"If any one faculty of our nature may be called more wonderful than the rest, I do think it is memory. ...
our powers of recollecting and of forgetting do seem peculiarly past finding out."

Jane Austin -- *Mansfield Park*

Discussion on memory formation in matter
Sidney Nagel

Basic operations: imprinting, reading and erasure of information

1) Examples of memories: some trivial some not
     - similarities and distinctions
2) General questions

Some examples of memories in matter

Stone and chisel
Paper and pencil (erasable) or pen (non-erasable)
Photograph
Phonograph record: analog or digital (needs a code for retrieval)

Computer:
    Flipping magnetic domains
    ROM
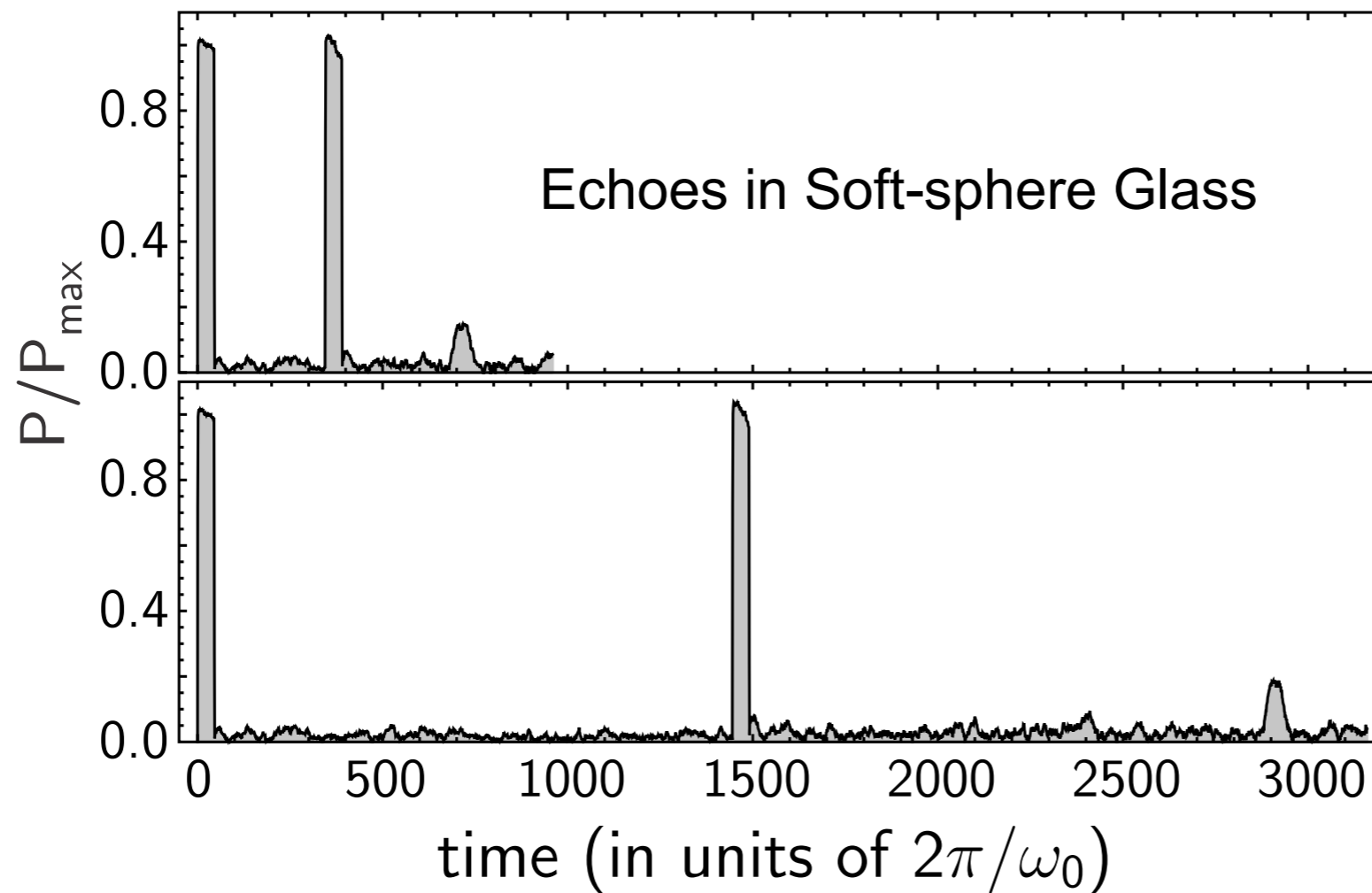   RAM or DRAM
    Volatile vs. non-volatile
    First in / first out or first in / last out

More examples of memories in matter

Sheared viscous fluid
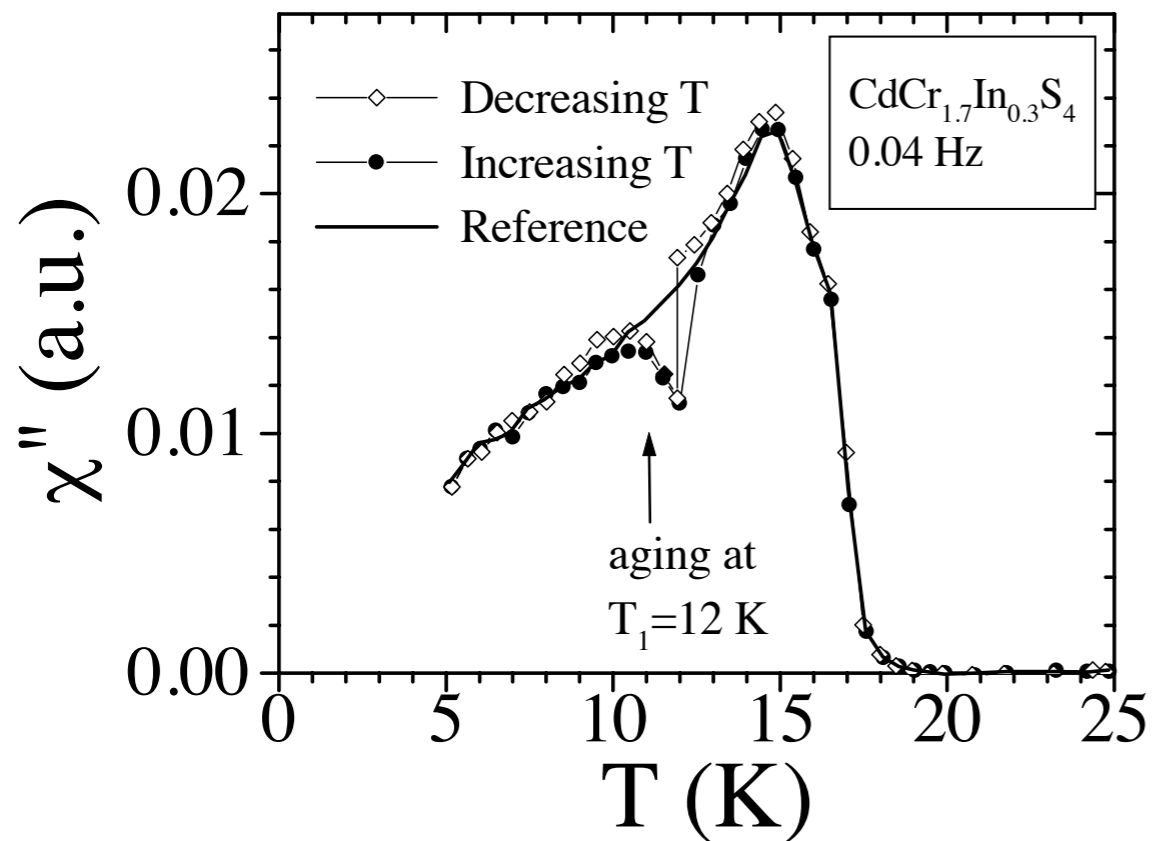
More examples of memories in matter

Echoes — time stored in coherence of oscillators
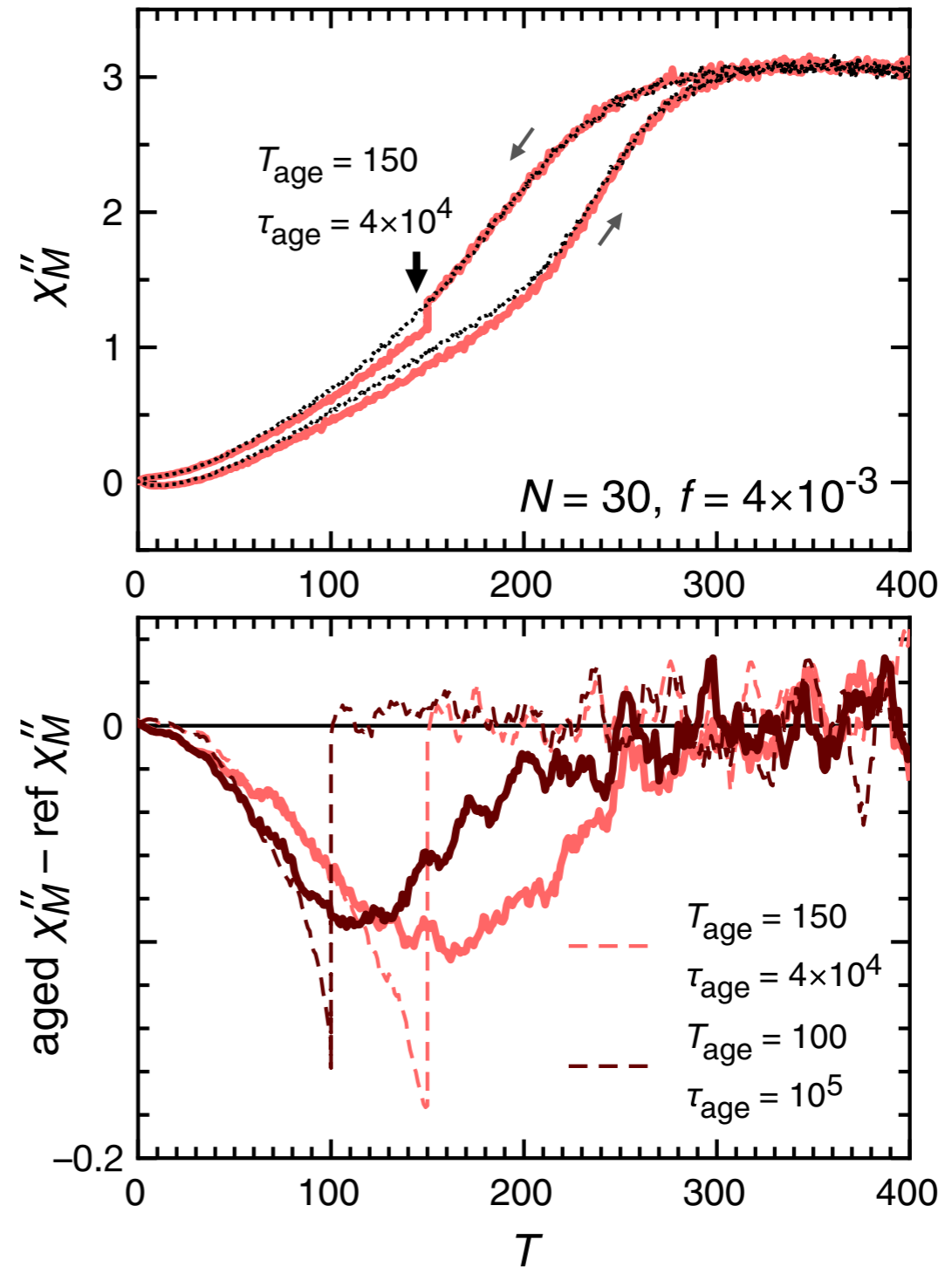2-state spin or photon; (anharmonic) phonon; quench echoes…

Echoes in Soft-sphere Glass

P/P_{max}

time (in units of $2\pi/\omega_0$)

J. Burton, SRN *PRE* 2016 "Echoes from anharmonic normal modes in model glasses"

More examples of memories in matter
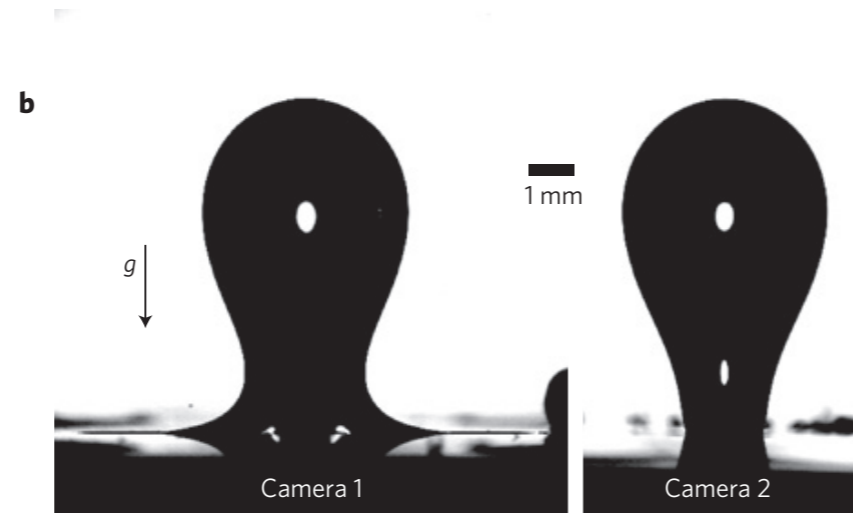
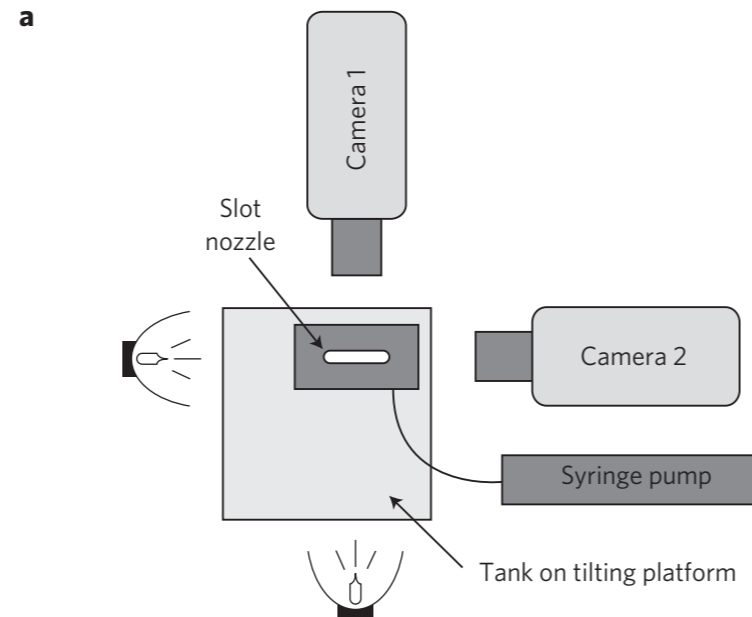## Memory and rejuvenation in glasses

K. Jonason, E. Vincent, J. Hammann, J. P.
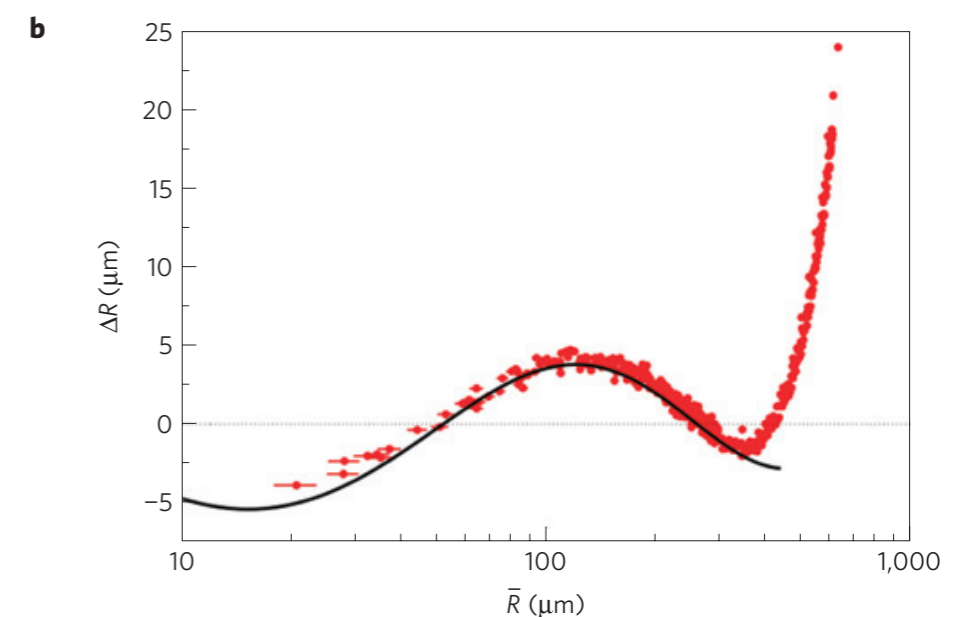Bouchaud, P. Nordblad *PRL 1998*   "Memory and Chaos Effects in Spin Glasses"
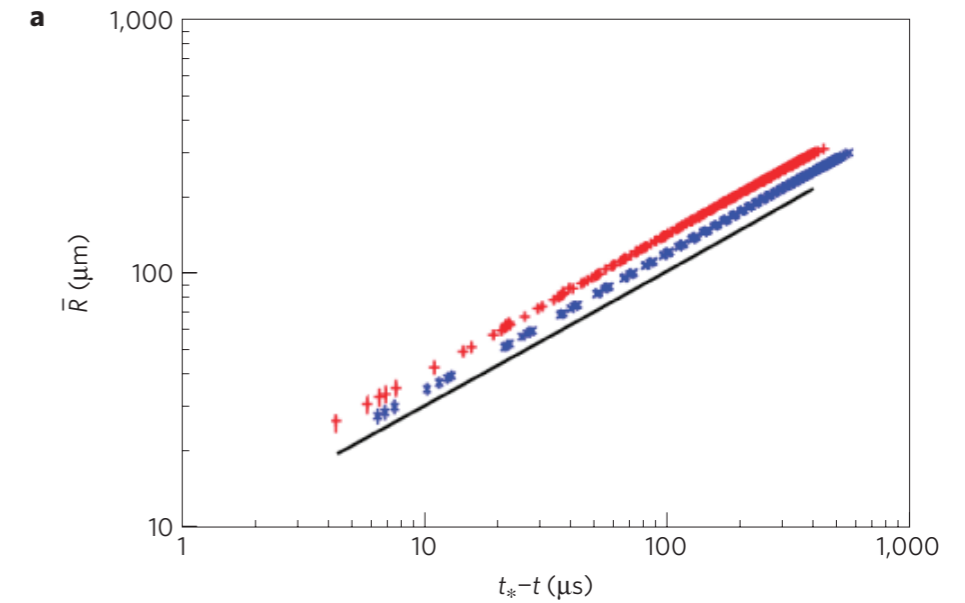
L.-N. Zou, SRN *PRL* 2010 "Thermally activated sorting"

More examples of memories in matter

Dynamical systems - remembers or forgets initial conditions (nature *vs.* nurture)

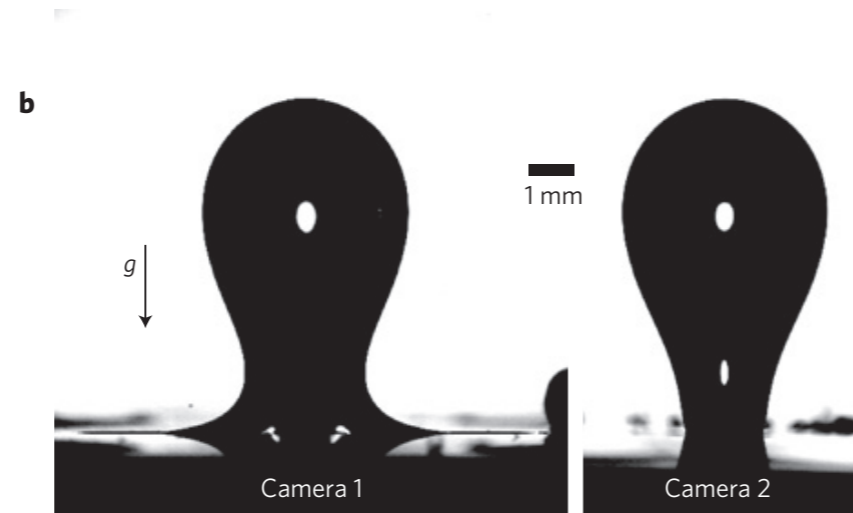**a** Set-up of experiment used to measure an $n = 2$ vibration.

b Disconnection dynamics from a slot nozzle.

Laura Schmidt, Nathan Keim. Wendy Zhang, SRN *Nature Phys.* (2009) "Memory-encoding vibrations in a disconnecting air bubble "

More examples of memories in matter

Dynamical systems - remembers or forgets initial conditions (nature *vs.* nurture)

a

Camera 1

Slot nozzle

Camera 2

Syringe pump

Tank on tilting platform

b

g

1 mm

Camera 1

Camera 2

Set-up of experiment used to measure an *n* = 2 vibration.

a

$\bar{R}$ (µm)

$t_* - t$ (µs)

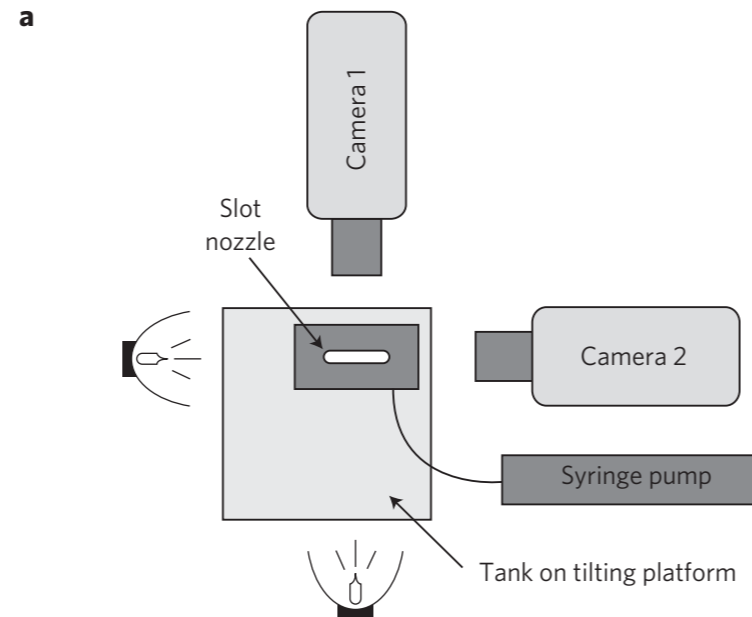**b**

ΔR (µm)

$\bar{R}$ (µm)
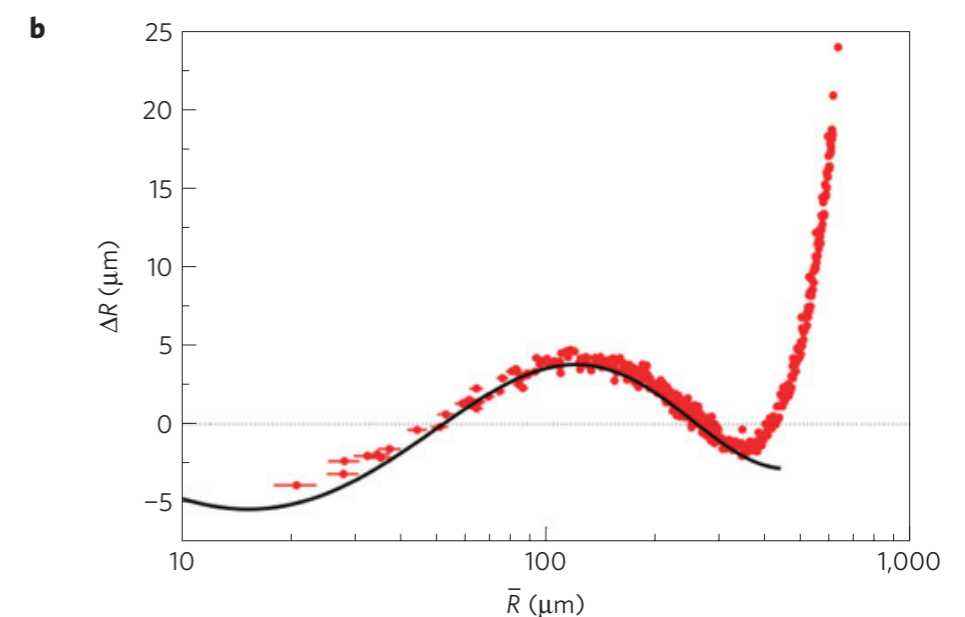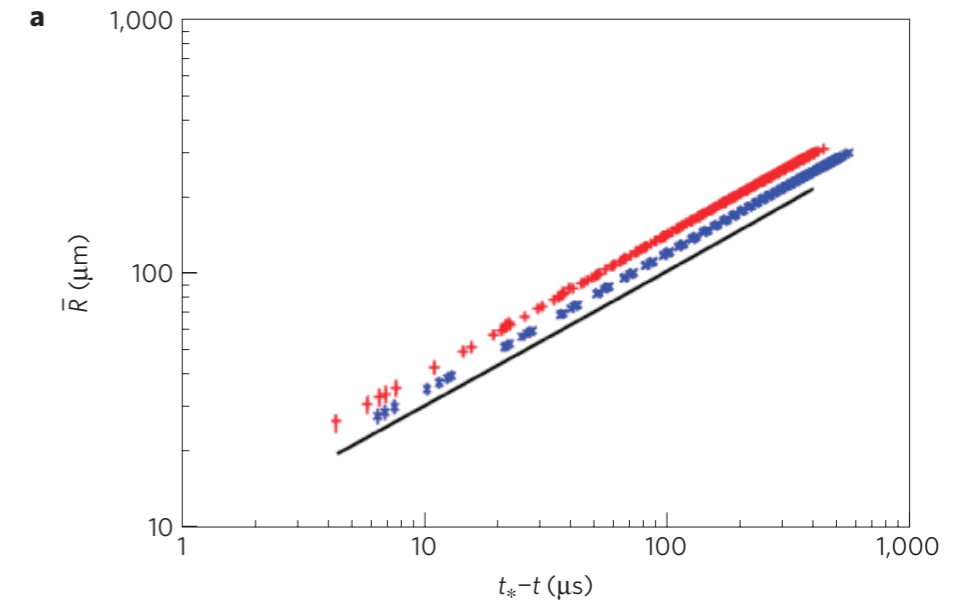
Disconnection dynamics from a slot nozzle.

Laura Schmidt, Nathan Keim. Wendy Zhang, SRN *Nature Phys.* (2009) "Memory-encoding vibrations in a disconnecting air bubble "

More examples of memories in matter

Return-point memory in magnets (and bi-phasic fluid flow in random porous media)

Nested hysteresis curves

More examples of memories in matter

Return-point memory in magnets (and bi-phasic fluid flow in random porous media)
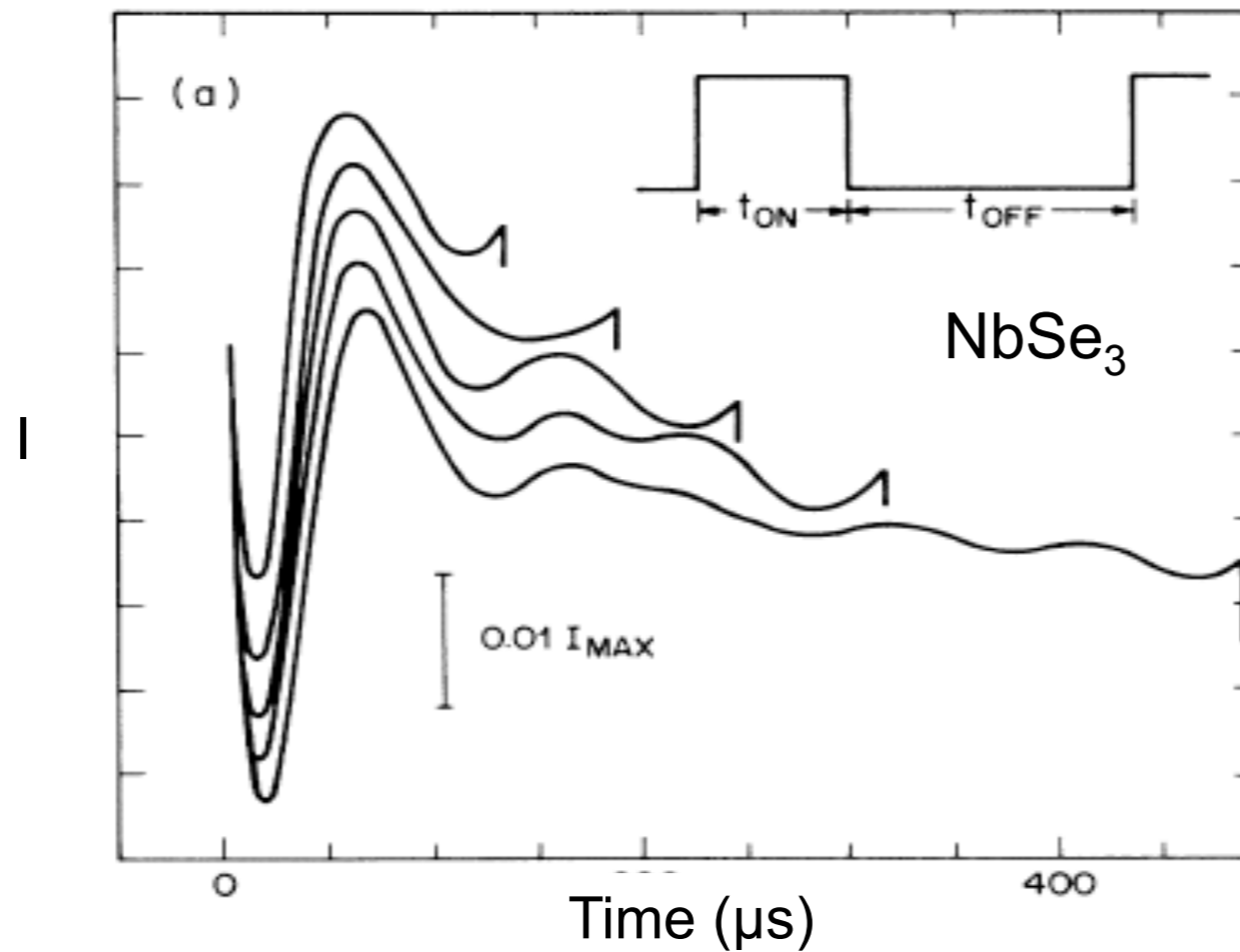
      Nested hysteresis curves

Associative memory in neural nets (Hopfield model)

    Need only partial information to find the full memory

More examples of memories in matter

Pulse duration memory

Current always rises when voltage turned off


R. M. Fleming, L. F. Schneemeyer *PRB* 1986

S, N Coppersmith, Peter Littlewood *PRB 1987*
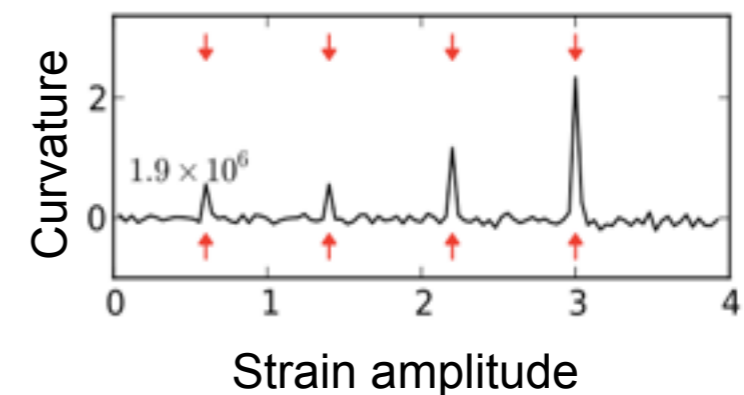
More examples of memories in matter

Multiple transient memories (charge density waves; non-Brownian Suspensions)
Remembers multiple inputs for a while, then forgets all but two of them. If noise, all
inputs retained indefinitely.

frac (F)

P(frac(F))
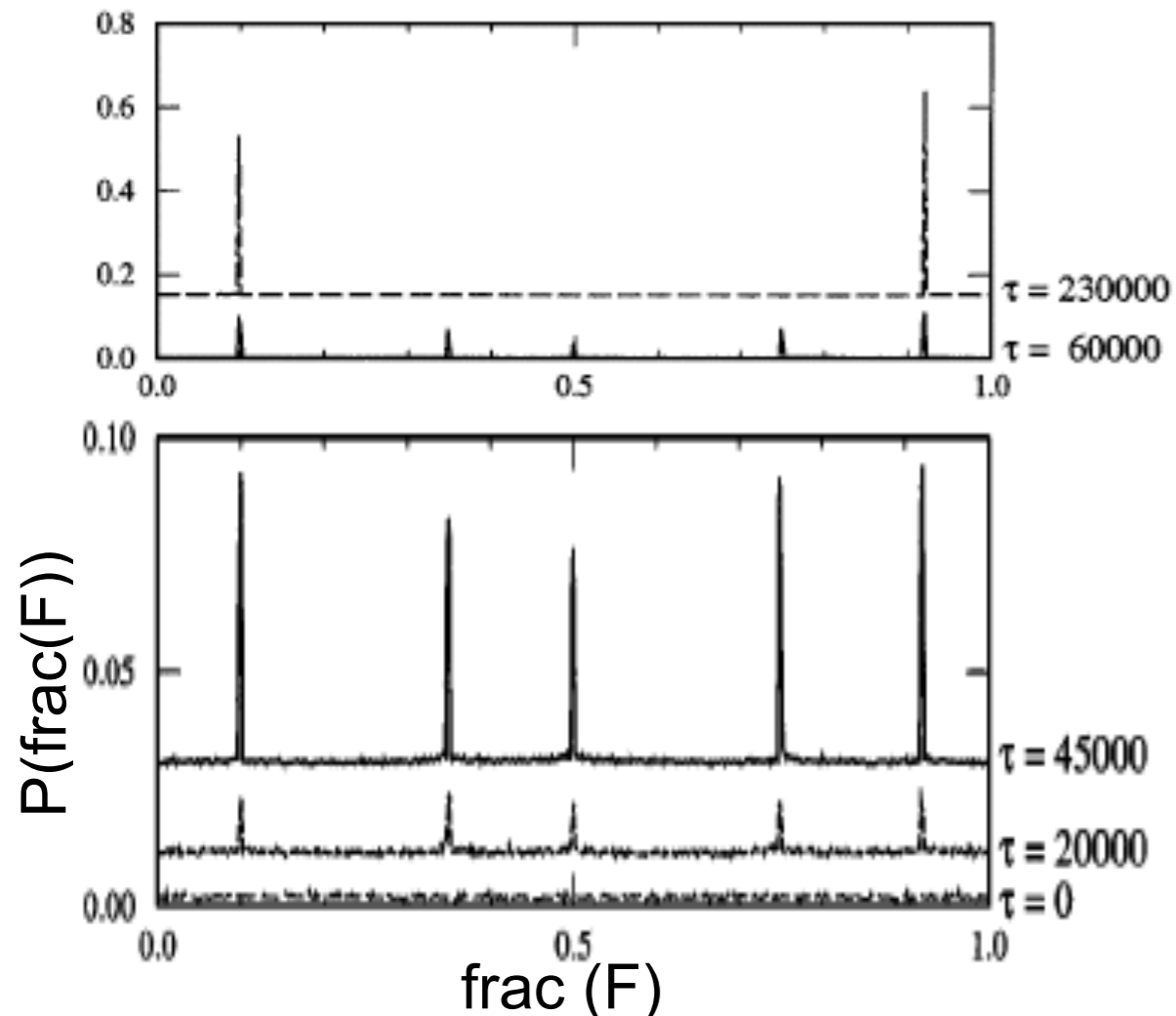
M. Povinelli, S. Coppersmith, L. Kadanoff,
SRN, S. Venkataramani, *Phys. Rev. E* (1999)
" Noise Stabilization of Self-Organized Memories," .
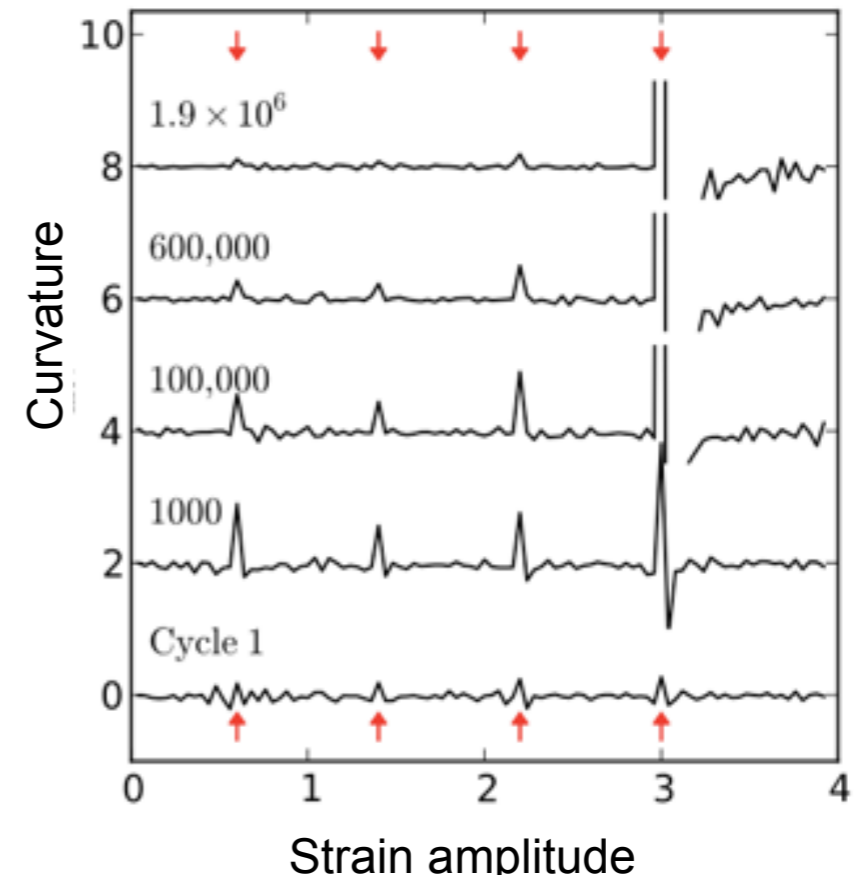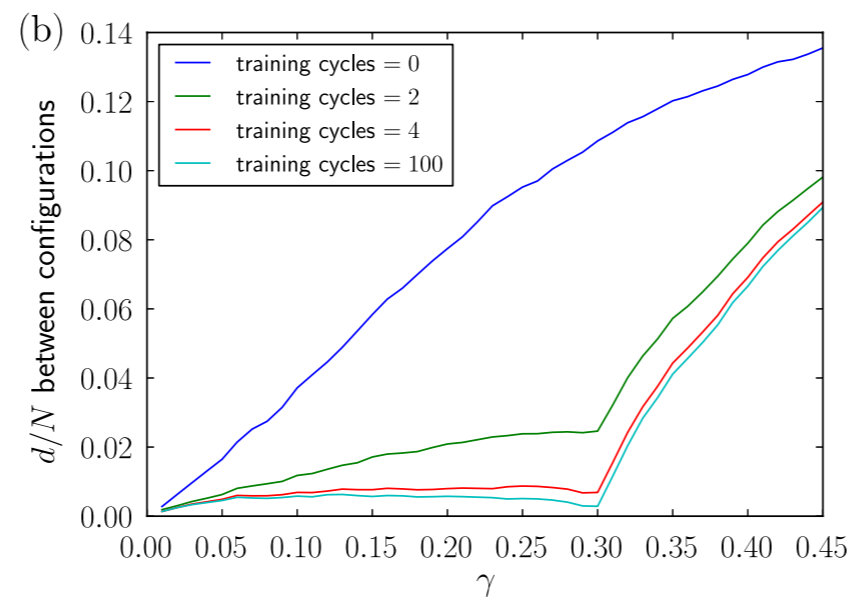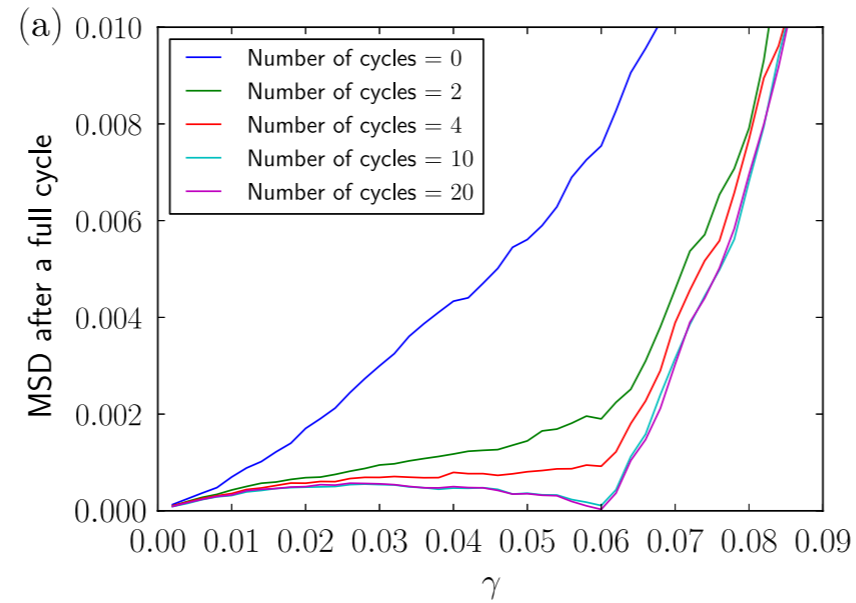
With noise

Nathan Keim, Joseph Paulsen, SRN *Phys. Rev. E (2013)*
"Multiple transient memories in sheared suspensions: robustness, structure, and routes to plasticity,"

More examples of memories in matter

Multiple transient memories in jammed solids

Davide Fiocco, Giuseppe Foffi, and Srikanth Sastry *PRL* (2014) "Encoding of Memory in Sheared Amorphous Solids"

More examples of memories in matter

Memory of treatment in hidden order
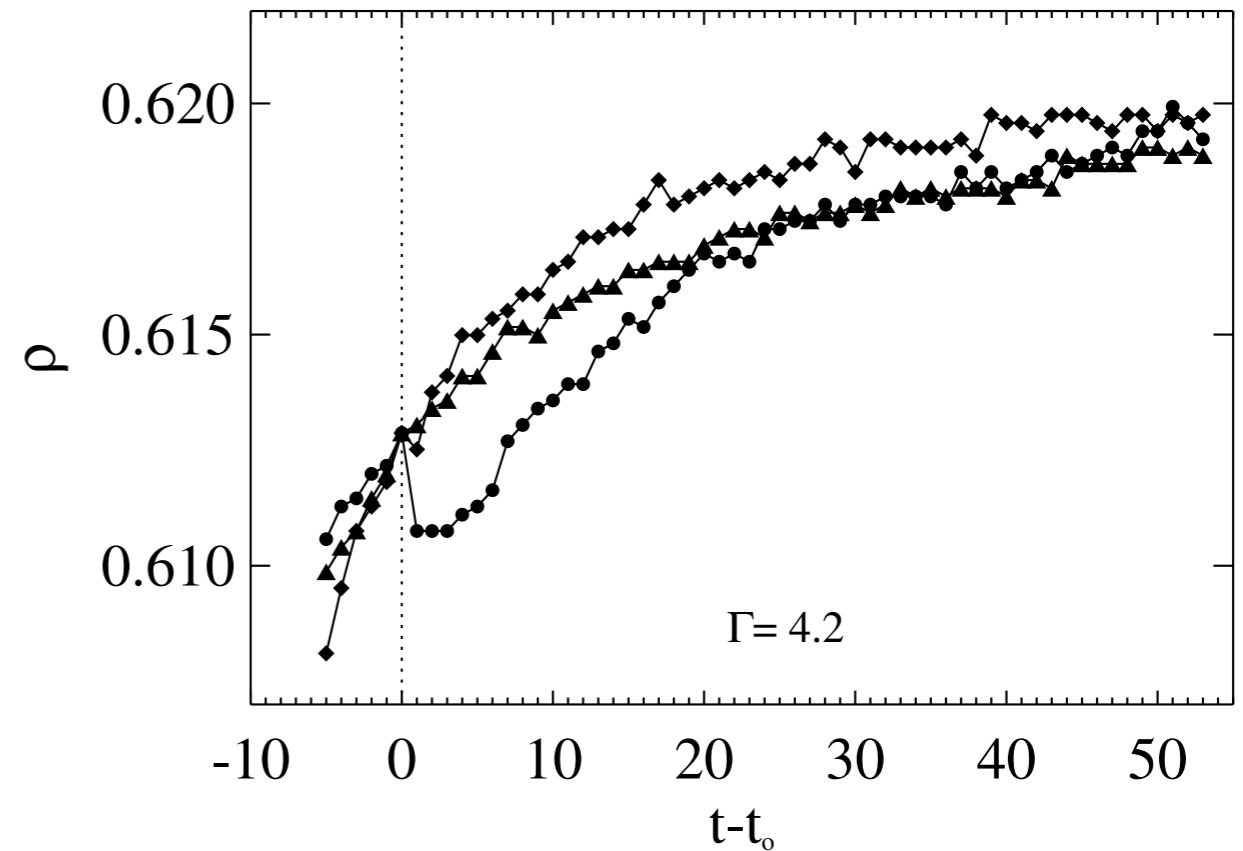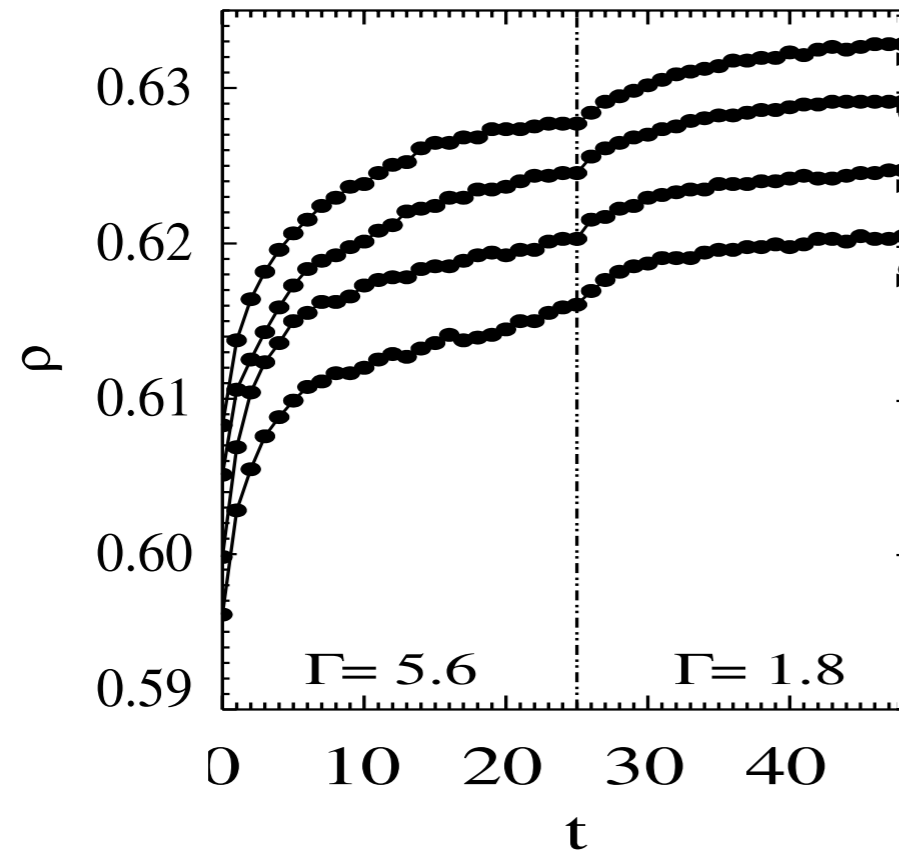
Christophe Josserand, Alexei V. Tkachenko, Daniel M. Mueth, Heinrich M. Jaeger   *PRL* 2000
"Memory Effects in Granular Materials"

More examples of memories in matter

Kovac's effect (polymer glasses, crumpled paper…)
    Remembers waiting time
Kaiser effect
    Remembers largest strain

Shape-memory alloys

Designing in function: memory

Some general questions

The basic operations of memory: imprinting, reading and erasure of information

What constitutes a memory?
How is one memory different *in kind* from another?
Can memories be placed into different categories?
How many *kinds* of memories are there?
What does a system need to possess in order to be able to store memories?
         (many degrees of freedom, far from equilibriumum,…)
How many memories can be stored in a system?
What is the entropy of having a memory?
What is plasticity?
How many ways can one erase memories?
Are all types of memory useful (*e.g.*, in biology)?

Some distinctions

Minima in a landscape
Marginal states

Heredity: DNA versus immune system or biome

Erasable or non-erasable
RAM or DRAM
Volatile vs. non-volatile
First-in / first-out vs. first-in / last-out

Biology

Associative memory
Short-term memory
Long-term memory
Where I parked the car?
Muscle memory