Experiments with Soft Jammed Solids: Return-Point Memory Meets Self-Organization

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Undergraduates:

- **Aidan McGuckin**
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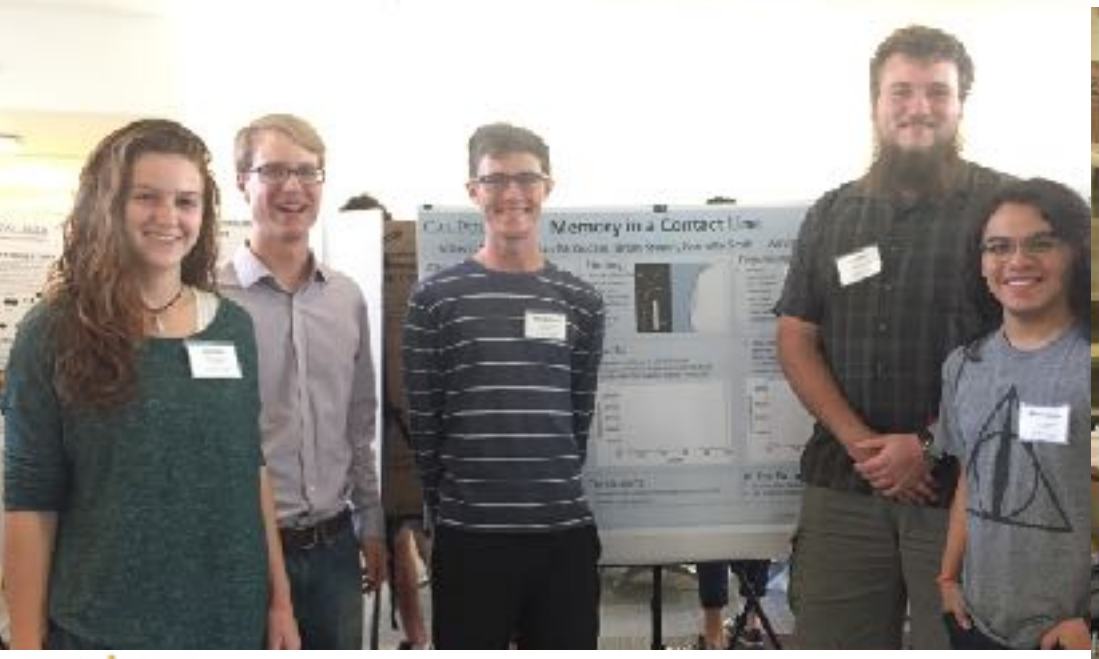
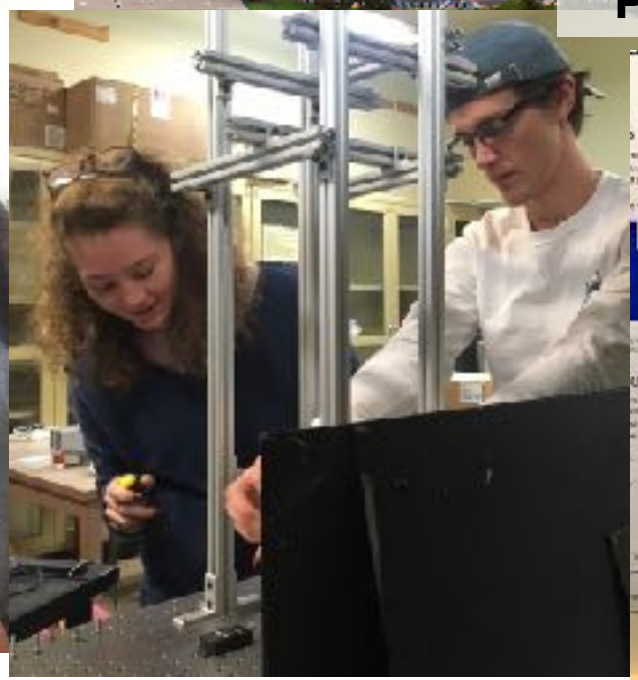
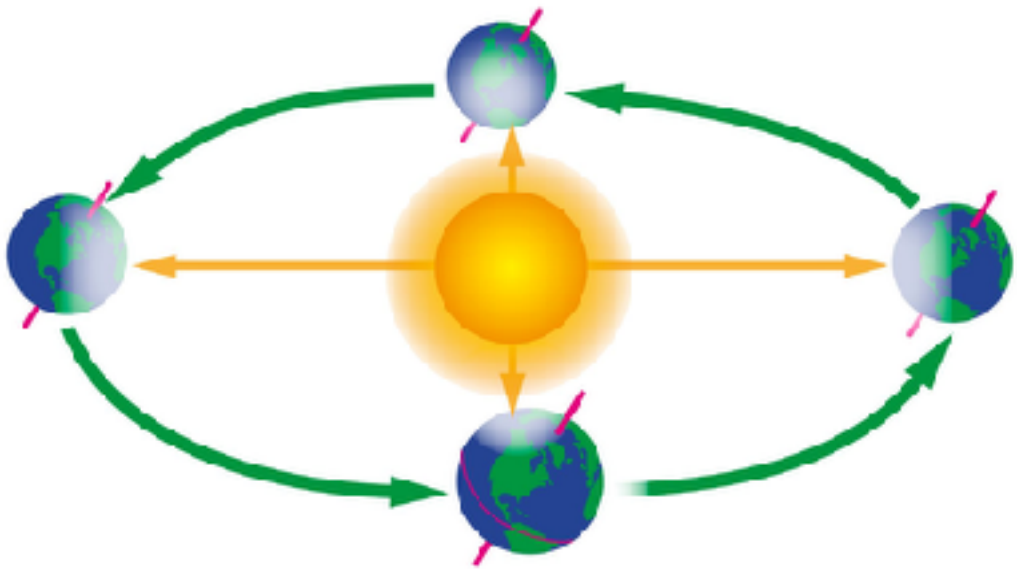
- **Audrey Profeta**
- **Brian Kroger**
- **Devin Wieker**
- **Donald Loveland**
- **Jacob Hass**
- **Jenny Smit**
- **Juan Ortiz Salazar**
- **Luke Horowitz**
- **Natasha Proctor**
- **Peter Nelson**





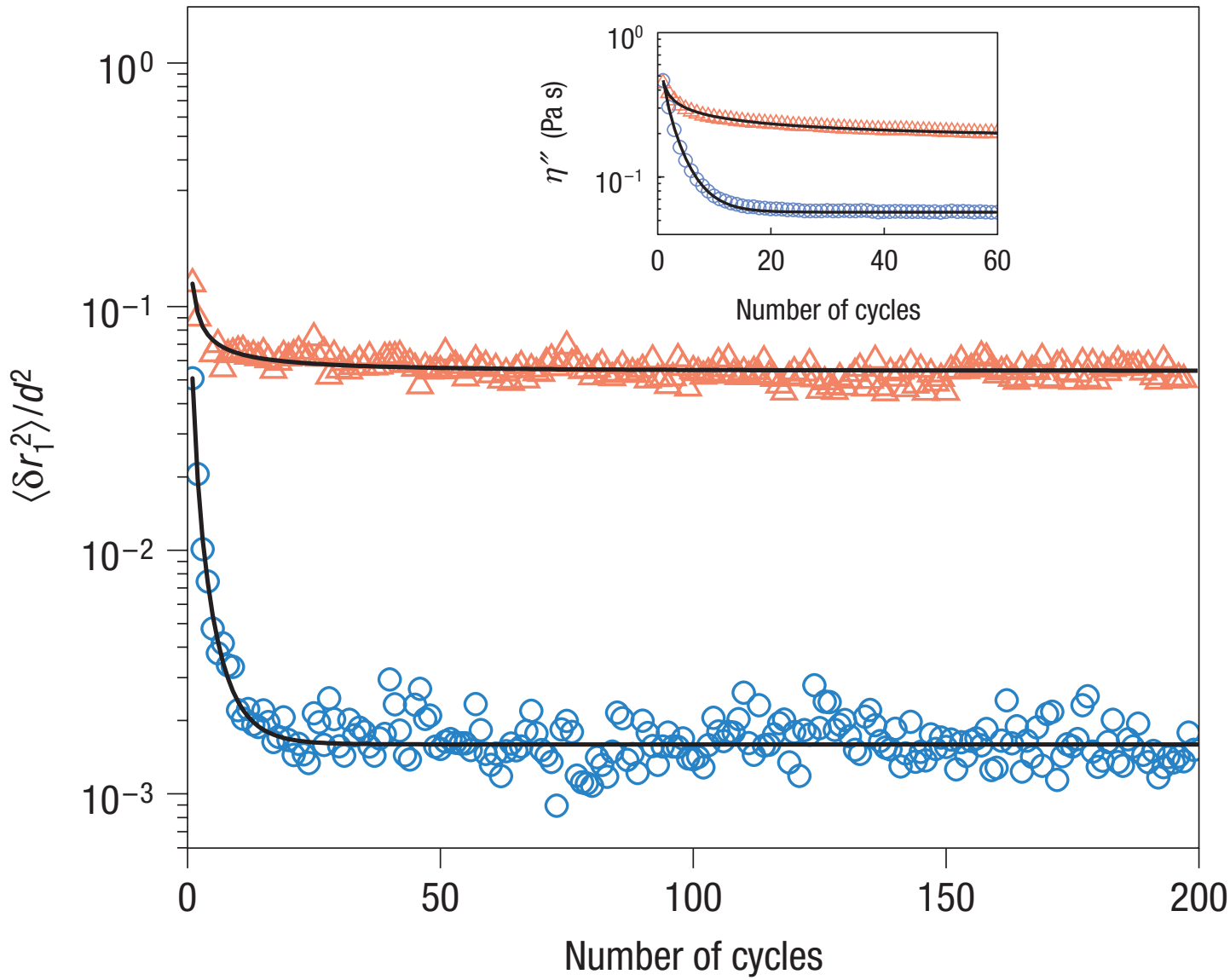
NSF DMR-1708870; CBET-1702352
Cal Poly RSCA Grant; Bill & Linda Frost Fund

- Cyclic driving is ubiquitous
- It can change non-equilibrium systems



DK Find Out, Granor

- Cyclic driving is ubiquitous
- It can change non-equilibrium systems
  - Steady state after many cycles



Corté *et al. Nat Phys.* 2008

- Cyclic driving is ubiquitous
- It can change non-equilibrium systems
  - Steady state after many cycles

- Multiple cycles → Multiple memories?
  - Different answers → different classes of memory

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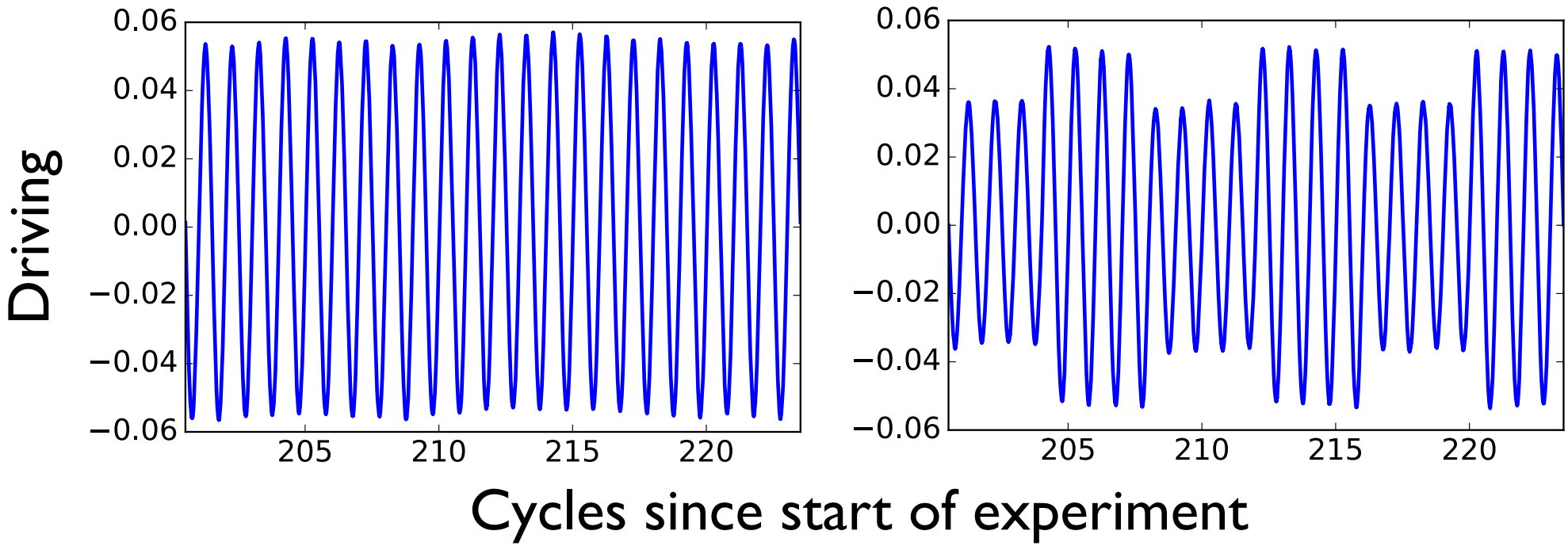
- Multiple cycles ➔ Multiple memories?
  - Different answers ➔ different classes of memory

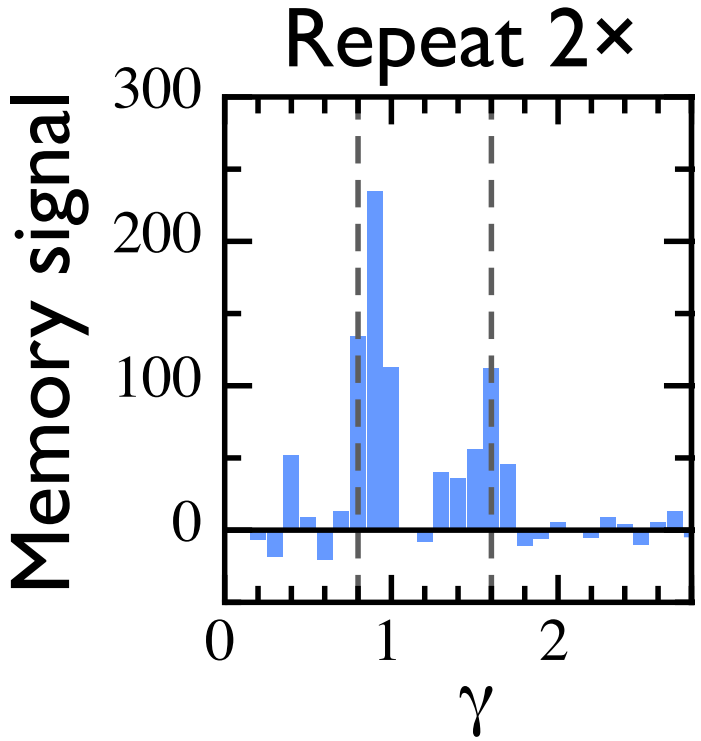
Train system 2 ways:



Is there a difference?

Two amplitudes: Sheared Suspension

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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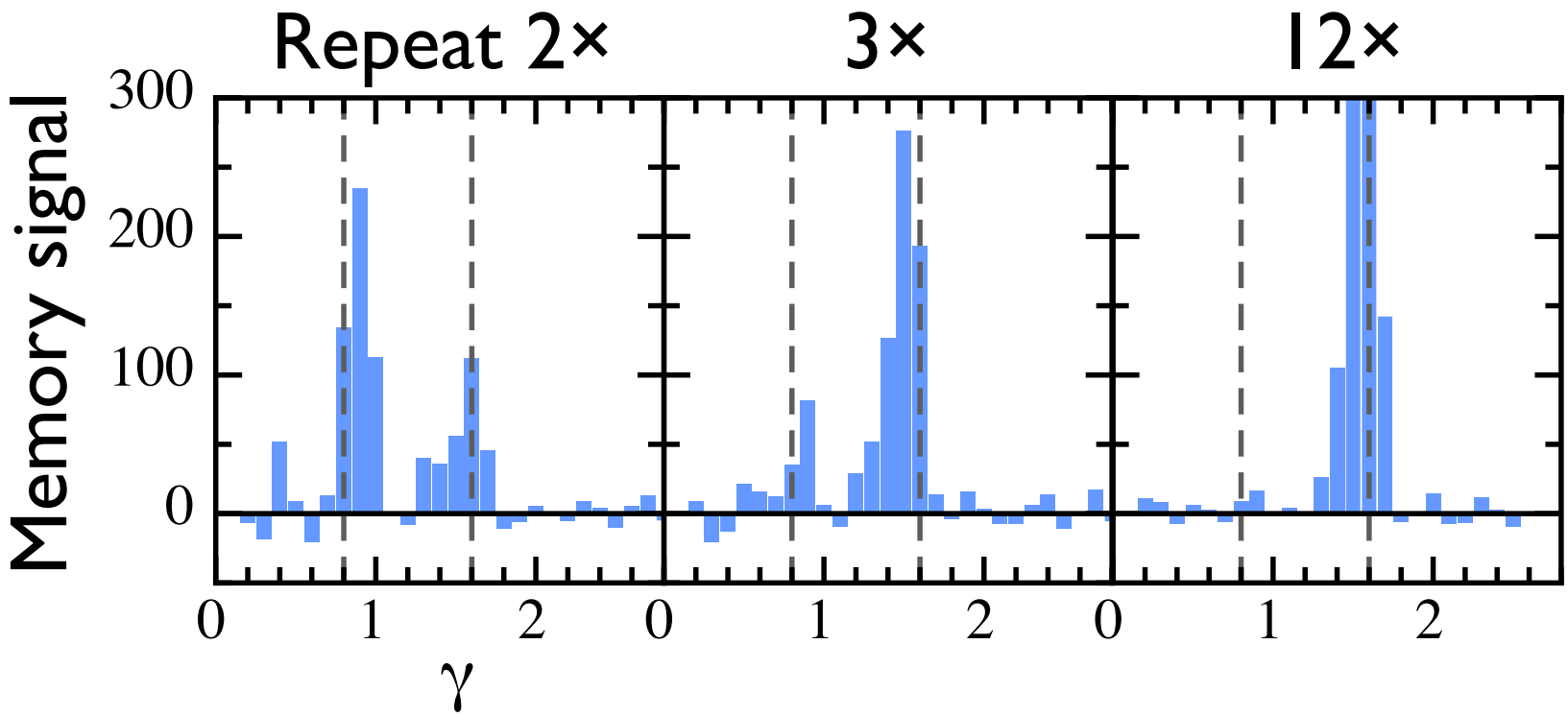

Paulsen, Keim, Nagel, *PRL* 2014

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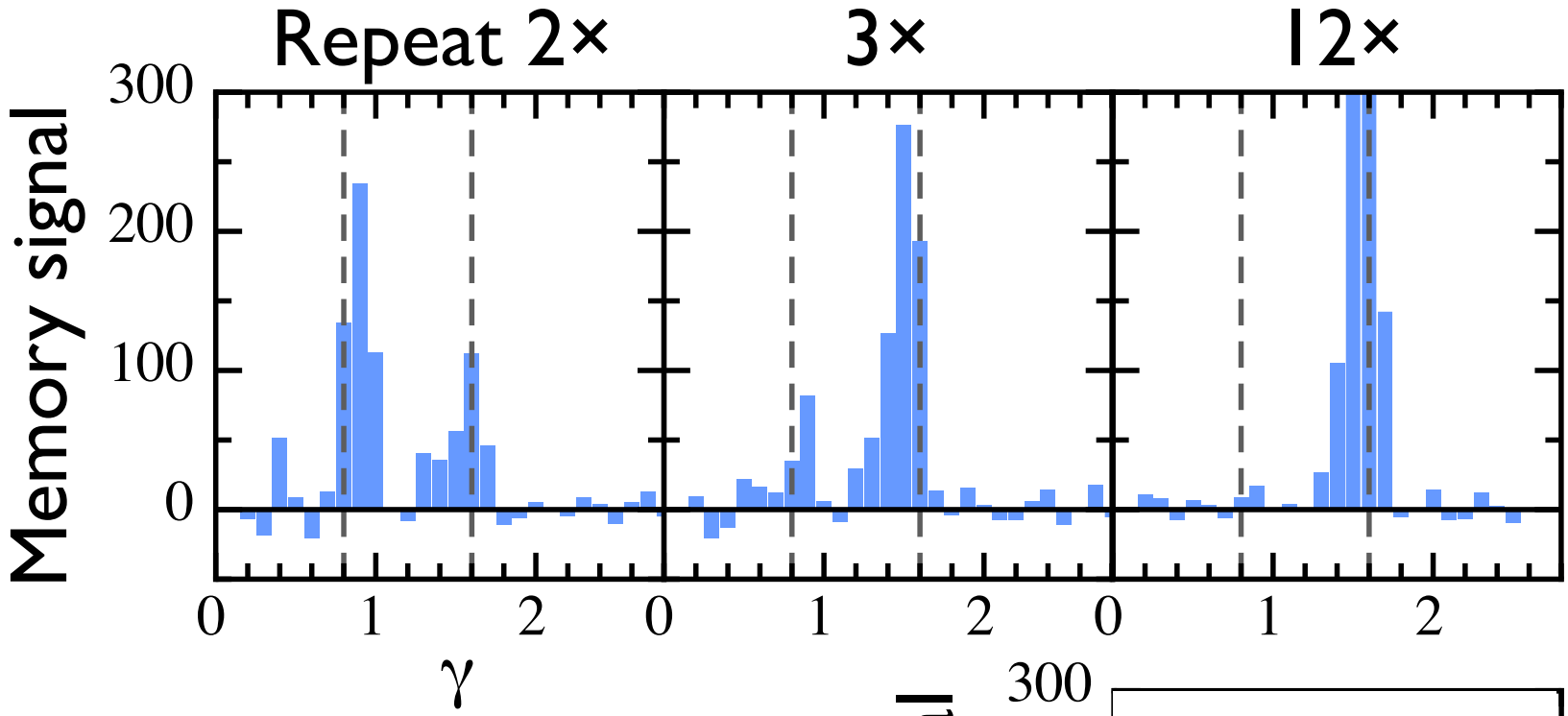
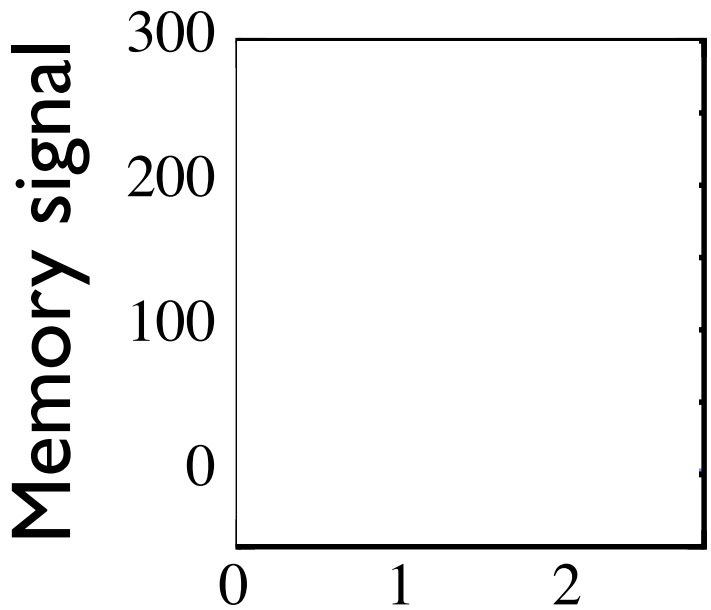


Add noise
(Wait 8 minutes
between cycles)



Paulsen, Keim, Nagel, *PRL* 2014

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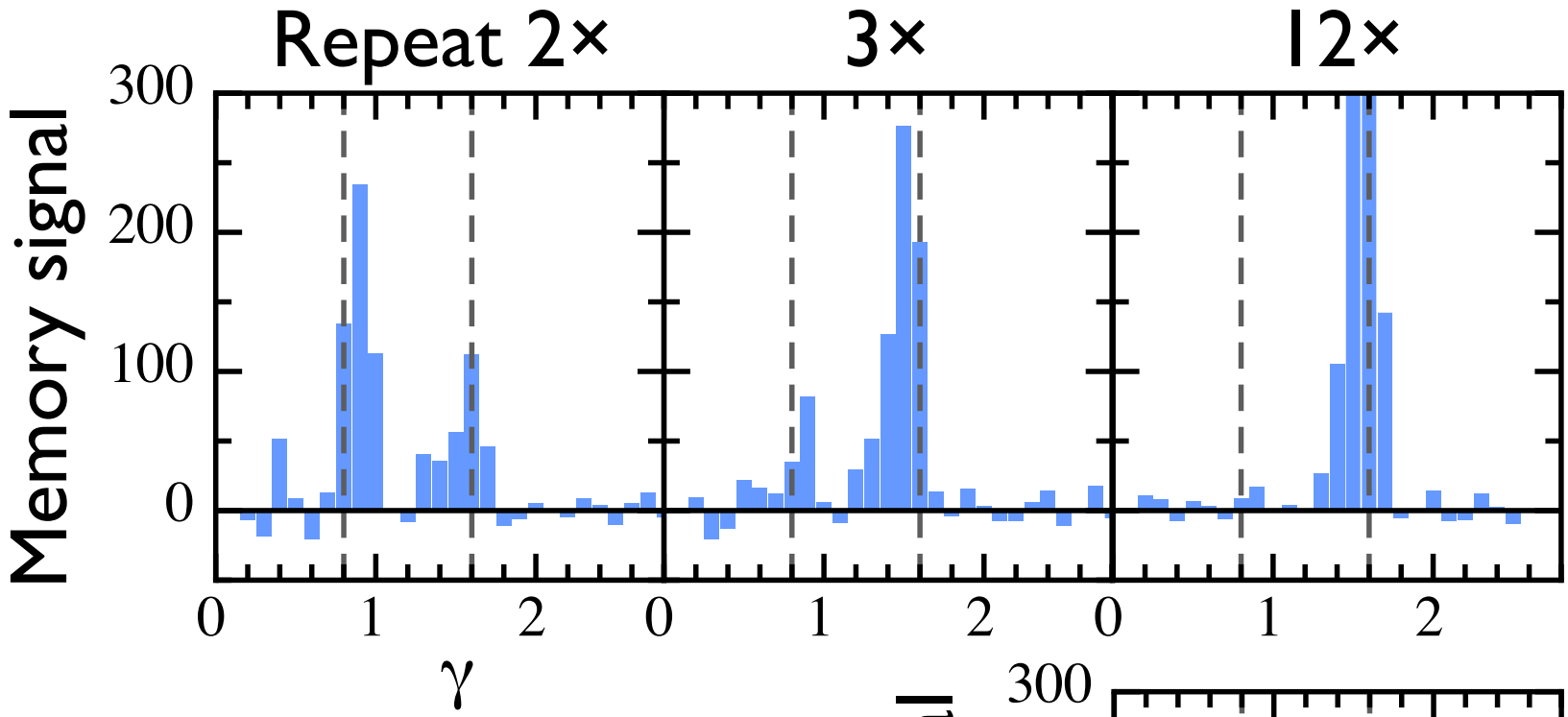

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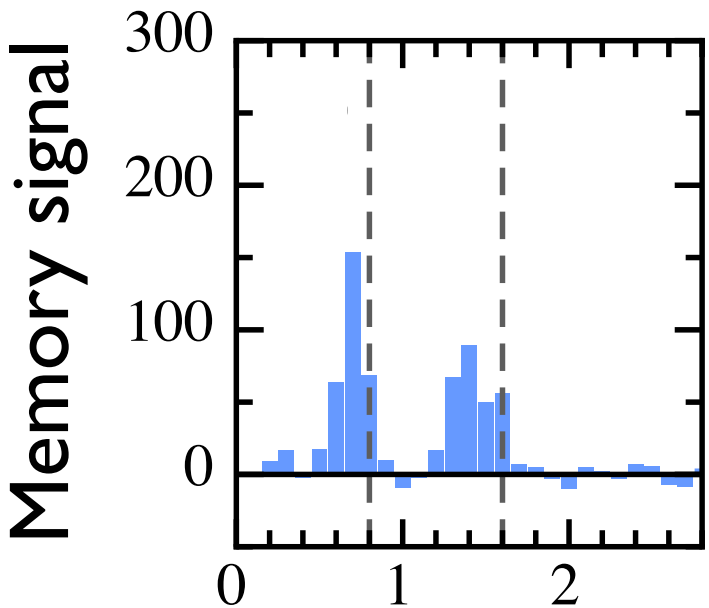
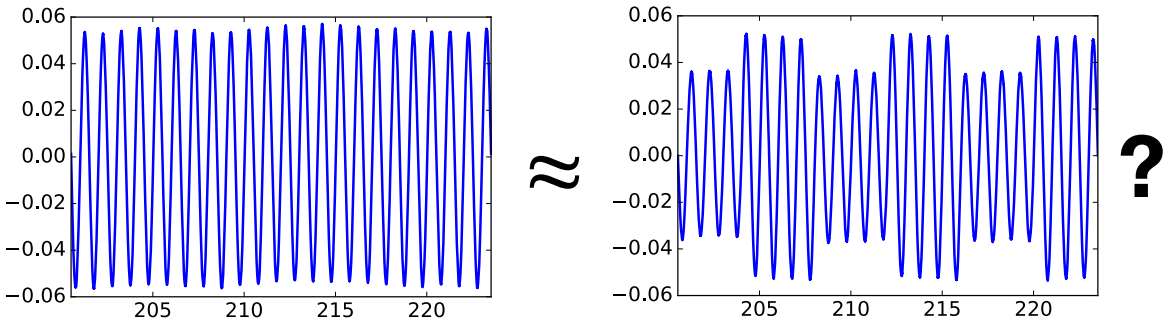
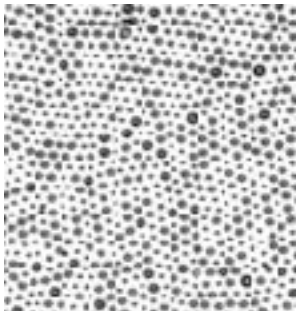


Paulsen, Keim, Nagel, *PRL* 2014

Outline

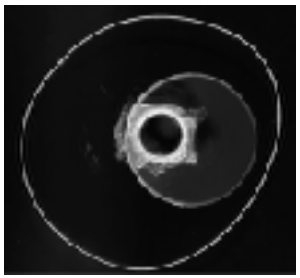




Disordered solids

No: Return-point memory

Yes: Transient self-organization

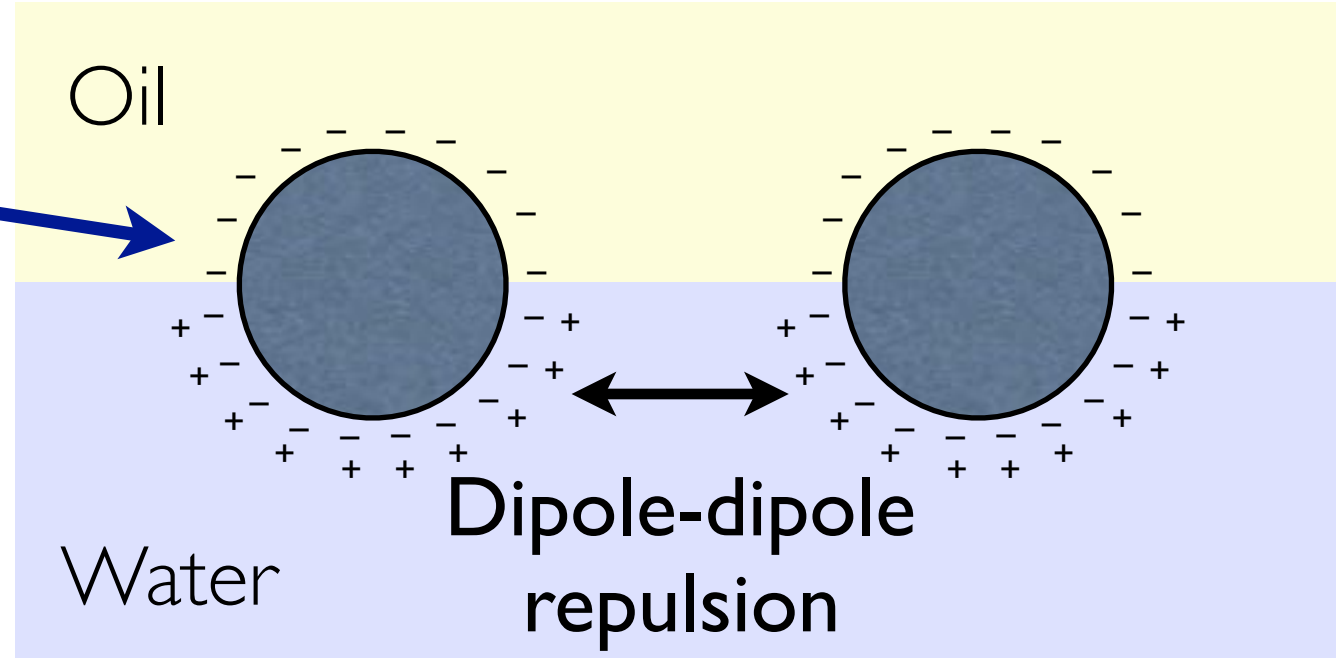


Contact lines

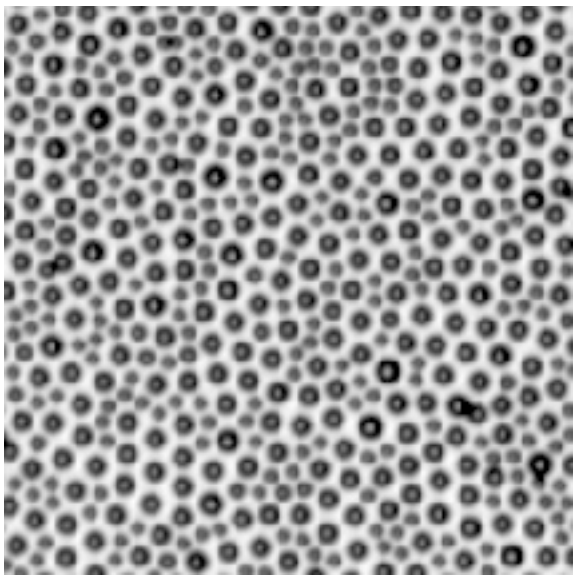
Maybe...

A 2D disordered solid

Polystyrene microspheres 3.8, 5.8 μm



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

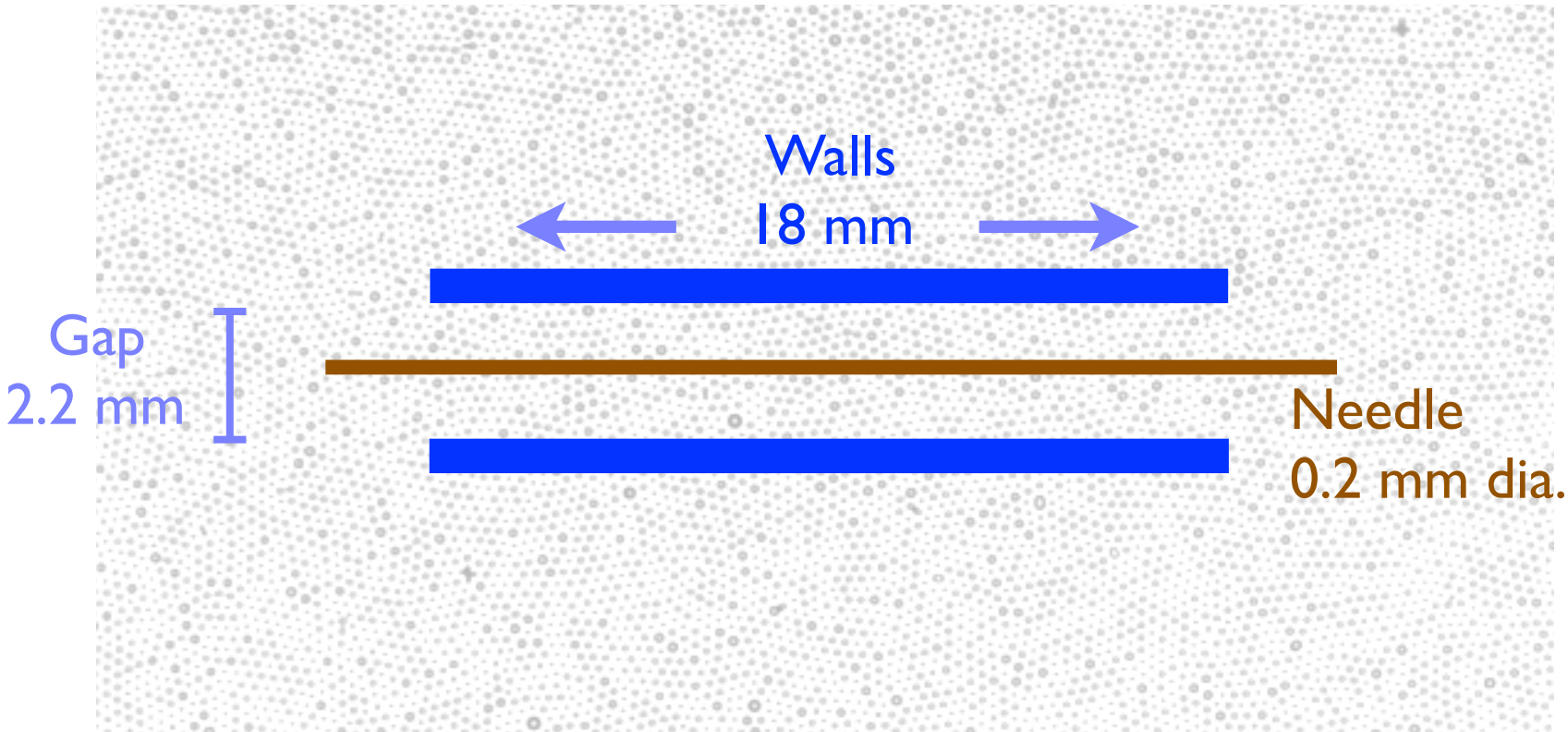


Long-range repulsion
→ Mechanically over-constrained (jammed)
Particles *not touching*
Negligible thermal motion

Keim & Arratia, *Soft Matter* 2013

Interfacial shear rheometer

Top view



Magnetic driving ➔ Shear stress

Brooks et al., *Langmuir* 1999
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Keim & Arratia, *PRL* 2014

Interfacial shear rheometer

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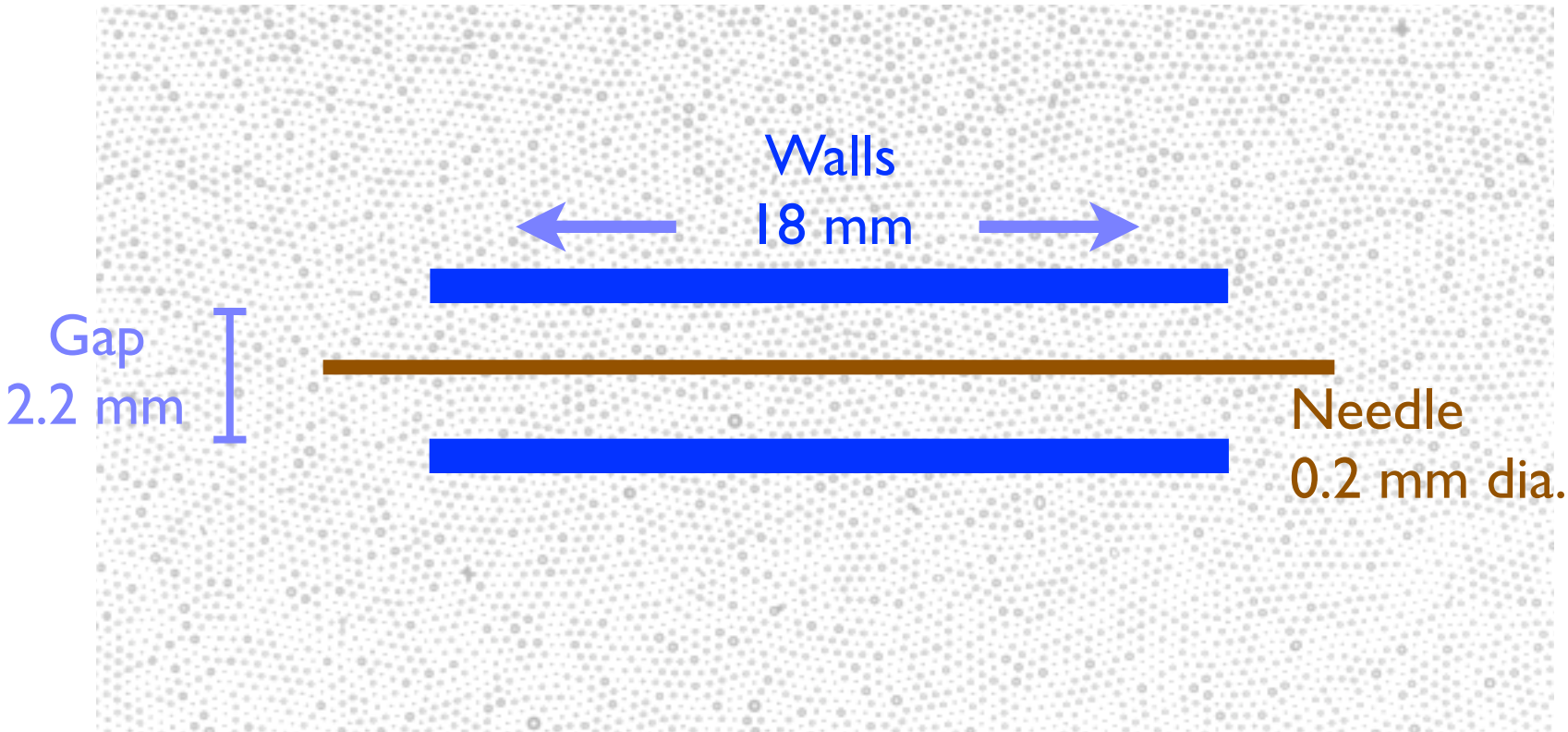

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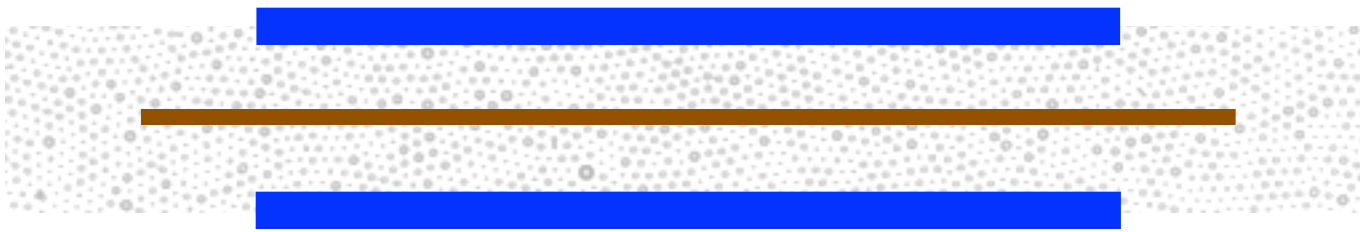
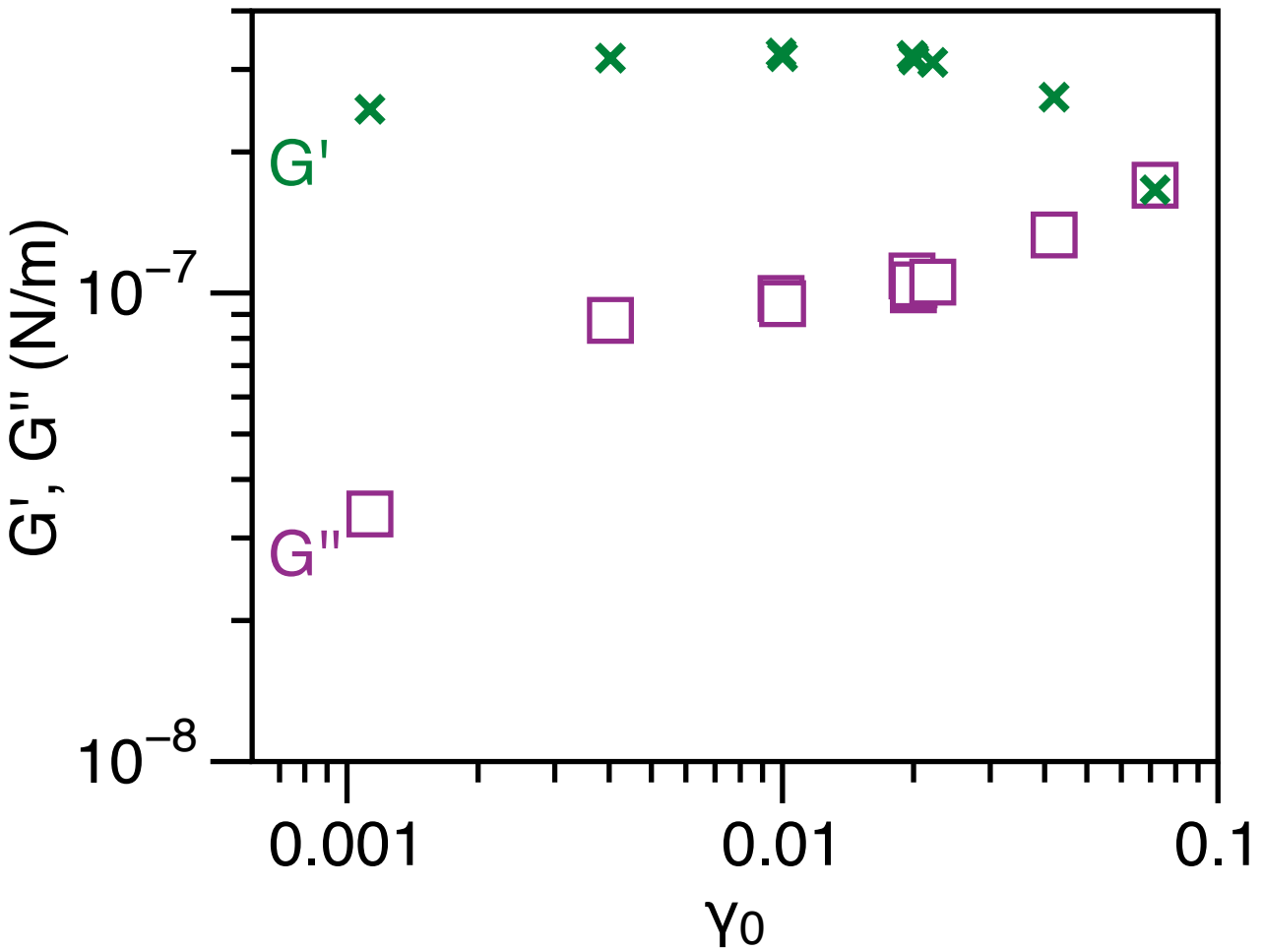


$$\text{Boussinesq \#} = \frac{\text{stress on material}}{\text{stress on oil, water}} \sim 100$$ ✔

➔ ~stress only at boundaries

Rheology: Yielding transition



flickr: elana's pantry

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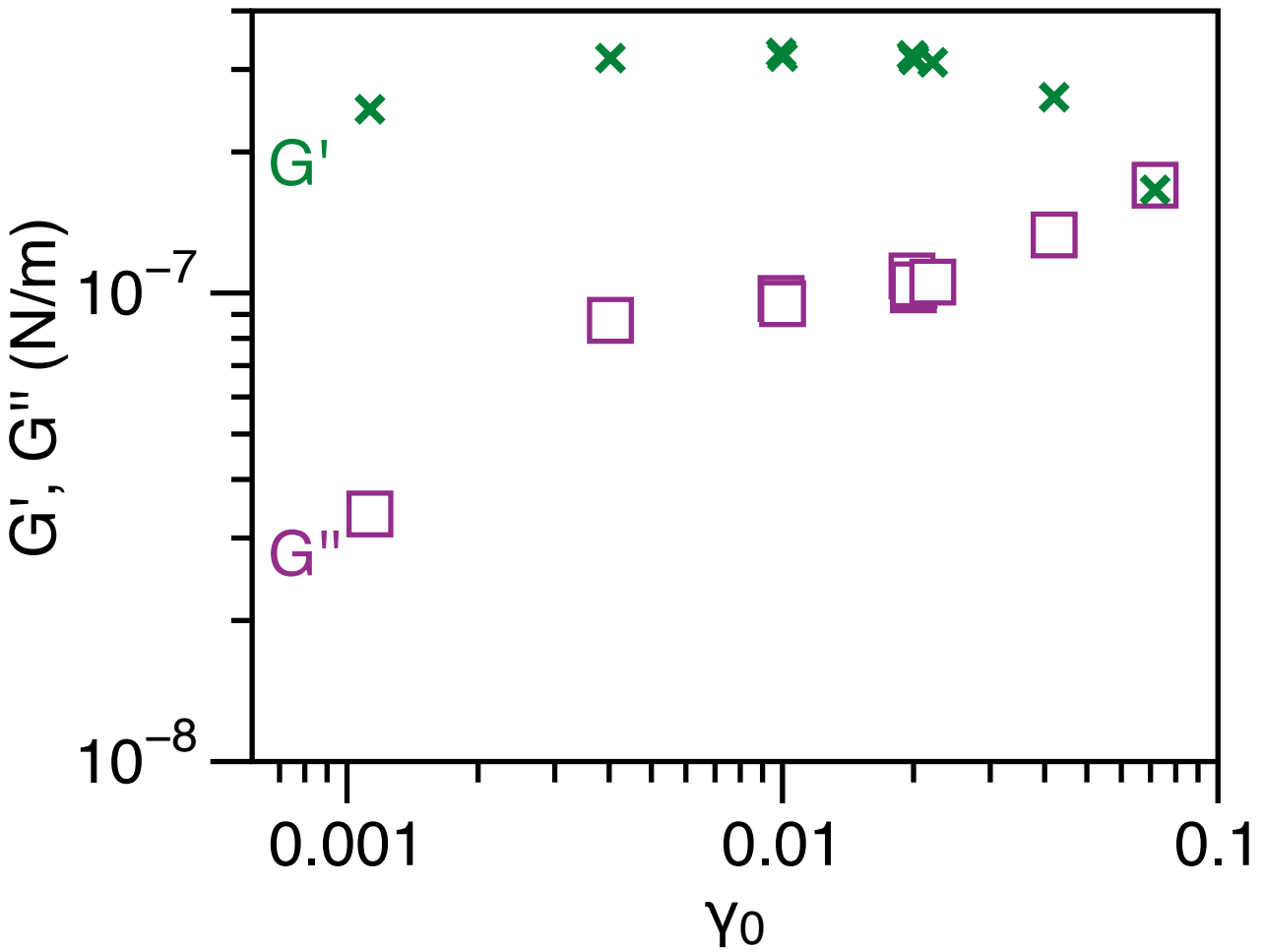

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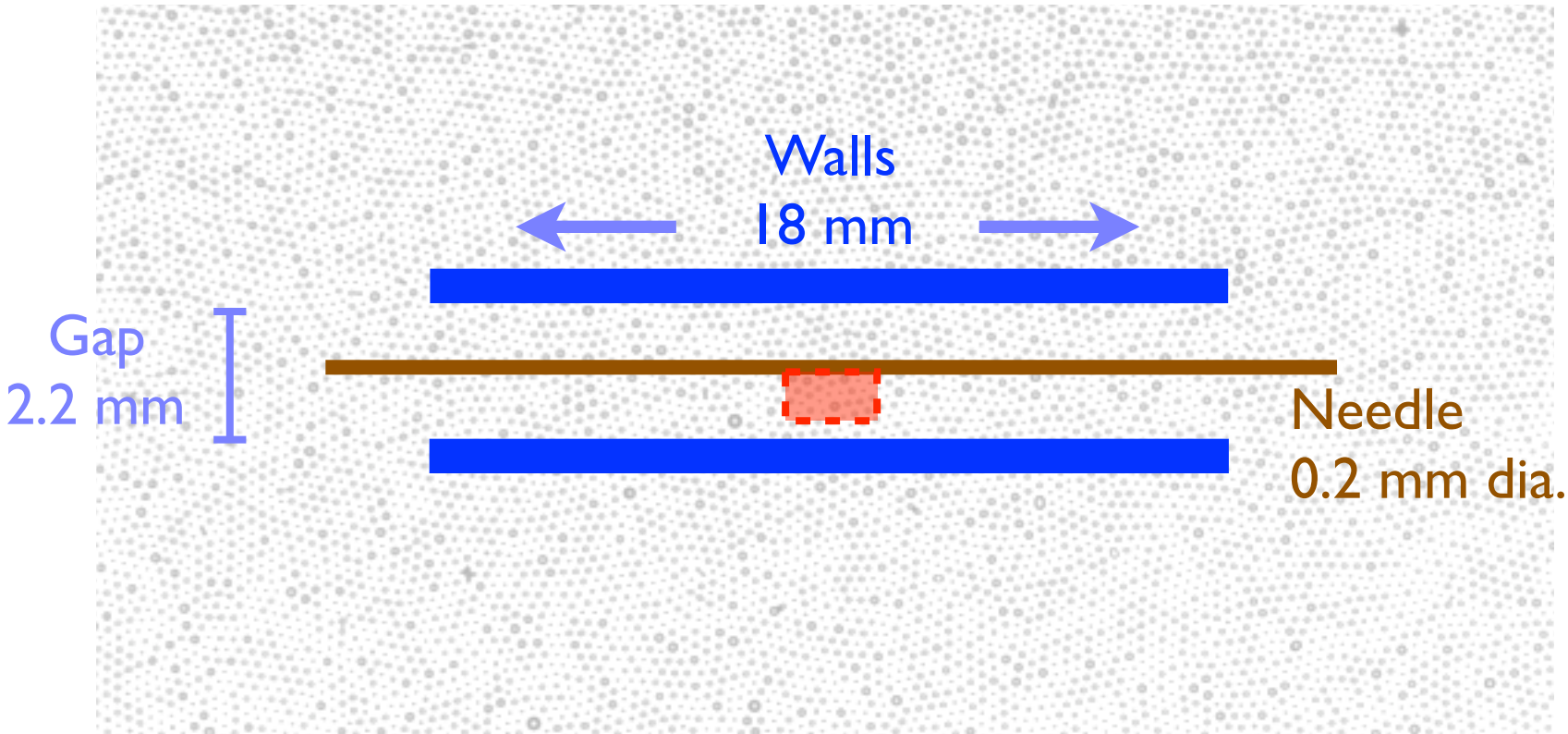
What is happening in microstructure?

Interfacial shear rheometer

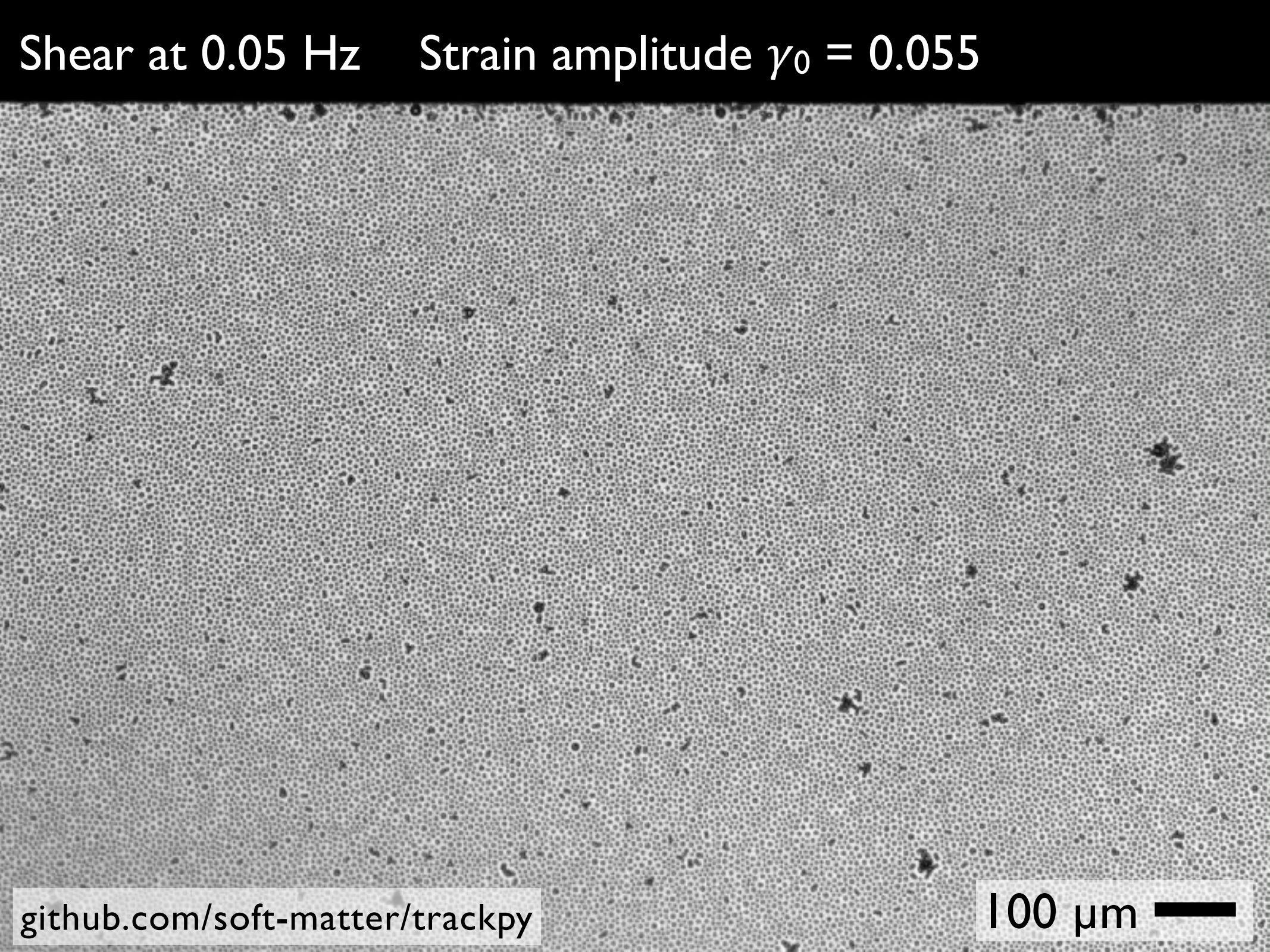
Top view

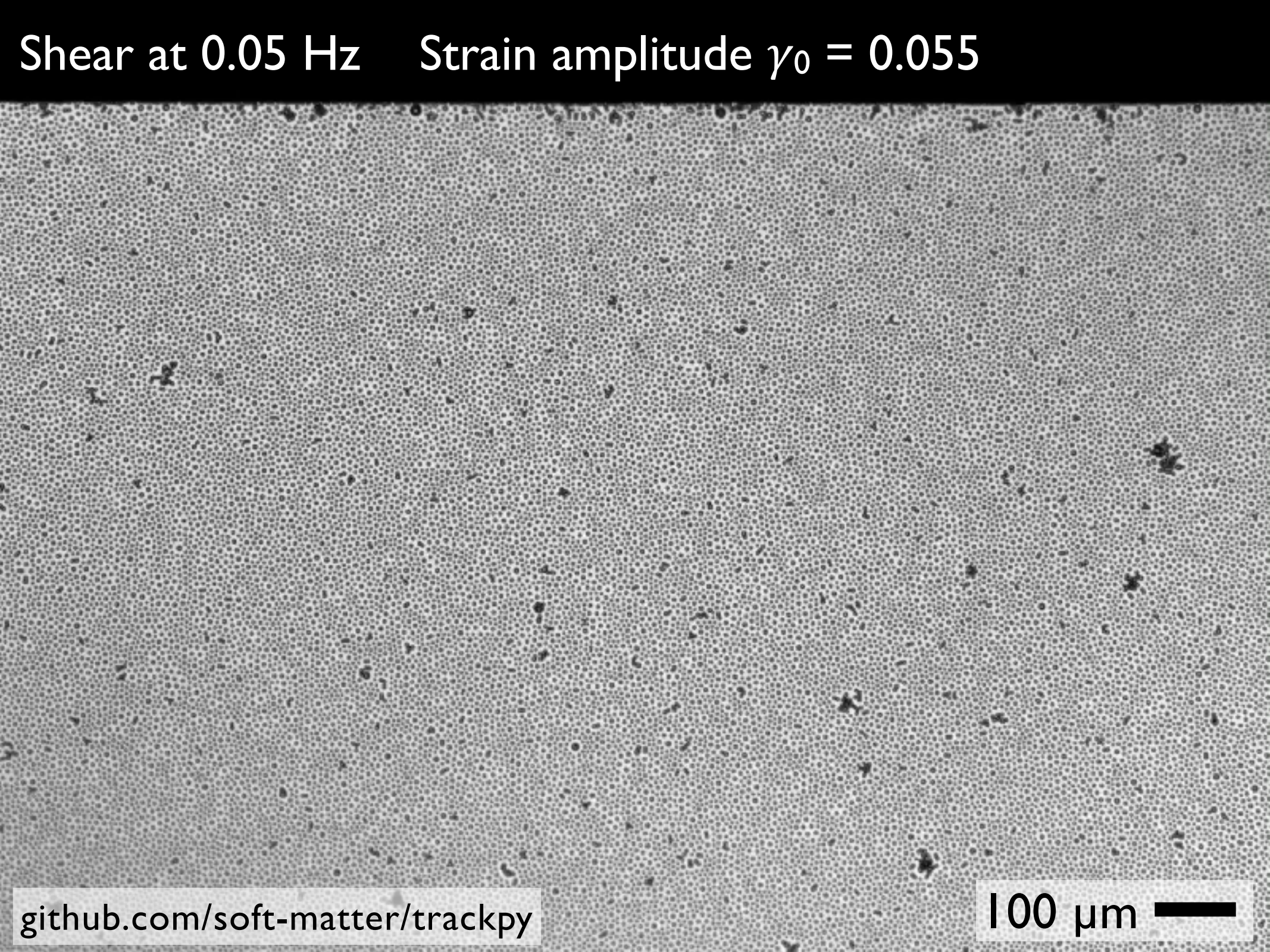


Brooks et al., *Langmuir* 1999
Keim & Arratia, *Soft Matter* 2013
Keim & Arratia, *PRL* 2014

About the Data

- Talk uses 4+ experiments between 2014 and 2018
  - Particles changed
  - Stress-controlled rheometer → Strain values vary
    - All strains below yielding
  - Memory results from just 2 recent experiments
    - Focus on visualizing microstructure


Shear at 0.05 Hz Strain amplitude γ_0 = 0.055
github.com/soft-matter/trackpy
100 μm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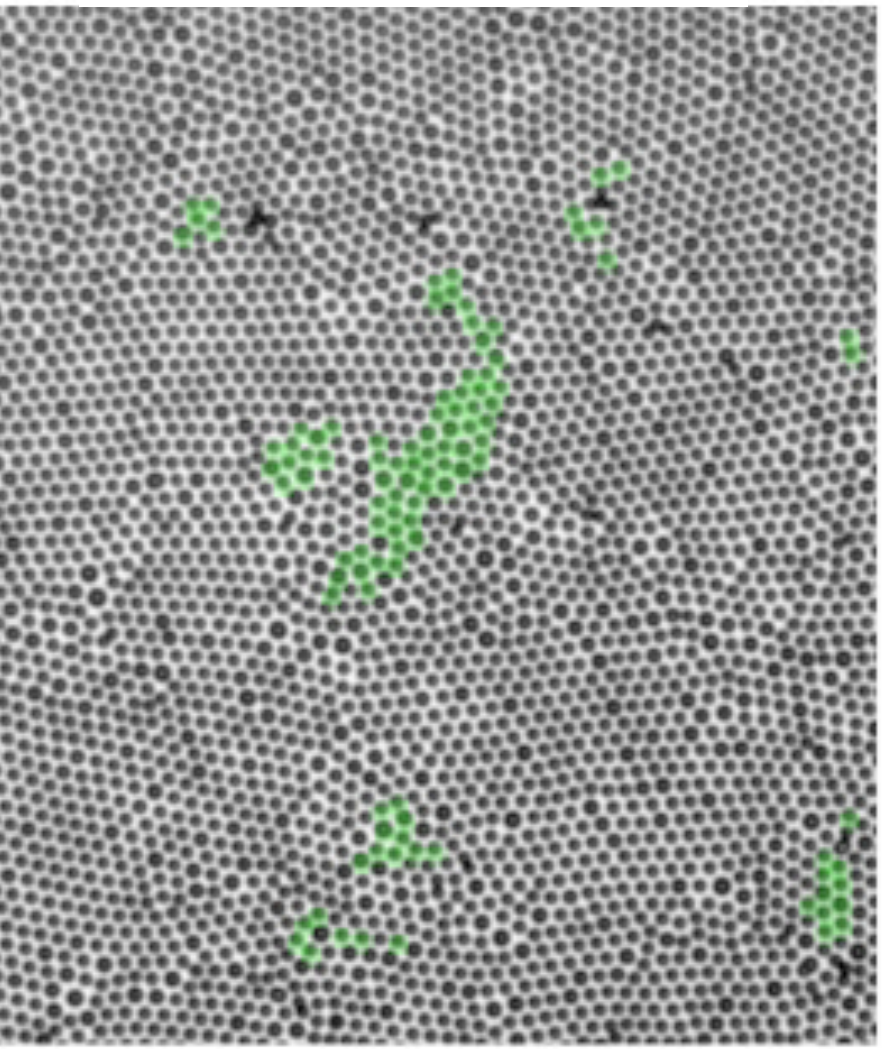
Watching particles rearrange

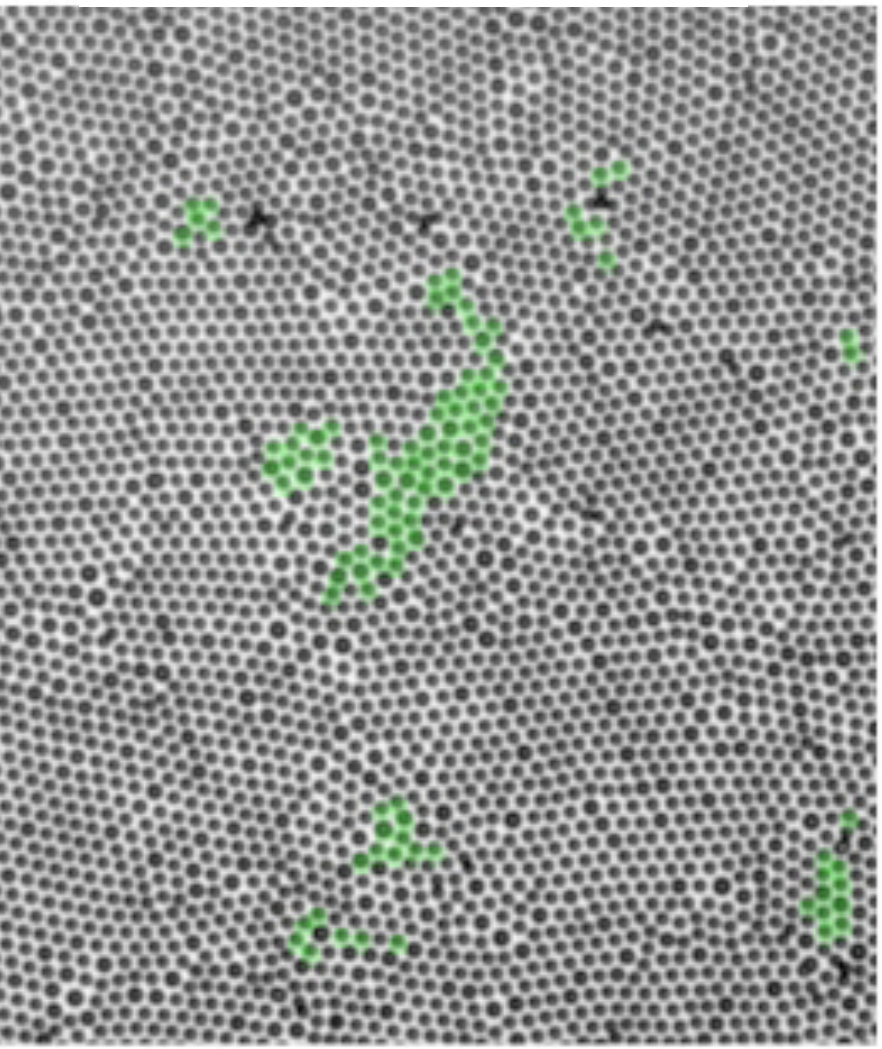


Rearranging particles highlighted

Note: Rearrangement time ≪ Period of driving

Keim & Arratia, *PRL* 2014

Watching particles rearrange



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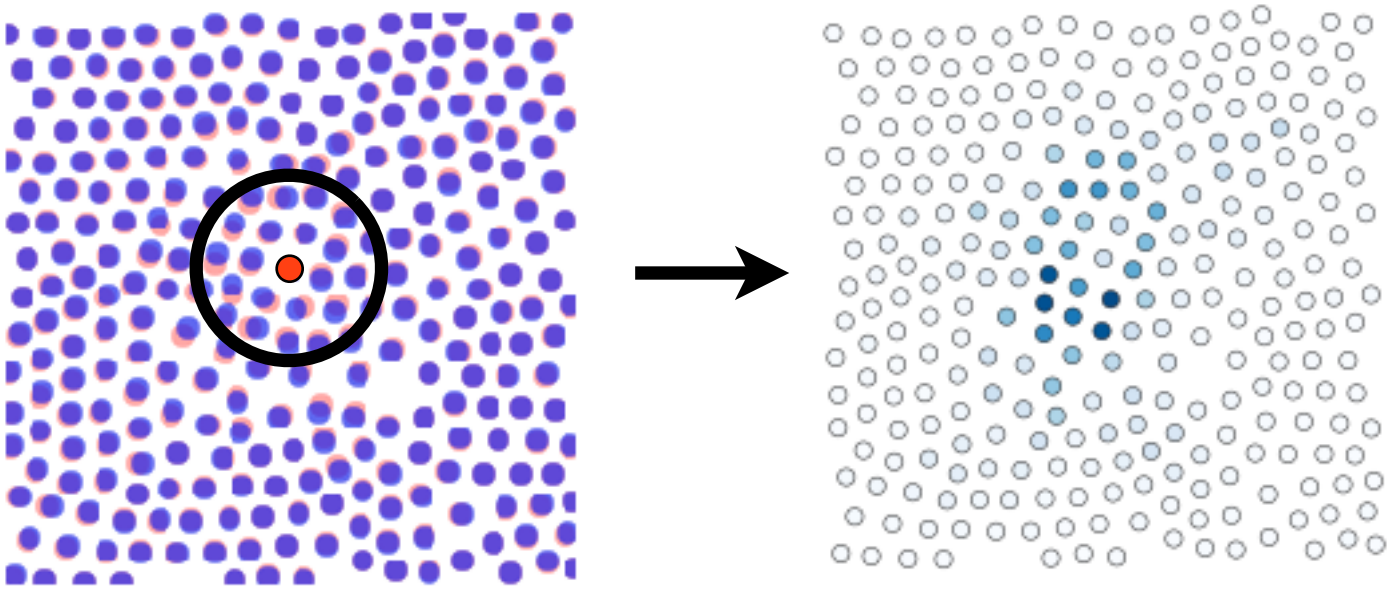
Identify rearrangements with D^2_{min}



"Are these particles behaving as an elastic solid?"

$D^2_{min}(t_1, t_2)$ ~ local plasticity between t_1, t_2

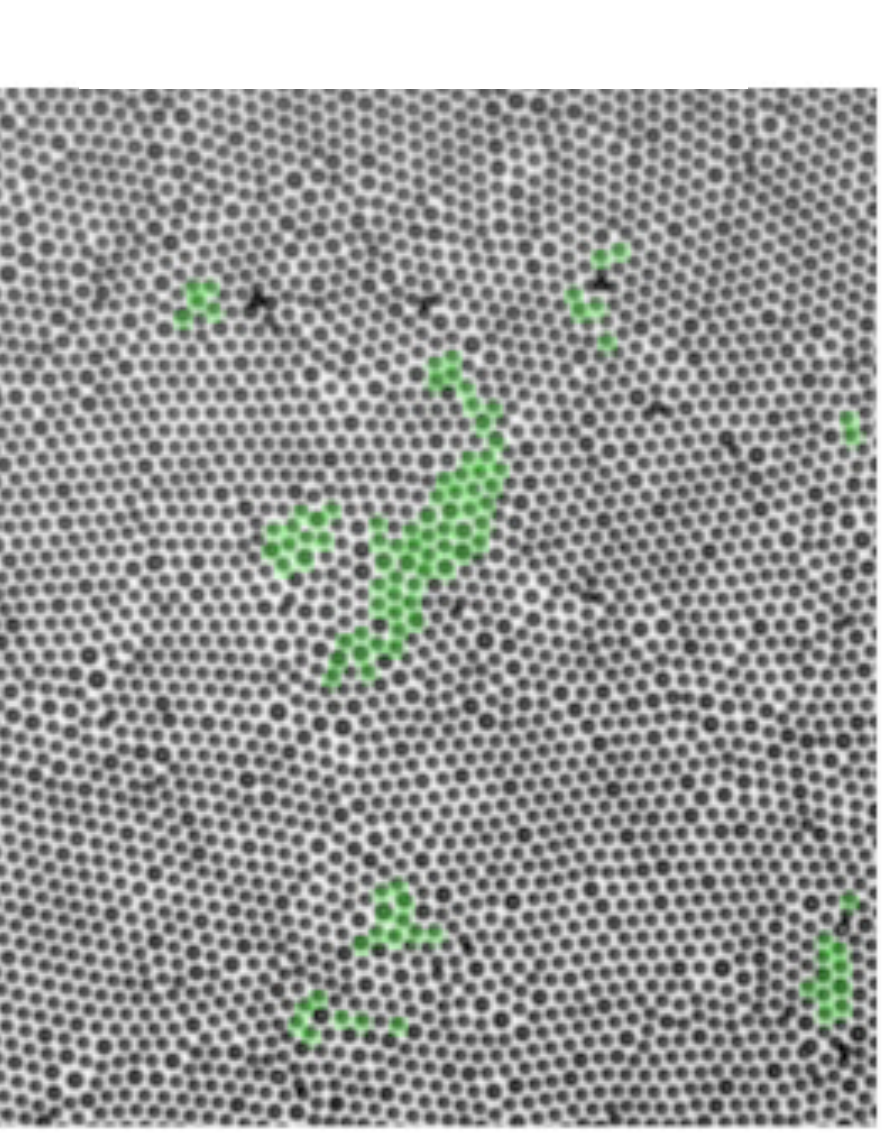
$$D^2_{\min} = \frac{1}{a^2 N_n} \|\vec{x}(t_2) - \epsilon \cdot \vec{x}(t_1)\|_2$$

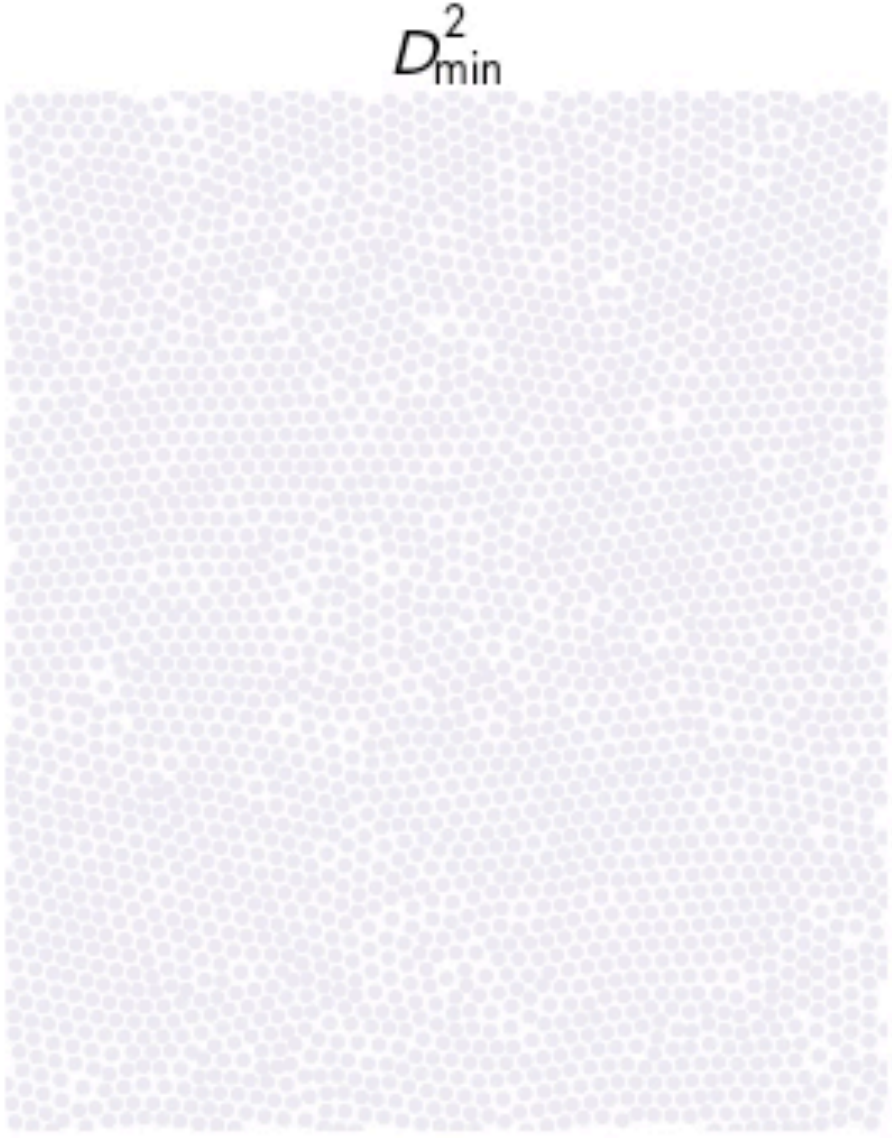
(residual of best affine transform ε)

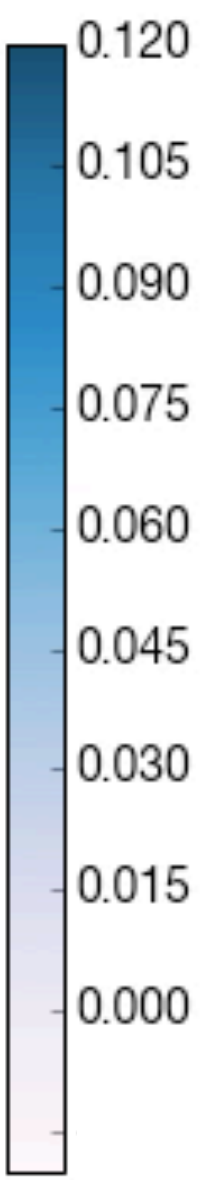
github.com/nkeim/philatracks

Falk & Langer, *PRE* 1998; Keim & Arratia *PRL* 2014

Finding particle rearrangements







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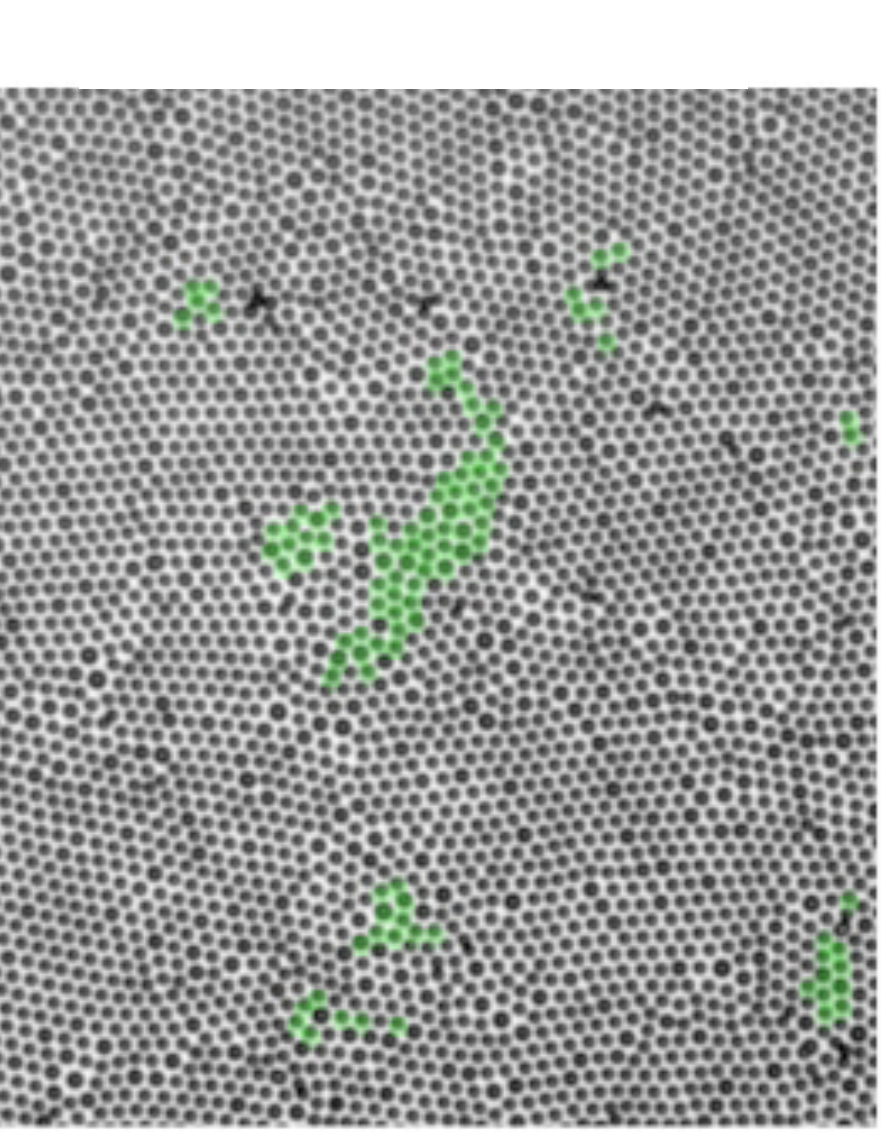

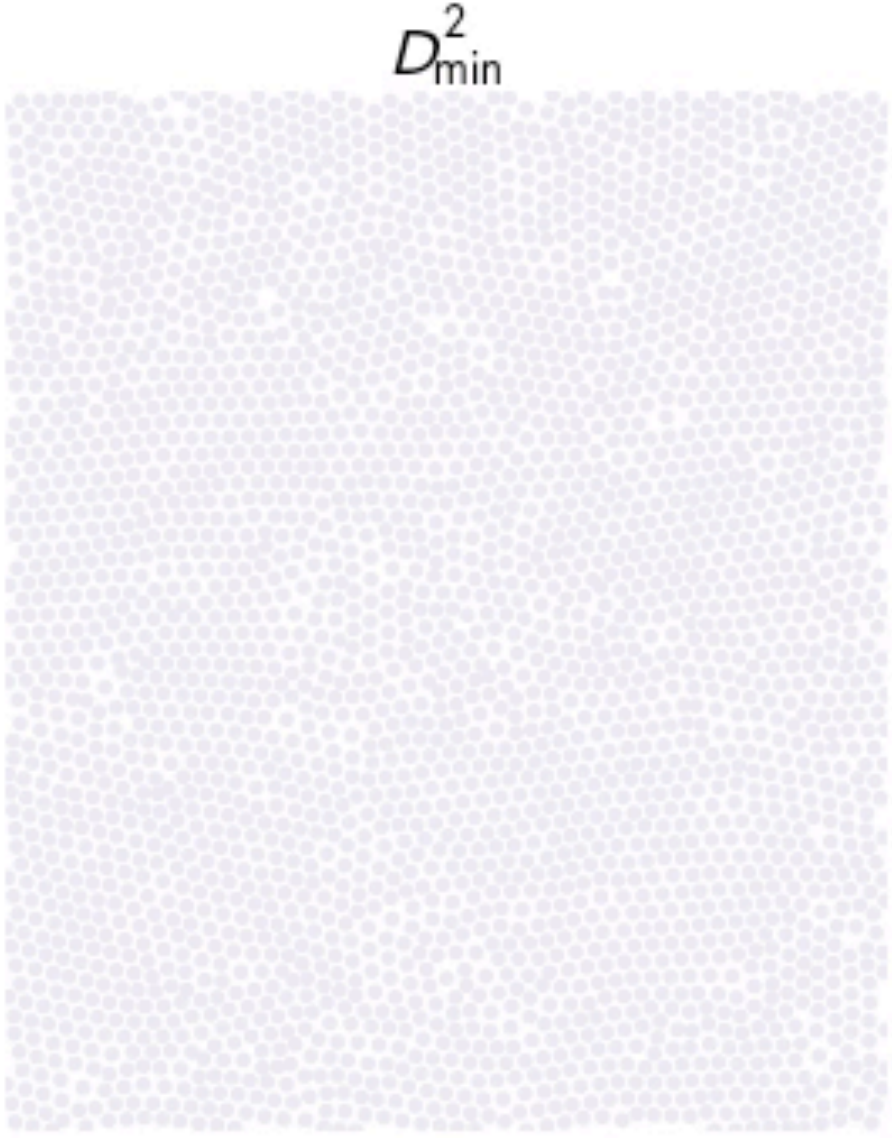

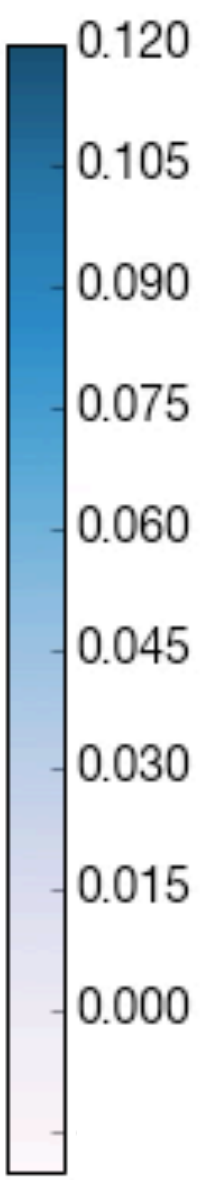

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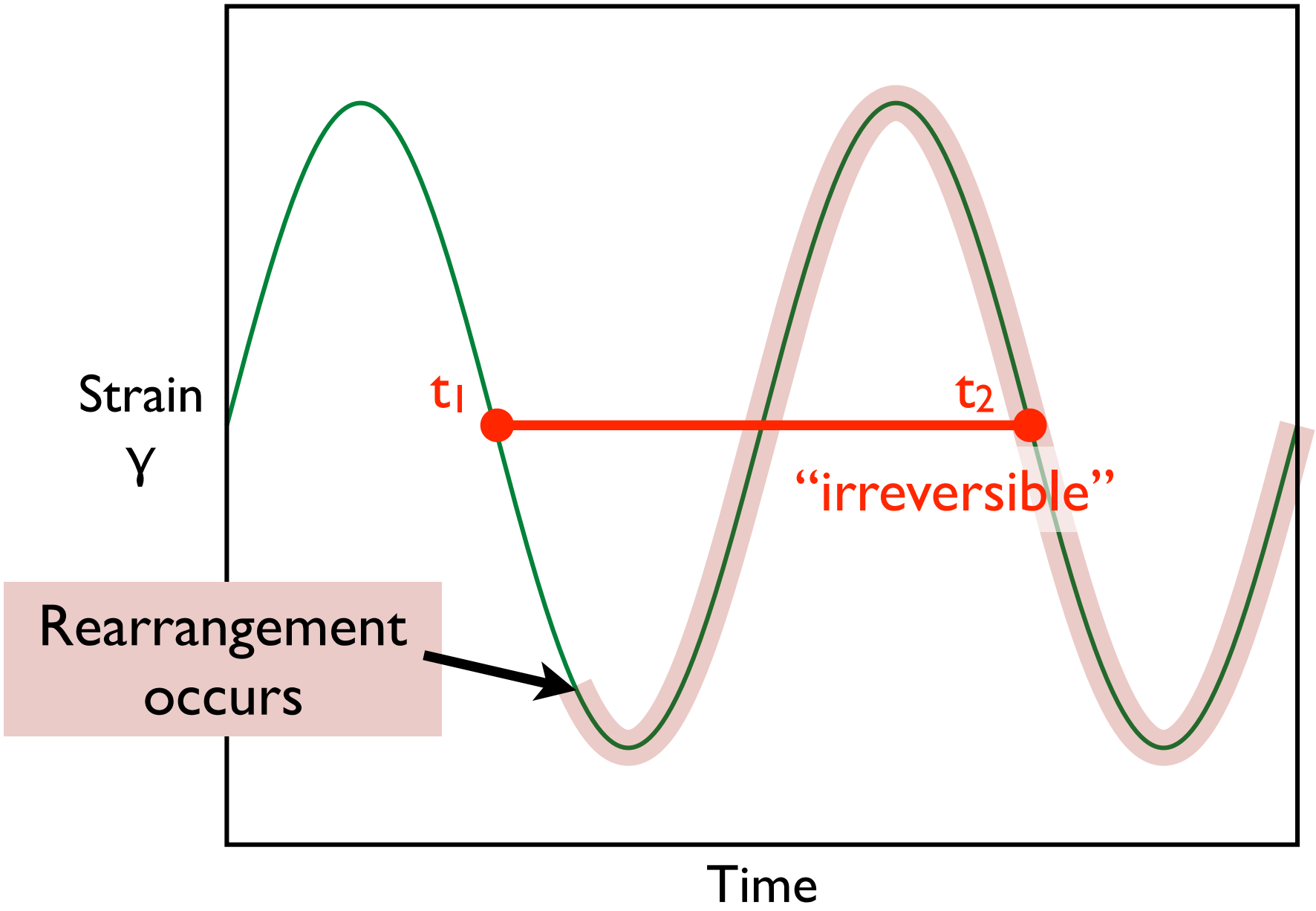
Sampling microstructure



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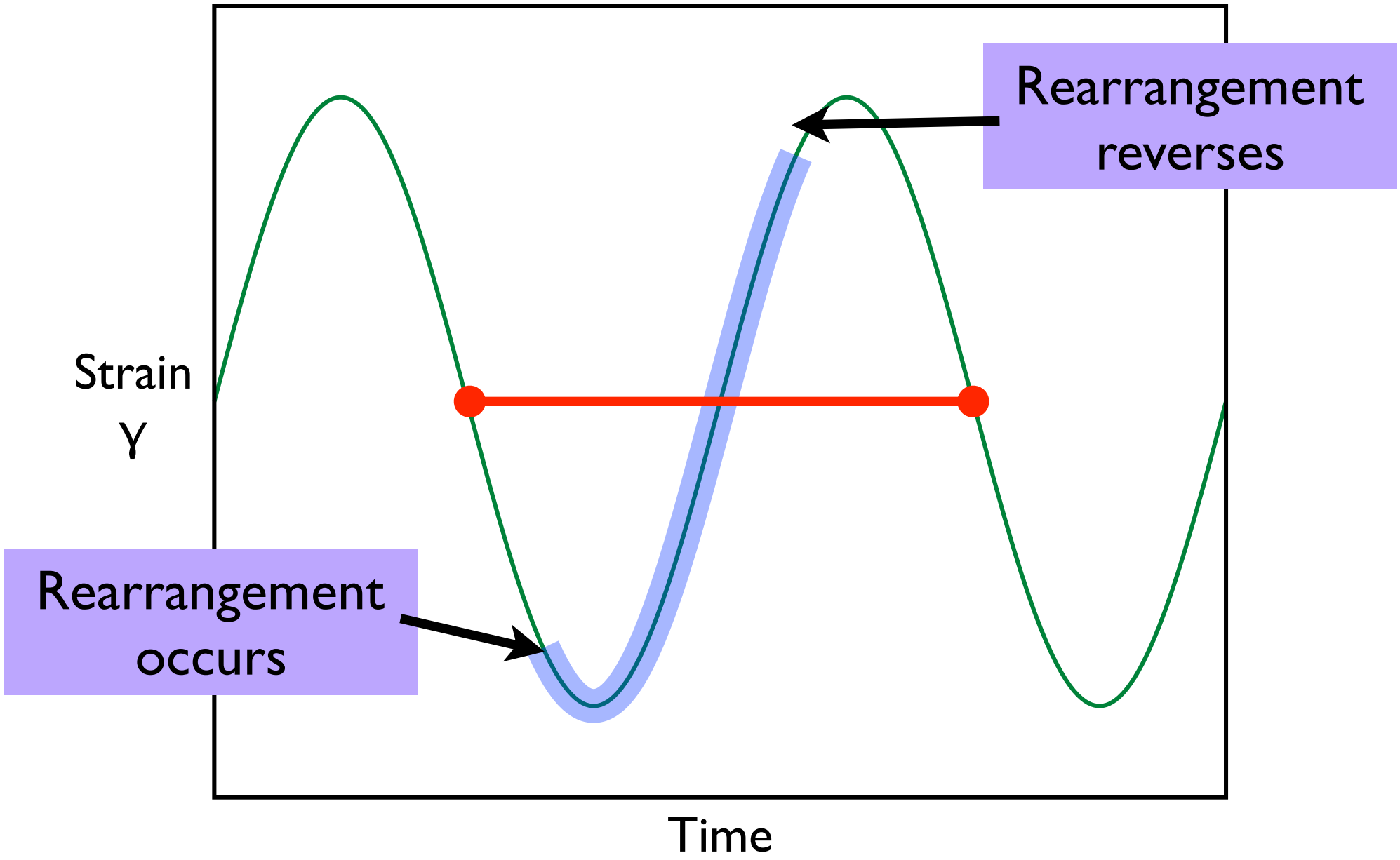

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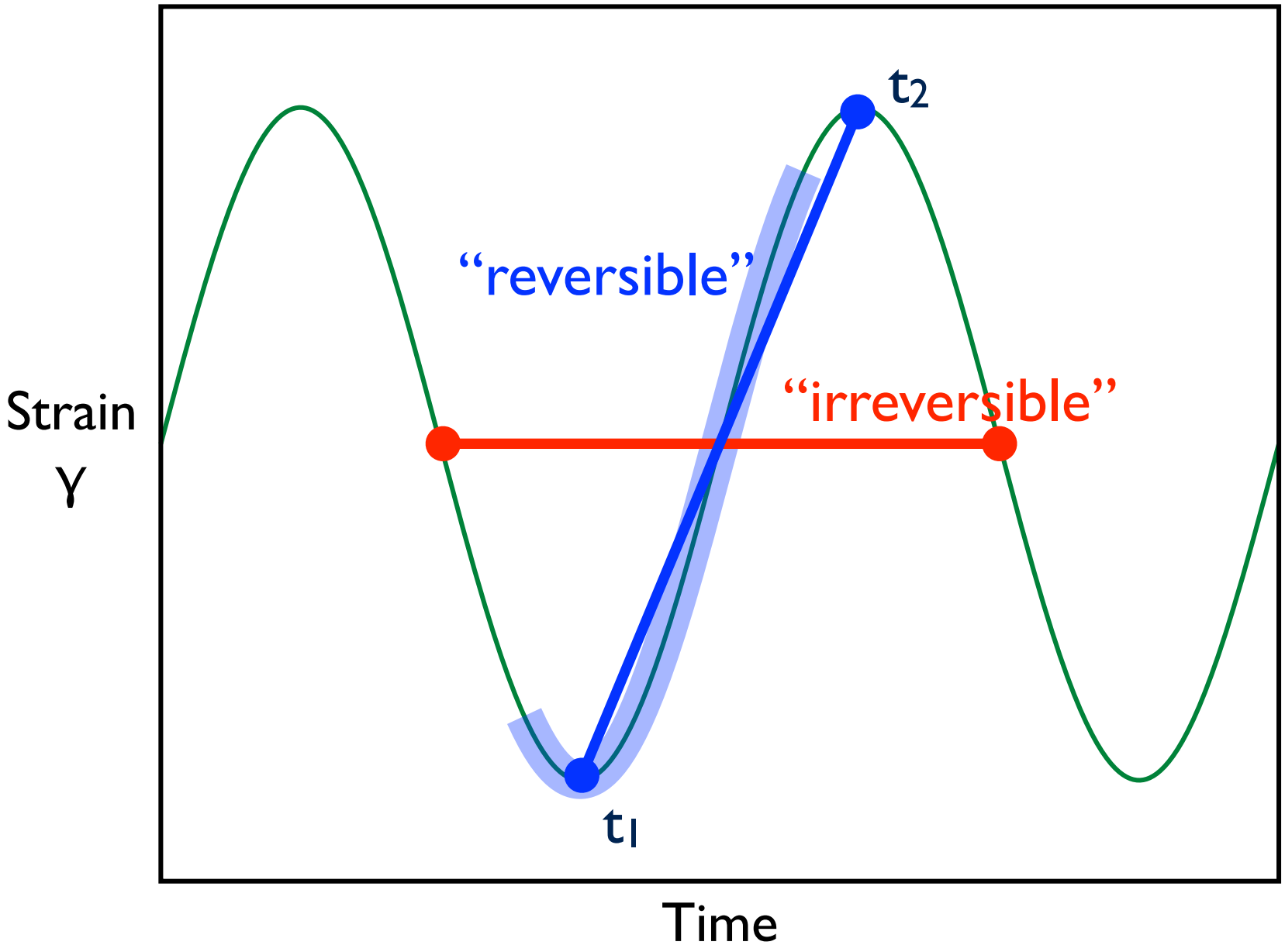
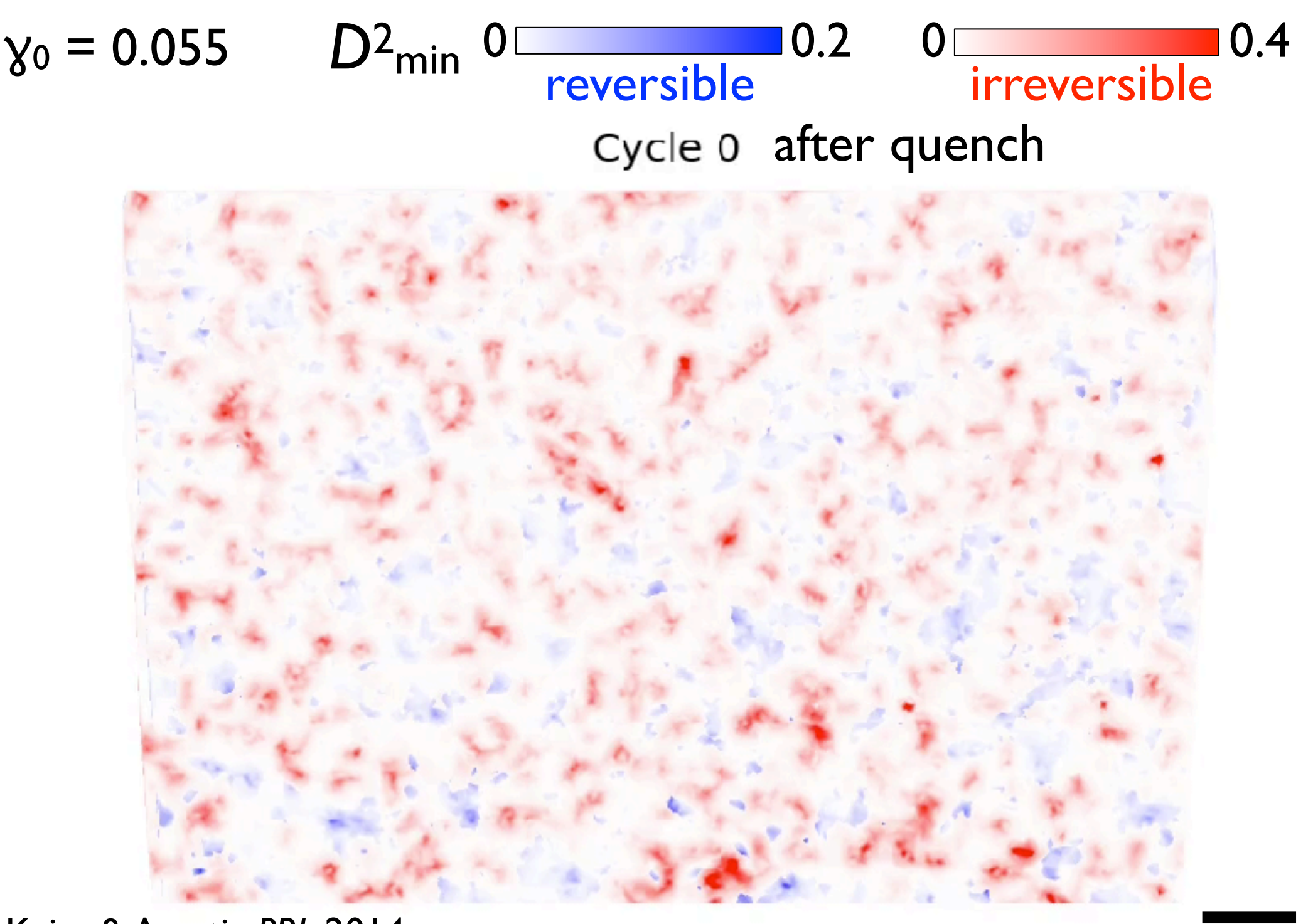
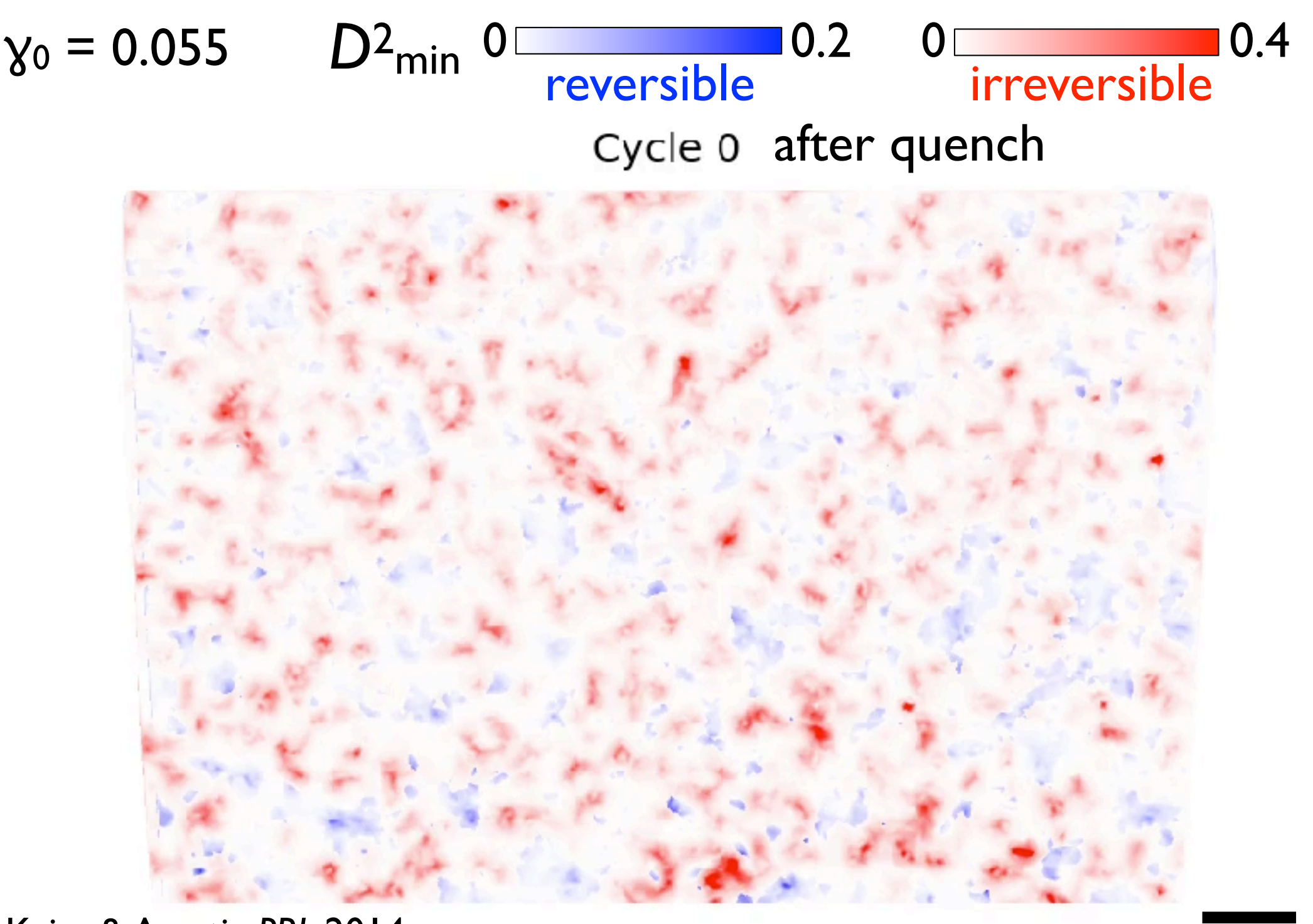




Keim & Arratia *PRL* 2014
Regev, Lookman, Ch. Reichhardt. *PRE* 2013; Priezjev, *PRE* 2016



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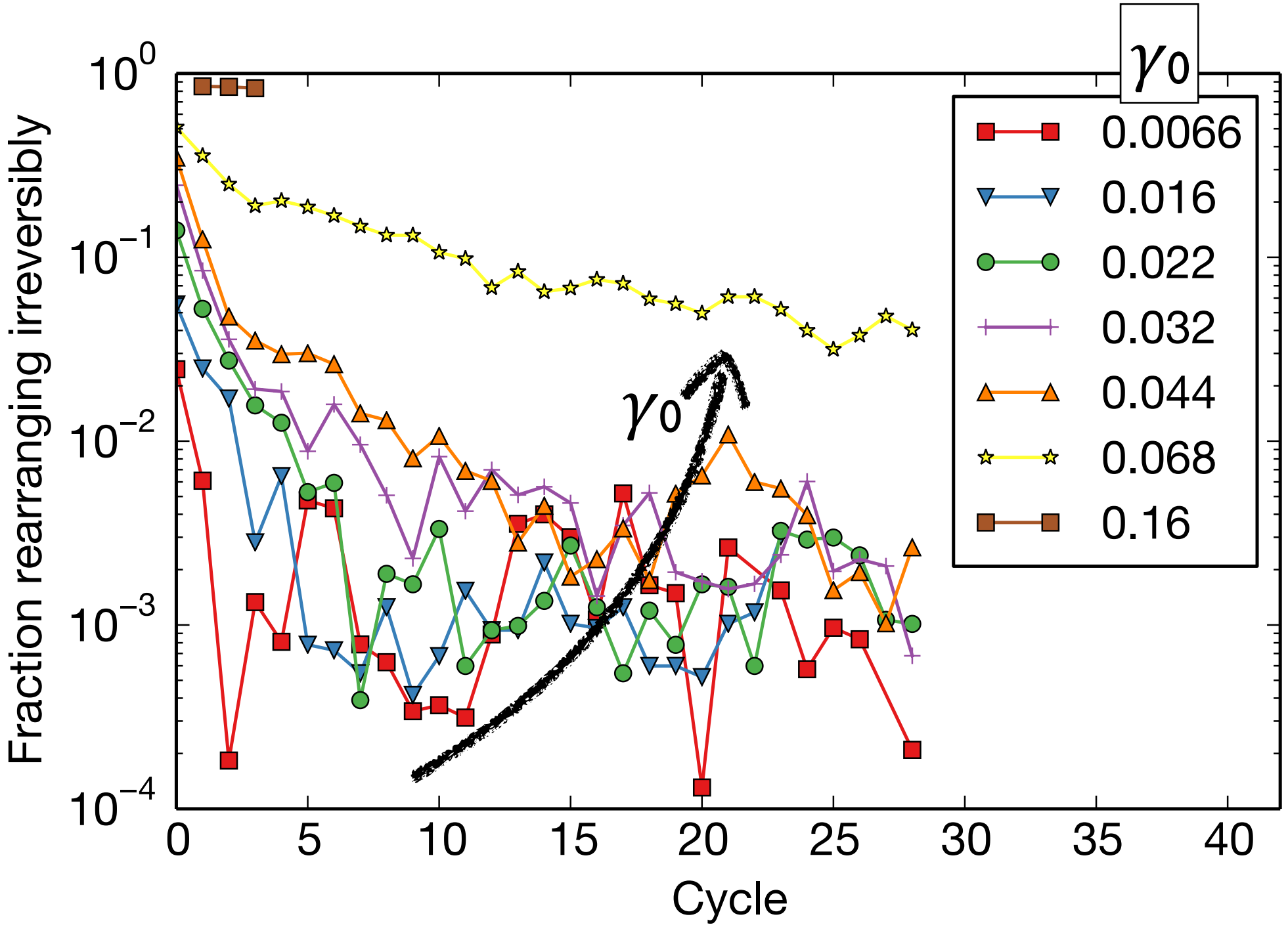
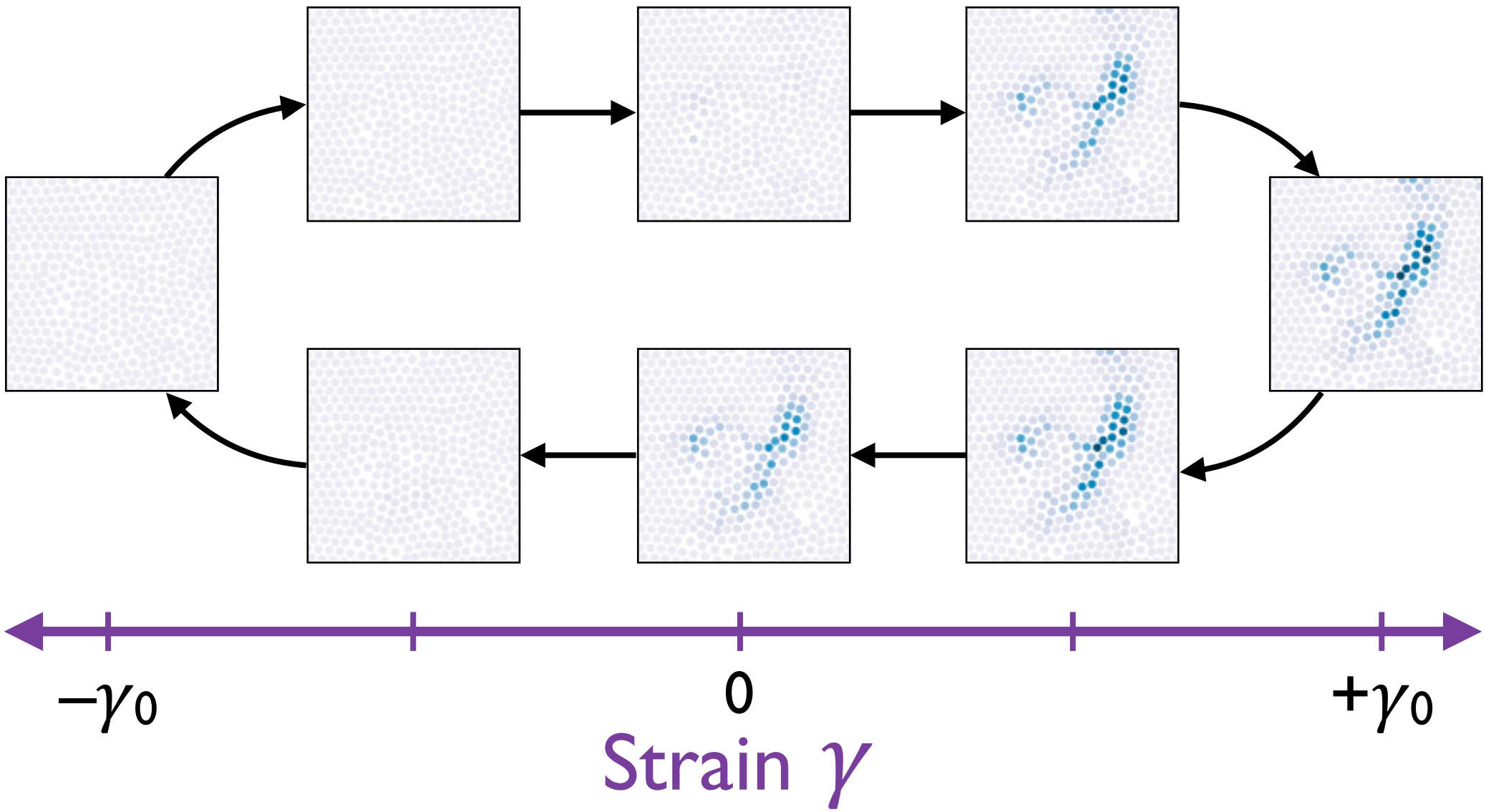
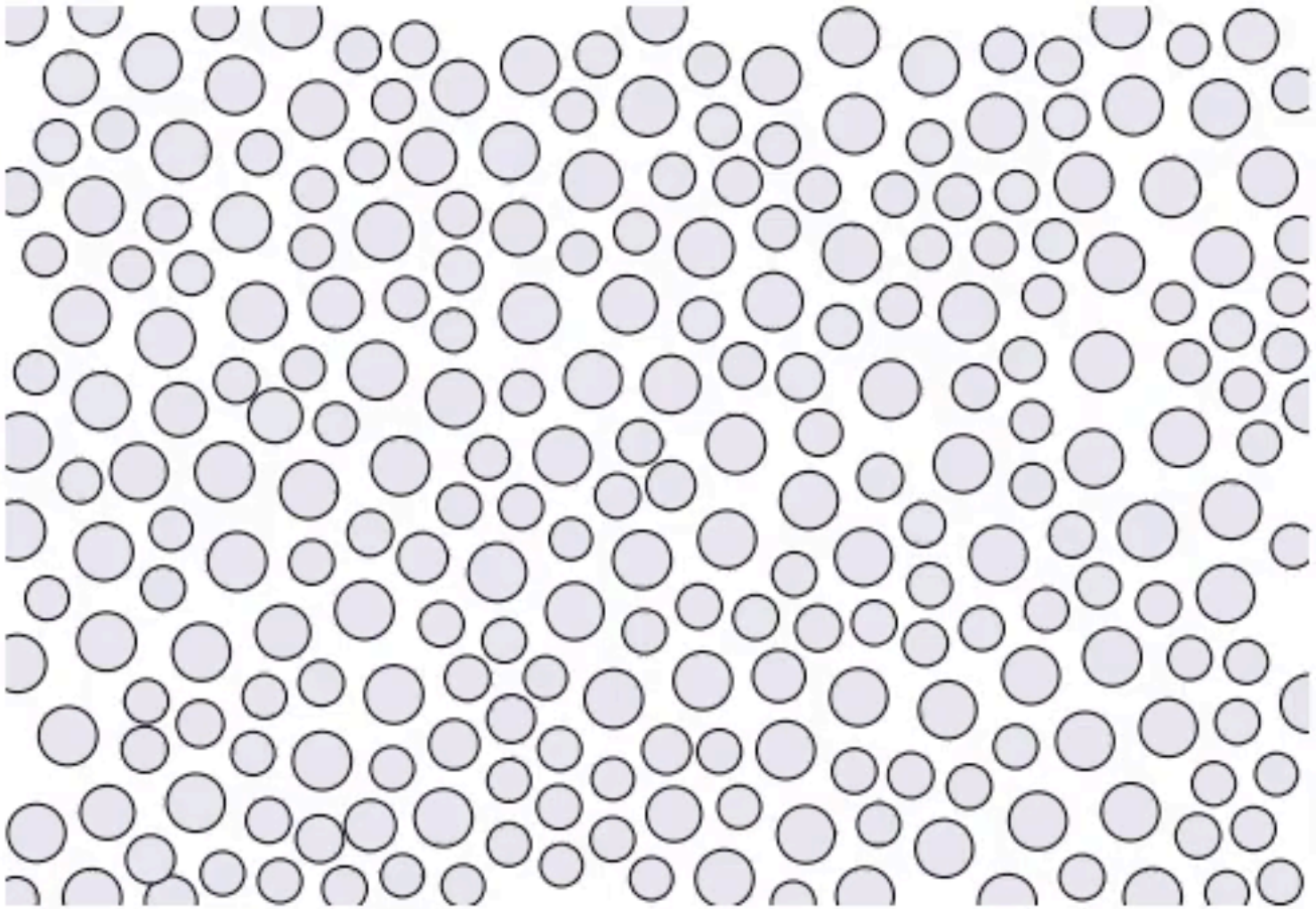

γ_0
0.0066
0.016
0.022
0.032
0.044
0.068
0.16
γ_0
Fraction rearranging irreversibly
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
40
Cycle

Rearrangements can be reversible, hysteretic



Making reversibility look easy



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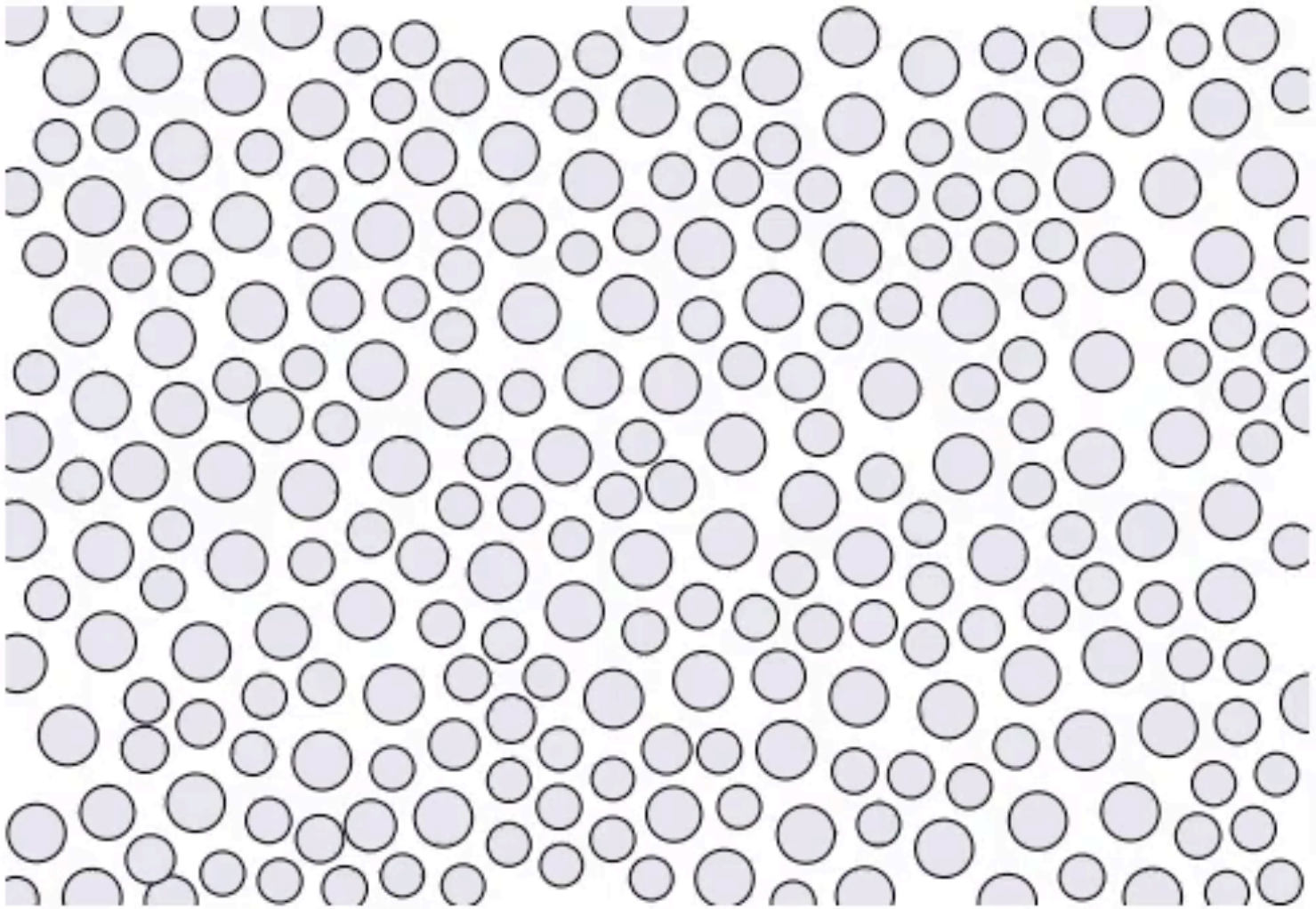

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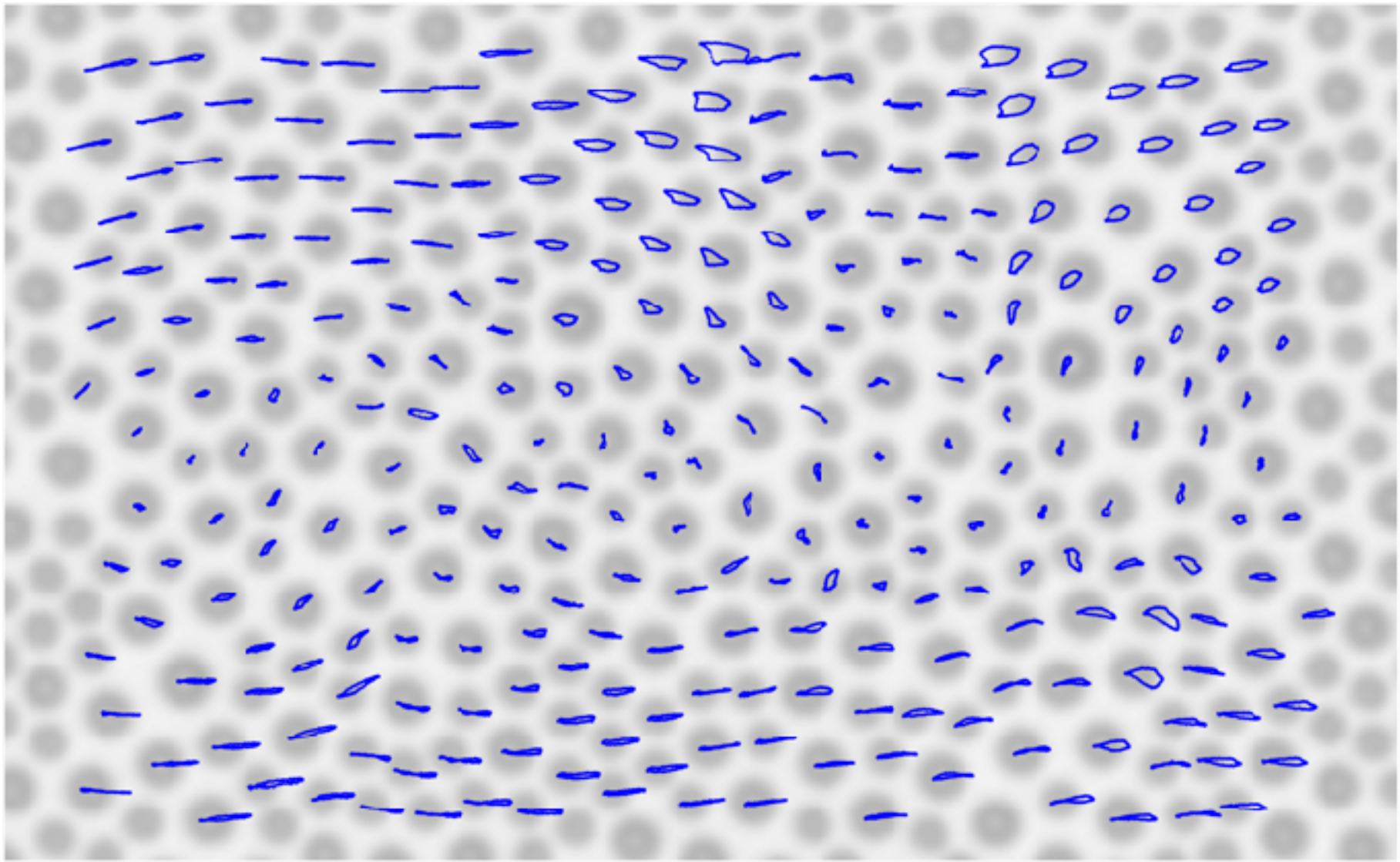
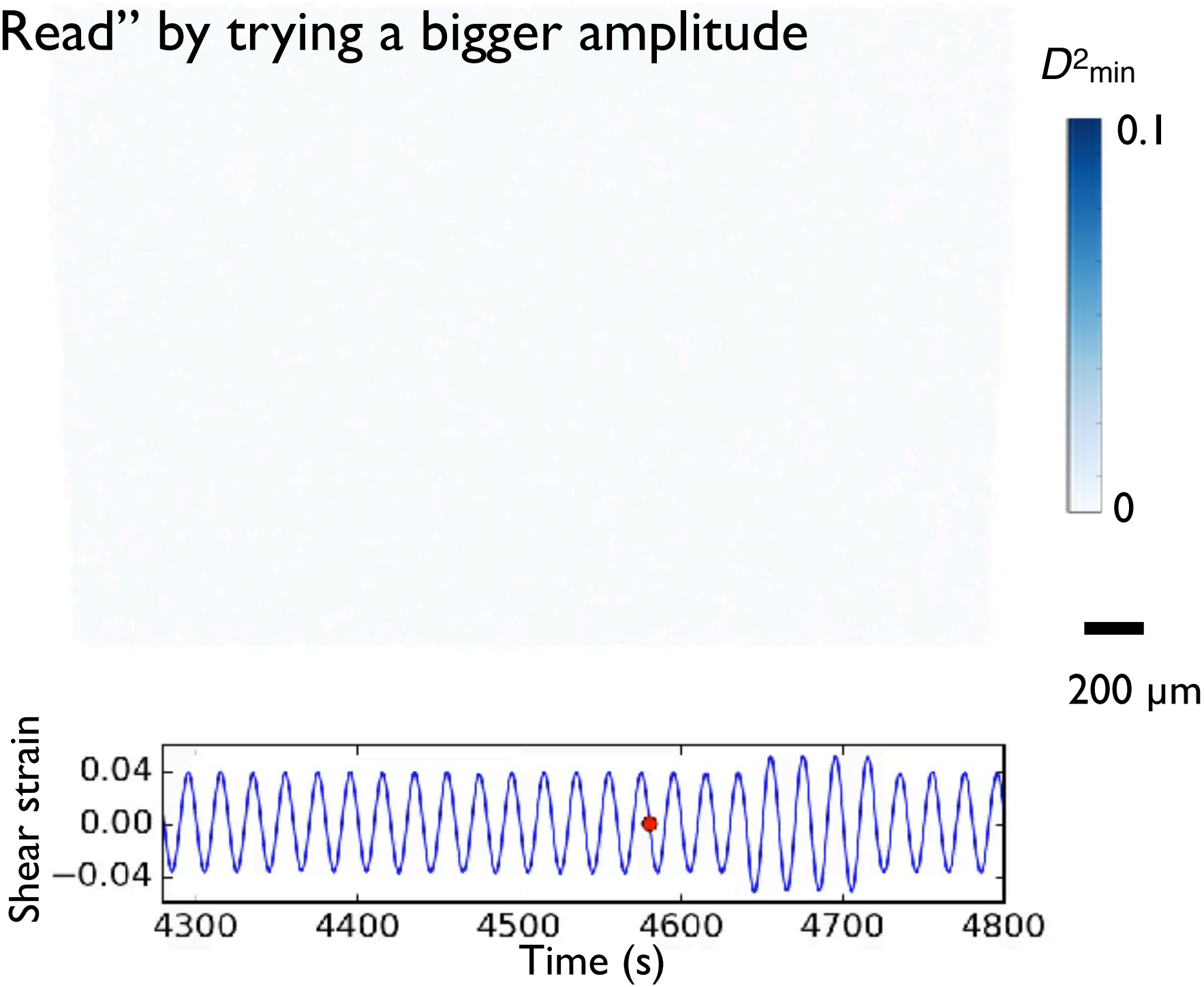
Steady state trajectories



Steady State = memory of training amplitude

"Read" by trying a bigger amplitude



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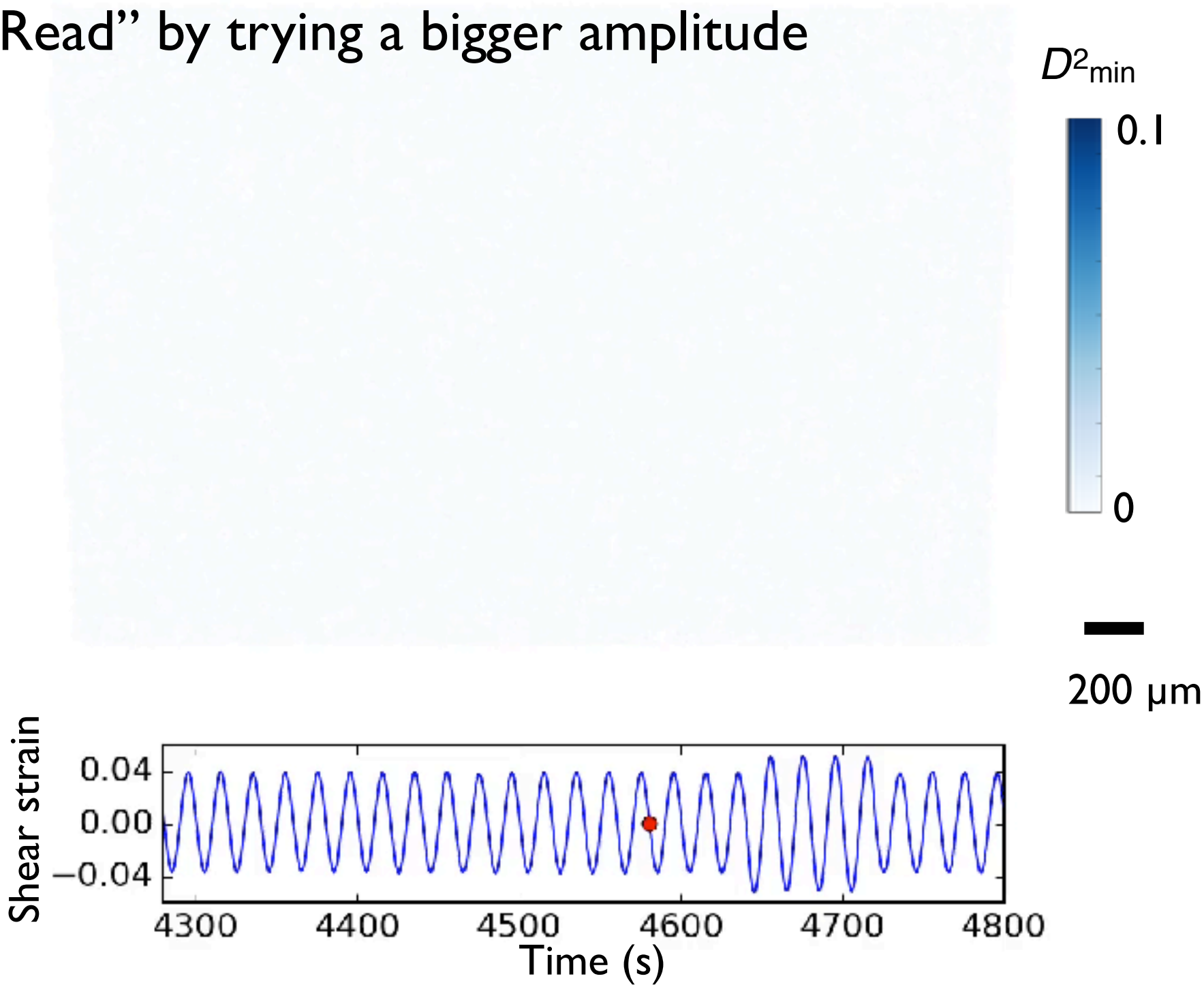

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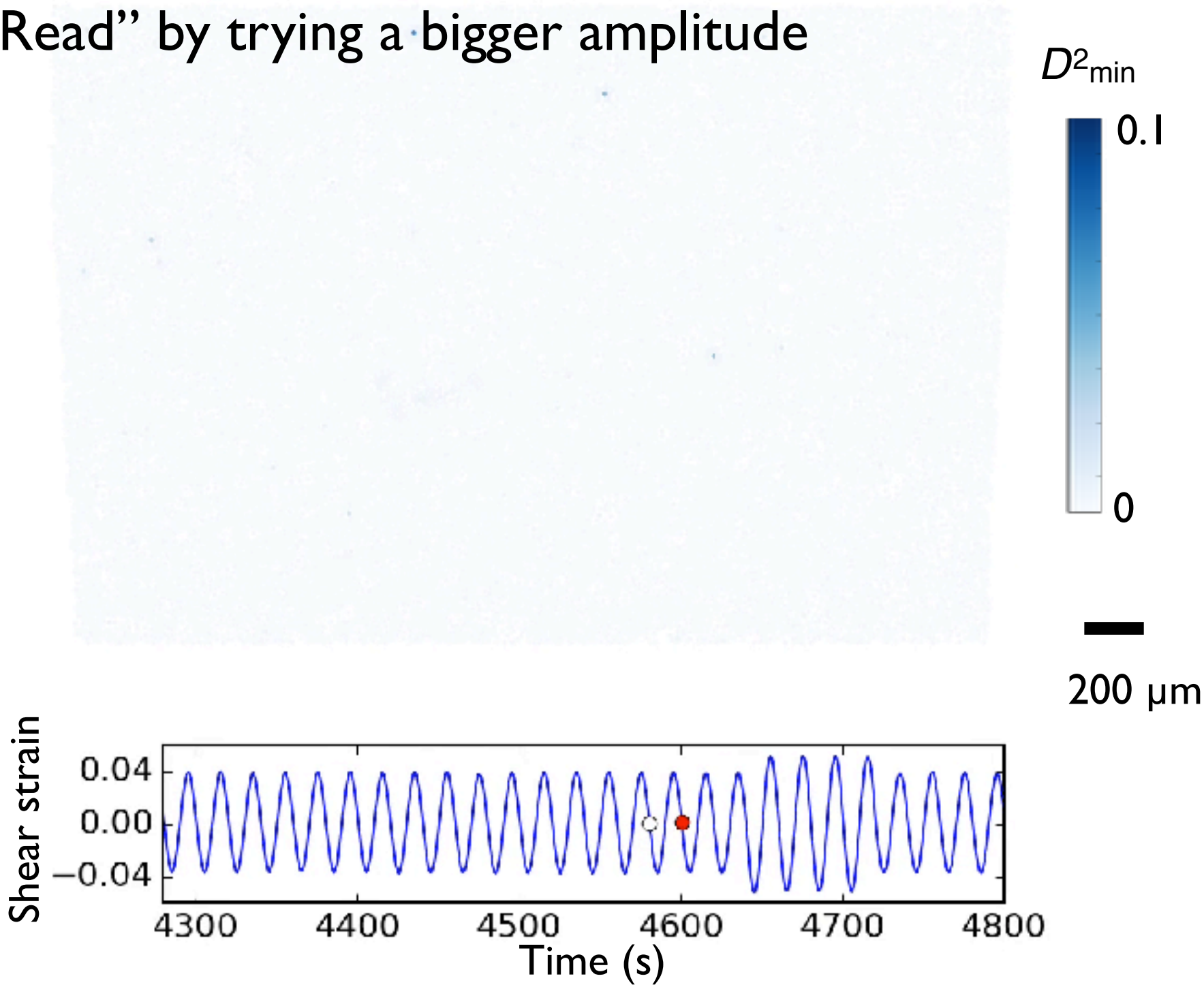

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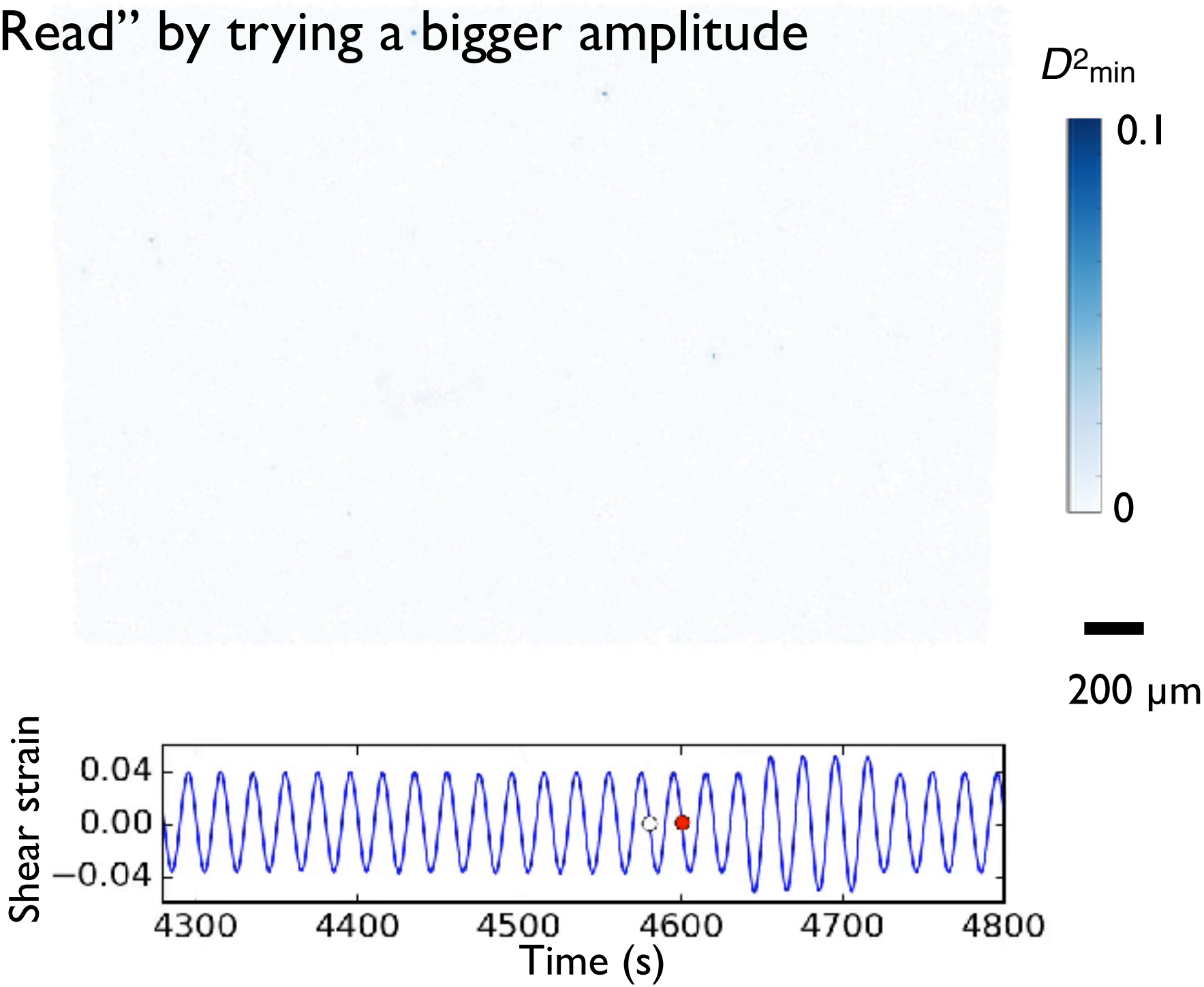

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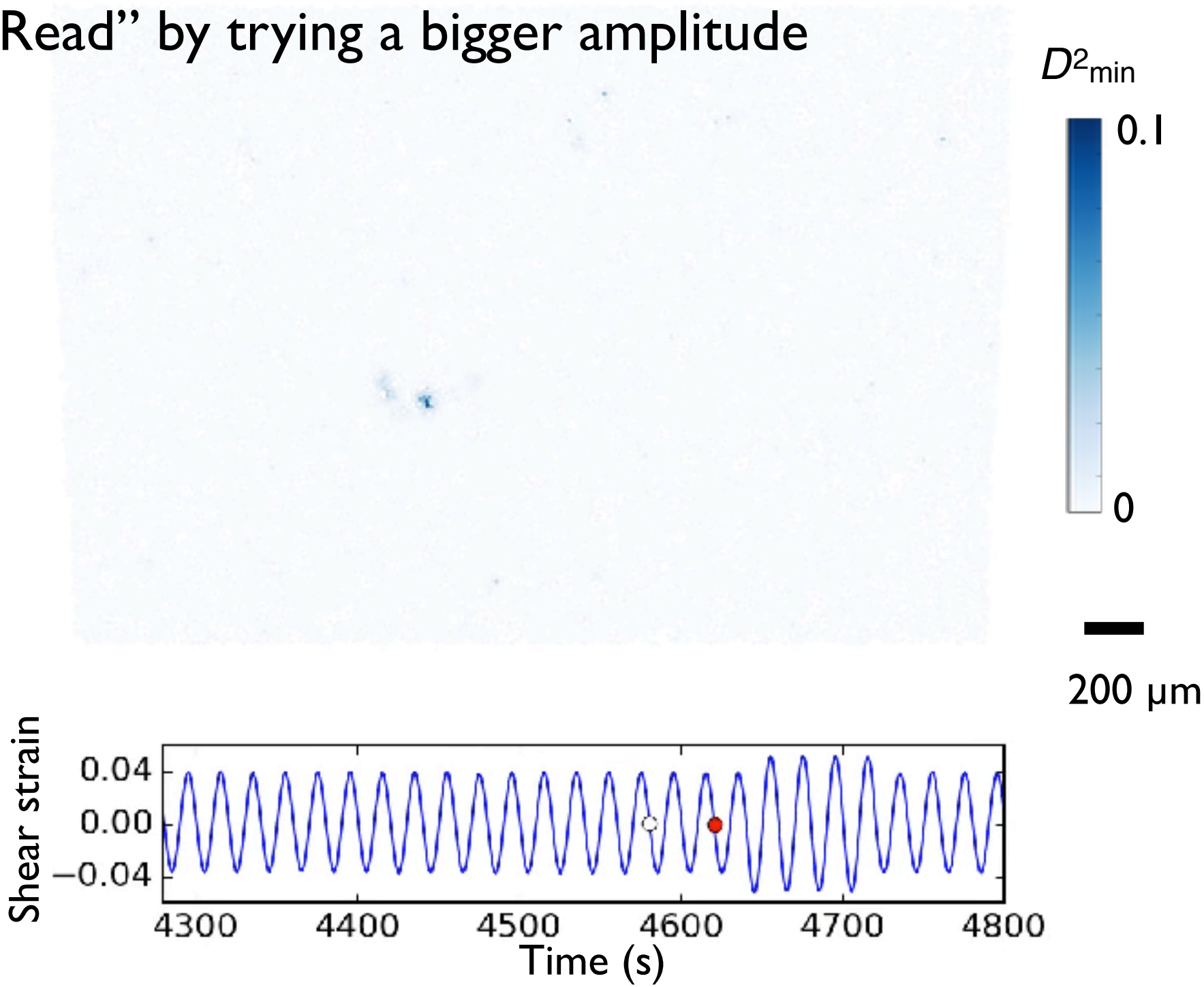
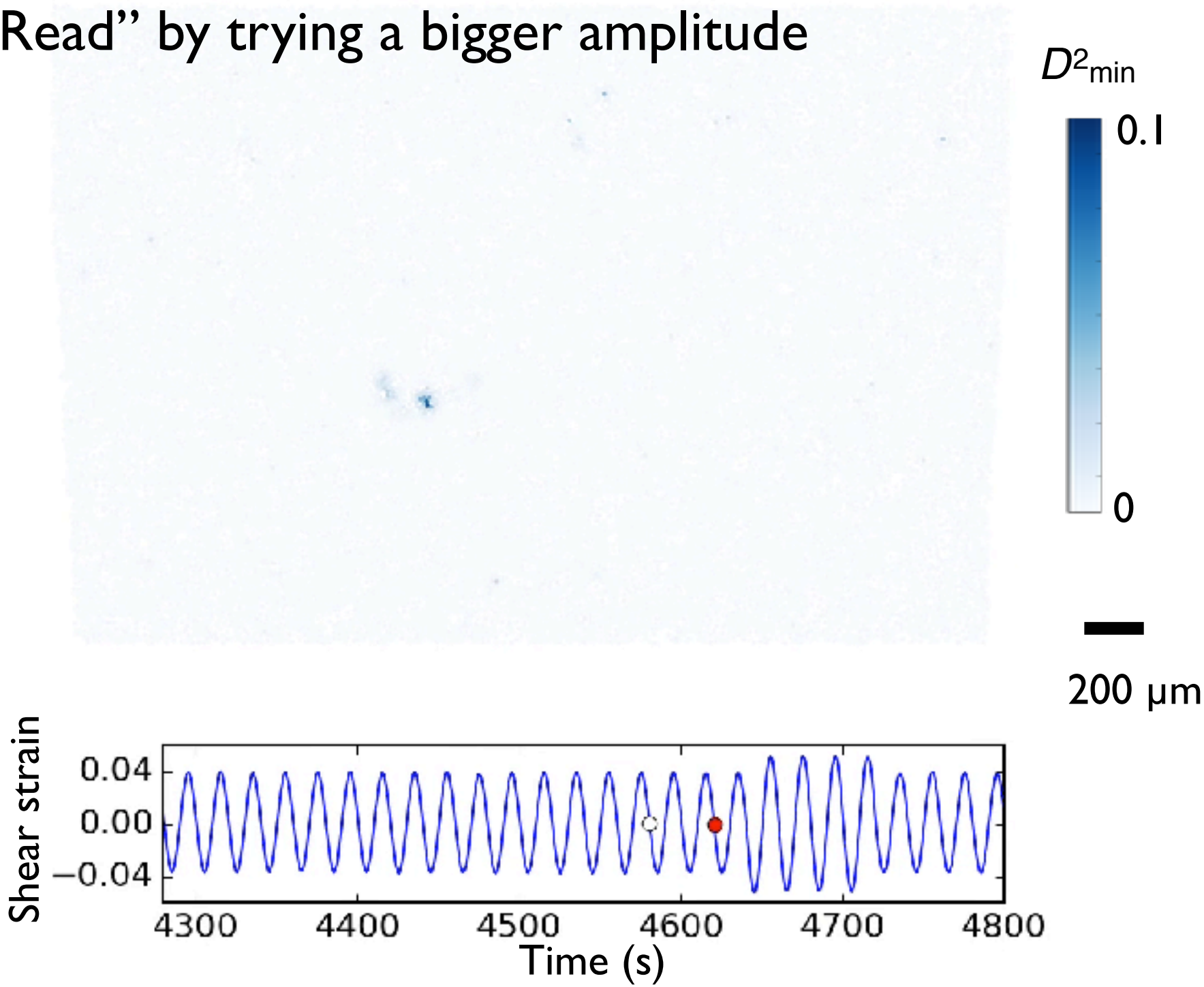
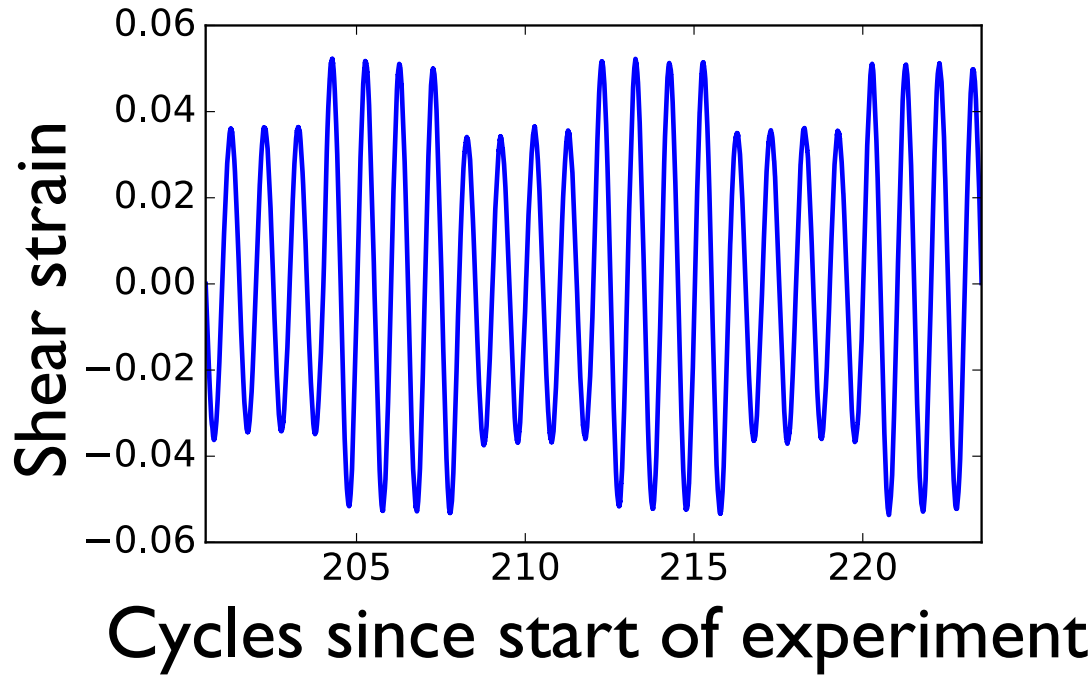


Steady State = memory of training amplitude

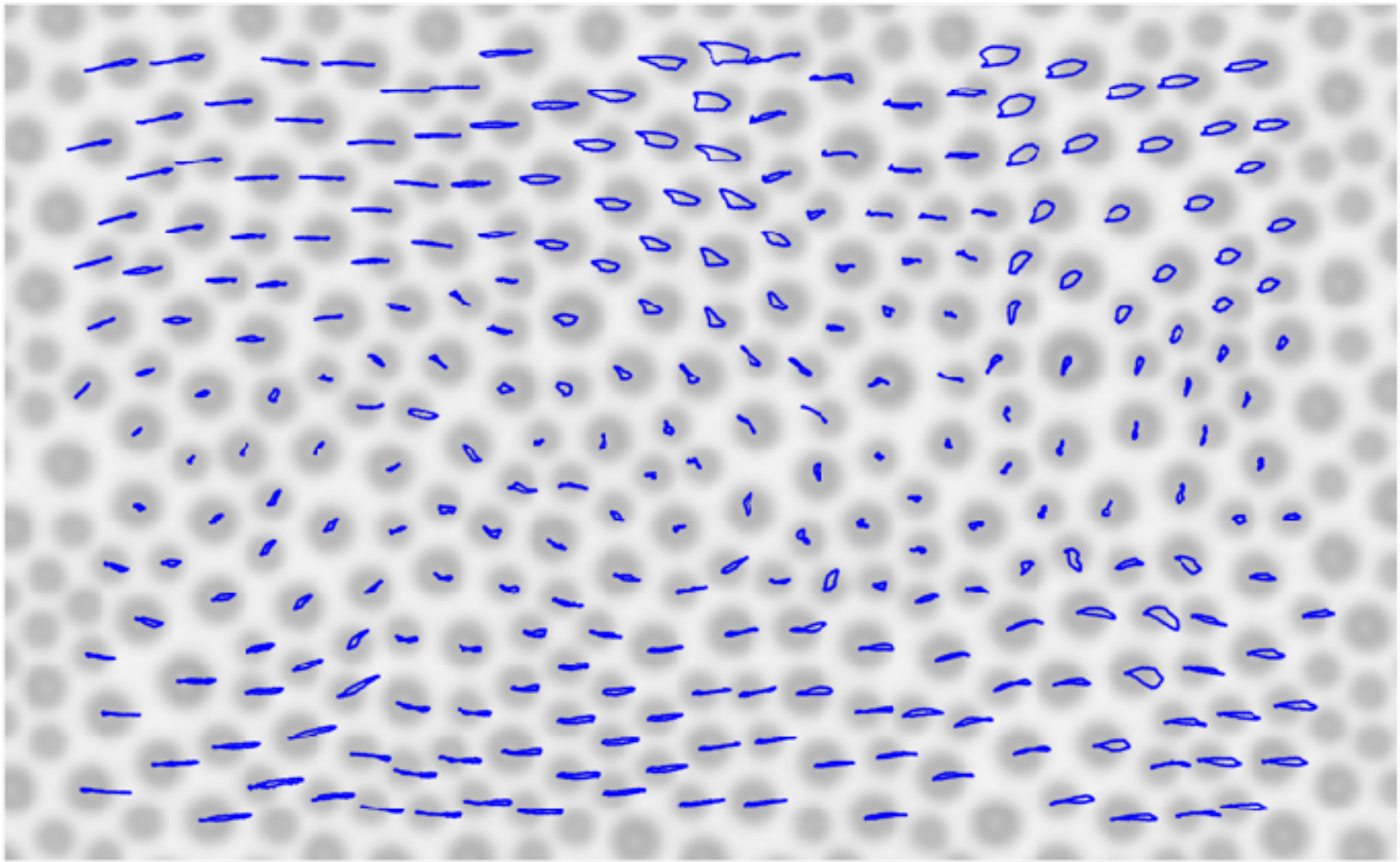
"Read" by trying a bigger amplitude



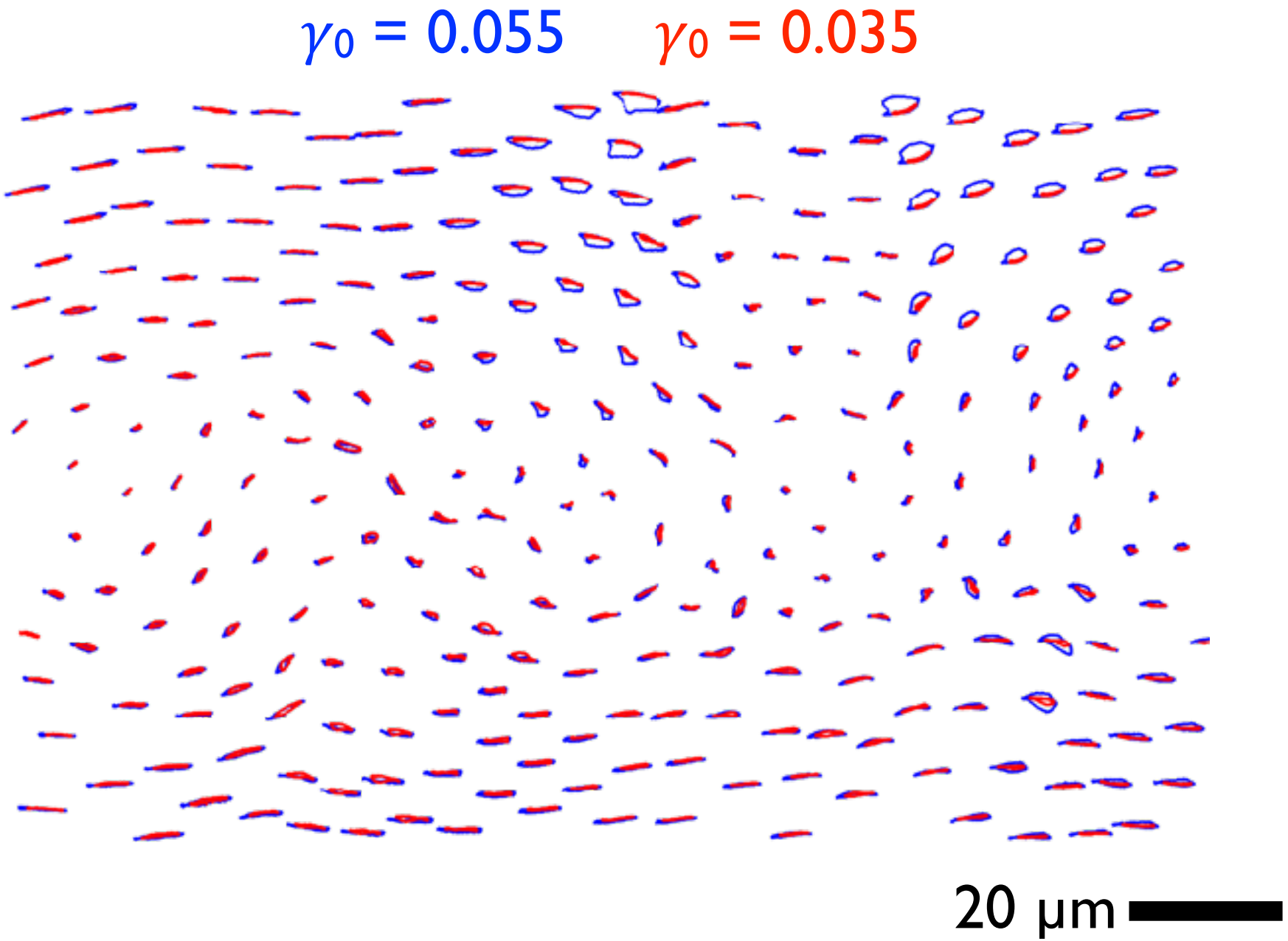
Two amplitudes?



Steady state trajectories

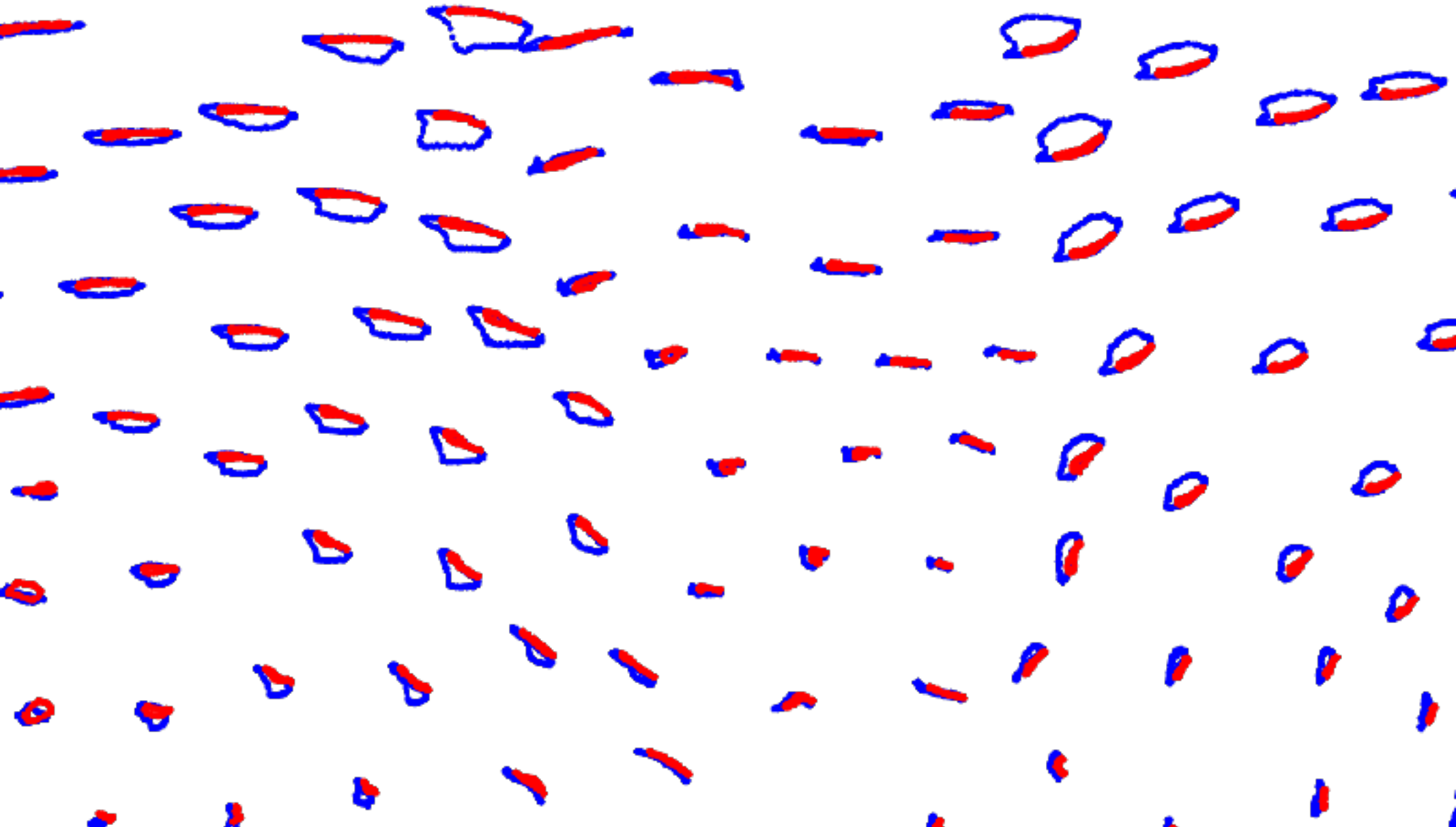


Steady state trajectories: 2 amplitudes

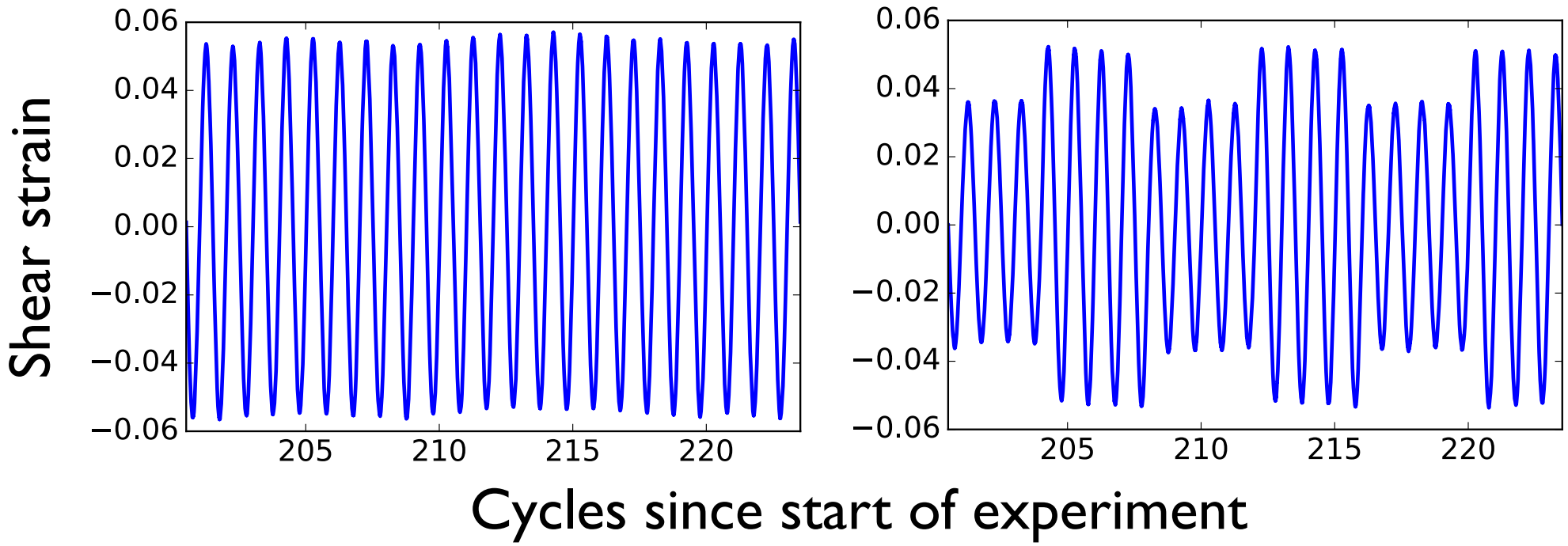


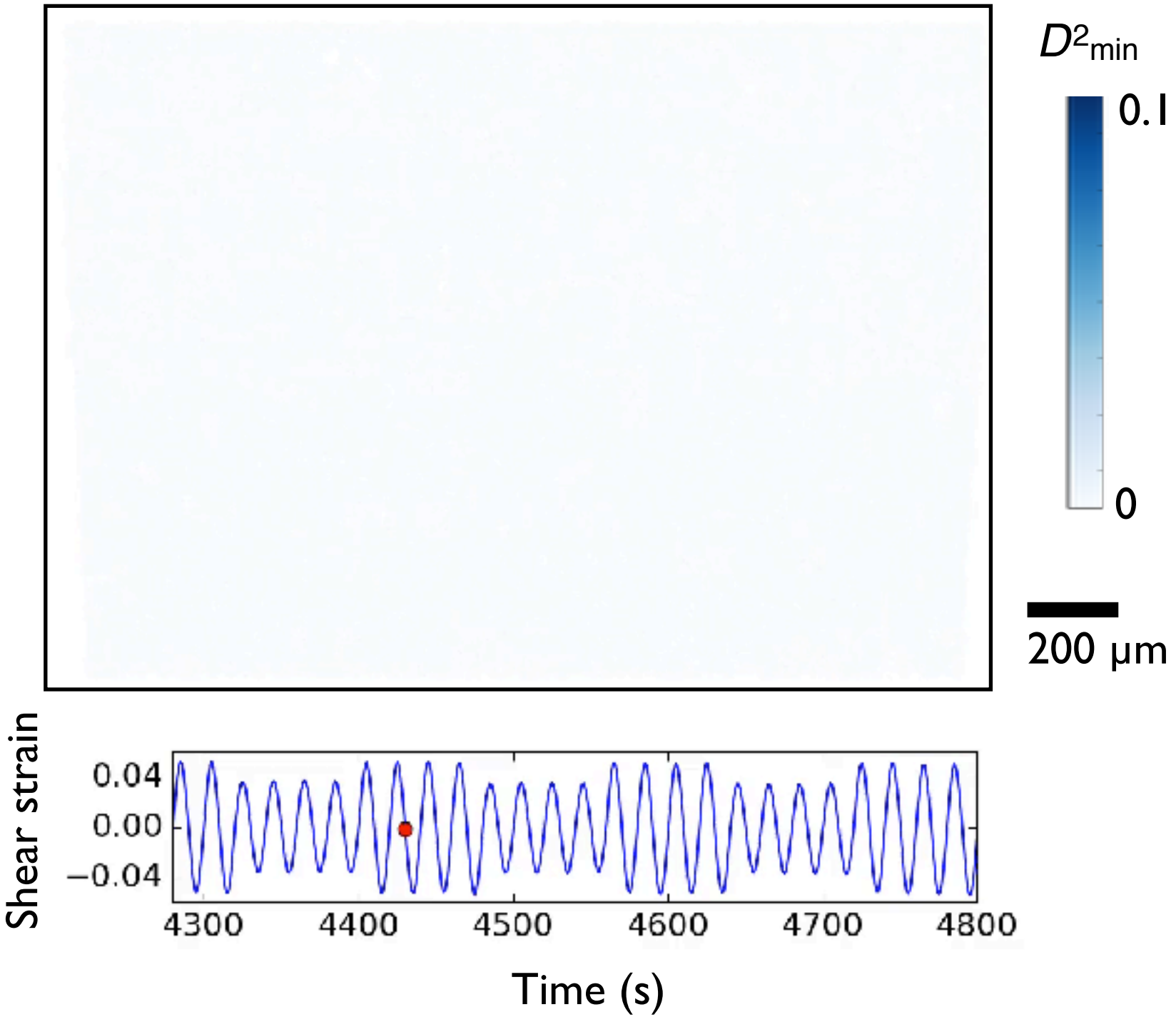
Steady state trajectories: 2 amplitudes

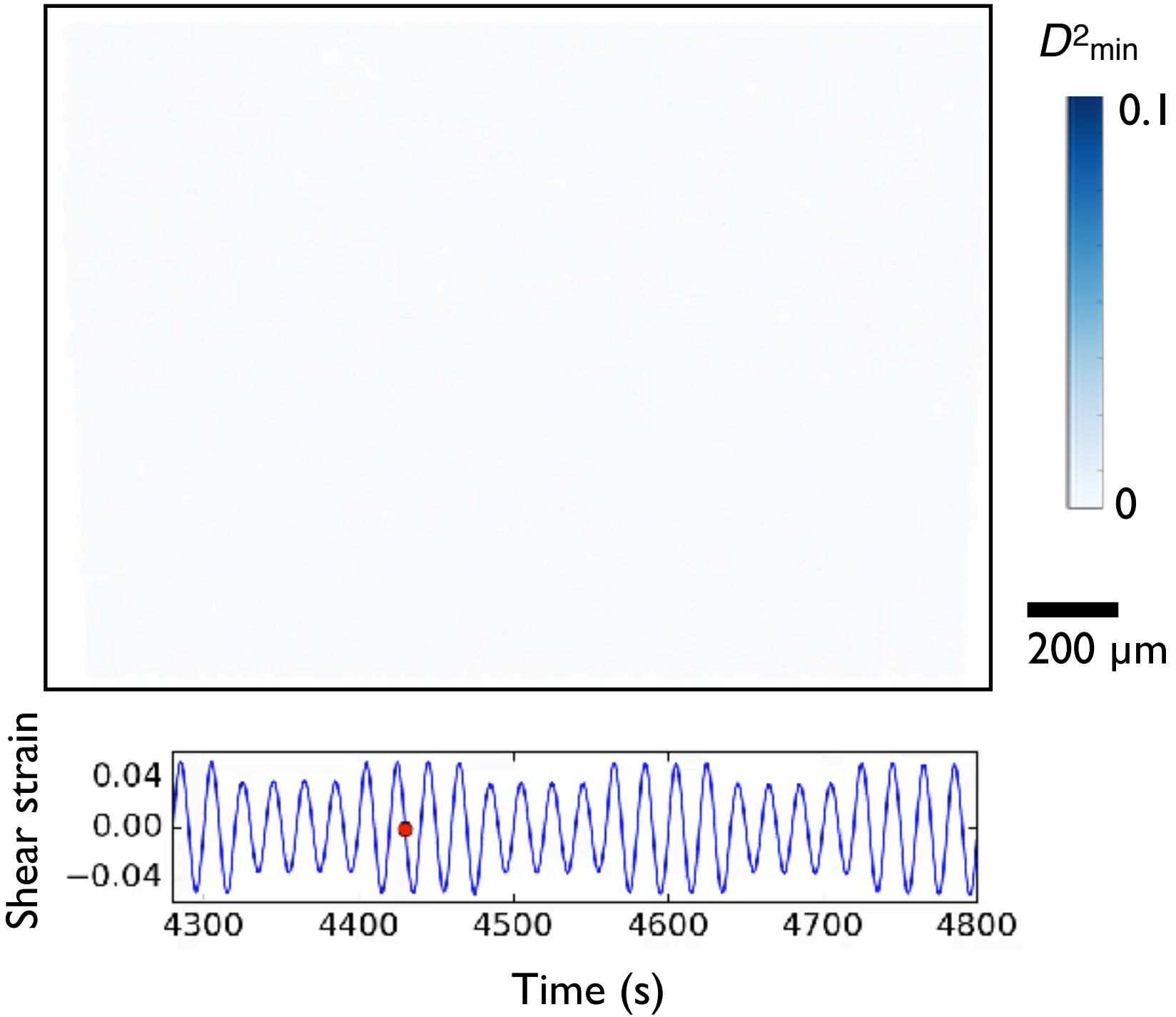
$\gamma_0 = 0.055$ $\gamma_0 = 0.035$



How does system switch trajectories?




D^2_{min}
0.1
0
200 μm
Shear strain
0.04
0.00
−0.04
4300
4400
4500
4600
4700
4800
Time (s)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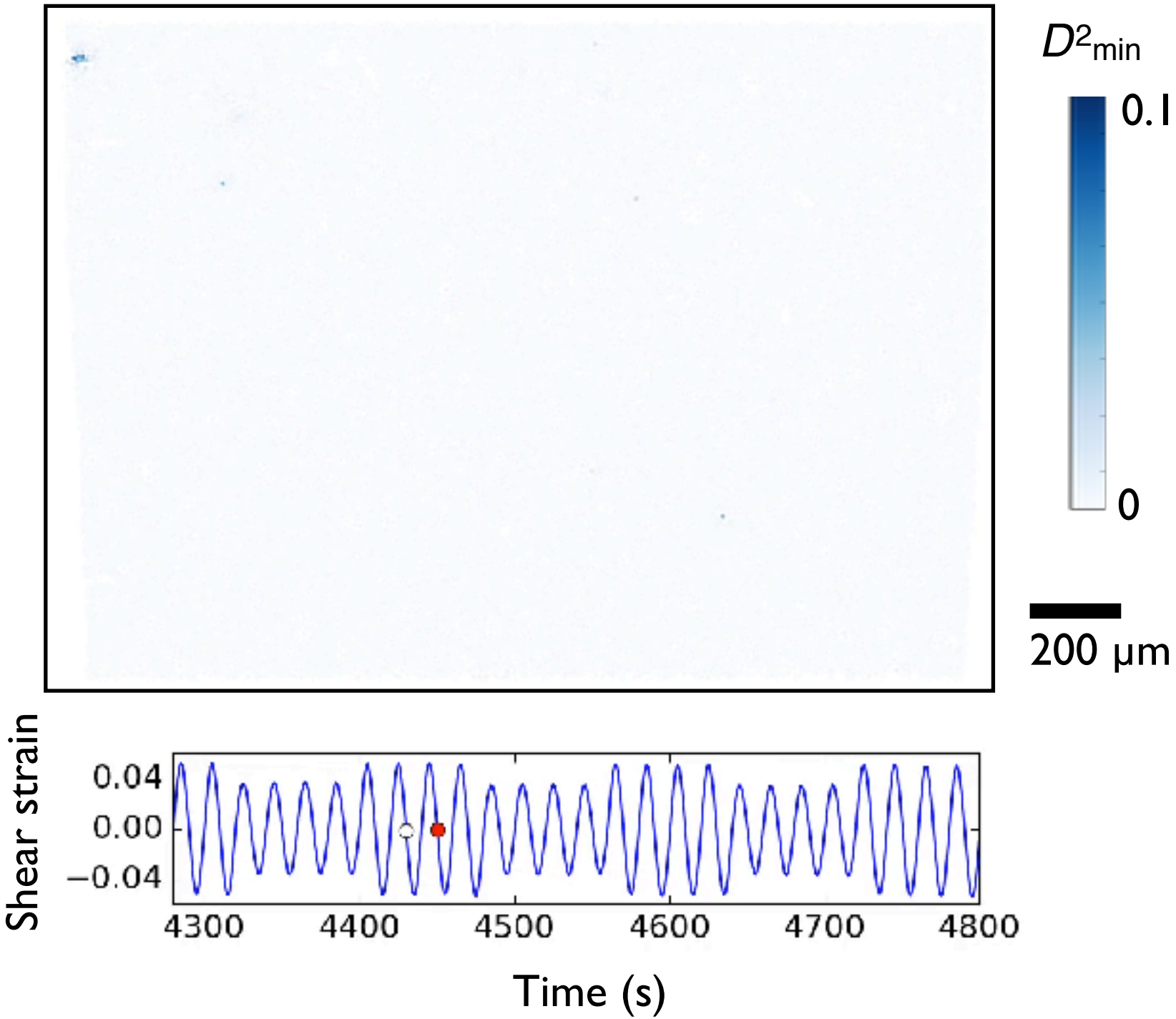
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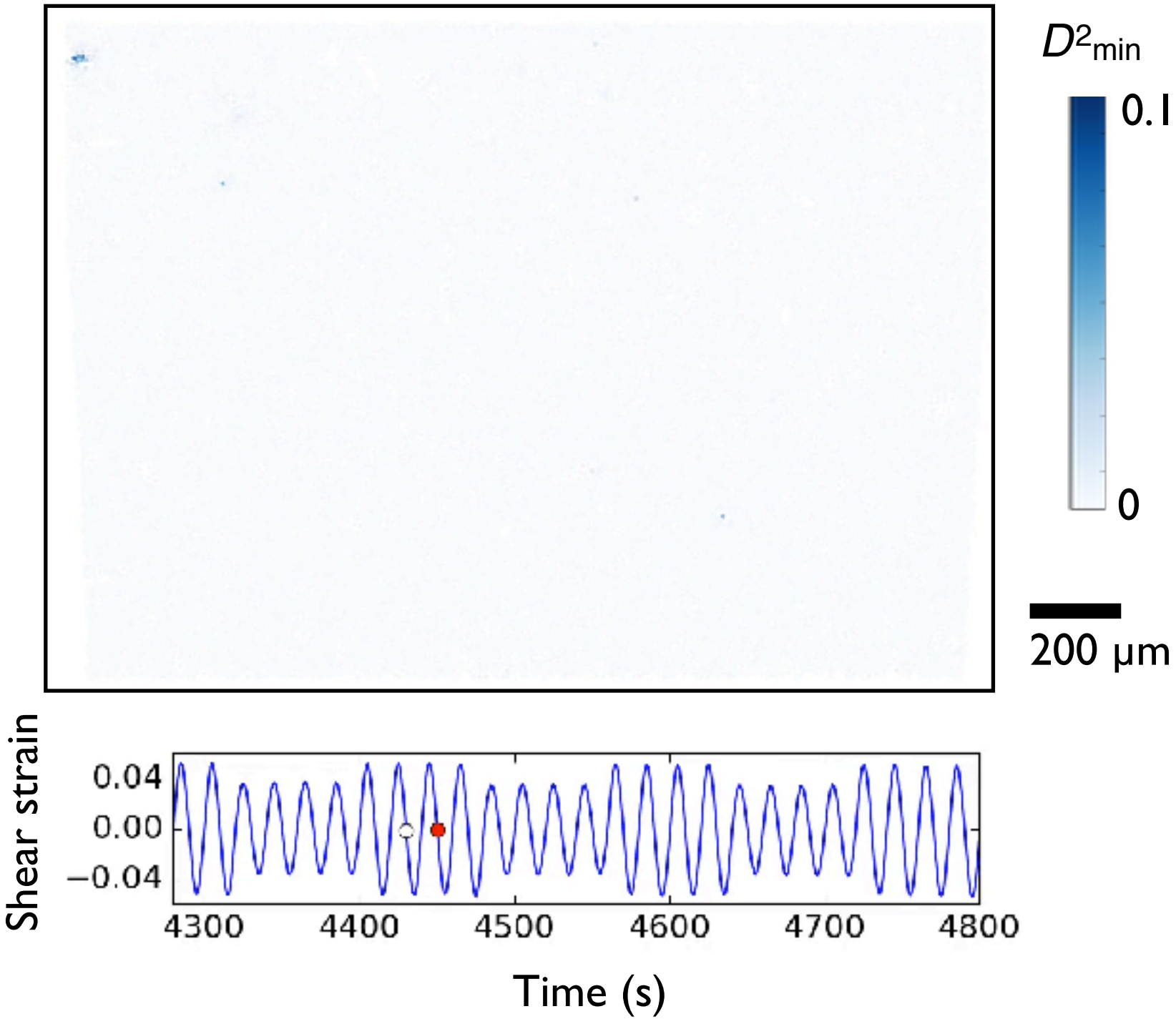
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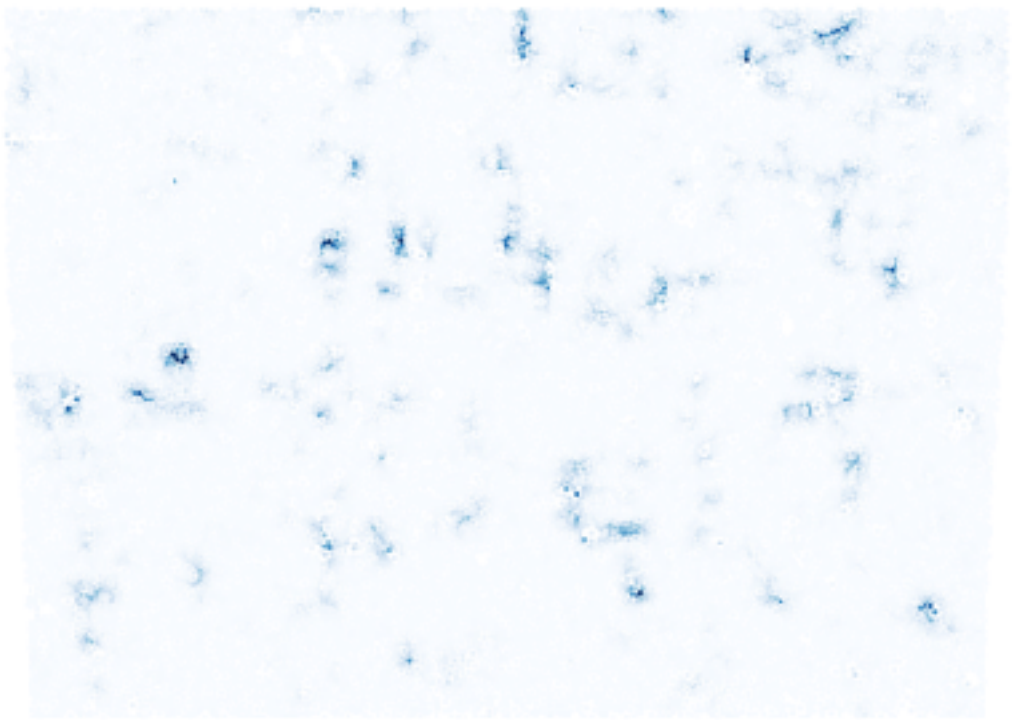
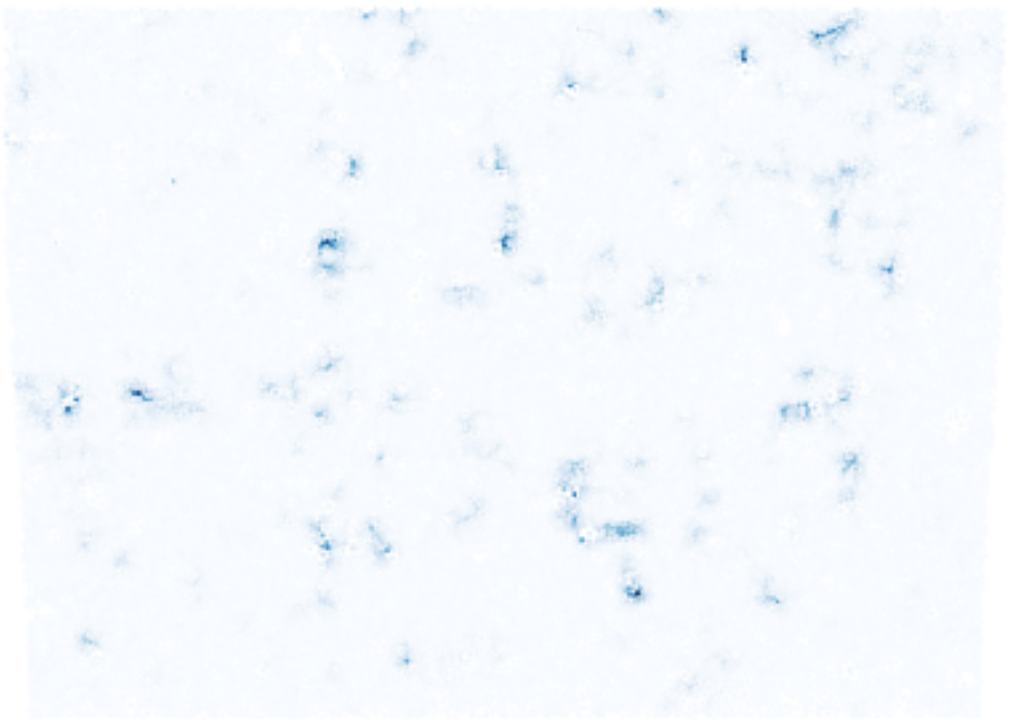
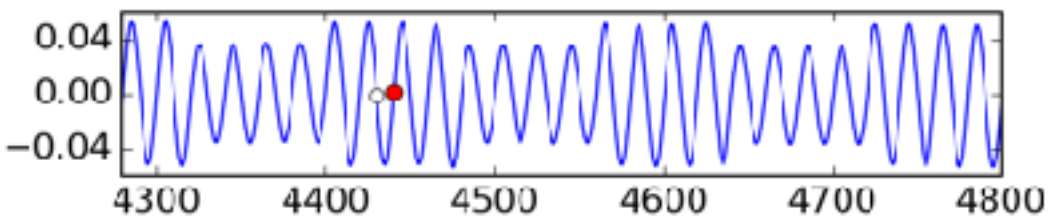
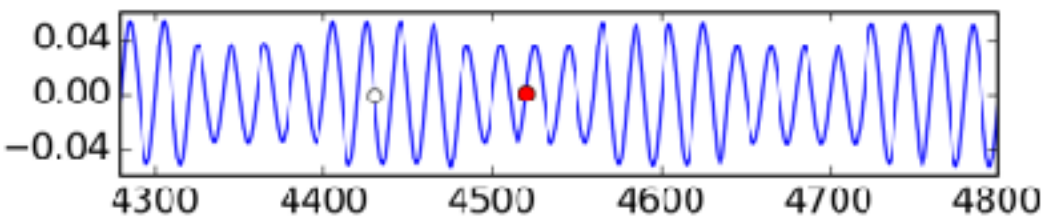
Time (s)

Small-amplitude resp. is subset of large-amplitude

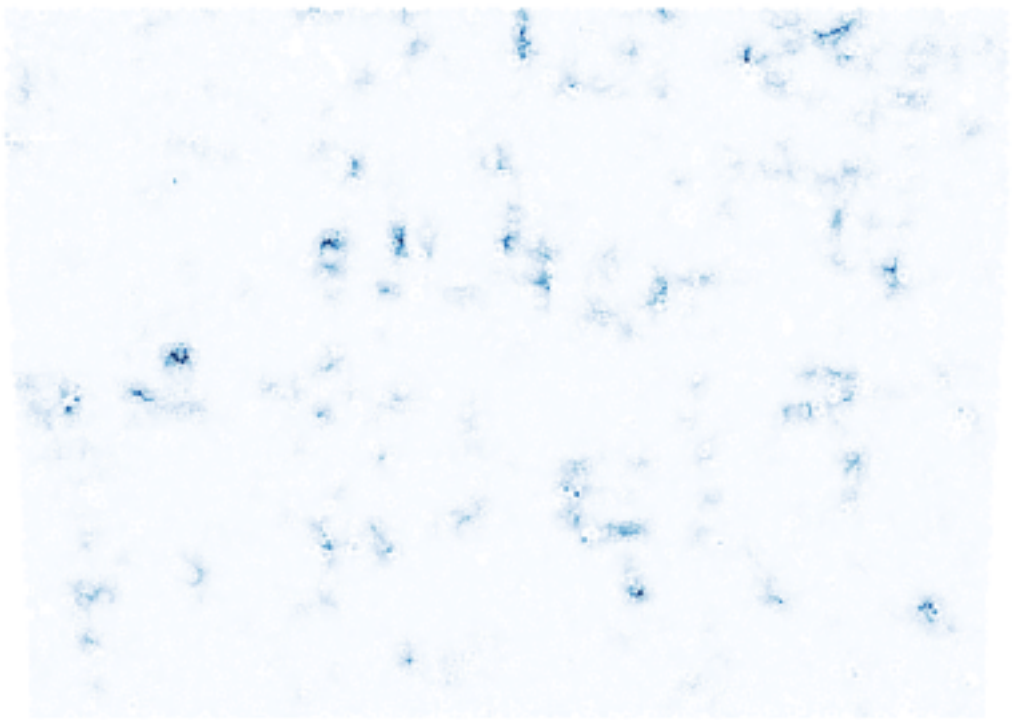


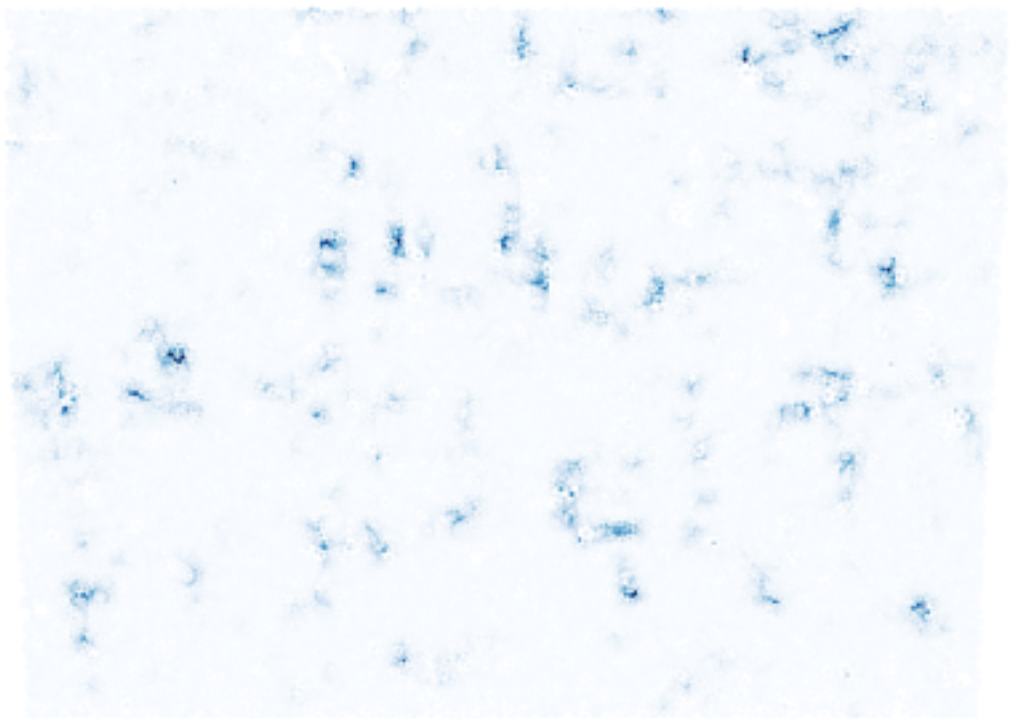


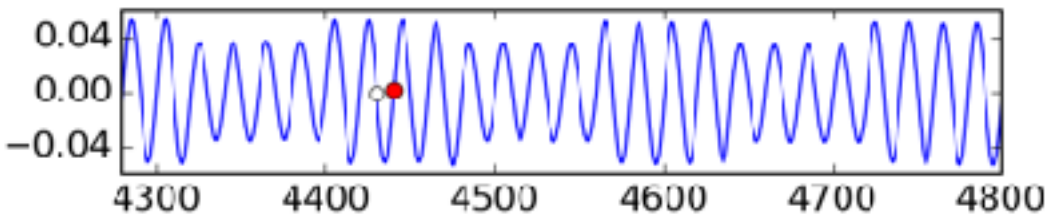


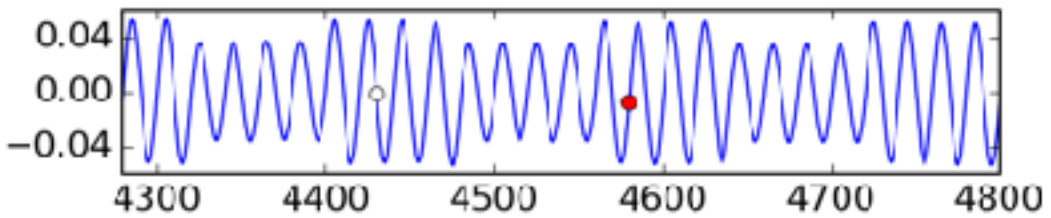


Return to large amplitude → Remember prev. behavior









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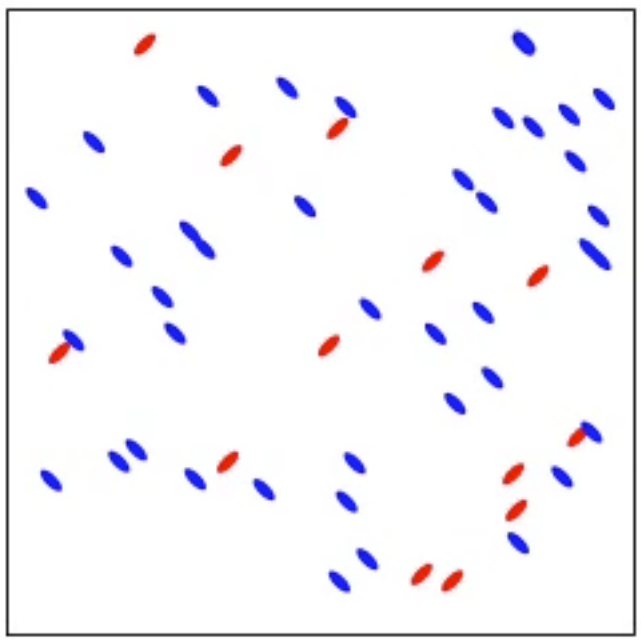

Preisach, Z. Physik 1935

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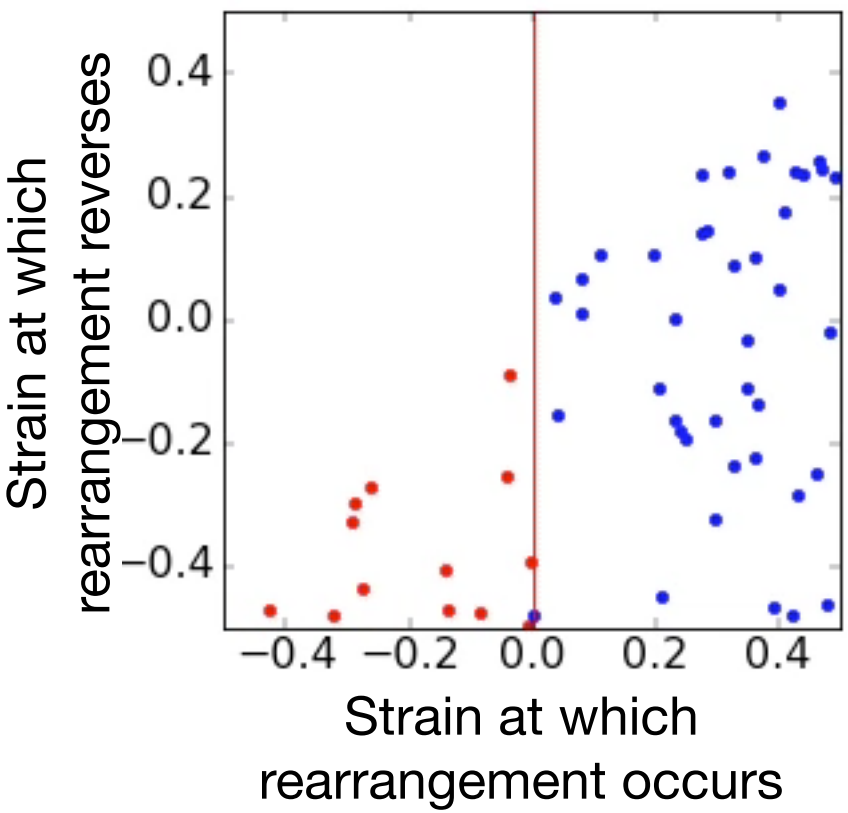

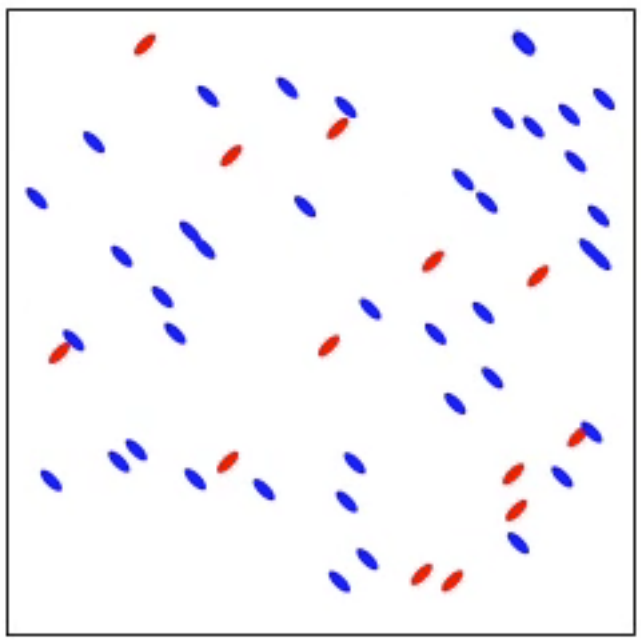

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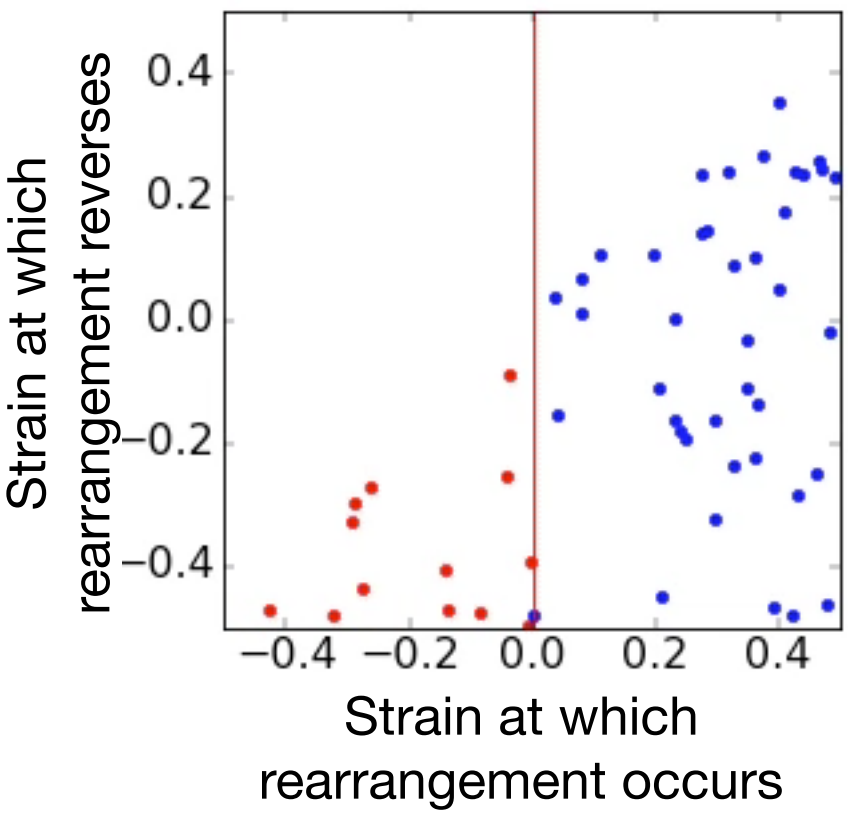

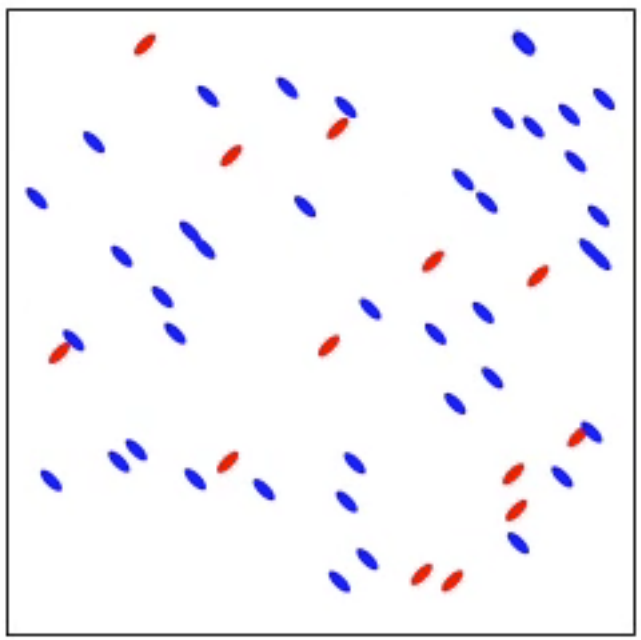

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Return-point memory is not just for magnets:

- Random-field Ising model: Sethna et al. *PRL* 1993
- Martensitic materials: e.g. Ortín *J. Appl. Phys* 1991
- Charge-density waves: Wang & Ong *PRB* 1986

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(Within extrema of training)

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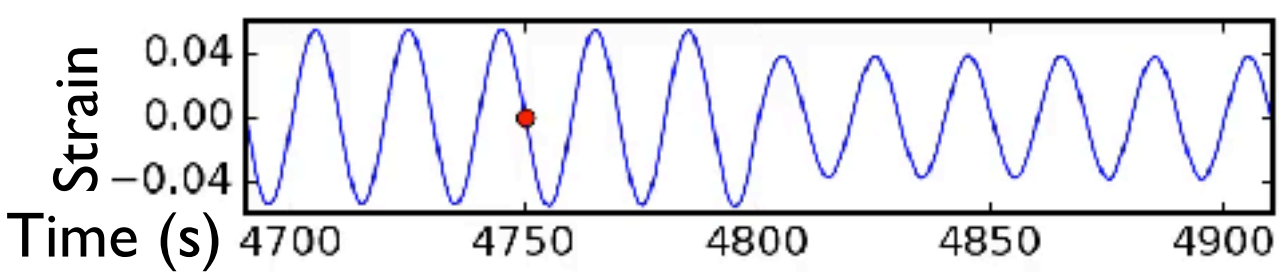
Check one more thing…

Steady state ≈ Fixed rearrangements?

- Train with 5.5%, then switch to 3.5%
- Response at 3.5% is subset of response at 5.5%?



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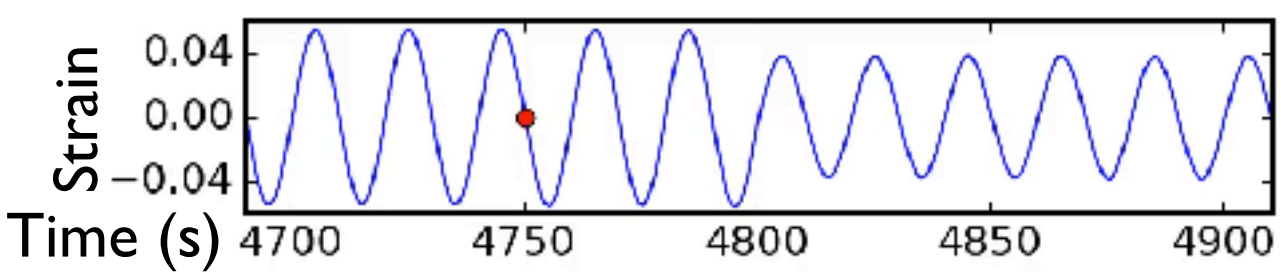

Steady state ≈ Fixed rearrangements?

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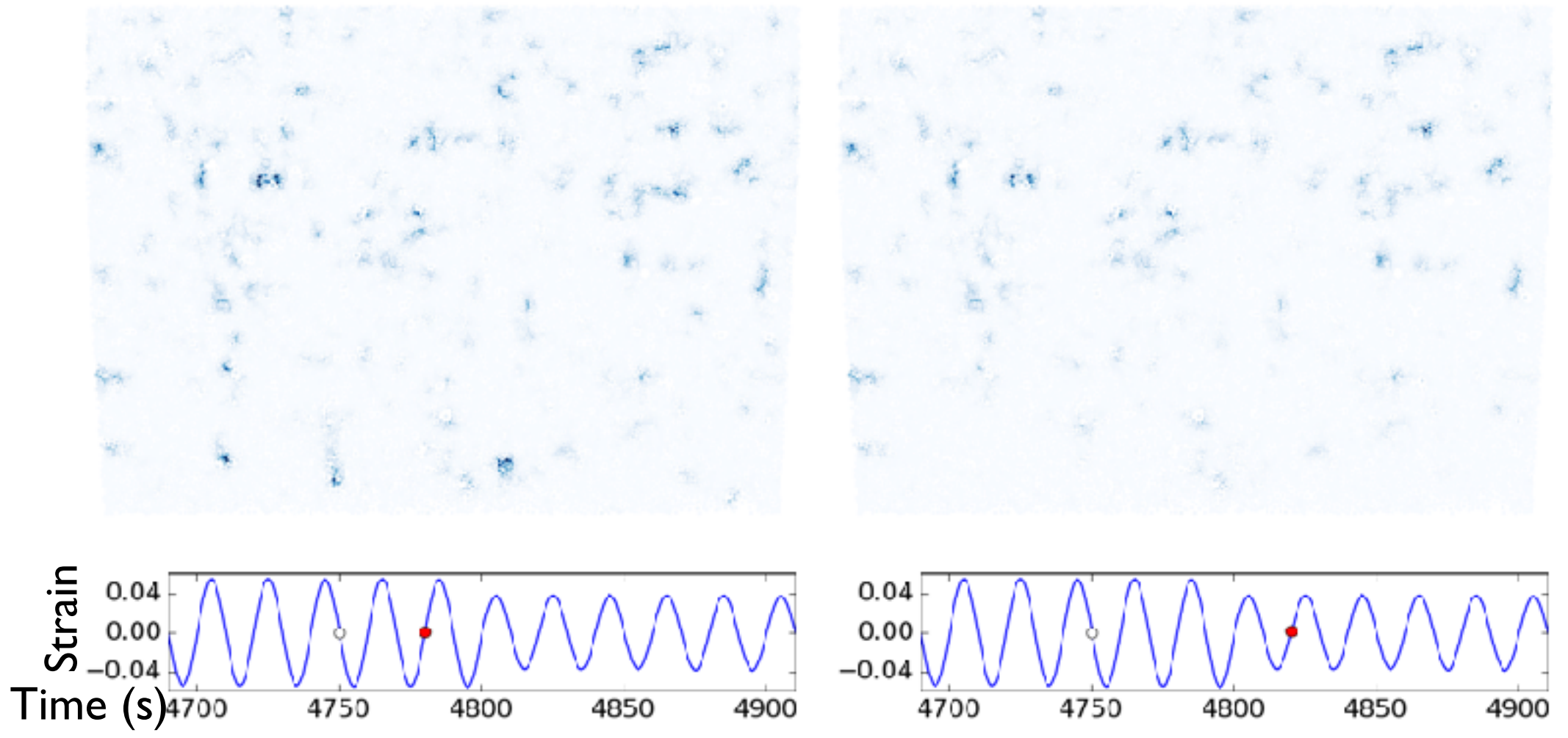

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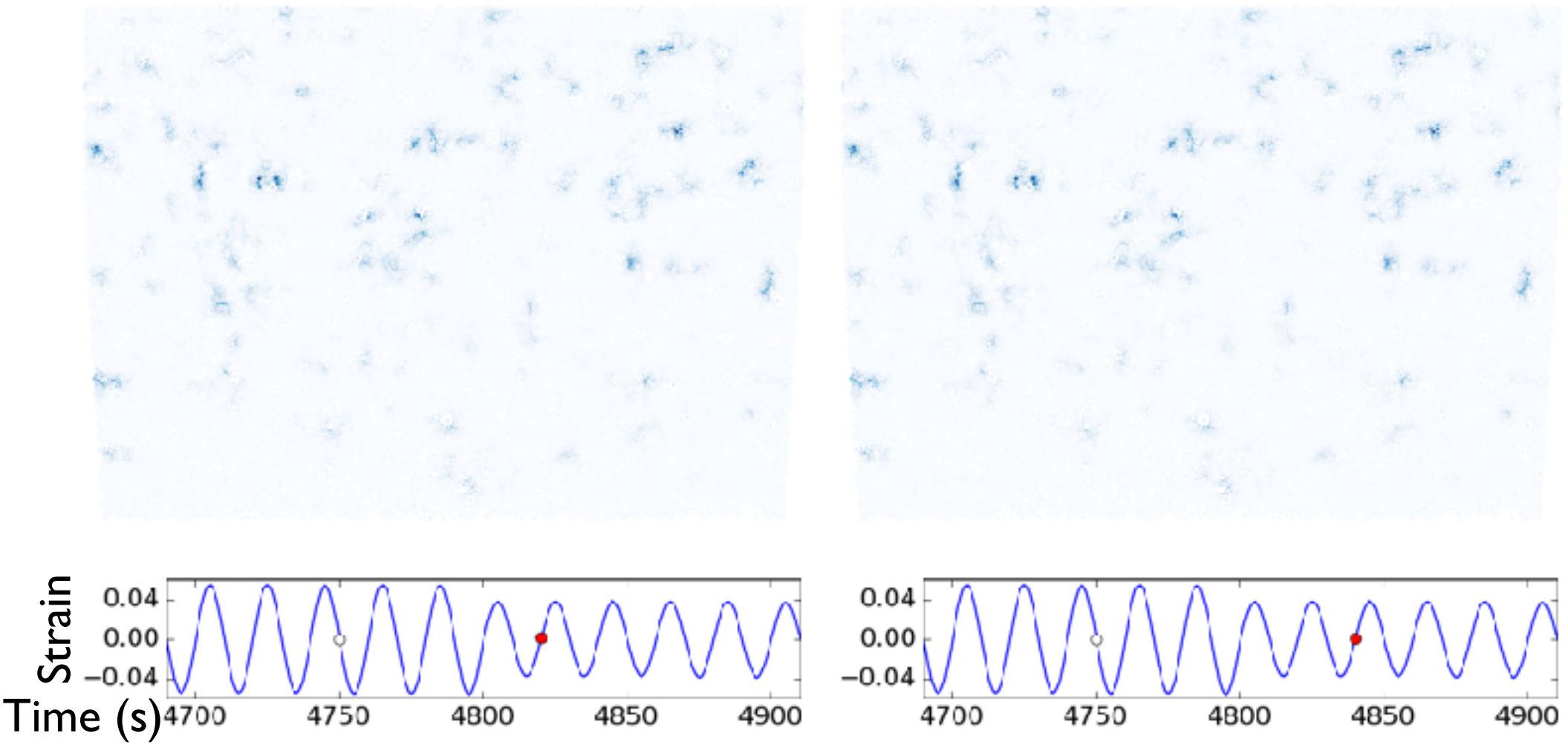
- Same steady state—no transient ✅



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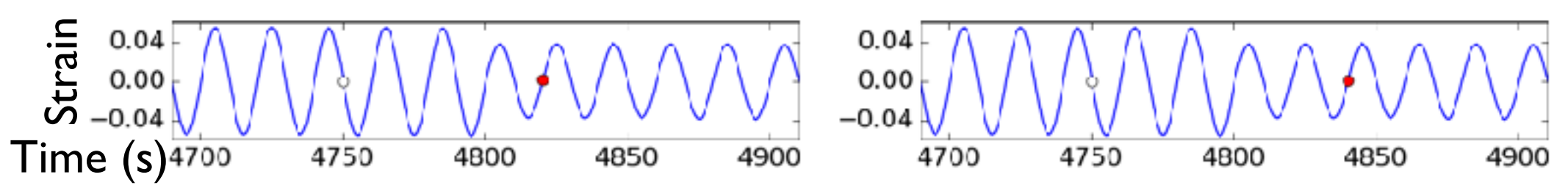
Same behavior as system trained with 2 amplitudes



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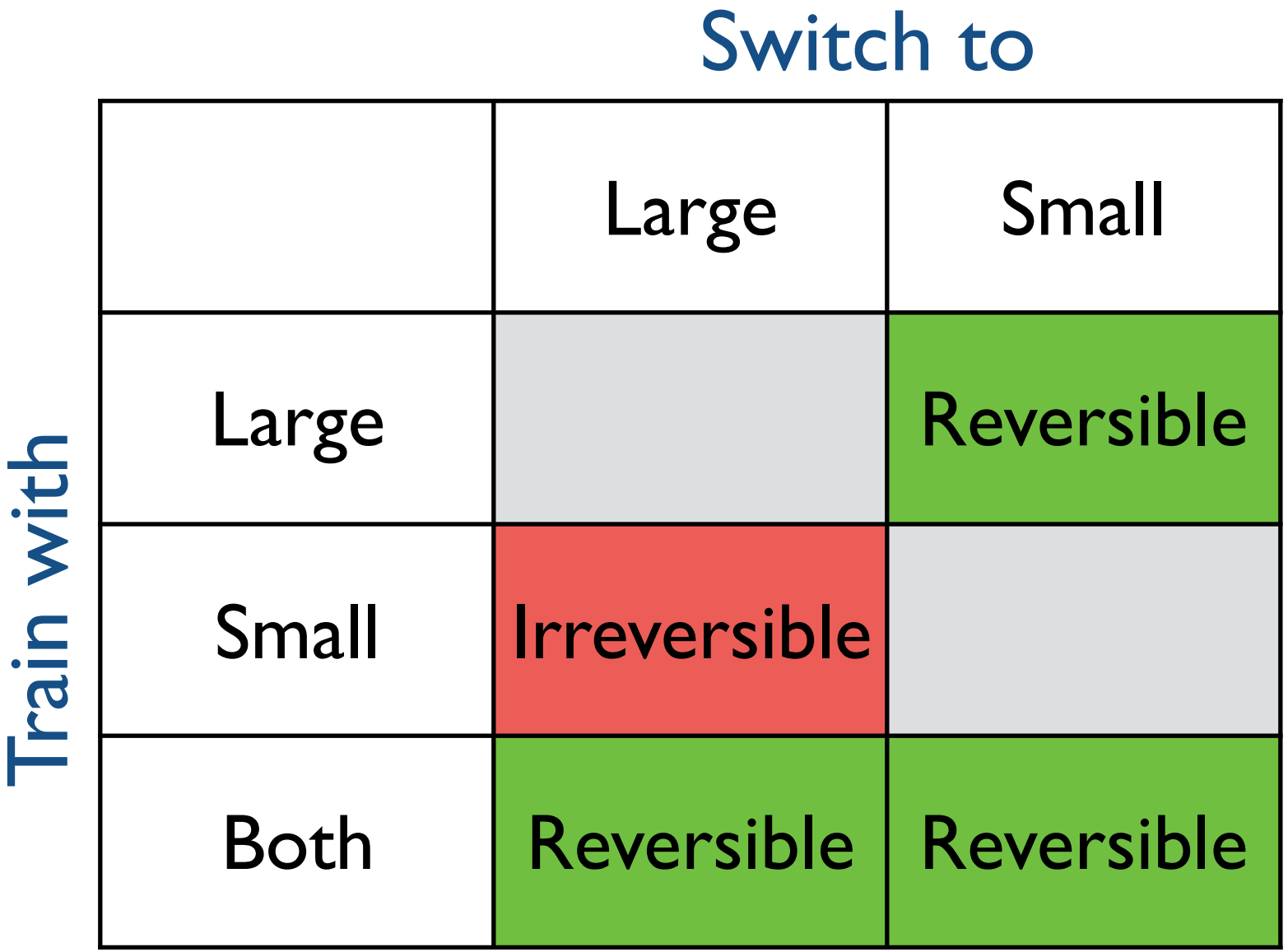
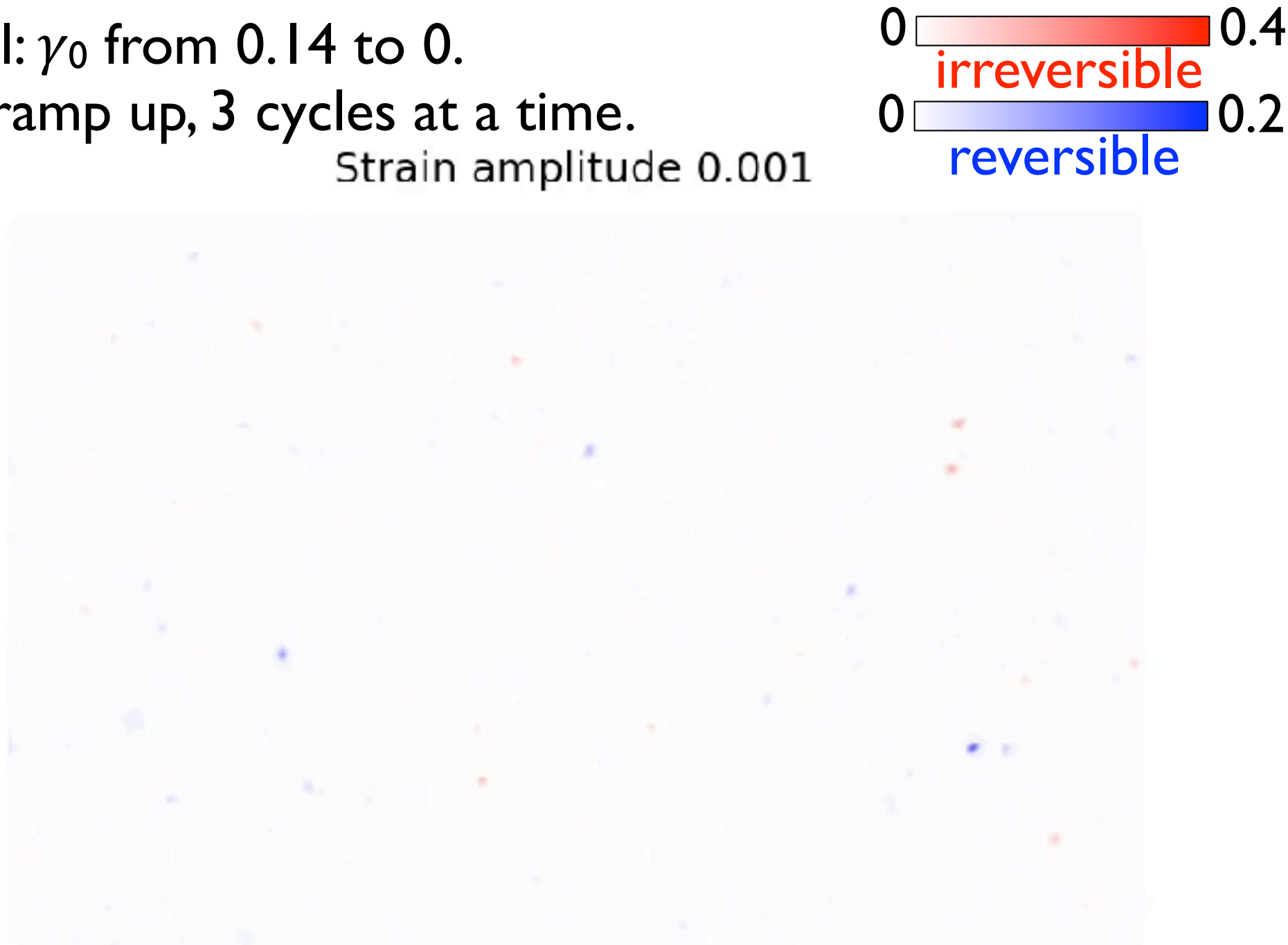


How "fixed" can the population be?

Anneal: γ_0 from 0.14 to 0.

Then ramp up, 3 cycles at a time.



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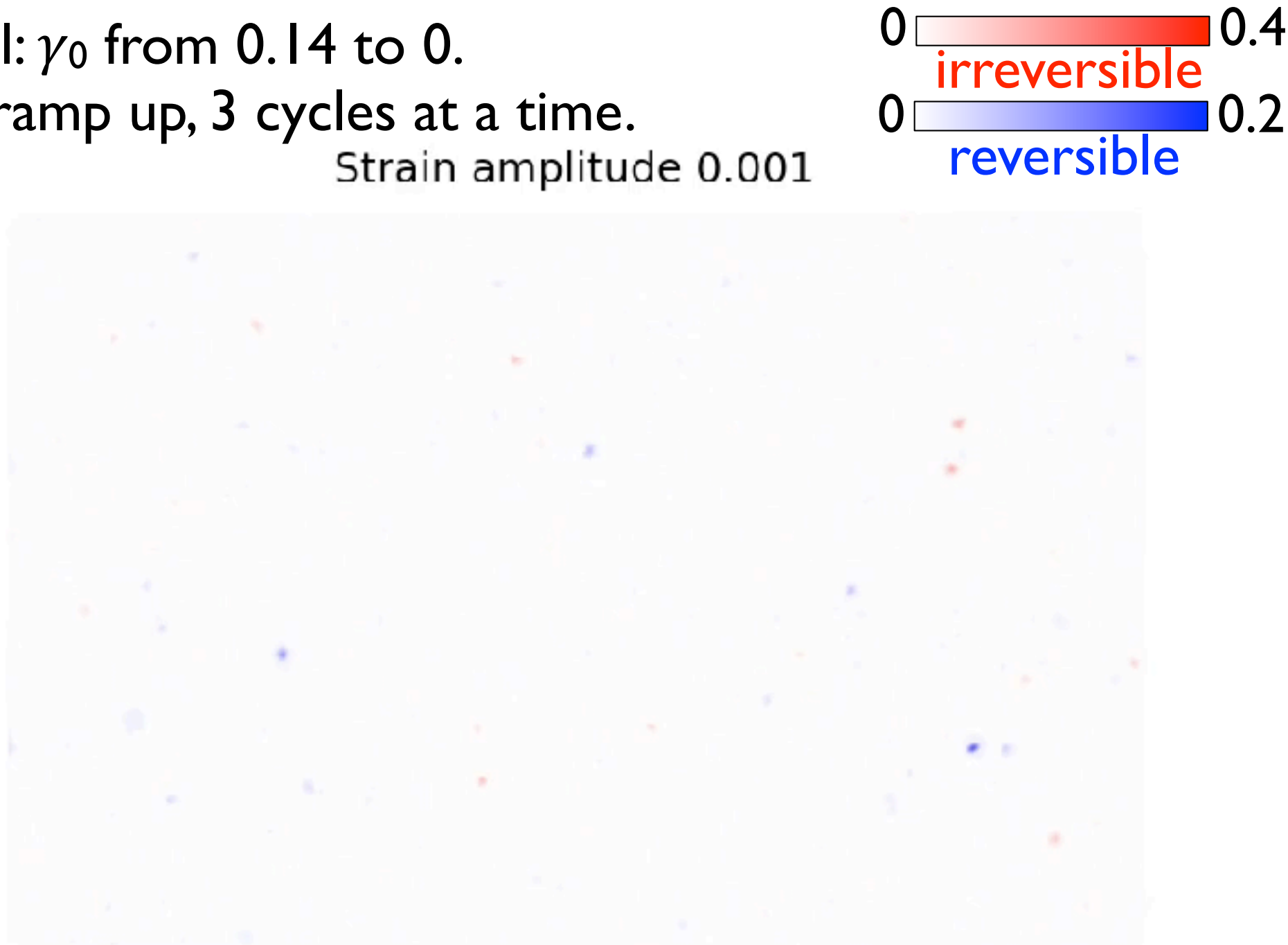

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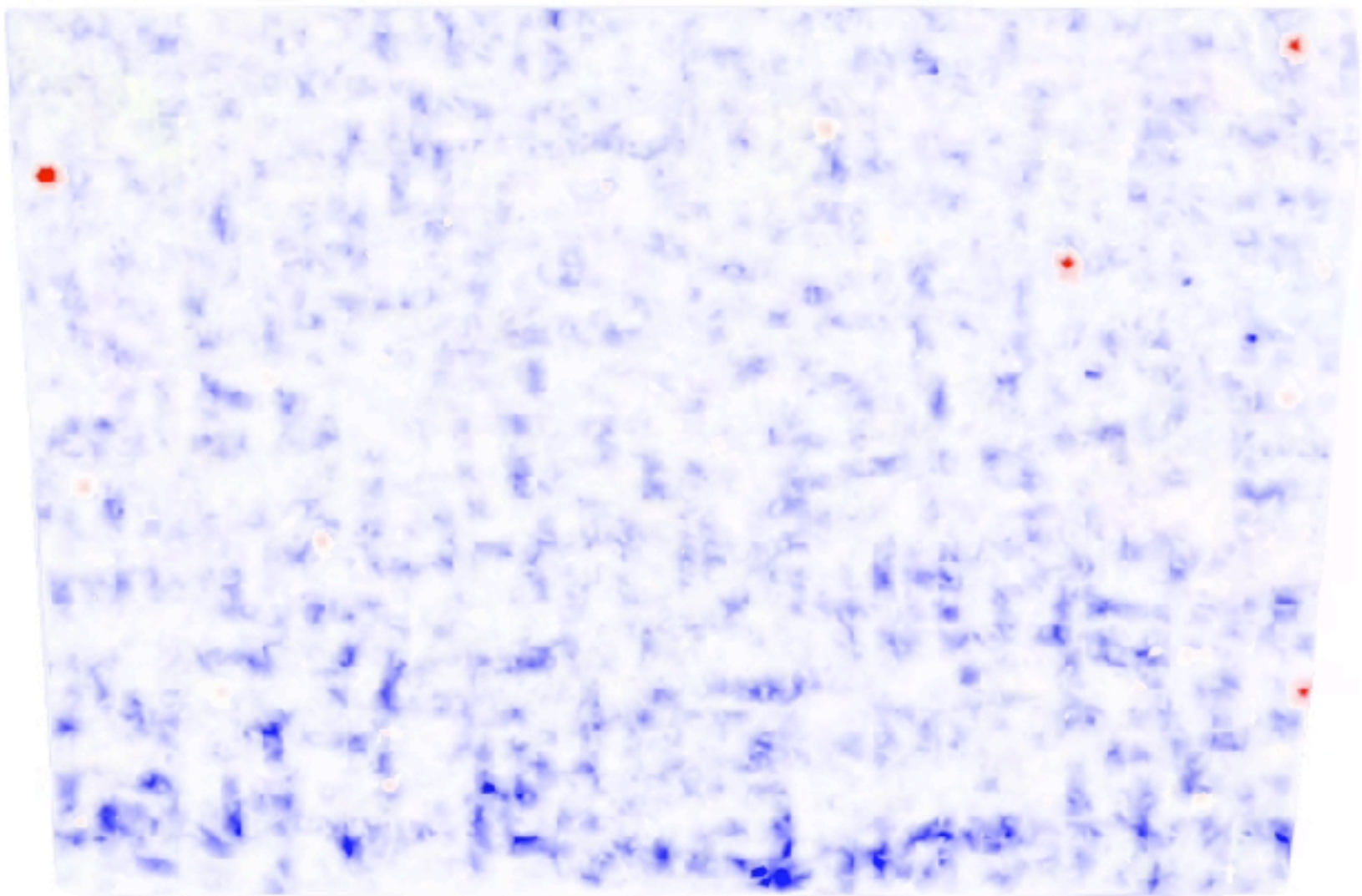
Strain amplitude 0.0538



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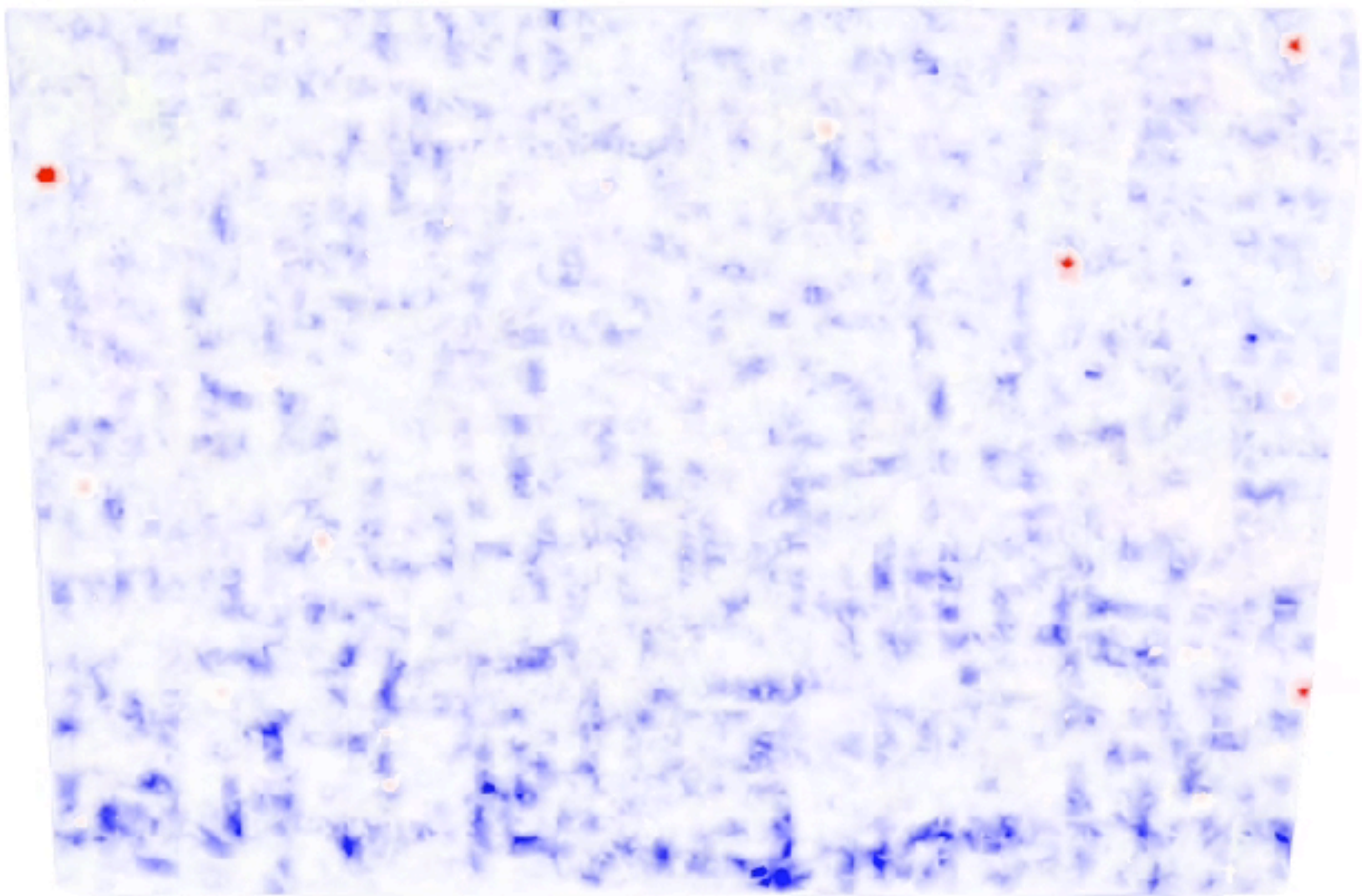
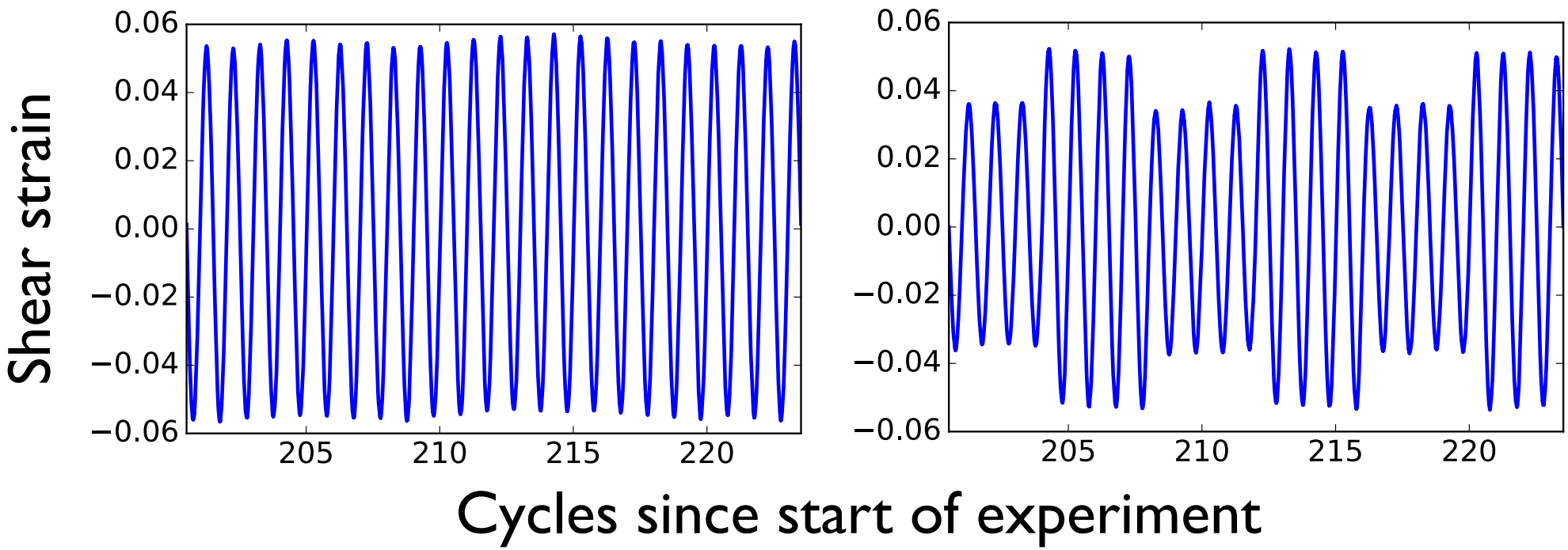


Steady State Conclusions

Does 2-amplitude training matter?

Fixed population of rearrangements → Return-point memory → Smaller amp. forgotten!



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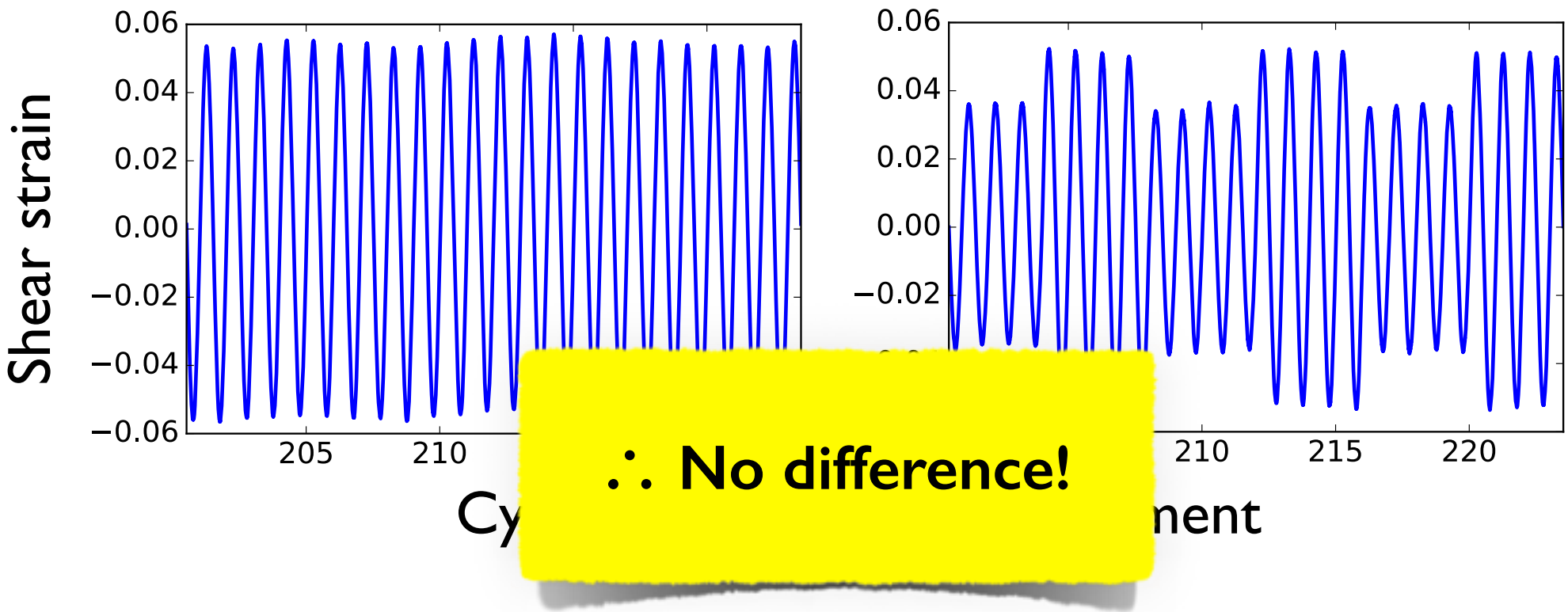
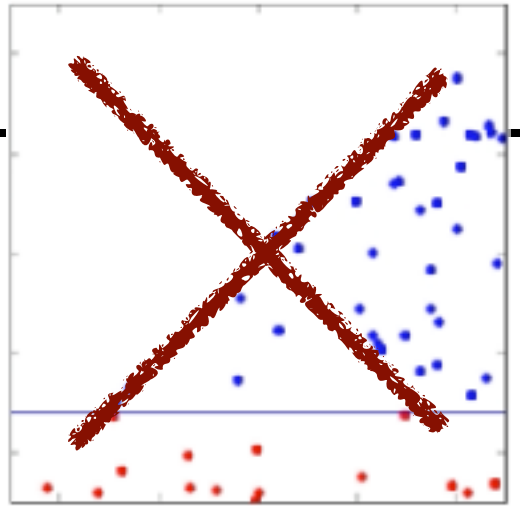


∴ No difference!

Digging deeper…



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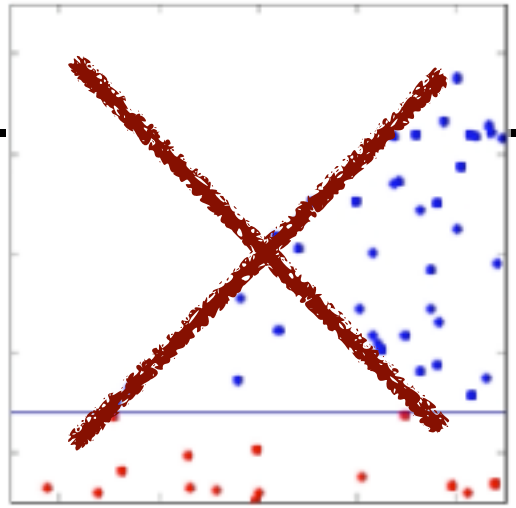
- Preisach diagram at 5.5% strain doesn't predict 3.5% response



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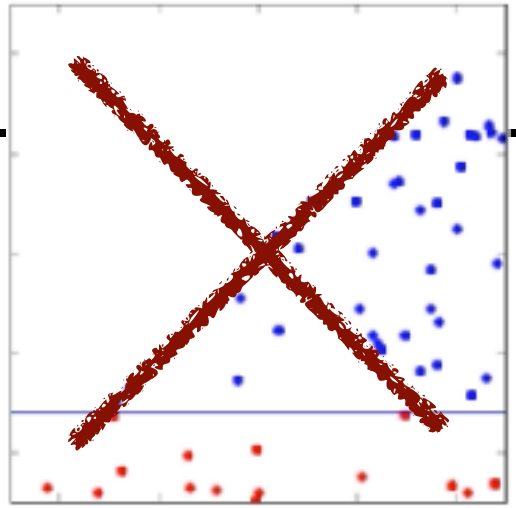
- **First small cycle can be slightly different**
  Could be due to frustration: e.g. Gilbert et al. *PRB* 2015



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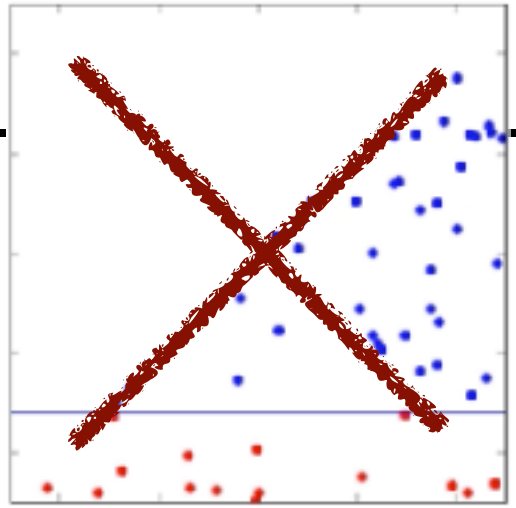

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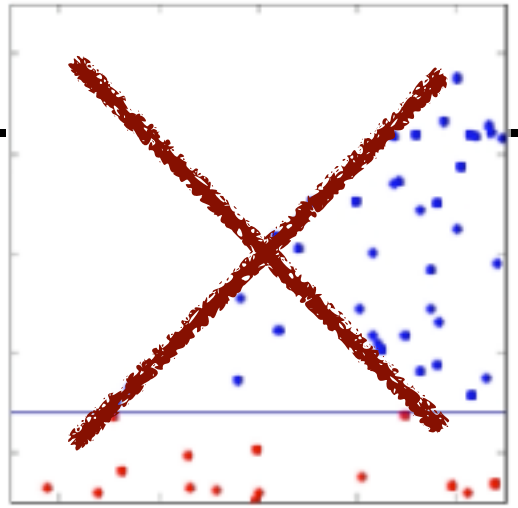

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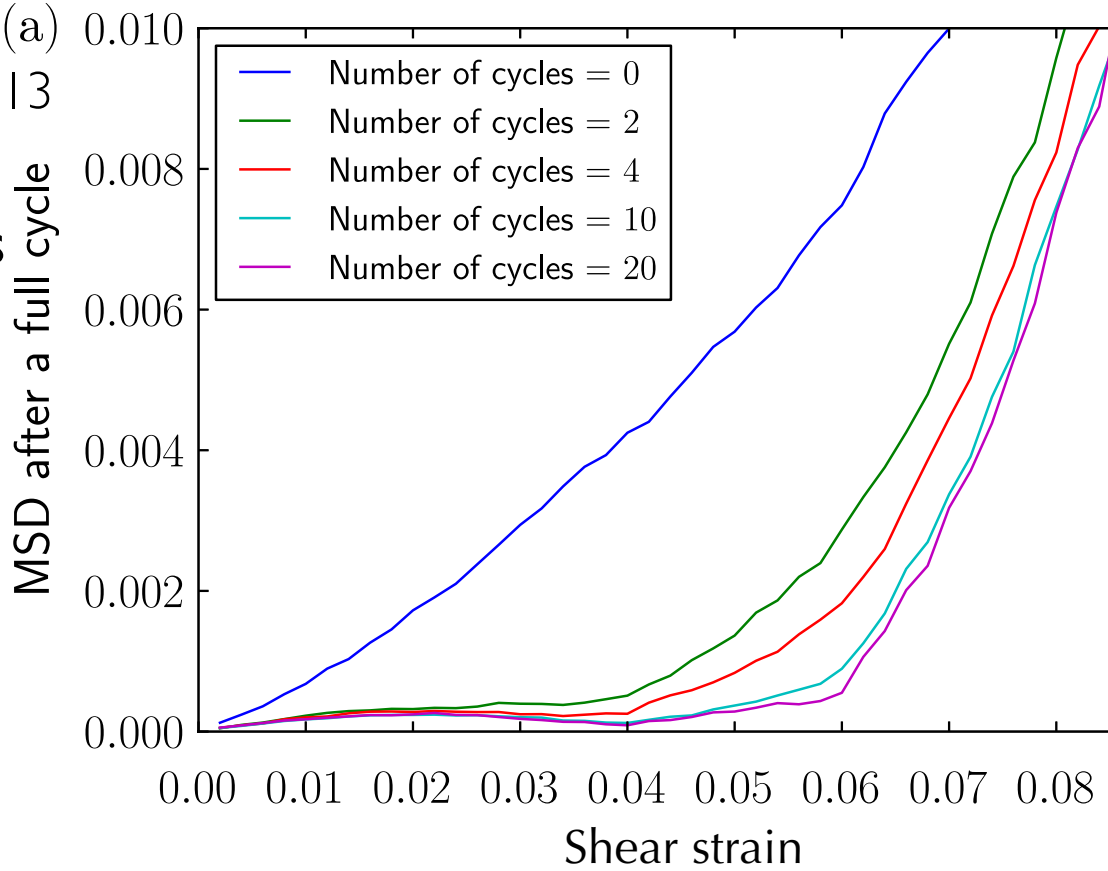

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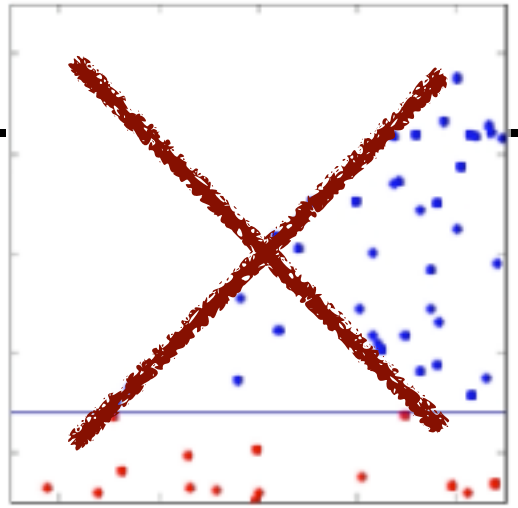

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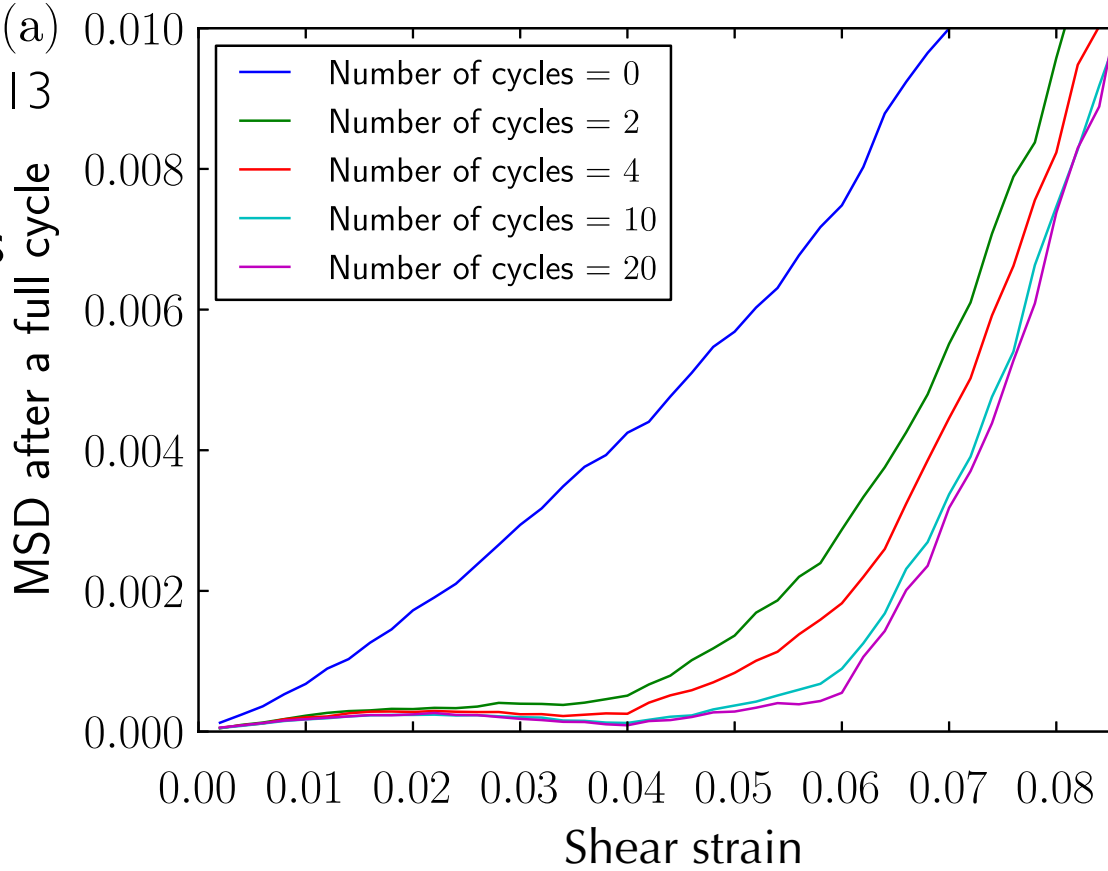
  Talk by Ajay Sood



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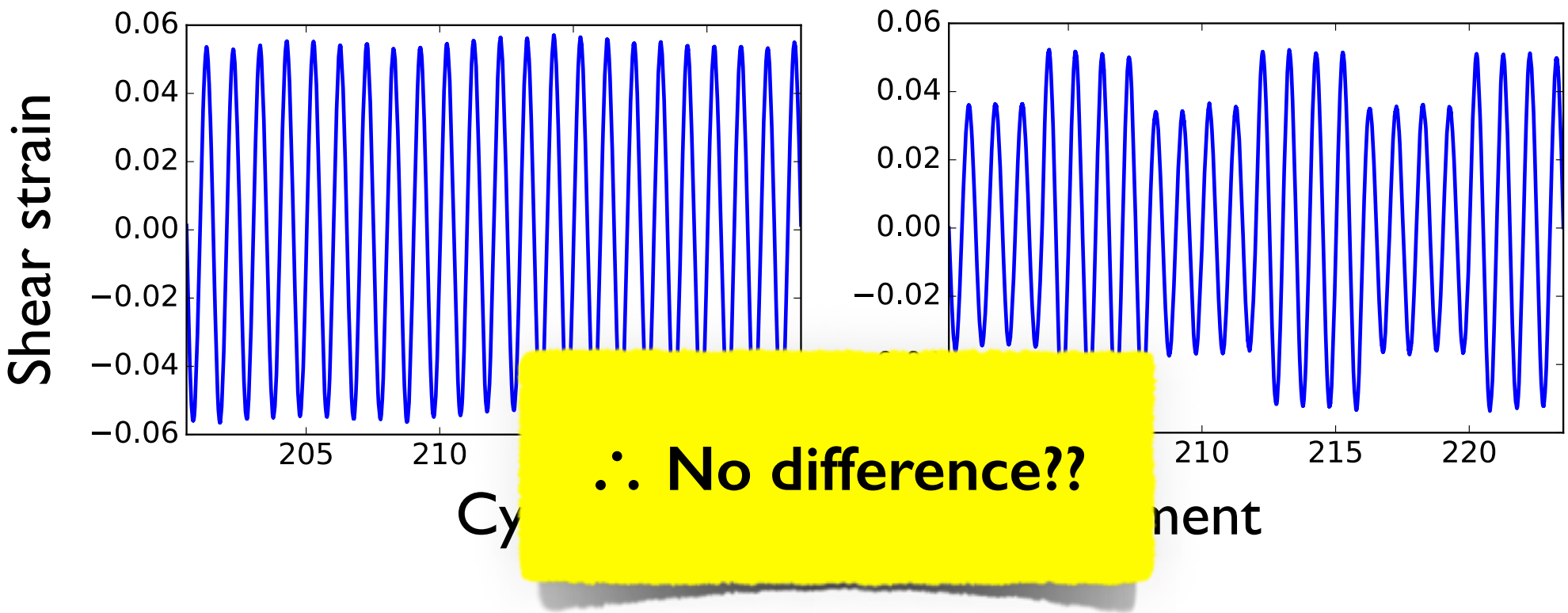

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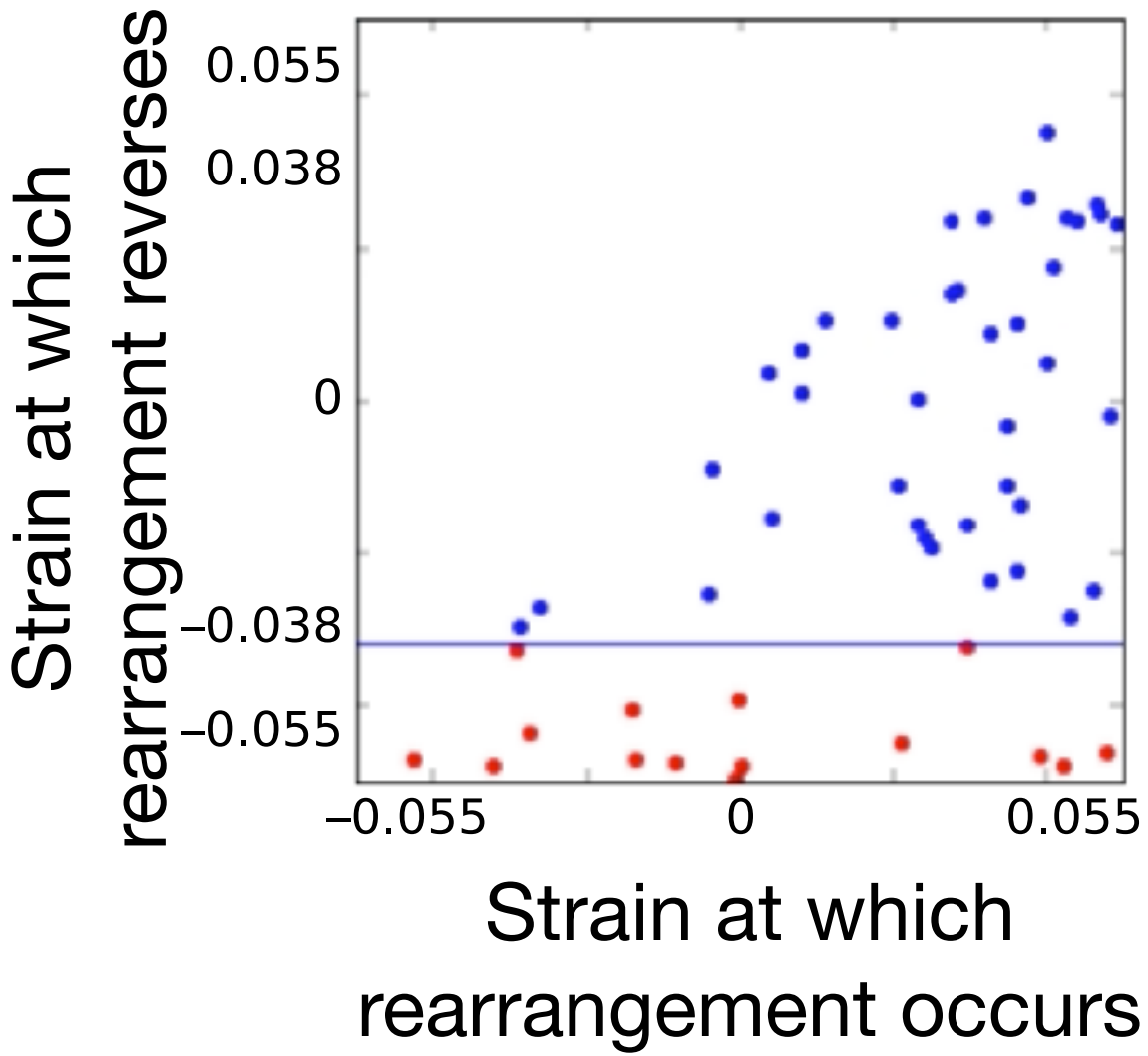
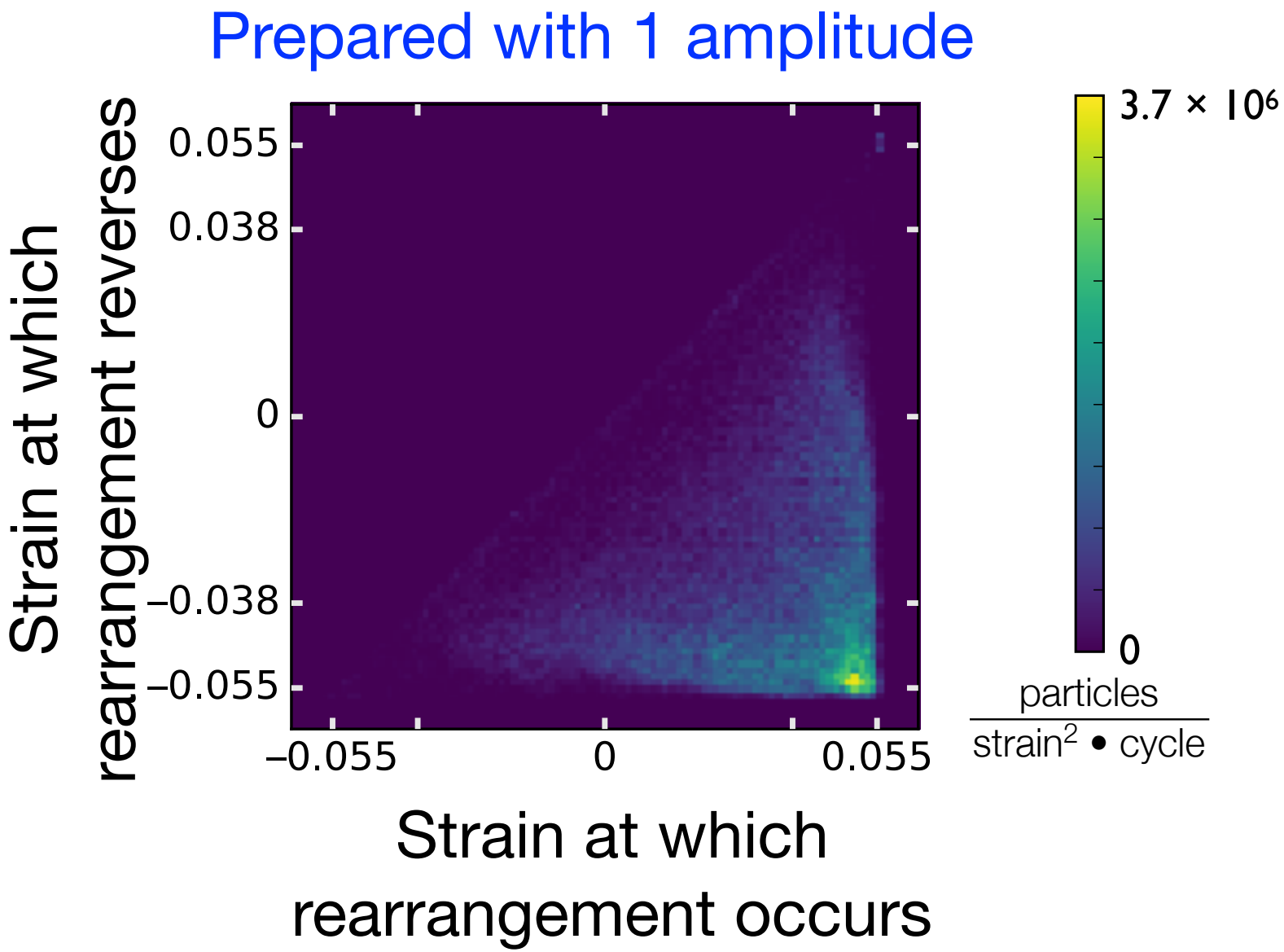
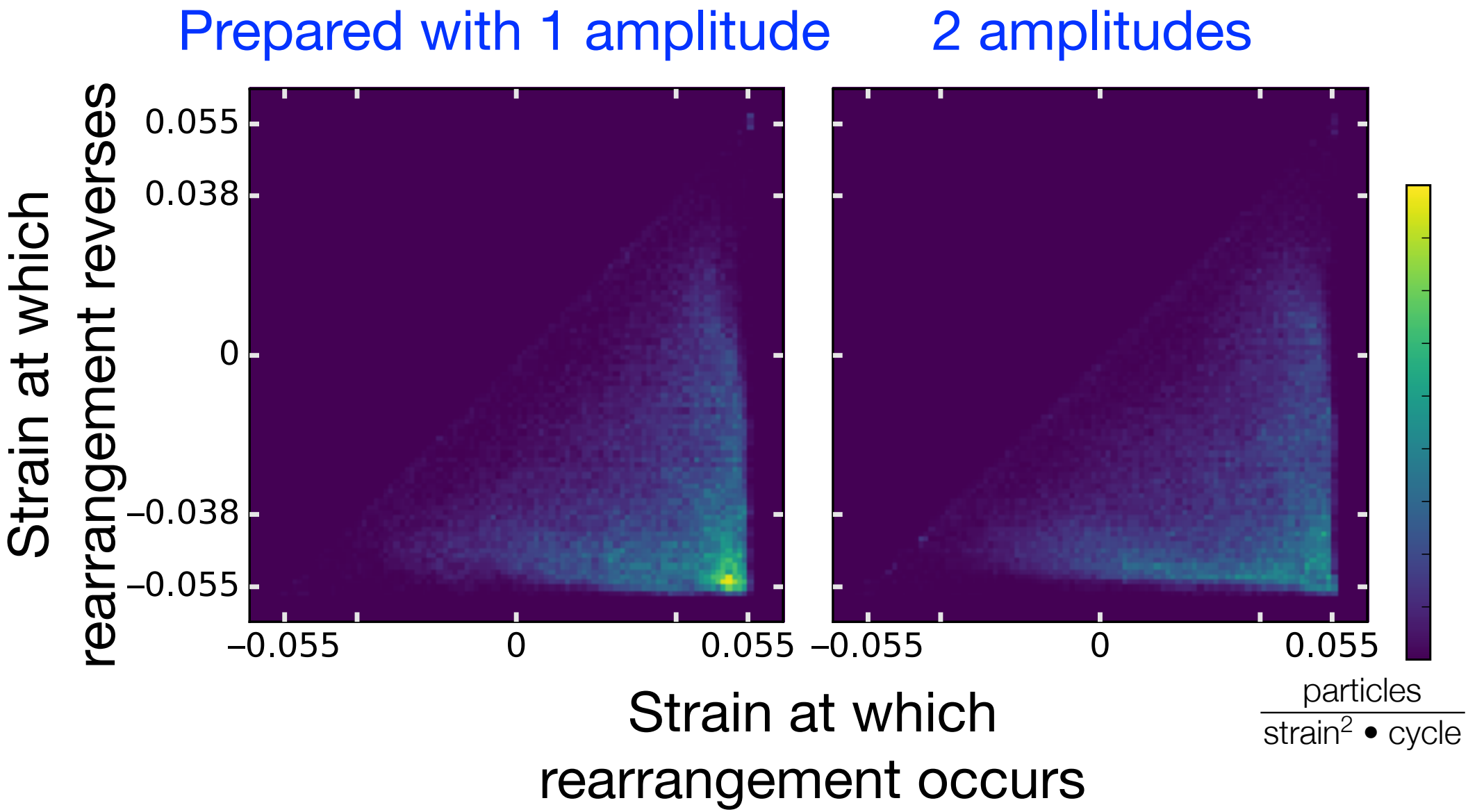


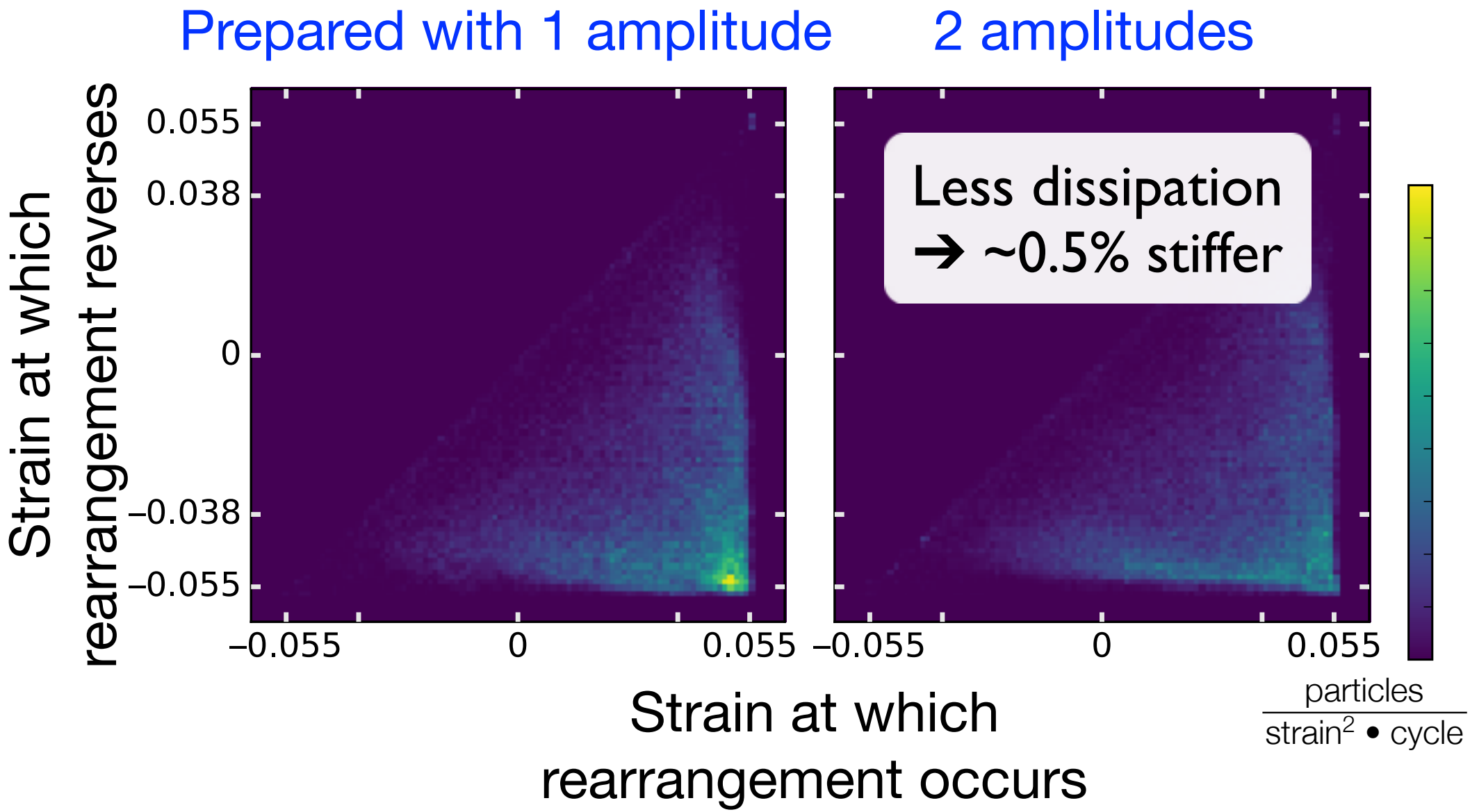
Does preparation matter?



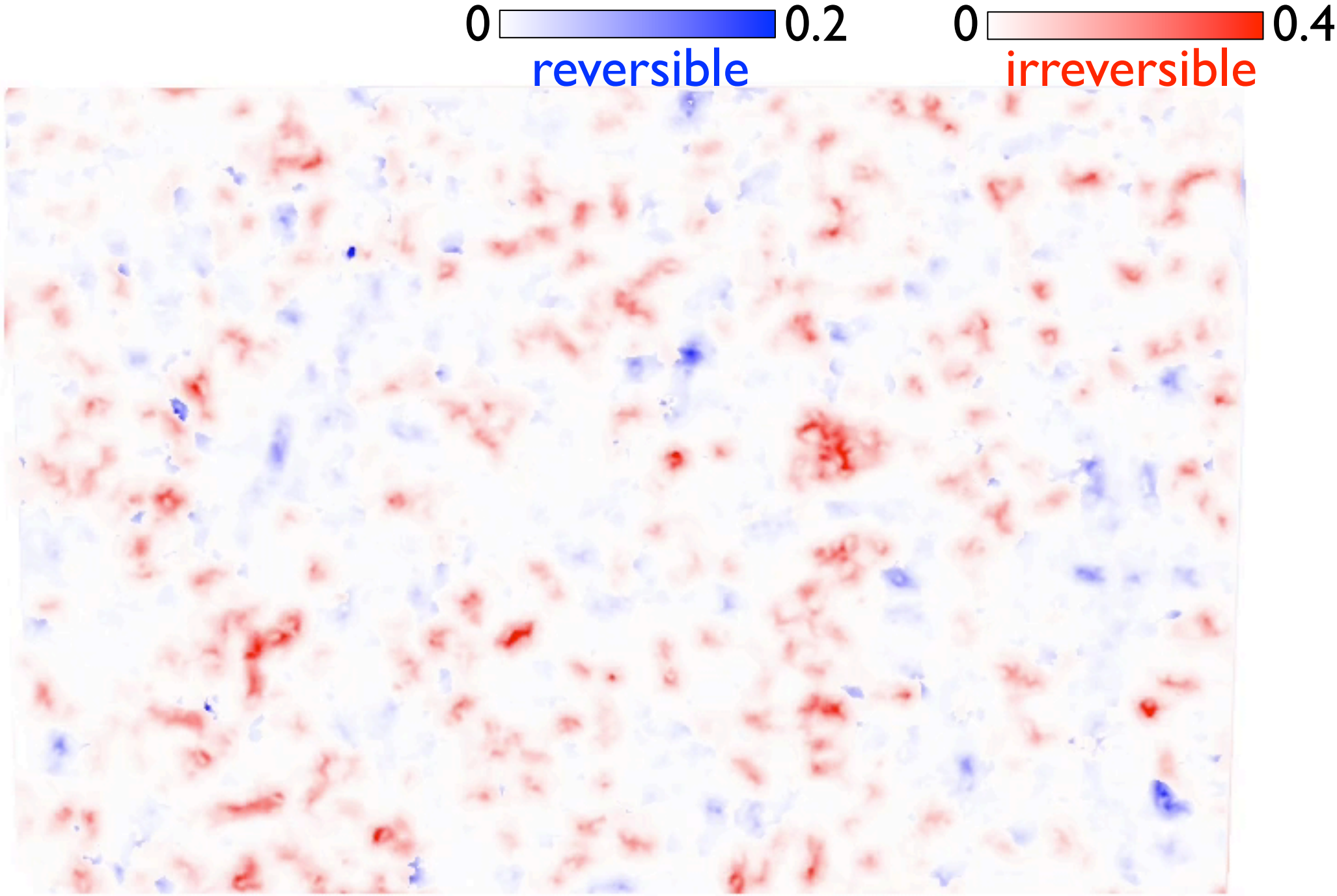
Does preparation matter?



Does preparation matter?



Transient with γ_0 = 3.5%, 5%



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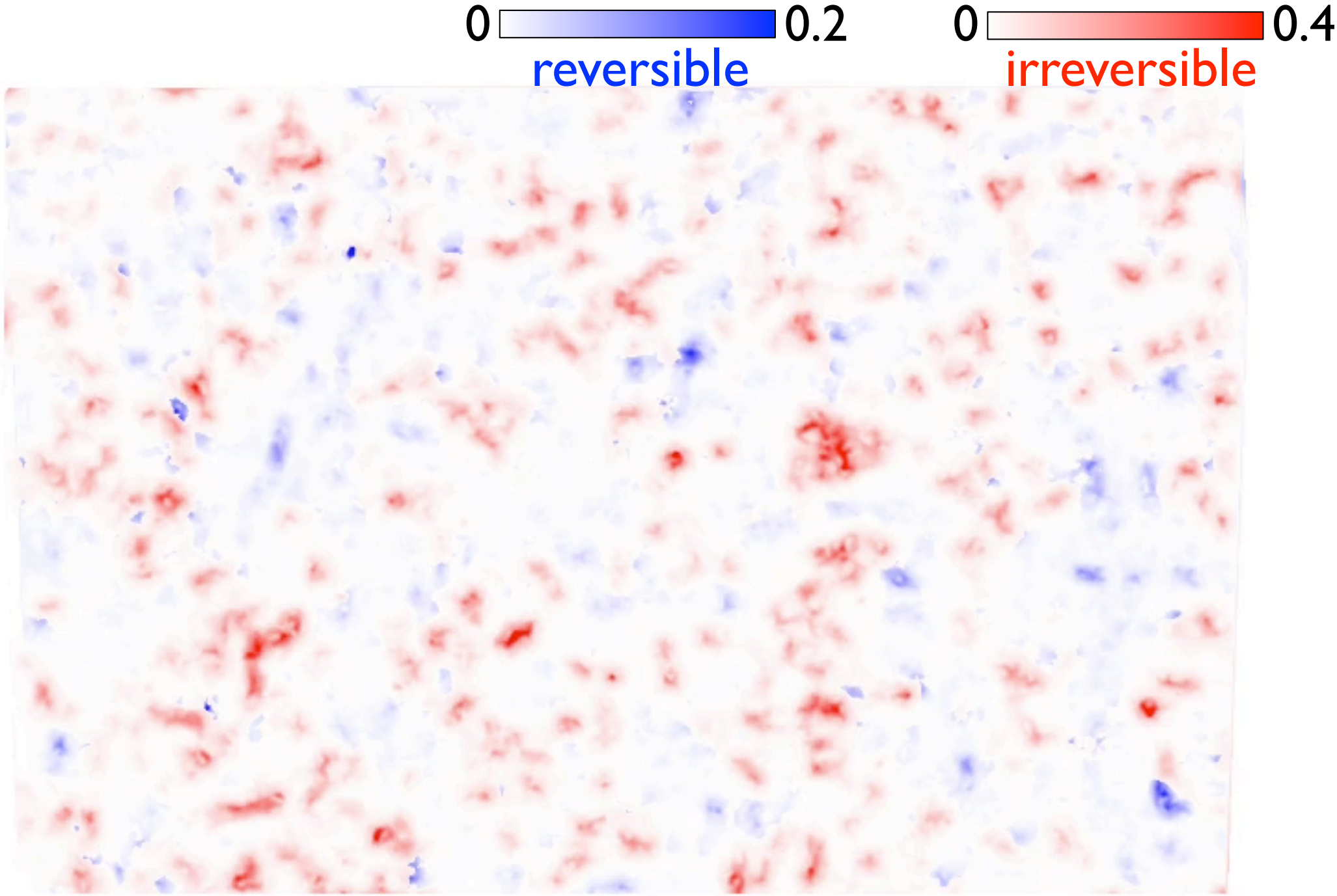
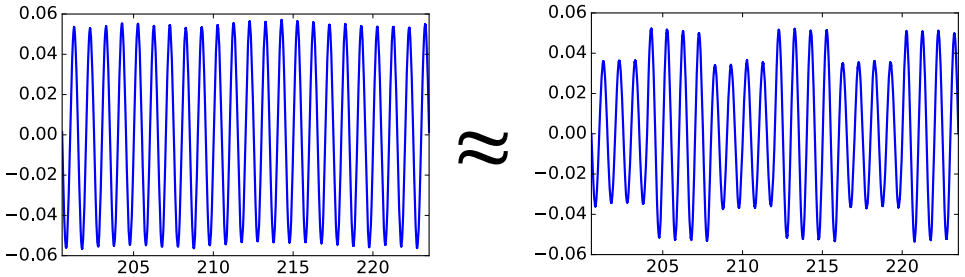


Conclusions — Amorphous Solids



≈ ?

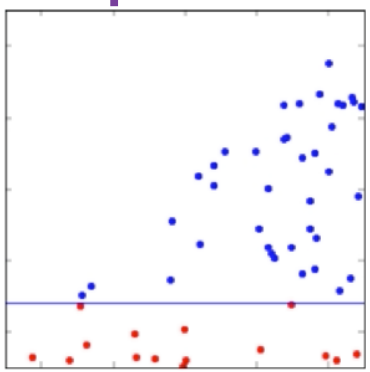
Split decision

Steady State

~Fixed population of hysteretic subsystems

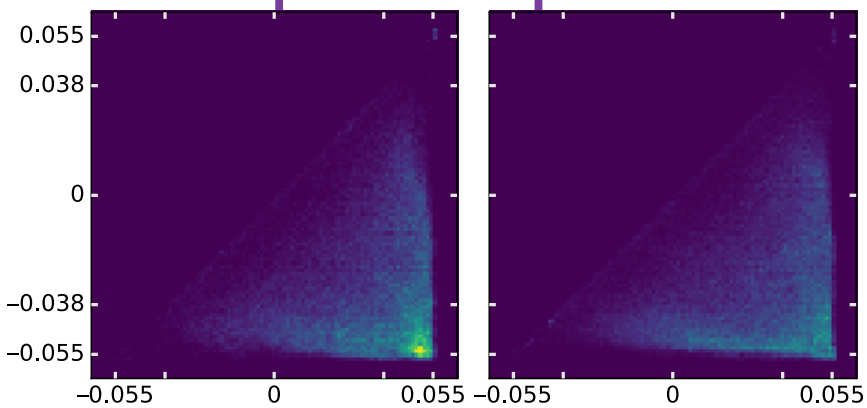
Return-Point Memory

Small amplitude erased

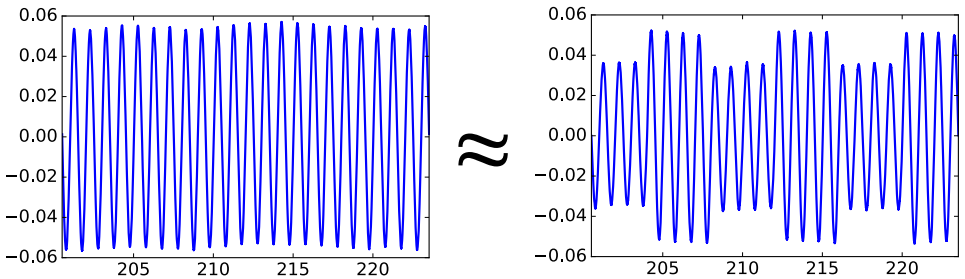


Imprint of *transient* persists

Small amplitude preserved?



Conclusions — Amorphous Solids



≈ ?

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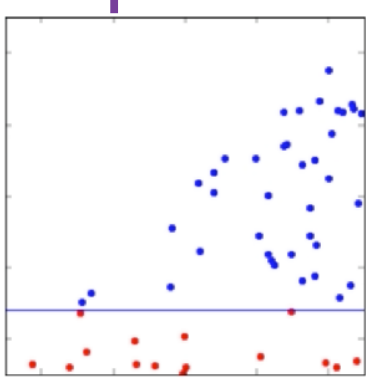
Small amplitude erased

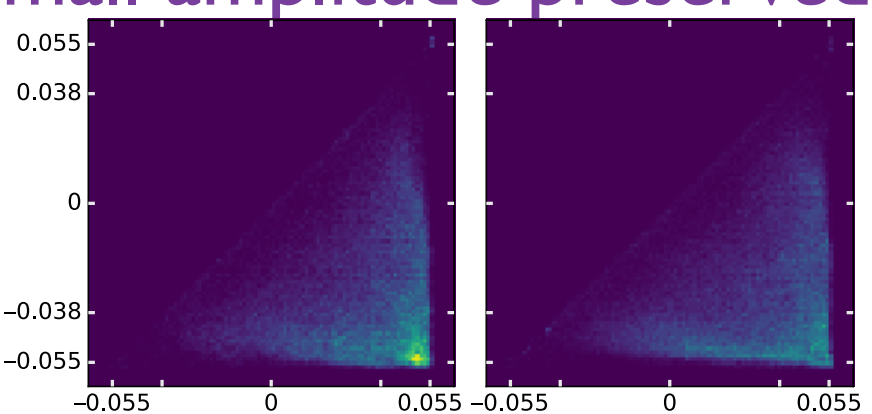


Encodes strain extrema

Destructive readout

Imprint of *transient* persists

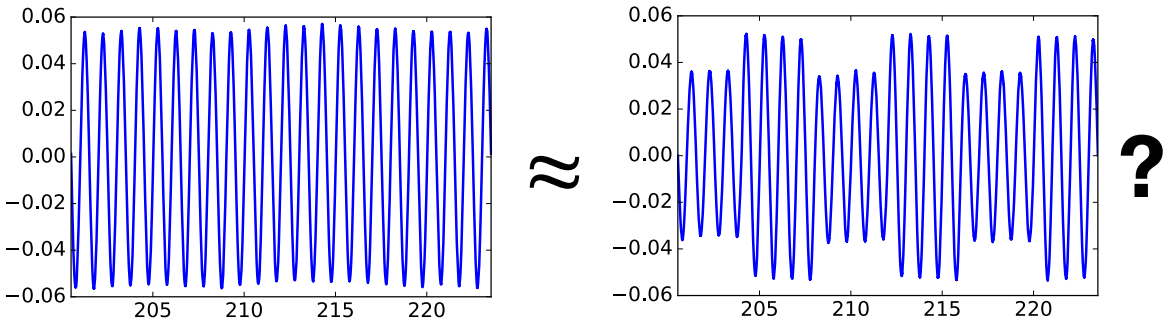
Small amplitude preserved?

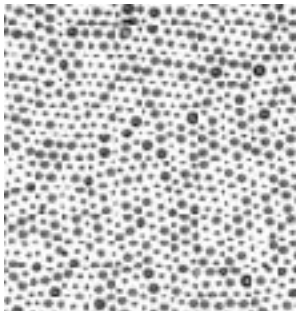


Encodes at least 1 bit

Non-destructive readout

Outline

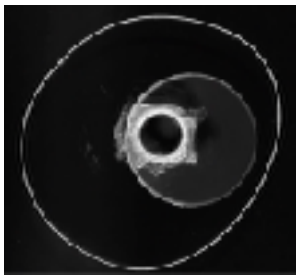




Disordered solids

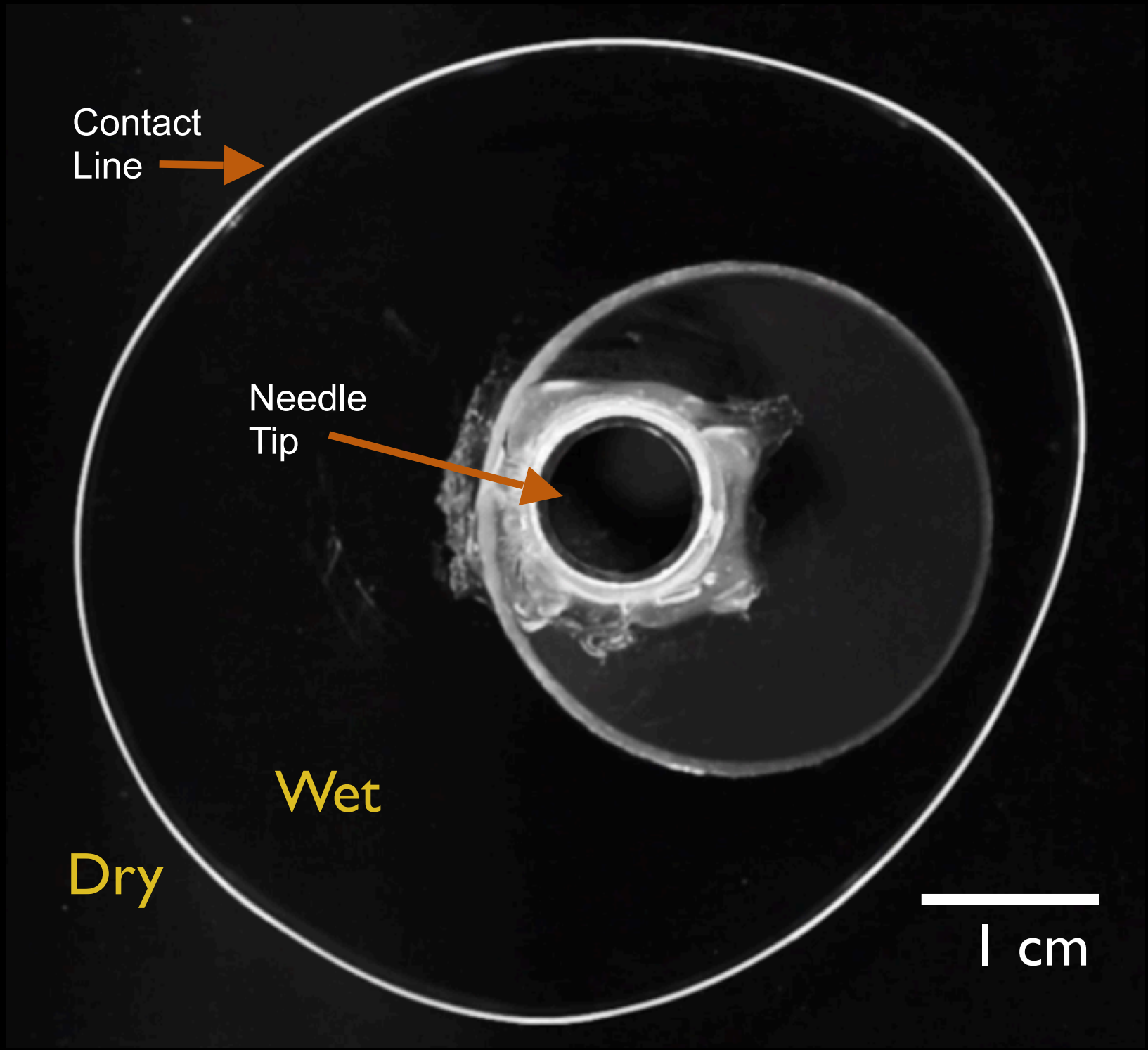
No: Return-point memory

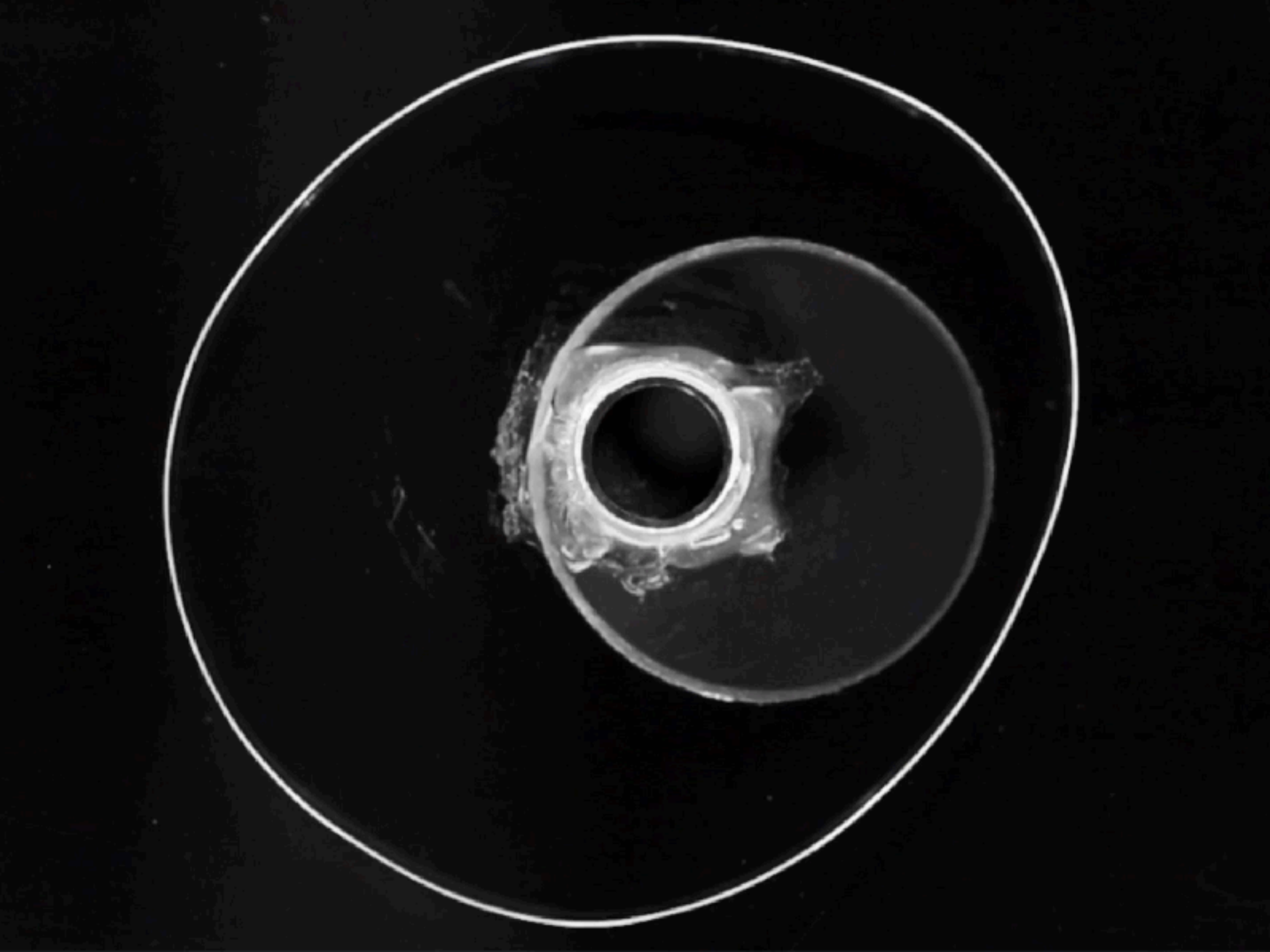
Yes: Transient self-organization

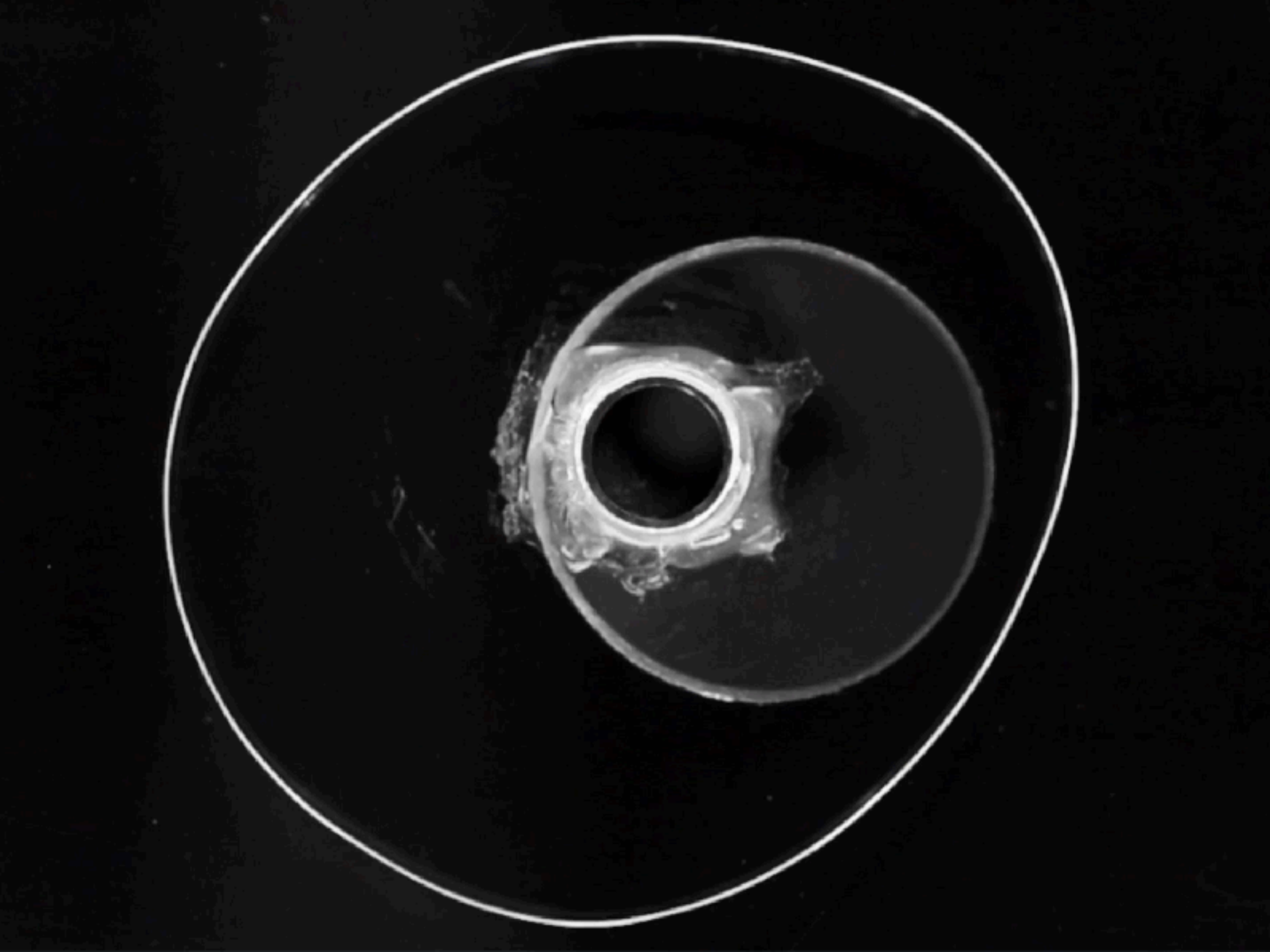


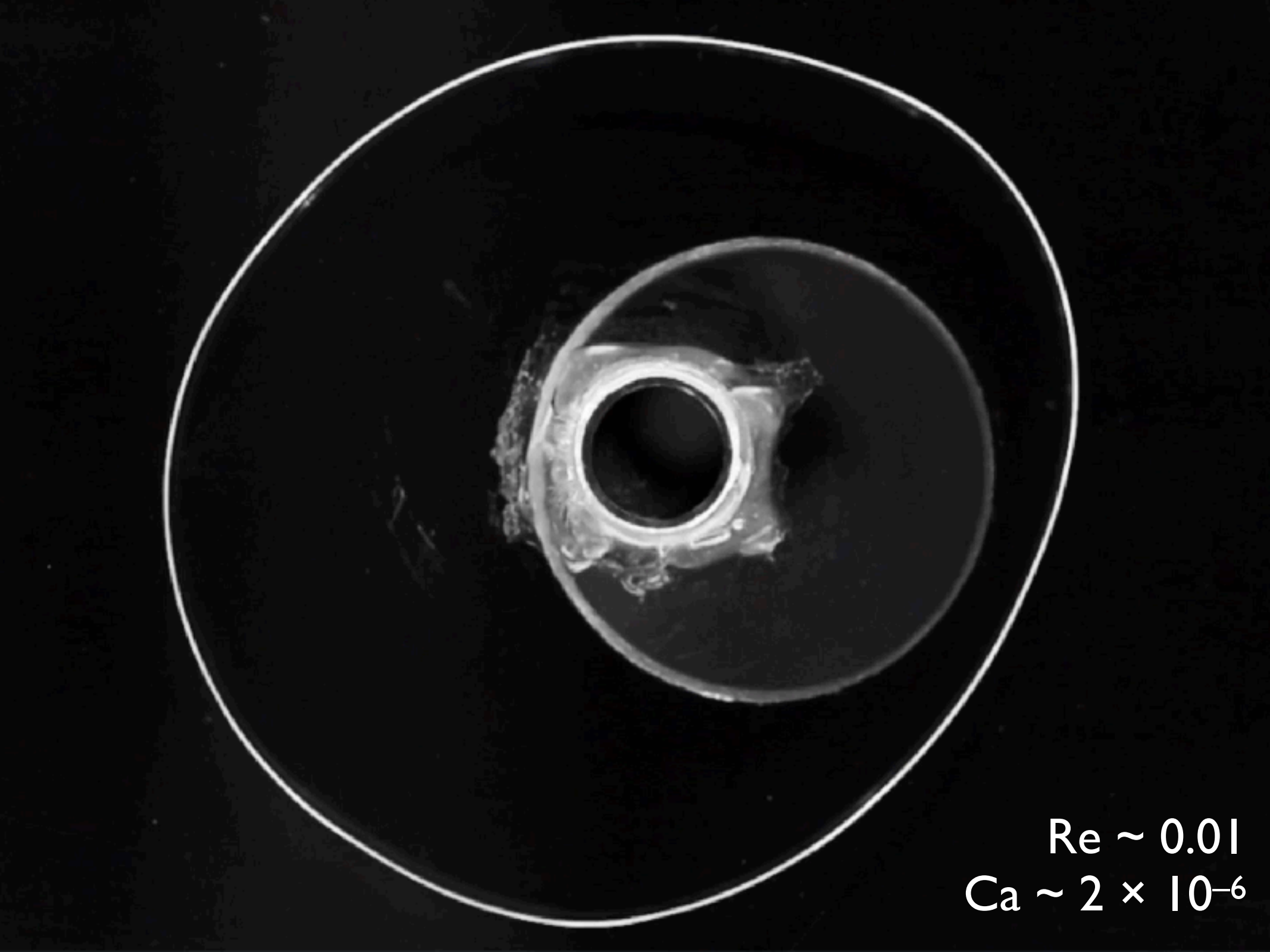
Contact lines

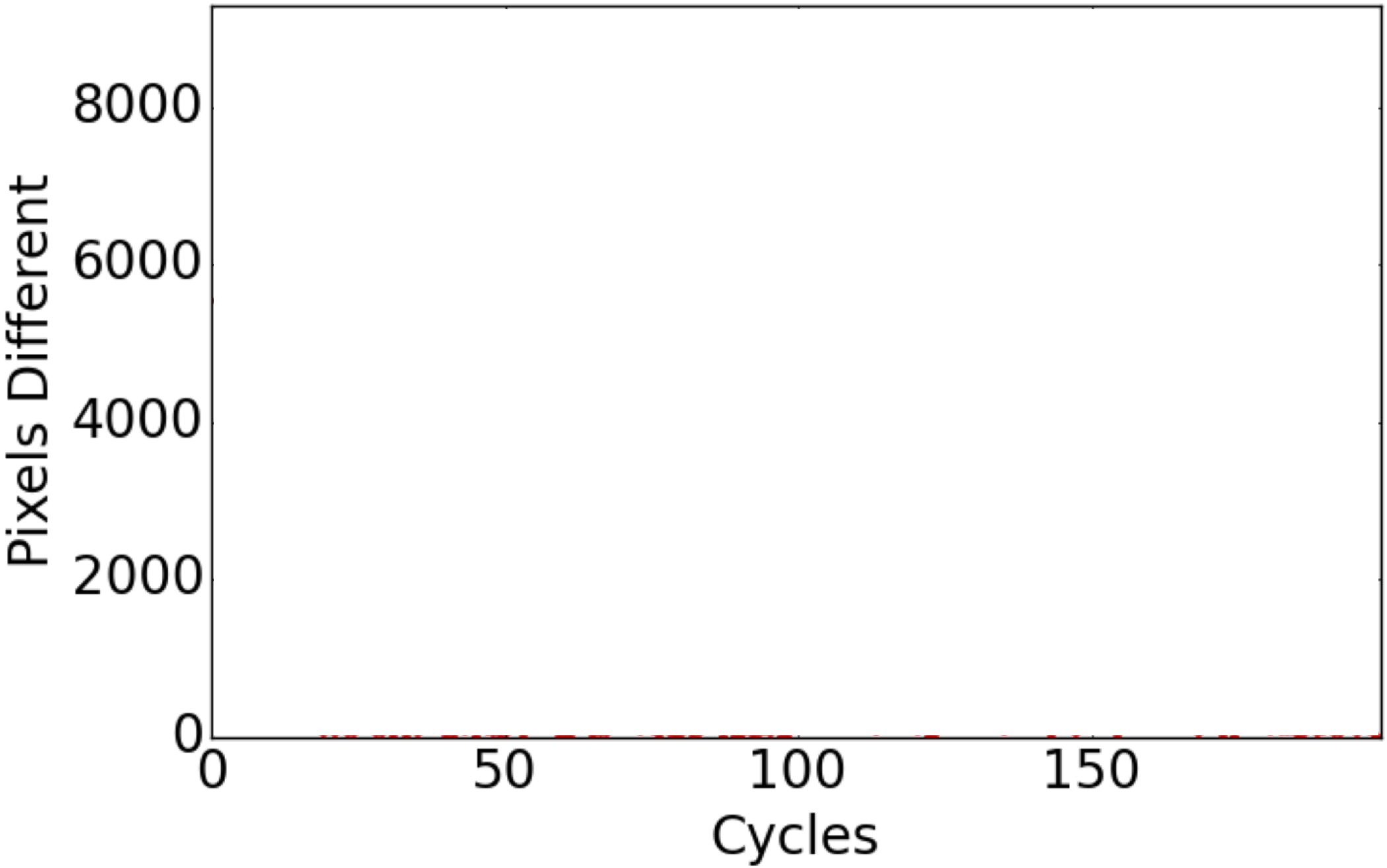
Maybe...

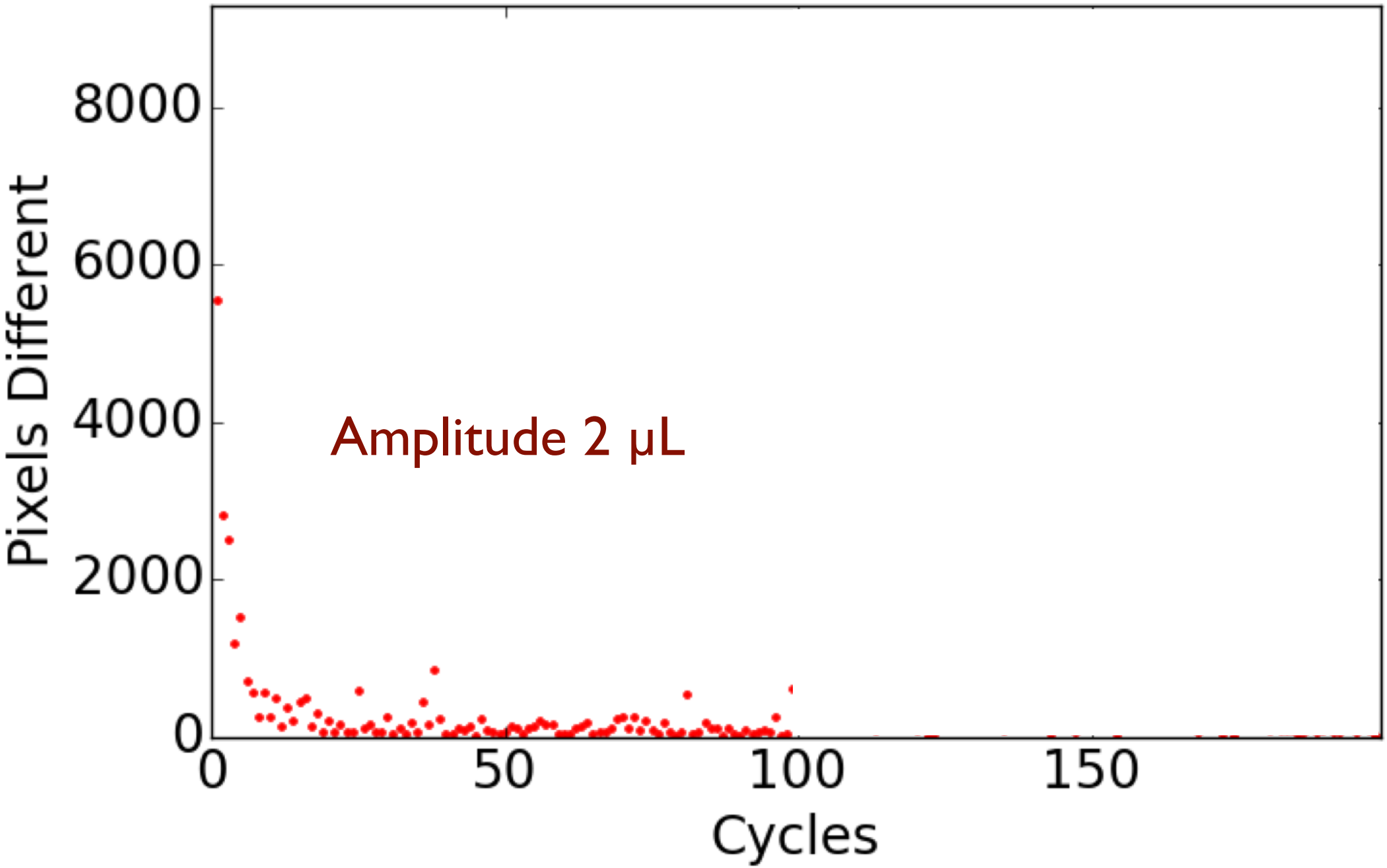

Contact
Line
Needle
Tip
Wet
Dry
1 cm

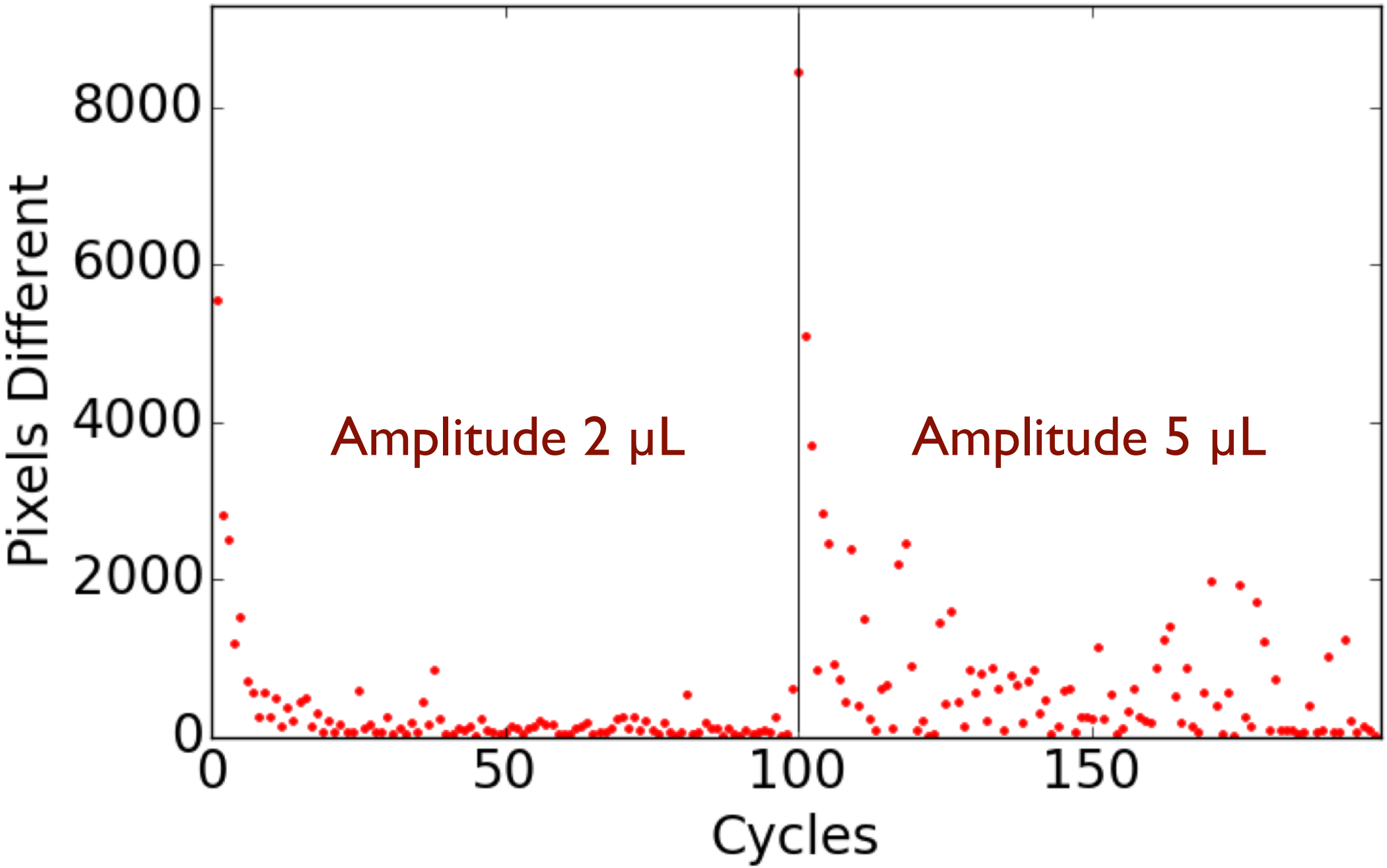


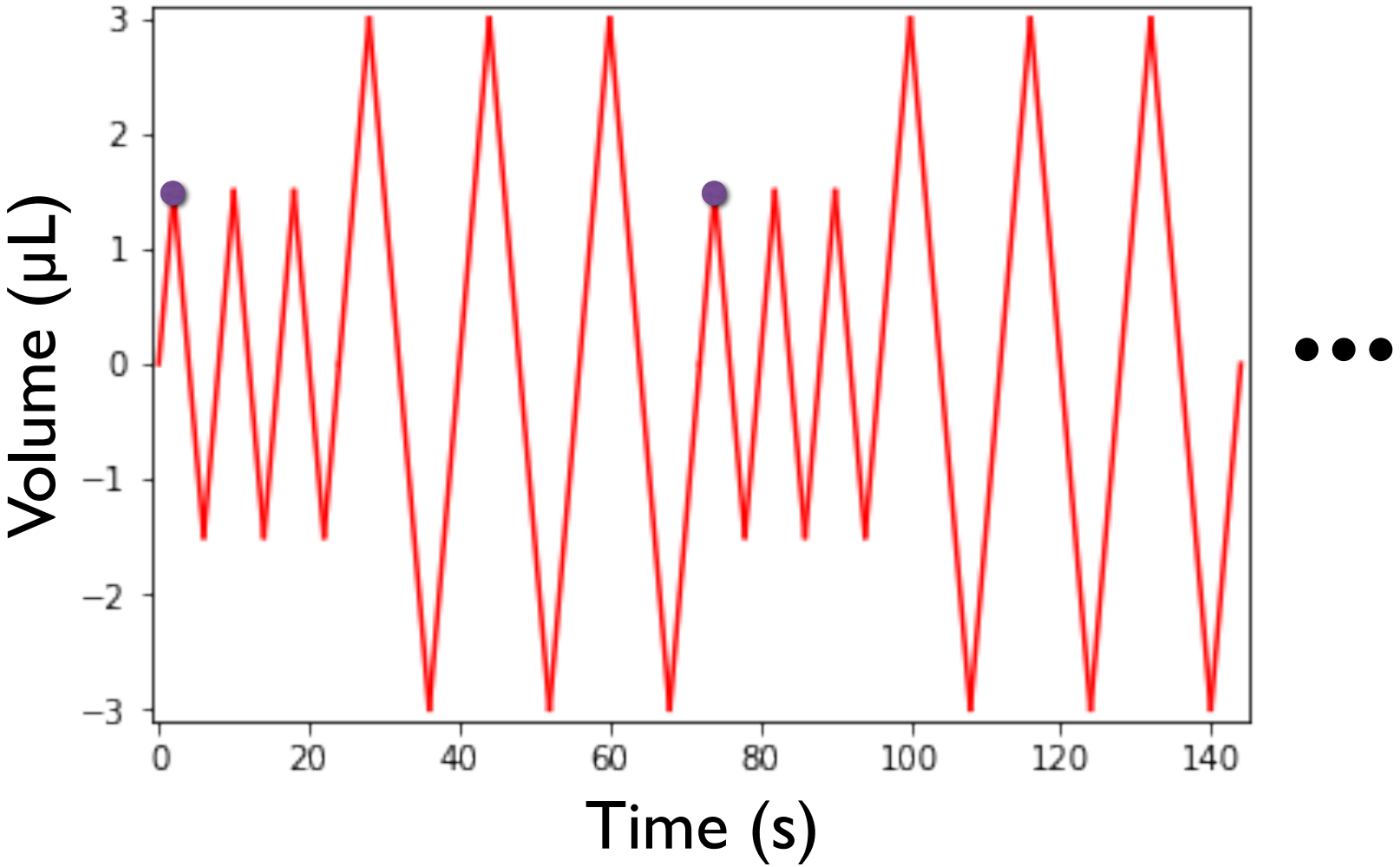


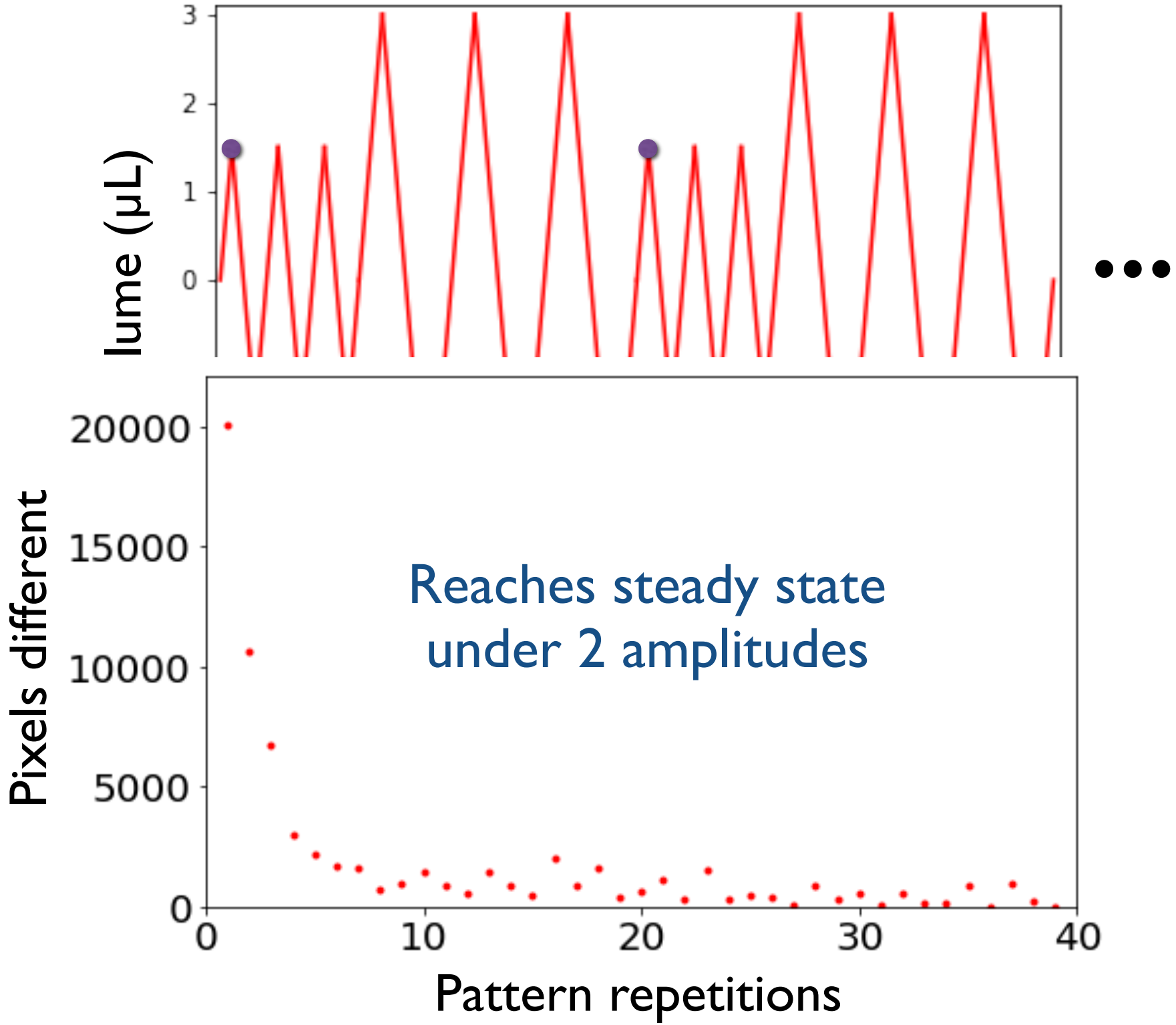

Re ~ 0.01
Ca ~ 2 × 10⁻⁶

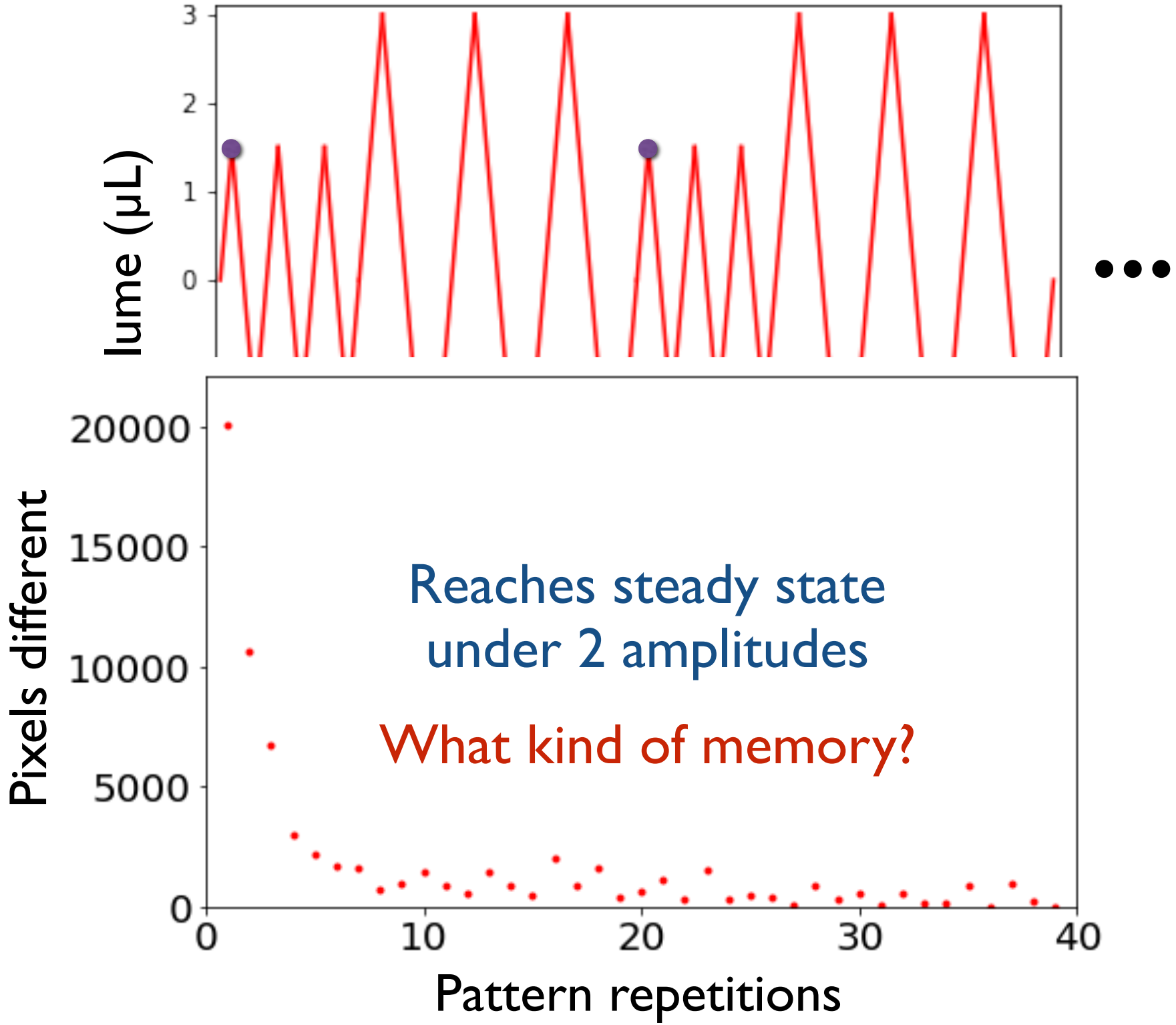

8000
6000
4000
2000
0
Pixels Different
0
50
100
150
Cycles


Pixels Different
8000
6000
4000
2000
0
Amplitude 2 µL
0
50
100
150
Cycles


Pixels Different
8000
6000
4000
2000
0
0
50
100
150
Cycles
Amplitude 2 µL
Amplitude 5 µL


Volume (µL)
3
2
1
0
−1
−2
−3
0
20
40
60
80
100
120
140
Time (s)


lume (µL)
3
2
1
0
Pixels different
20000
15000
10000
5000
0
0
10
20
30
40
Pattern repetitions
Reaches steady state
under 2 amplitudes


lume (µL)
3
2
1
0
Pixels different
20000
15000
10000
5000
0
0
10
20
30
40
Pattern repetitions
Reaches steady state
under 2 amplitudes
What kind of memory?

Conclusions

- Cyclic memory comes in different classes

Funding: NSF DMR-1708870, CBET 1702352;
Cal Poly RSCA Grant; Bill & Linda Frost Fund
Thanks: Tom Witten, Paulo Arratia, Kevin Thompson

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- Cyclic memory comes in different classes
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  - Memory appears to be stored locally

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  - Two classes of memory in one system?

"Cyclic Memory Formation" ⟷ Return-Point Memory

Is there transition/crossover?

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Rearrangements in transient ⟷ Rearrangements in steady state

Crossover involves irreversibility, yielding, role of interactions

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- Contact line: Test ideas about cyclic memory

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