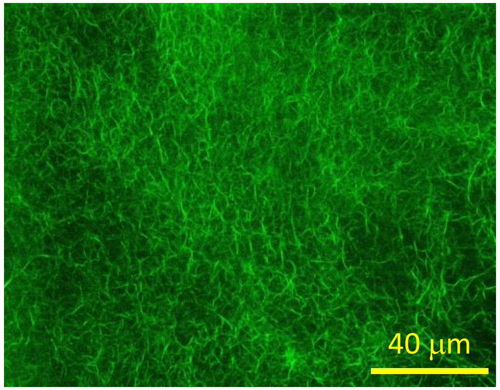
Memory retention in disordered bio-polymer networks

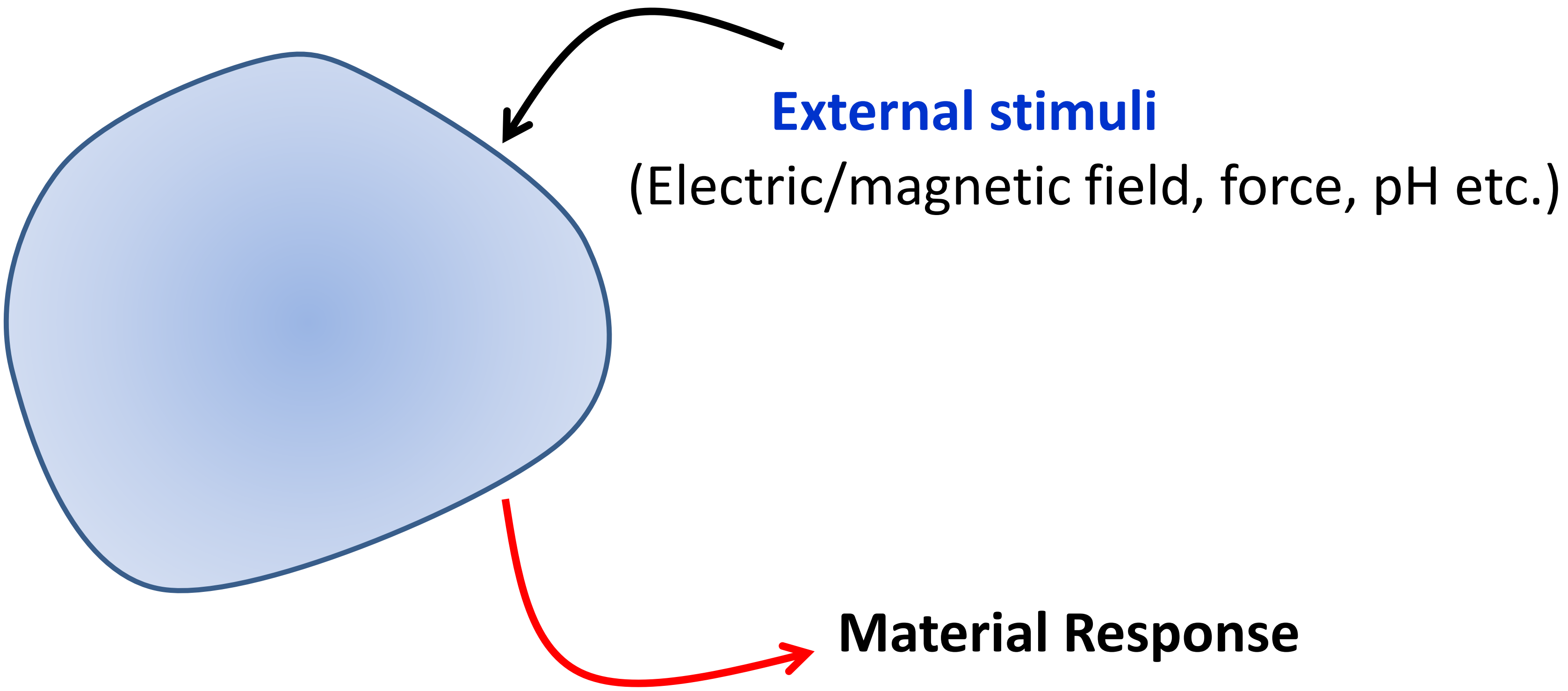
Sayantan Majumdar

Raman Research Institute, Bangalore



EIOSM, ICTS 2018

Adaptive materials

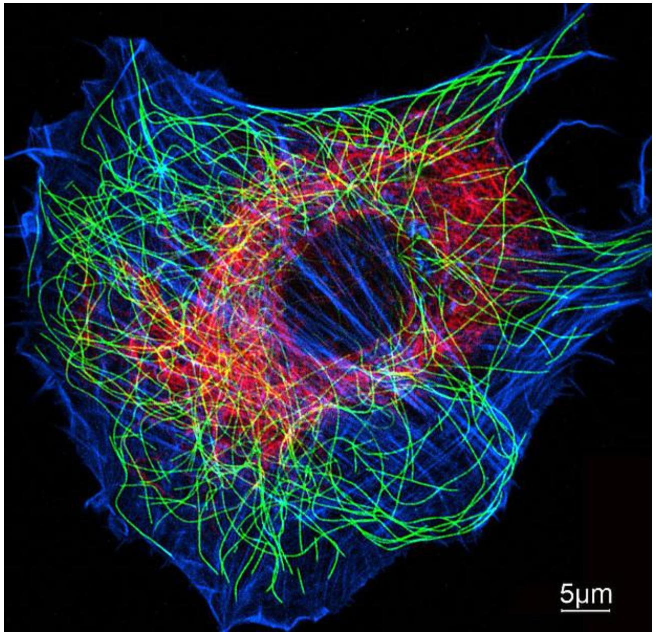


Rapid, controlled reversible changes: adapting to changing environment

Designing such materials is extremely challenging

Biological polymers: new design motif

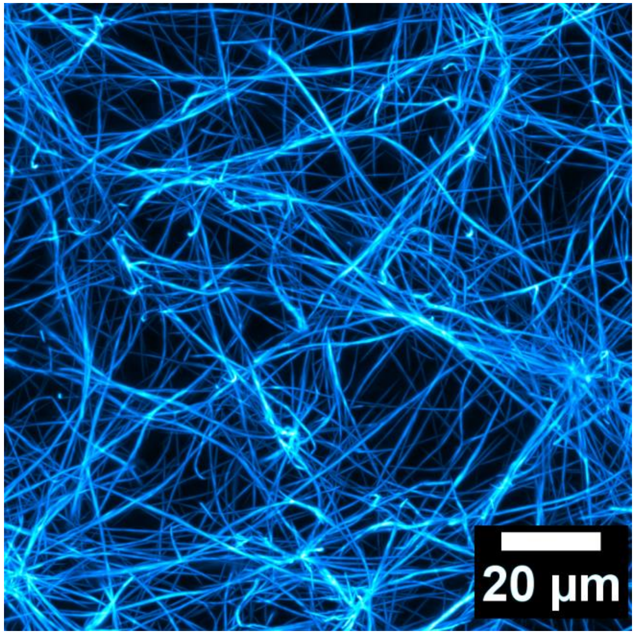
Inside Eukaryotic cell



biozentrum.unibas.ch

Actin, Microtubule, IF

Extracellular matrix



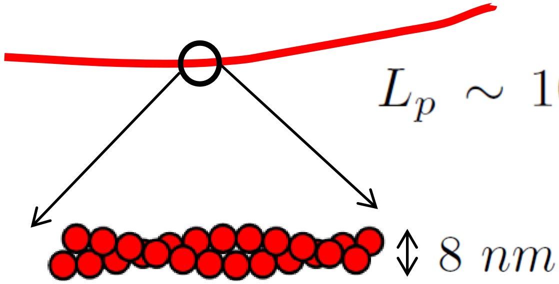
physgeo.uni-leipzig.de

Collagen

Unique materials: no synthetic analogue

Cross-linked actin networks: design motif for programmable materials

Persistence Length quantifies bending stiffness $L_p = \frac{\kappa_{bend}}{k_B T}$

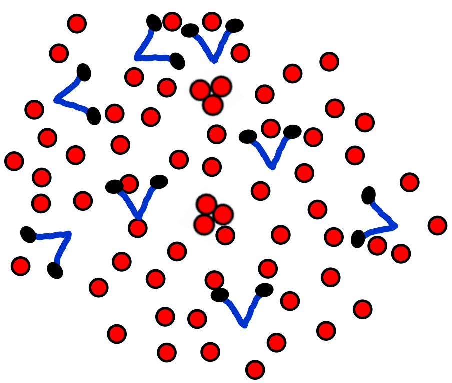


F- actin

$L_p \sim 1$ nm

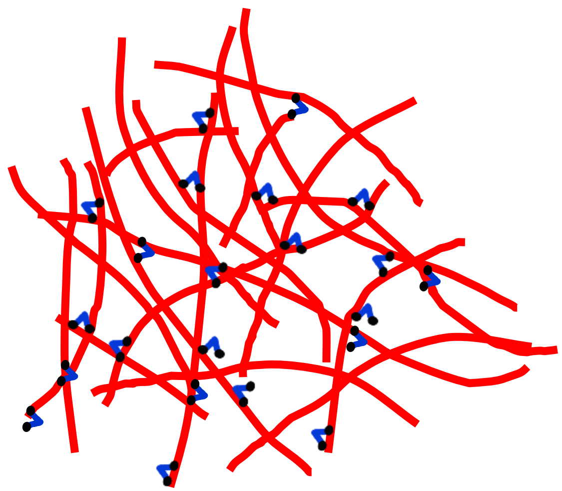
Poly-ethylene

Monomeric actin:
purified from rabbit skeletal muscle

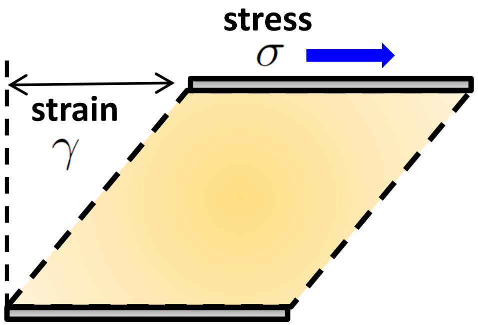


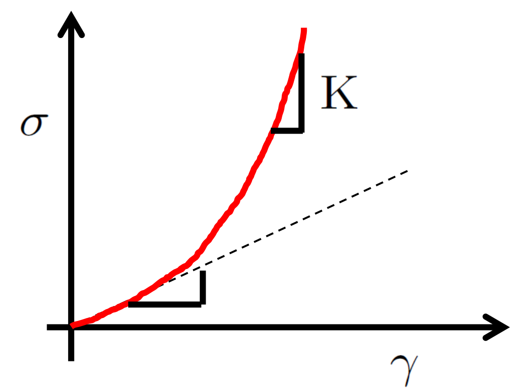
Actin + cross-linkers

ATP, salt

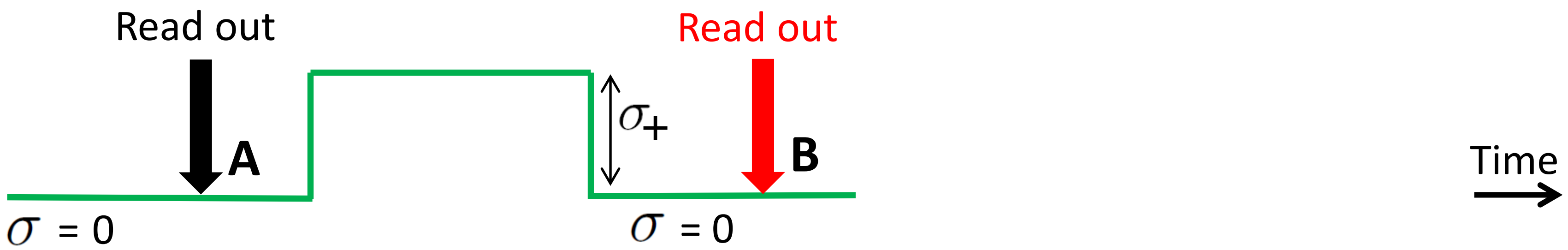


Cross-linked actin network





Stress history significantly alters the material moduli

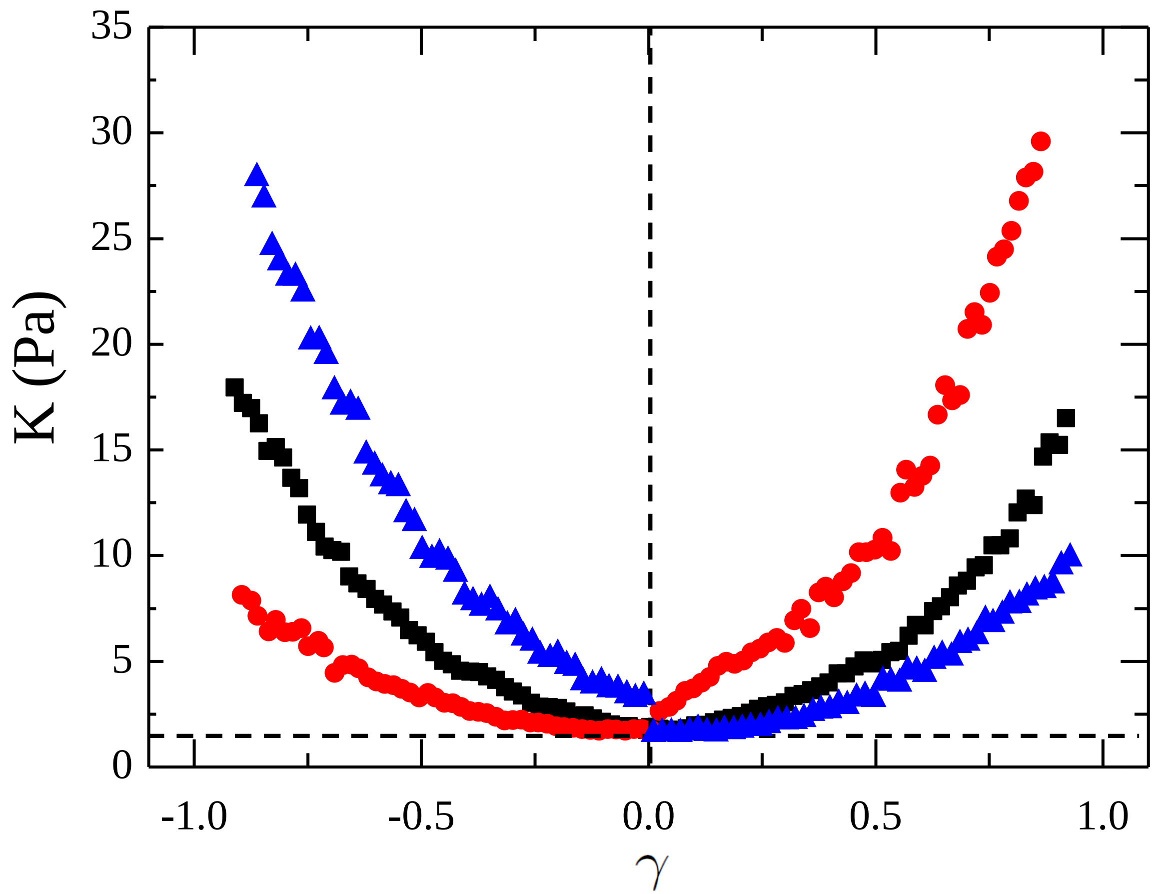


Deformation History

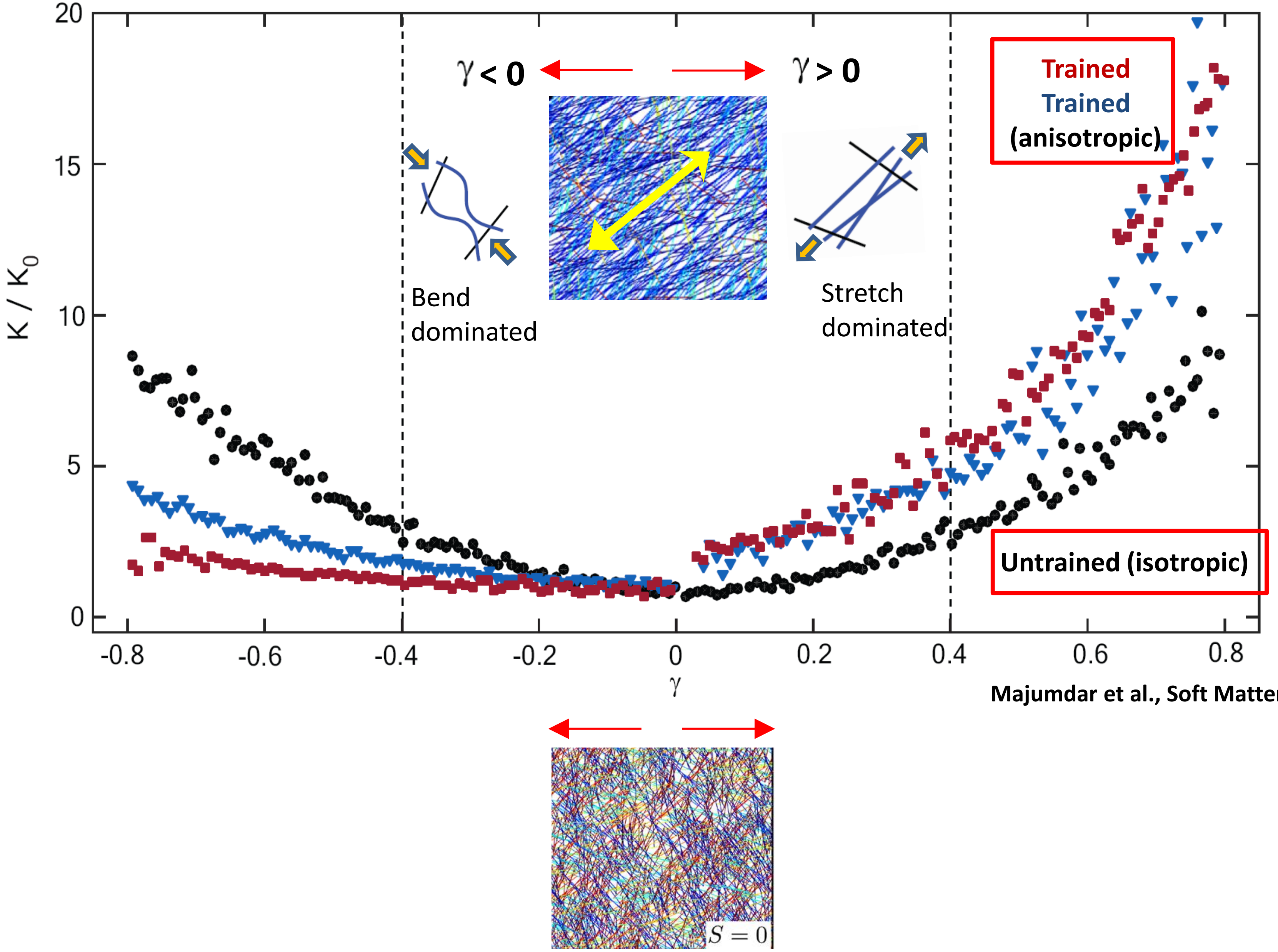
1. **No Training**
2. **+ 4 Pa Training**
3. **- 4 Pa Training**

Stress history can be reversibly encoded.

Mechanical memory

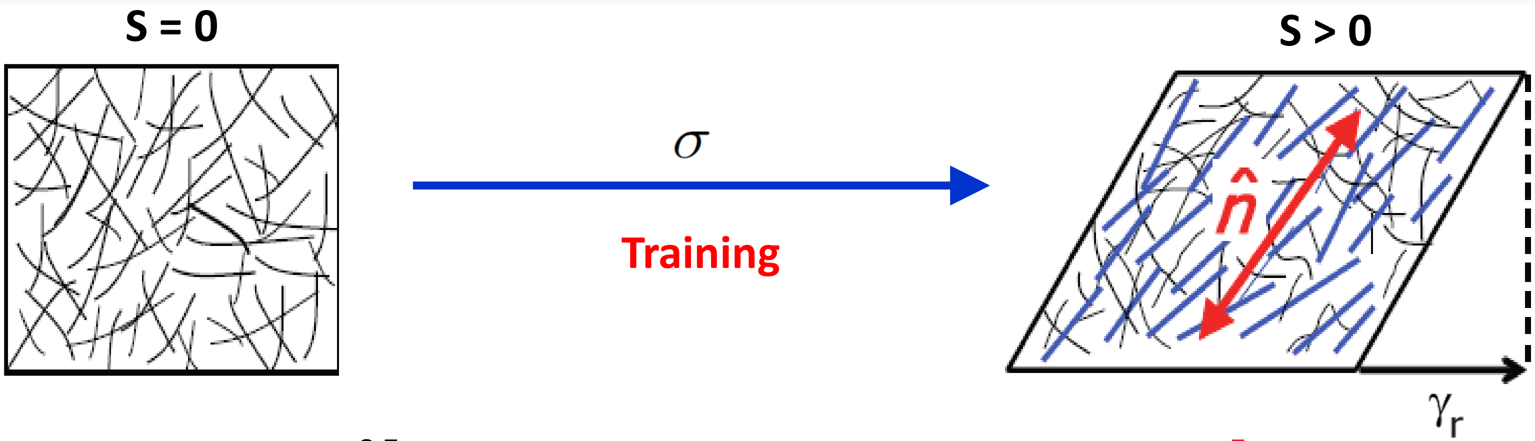


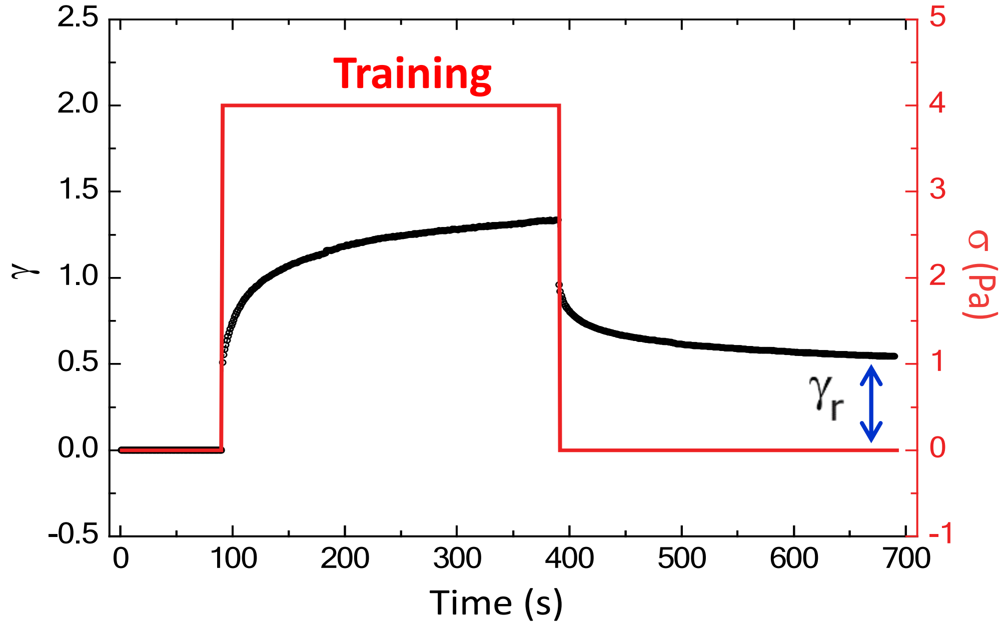
Mechano-memory ➡ Frozen nematic order



Majumdar et al., Soft Matter (2018)

Training stress reorganizes the network





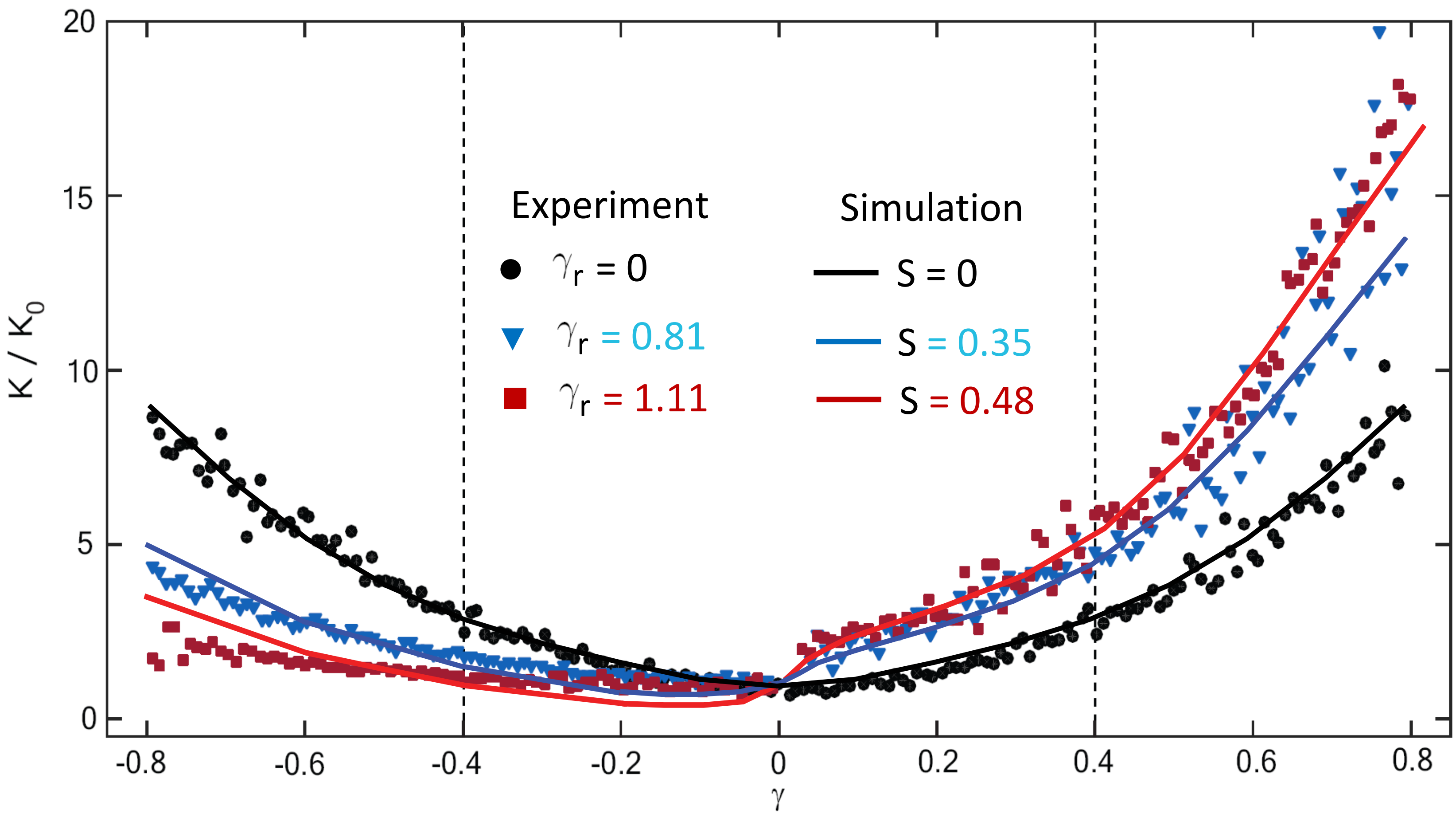
$$S = \frac{\gamma_r}{\sqrt{\gamma_r^2 + 4}}$$

Residual strain ⟺ Nematic order

Simple model captures the mechanical response with no fitting parameter

$$S = \frac{\gamma_r}{\sqrt{\gamma_r^2 + 4}}$$

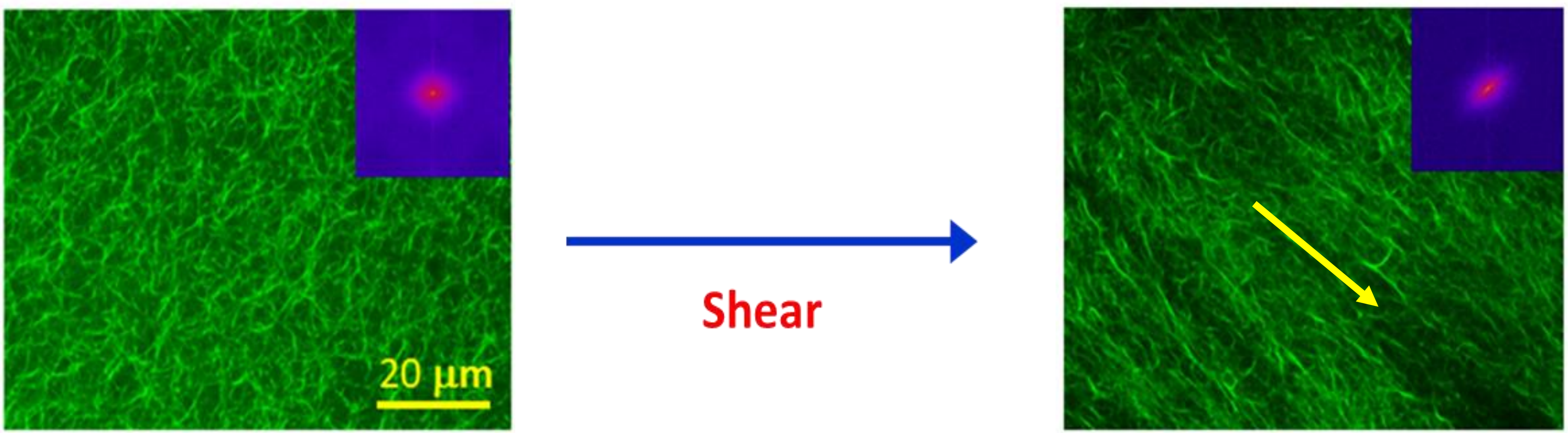
Nematic order estimated from experimentally measured residual strain



Simulation: Alex Levine and Louis Foucard, UCLA

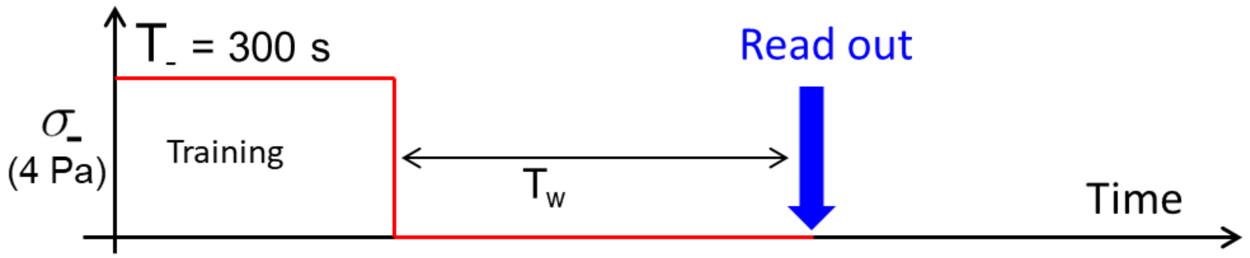
Experimentally observed frozen nematic order

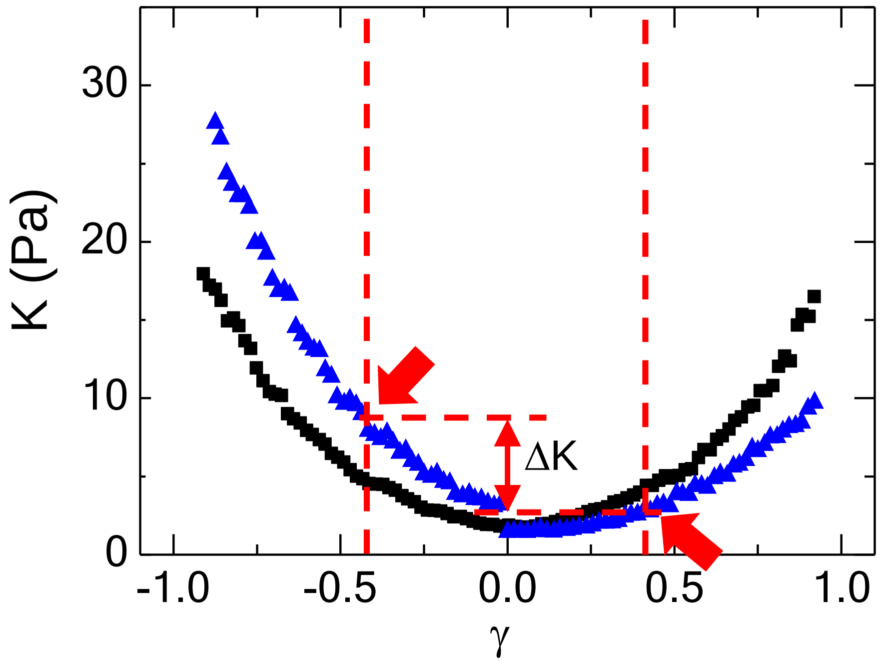
Unidirectional stress (training stress) ➡ Frozen nematic order

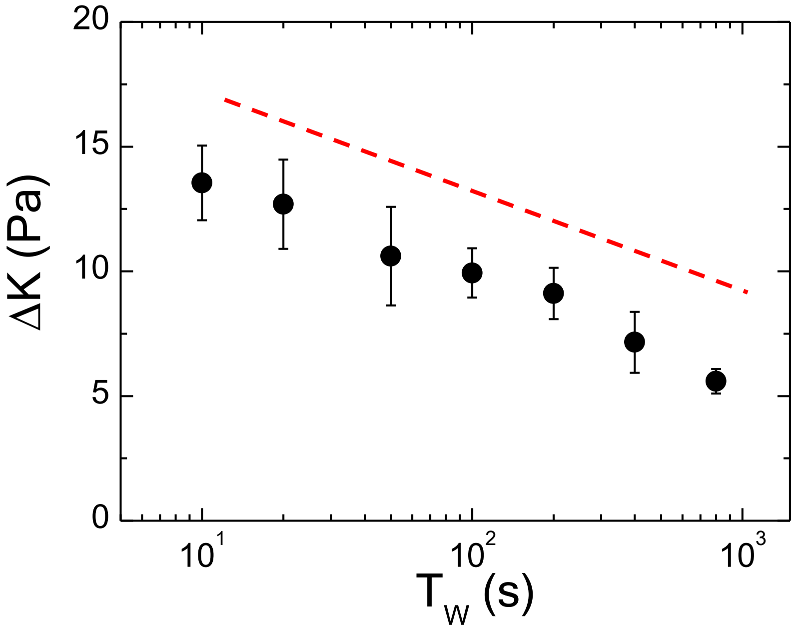


Majumdar *et al.*, Soft Matter (2018)

Mechano-memory: Dynamics



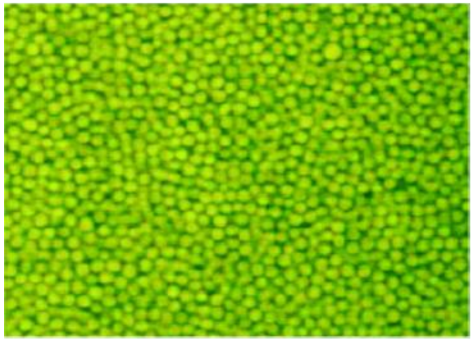




Slow non-exponential relaxation

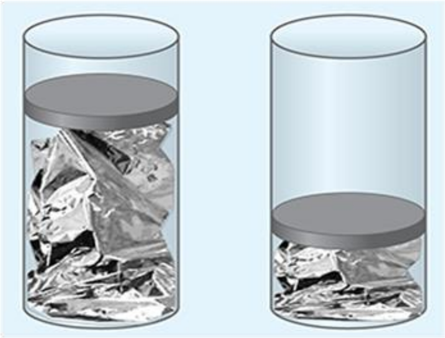
Wide range of disordered condensed matter systems show slow non-exponential relaxations:

Colloidal glass



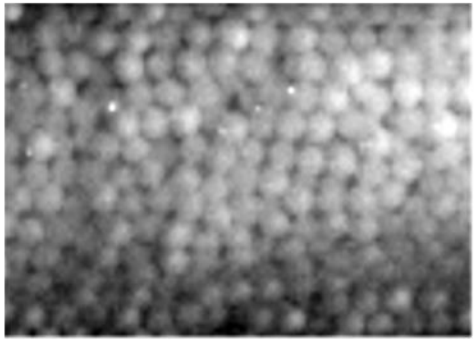
Ghosh et al. (2010)

Crumpled sheet



Lahini et al. (2017)

Granular materials

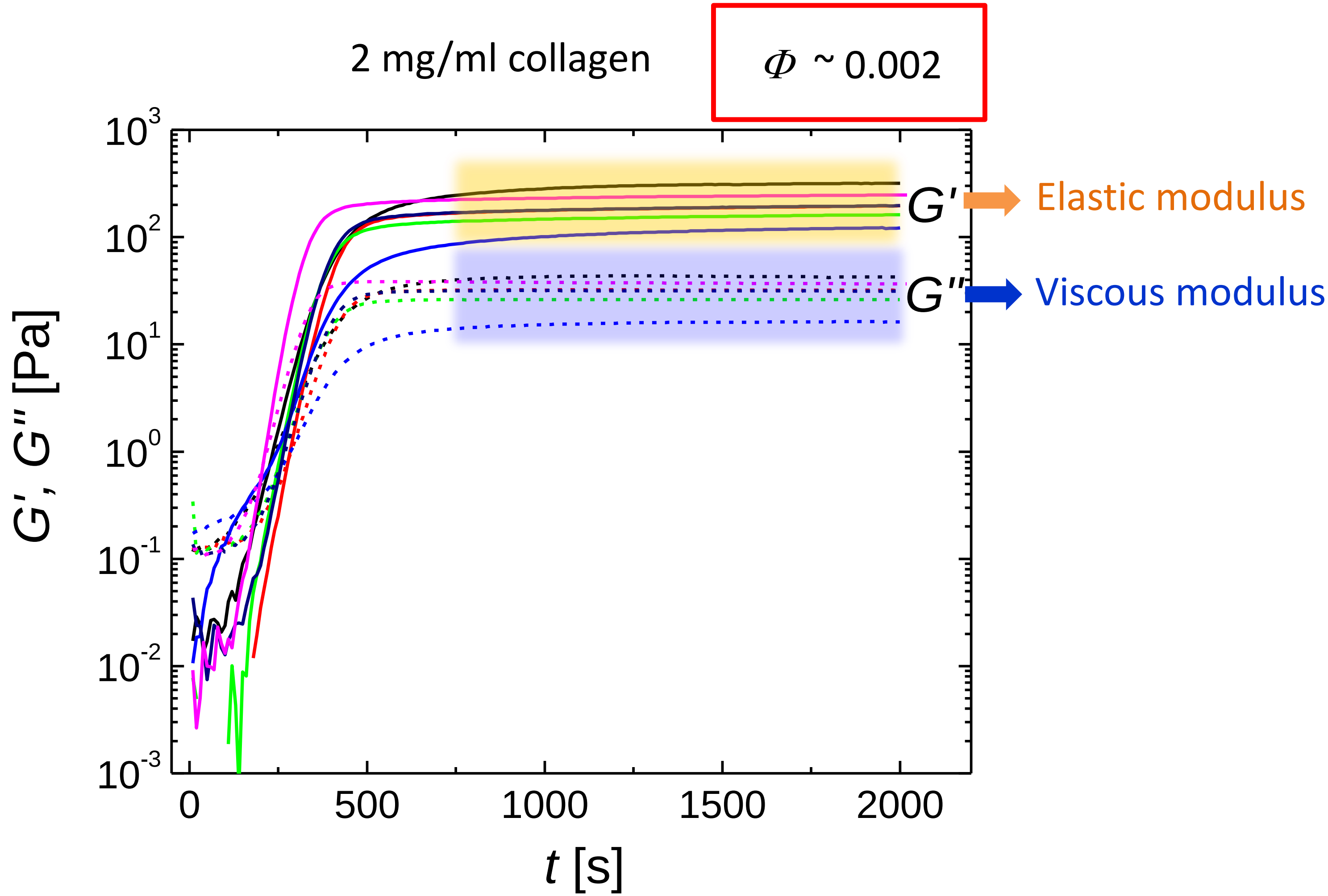


Current / voltage relaxation in CDW conductors

Thermal expansion of glassy polymers

Flux creep in superconductors

Collagen networks: polymerization dynamics



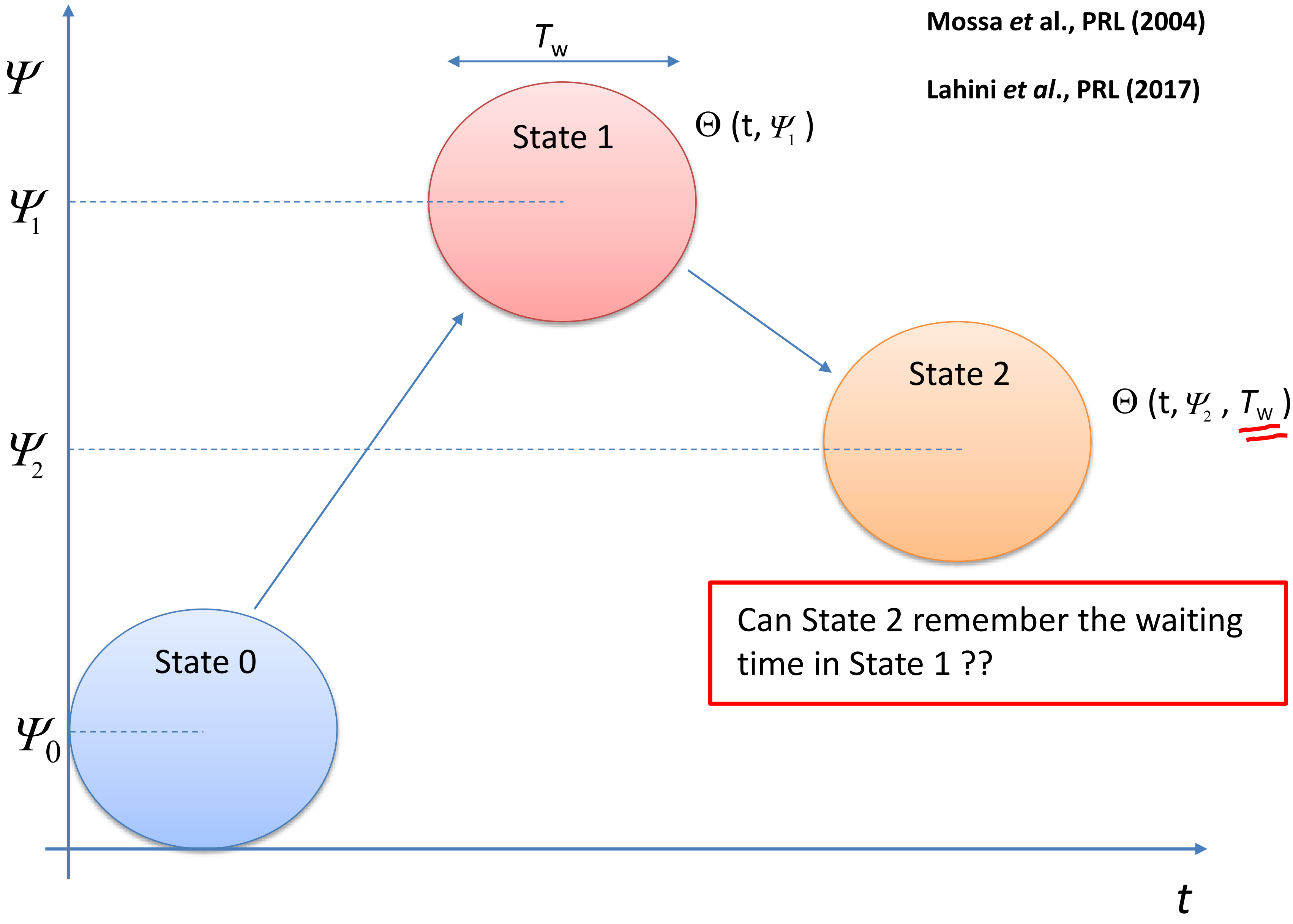
Does it show time dependent properties of glassy systems ?

Non-monotonic aging dynamics: Kocavs Effect

Kovacs *et* al., Adv. Poly. Sci. (1963)

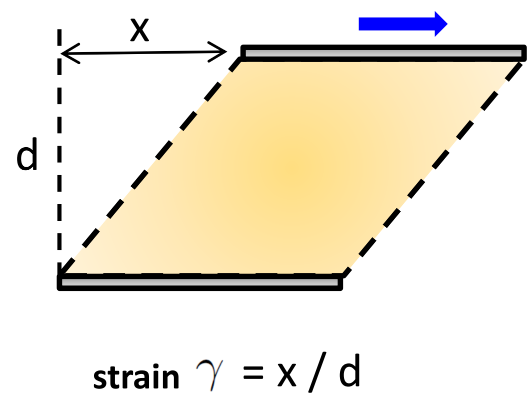
Mossa *et* al., PRL (2004)

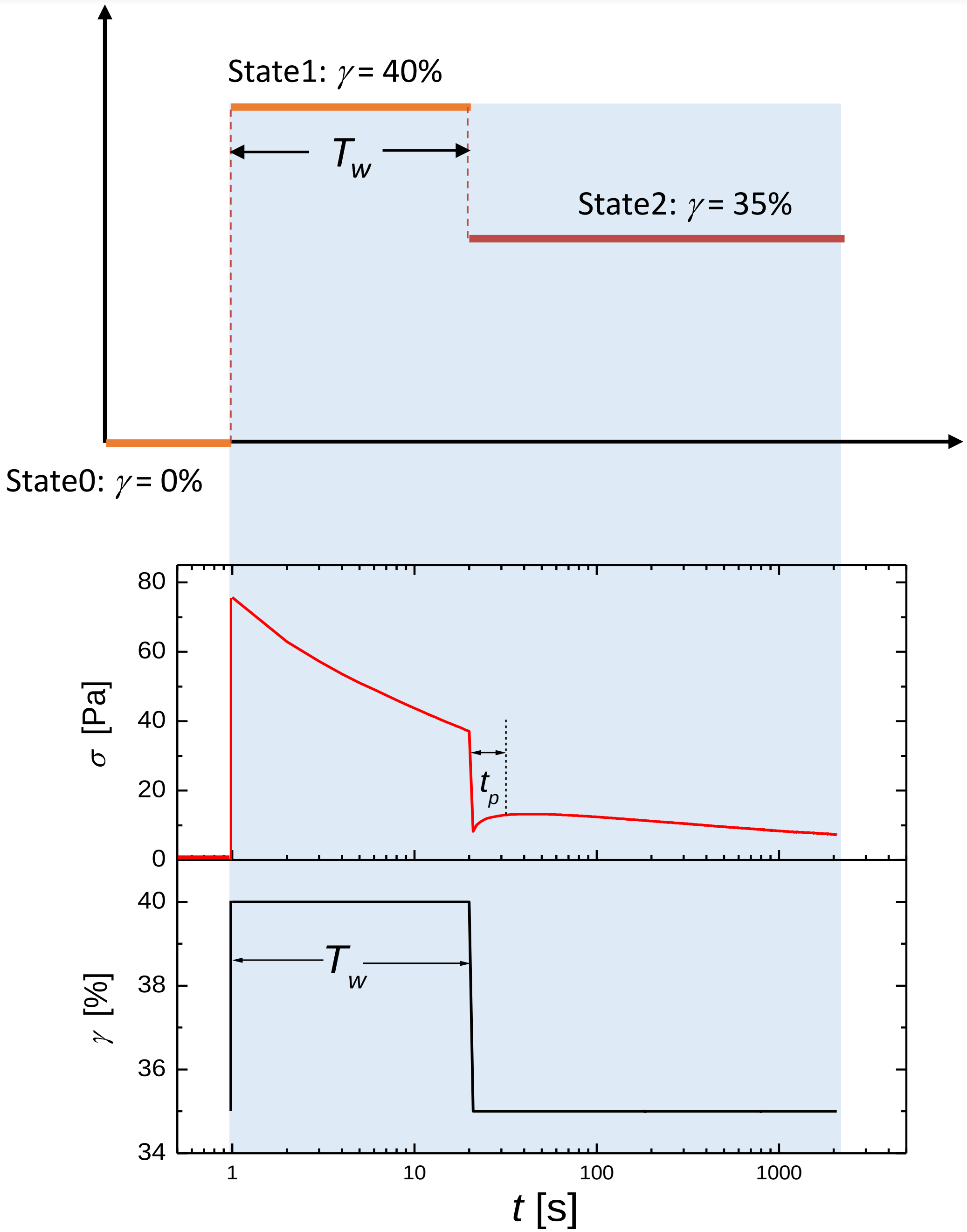
Lahini *et al*., PRL (2017)



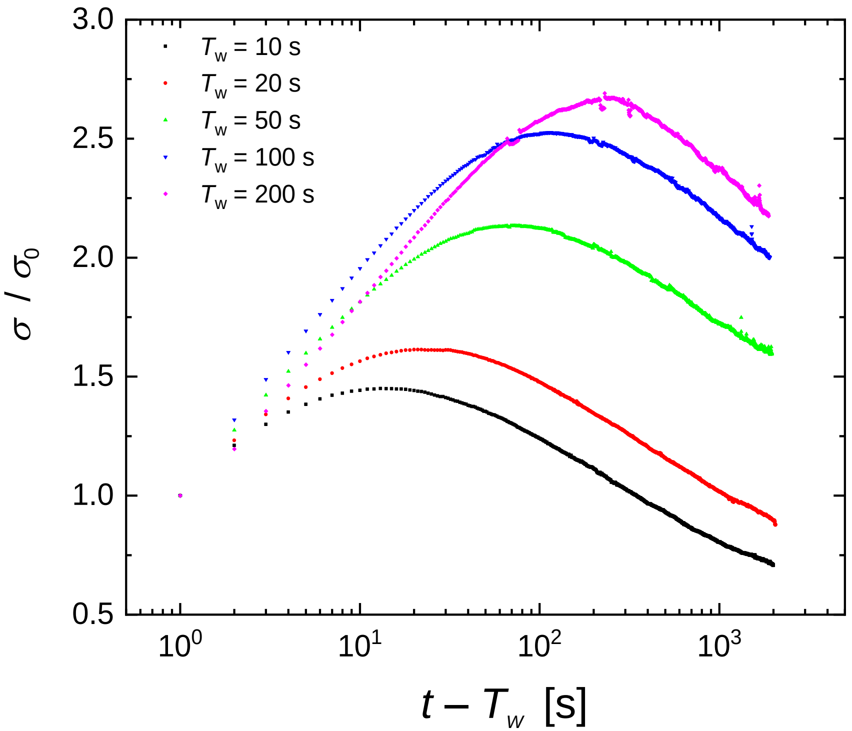
Can State 2 remember the waiting time in State 1 ??

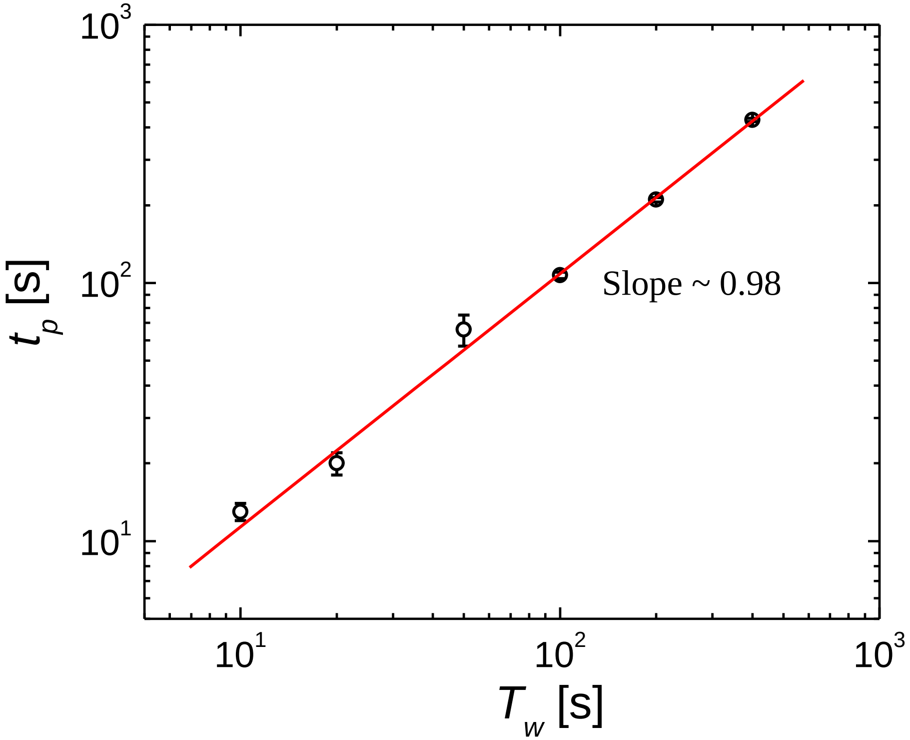
Strain protocol to probe pulse duration memory





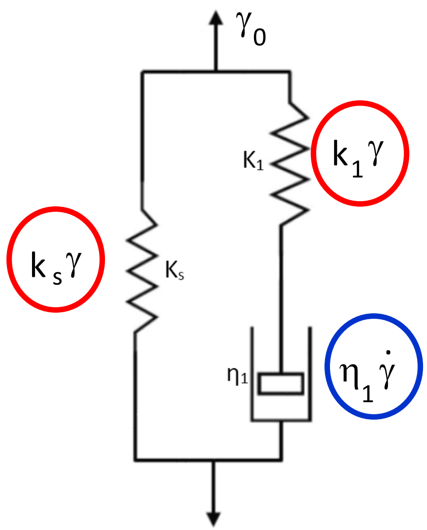
Waiting time can be predicted from peak position





Modelling non-monotonic relaxation

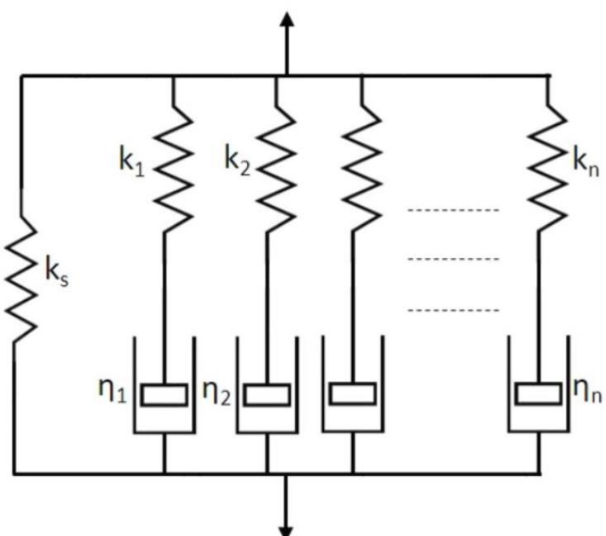
Single element Maxwell's model



$$\sigma(t) = \sigma_s + \sigma_0 e^{-\frac{t}{\tau}}$$

$$\tau = 1/\lambda = \eta_1/k_1$$

Multi-elements Maxwell's model



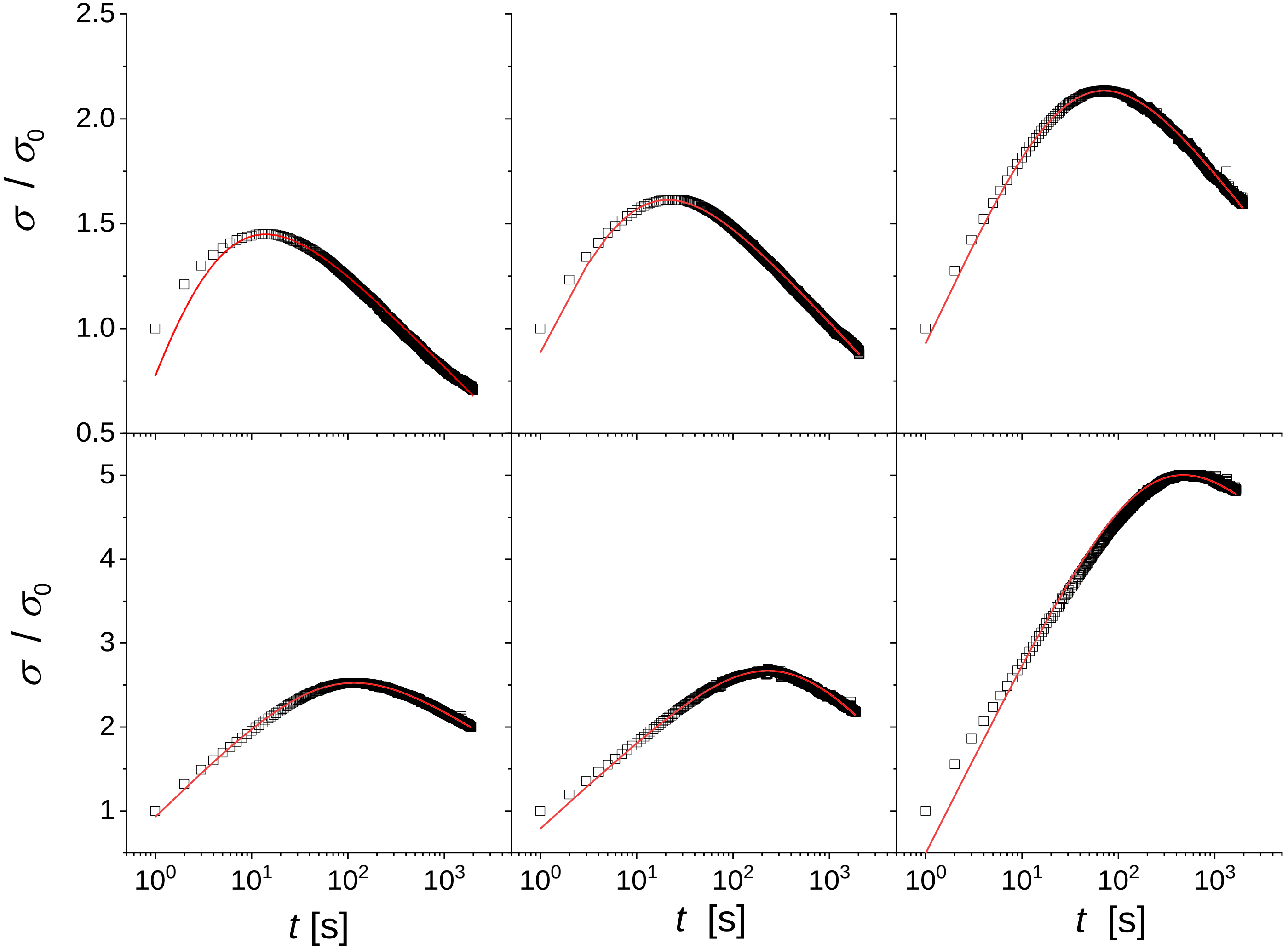
$$\sigma(t) = \sigma_s + \Sigma\sigma_i e^{-t/\tau_i}$$

Two elements can give non-monotonic relaxation

With M.K. Firoz (VSP student, RRI)

Competing logarithmic relaxations

$$\frac{\sigma(t)}{\sigma_0} = a + b\log(t) + c\log(t + t_0)$$



Modelling non-monotonic relaxation

$$X(t) = X_0 \sum_i e^{-\lambda_i t}$$

$$X(t) = X_0 \int_{\lambda_{\min}}^{\lambda_{\max}} d\lambda P(\lambda) e^{-\lambda t}$$

$$\mathrm{P}(\lambda) \sim 1/\lambda$$ → Logarithmic relaxation

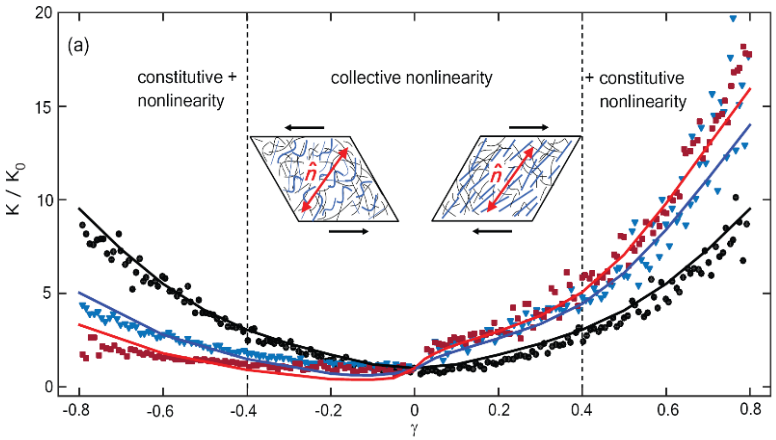
Slow modes dominate the distribution

How do we understand it physically?

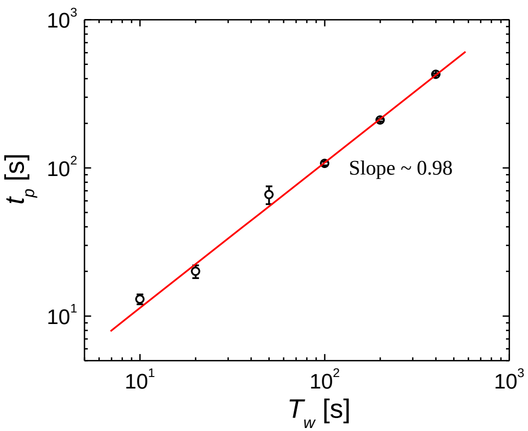
Amir *et al.*, PNAS, 2012

Summary and outlook

- **Disordered bio-polymer networks show reversible mechano-memory.**
- **Such memory arises from induced nematic order.**

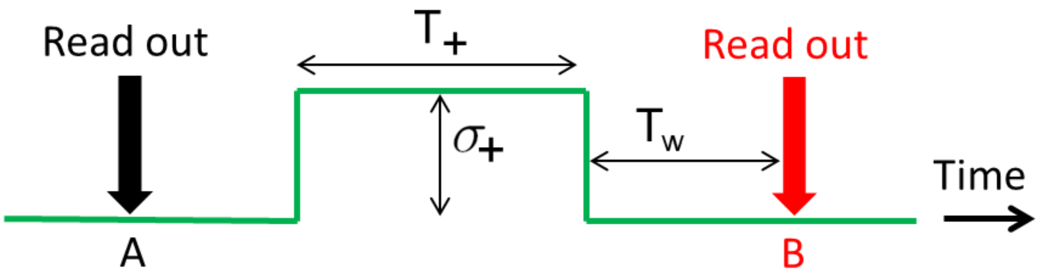


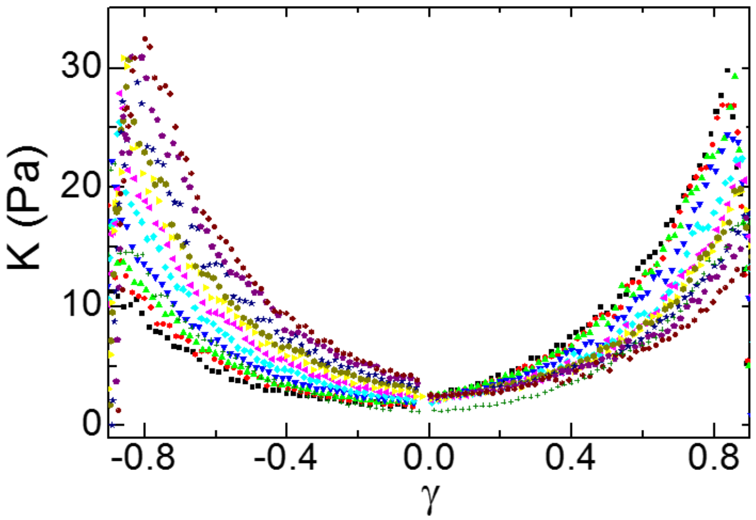
- **Slow, logarithmic relaxation dynamics give rise to pulse duration memory.**



Summary and outlook

- **Force induced adaptations in bulk soft materials**





- **Origin, spatial distribution of fast and slow modes in our system ??**

- **Implications in cell mechanics.**

Acknowledgements

Prof. Heinrich Jaeger, U. Chicago

Prof. Margaret Gardel, U. Chicago

Prof. Alex Levine, UCLA

Dr. Louis Foucard, UCLA

Sebanti Chattopadhyay, RRI

M.K. Firoz, VSP student, RRI

Prof. Sid Negal and Dr. D. Hexner (U. Chicago) for helpful discussions

NATIONAL SCIENCE FOUNDATION MRSEC MATERIALS RESEARCH SCIENCE & ENGINEERING CENTERS

For Kadanoff-Rice Post-Doctoral Fellowship

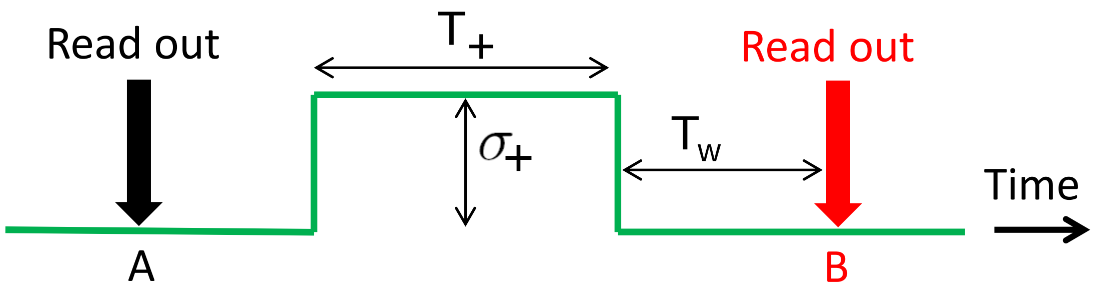
Raman Research Institute

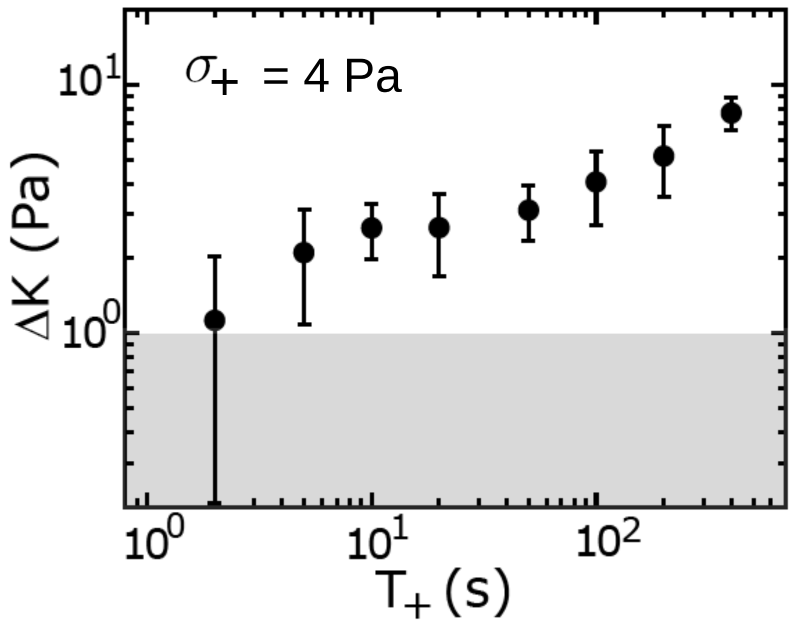
SERB INDIA

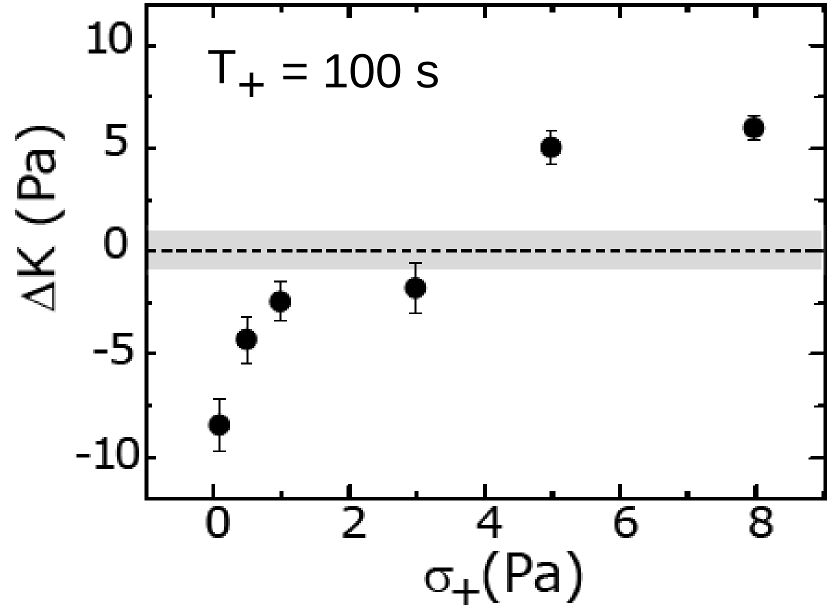
For Ramanujan Fellowship

Thank you for your attention

Continuous tuning of mechanical response by mechano-memory







Tuning mechanical response by Mechano-memory