Multiple memory formation
in a
sheared non-Brownian suspension

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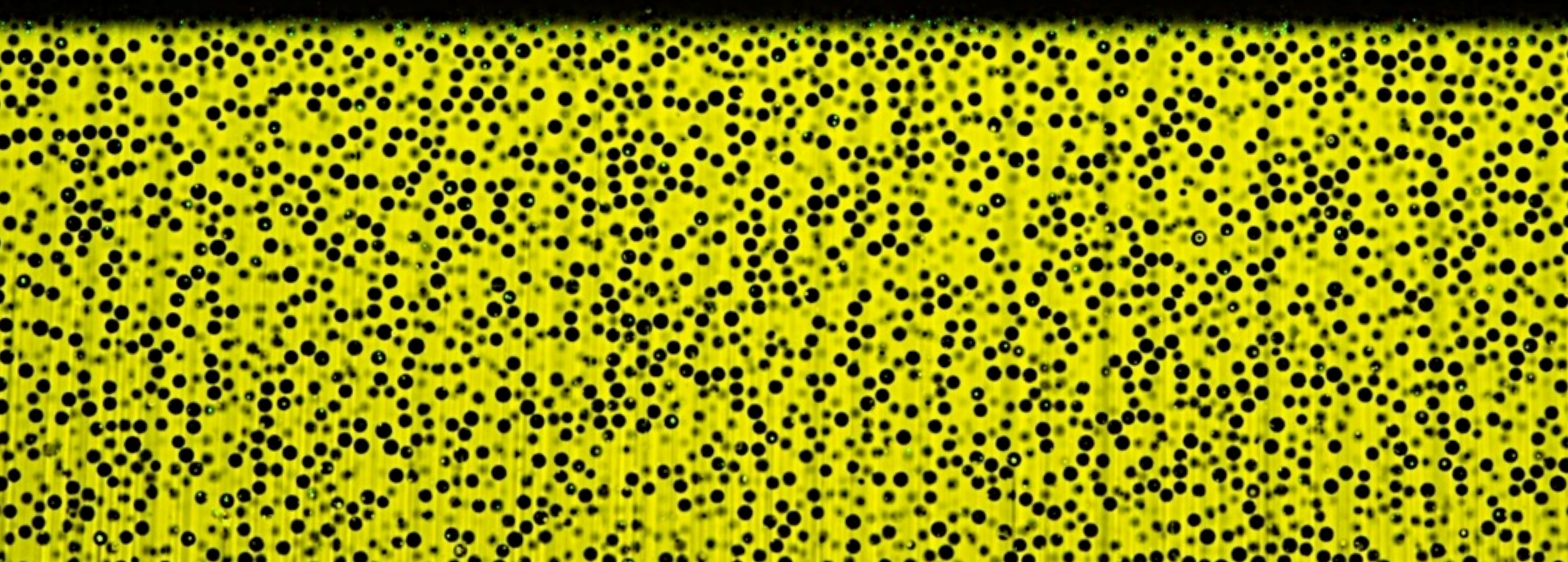
Joseph Paulsen

Syracuse University, Syracuse, NY



This Talk:

Memories in a sheared suspension

Keim & Nagel, PRL 2011

Robustness, structure, plasticity

Keim, Paulsen, & Nagel, PRE 2013

Experiments

Paulsen, Keim, & Nagel, PRL 2014

Related Work:

Glassy behavior in 1D model

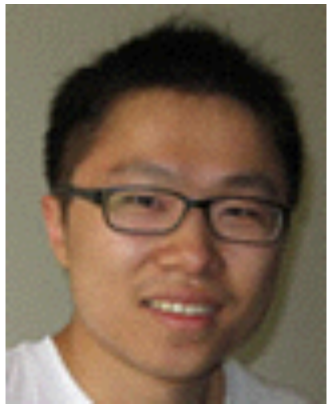
Paulsen & Nagel, J Stat Phys 2017

Shear + sedimentation leads to hyperuniform states

Wang, Schwarz, & Paulsen, *Under review*

Sidney Nagel, UChicago

Nathan Keim, UChicago
Current: Cal Poly, San Luis Obispo



Jikai Wang, Syracuse

Jen Schwarz, Syracuse

Not This Talk:

Geometry & mechanics of thin sheets

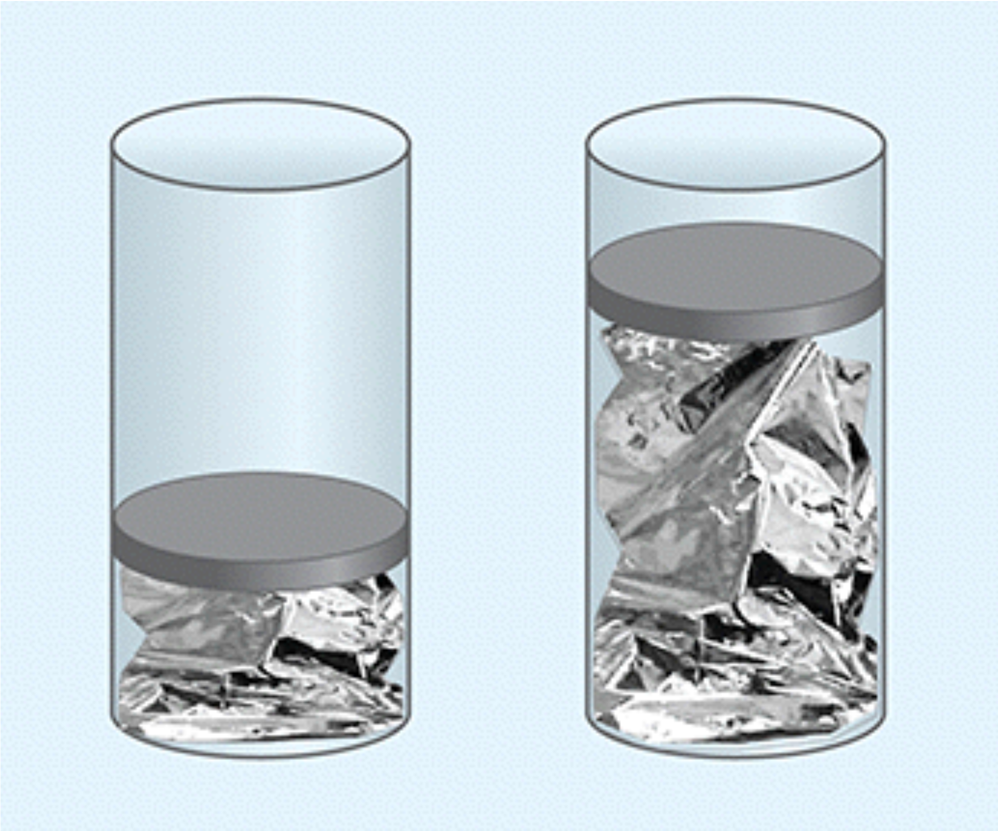
Nat Mater 2015, PNAS 2016, PRL 2017

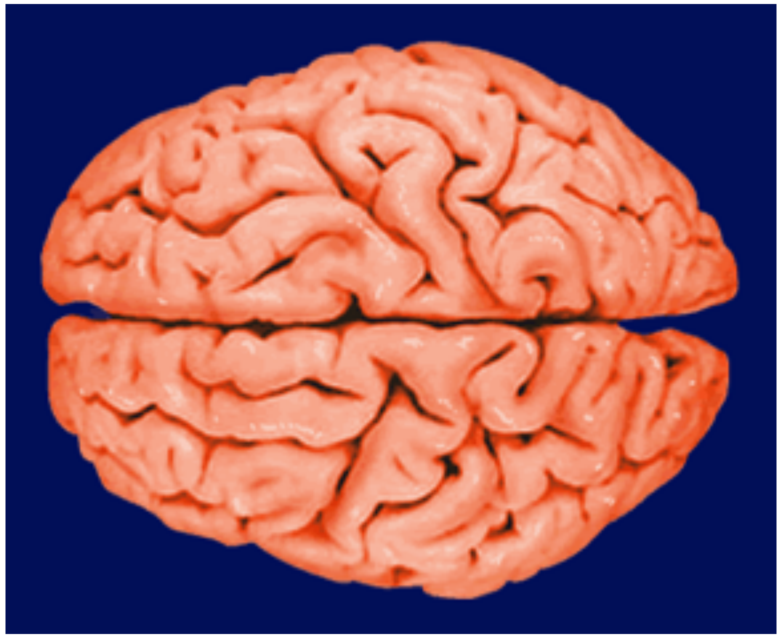
Paulsen, Ripp, Zhang (Syracuse)
Davidovitch, Menon, Russell (UMass)
Démery (ESPCI)
Vella (Oxford)

Not Even Me:

Memory in a crumpled sheet

Lahini et al., PRL 2017
(*Physics viewpoint* by Nathan Keim)

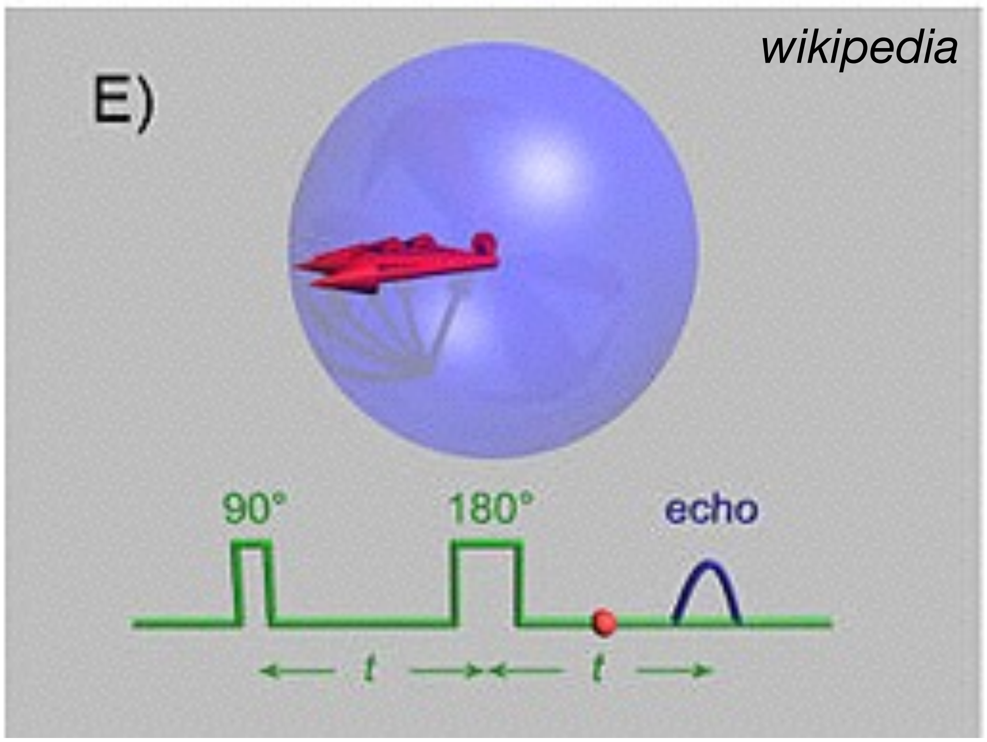




*A **memory** is a capacity for encoding, storing, and retrieving pieces of information*

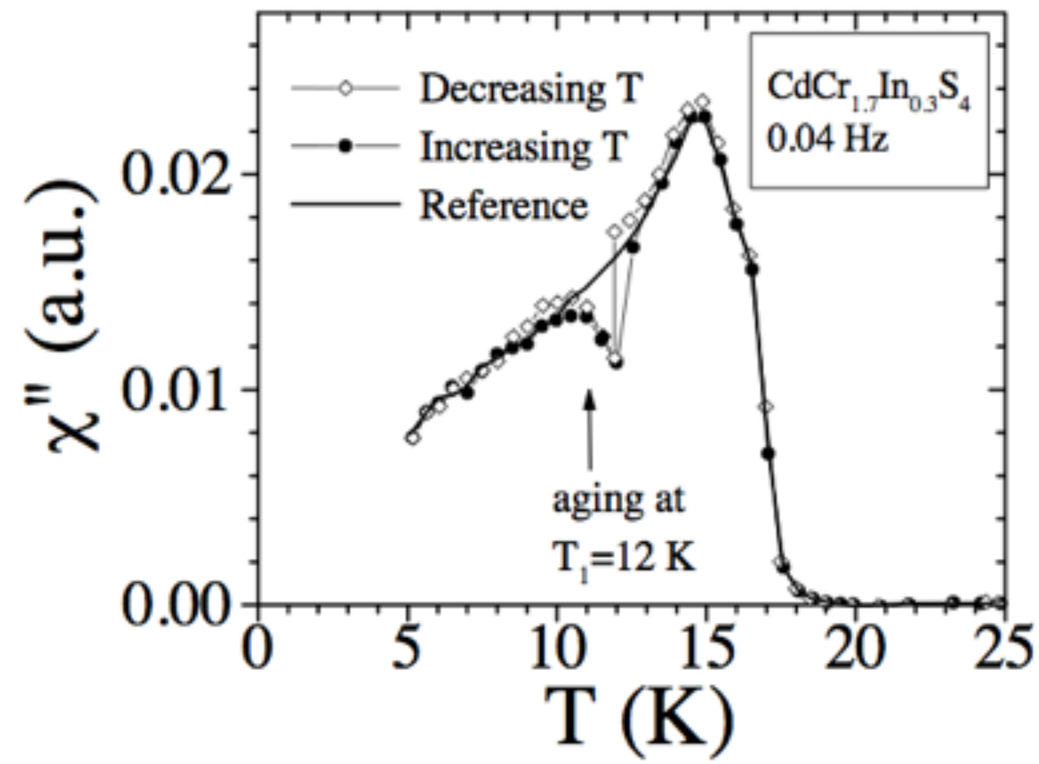
Spin-echo

Hahn 1950, Carr & Purcell 1954



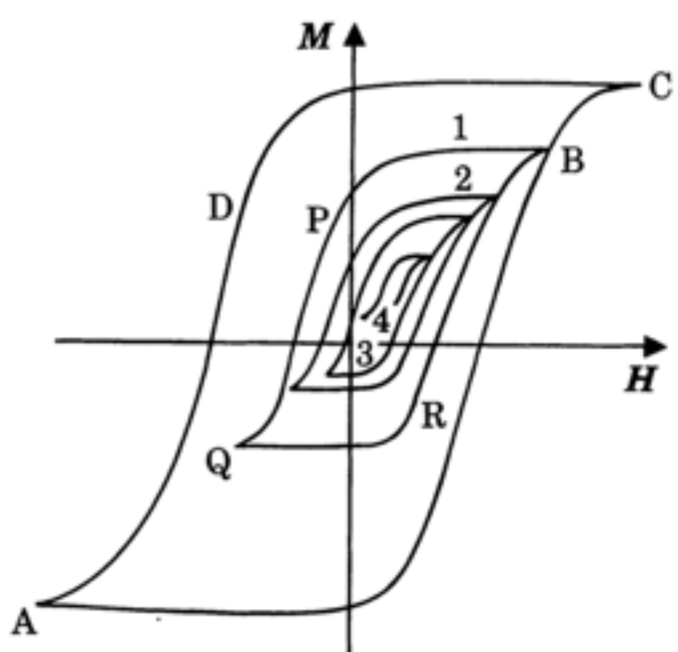
Aging & rejuvination in glasses

Jonason et al. 1998



Return point memory

Barker et al. 1983



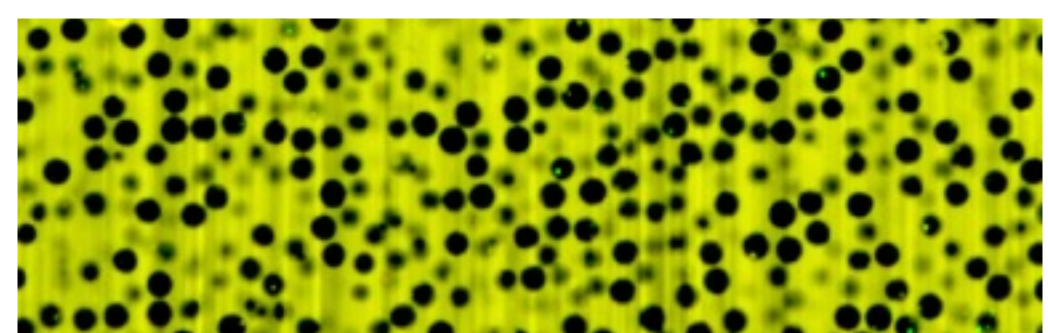
Multiple transient memories

...in charge-density waves

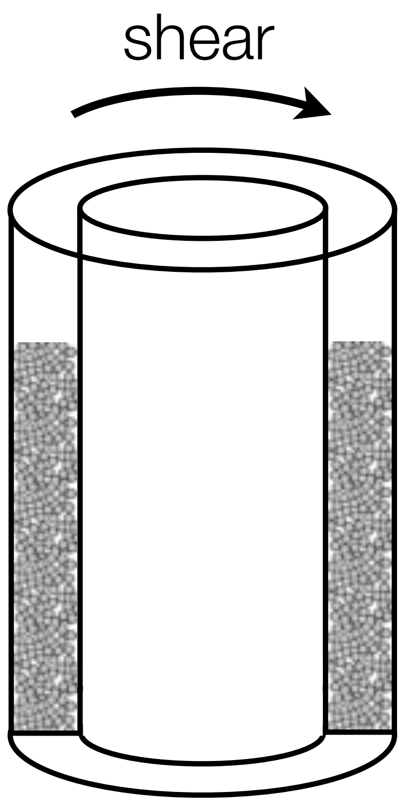
Coppersmith et al. 1997; Povinelli et al. 1999

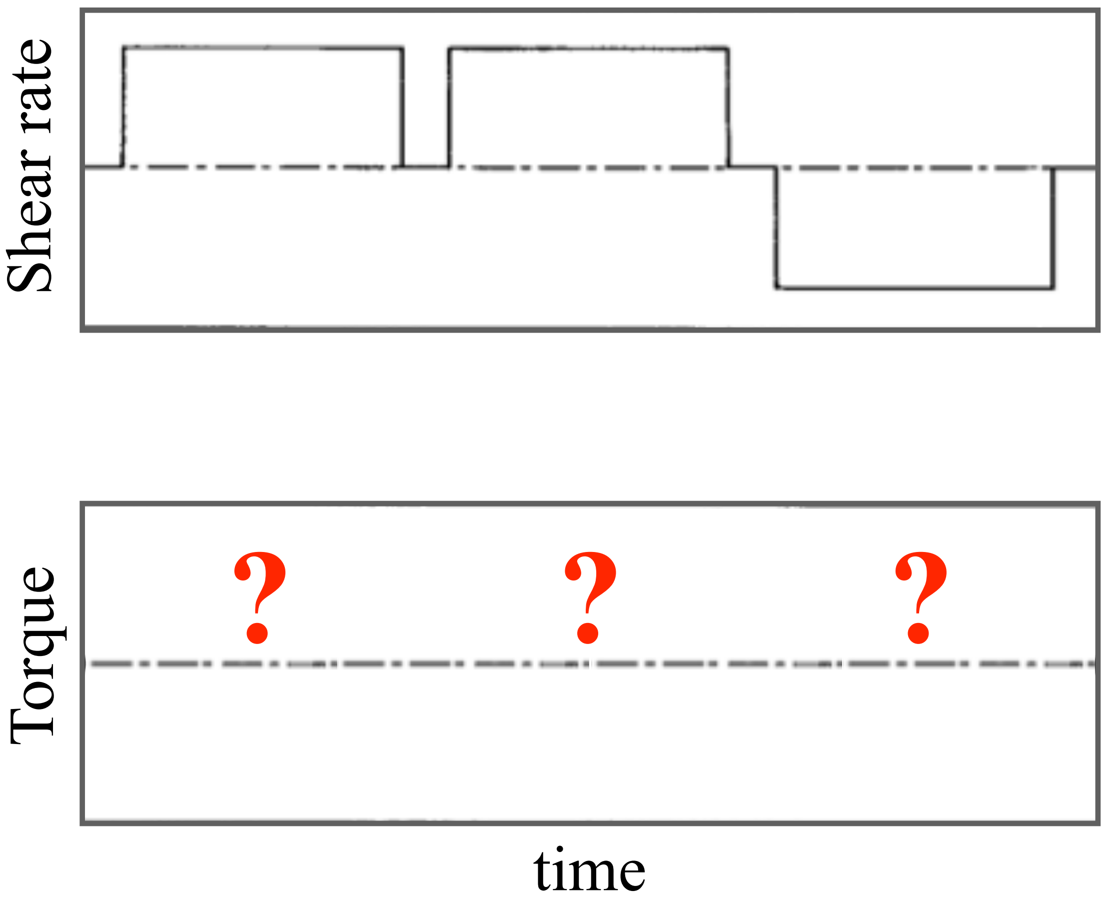
...in a sheared granular suspension

This Talk

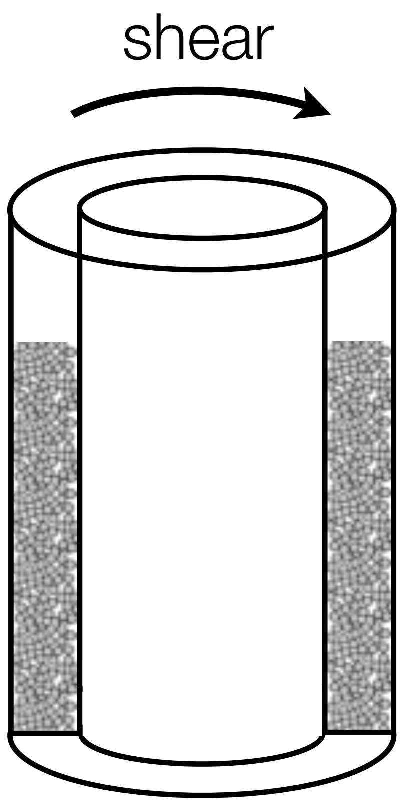


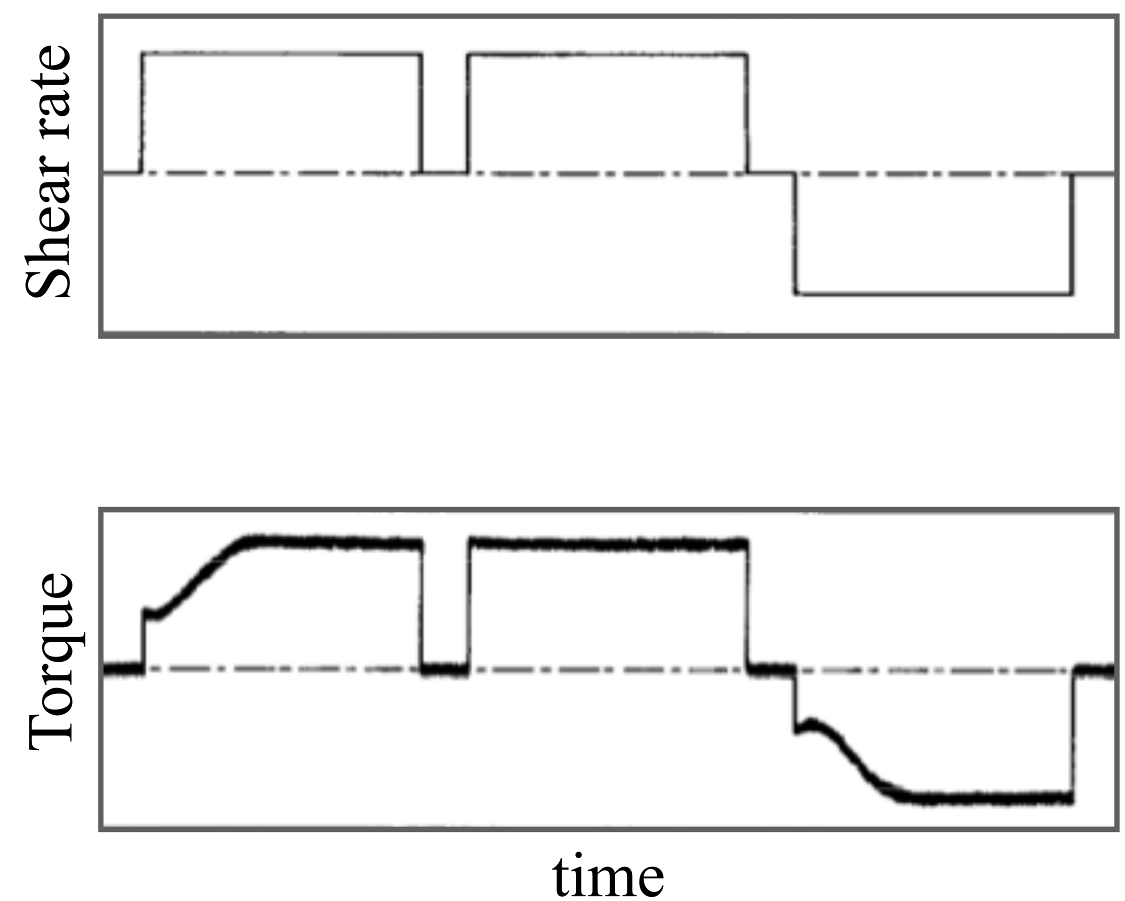
Memory in a pile of sand



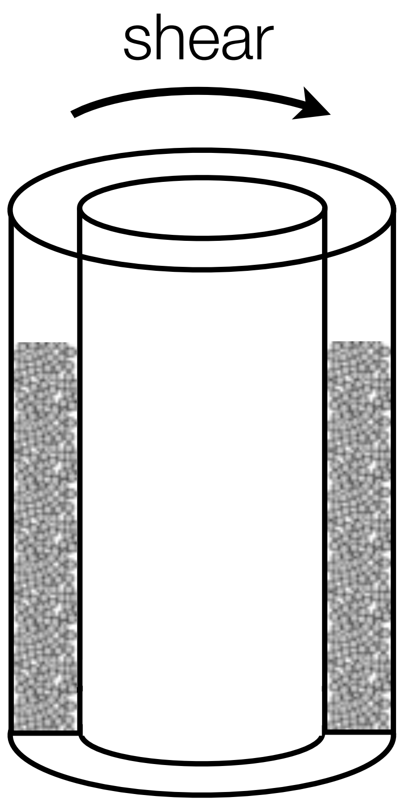


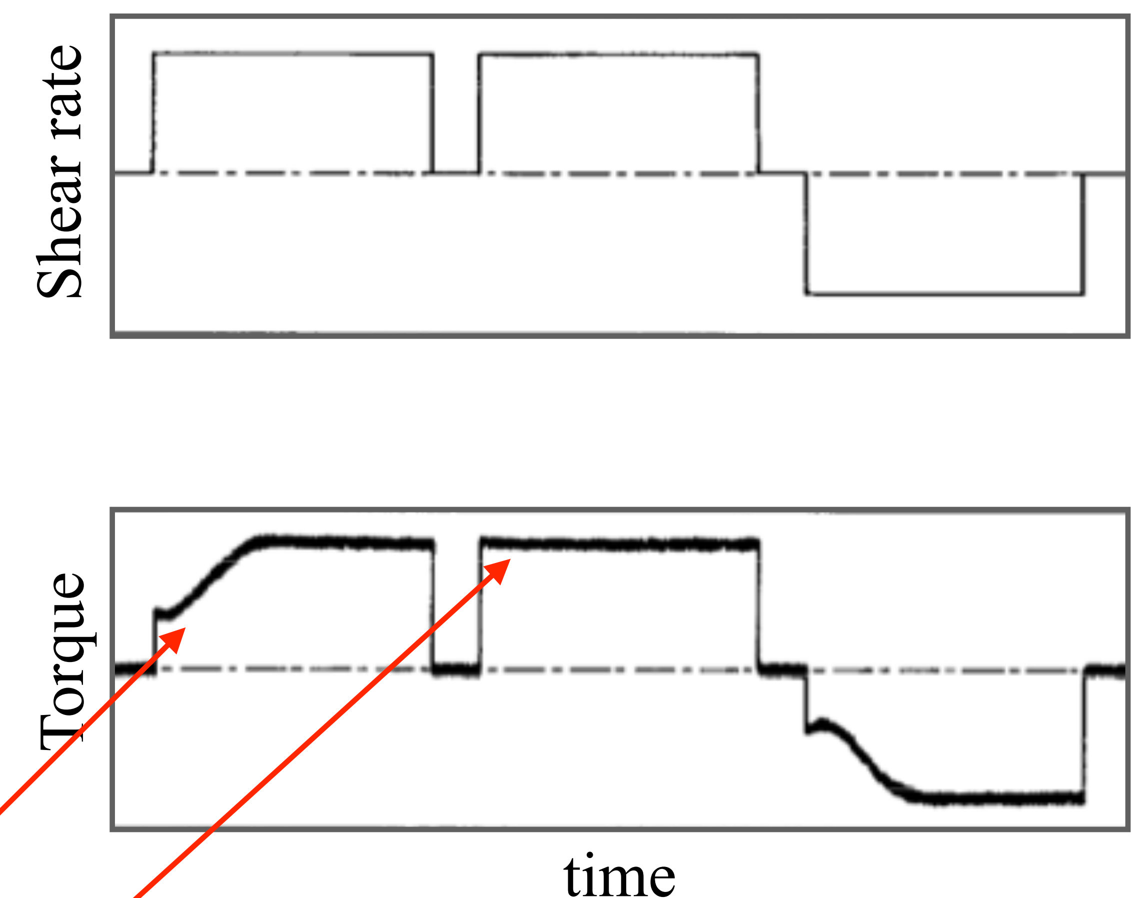
Memory in a pile of sand





Memory in a pile of sand

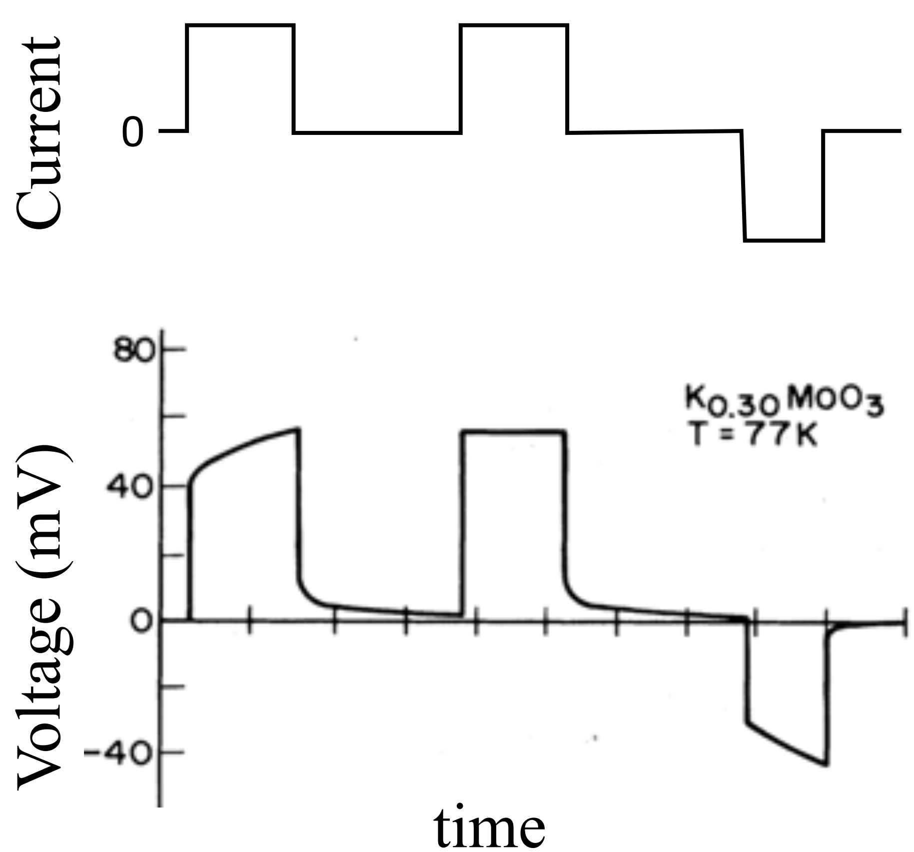




Enzo: "I (am) (am not) going out to dinner with my friends tonight"

A memory of a direction

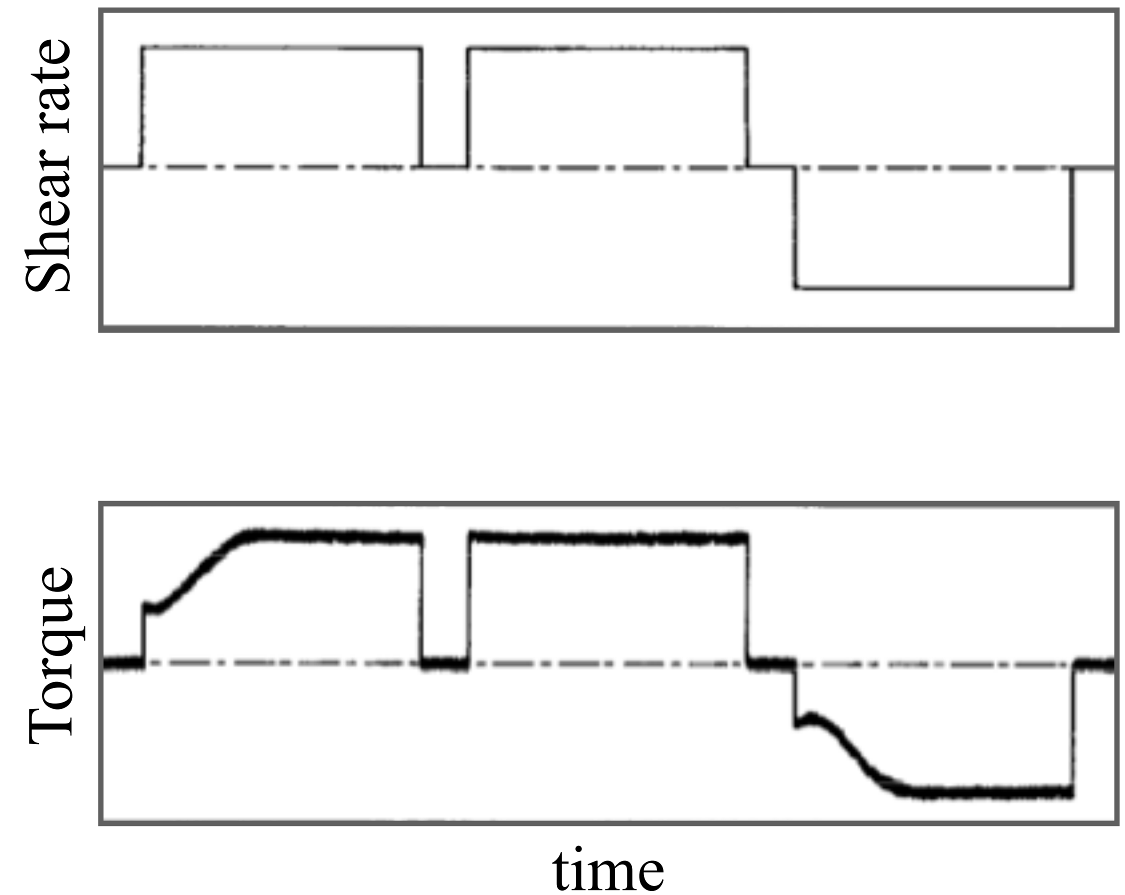
Charge-density waves:



"Pulse-sign memory"

Gill, 1981
Fleming & Schneemeyer, 1983

Granular material:



Sheared suspensions:

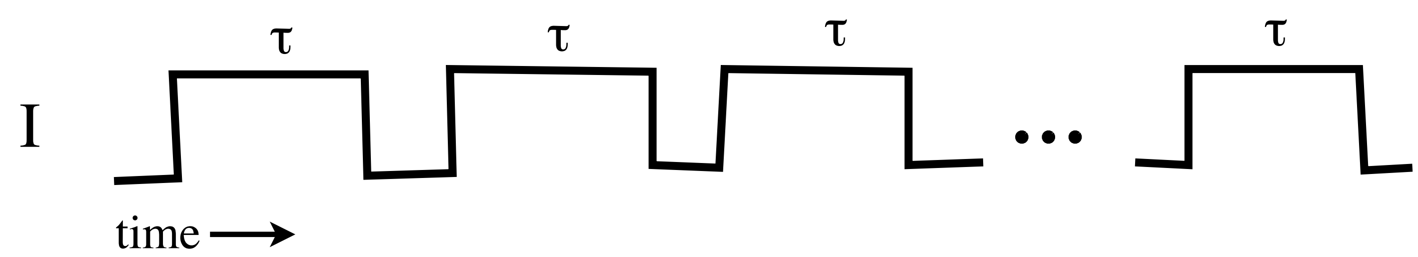
Gadala-Maria & Acrivos, 1980

Dry grains:

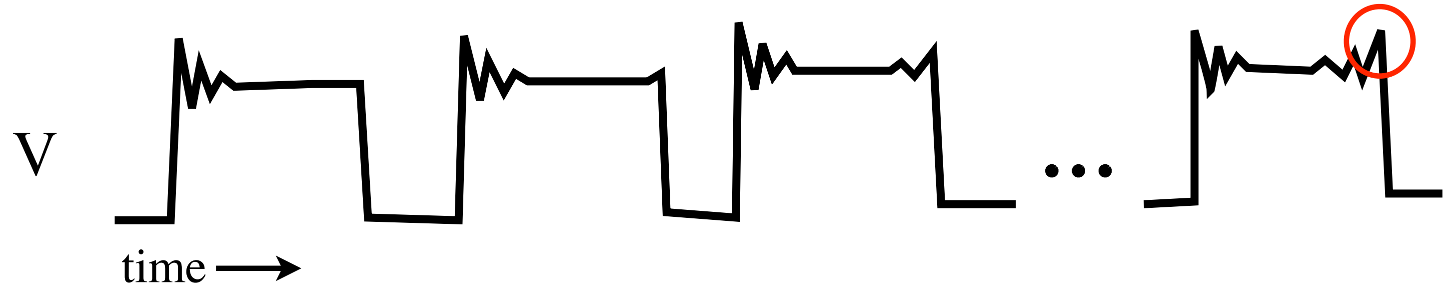
Toiya, Stambaugh, & Losert, 2004

Memories in Charge Density Waves

Input: train of fixed-width current pulses



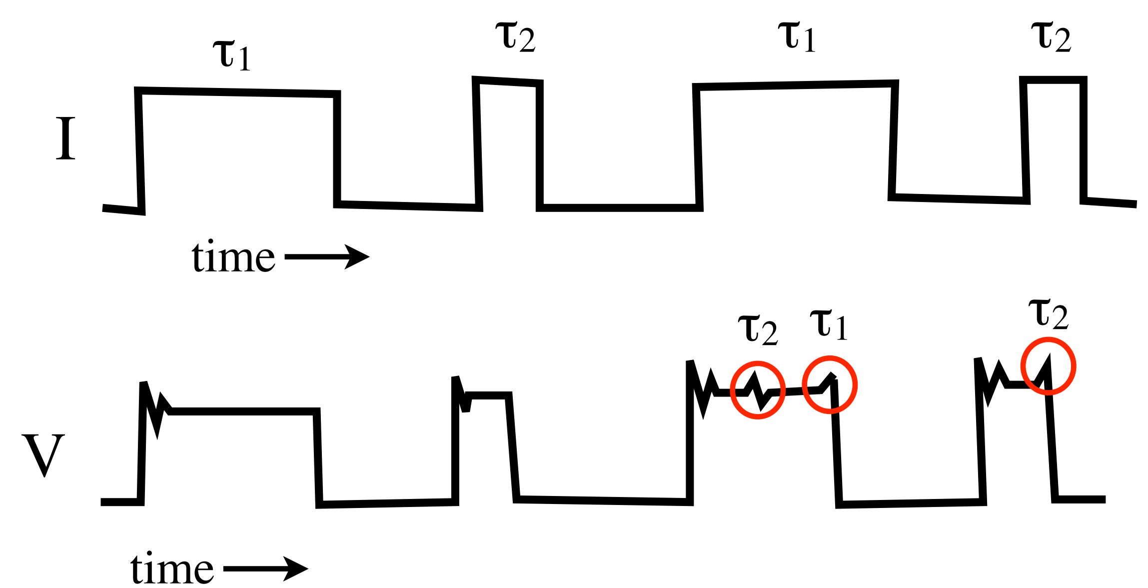
Phase of voltage oscillations *locked to end* of pulse



Brown, Grüner & Mihály, 1986
Fleming & Schneemeyer, 1986
Coppersmith & Littlewood, 1987

Memories in Charge Density Waves

Multiple memories:



Simulations: *forget all but longest, shortest* pulse widths

+Noise: remember all

Experiments: retained all memories

Coppersmith, Jones, Kadanoff, Levine, McCarten, Nagel, Venkataramani & Wu, 1997

Povinelli, Coppersmith, Kadanoff, Nagel & Venkataramani, 1999

*What do we **expect** of a memory?*

- The more times you (re-)write, the stronger the memory
- Random noise garbles memory

Transient Memories violate both!

- System *learns* multiple inputs
- Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

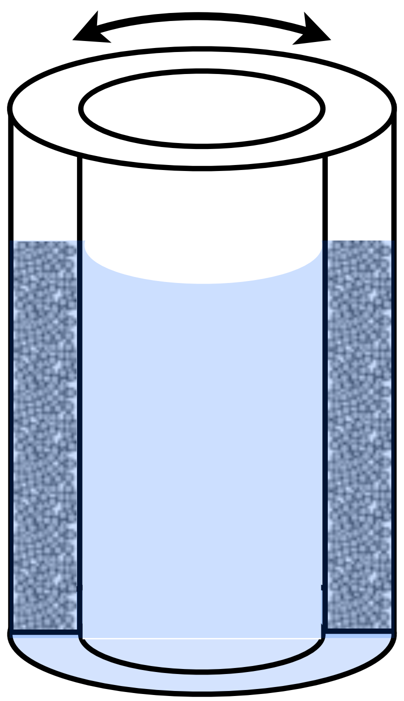
- *Is this memory generalizable, or specific to CDWs?*
- *How would we find it in other systems?*
- ***Clue:** memory is in a **steady-state***

Hydrodynamic Reversibility of Stokes Flows

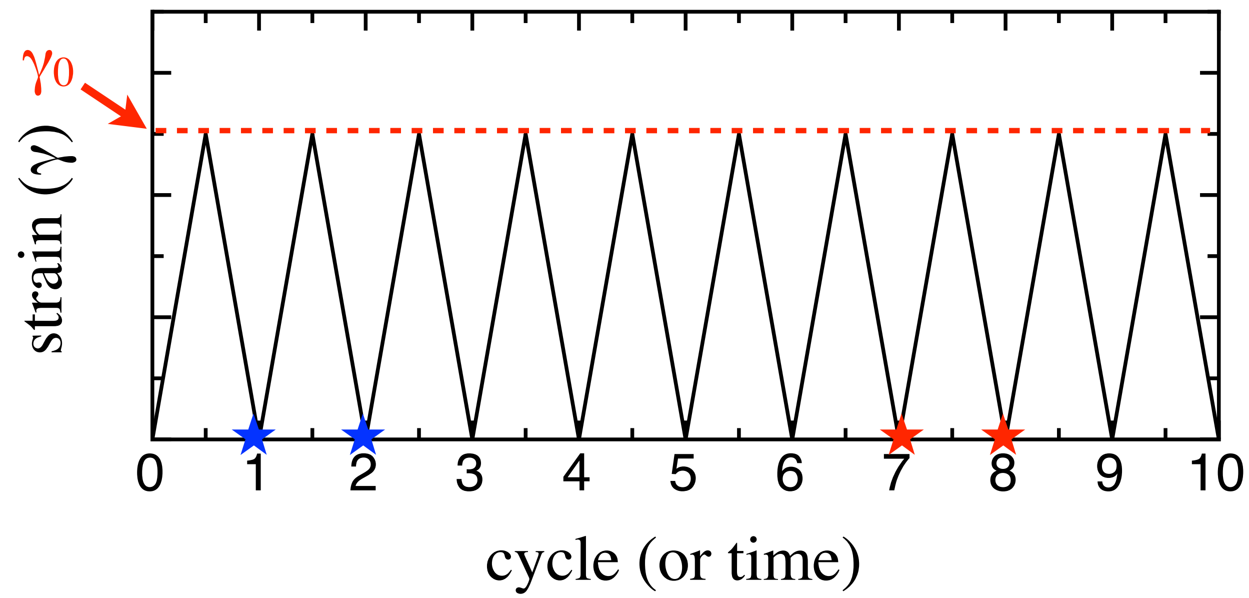
Hydrodynamic Reversibility of Stokes Flows

*Sheared suspension of **particles***

Pine, Gollub, Brady & Leshansky, 2005
Corté, Chaikin, Gollub & Pine, 2008



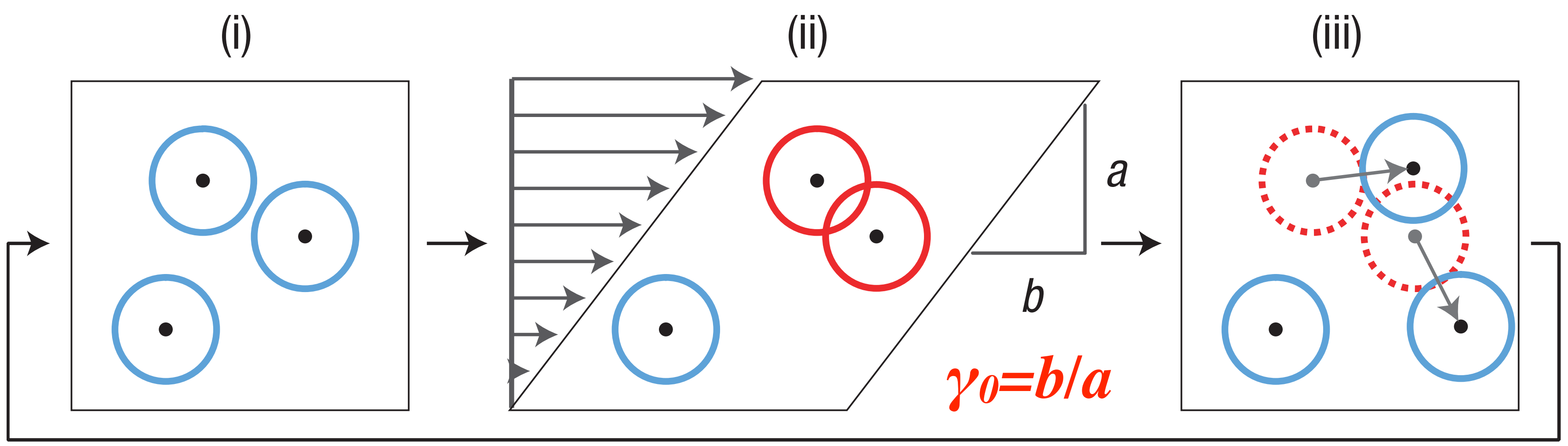
- Particles destroy reversibility for first cycles
- For small enough γ, finds **reversible steady-state**



***Stroboscopic imaging*:**
Compare particle positions after each cycle

A ***model*** showing transient irreversibility:

Corté, Chaikin, Gollub & Pine, 2008



Random initial state, area fraction ϕ

cycle

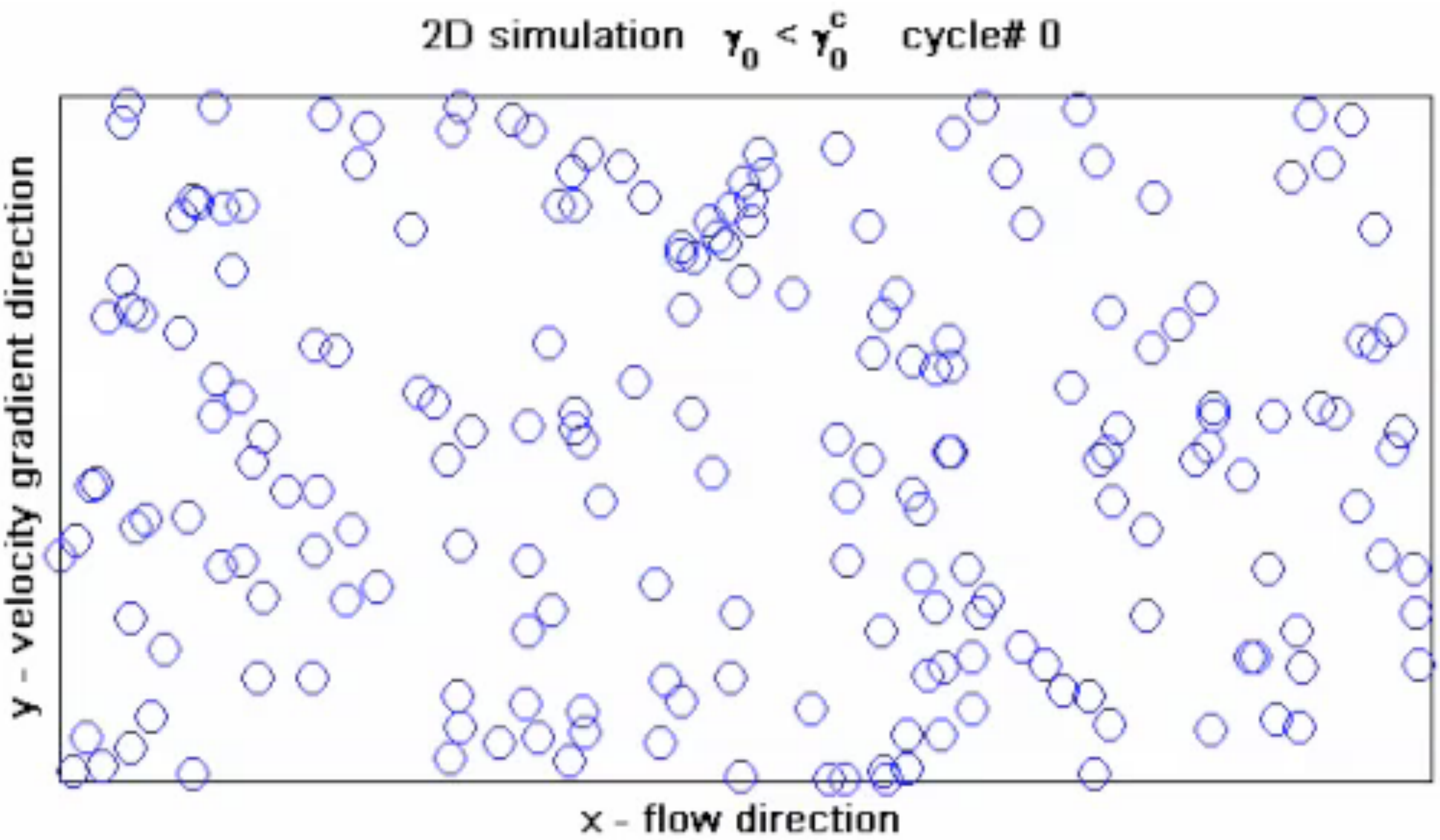
(i) Particles at $\gamma=0$

(ii) Shear by strain amplitude γ_0, tag particles that collide

(iii) Shear back to $\gamma=0$,
Give tagged particles a small random kick

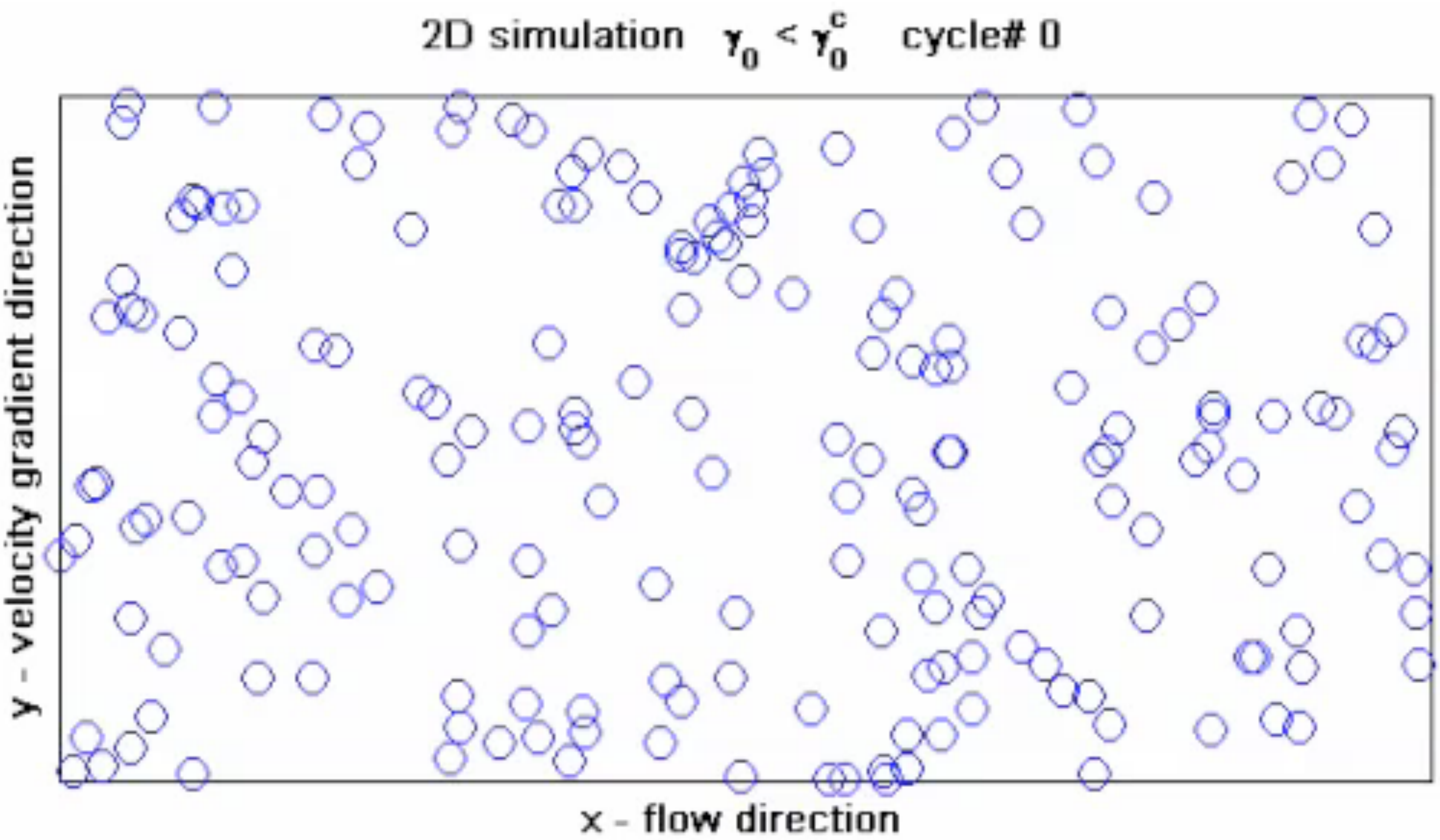
Stroboscopic video of particle positions

Corté, Chaikin, Gollub & Pine, 2008

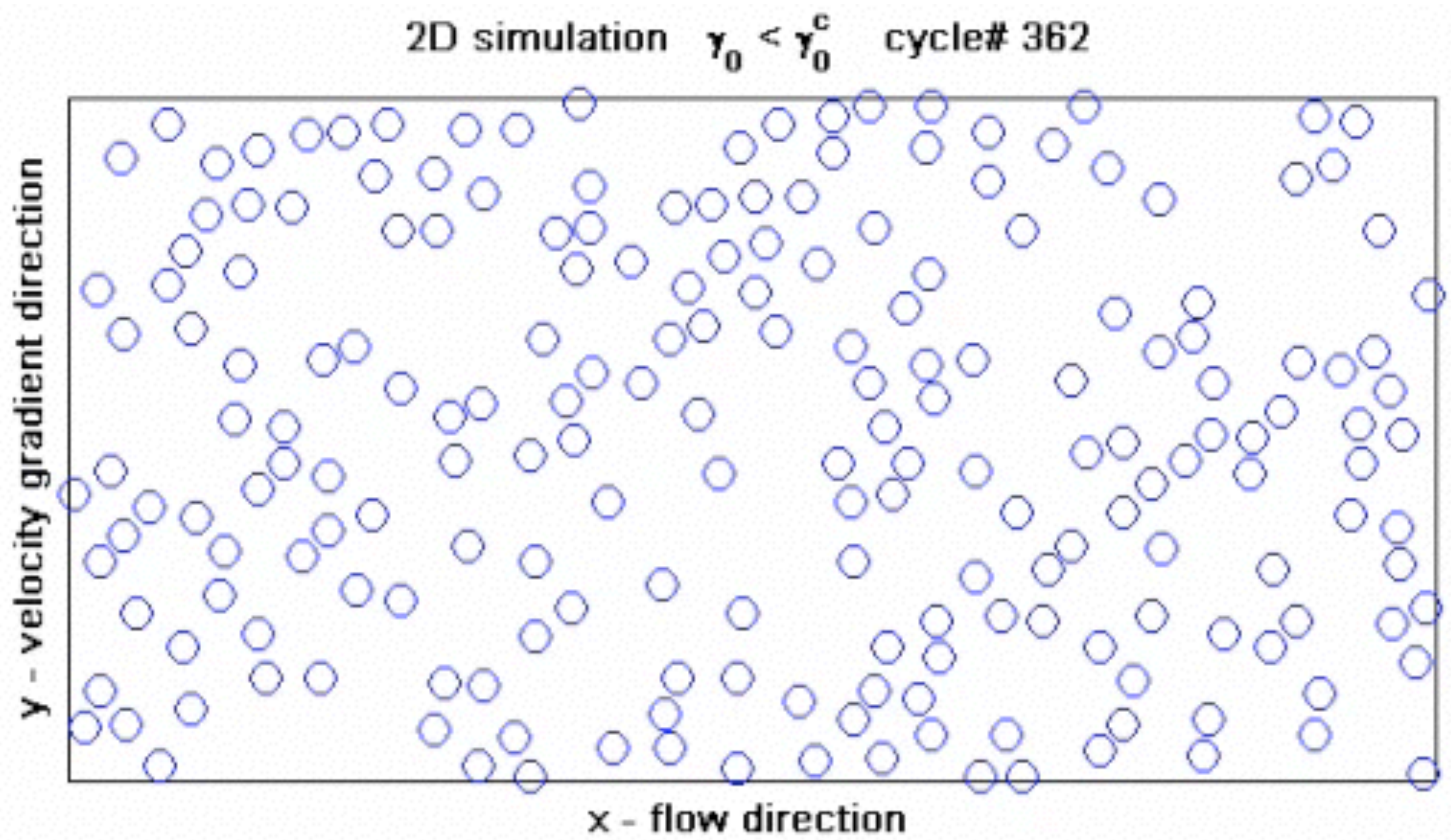


Stroboscopic video of particle positions

Corté, Chaikin, Gollub & Pine, 2008



Reversible steady state is a **memory of γ_0**

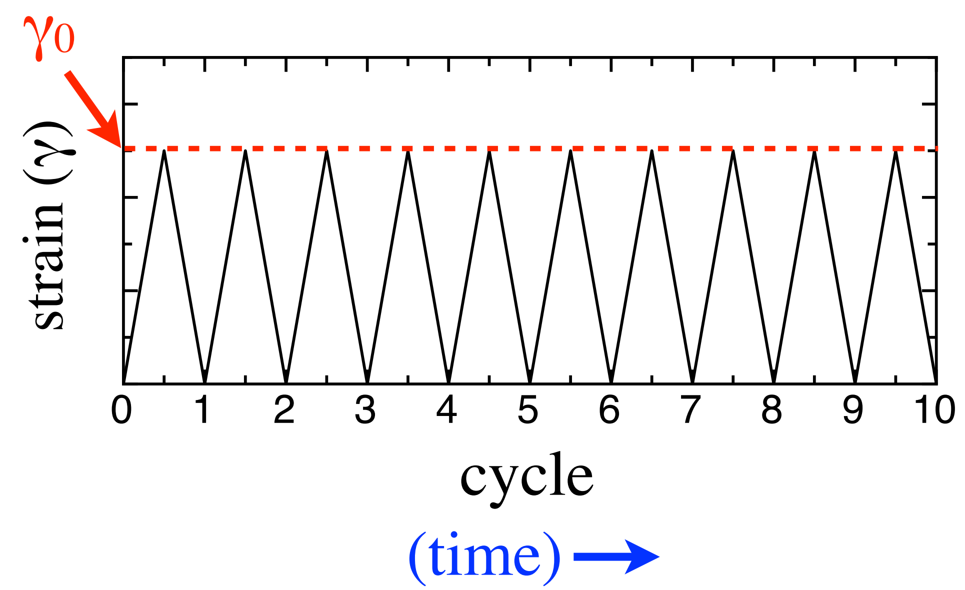


- Reversible up to γ_0
- Some particles will collide if we now shear to $\gamma_0+\varepsilon$

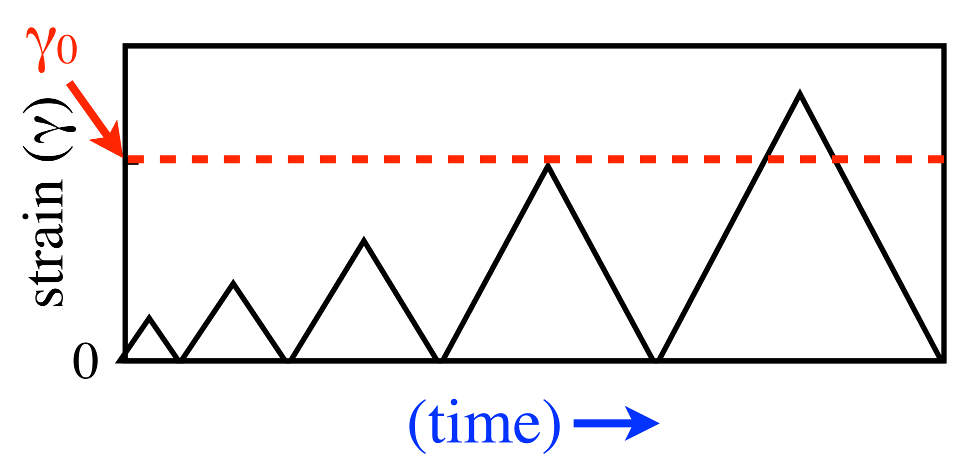
Writing and reading a single memory

Keim & Nagel, PRL 2011

1. Training



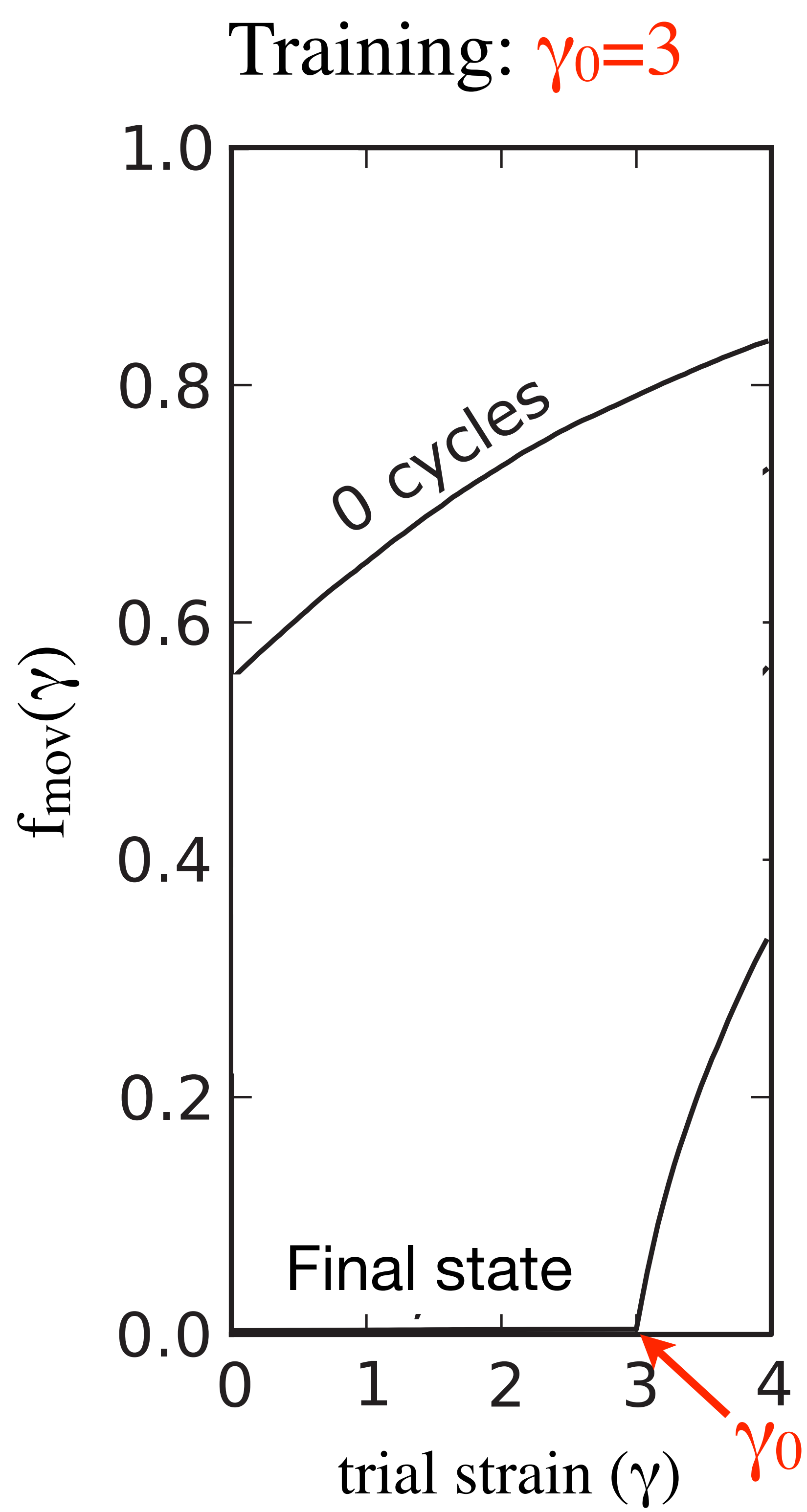
2. Readout



$f_{mov}(\gamma)$: Fraction of particles that collide at trial shear of γ

Single Memory: 2D Simulation

Keim & Nagel, PRL 2011



Shown: Toy model 'learns' single memory in steady-state

Will show: Toy model can learn multiple memories…

…forgets all but largest in steady-state

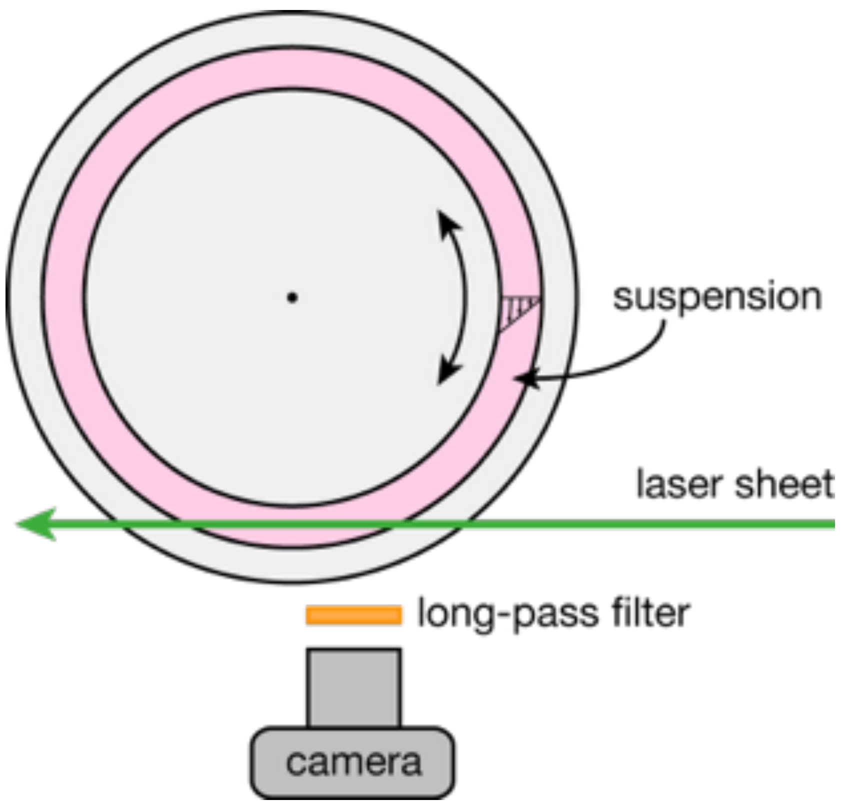
…noise can stabilize all memories

Now: Single memory in experiment

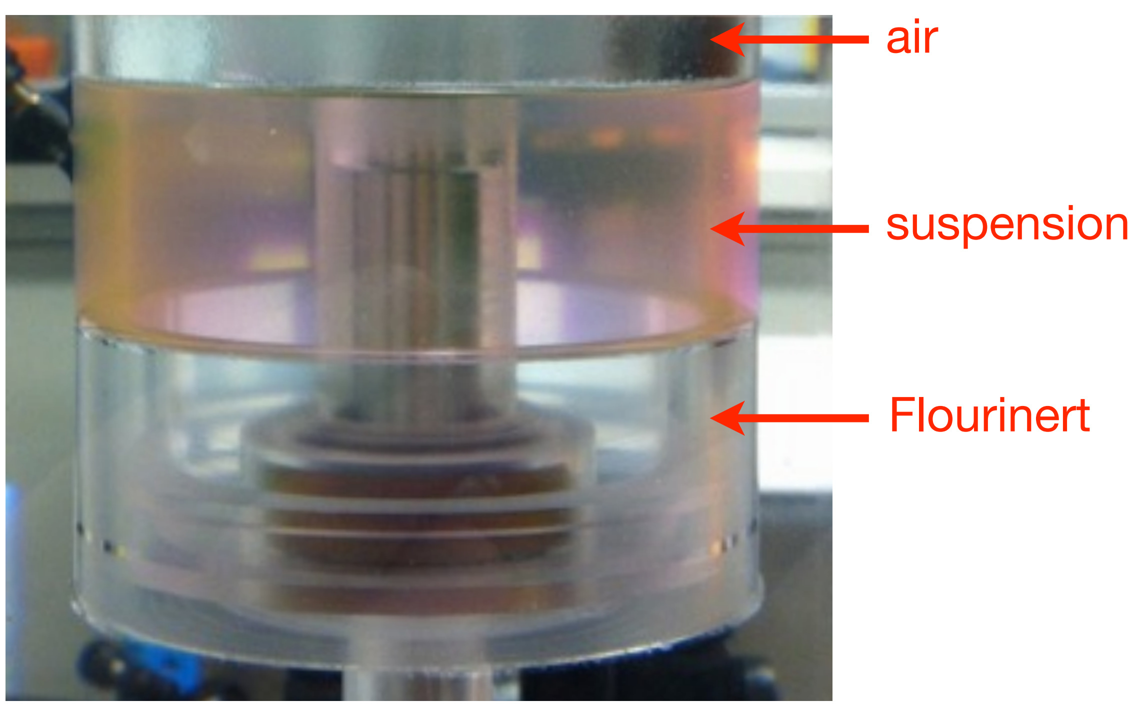
Experiment

A neutrally buoyant, non-Brownian suspension under cyclic, low Reynolds-number shear [1,2]

Top View:

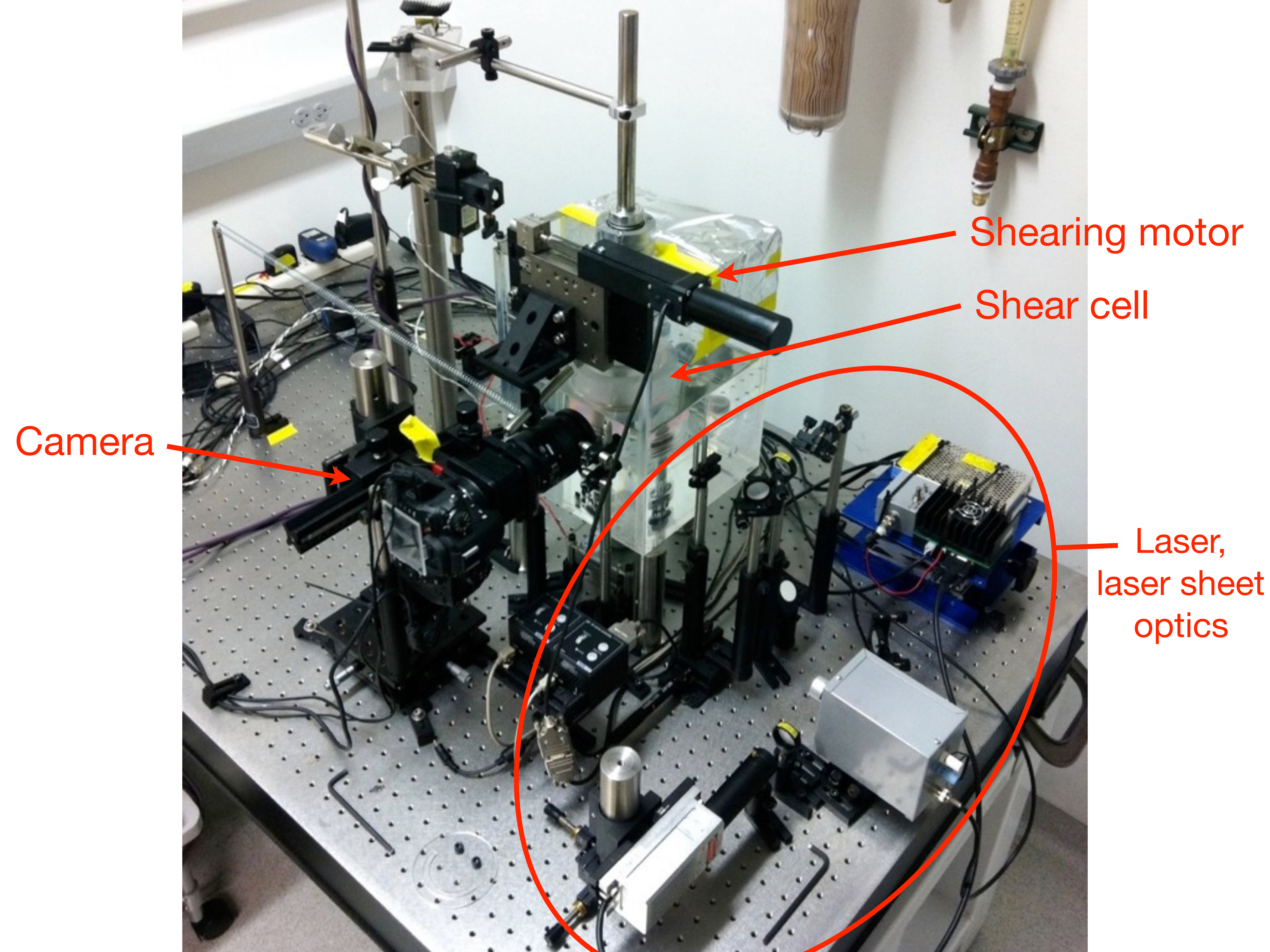


Side View:



- Suspension:
  - -Fluid: Water, $ZnCl_2$, Triton X-100
  - -Particles: PMMA spheres, $d = 106\text{-}125\ \mu m$
  - -Density matched: $(\Delta\rho)/\rho < 10^{-4}$
  - -Fluid viscosity: $\mu \sim 4000$ cP
  - -Volume fraction: $\phi = 0.10$ to 0.45
  - -Refractive index matched
- Geometry/Driving:
  - -Frequency: $f \sim 0.16$ Hz
  - -Péclet number: **Pe ~ 10^9**
  - -Gap: 6 mm
  - -Reynolds number: **Re < 0.007**
- Top & bottom surfaces stress-free:
  - -Suspension floats on Flourinert (μ=24 cP)
  - -Top surface open to air
- Imaging:
  - -Fluid flourescently dyed, laser sheet
- Analysis (particle locating):
  - -Blair implementation of Crocker-Grier code

[1] Pine, Gollub, Brady & Leshansky 2005
[2] Corté, Chaikin, Gollub & Pine 2008


Shearing motor
Shear cell
Camera
Laser,
laser sheet
optics

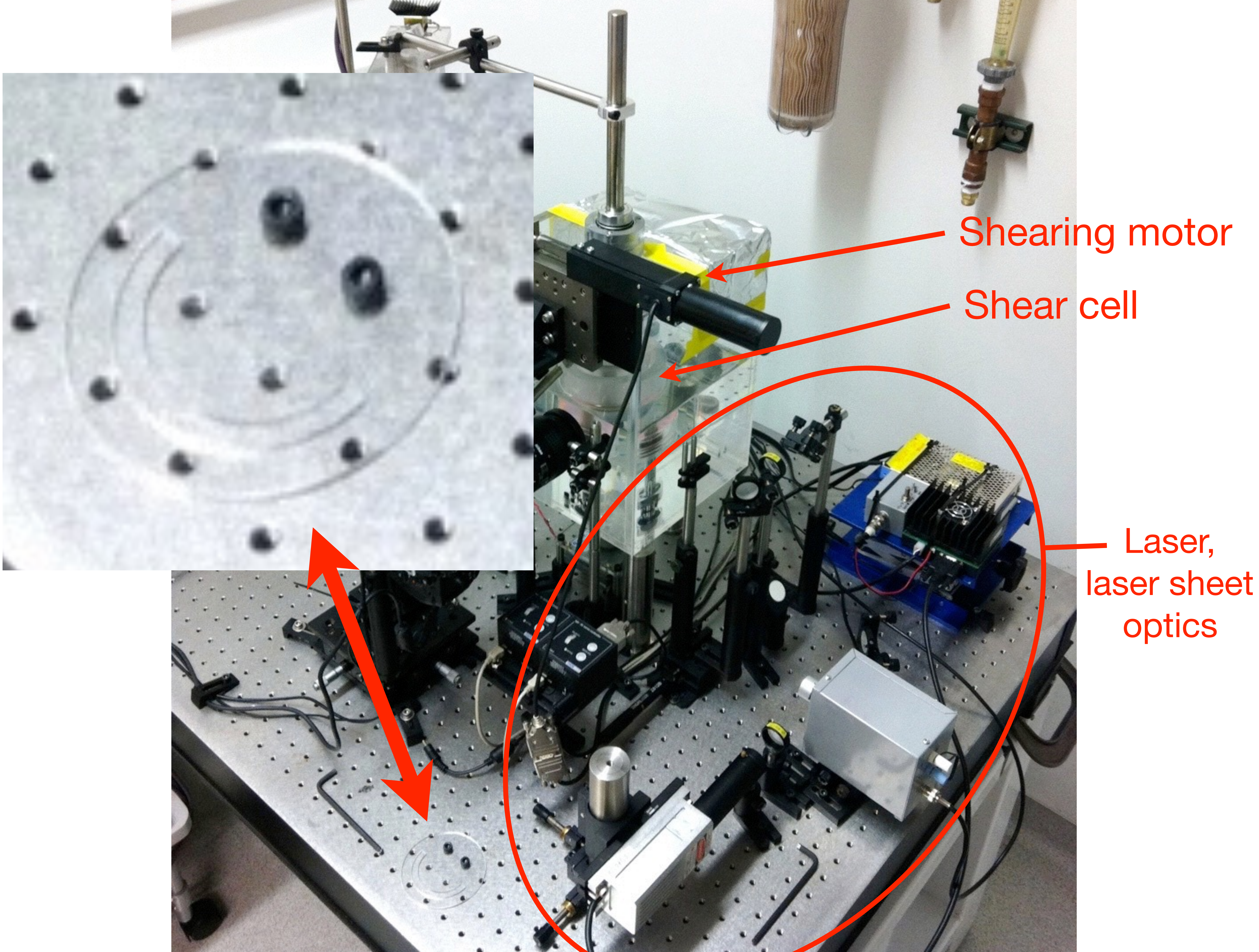
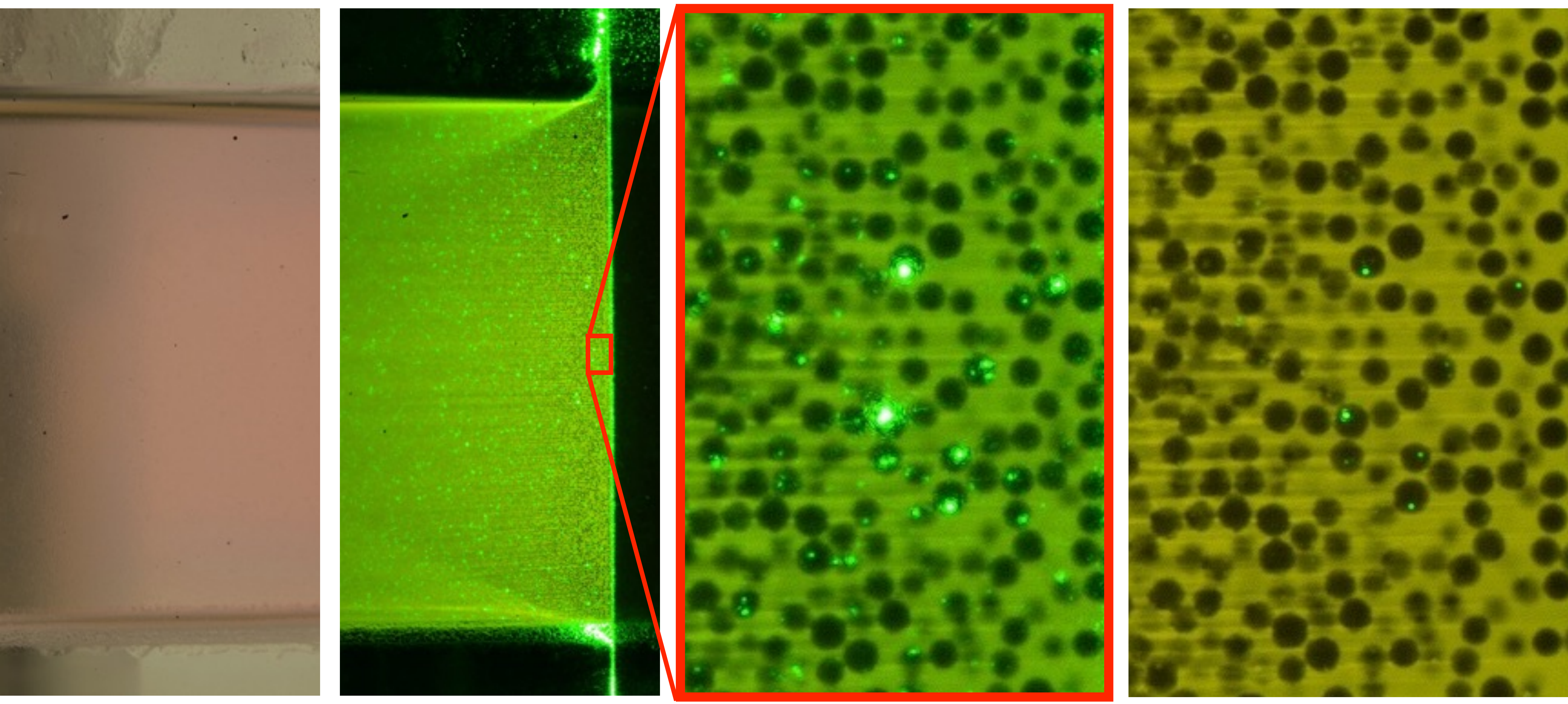

Shearing motor
Shear cell
Laser,
laser sheet
optics

Image 2D Slice

Room lighting: *Laser sheet:* *Zoom:* *Long-pass filter*



“Readout” after 100 training cycles at γ=1.6

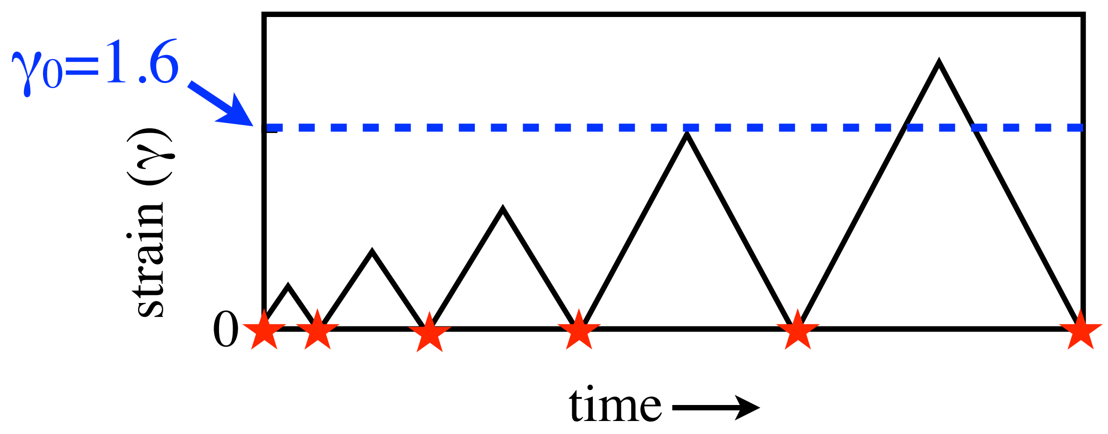
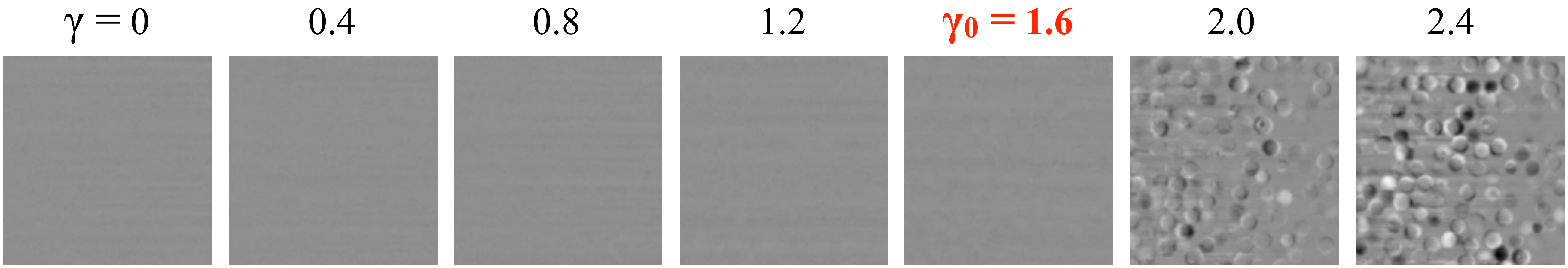
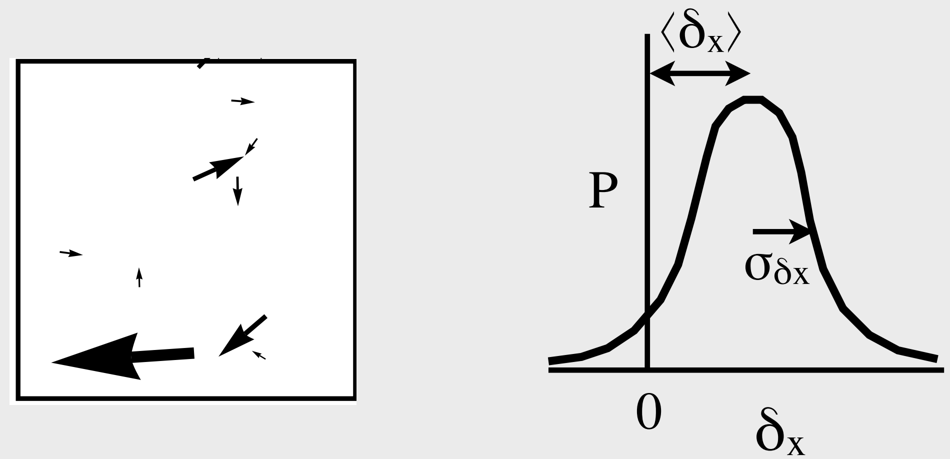


Image subtractions between adjacent ★s



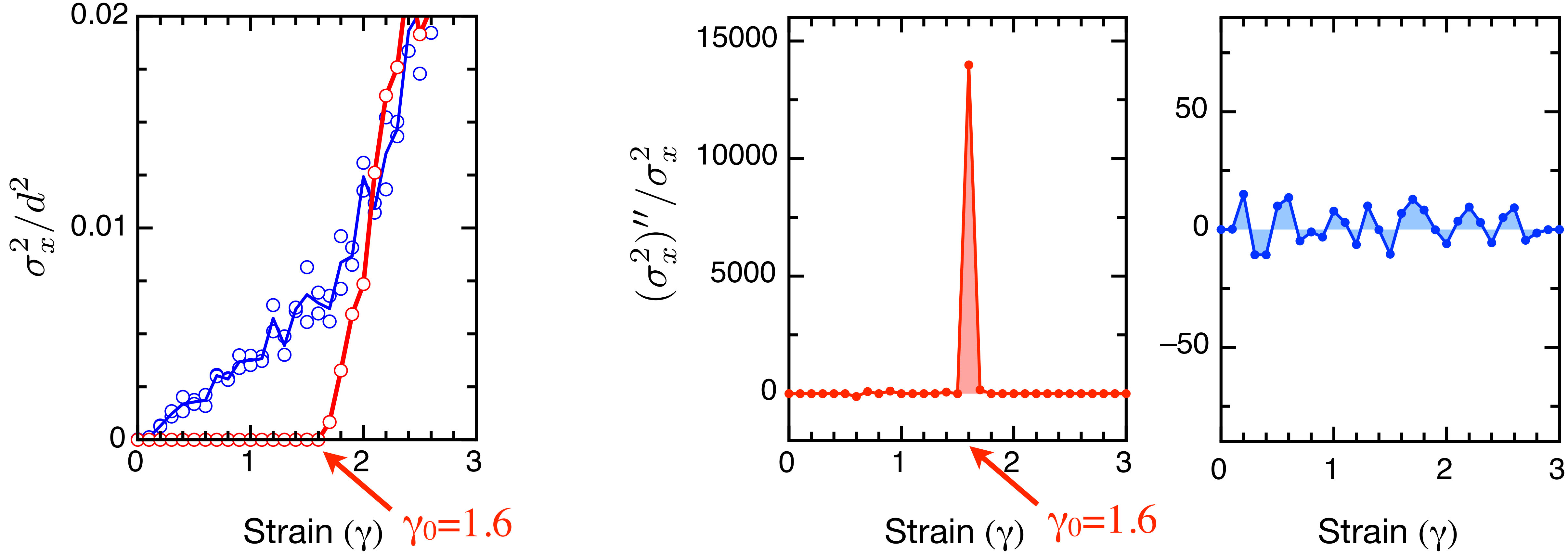
Single Memory



Metric for Irreversibility:

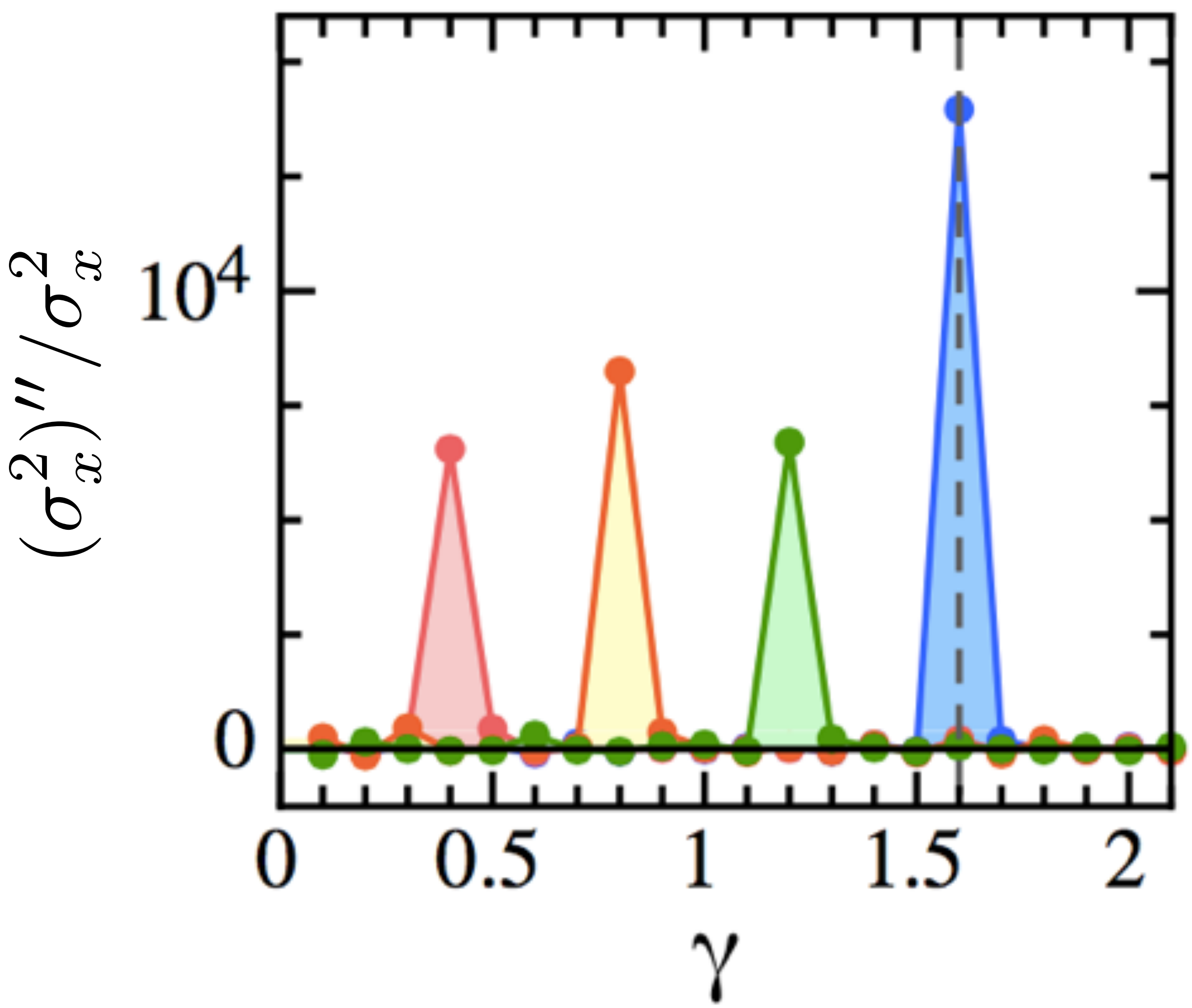
σ_x^2/d^2

1. Training: γ_0=1.6 x 100 versus no training
2. Readout:



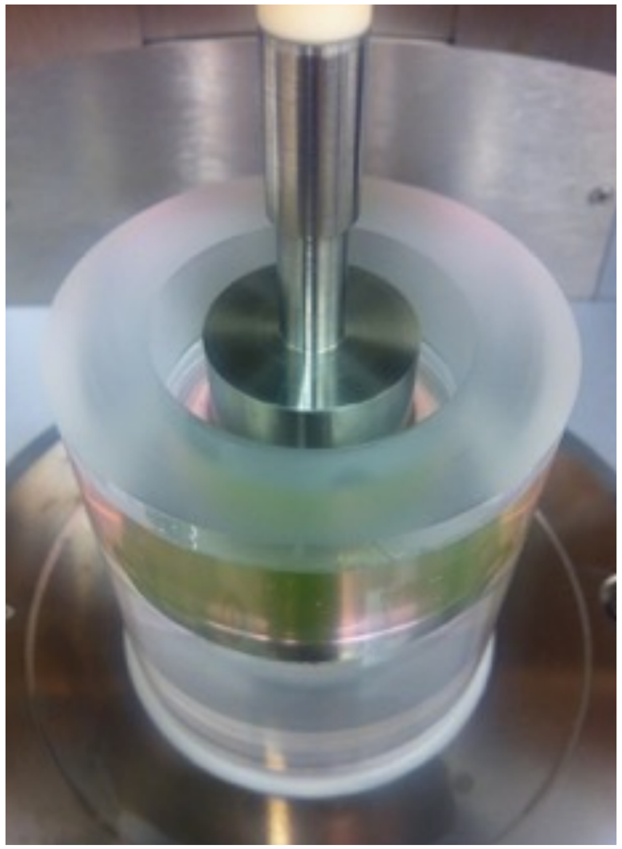
Paulsen, Keim, & Nagel, PRL 2014

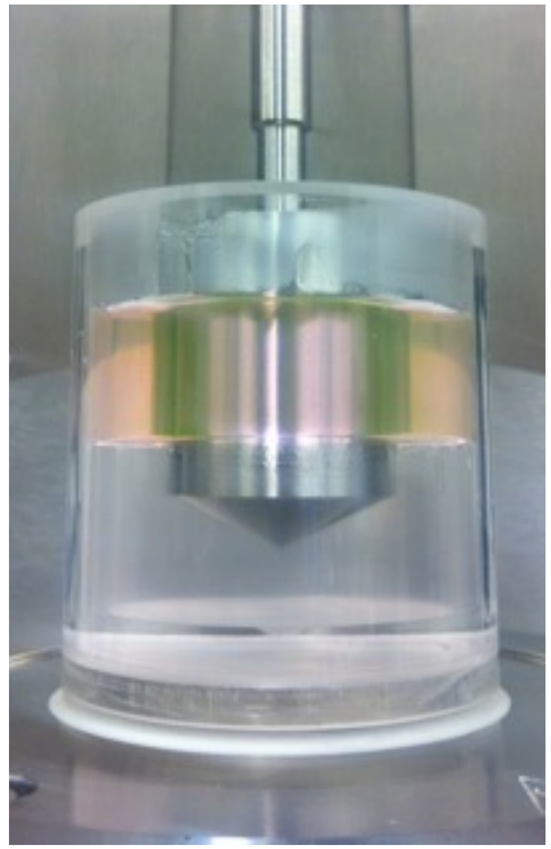
Single Memory: Can place wherever we want (below γ_c)



Paulsen, Keim, & Nagel, PRL 2014

Stress signature of memory

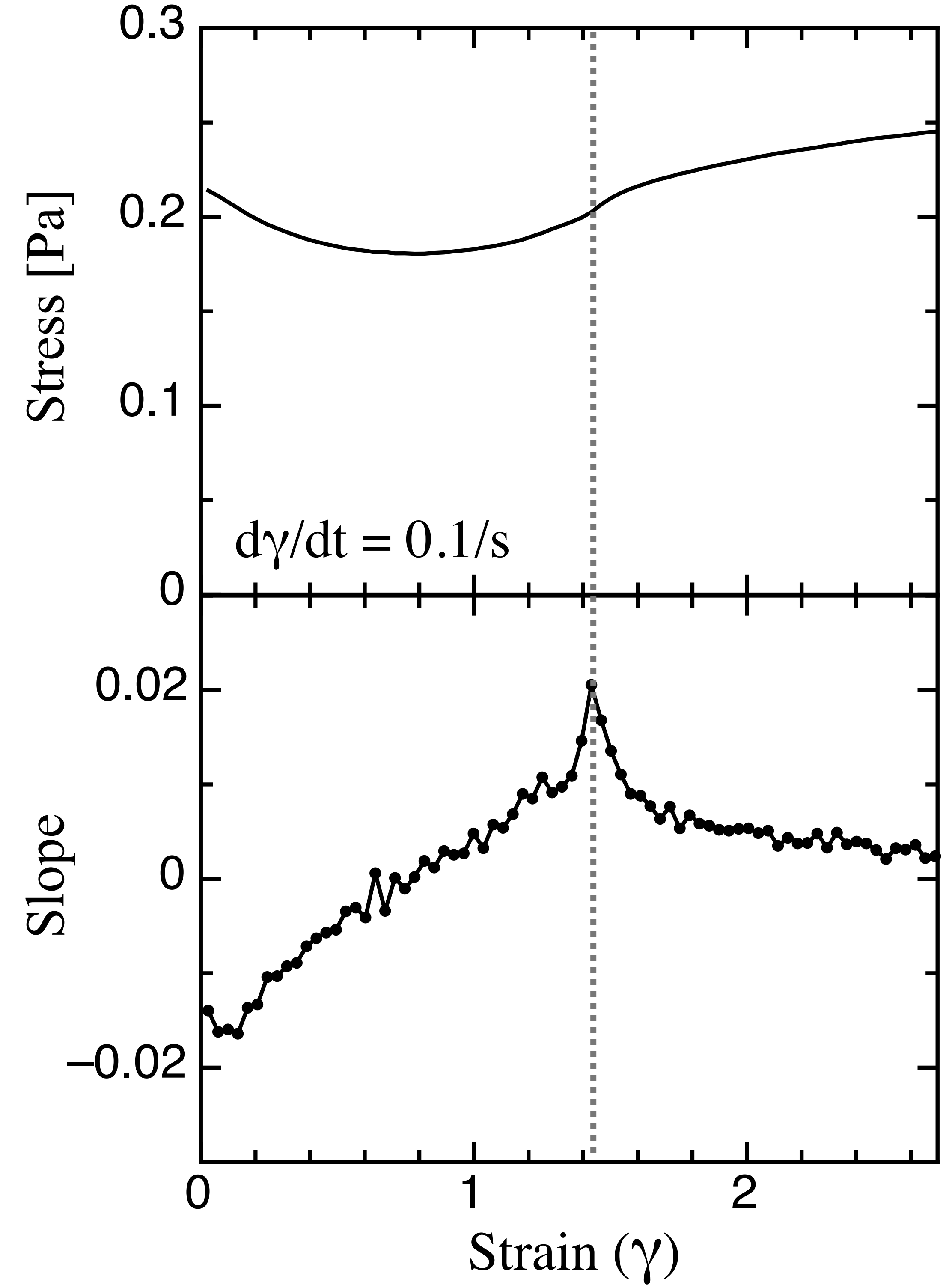




1.) Training: cyclic shear, γ_0=1.44x10

2.) Readout:
-*Shear* at constant strain rate
-Measure *stress* on inner cylinder

Expect sharp increase in stress at $\gamma=\gamma_0$



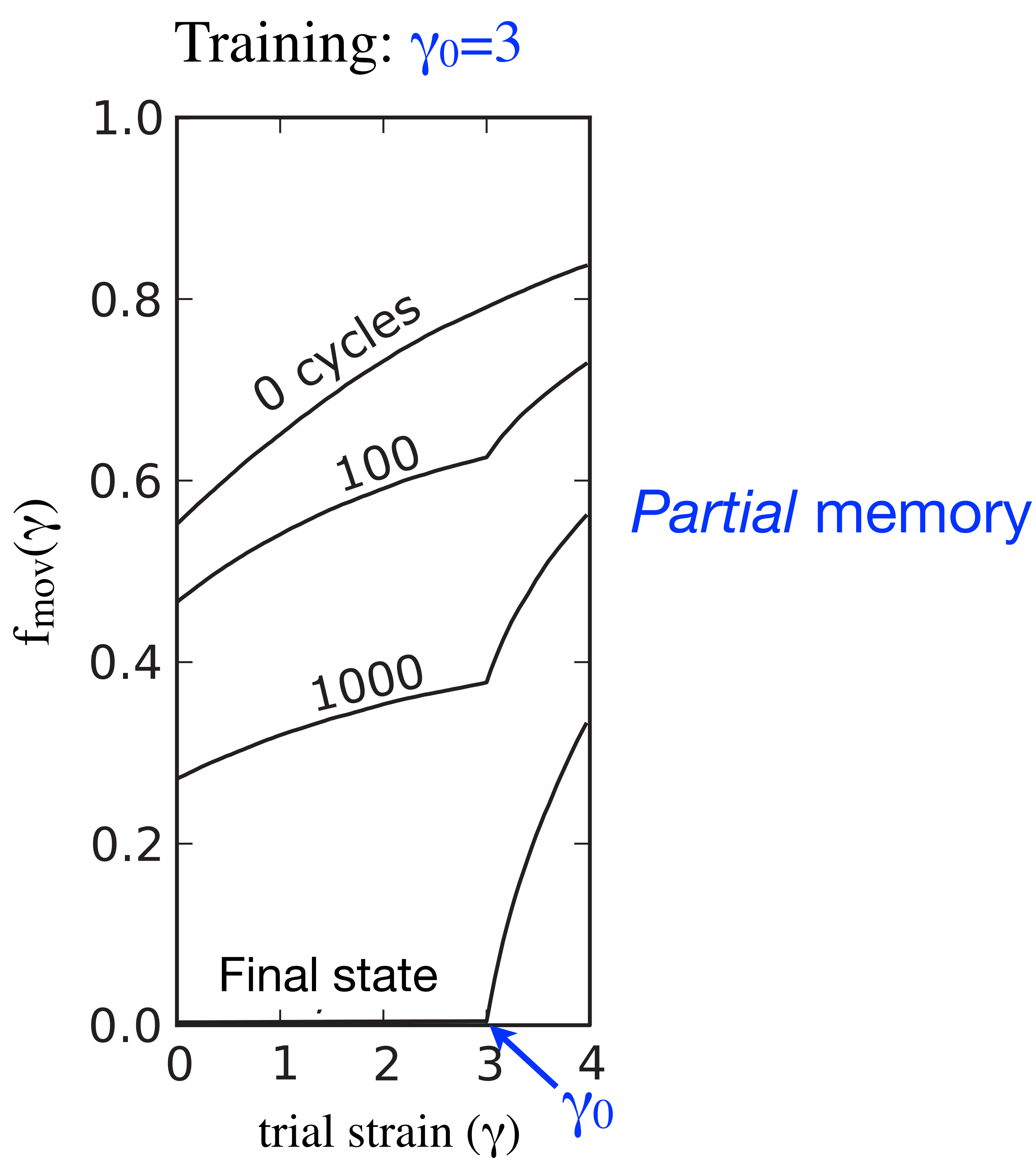
Paulsen, Keim, & Nagel, PRL 2014

Multiple Transient Memories

- System *learns* multiple inputs
- Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

Single Memory: 2D Simulation

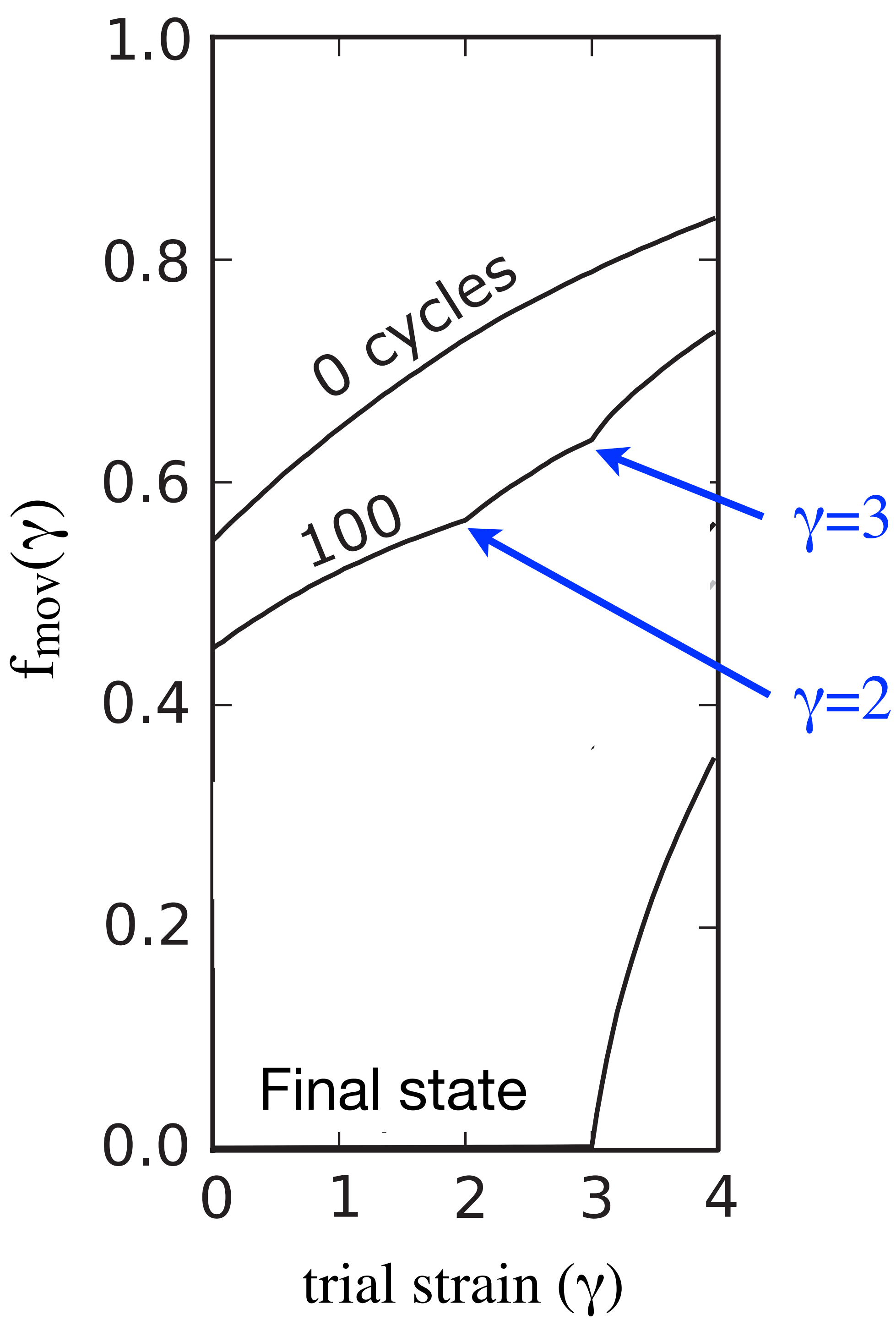
Keim & Nagel, PRL 2011



Multiple Memories: 2D Simulation

Keim & Nagel, PRL 2011

Training: γ=3,2,2,2,2,2,3,2,2,2,2,2, repeat...



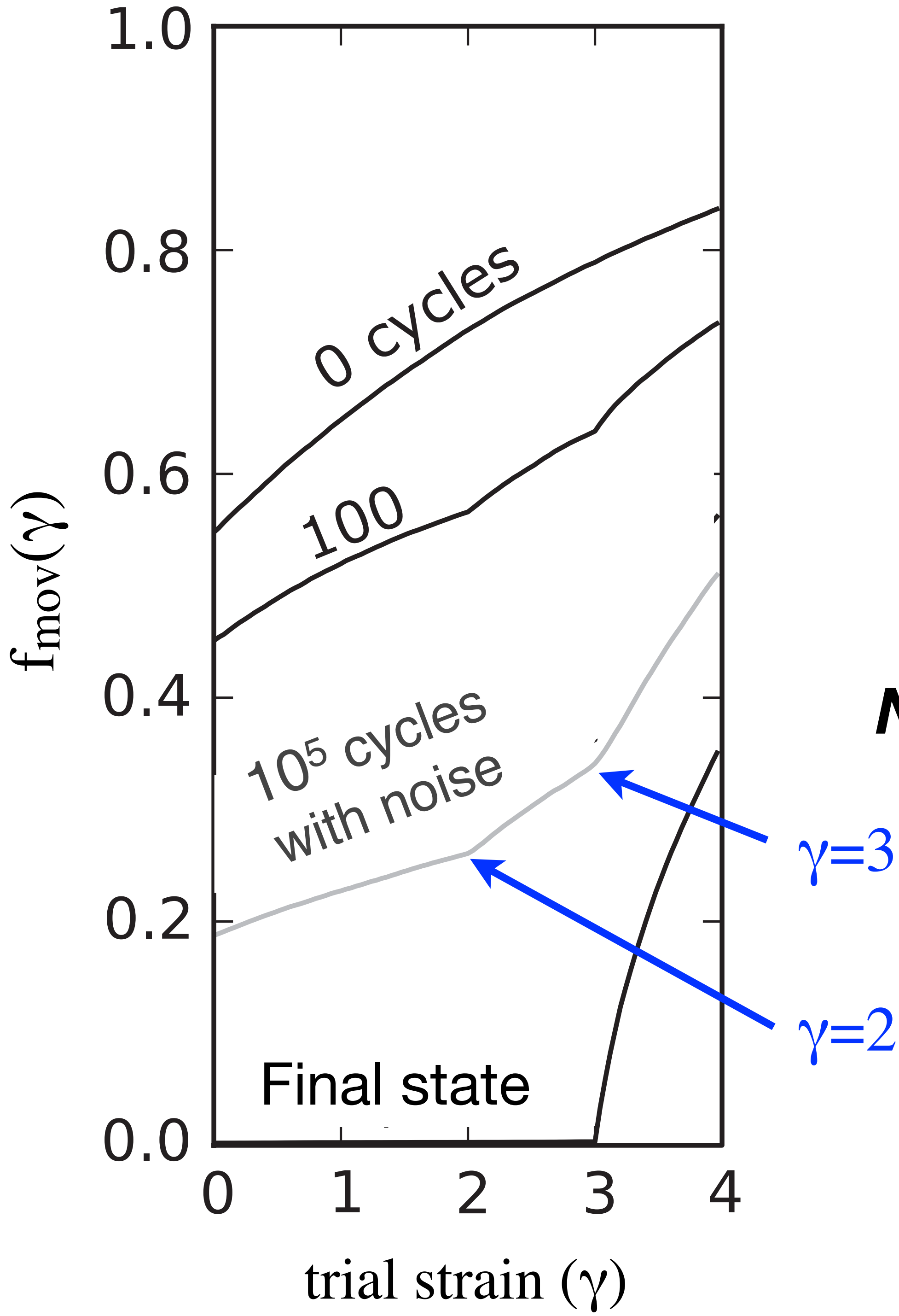
100 cycles: memory of γ=3 and γ=2

Final state: memory of γ=3,
forgot γ=2

Multiple Memories: 2D Simulation

Keim & Nagel, PRL 2011

Training: γ=3,2,2,2,2,2,3,2,2,2,2,2, repeat…

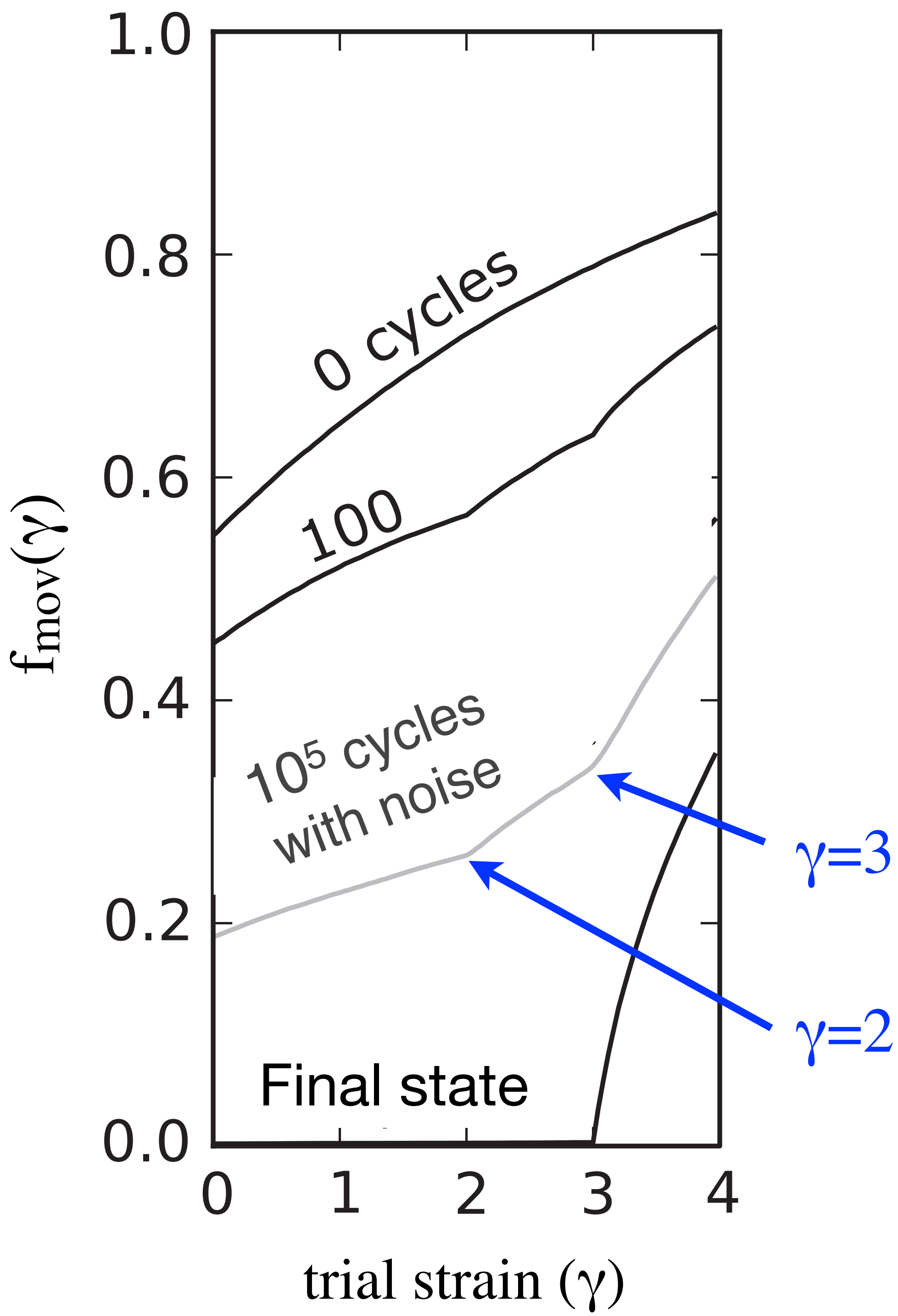


***Noise** prevents getting to fixed point*

Multiple Memories: 2D Simulation

Keim & Nagel, PRL 2011

Training: γ=3,2,2,2,2,2,3,2,2,2,2,2, repeat…

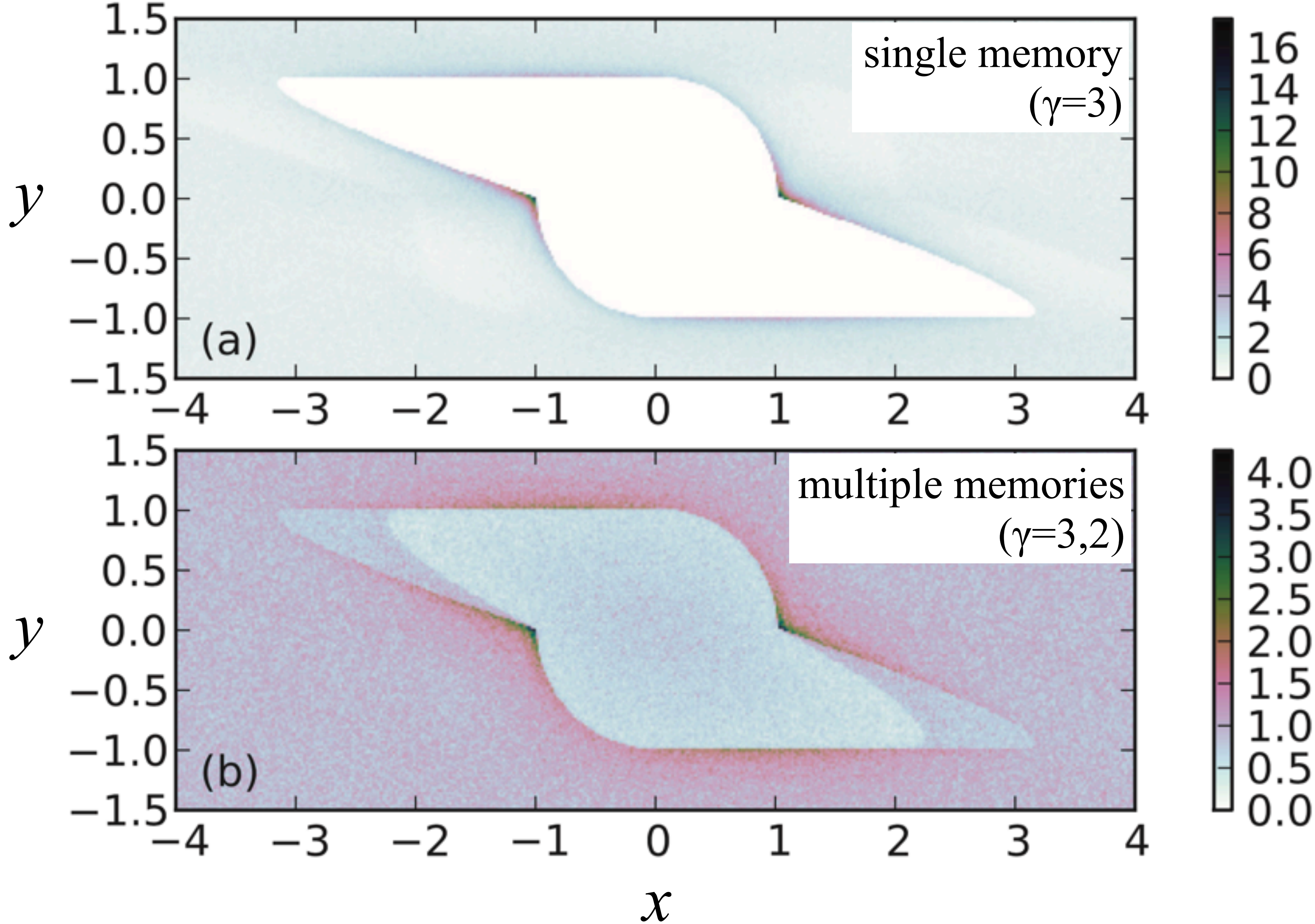


Transient Memories

- System *learns* multiple inputs
- Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

Multiple Memories: 2D Simulation

Keim, Paulsen, & Nagel, PRE 2013



Memories are **robust** in simulation

Keim, Paulsen, & Nagel, PRE 2013

- **Driving**
  - Simple shear
  - Pure shear
  - Particle swelling
- **Interactions**
  - Random direction kicks
  - Center-of-mass conserving kicks
  - Kicks push particles away
- **Kick size**
  - Ranged from 0.001 to 0.5 particle diameters

Evidence of transient memories in all cases

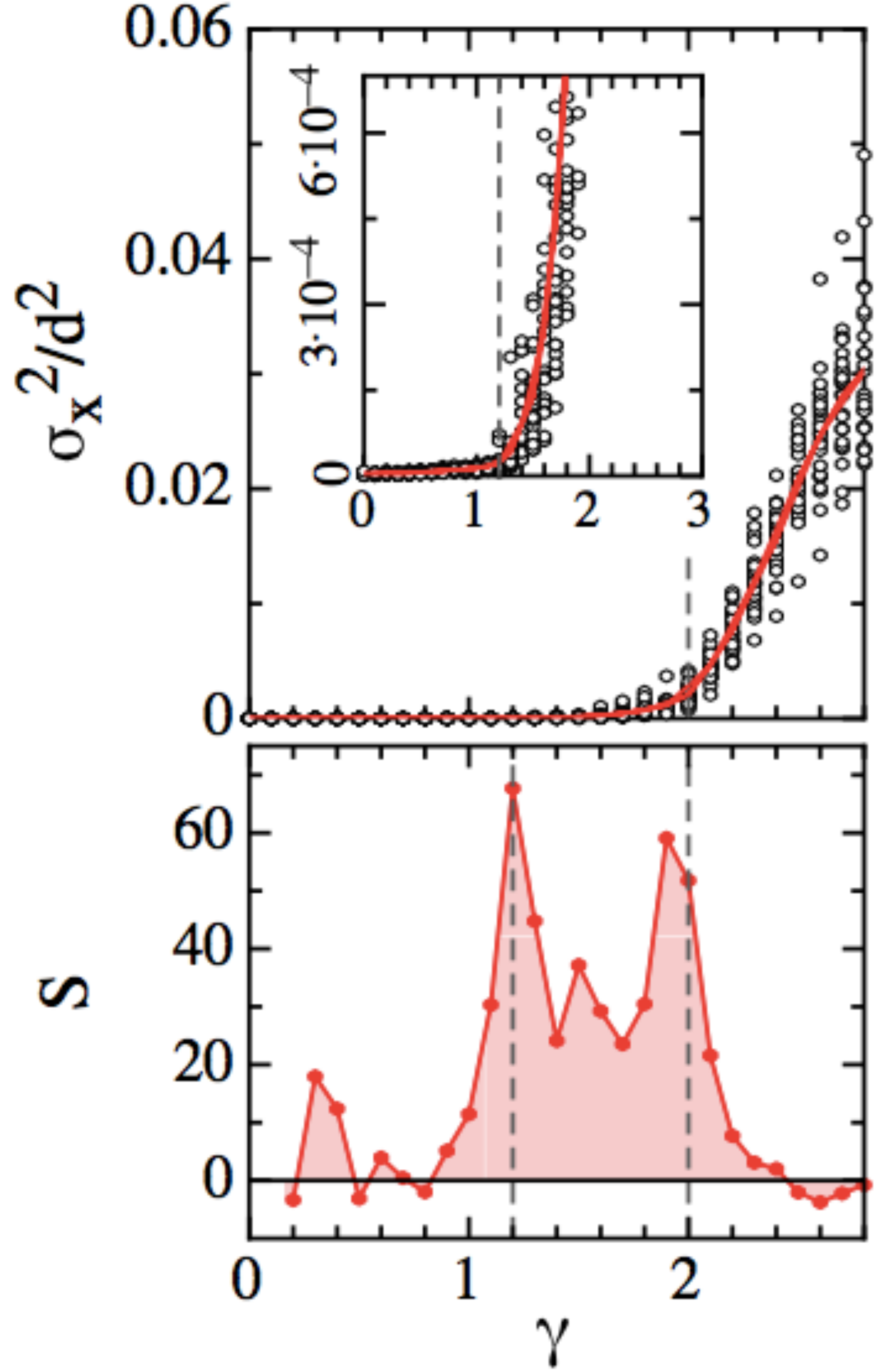
WHAT ABOUT EXPERIMENT!?

Multiple Memories: **Experiment**

Training:

$\gamma = (2, 1.2, 1.2, 1.2, 1.2)$ x **4**

Readout (48 independent experiments):



"Signal":

$$S \equiv (\sigma_x^2)''/\sigma_x^2$$

Paulsen, Keim, & Nagel, PRL 2014

Transient Memories

- System *learns* multiple inputs
- Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

Forgetting: **Experiment**

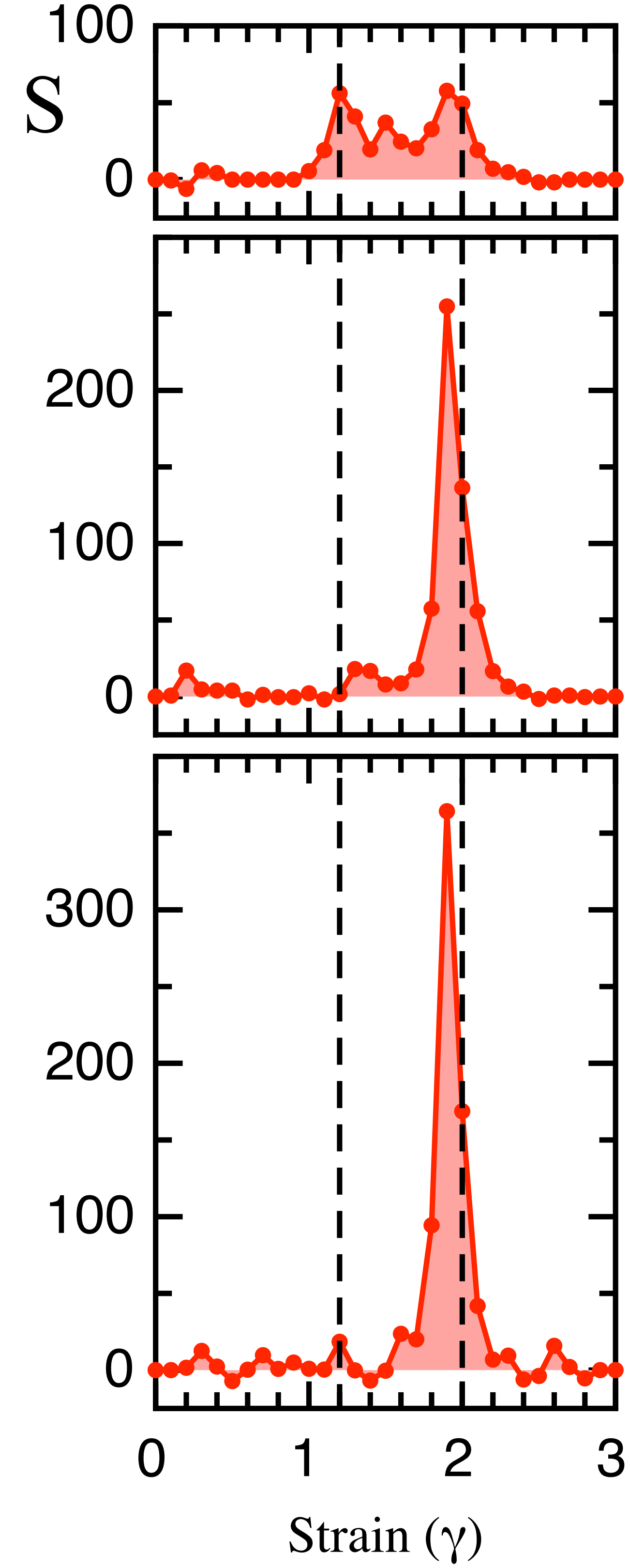
Training:

$\gamma = (2, 1.2, 1.2, 1.2, 1.2)$ x **4** →

$\gamma = (2, 1.2, 1.2, 1.2, 1.2)$ x **8** →

$\gamma = (2, 1.2, 1.2, 1.2, 1.2)$ x **16** →

Readout:

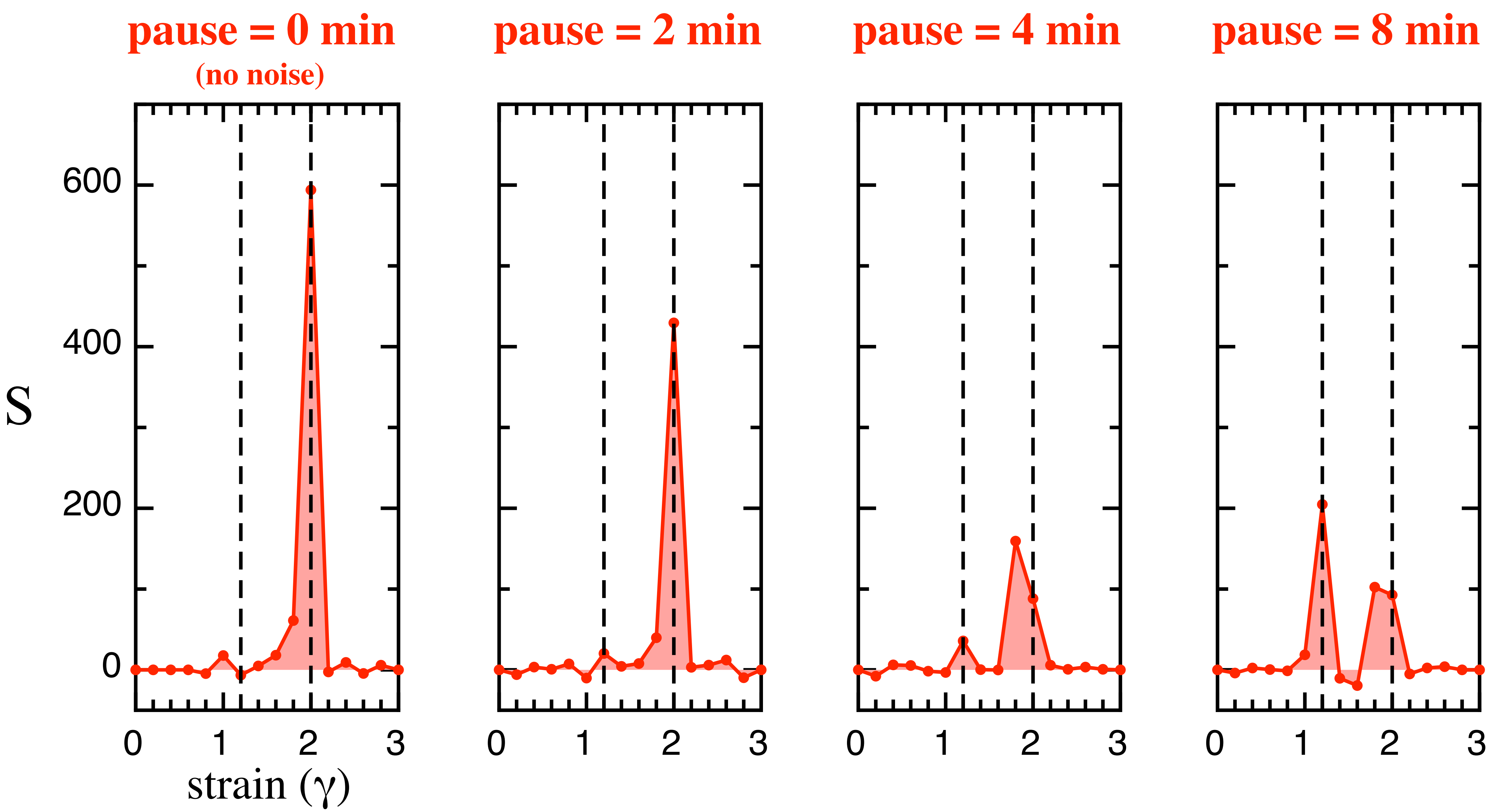


Transient Memories

- ✓ System *learns* multiple inputs
- ✓ Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

Noise Stabilization of Multiple Memories

Training: γ = (2, pause, 1.2, pause, 1.2, pause, 1.2, pause, 1.2, pause) x **8**



Paulsen, Keim, & Nagel, PRL 2014

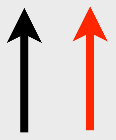
Transient Memories

- System *learns* multiple inputs
- Eventually *forgets* most *under continual training*
- Addition of noise: *remembers* all

Transient Memories: Takes *many cycles* to erase smaller memories*

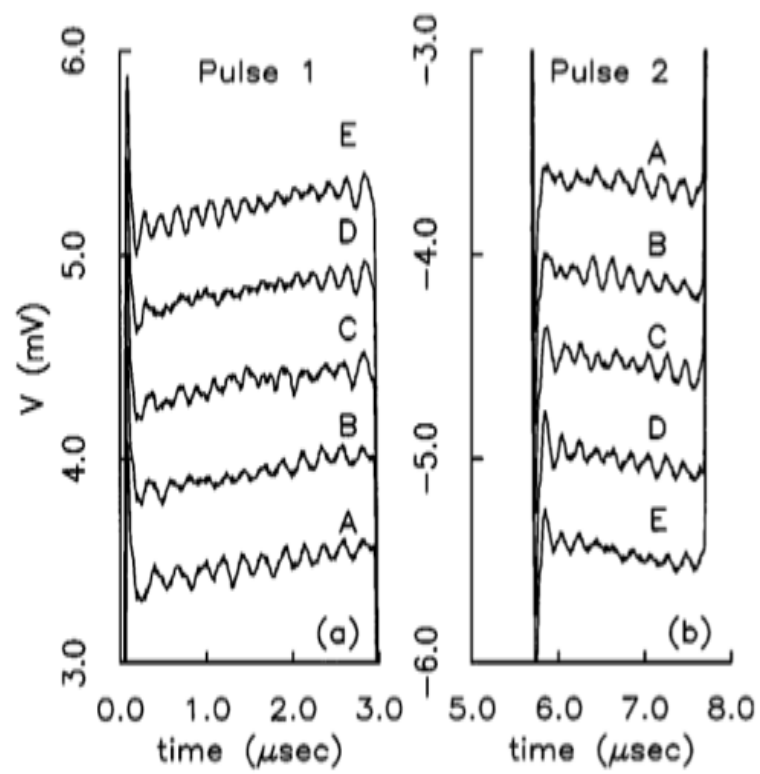
* *-True for simulations*
-Not yet demonstrated in experiment

$\gamma=3$

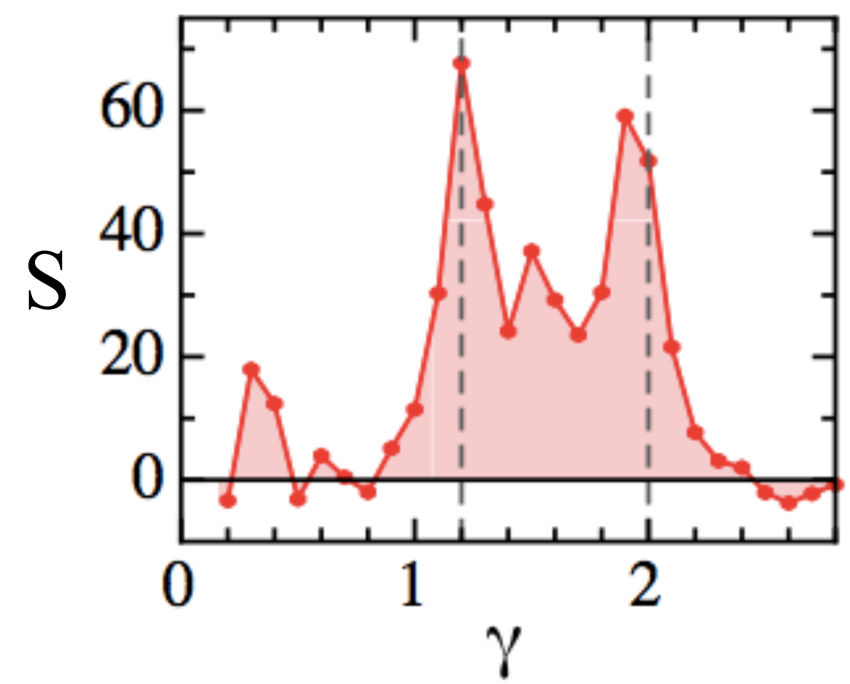


-Is memory simply smoothed out?
-Is it hidden under noise?

Charge-density waves:

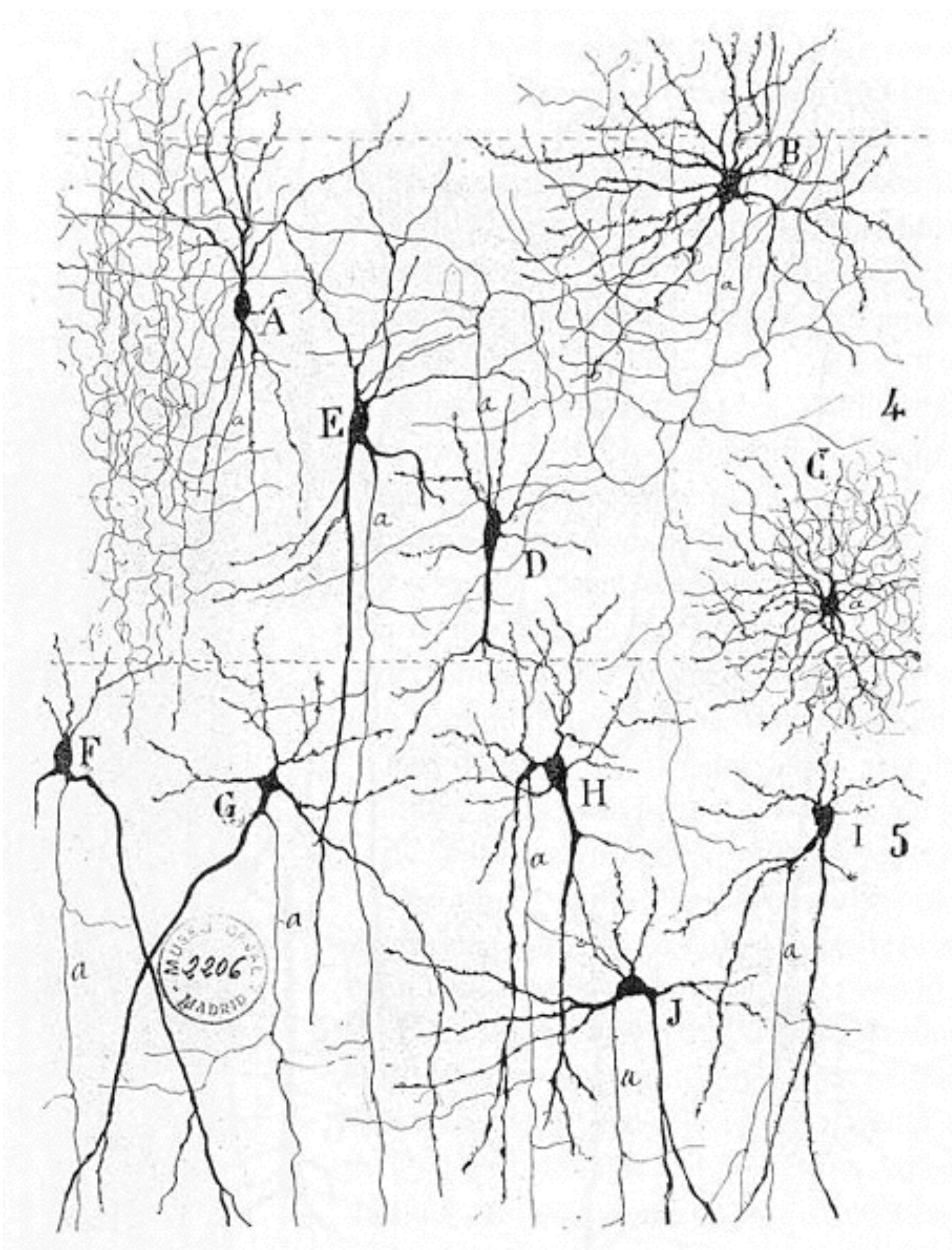


Sheared suspensions:



An intrinsic way matter behaves, far from equilibrium

Aspects shared with biology



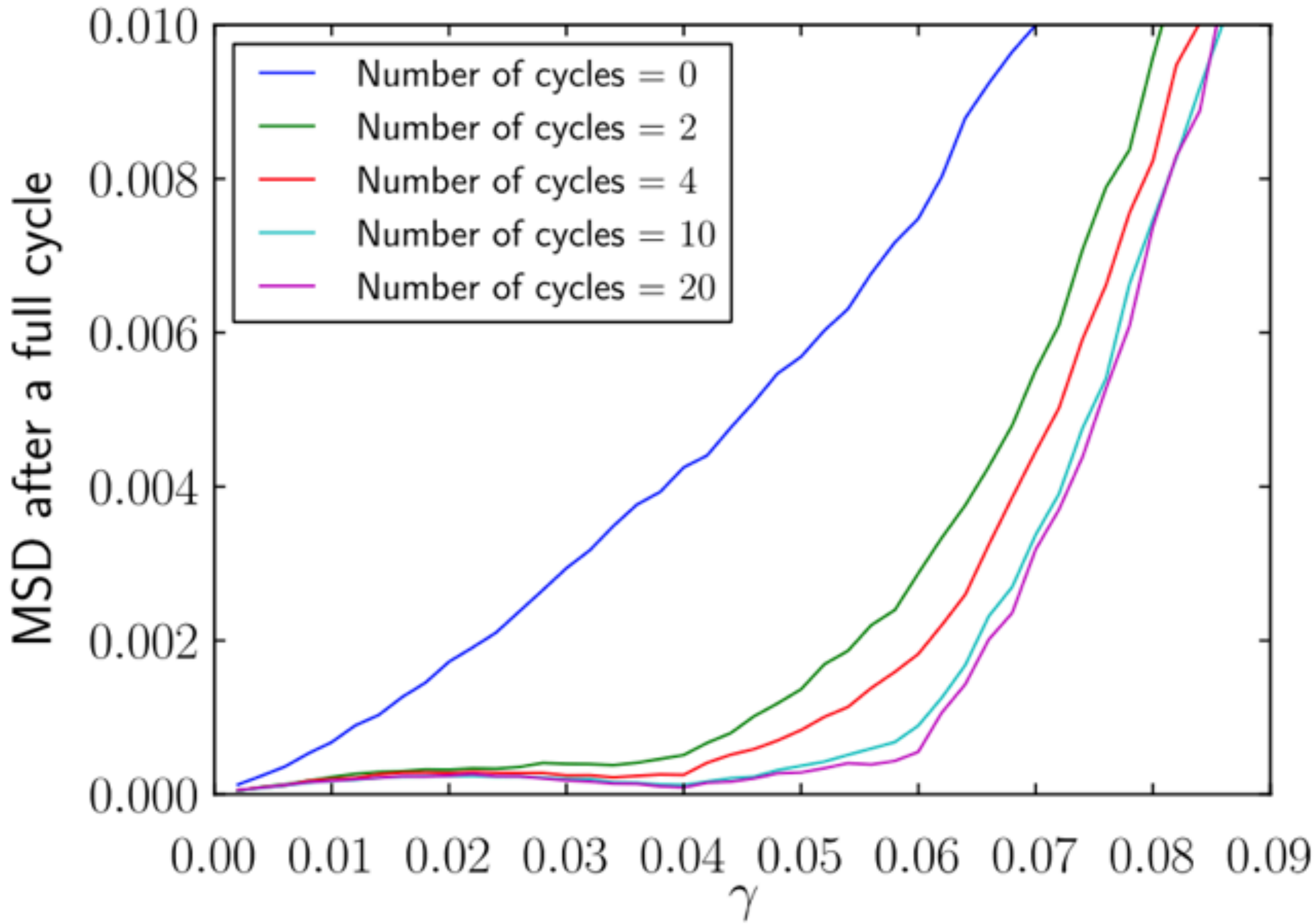
"Texture of the Nervous System of Man and the Vertebrates"
Santiago Ramón y Cajal. 1897

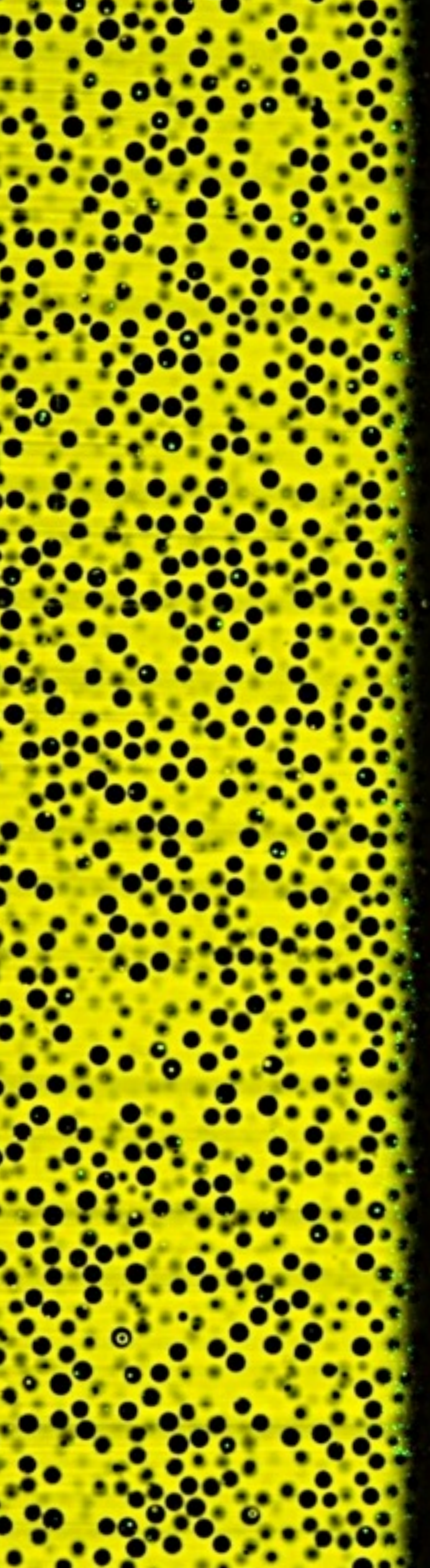
Concrete example of ***plasticity***

Cyclic driving

Similar but distinct from sheared amorphous solid

Fiocco, Foffi, & Sastry, PRL 2014





Multiple Transient Memories:

- –Counterintuitive physics
- –A distinct **class** of memories

Read more:
Keim & Nagel, PRL 2011
Keim, Paulsen, & Nagel, PRE 2013
Paulsen, Keim, & Nagel, PRL 2014
Paulsen & Nagel, J Stat Phys 2017

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