Plastic flow and stochastic resonance in soft glassy materials

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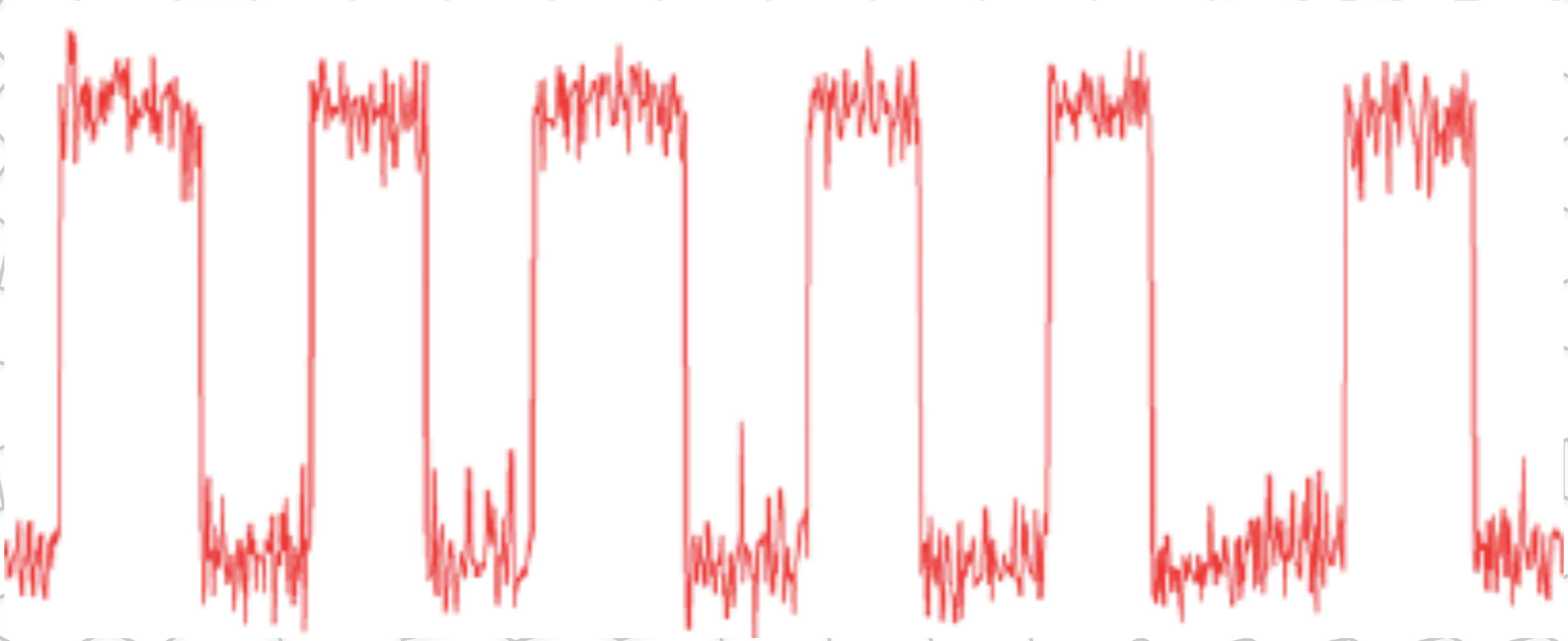

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Not liquids, nor solids

"a **solid** has a stable definite shape" "a **liquid** conforms to the shape of its container"

(from Wikipedia)

?!?

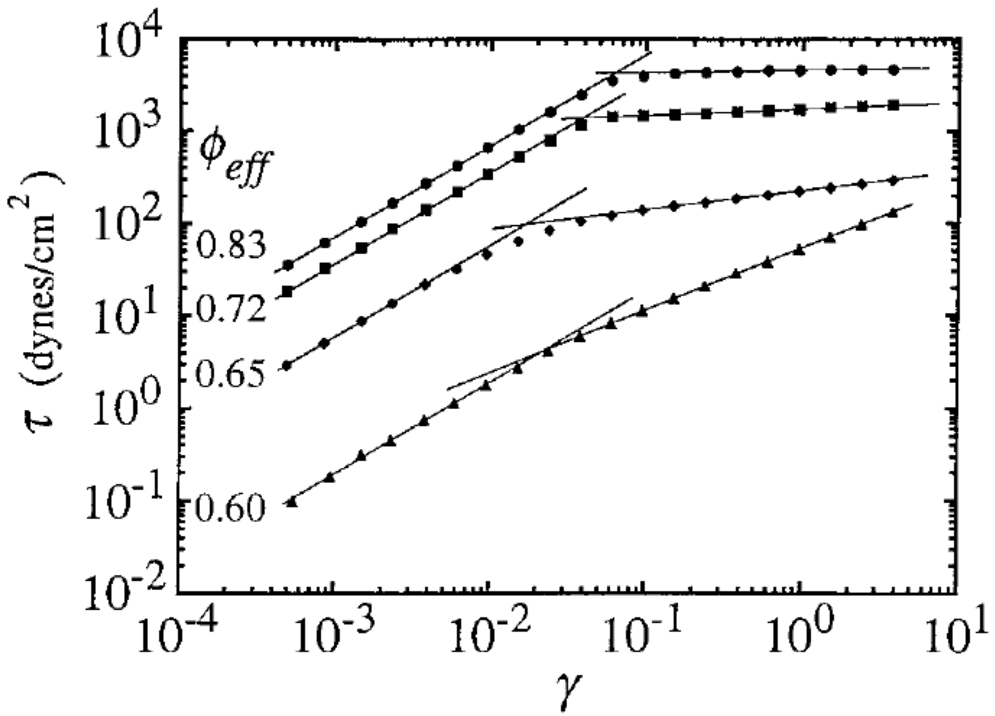
Yielding and non-Newtonian rheology

Stress-strain curves for dense microemulsions/dry foams

$$\sigma = \sigma_Y + K\dot{\gamma}^a$$ Herschel-Bulkley relation

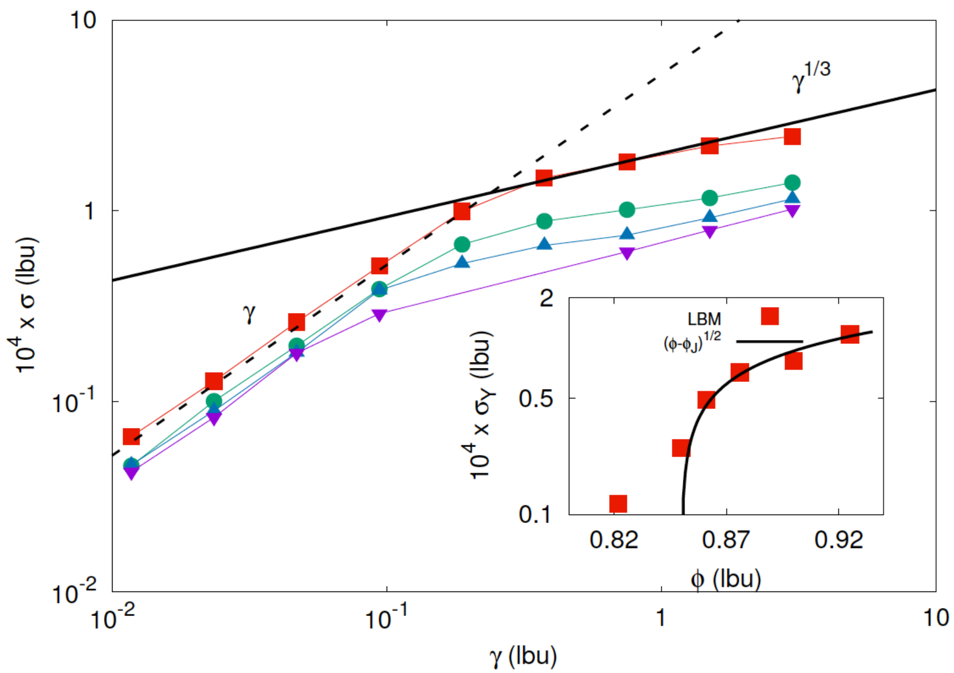
σ_Y **Yield stress**

experiments



(TG Mason et al, J. Colloid Interface Sci. **179**, 439 (1996))

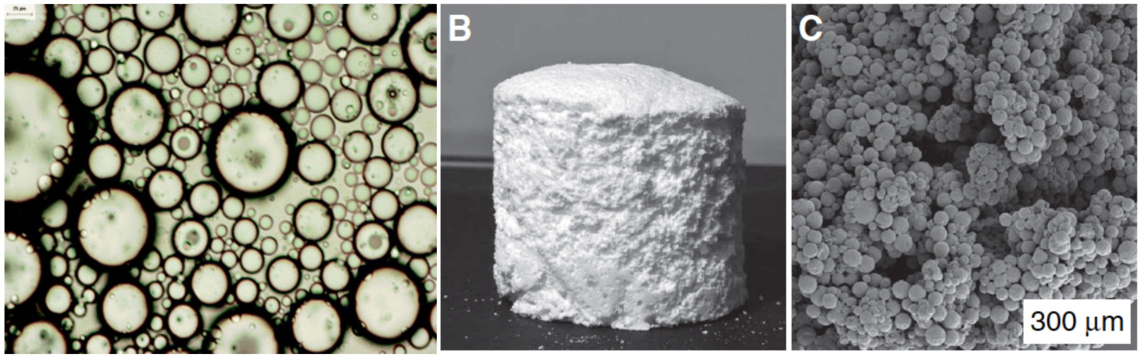
simulations



(AS et al, Europhys. Lett **114**, 64003 (2016))

Complex fluids

Emulsions, foams, gels, polymers, pastes…



Composition

- Multiple phases
- Multiple components
- (Often **both**)

Structural complexity

- Dynamical arrest
- **Structural disorder**
- Heterogeneities

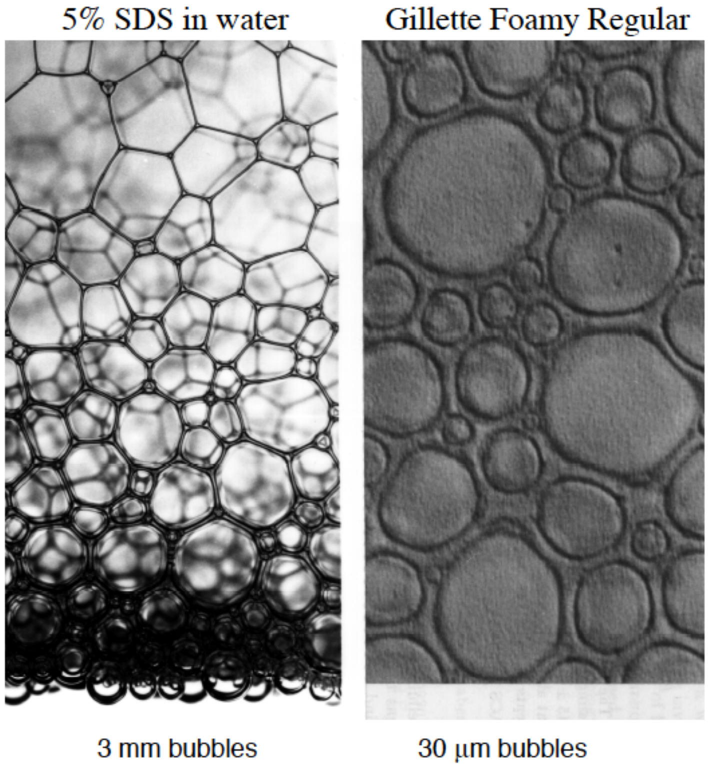
Rheological complexity

- Yield stress
- Viscoelasticity
- **Non-local plastic activity**

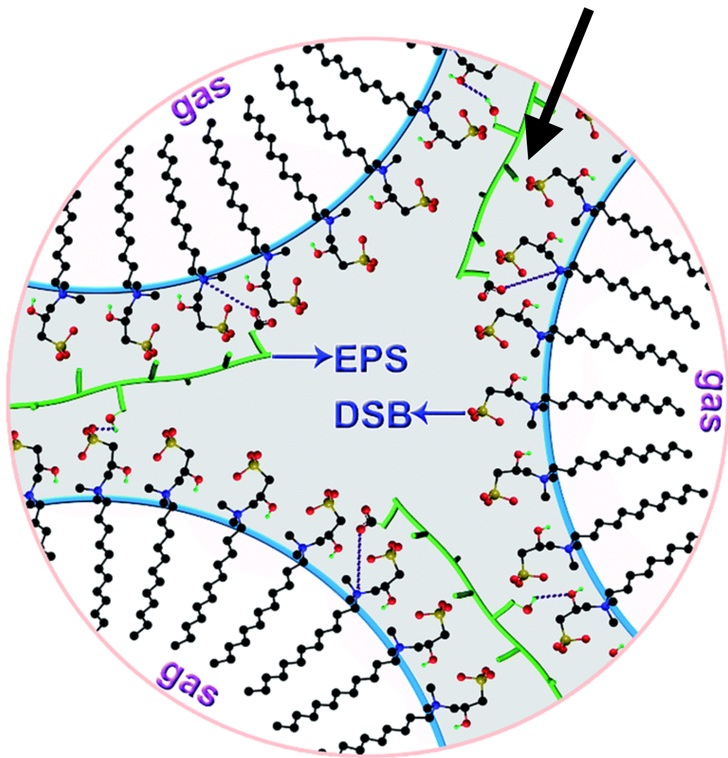
Foams and emulsions

gas (dispersed) + liquid (continuous)

liquid (dispersed) + liquid (continuous)



surfactant-stabilised films



(Deng et al, *RSC Adv.* **5**, 61868 (2015))

"Effective" modelling of surfactants. What is their the mechanical 'translation'?

Lattice Boltzmann Method (LBM): basics

Lattice Boltzmann Equation (LBE)

$$f_i^{(\alpha)}(\mathbf{r}+\mathbf{c}_i\Delta t, t+\Delta t) - f_i^{(\alpha)}(\mathbf{r},t) = \Lambda_{ij}^{(\alpha)}\left(f_j^{(\alpha)} - f_j^{(\alpha)(eq)}\right)$$

FREE-STREAMING

COLLISIONS
(relaxation towards a local equilibrium)

$$f_i^{(\alpha)(eq)} = w_i \rho^{(\alpha)}\left[1 + \frac{\mathbf{u}\cdot\mathbf{c}_i}{c_s^2} + \frac{\mathbf{uu}:\left(\mathbf{c}_i\mathbf{c}_i - c_s^2\mathbf{1}\right)}{c_s^4}\right]$$

local equilibrium
(low Mach number expansion of Maxwellian equilibrium)

$$\alpha = A, B$$

$$i = 0, 2, \ldots, 8$$

Hydrodynamic fields

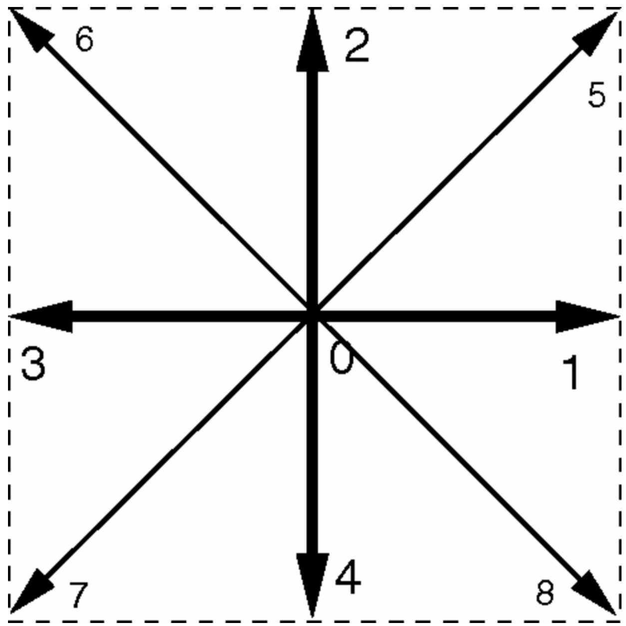
density

$$\rho^{(\alpha)}(\mathbf{r},t) = \sum_i f_i^{(\alpha)}(\mathbf{r},t)$$

momentum

$$\rho(\mathbf{r},t)\mathbf{u}(\mathbf{r},t) = \sum_{i,\alpha} f_i^{(\alpha)}(\mathbf{r},t)\mathbf{c}_i$$

lattice speeds

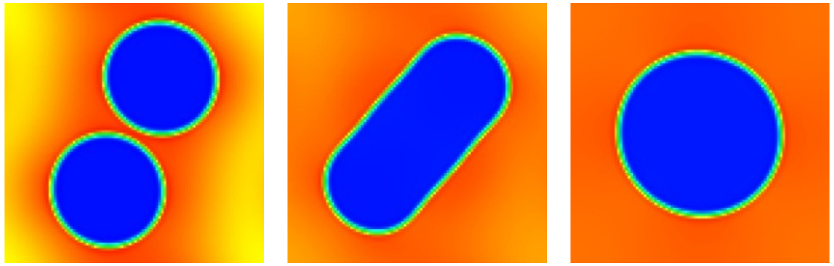


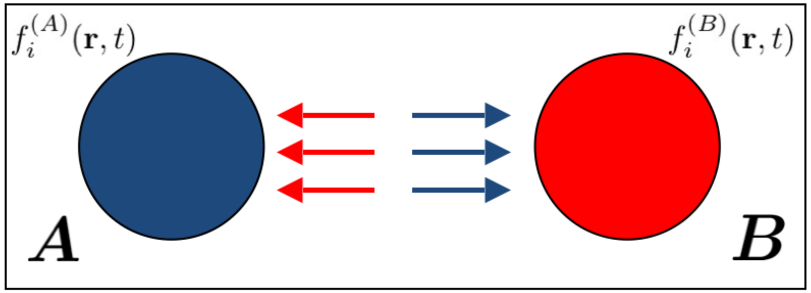
Force enters through the local equilibrium

$$f_i^{(\alpha)(eq)}\left(\rho^{(\alpha)}, \mathbf{u}\right) \rightarrow f_i^{(\alpha)(eq)}\left(\rho^{(\alpha)}, \mathbf{u} + \tau_{LB}\mathbf{F}^{(\alpha)}/\rho^{(\alpha)}\right)$$

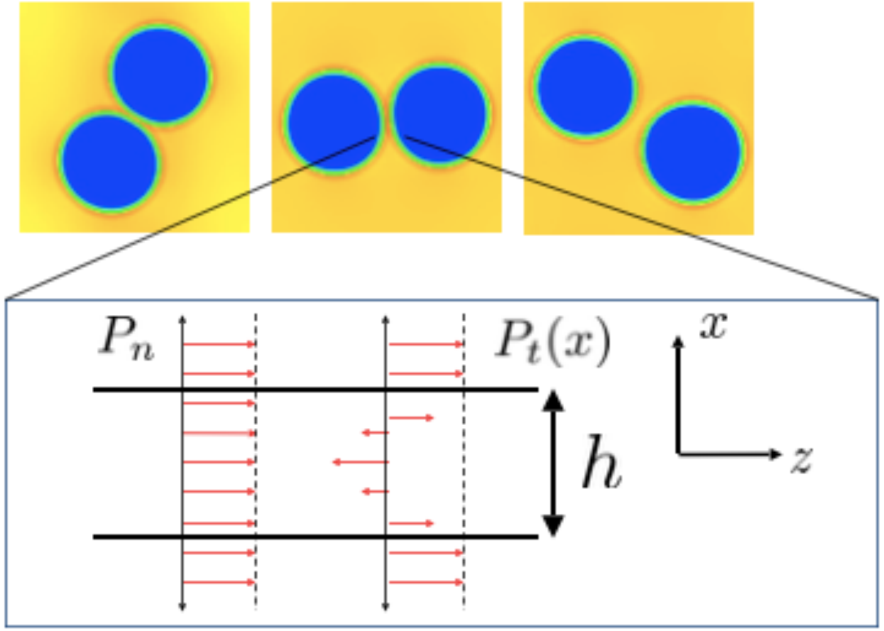
Modelling the surface tension and **disjoining pressure**

Surface tension (phase separation)

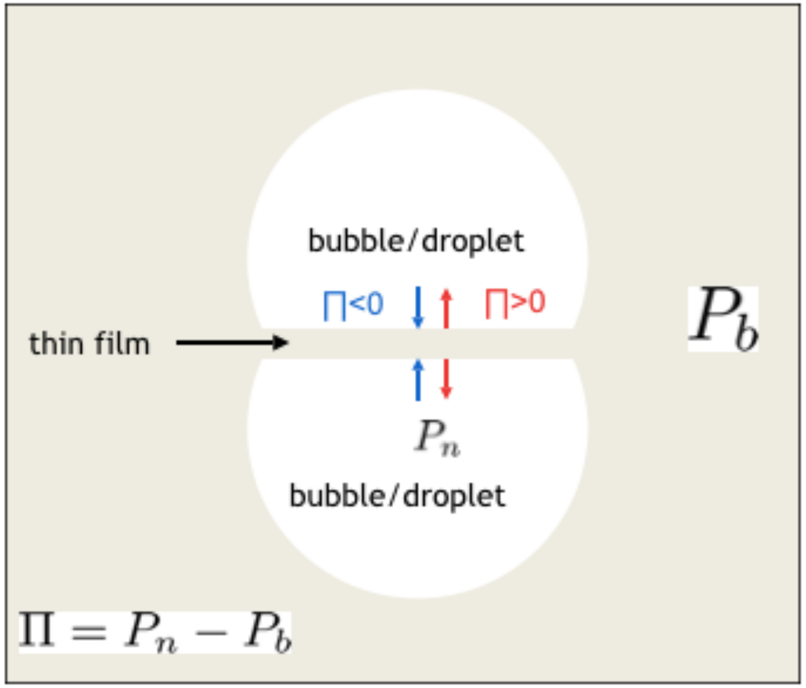




Disjoining pressure (stabilisation of thin films)

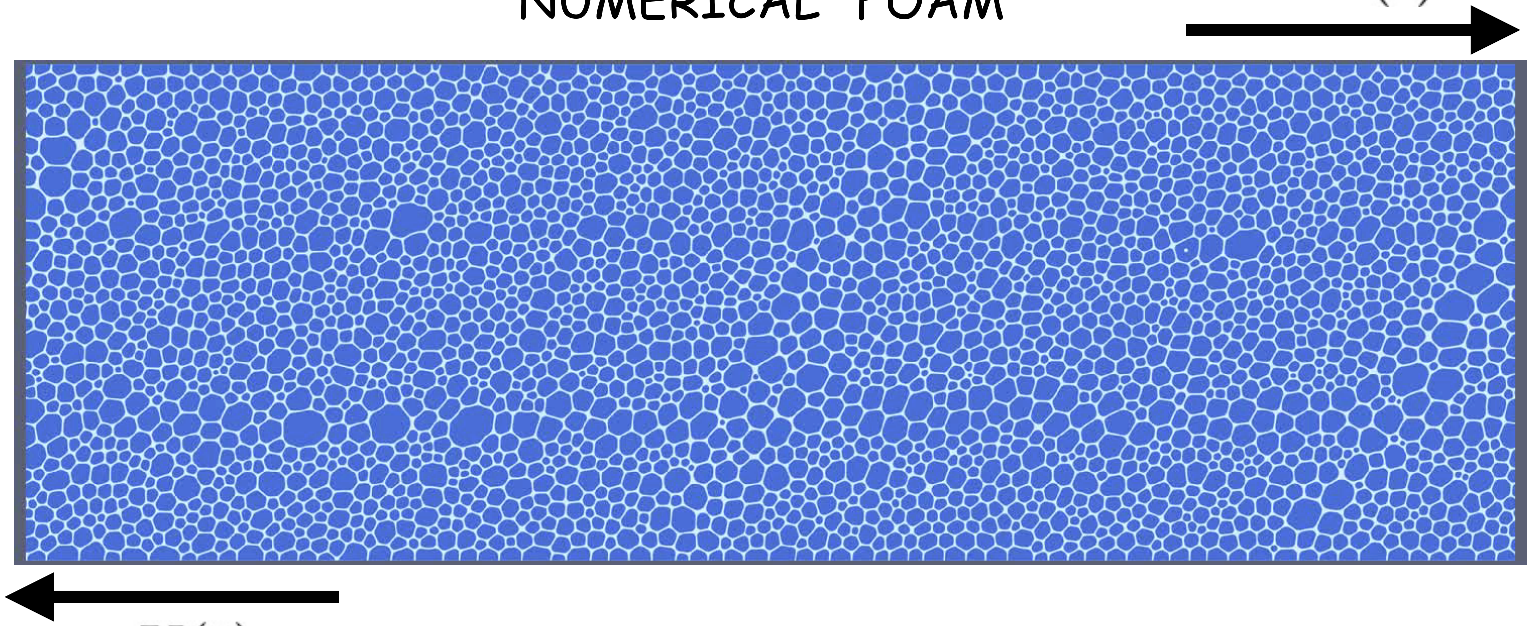


(Derjaguin & Churaev, *J. Colloid. Interface Sci.* **66**, 389 (1978))



NUMERICAL “FOAM”

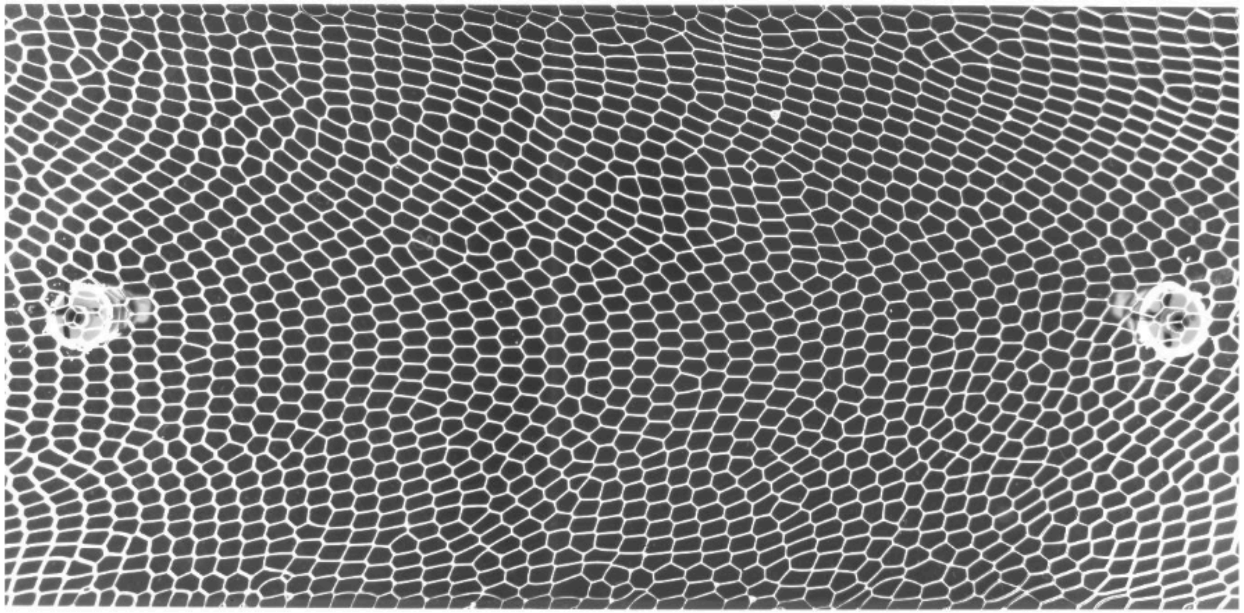
$+U(t)$



$-U(t)$

REAL ONE

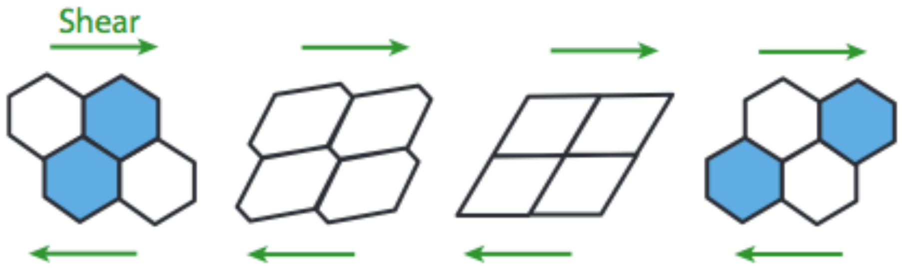
$$U(t) = U_P \sin(\omega t)$$



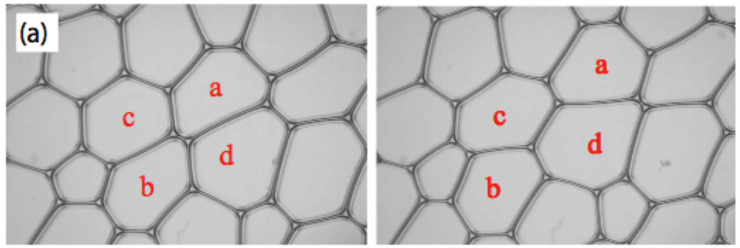
(B. Dollet, AS and M. Sbragaglia, J. Fluid Mech. **766**, 556-589 (2015))

Plastic events and non-local stress relaxation

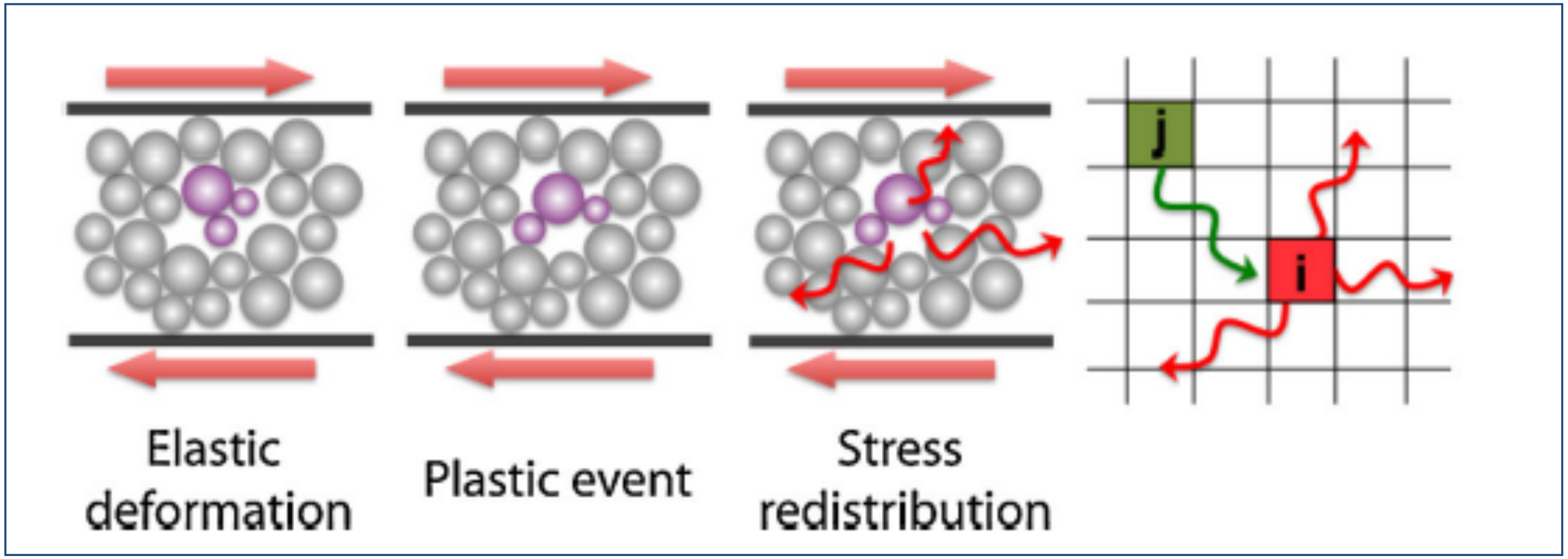
Plastic rearrangements: **T1 event**



(S. Cohen-Addad et al, Annu. Rev. Fluid Mech. **45**, 241 (2013))



(A. Kabla et al, J. Fluid Mech. **587**, 45 (2007))



(L. Bocquet et al, Phys. Rev. Lett. **103**, 036001 (2009))

Theory of Soft-Glassy Rheology

Equation for the probability distribution of stresses

$$\frac{\partial}{\partial t} P = -\dot{\gamma} \frac{\partial}{\partial l} P - \Gamma_0 e^{-(E - \frac{1}{2} k l^2)/x} P + \Gamma(t) \rho(E) \delta(l)$$

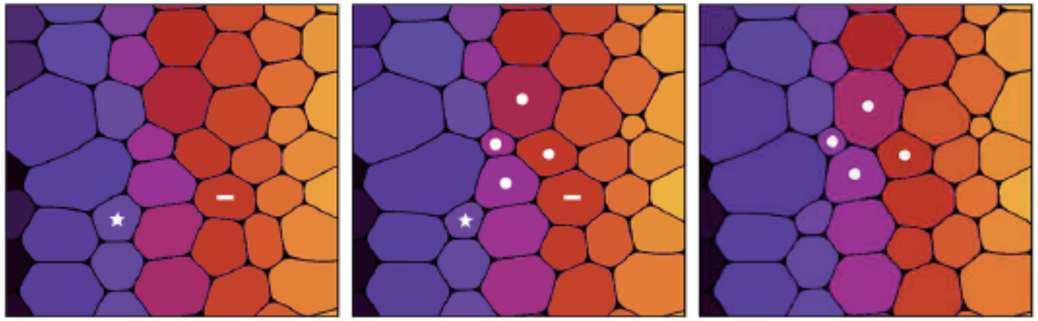
structural disorder → "complex" energy landscape (distribution of energy wells)

(non-local) coupling among plastic rearrangements → **effective "noise temperature"**

Does such conjecture make any sense?

(P. Sollich et al, Phys. Rev. Lett. **78**, 2020-2023 (1997); J.-P. Bouchaud et al, J. Phys. I France **5**, 1521-1526 (1995))

"Ageing" and rearrangements

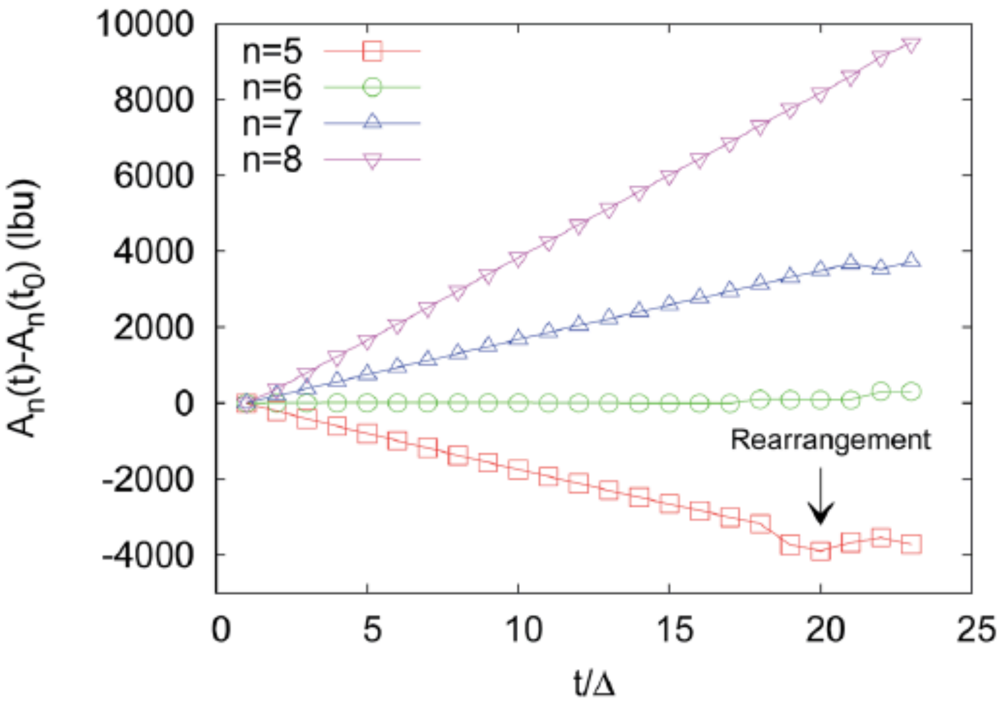


(a) t=t_0 (b) t=t_0+20Δ (c) t=t_0+23Δ

von Neumann's law

$$\frac{dA_n(t)}{dt} = K(n-6)$$

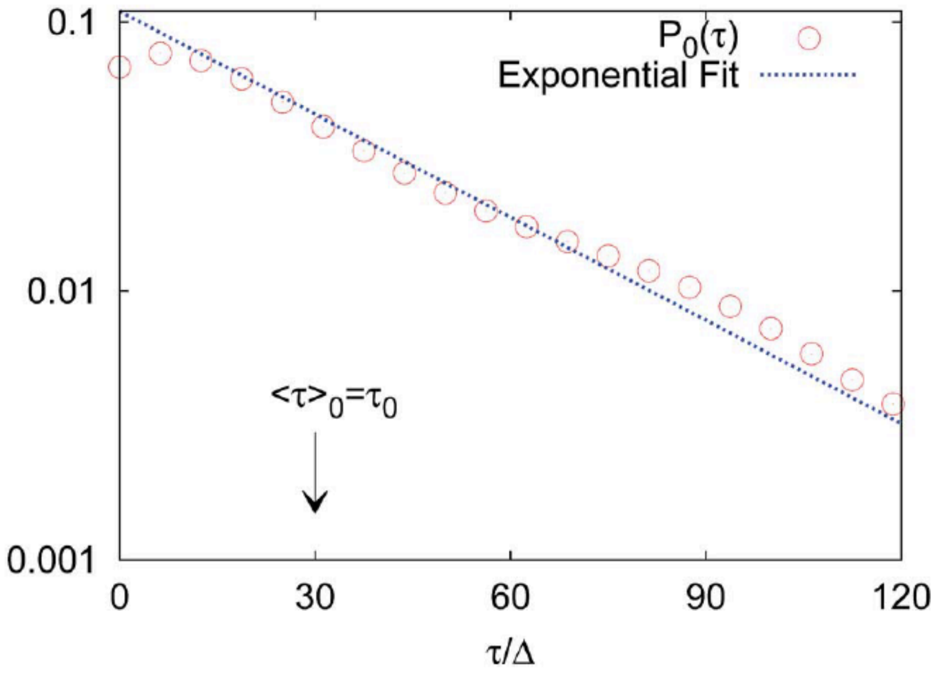
(variation of area of bubbles with n neighbours)



coarsening as a source of effective "mechanical noise"

Statistics of rearrangements during coarsening

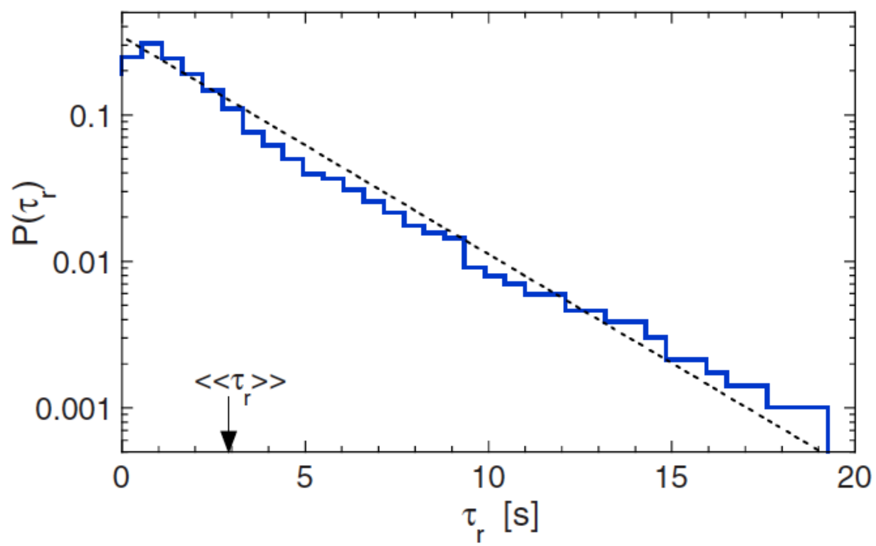
Probability density function of time lapses between successive plastic rearrangements



$$P(\tau) \sim e^{-\tau/\tau_0}$$

τ_0 **internal** characteristic time-scale (**NO STRAIN** APPLIED!)

experiments



(A.S. Gittings & D.J. Durian, Phys. Rev. E **78**, 066313 (2008))

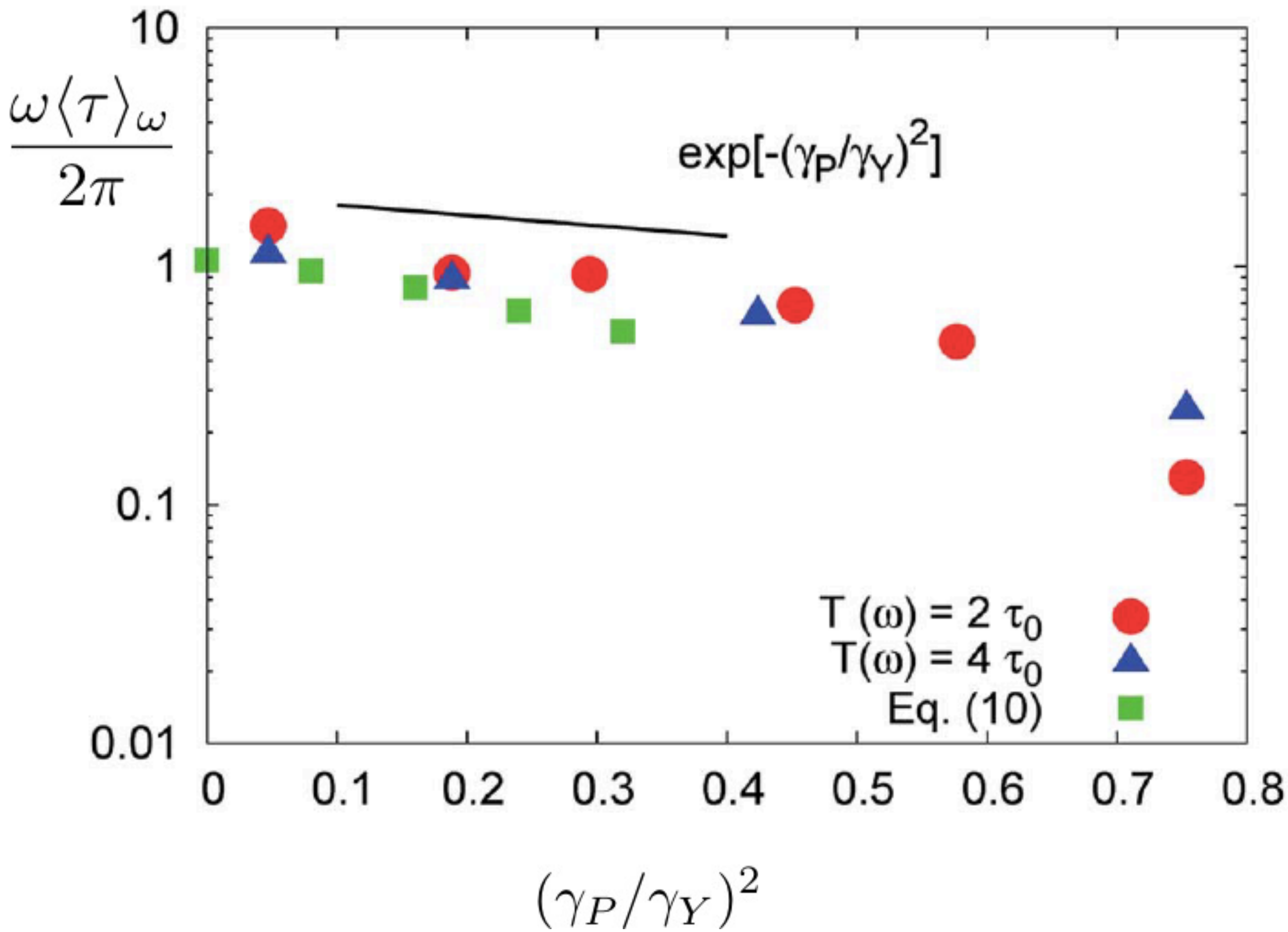
Mean time lapse under oscillatory strain

oscillatory strain

$$\gamma(t) = \gamma_P \sin(\omega t)$$

below yield conditions!

$$\gamma_P < \gamma_Y$$



Energy input $\sim E\frac{\gamma_P^2}{2}$

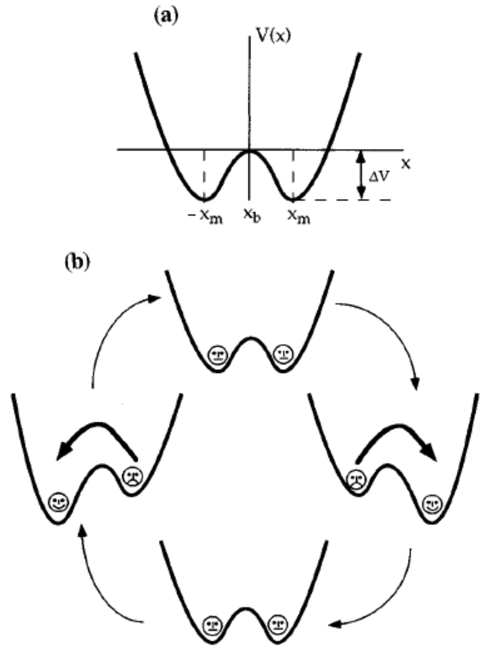
Energy barrier $\sim E\frac{\gamma_Y^2}{2}$

hints for the activated processes scenario...

Stochastic Resonance (SR) in a nutshell

overdamped of a Brownian particle + periodic forcing

$$\dot{x} = x(1 - x^2) + A\sin(\omega t) + \xi(t) \quad \langle \xi(t)\xi(t') \rangle = \varepsilon\delta(t - t')$$

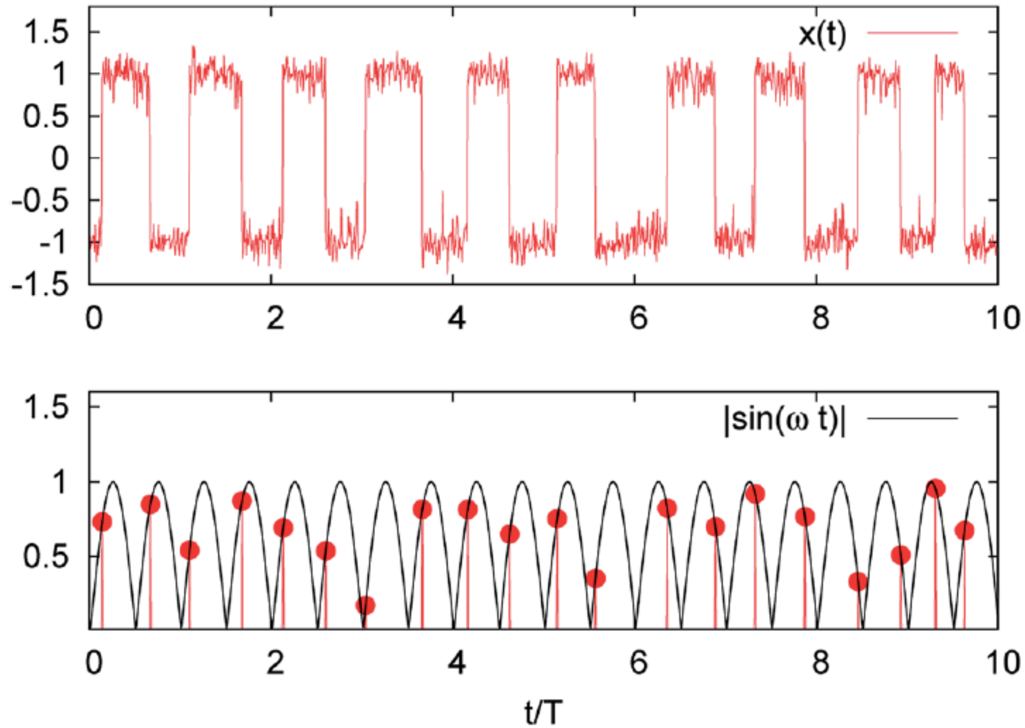


(L. Gammaitoni et al, Rev. Mod. Phys. **70**, 223-287 (1998))

mean hopping time

$$A = 0 \quad \Rightarrow \quad \tau_x = \frac{\pi}{\sqrt{2}} \exp\left(\frac{2\Delta V}{\varepsilon}\right)$$

$$A \neq 0$$



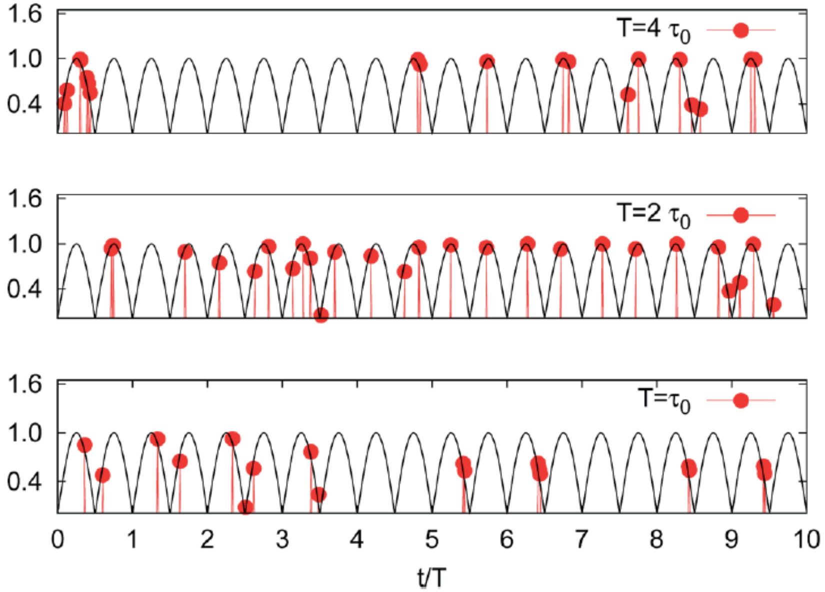
matching condition

$$\frac{\pi}{\omega} = \tau_x$$

(R. Benzi et al, J, Phys. A: Math. Gen. **14**, L453-L457 (1981); Tellus **34**, 10-15 (1982))

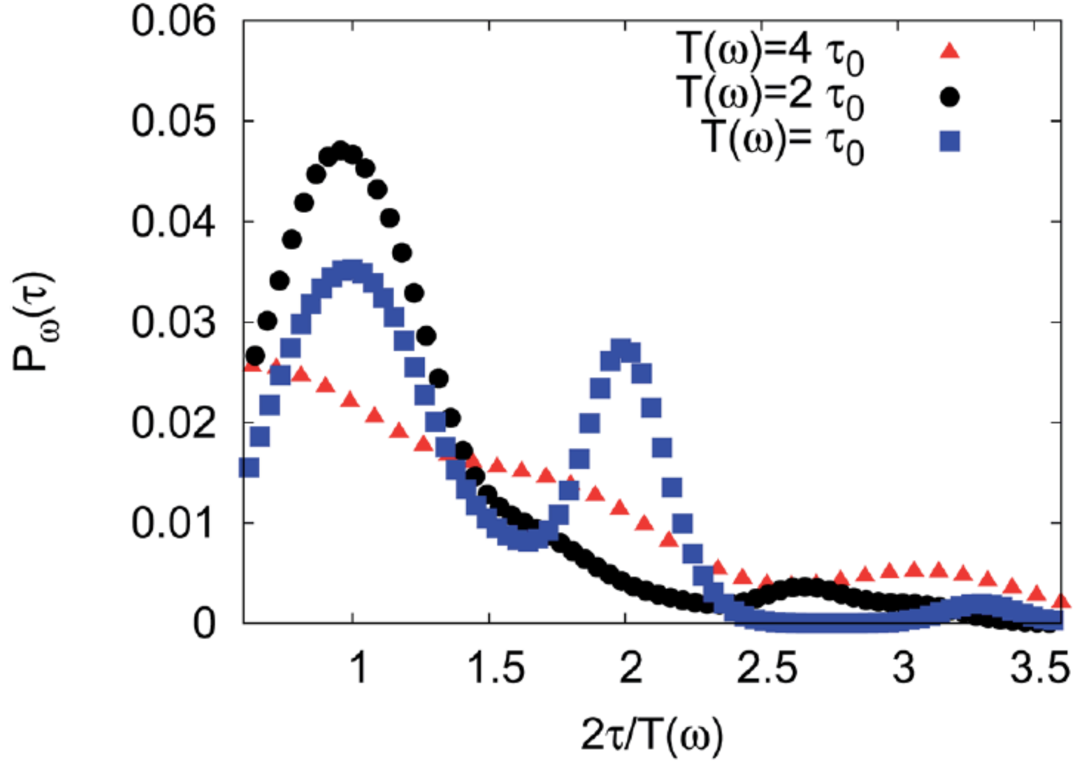
SR signatures in the plastic dynamics of Soft-Glassy Materials

$|\sin(\omega t)|$ and occurrence of plastic events



matching frequency

PDFs of time lapses between successive plastic events

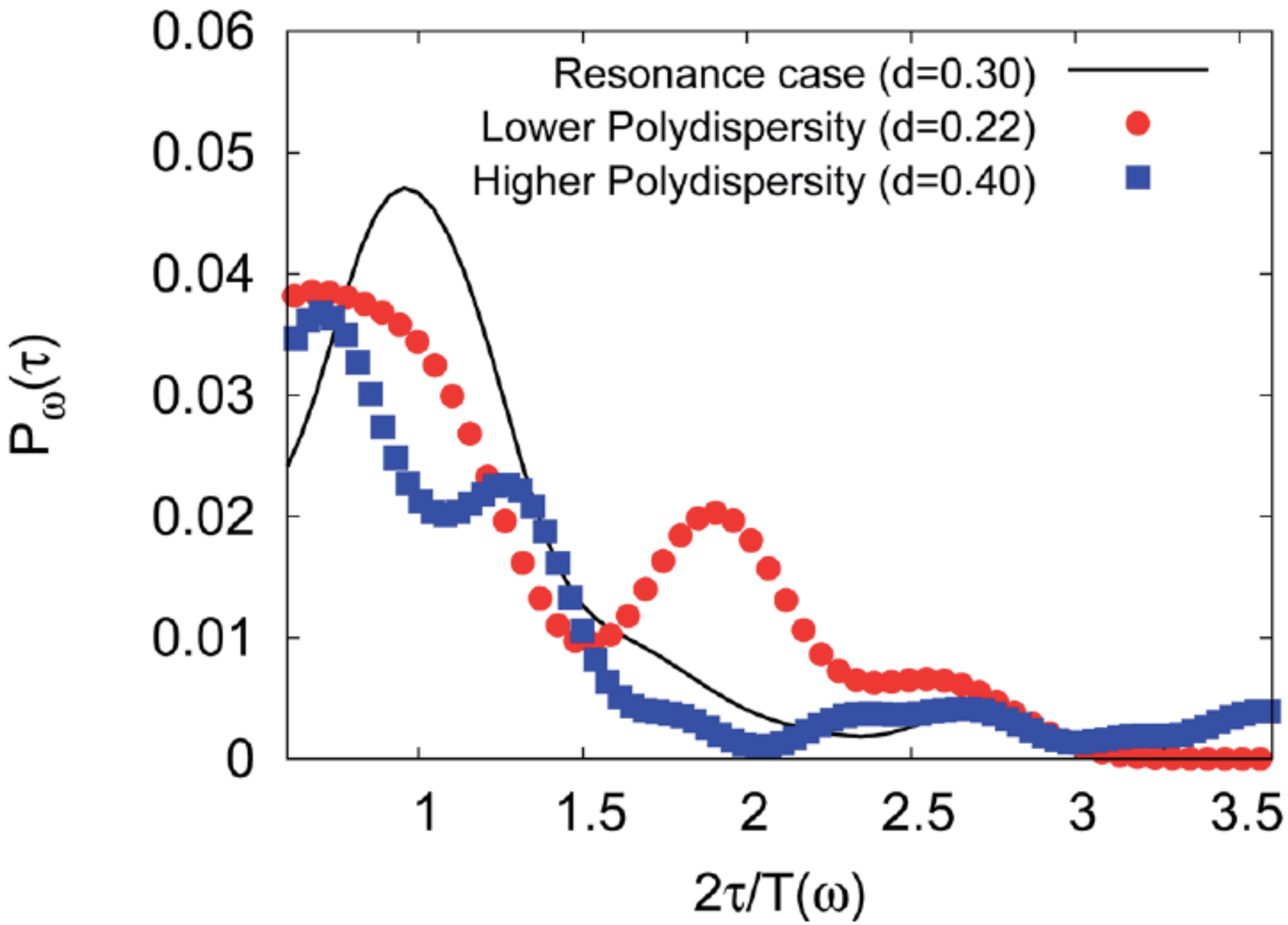


how to "change" the intrinsic noise?

(R. Benzi, M. Sbragalia, AS et al, Soft Matter **11**, 1271-1280 (2015))

Polydispersity: a control on the intrinsic effective noise?

PDFs for **fixed** strain frequency



polydispersity

$$d = \frac{\langle \mathcal{A}^2 \rangle^{1/2}}{\langle \mathcal{A} \rangle}$$

changing polydispersity drives the system out of the matching condition!

polydispersity $\sim$ **noise**

Take home messages…

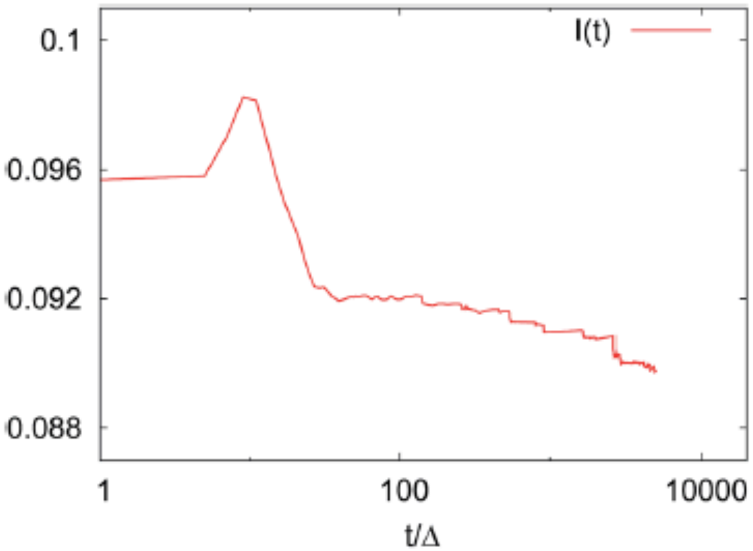
- **Instrinsic** characteristic **time-scale** of plastic activity induced by **coarsening**
- **Plastic rearrangements** can be regarded as **activated processes** induced by a “noise”
- **Signatures of stochastic resonance** from simulations of oscillatory strain
- **Intrinsic noise** correlates to **spatial disorder**, quantified by **polydispersity**

…and perspectives

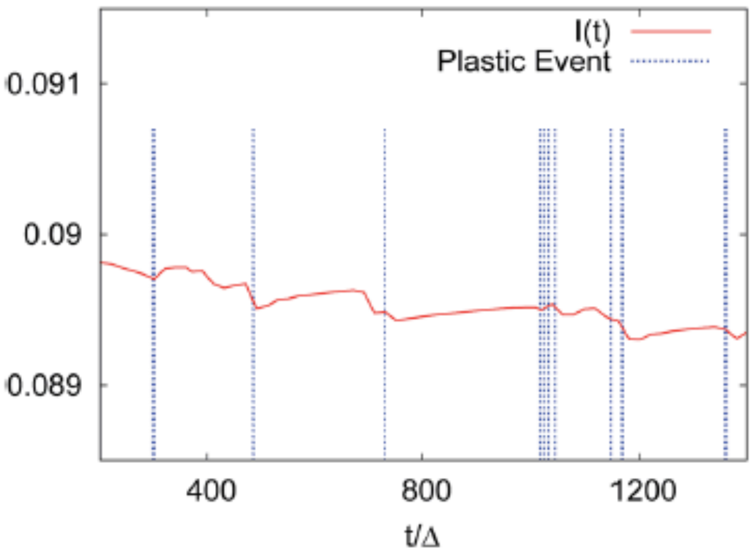
- Quantification of the intrinsic noise from non-equilibrium fluctuation-dissipation theorems

CREDITS: R. Benzi and M. Sbragaglia (UniToV)
M. Bernaschi and S. Succi (IAC-CNR)
F. Toschi (TU/e)

Grazie per l’attenzione!



(a)



$$I(t) = \frac{1}{L^2} \int |\nabla \phi(r)|^2 \mathrm{d}r$$