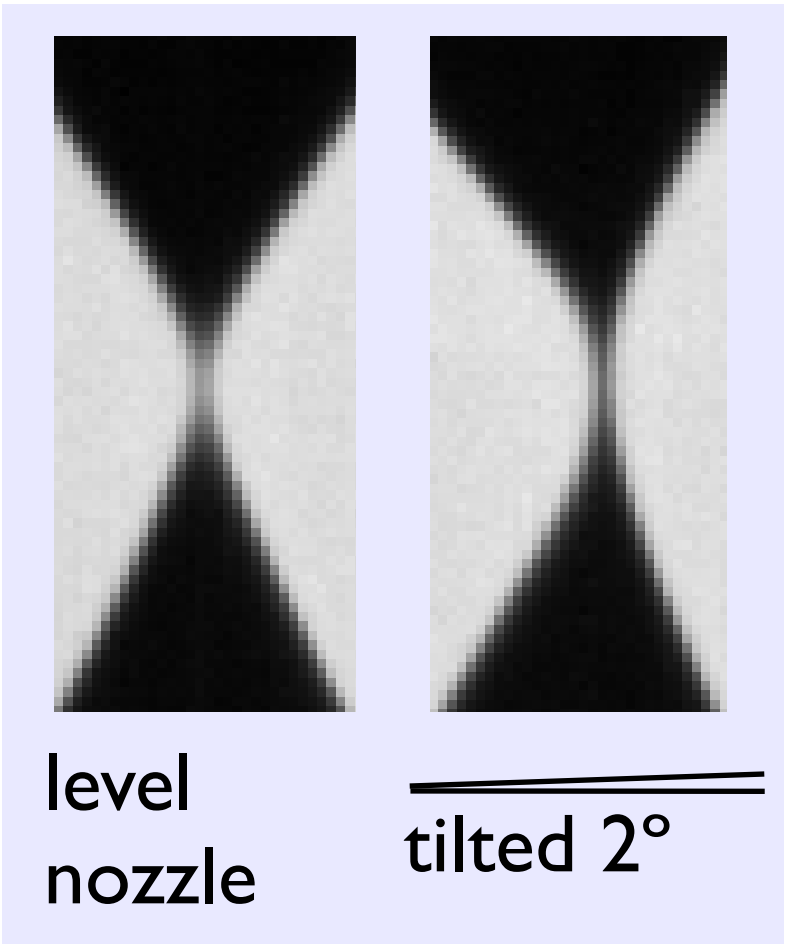
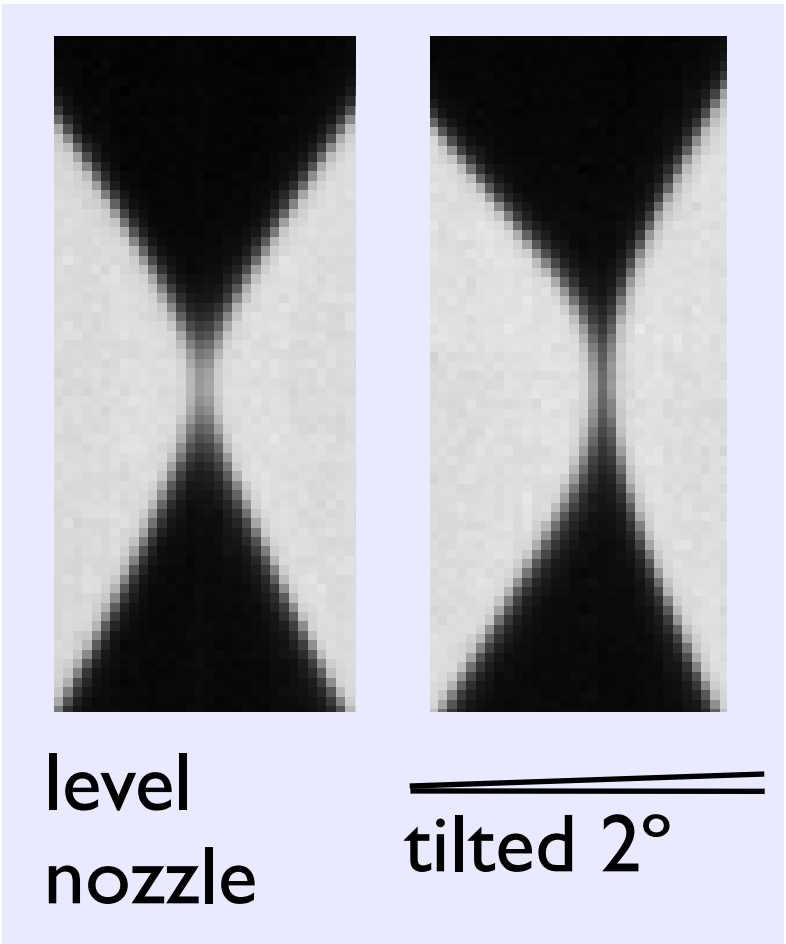


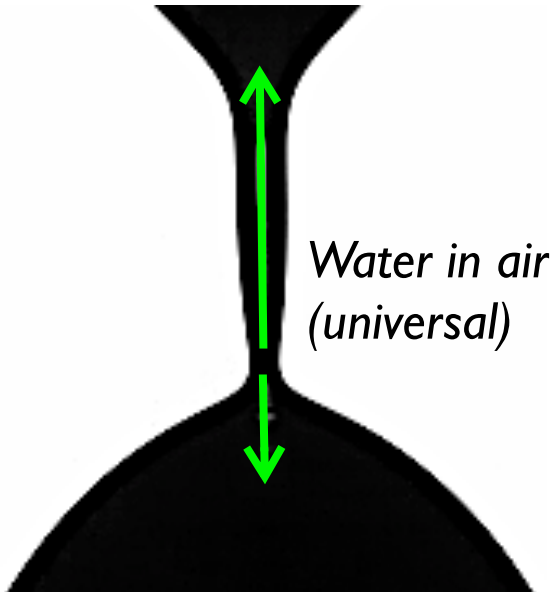
Keim *et al.*, *PRL* 2006

Tilting the nozzle



Reason: For singularity to be universal, must influence parts above and below

– Fluid leaving neck "communicates" vertically



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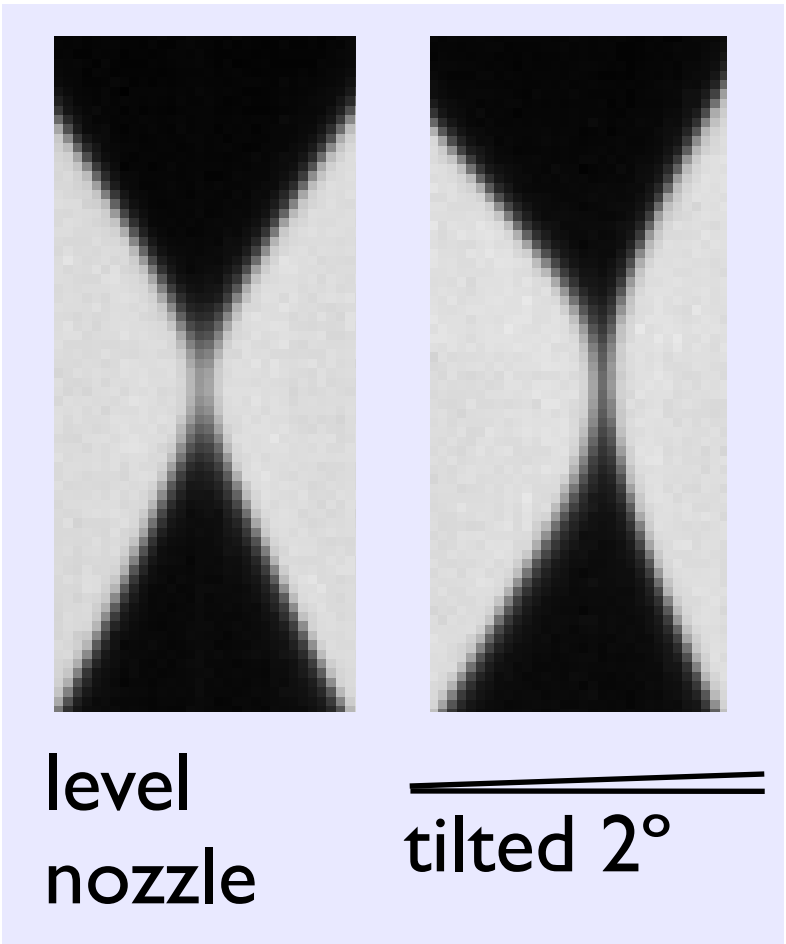

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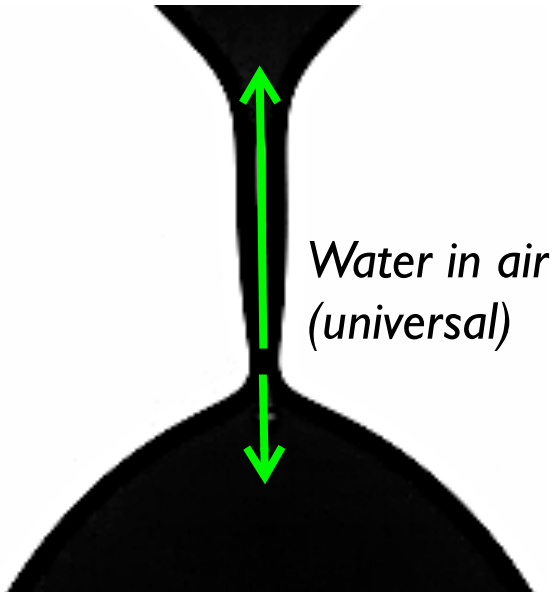
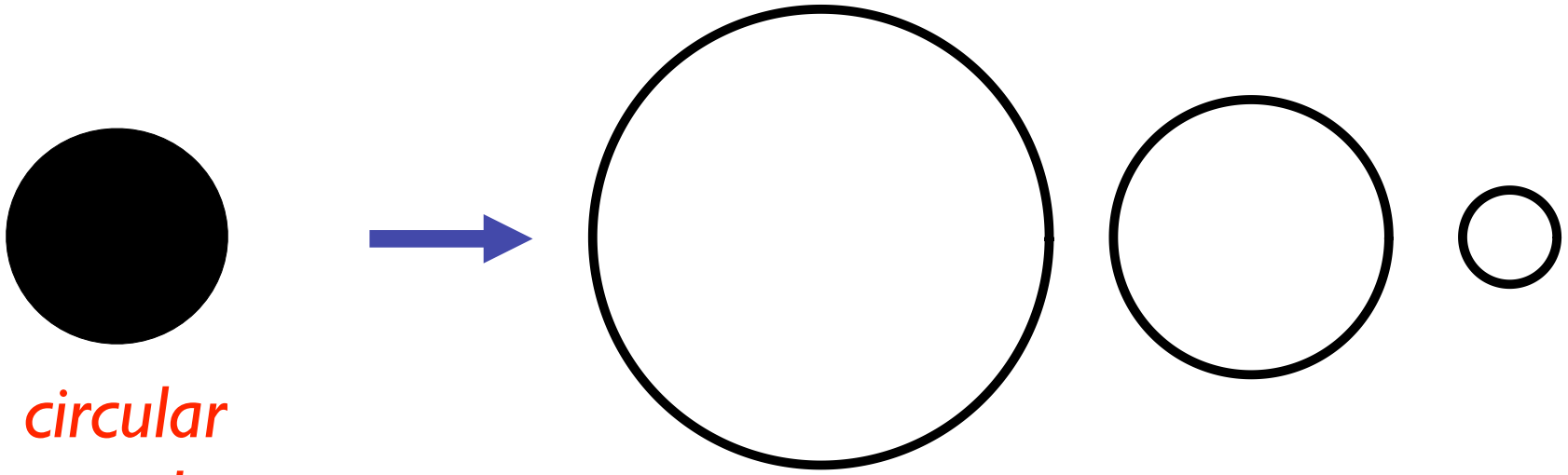


– ***When inner fluid insignificant, universality broken!***

Keim *et al.*, *PRL* 2006

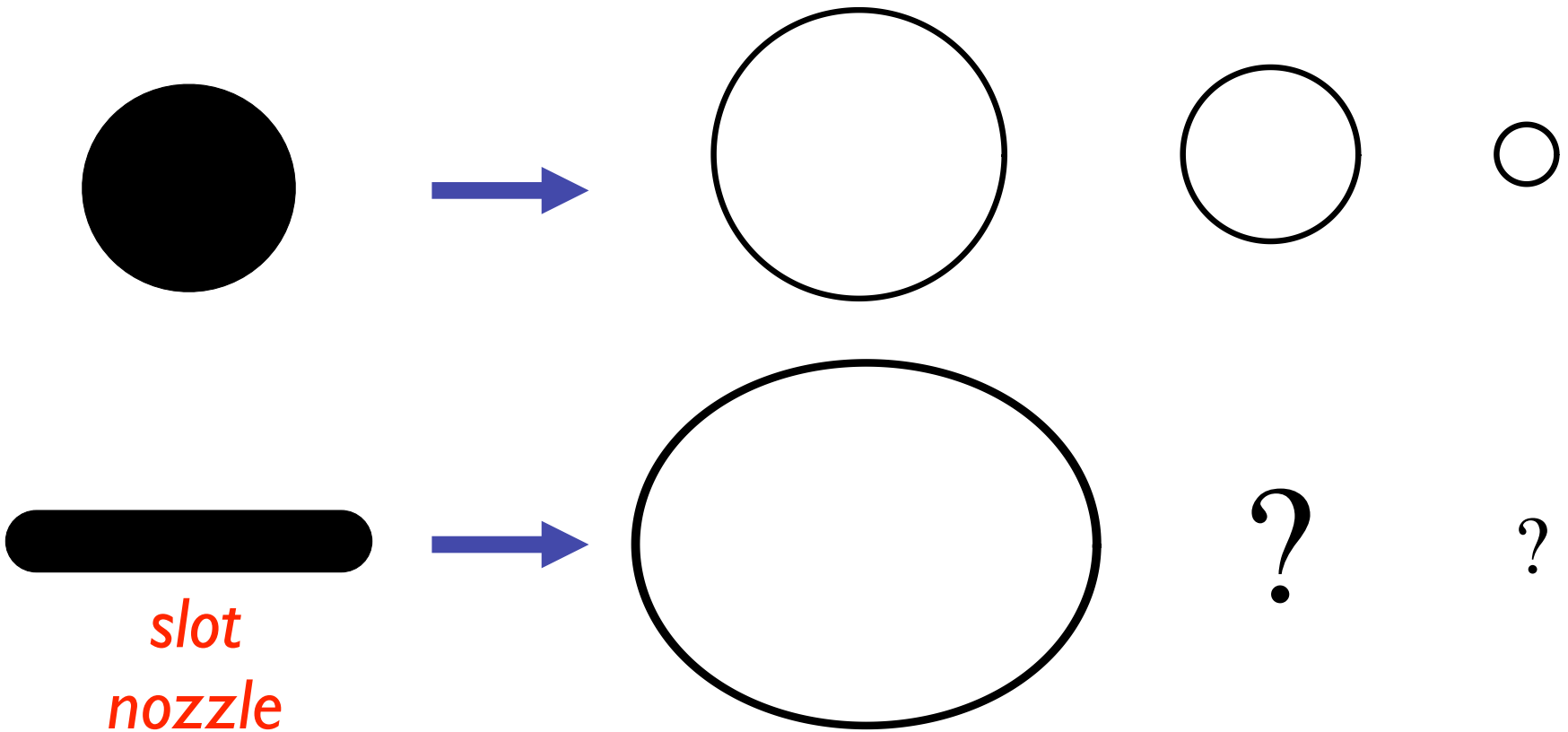
Changing Initial Conditions



circular nozzle

circular cross-sections

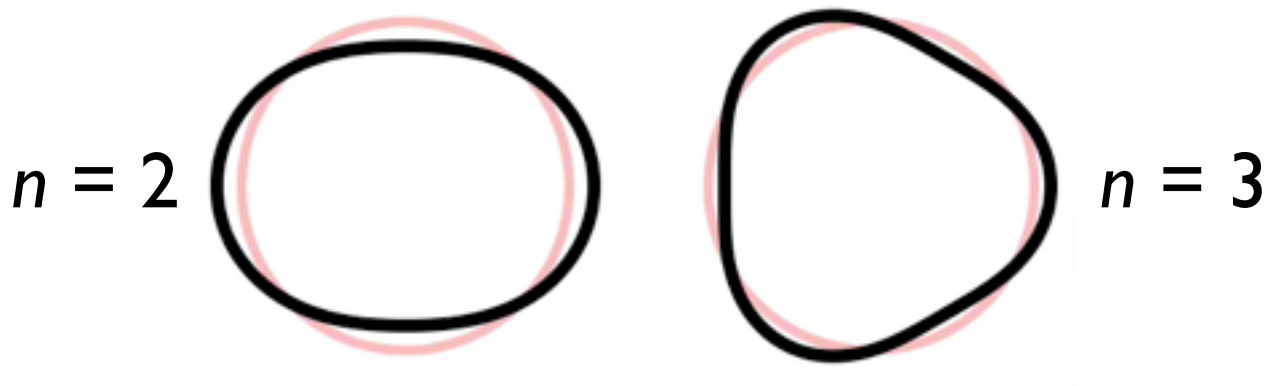
Changing Initial Conditions



Schmidt et al., Nat. Phys. 2009

Model Predicts Memory Vibrations

- Theory by Laura Schmidt and Wendy Zhang
- Vibration modes n = 2, 3, 4…



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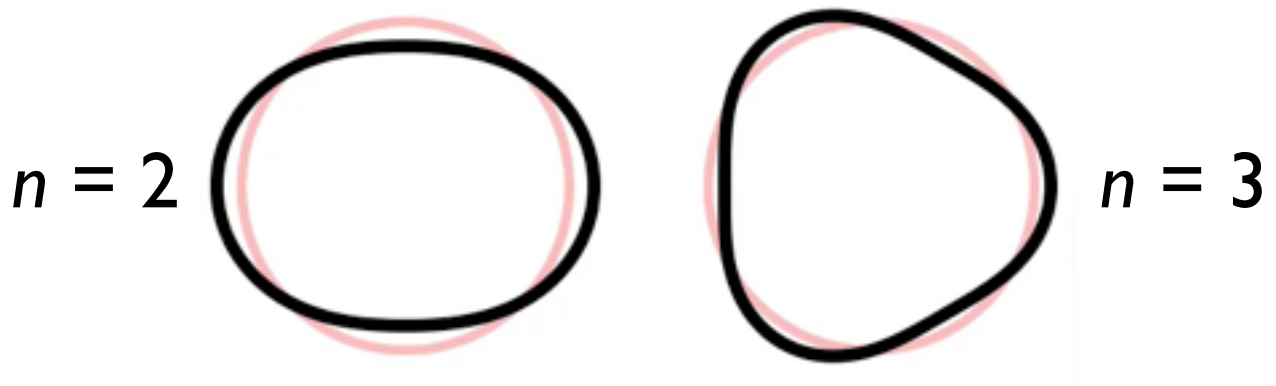

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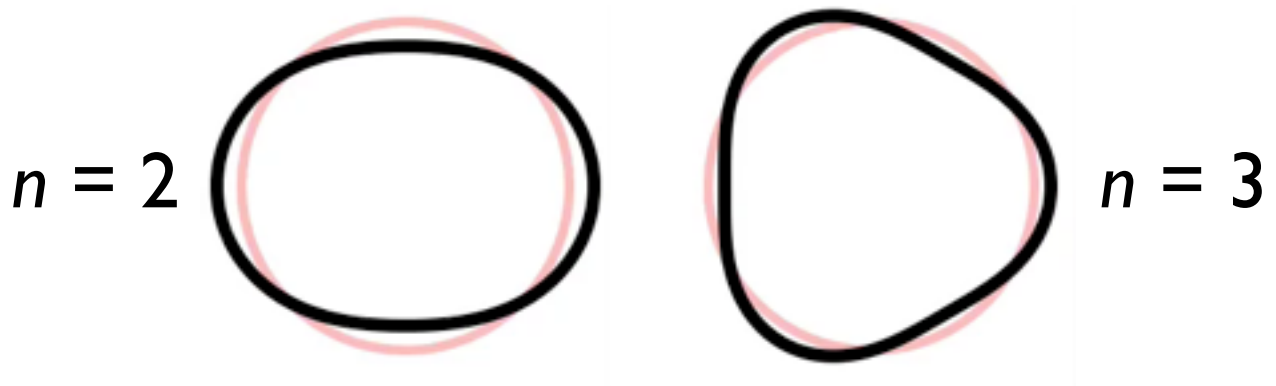

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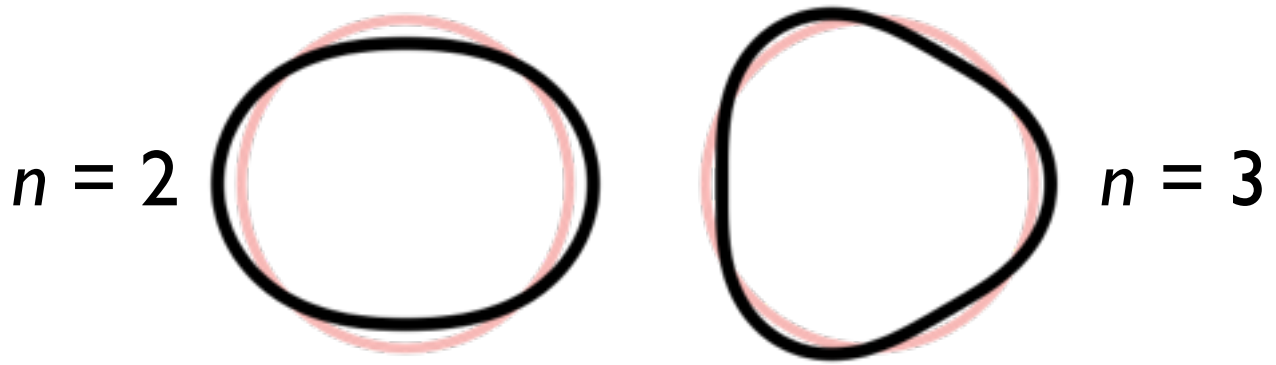
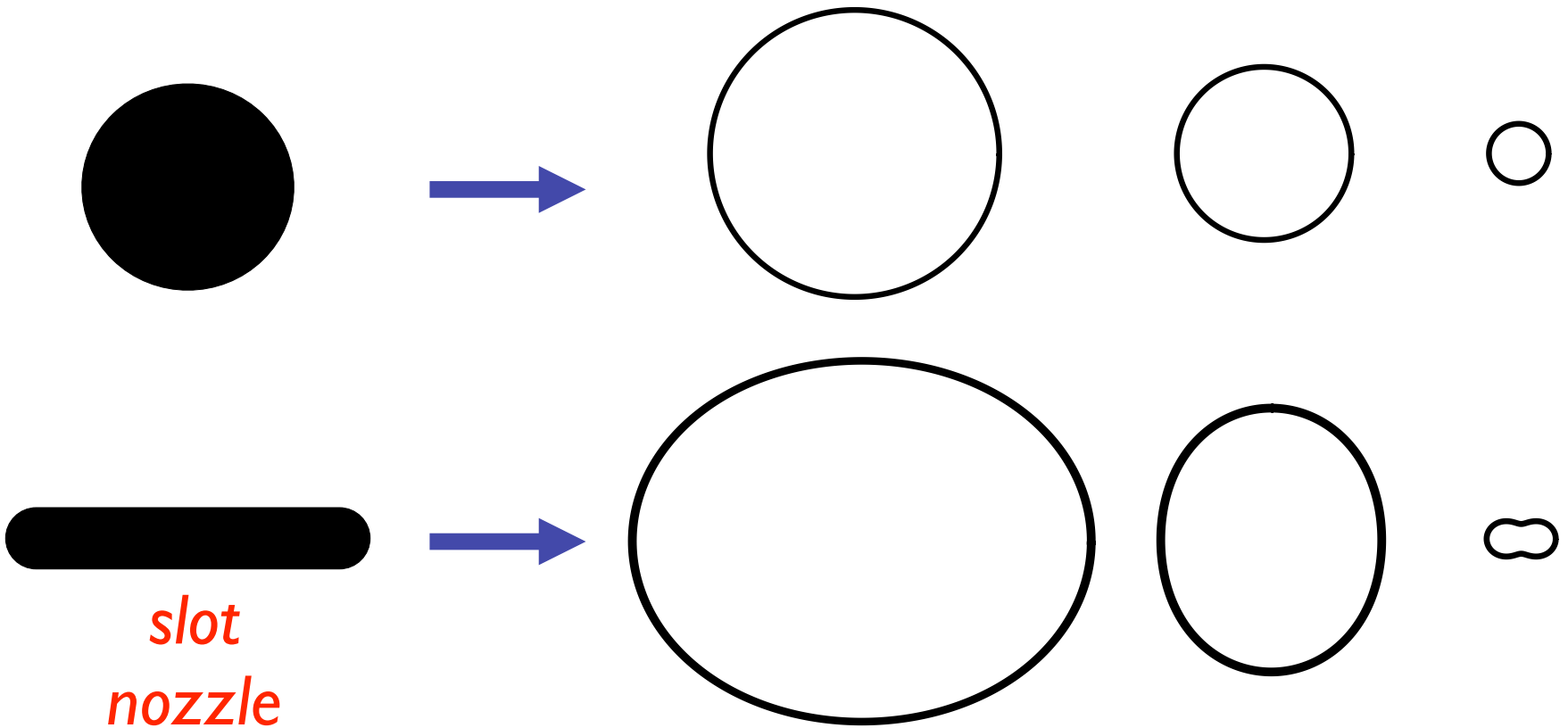


- Considers 2D slice of water only
- No surface tension in model—only inertia of water

Changing Initial Conditions



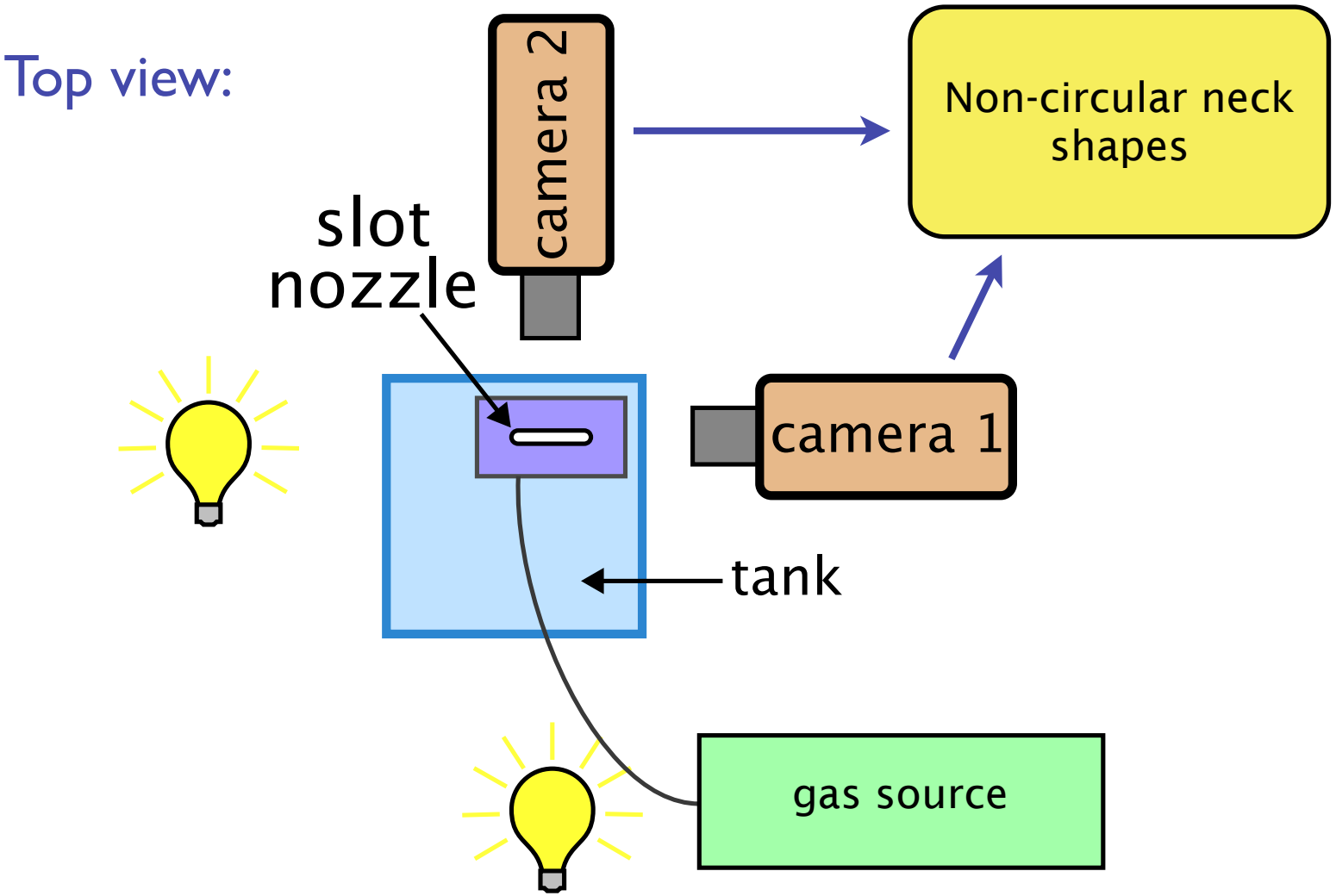
slot nozzle

n = 2 shape vibration

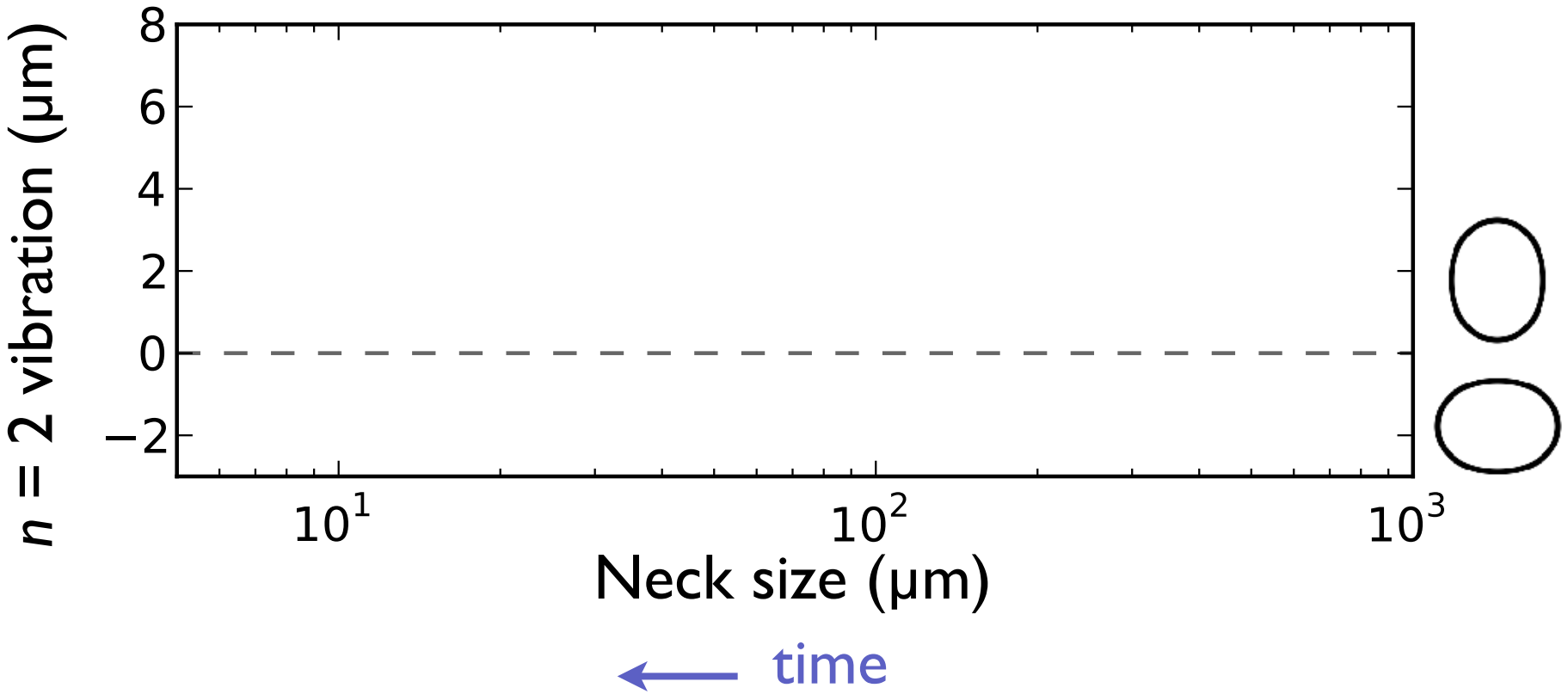
Schmidt et al., Nat. Phys. 2009

Measuring Vibrations

Measure shapes in experiment



$n = 2$ Vibrations Observed



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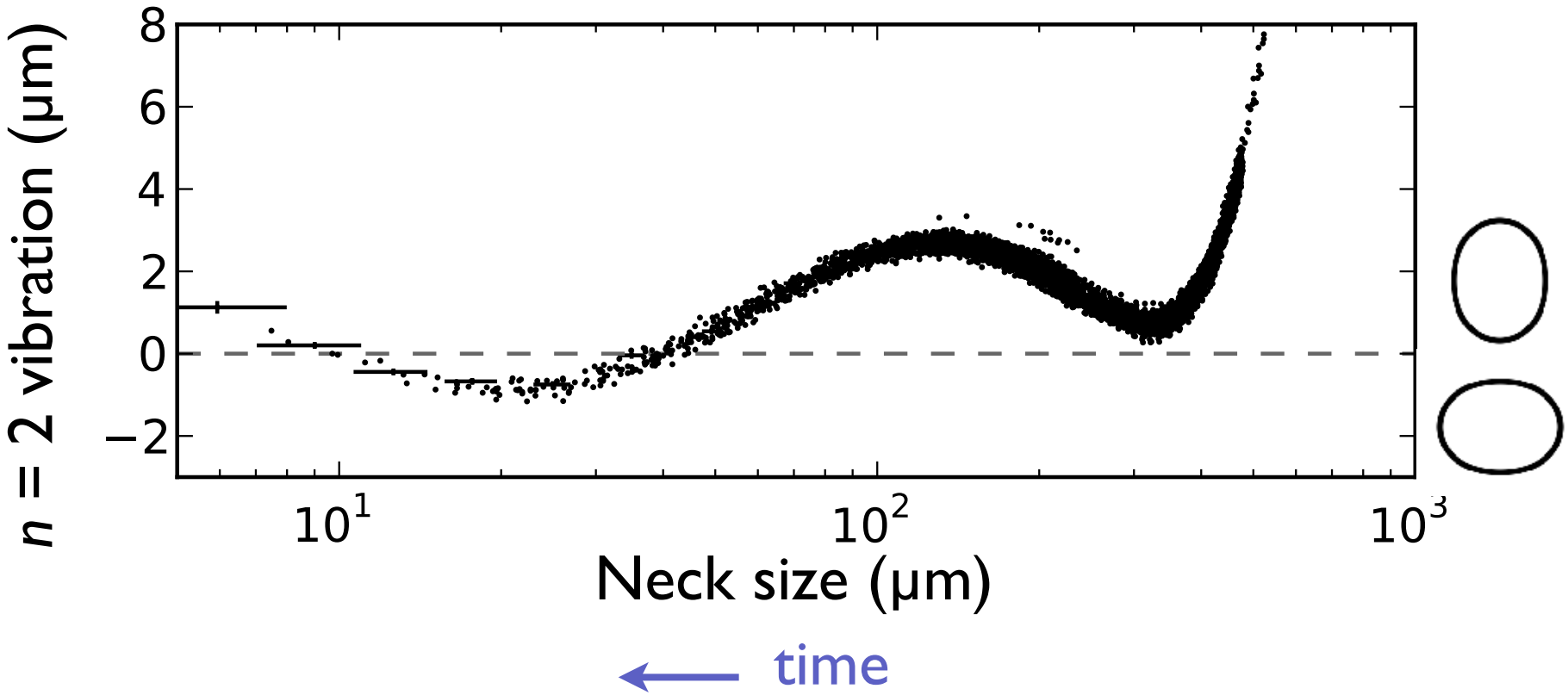
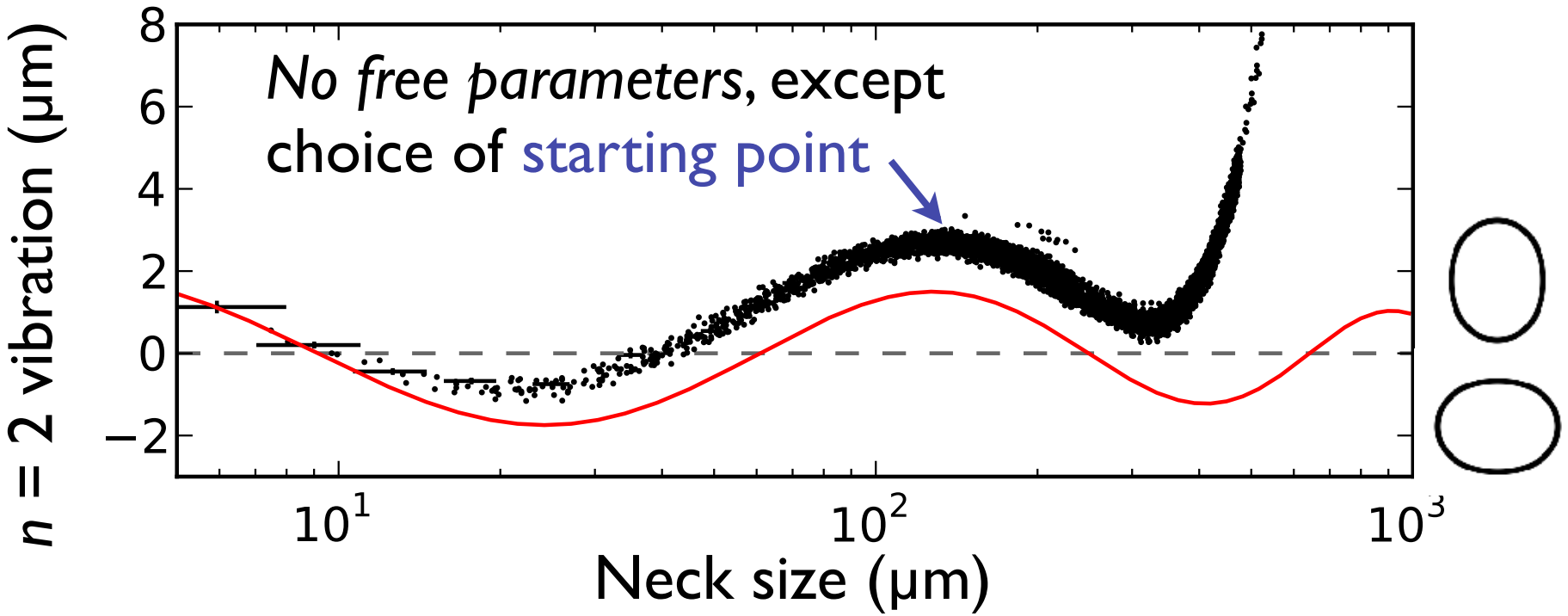


Vibrations Confirm Prediction



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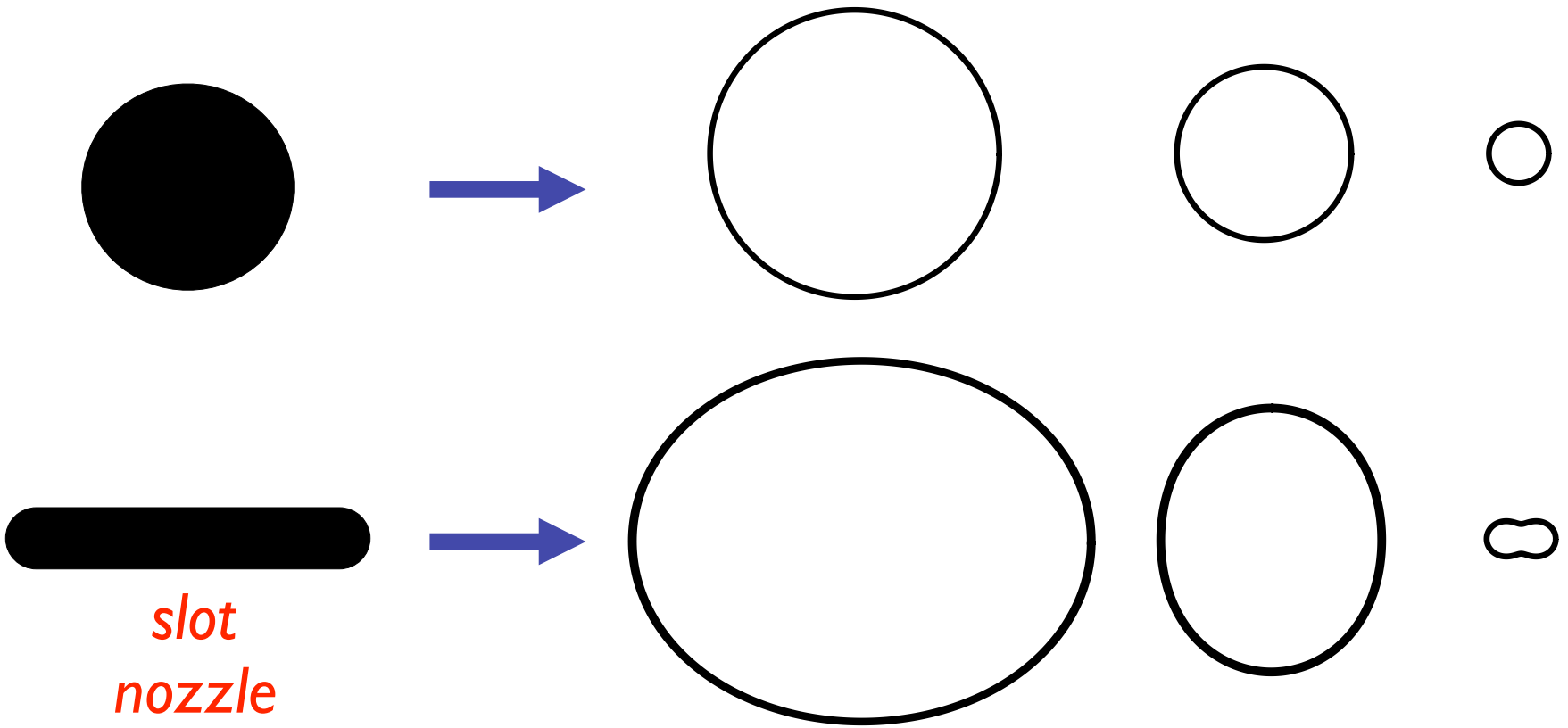

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Schmidt et al., Nat. Phys. 2009

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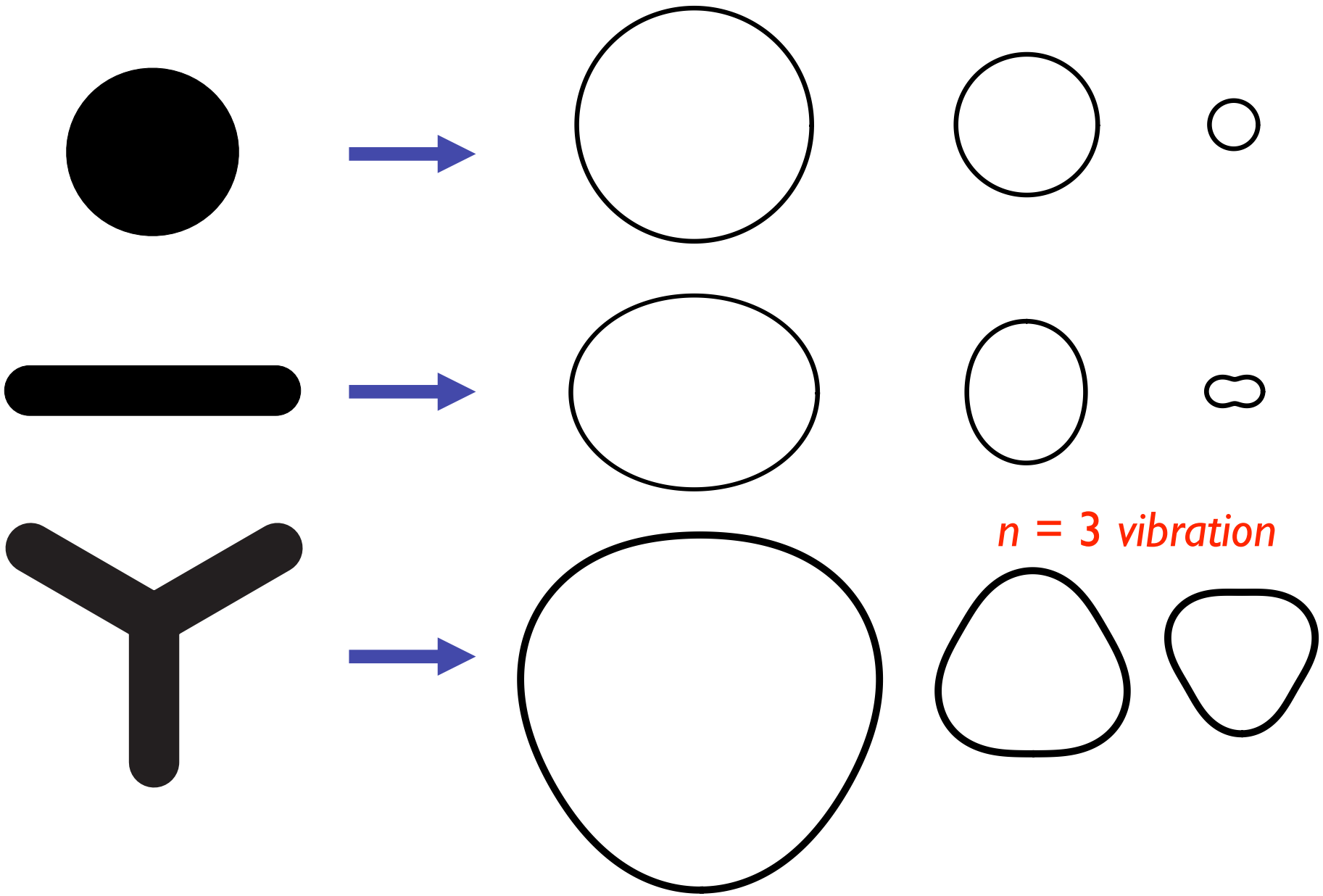

https://www.youtube.com/watch?v=Dy7Zf0hbXyU

Enríquez et al.
Physics of Fluids 2011 Disc diameter = 2 cm

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Enríquez et al.
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An underwater side view reveals the
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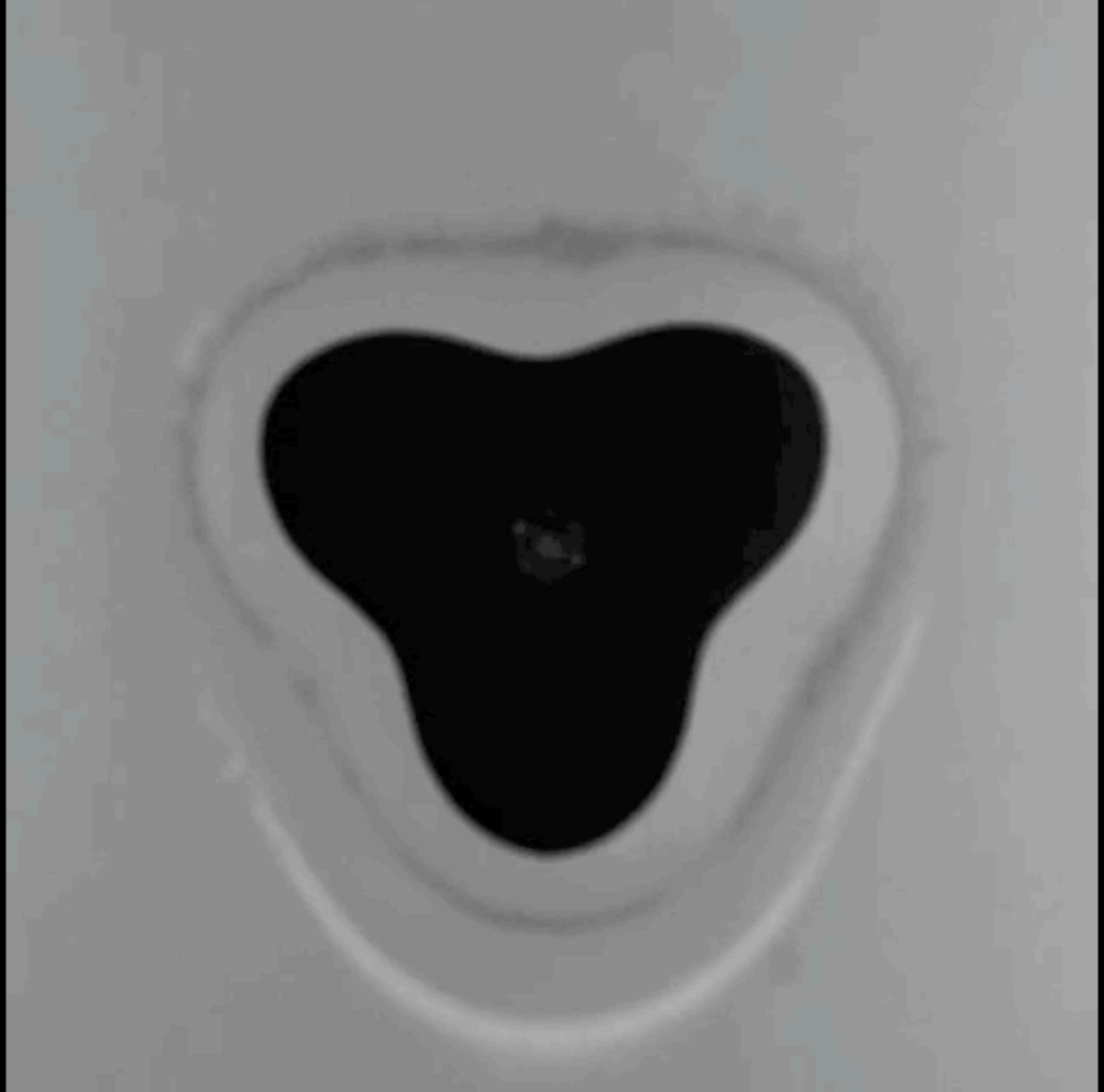
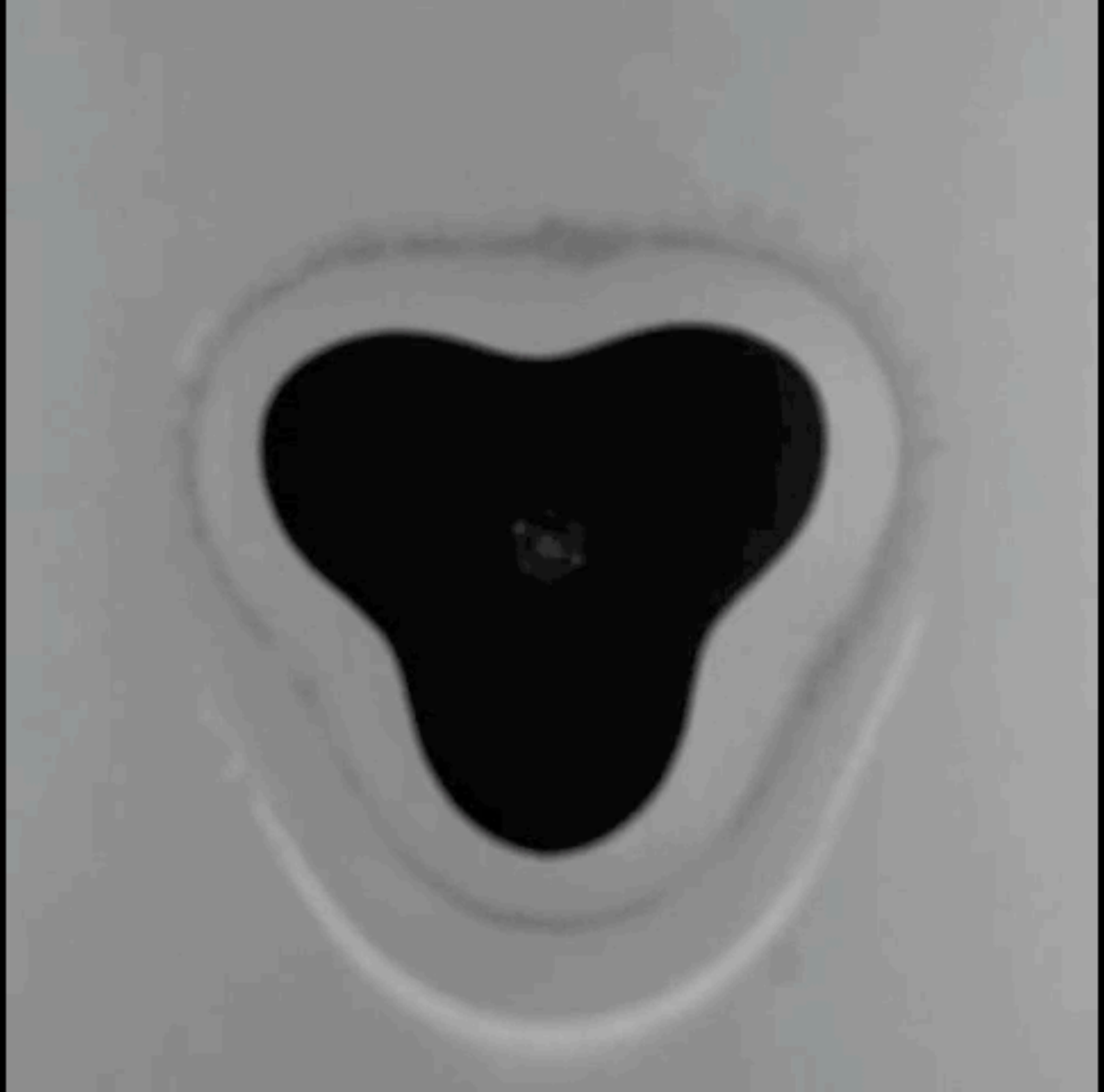
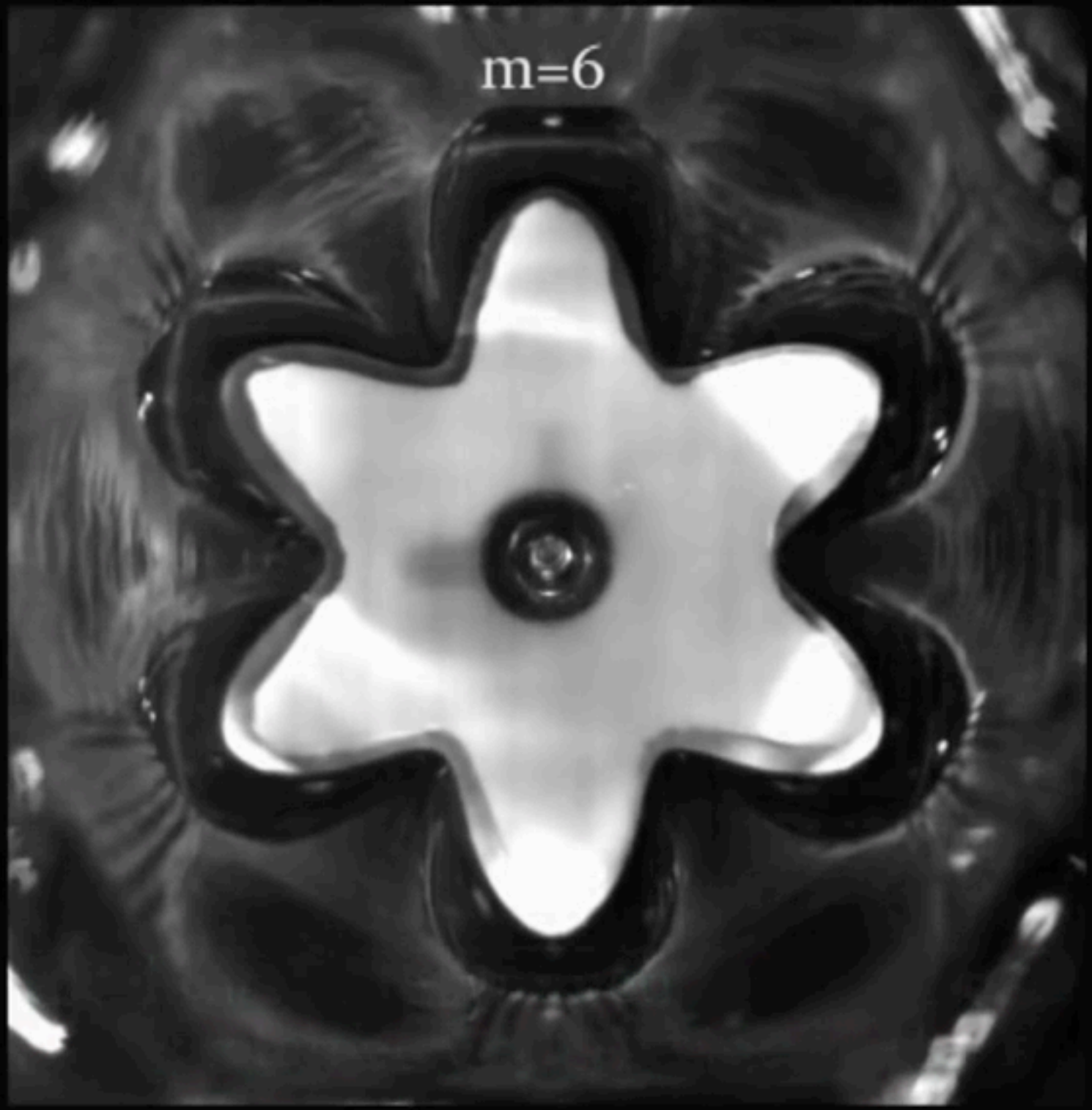
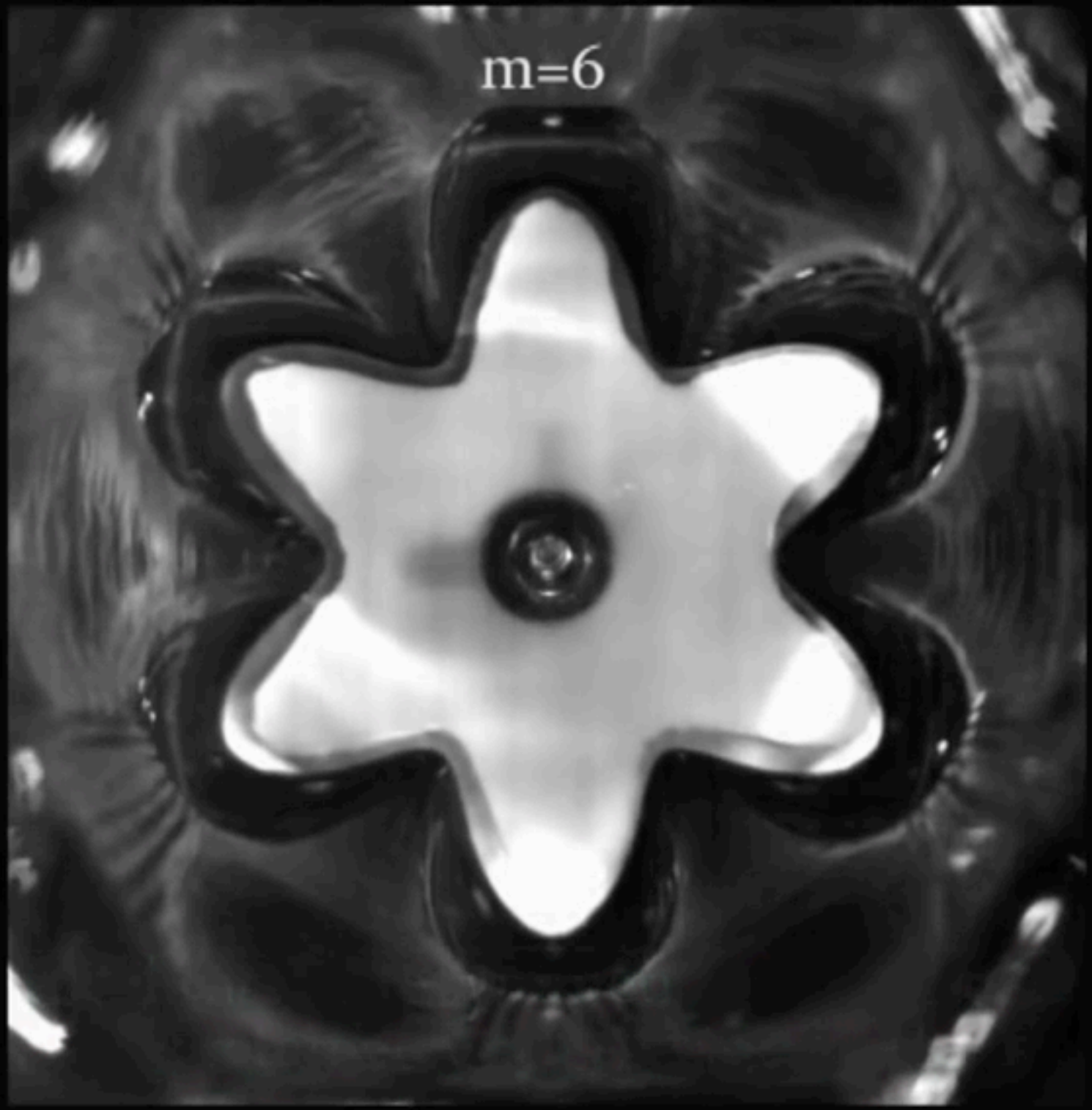





m=6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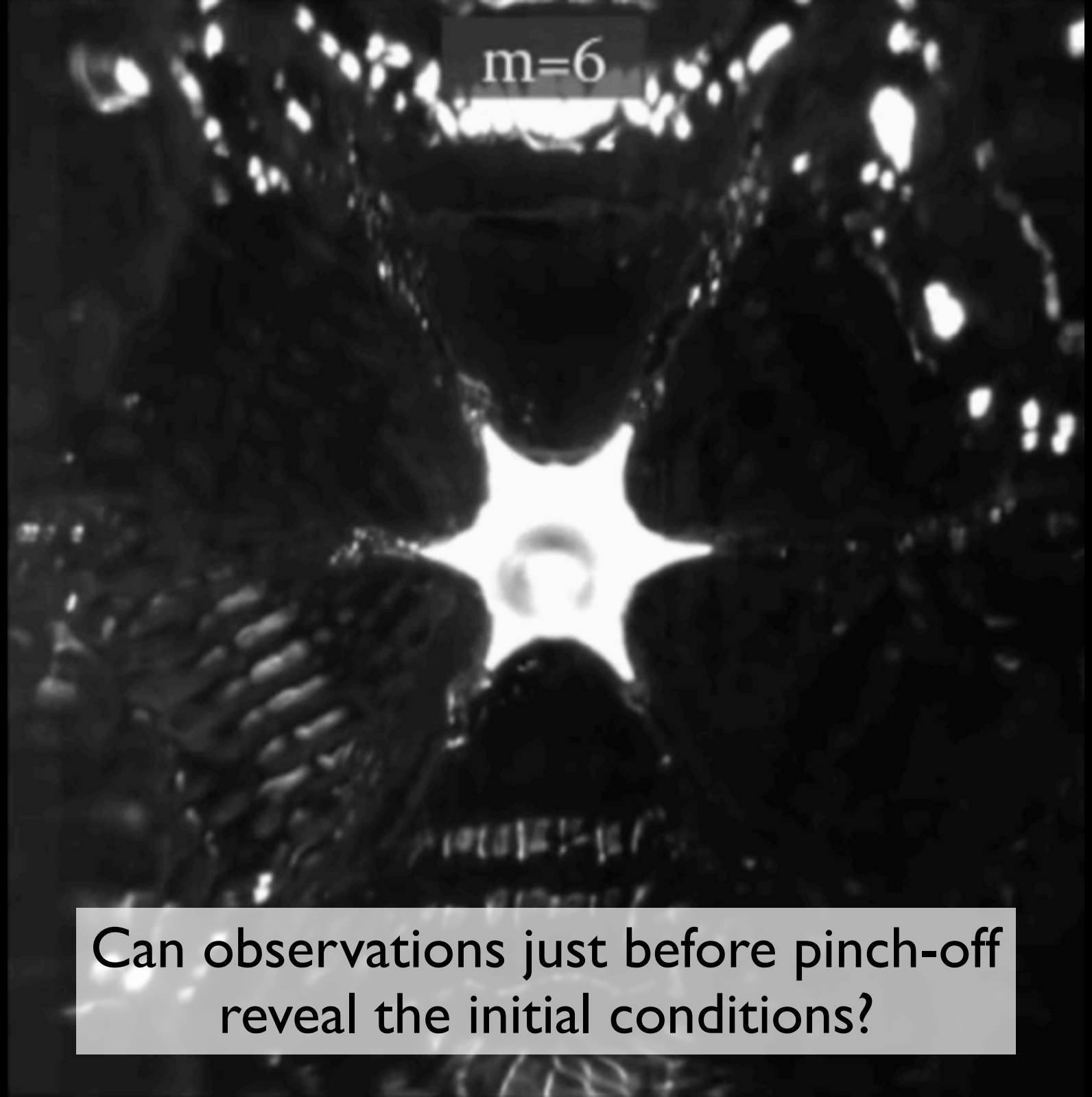
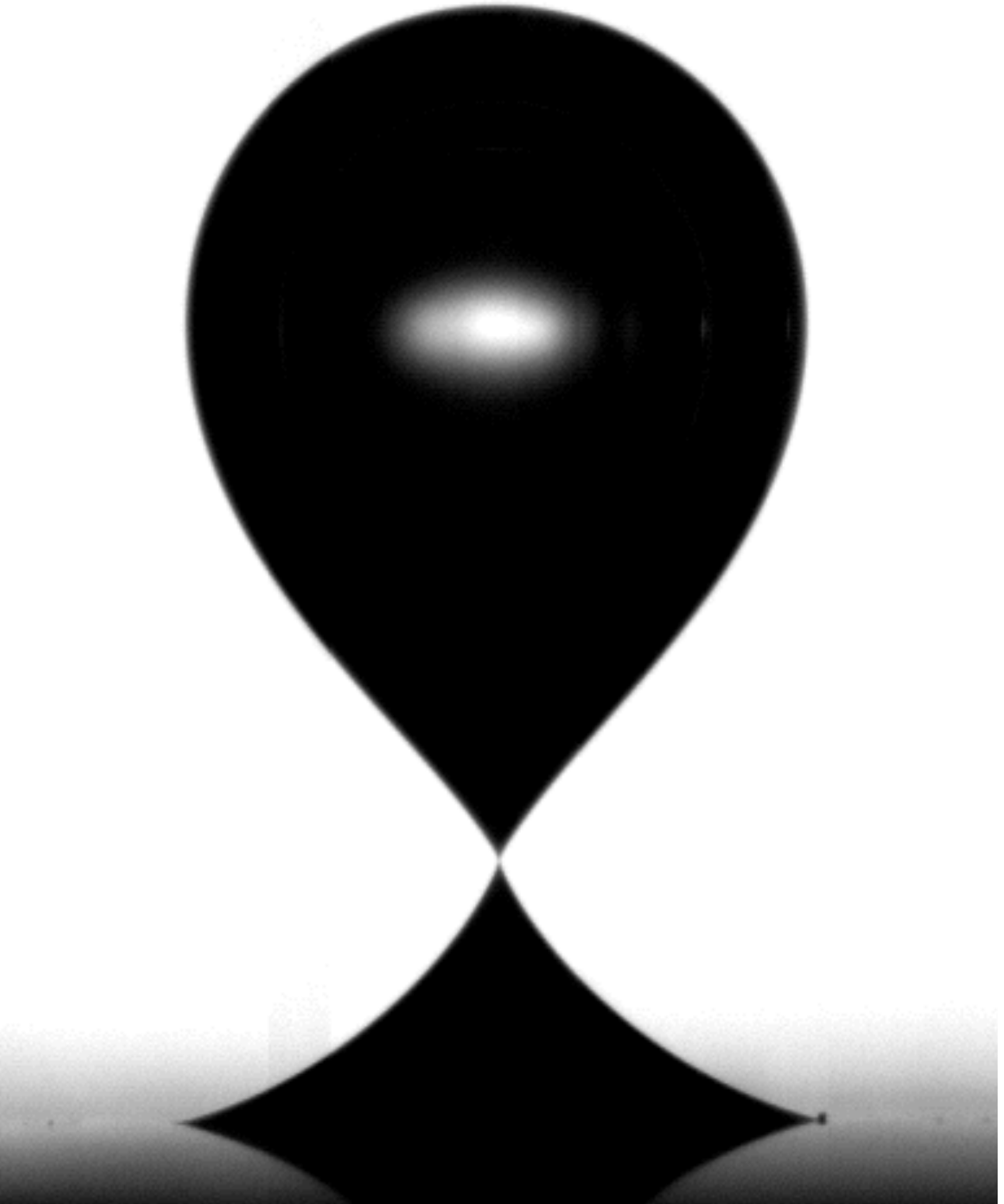
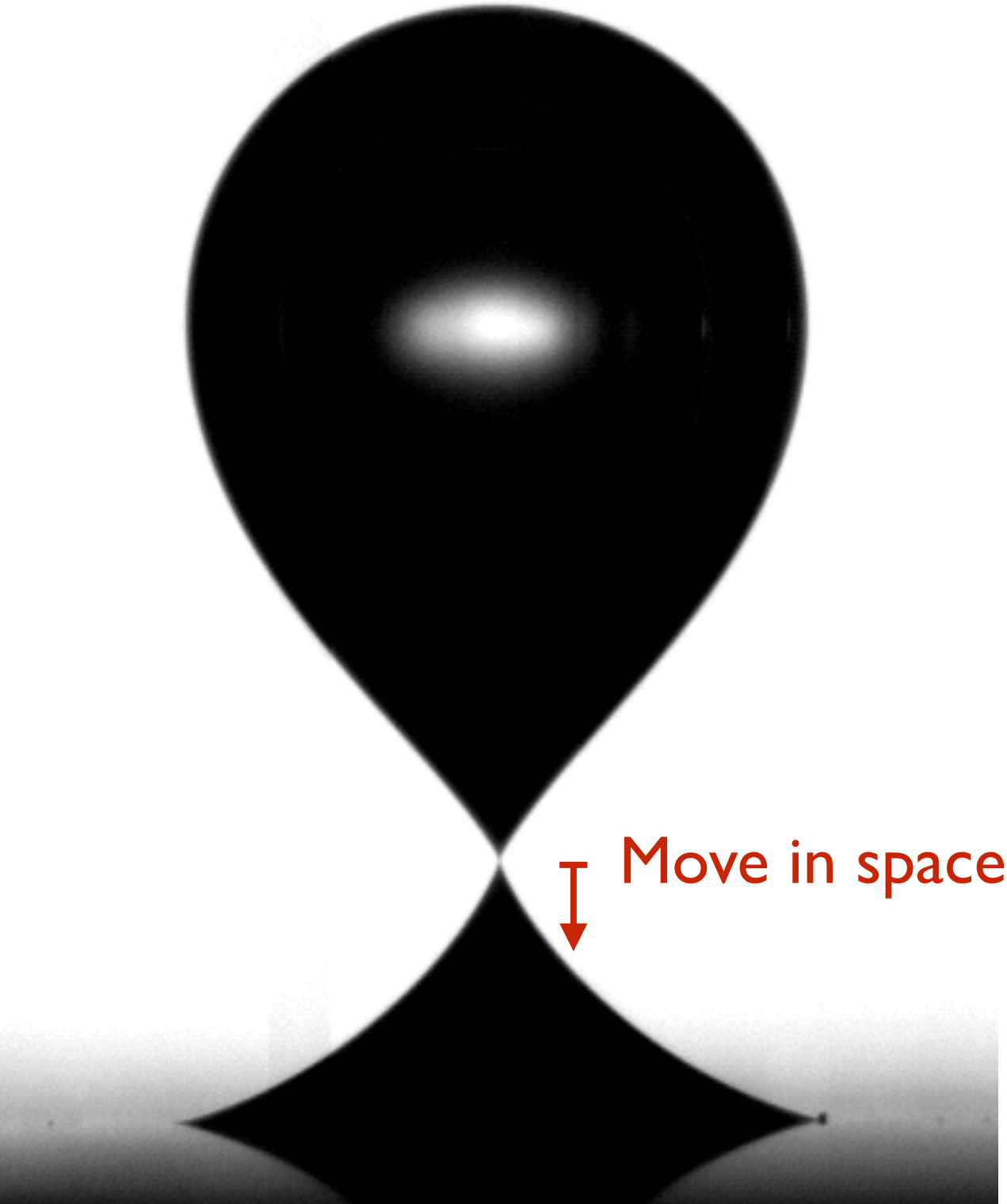


Can observations just before pinch-off reveal the initial conditions?

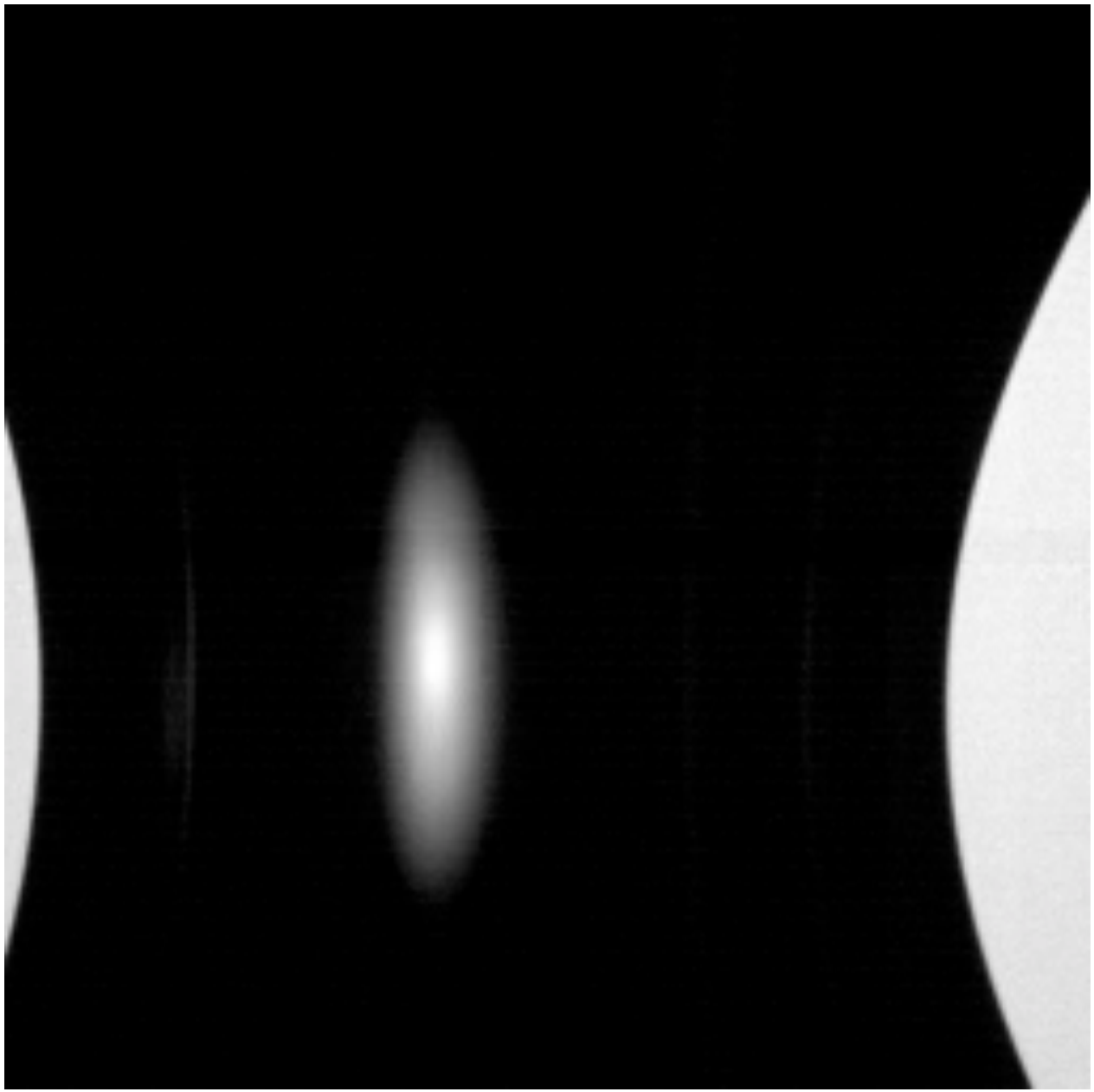




Move in space → move back in time

Shape recapitulates history of oscillation

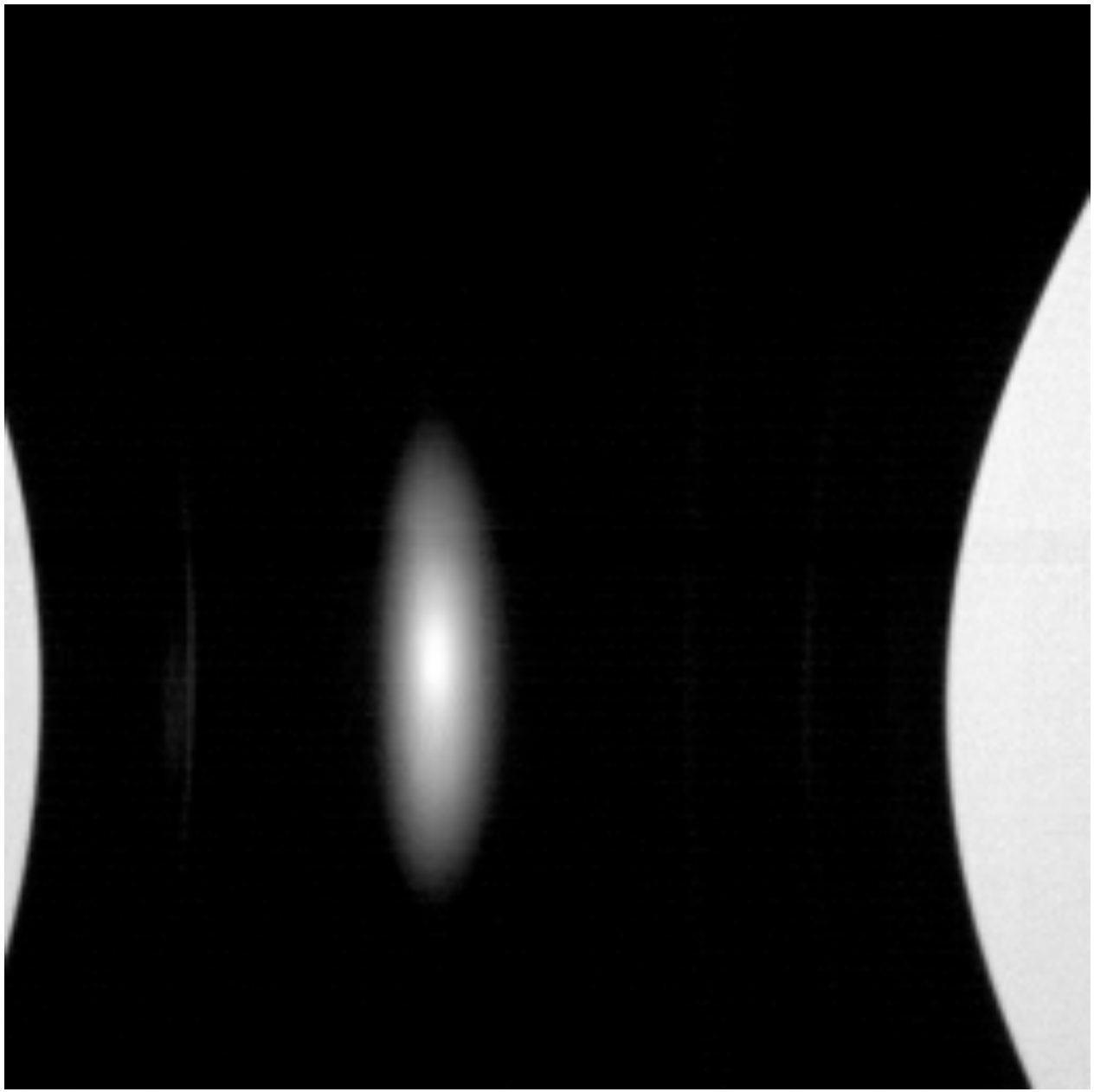
Shape is memory: n = 3 vibration



66,000 frames/s

200 μm

Shape is memory: n = 3 vibration



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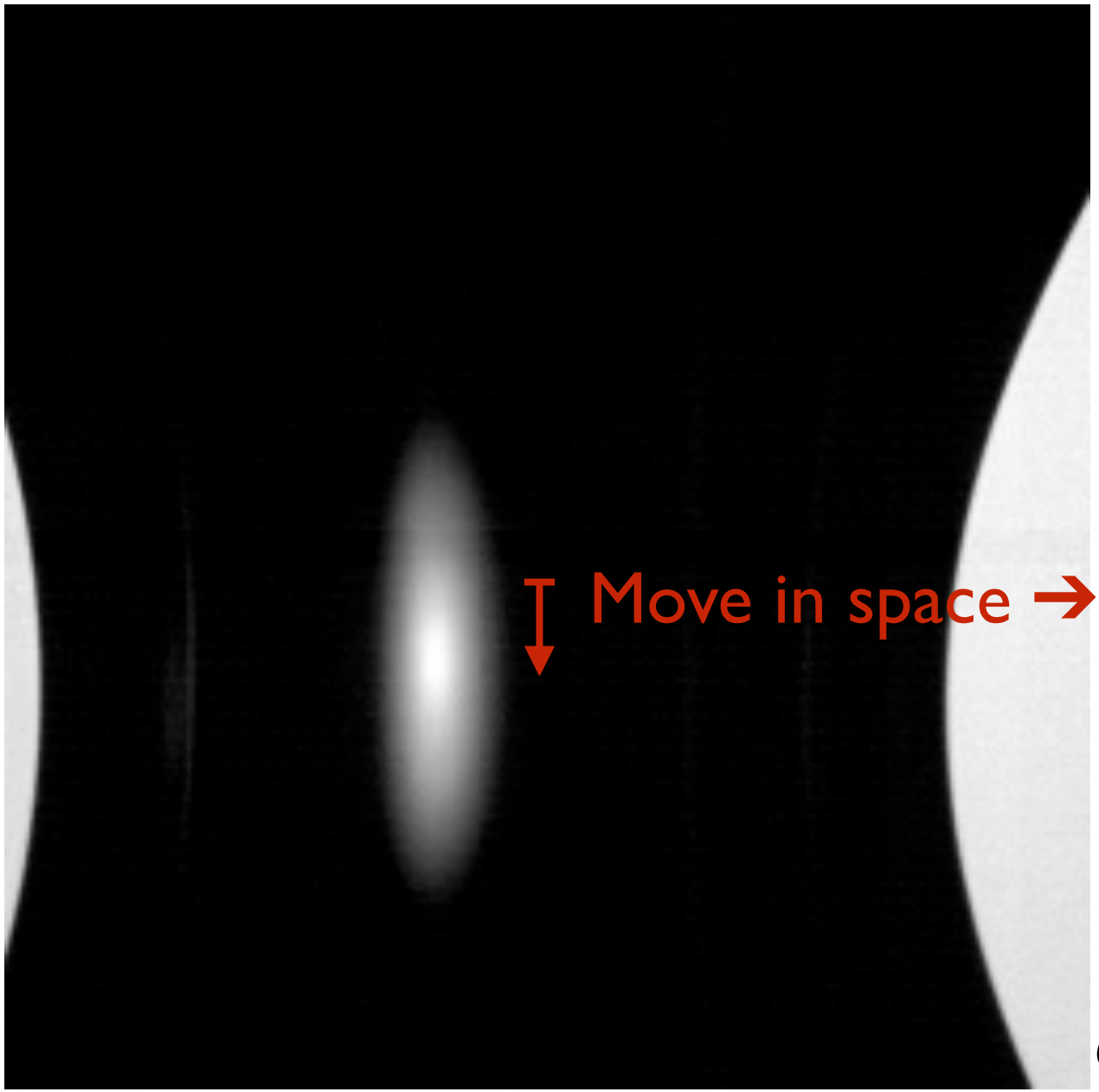

$n = 20$

Enríquez et al., *Physics of Fluids* 2011

Summary

Memory = language for history dependence

Summary

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Slow

Suspensions

- Cyclic driving
  + Non-equilibrium
  + Steady state
  ➔ memory
- Slow, noisy learning ➔ more learning

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Bubble pinch-off

- Singularities tend to erase memory (universality)
- Bubbles are an exception
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Memory can reveal nature of material or its dynamics

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Stay away from equilibrium!