Kovacs-Like Memory Effect in Disordered Mechanical Systems

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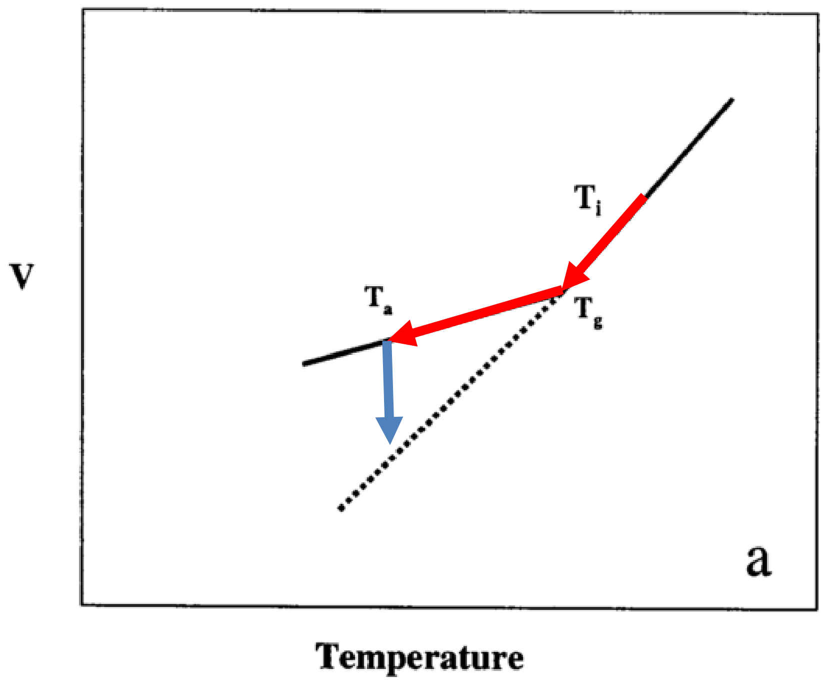
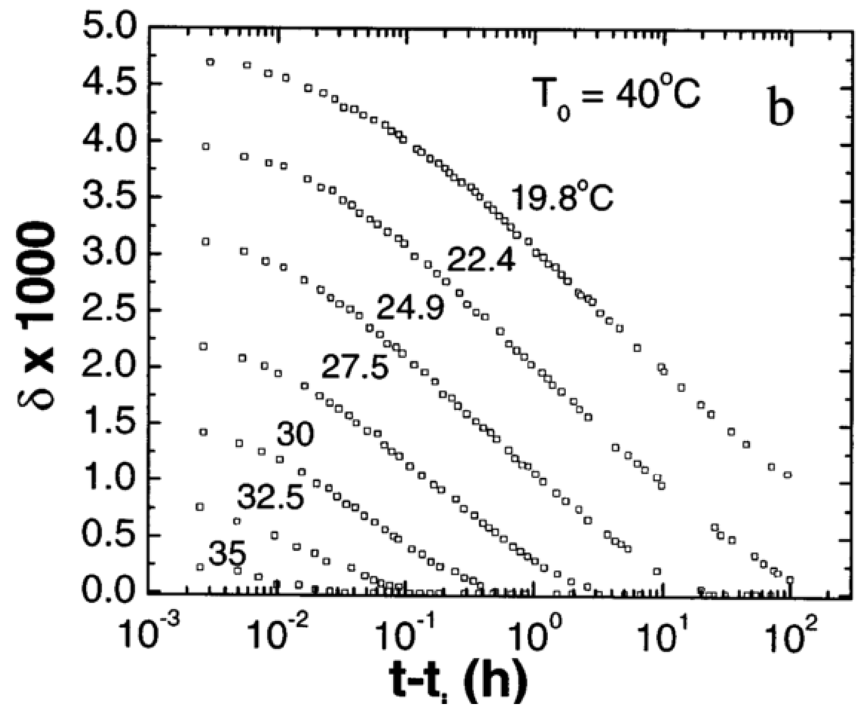
The Kovacs Memory Effect



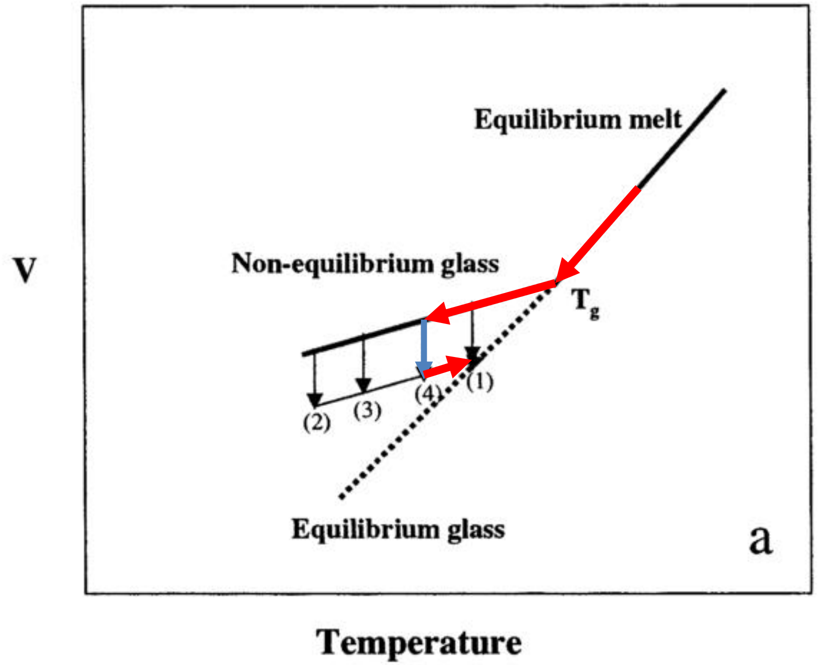


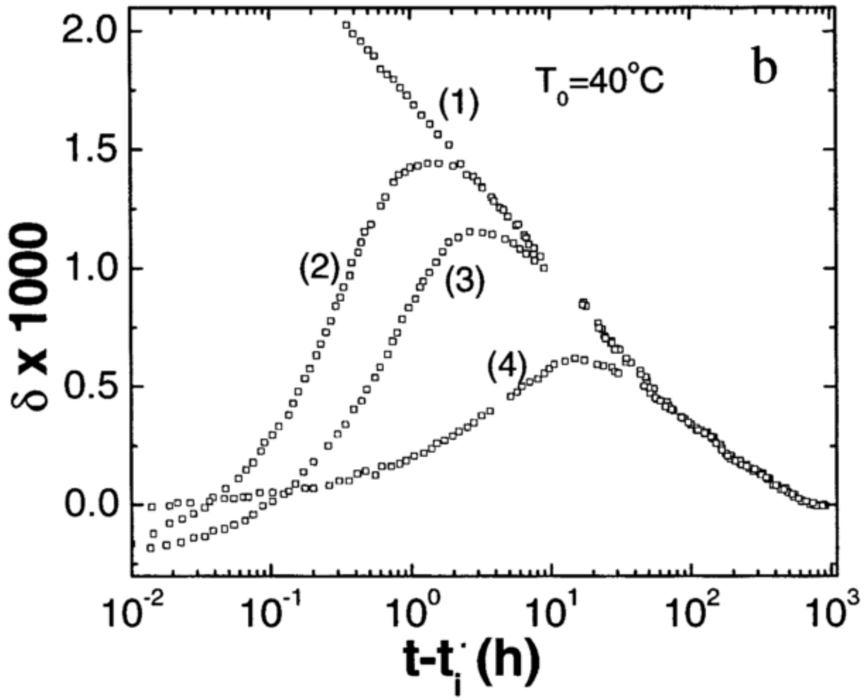
$$\delta = (V/V_\infty) - 1$$

Departure from Equilibrium

A. J. Kovacs, Adv. Polym. Sci. **3**, 394 (1963)
A. J. Kovacs et. al, J. Polym. Sci. B. **17**, 1097 (1979)

The Kovacs Memory Effect

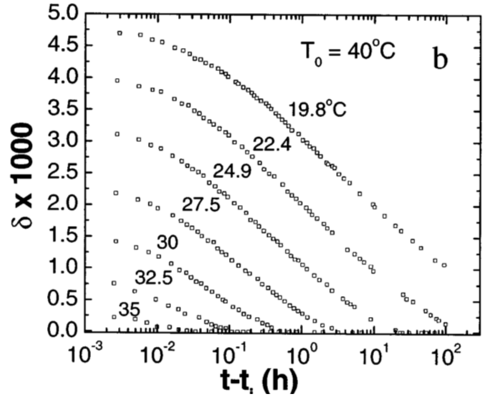




A. J. Kovacs, Adv. Polym. Sci. **3**, 394 (1963)
A. J. Kovacs et. al, J. Polym. Sci. B. **17**, 1097 (1979)

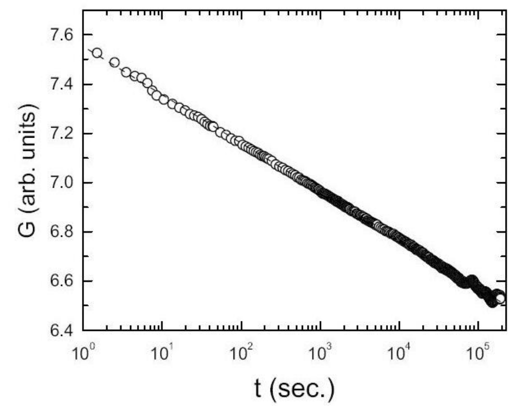
Slow Relaxations in disordered Systems

Amorphous materials



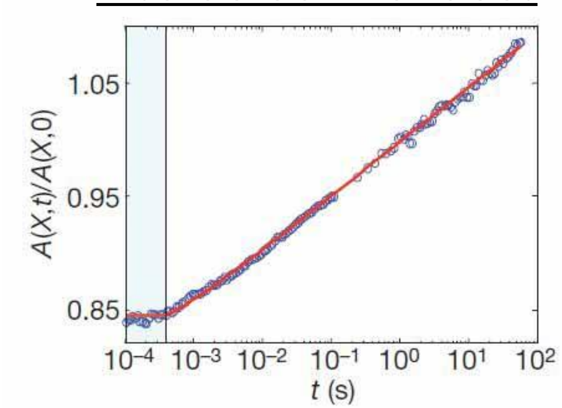
Kovacs, Adv. Polym. Sci (1963)

Disordered Electronic systems



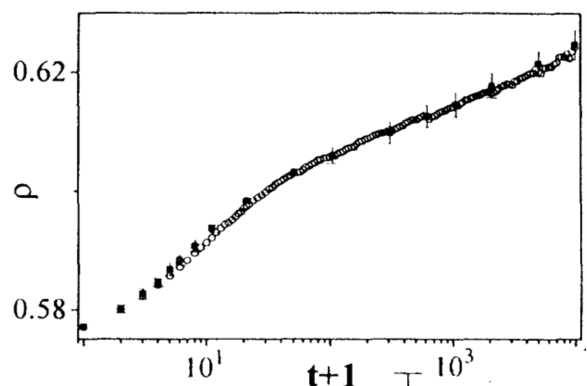
Ovadyahu, PRL (2003)

Disordered Interfaces



Ben-David, Rubinstein and Fineberg, Nature (2010)

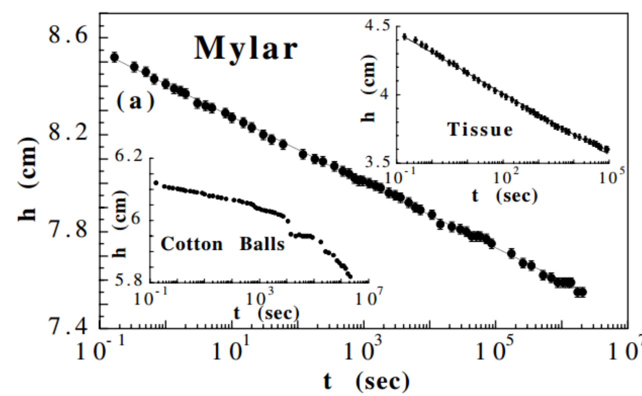
Granular compaction



Knight, Fandrich, Lau, Jaeger and Nagel, PRE (1995)

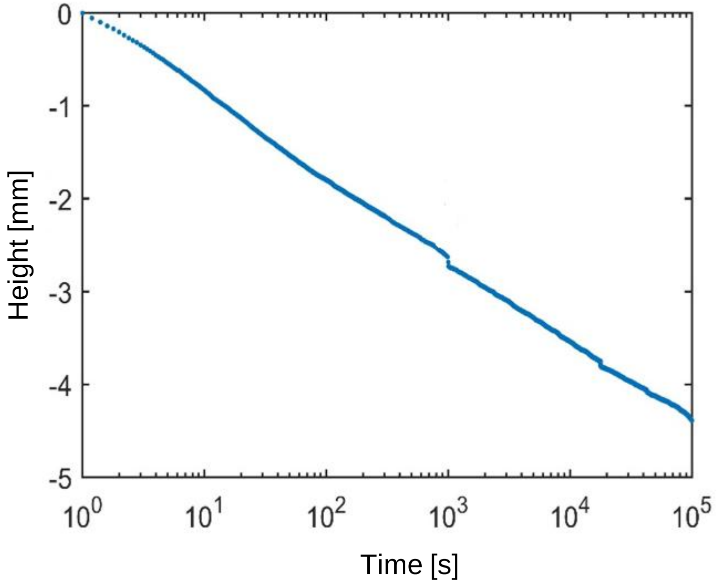
Brujic et al., PRL (2005)

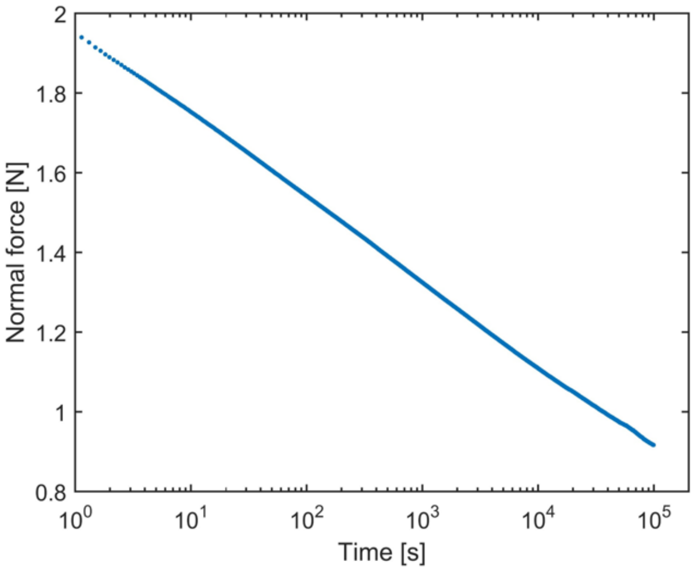
Crumpled sheets under load



Matan, Williams, Witten and Nagel, PRL(2002)

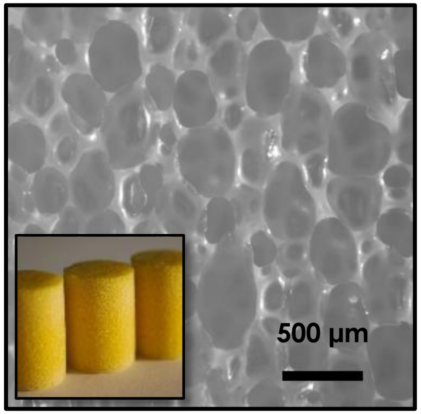
Slow Relaxation of Crumpled Thin Sheets

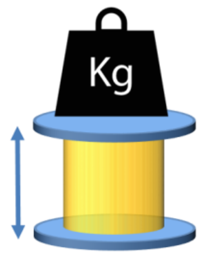


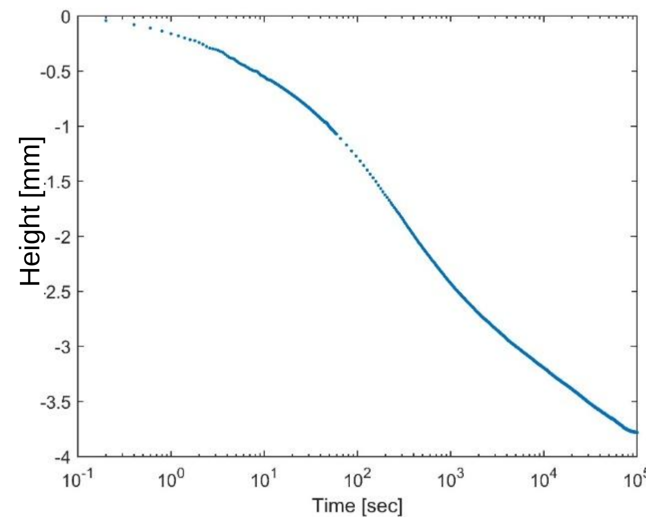


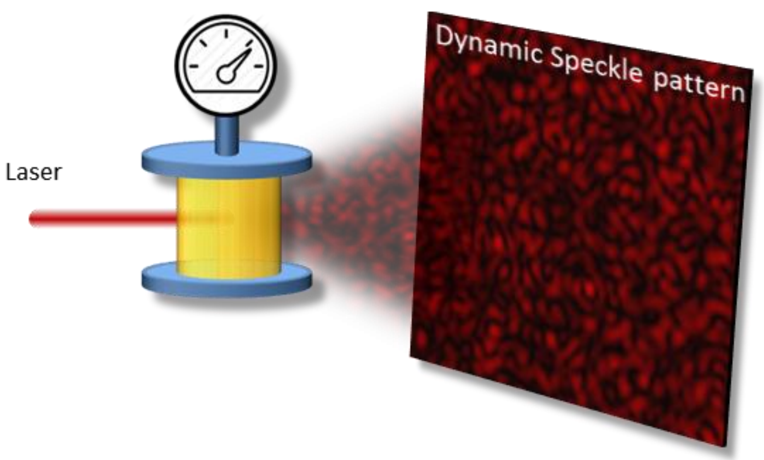
K. Matan, R. B. Williams, T. A. Witten, and S. R. Nagel, Phys. Rev. Lett. 88, 076101 (2002)

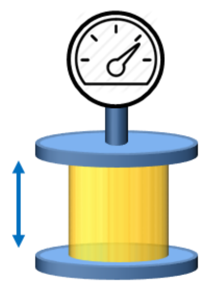
Slow relaxation of Elastic Foams

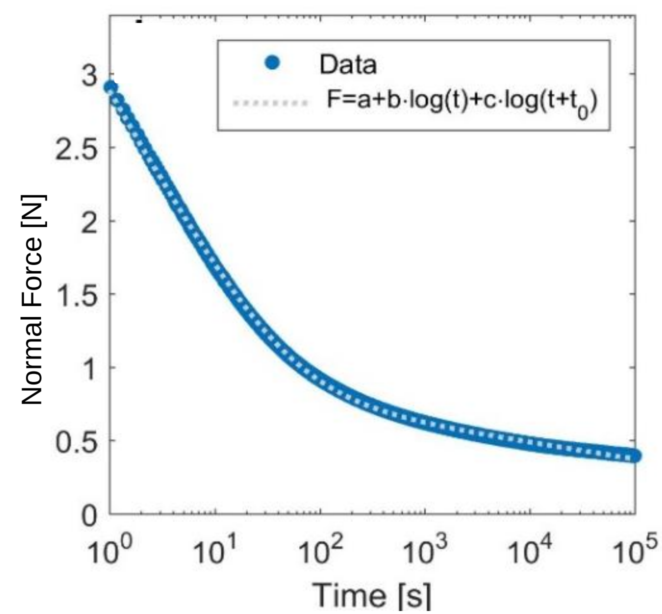




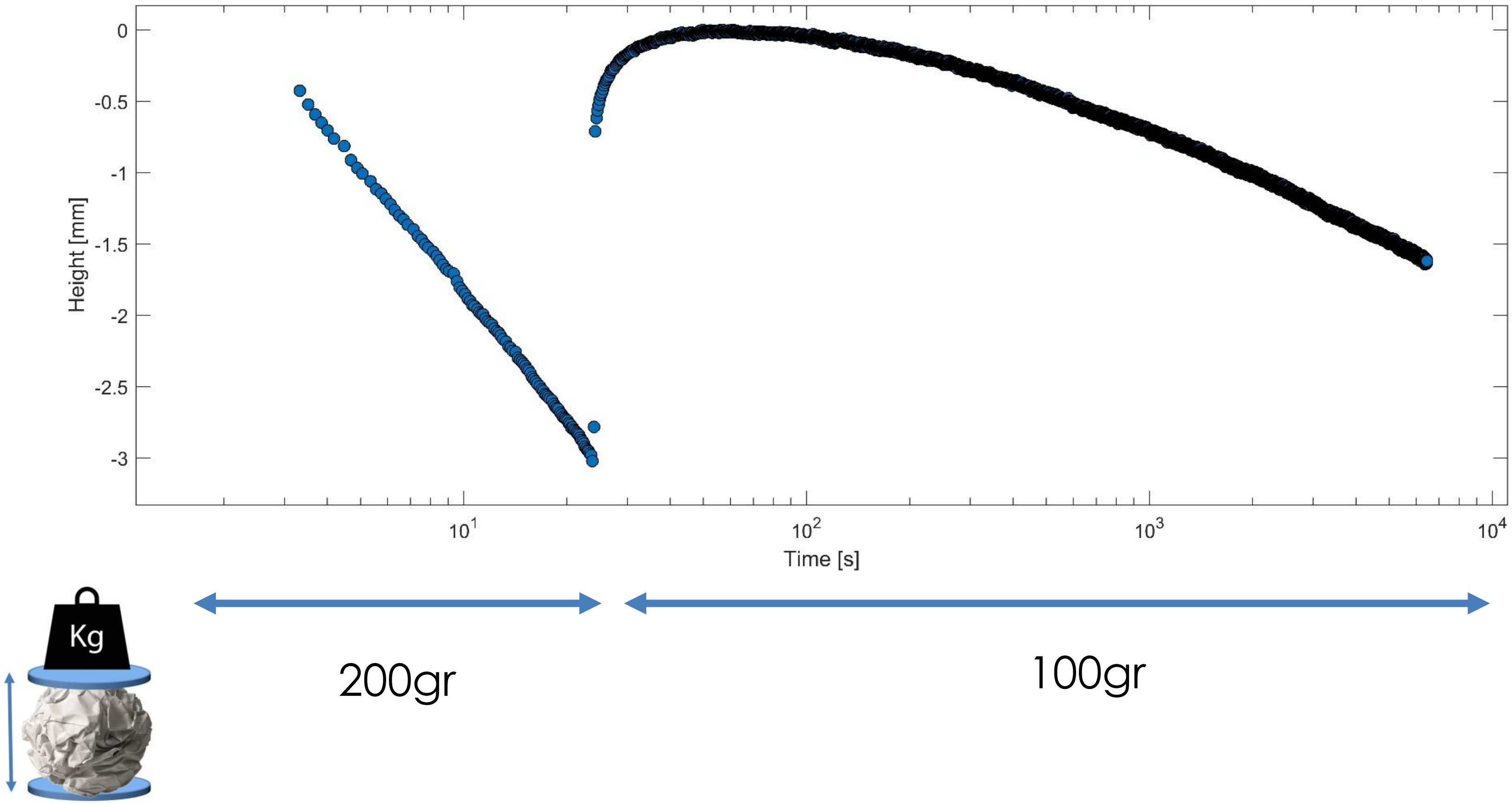








A two-step protocol



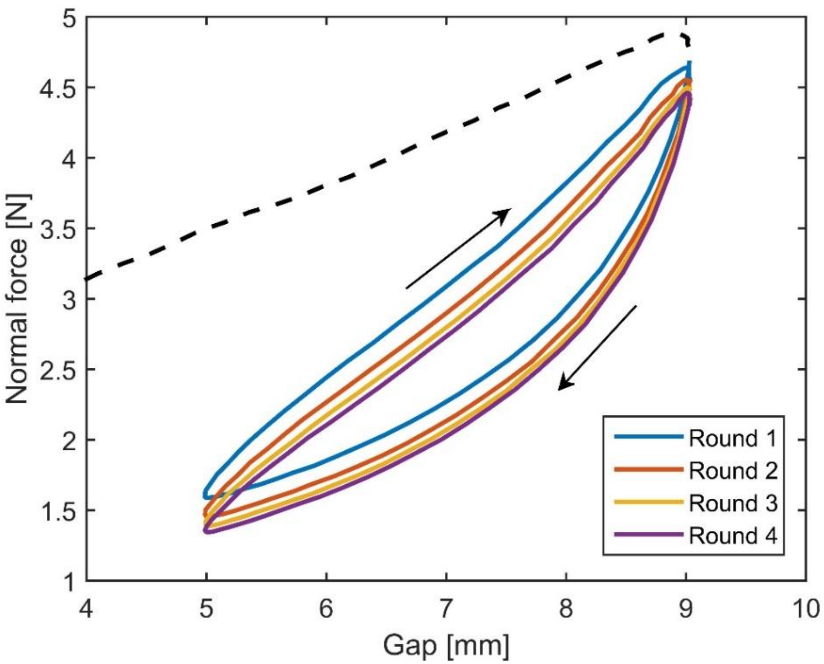
YL, O. Gottesman, A. Amir and S. M. Rubinstein, Phys. Rev. Lett. 118, 085501 (2017)

A. J. Kovacs, Adv. Polym. Sci. **3**, 394 (1963)

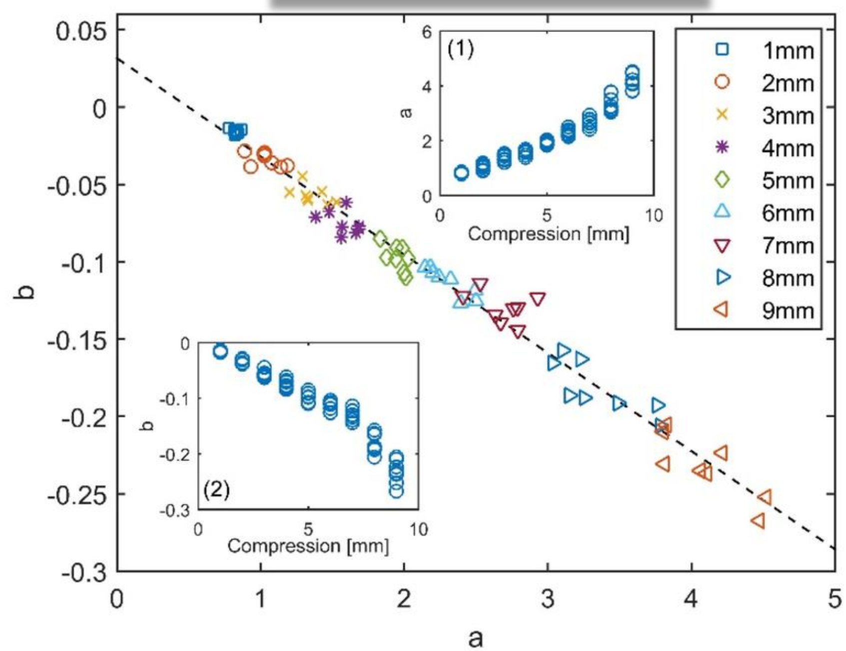
Getting reproducible results

Step 1: Make sure the system is disordered enough

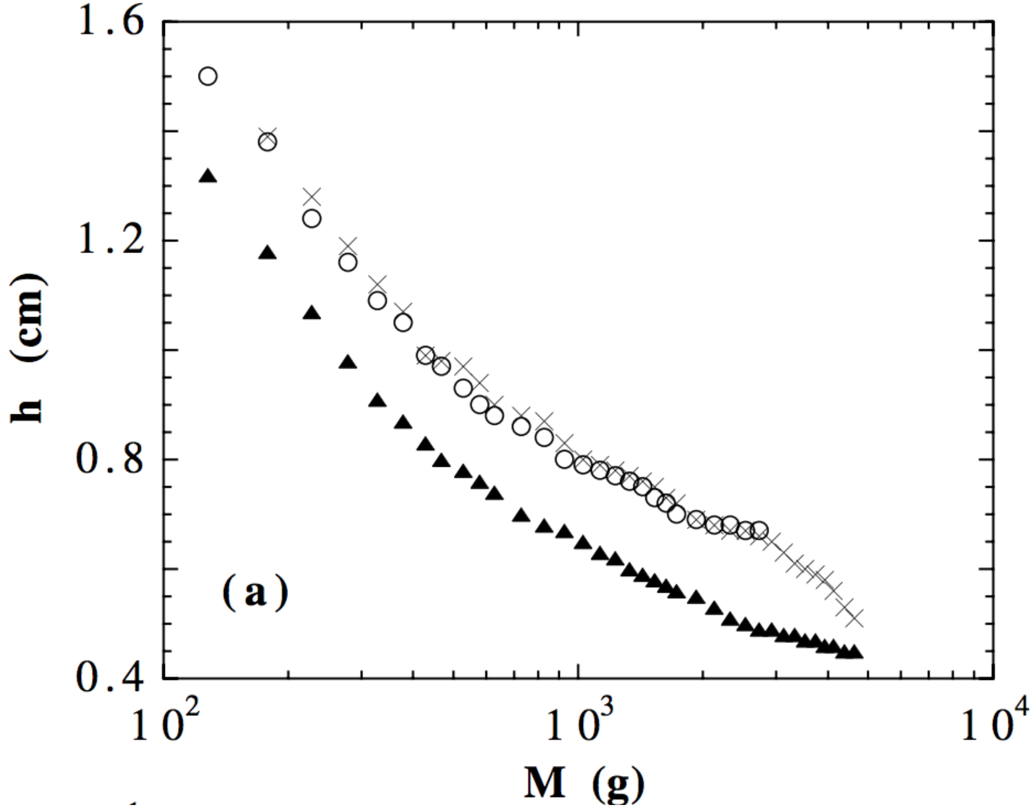
Step 2: Give it an initial "kvetch"



$$E(t) = a - b * \log(t)$$



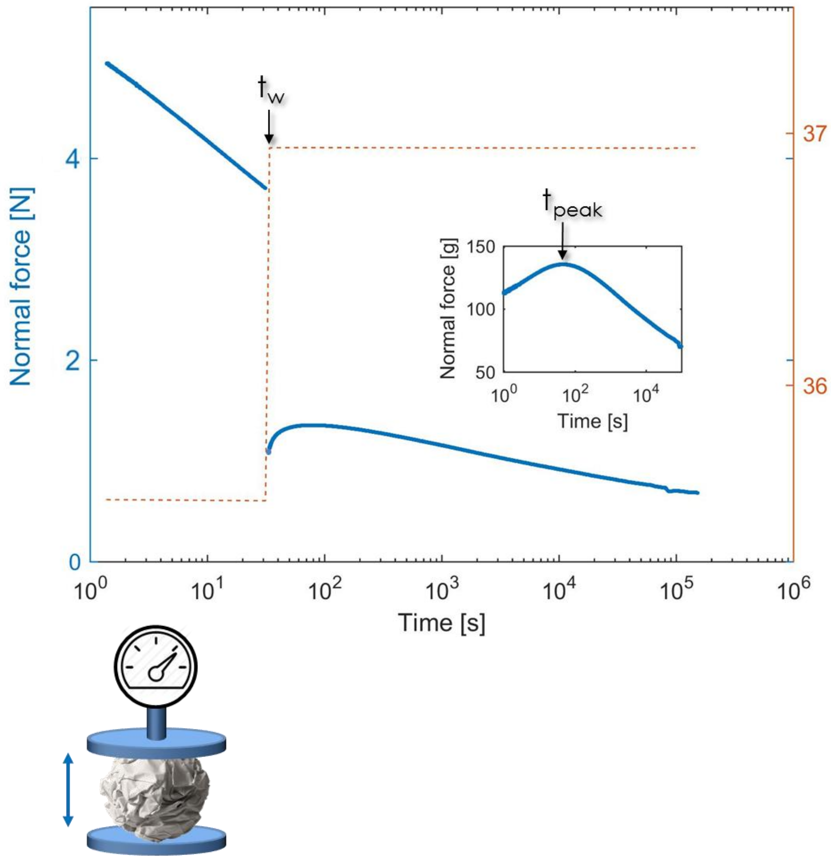
Memory or largest load in a crumpled sheet



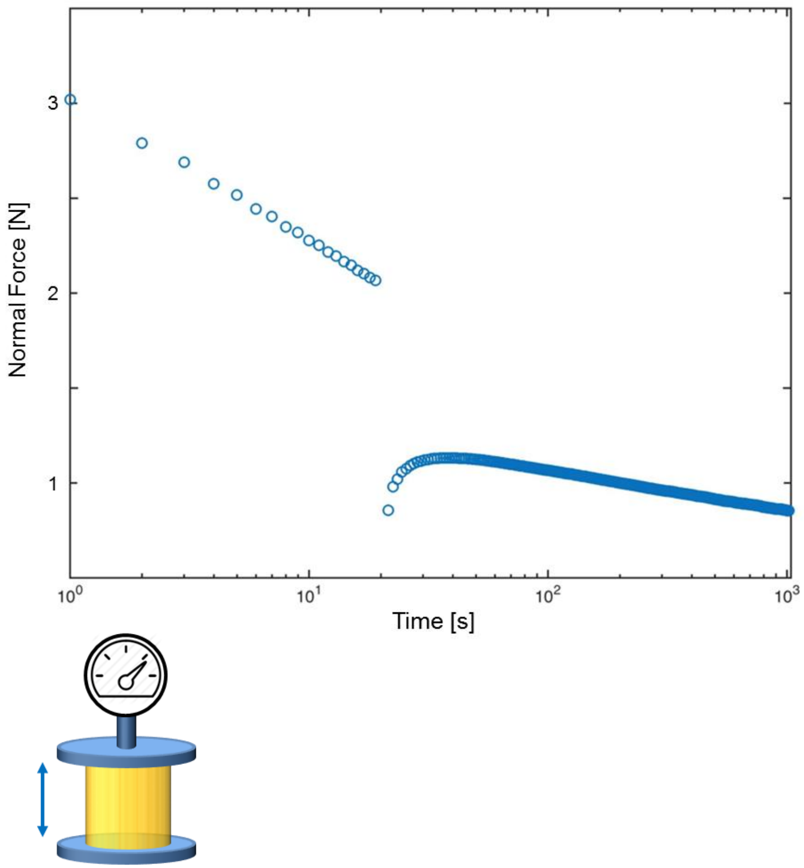
Matan, Williams, Witten and Nagel, PRL(2002)

Non-Monotonic Stress Relaxation

<u>Crumpled sheets</u>



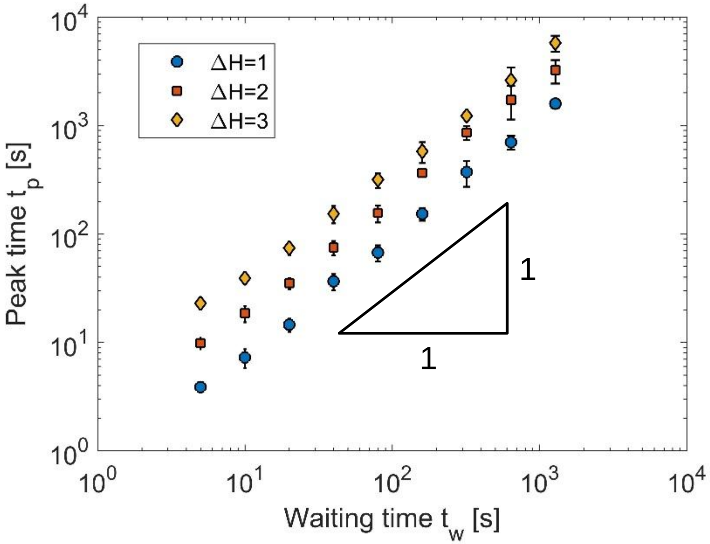
<u>Elastic foams</u>

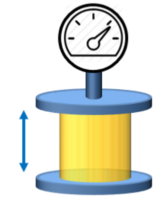


YL, O. Gottesman, A. Amir and S. M. Rubinstein, Phys. Rev. Lett. 118, 085501 (2017)

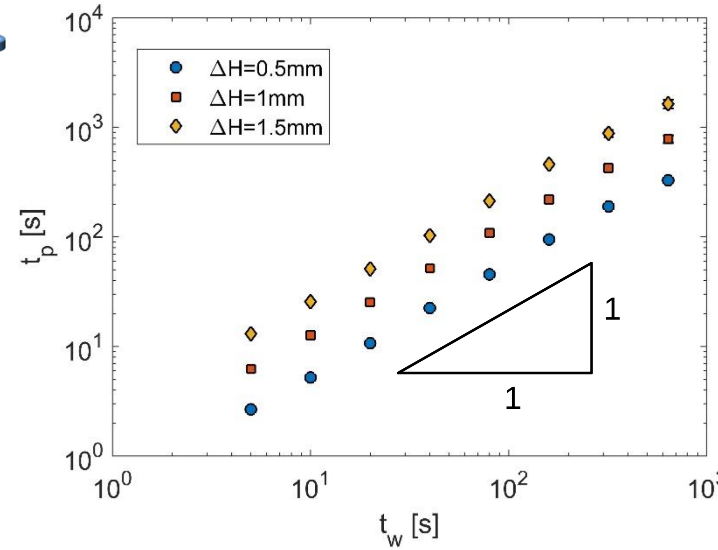
A memory Effect!

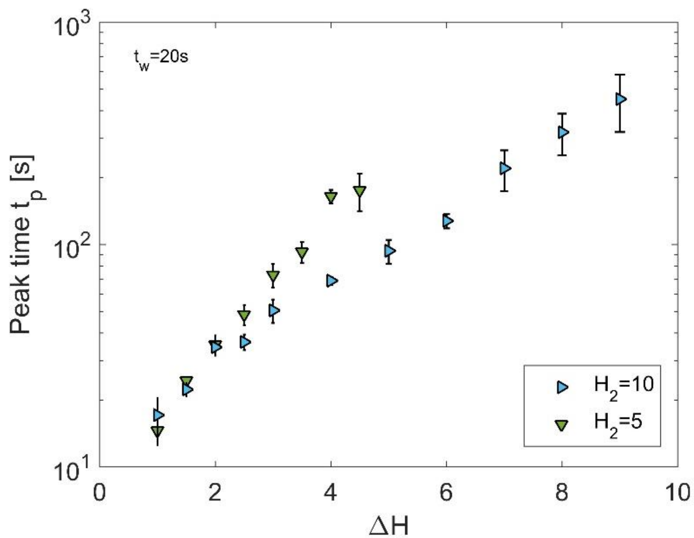
Crumpled sheets

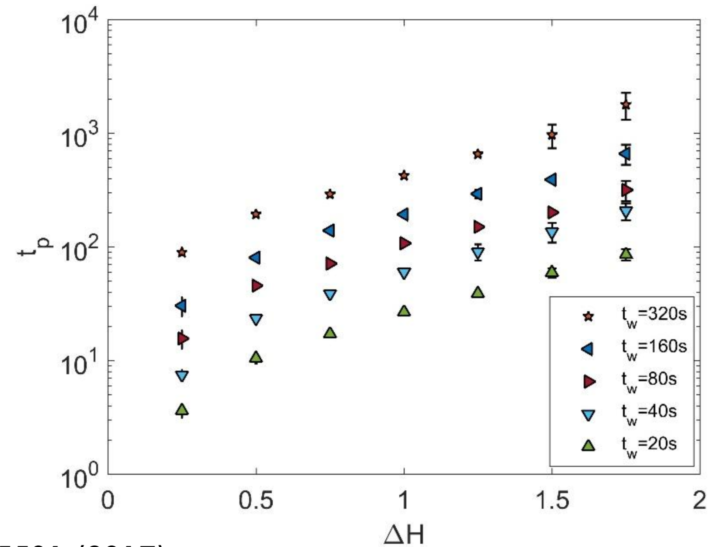




Elastic foams







YL, O. Gottesman, A. Amir and S. M. Rubinstein, Phys. Rev. Lett. 118, 085501 (2017)

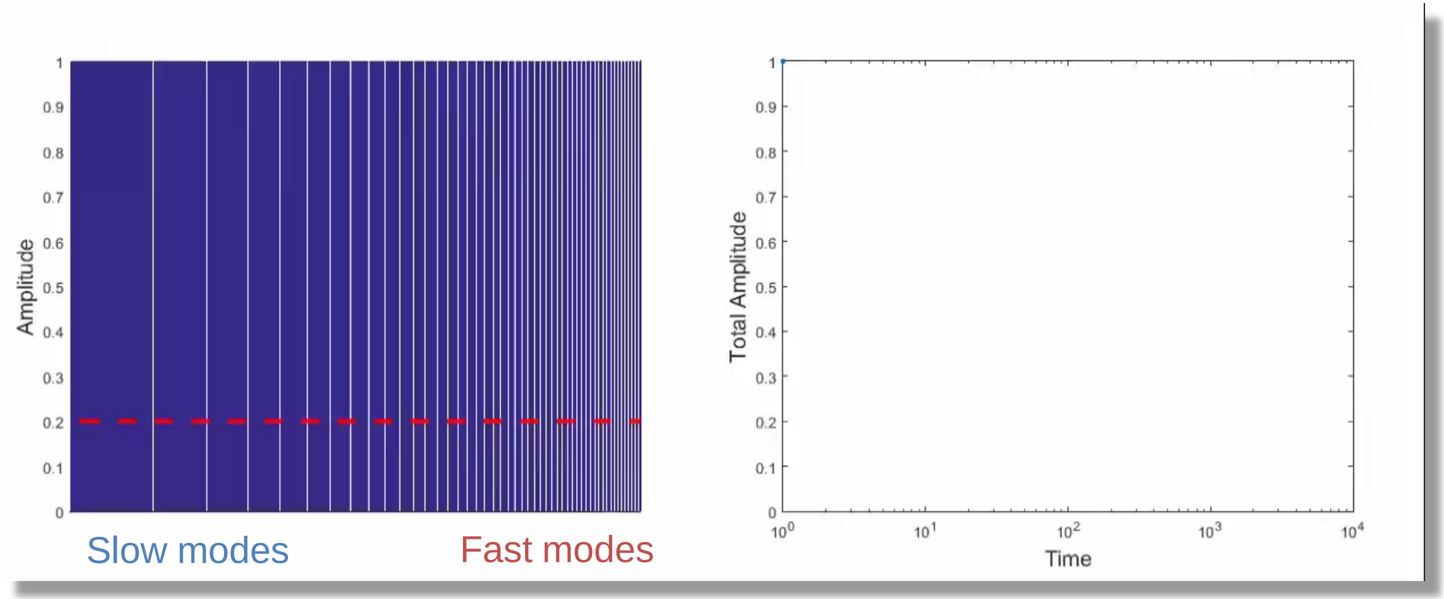
A phenomenological model for slow relaxation and aging

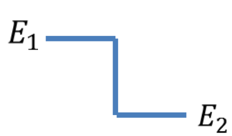
Assumptions:

- The overall Relaxation is a superposition of **many** exponential relaxations $e^{-\lambda t}$

- The relaxation rates are **broadly** distributed $\lambda_{min} \ll \lambda_{max}$

- The **distribution** of relaxations rates λ goes like $1/\lambda$





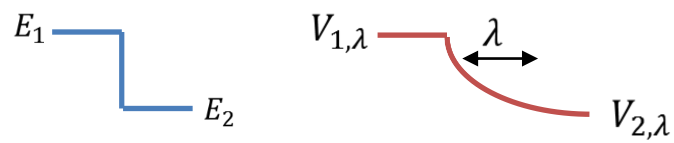
$$V(t) = A - B(E_2 - E_1)\log(t)$$

A. Amir, Y. Oreg, and Y. Imry PRB 77, 165207 (2008); PRL 103, 126403 (2009); PRL105, 070601 (2010); PNAS 109 (6), 1850-1855 (2012); PRL 107 186407 (2011)

A phenomenological model for slow relaxation and aging

Assume relaxation due to a superposition of **many** exponential relaxations, with a **broad distribution of relaxation rates.**

Single relaxation:



$$V_\lambda(t) = V_{E_2,\lambda} + e^{-\lambda t}\left(V_{E_1,\lambda} - V_{E_2,\lambda}\right) = V_{E_2,\lambda} + b e^{-\lambda t}(E_1 - E_2)$$

$$V_i = a + bE_i$$

Sum of all relaxations

$$V(t) = \int_{\lambda_{min}}^{\lambda_{max}} P(\lambda) V_\lambda(t) = V_{eq,E_2} + b(E_1 - E_2)\int_{\lambda_{min}}^{\lambda_{max}} \frac{1}{\lambda} e^{-\lambda t}$$

$$P(\lambda) \sim \frac{1}{\lambda}$$

$$= V_{eq,E_2} + b(E_2 - E_1)[E_i(\lambda_{min} t) - E_i(\lambda_{max} t)]$$

$$\frac{1}{\lambda_{min}} \gg t \gg \frac{1}{\lambda_{max}}$$

$$V(t) = V_{eq,E_2} - b(E_2 - E_1)\log(\lambda_{min} t)$$

$$V(t) = A - B\log(t)$$

A. Amir, Y. Oreg, and Y. Imry PRB 77, 165207 (2008); PRL 103, 126403 (2009); PRL 105, 070601 (2010); PNAS 109 (6), 1850-1855 (2012); PRL 107 186407 (2011)

A model for non-monotonic aging and Memory (A. Amir)

External drive is switched during the relaxation:

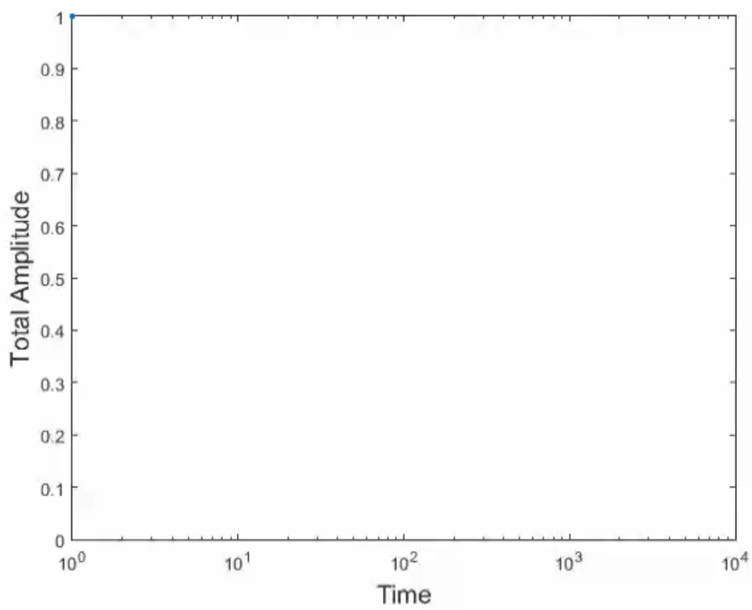
$$0 < t < t_w \qquad V_\lambda(t) = V_{E_2,\lambda} + \mathrm{e}^{-\lambda t}\left(V_{E_1,\lambda} - V_{E_2,\lambda}\right)$$

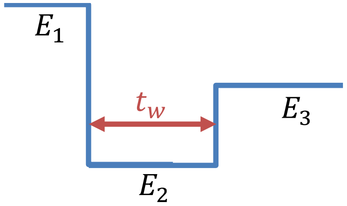
$$t > t_w \quad V_\lambda(t) = V_{E_3,\lambda} + e^{-\lambda t}\left(\left[V_{E_2,\lambda} + e^{-\lambda t_w}\left(V_{E_1,\lambda} - V_{E_2,\lambda}\right)\right] - V_{E_3,\lambda}\right)$$

$$V(t) = A - B(E_3 - E_2)\log(t) + B(E_2 - E_1)\log(t + t_w)$$

YL, O. Gottesman, A. Amir, and S. M. Rubinstein, Phys. Rev. Lett. **118**, 085501 (2017)

A model for non-monotonic aging and Memory (A. Amir)





$$V(t) = A - B(E_3 - E_2)\log(t) + B(E_2 - E_1)\log(t + t_w)$$

When is the peak?

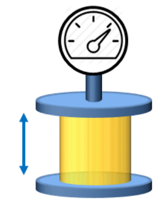
$$\frac{E_2 - E_3}{t_{peak}} = \frac{E_2 - E_1}{t_{peak} + t_w}$$

$$t_{peak} = \frac{E_2 - E_3}{E_3 - E_1} t_w$$

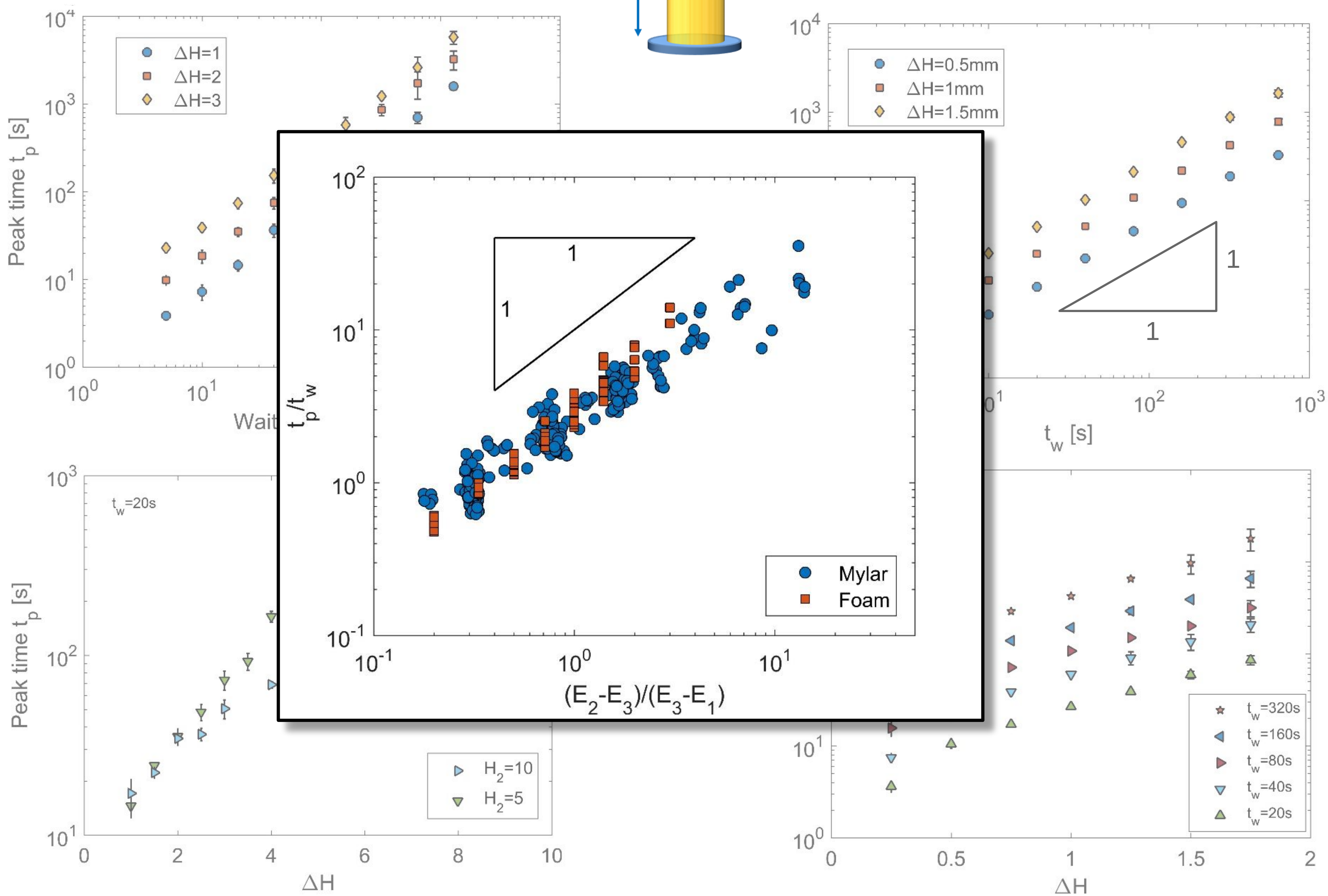
YL, O. Gottesman, A. Amir, and S. M. Rubinstein, Phys. Rev. Lett. **118**, 085501 (2017)

Memory effects

Crumpled sheets



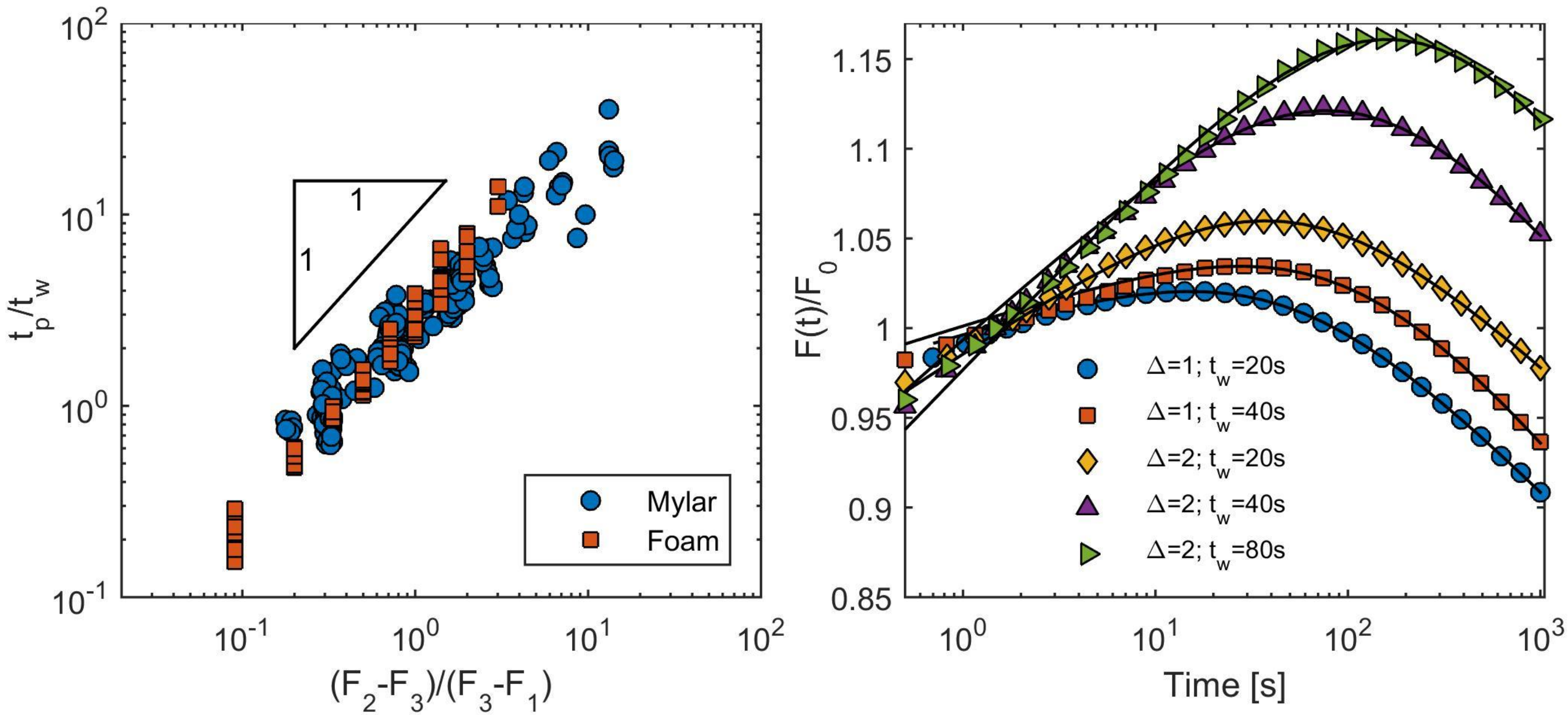
Elastic foams



Y. Lahini, O. Gottesman, A. Amir and S. M. Rubinstein, Phys. Rev. Lett. 118, 085501 (2017)

Fitting the memory curve

$$V(t) = A - B\,(E_3 - E_2)\log(t) + B(E_2 - E_1)\log(t + Ct_w)$$



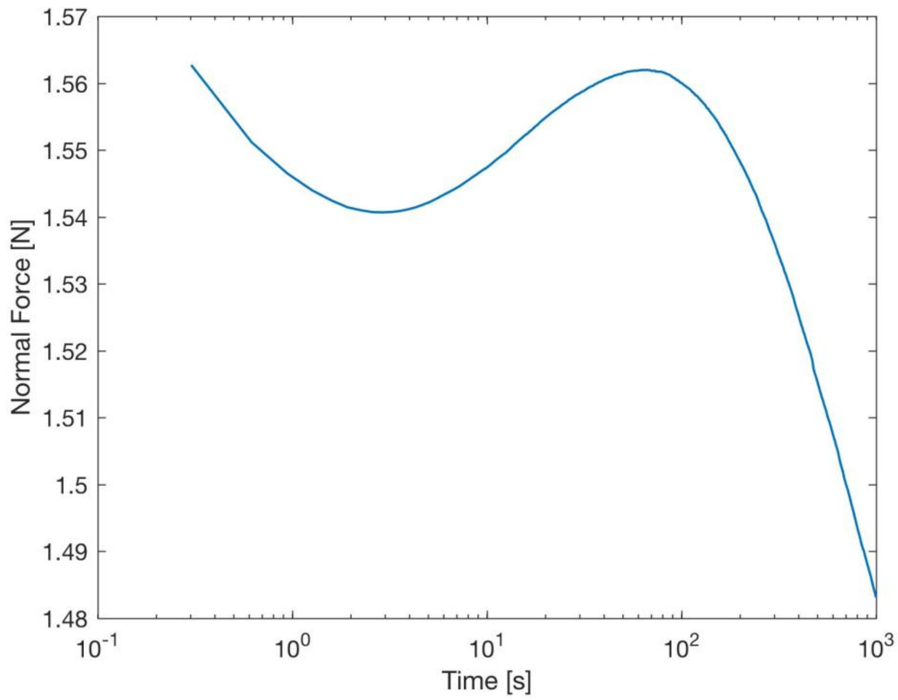
Crumpled sheets C=~2.6±0.2

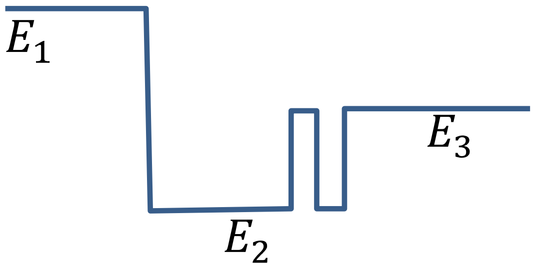
Elastic Foams C=~2.5±0.2

Y. Lahini, O. Gottesman, A. Amir and S. M. Rubinstein, Phys. Rev. Lett. 118, 085501 (2017)

Question:

How Much Memory can be stored in a given system?
What determines the memory capacity? (Size, disorder, ...?)

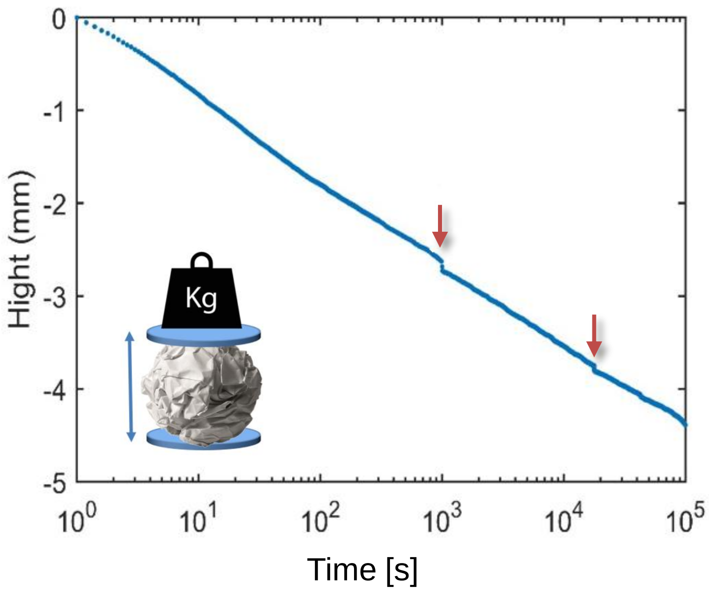




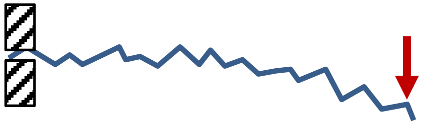
Questions:

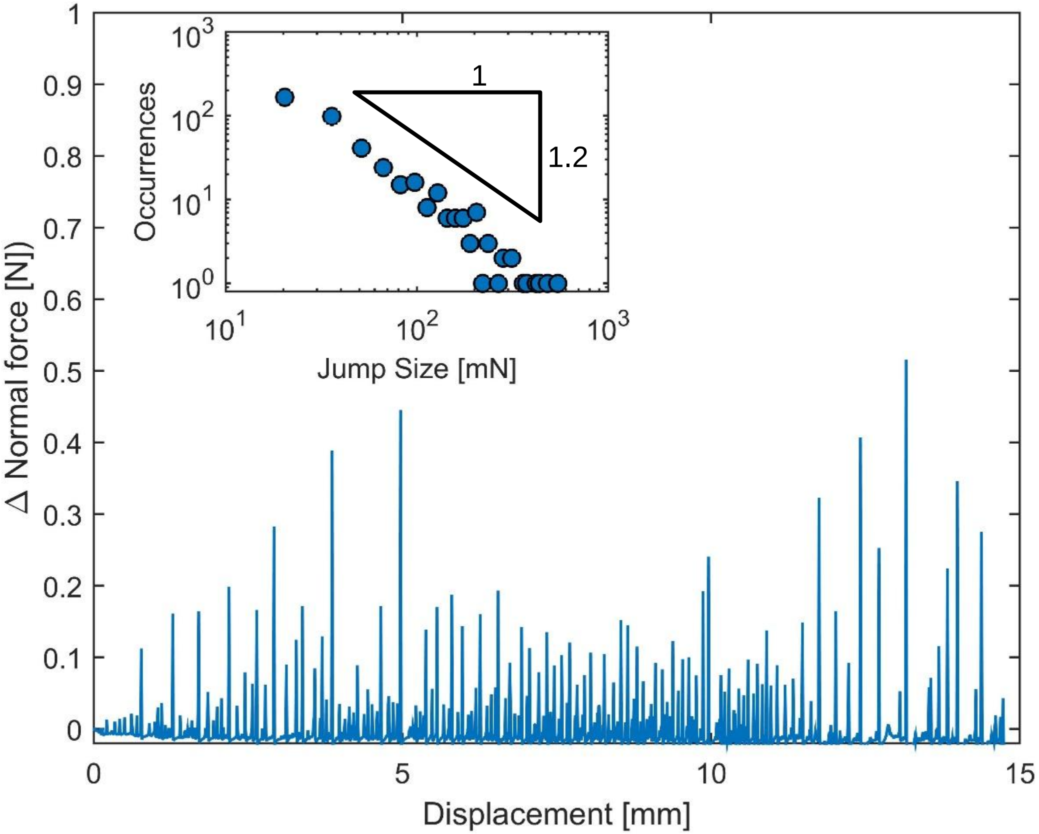
- Where is the memory stored? (Material? Meta-material structure?...)
- How is memory encoded and retrieved?

Intermittent dynamics of crumpled sheets

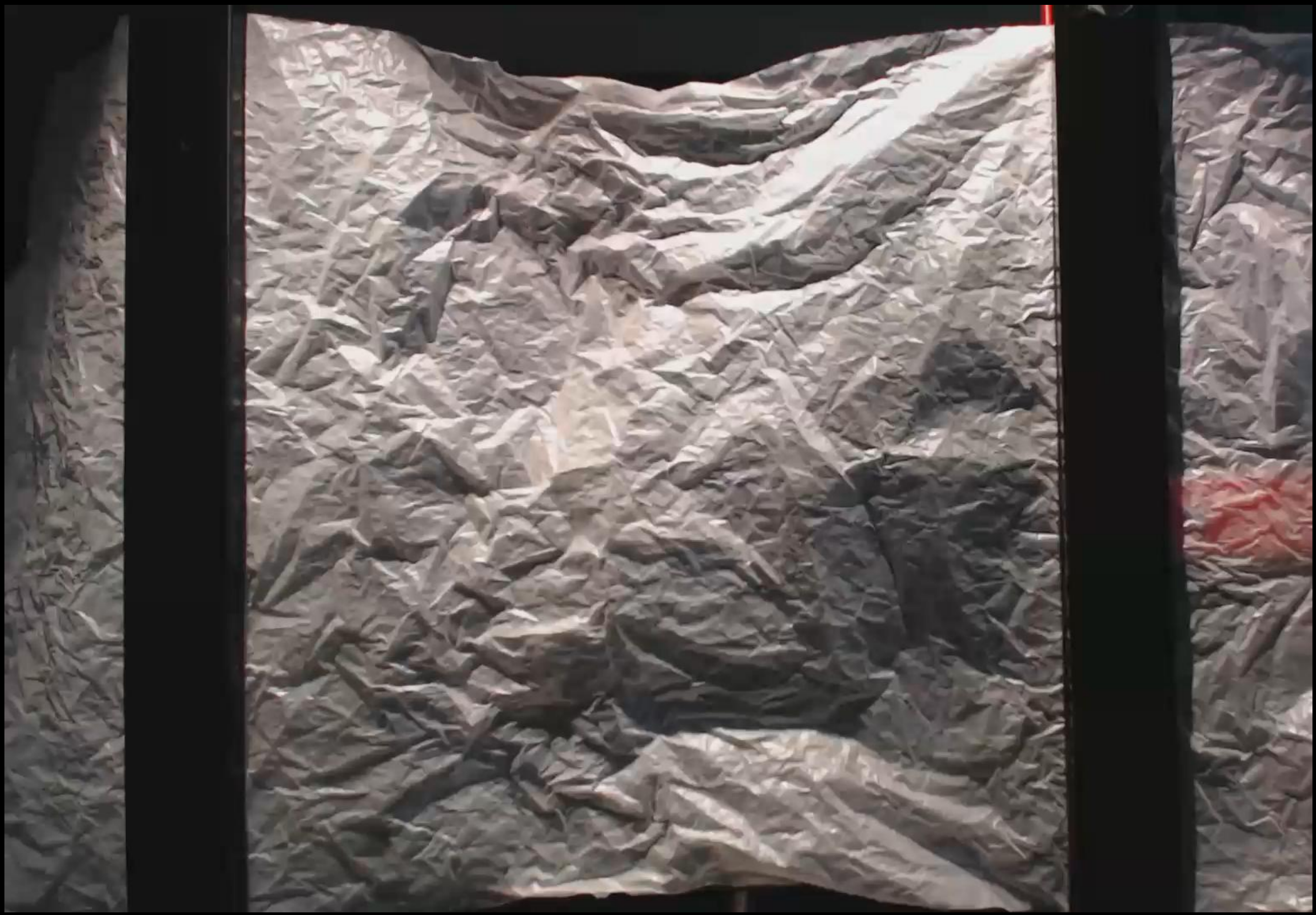


Intermittent Mechanics of crumpled sheets

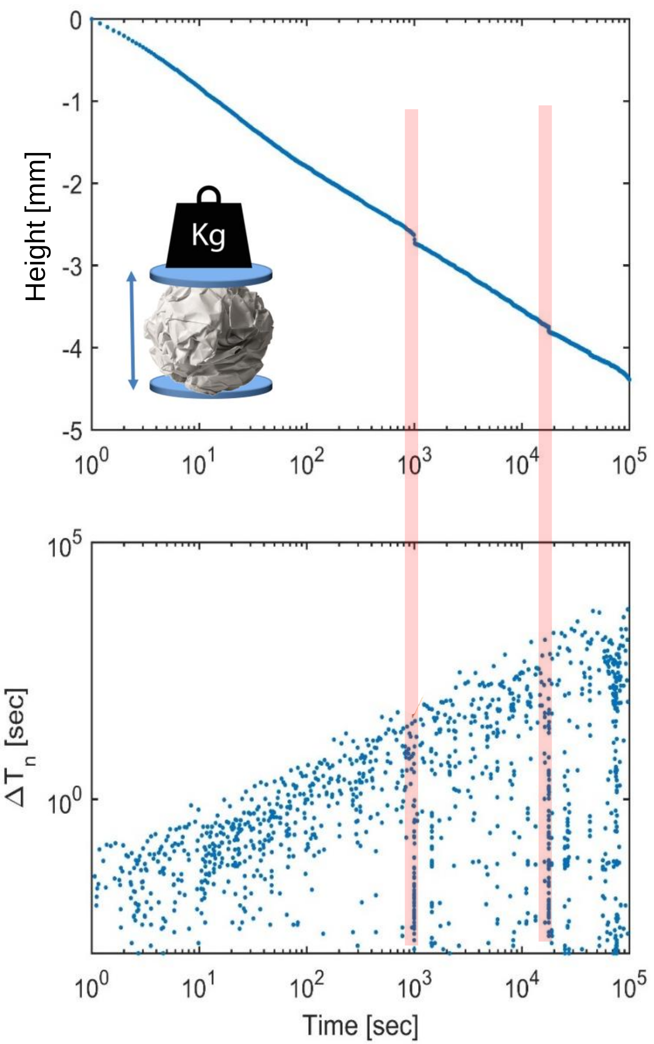


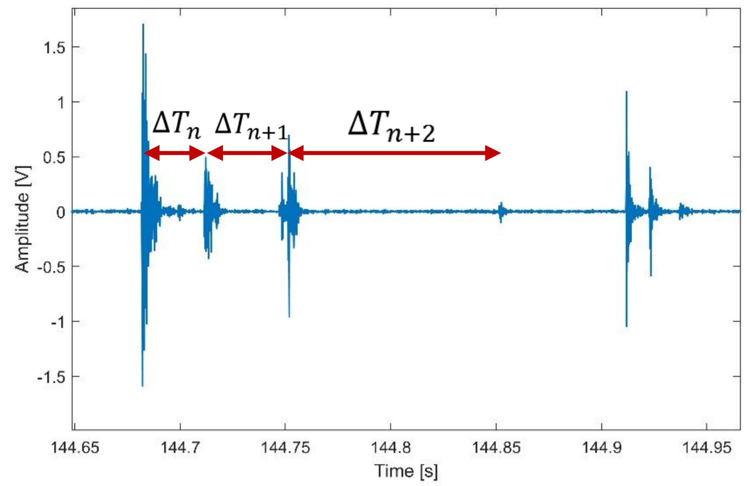


What's crackling?



Crackling and avalanches during relaxation



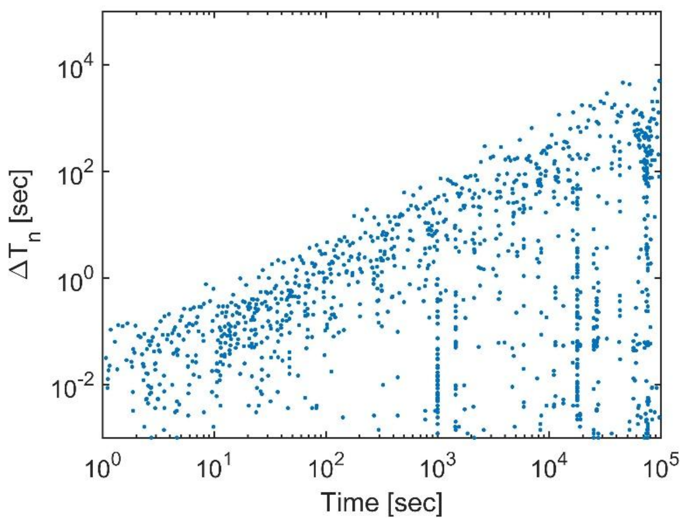


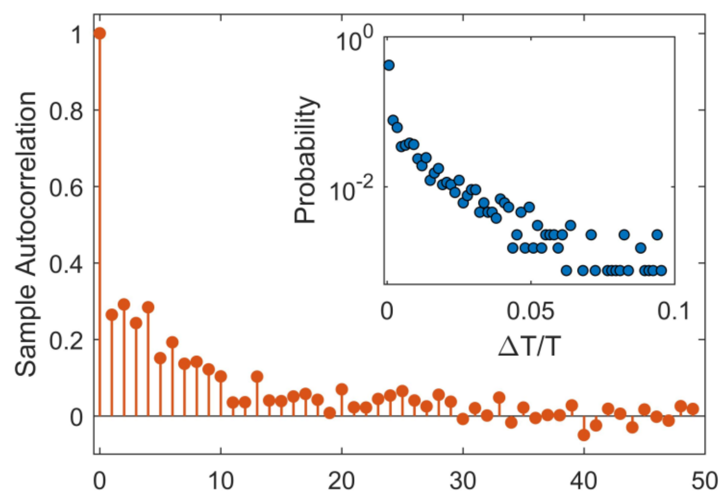
Intermittent features in the relaxation curve correspond to **avalanches** in the crackling sounds

Kramer EM, Lobkovsky A, PRE 53,1465 (1996)
Houle P, Sethna J, PRE 54 278 (1996)

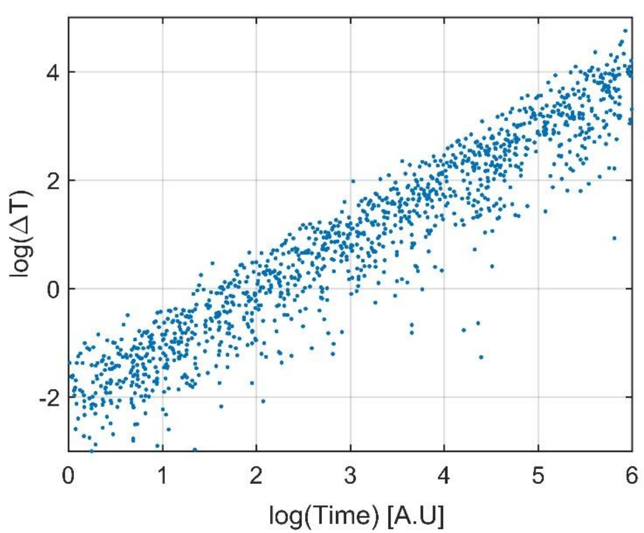
Correlated crackling during logarithmic relaxation

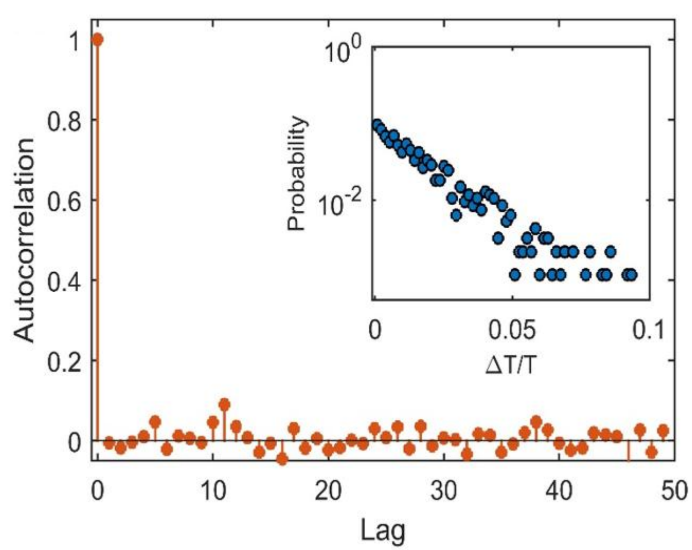
Experiment



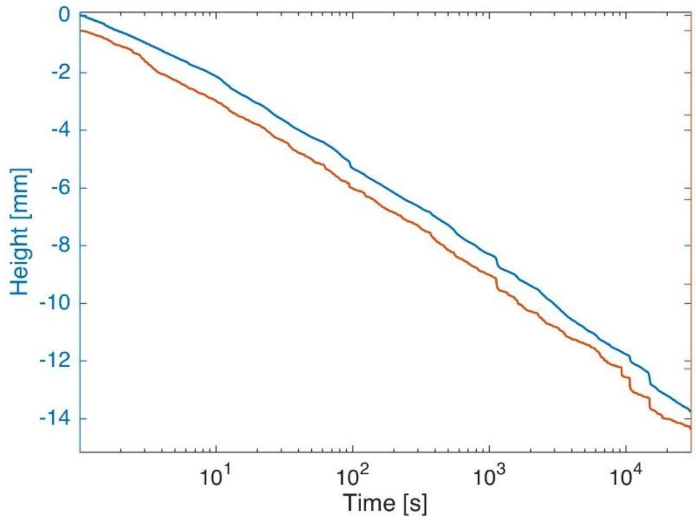


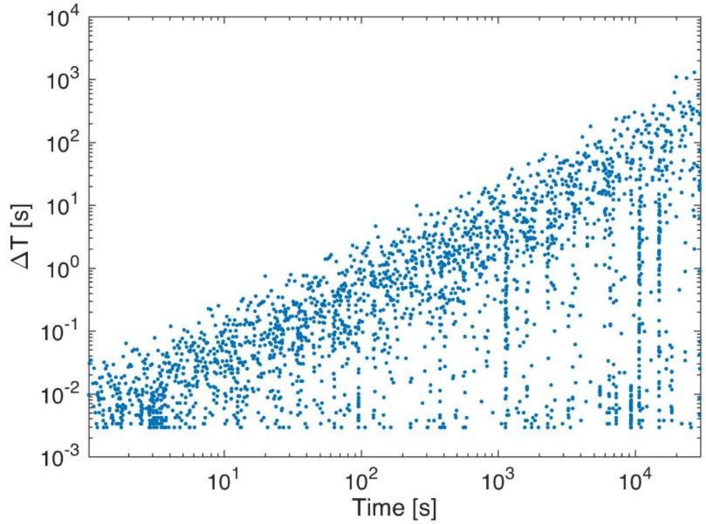
Model prediction





Emitted Acoustic Energy VS Height

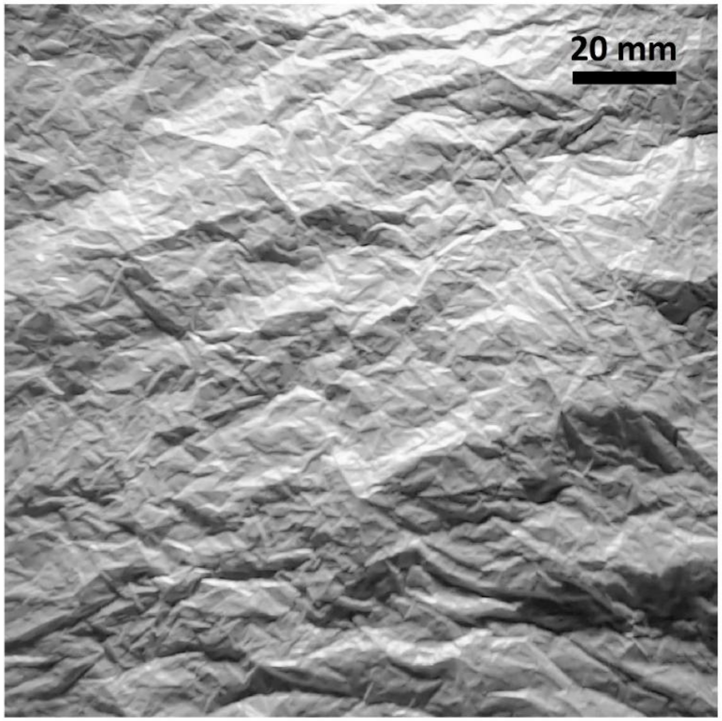


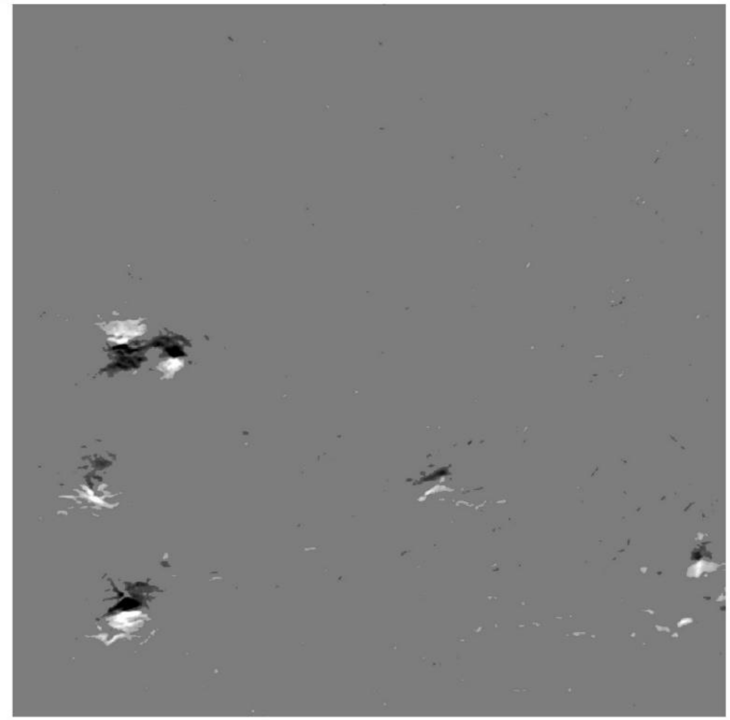


Single snap-through event

Delayed instabilities in viscoelastic solids through a metric description
Erez Y. Urbach, Efi Efrati arXiv:1711.09491

The mechanics of crumpled media

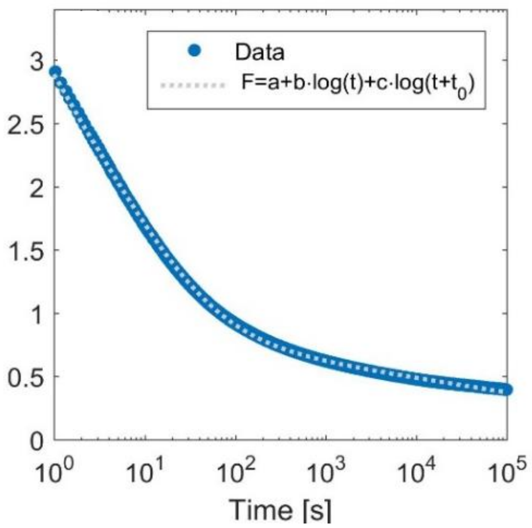


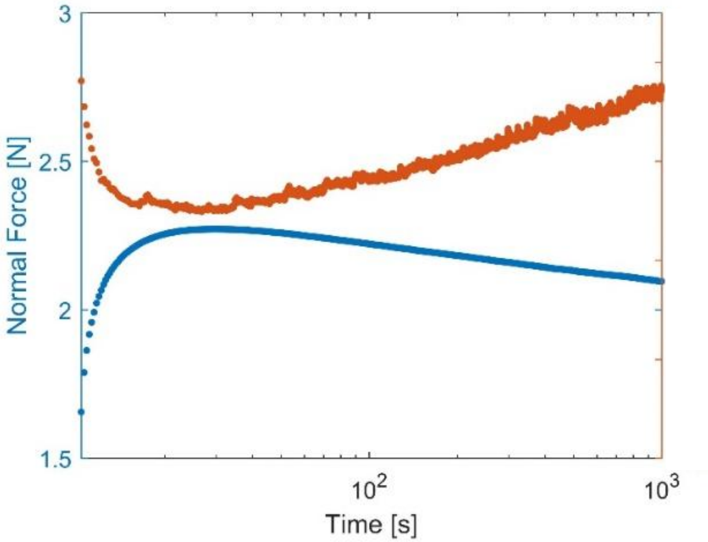


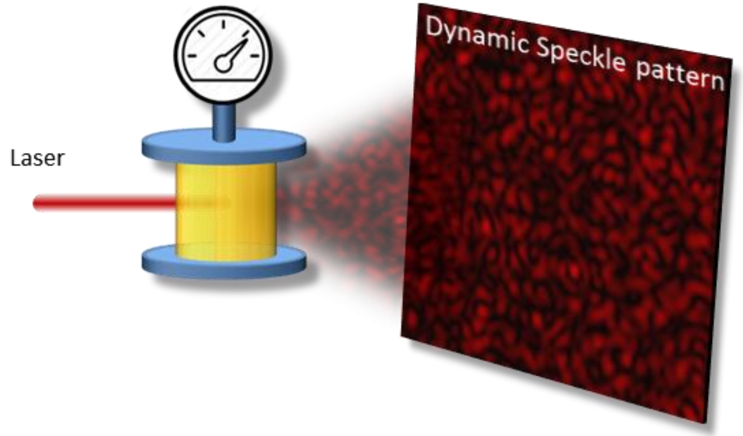
- Are there spatial and / or temporal correlations between events?
- Are these similar to the avalanche dynamics during relaxation?
- Can we see growing length scales?
- Can we observe log relaxation? Memeory? What happens during the non-monotonic response?

3D structure – crumpled sheets

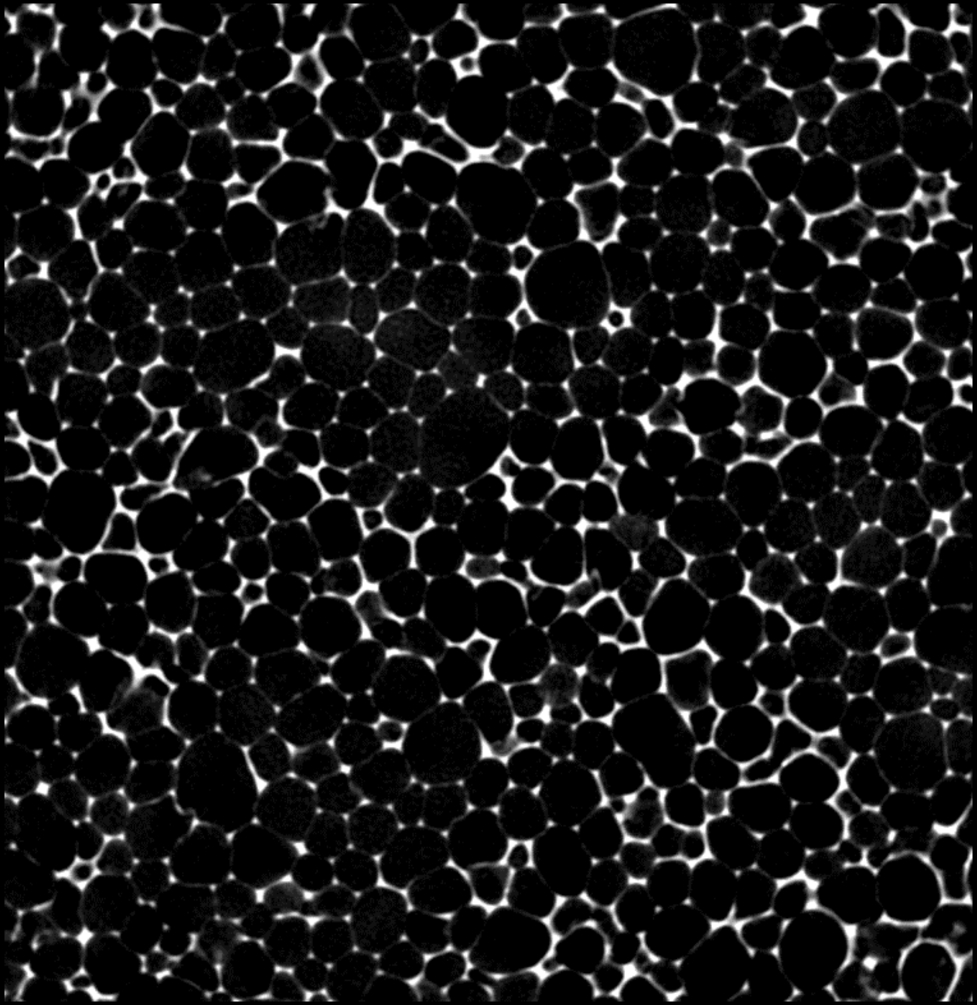
Probing the internal dynamics in elastic foams



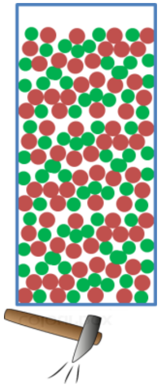


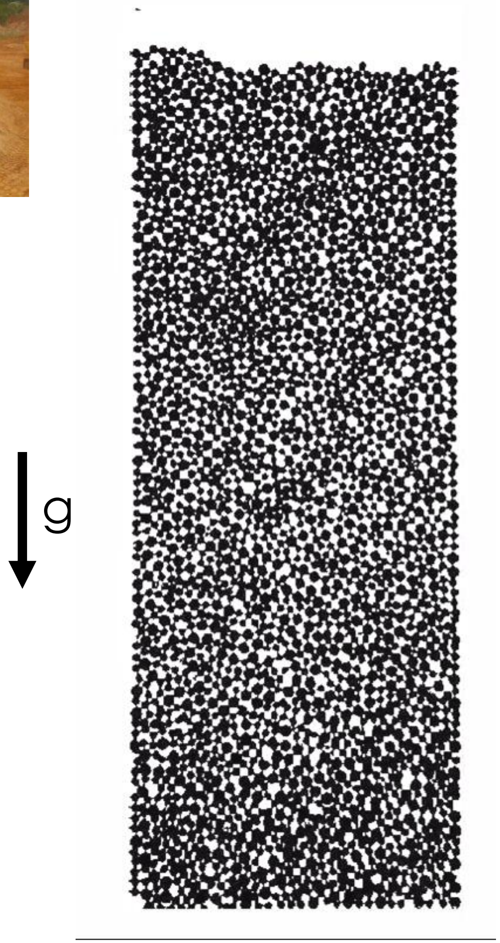


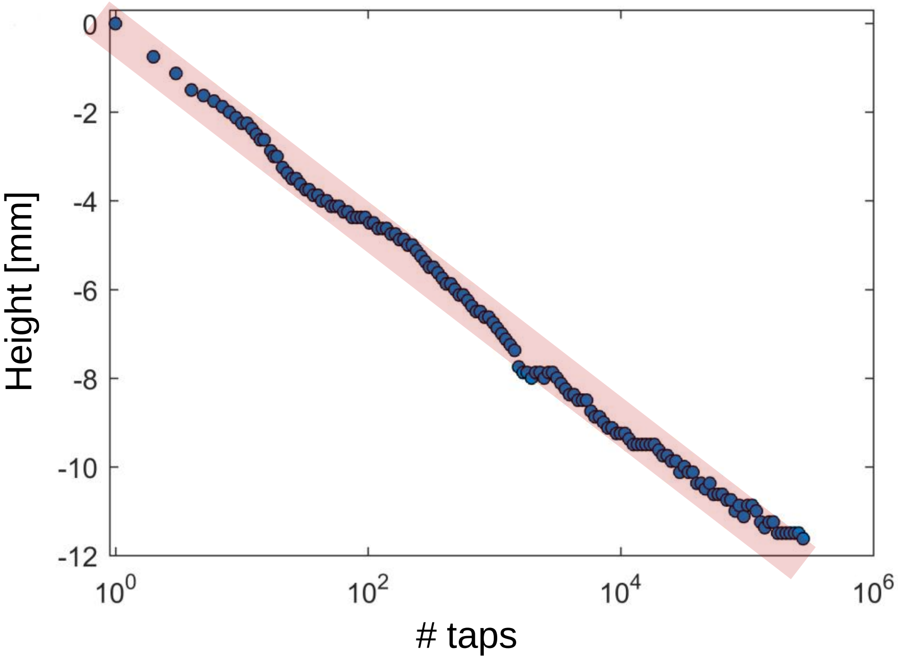
3D structure – elastic foams



Granular piles

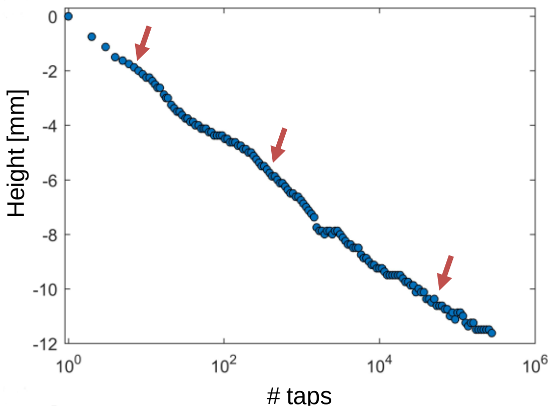


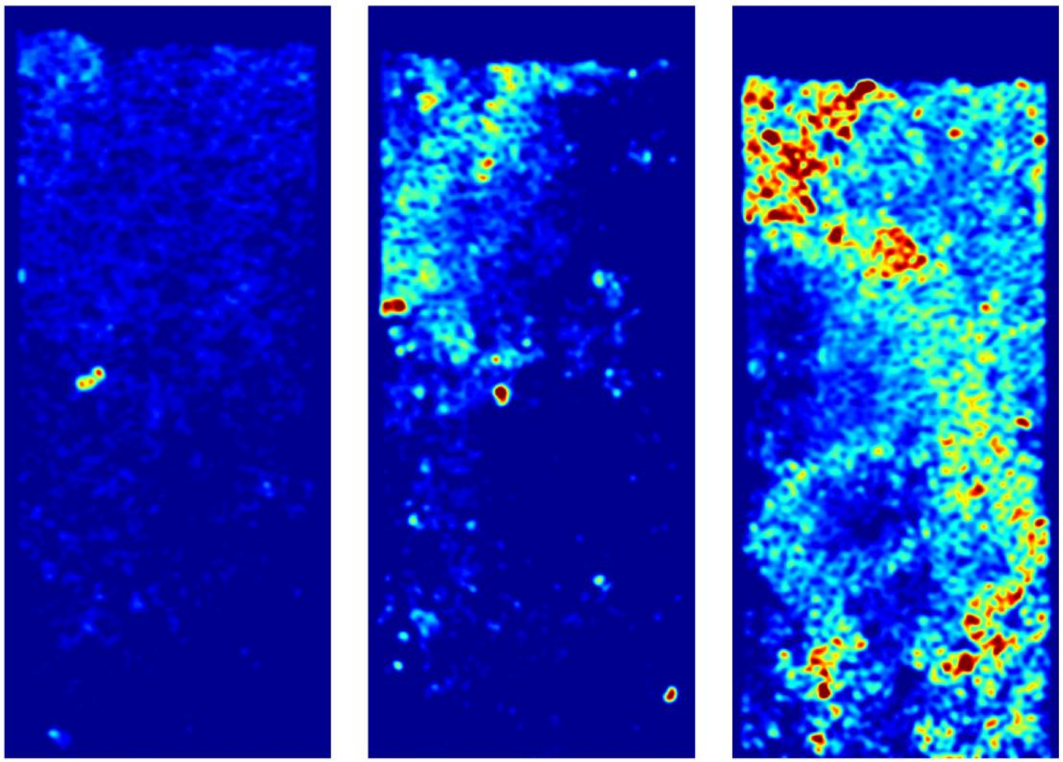




Knight et al., PRE 1995
Brujic et al., PRL 2005

Growing length scales during compaction





Memory effects in granular piles?

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Memory Effects in Granular Materials

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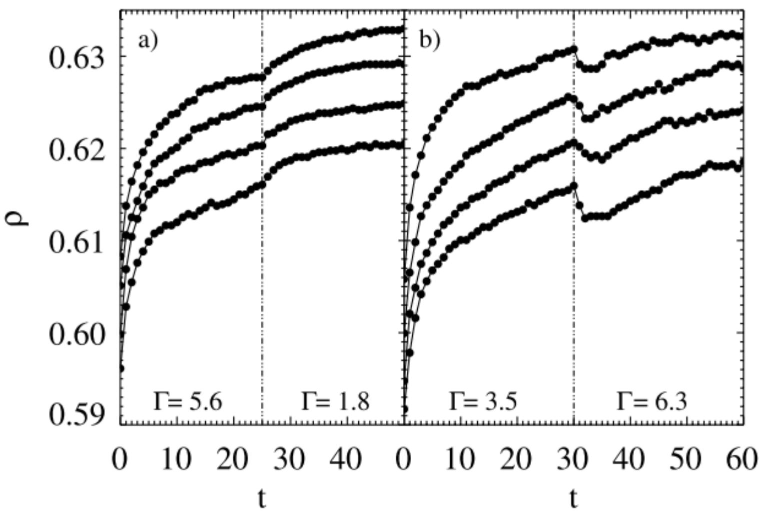
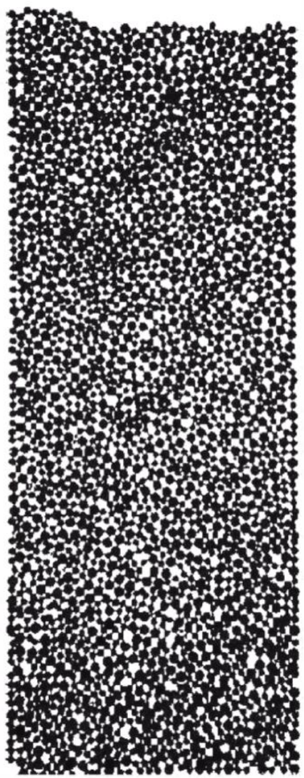


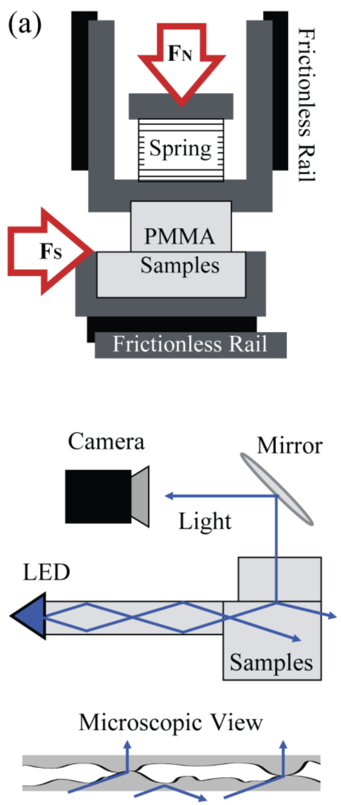
FIG. 1. Evolution of the packing fraction, ρ, at four heights in the column, as a function of tap number, t. Two different single-switch experiments: (a) Γ was lowered from 5.6 to 1.8 at $t_0 = 25$; and (b) Γ was increased from 3.5 to 6.3 at $t_0 = 30$. Curves are shifted vertically for clarity. Each curve is an average over 4 runs, and the measurement uncertainty in ρ is 4×10^{-4}.

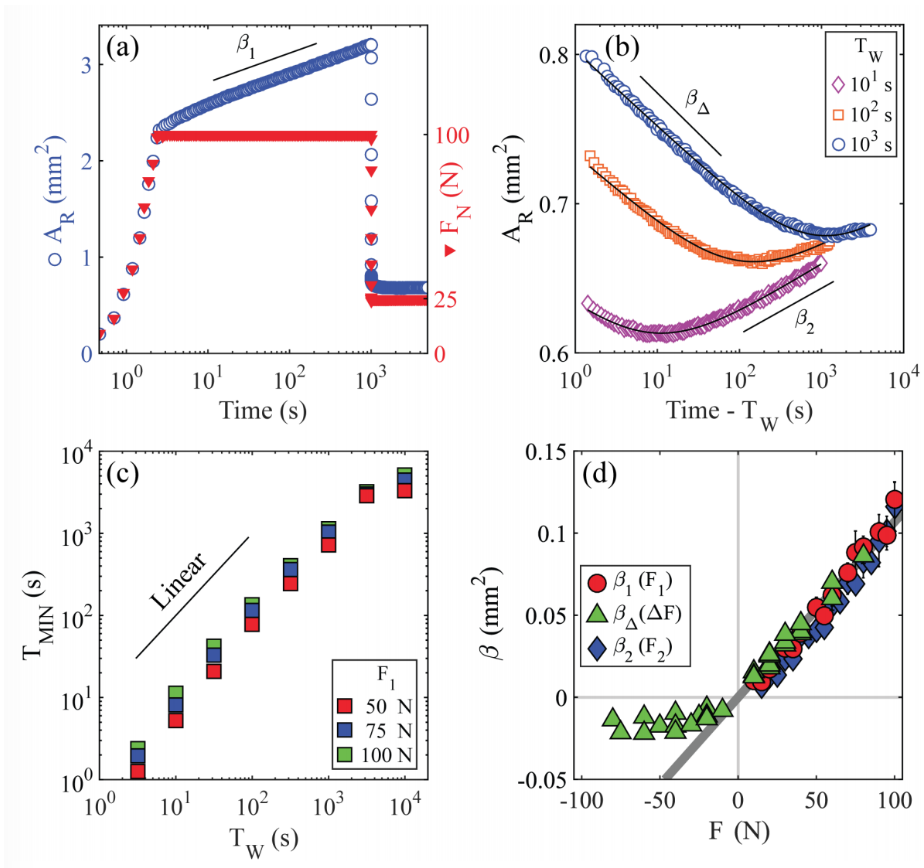


Kovacs effect in Friction!

Nonmonotonic Aging and Memory in a Frictional Interface

Sam Dillavou, Shmuel M Rubinstein arXiv:1801.00011





Thank you!