# Plastic events in Soft Glasses

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*with*

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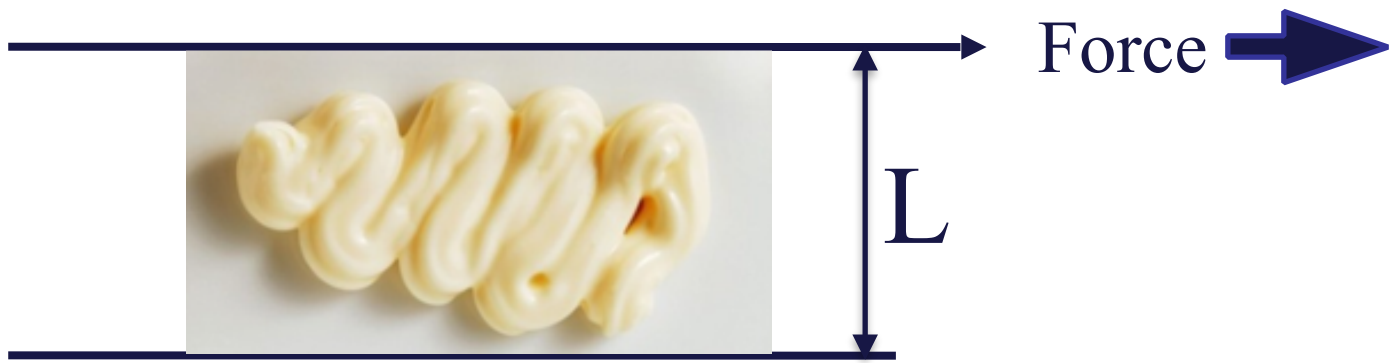
# Solid / Liquid transition

The difference between solids and liquids is one of the very first knowledge in our life.

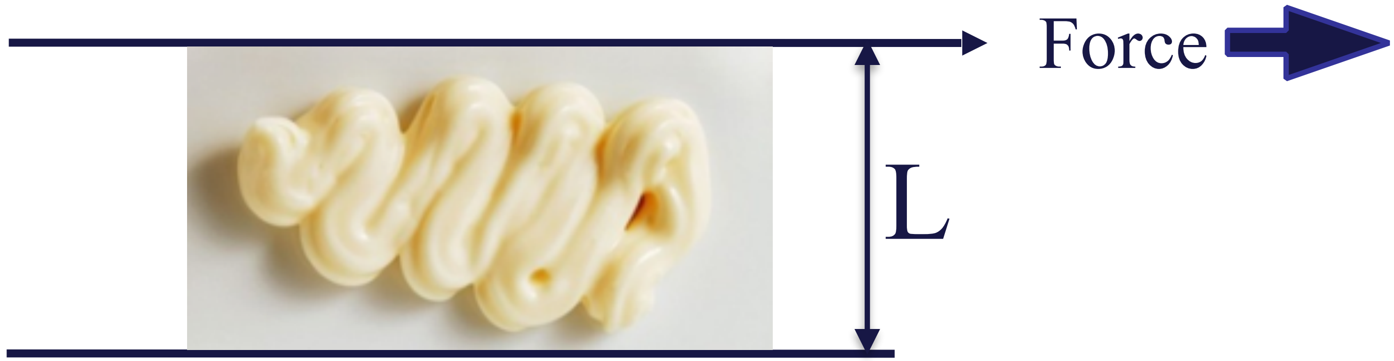
However, as physicists, we are still in trouble to understand the liquid/solid transition for amorphous materials like maionese.

# The basic statement: liquids flow and solids do not




$$\text{Force} > 0 \Rightarrow \begin{cases} \text{the system flows} \rightarrow \text{fluid} \\ \text{the system does not flow} \rightarrow \text{solid} \end{cases}$$

Maionese is an example of “soft glass”:
two liquids with peculiar surface forces between them.




Force $< F_c \Rightarrow$ the system does not flow $\rightarrow$ solid

Force $> F_c \Rightarrow$ the system flows $\rightarrow$ liquid

<u>$F_c$ is known as yield stress</u>

*P. Sollich, F Lequeux, P Hébraud, ME Cates PRL (2000), L Berthier, G Biroli Rev. Mod. Phys. (2007), A. Cavagna Phys. Rep. (2009), M Megard, G Parisi, MA Virasoro (1987)*

## Can we make a (soft) glass from two liquids A and B?
## Can we perform numerical simulation of soft glasses?

In many complex systems numerical simulations provide a valuable insight to understand the physics (e.g.turbulence).

For soft glass materials we must handle a huge number of different physical scales:

Atomic scale;  0.1 nm

Molecular scale; 1/100 nm

Mesoscopic structures; 50/1000 nm

Hydrodynamic scale. 1 mm

**We need a coarse grained approach to the problem**

# The coarse grained approach is based on the Lattice Boltzmann Equation

(Mc Namara Zanetti 1989, Higuera Jimenez 1989, R.B. Succi Vergassola 1992,…).

<u>Mesoscopic forces</u>

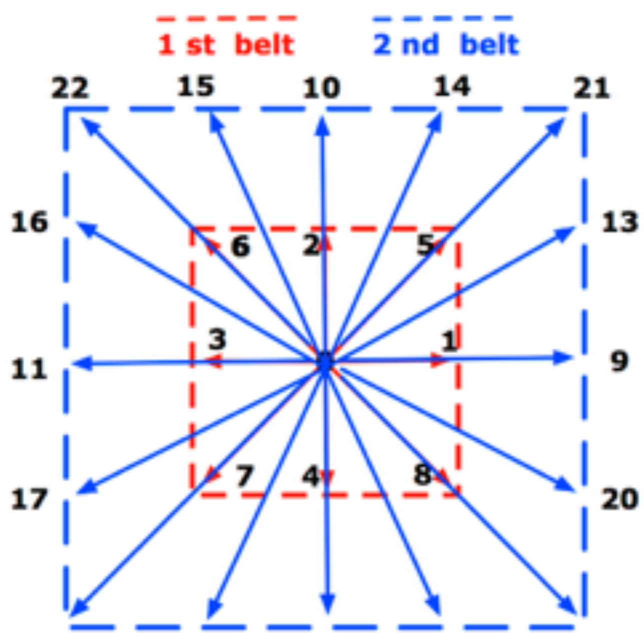
$$f_i(\mathbf{x}+\mathbf{c_i}, t+1) - f_i(\mathbf{x}, t) = -\frac{1}{\tau}[f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)] + force_i$$

$\mathbf{c_i}$ is discrete set of velocities on a lattice

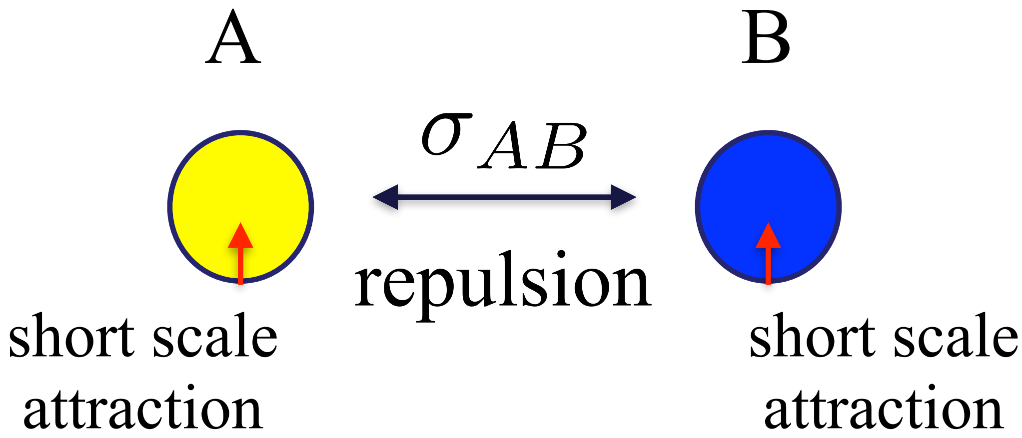
$$\rho = \Sigma_i f_i(\mathbf{x}, \mathbf{c_i}, t)$$

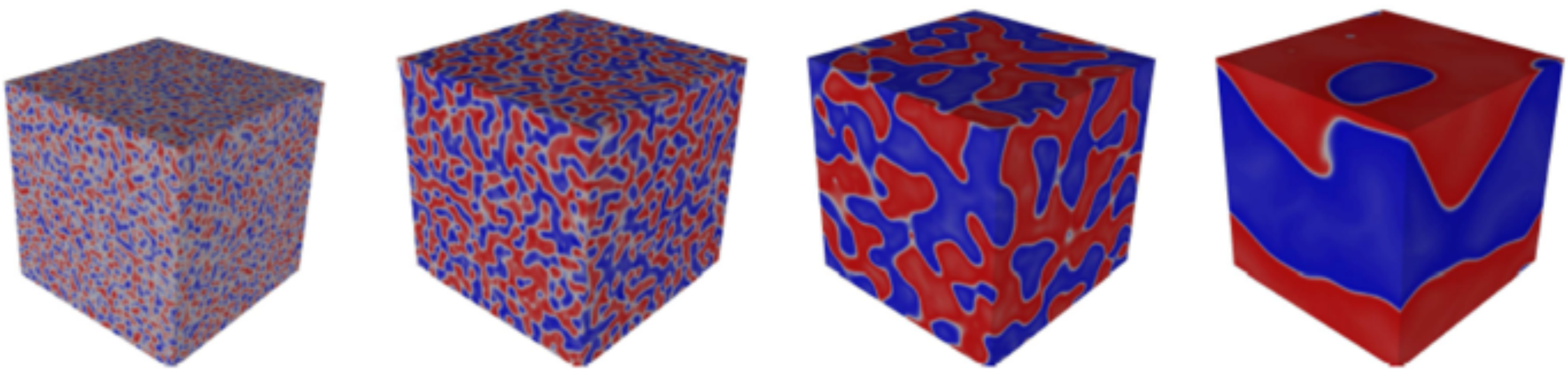
$$\rho\mathbf{u} = \Sigma_i \mathbf{c_i} f_i(\mathbf{x}, \mathbf{c_i}, t)$$

The set of $\mathbf{c_i}$ is chosen such that isotropy is recovered in the thermodynamic limit, i e. with a suitable choice of the k-order tensors



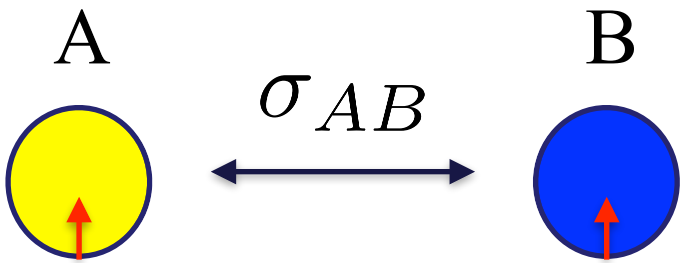
# Modeling two fluids with surface tension $\sigma_{AB}$

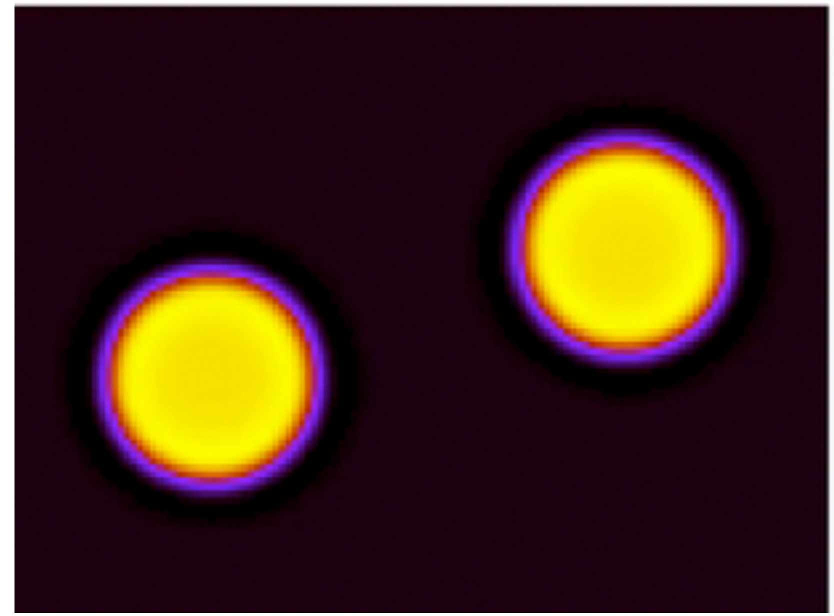


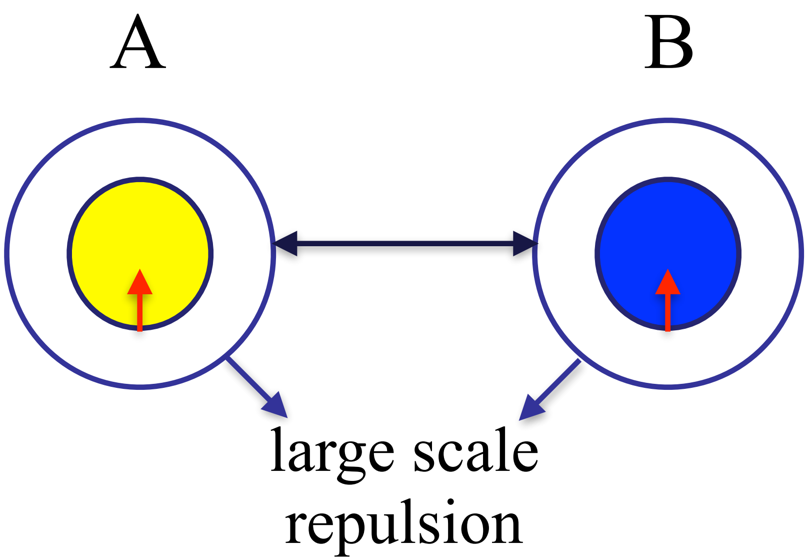
Starting from a well mixed system, we observe coarsening (spinodal decomposition)

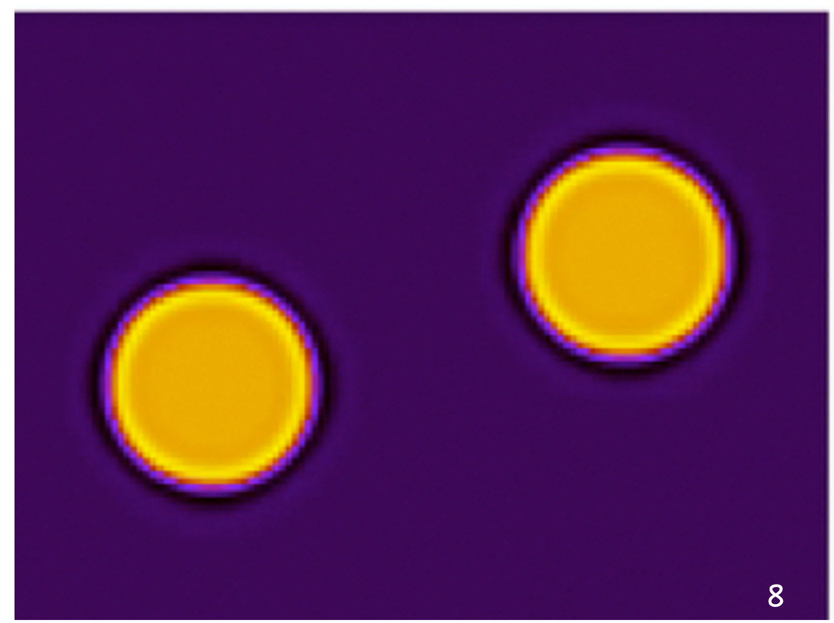
*P. Perlekar, R. Benzi, H.J.H.Clercx,D.R. Nelson, F. Toschi, PRL 2014*



Introducing frustration!!



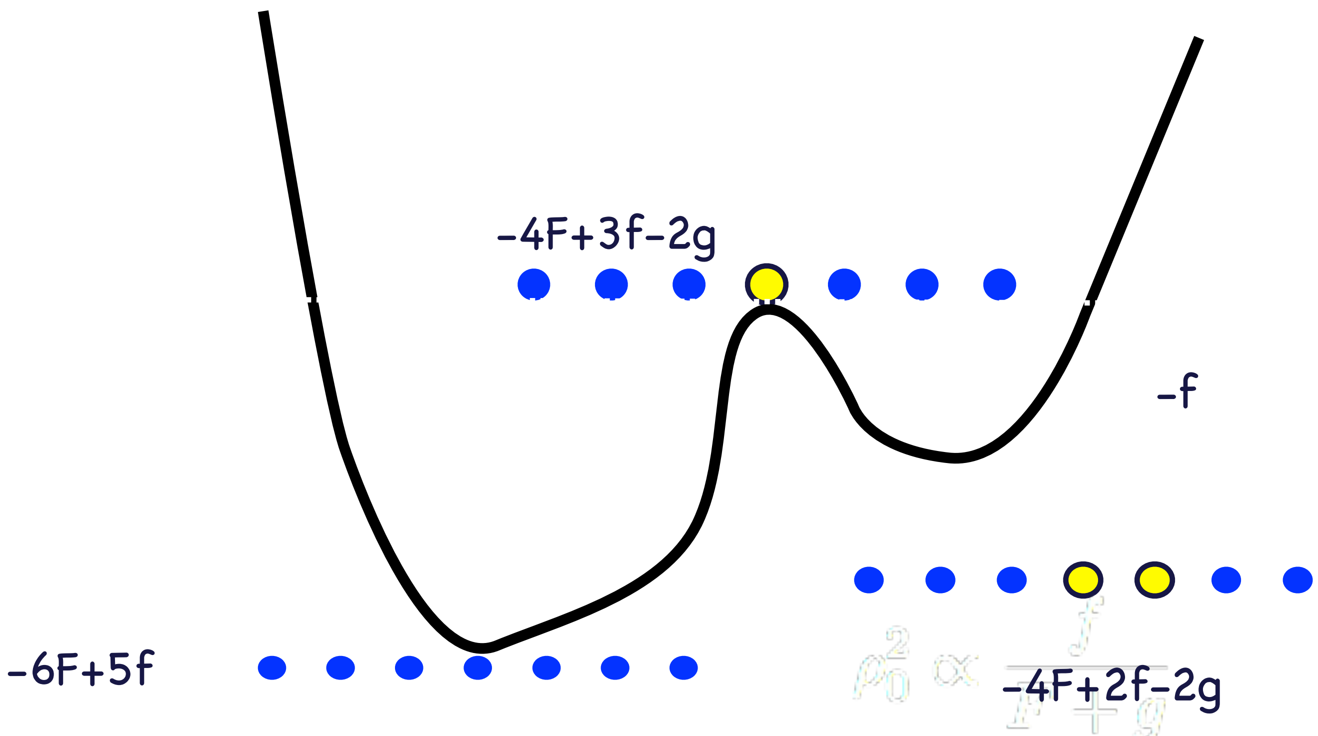
# Why frustration ??

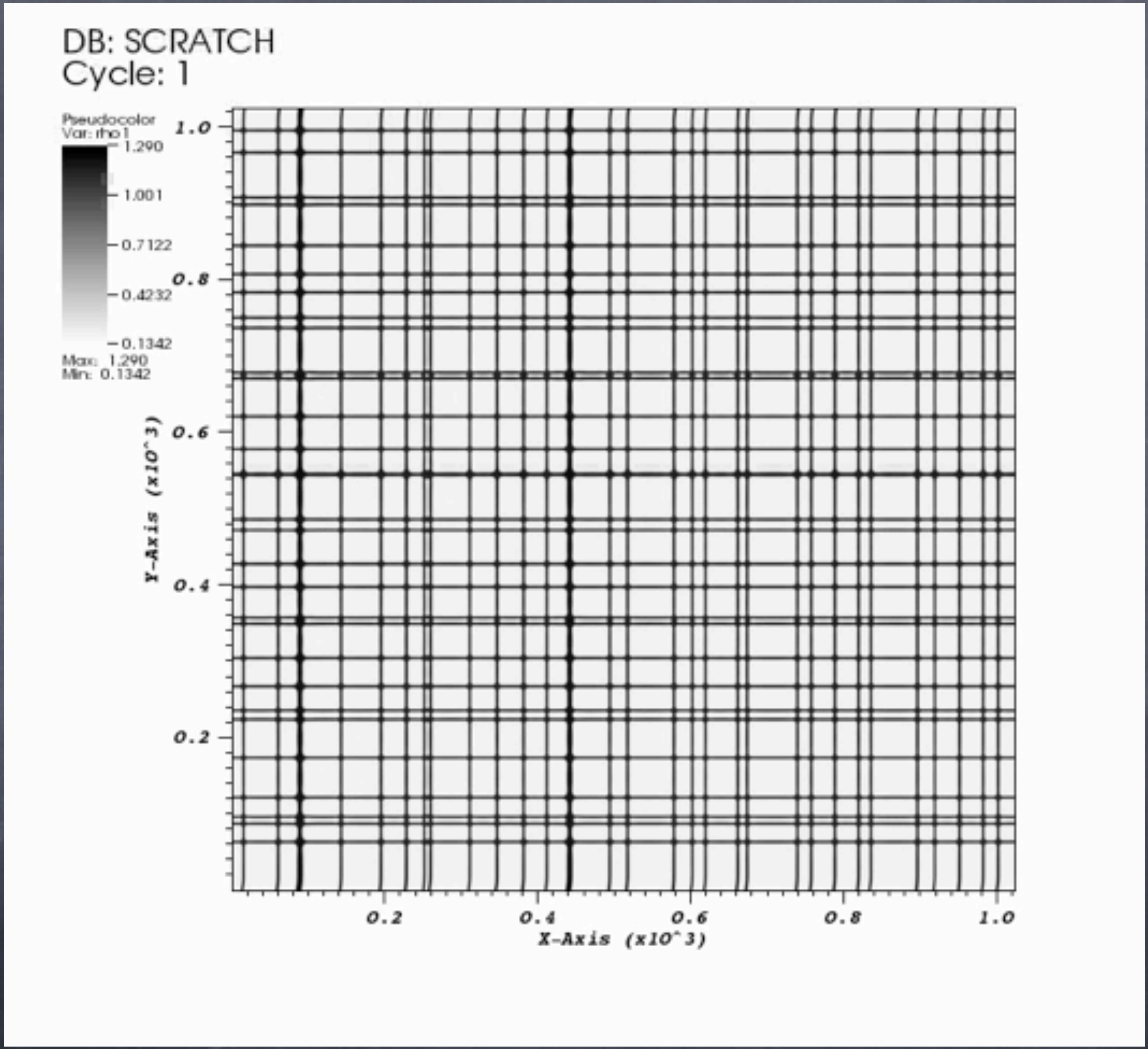
-F pot. energy of att. force AA and BB

f pot. energy of rep. force AA and BB

g pot. energy of rep. force AB

**Sethna et.al. 1992**

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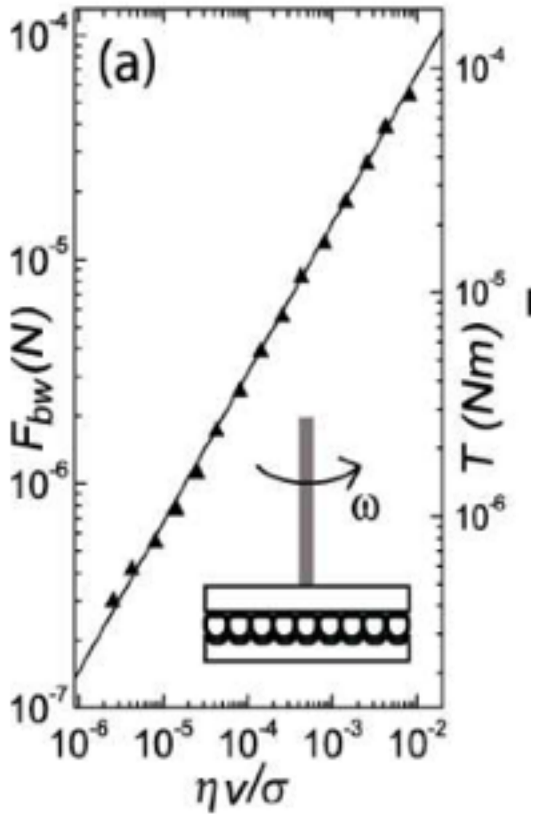
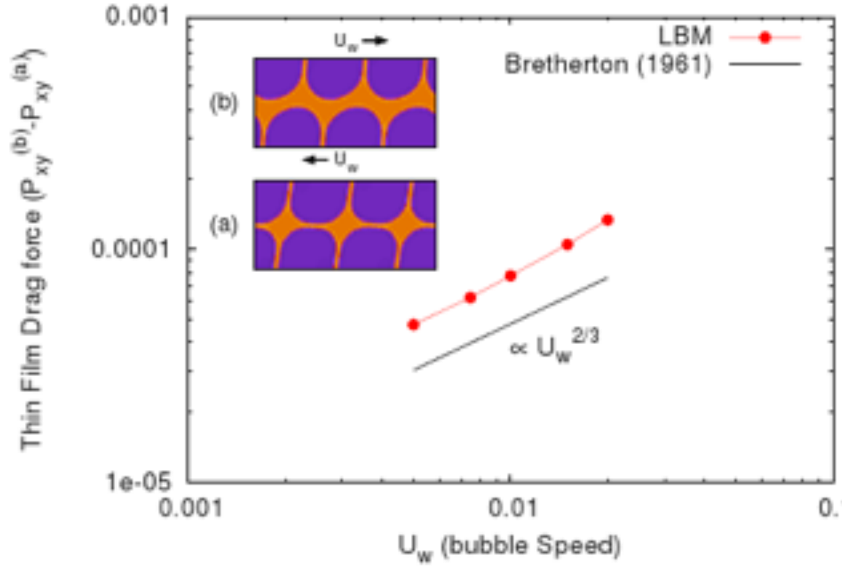
Cycle: 1
Pseudocolor
Var: rho1
1.290
1.001
0.7122
0.4232
0.1342
Max: 1.290
Min: 0.1342
1.0
0.8
0.6
0.4
0.2
Y-Axis (x10^3)
0.2
0.4
0.6
0.8
1.0
X-Axis (x10^3)

# Frustration = Disjoining pressure at the interface

## Benchmark against the theoretical prediction for bubble-bubble drag (Bretherton 1961)



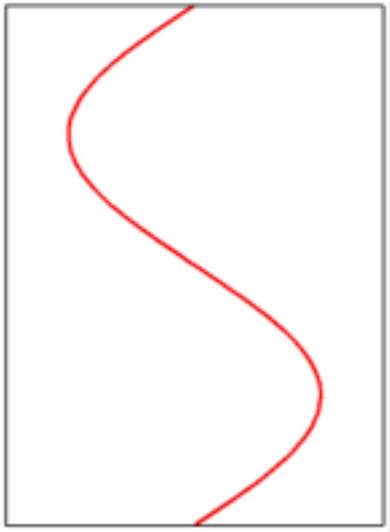

Katgert, Mobius, van Hecke 2008

Remember the definition of yield stress


Force $< F_c \Rightarrow$ the system does not flow $\rightarrow$ solid

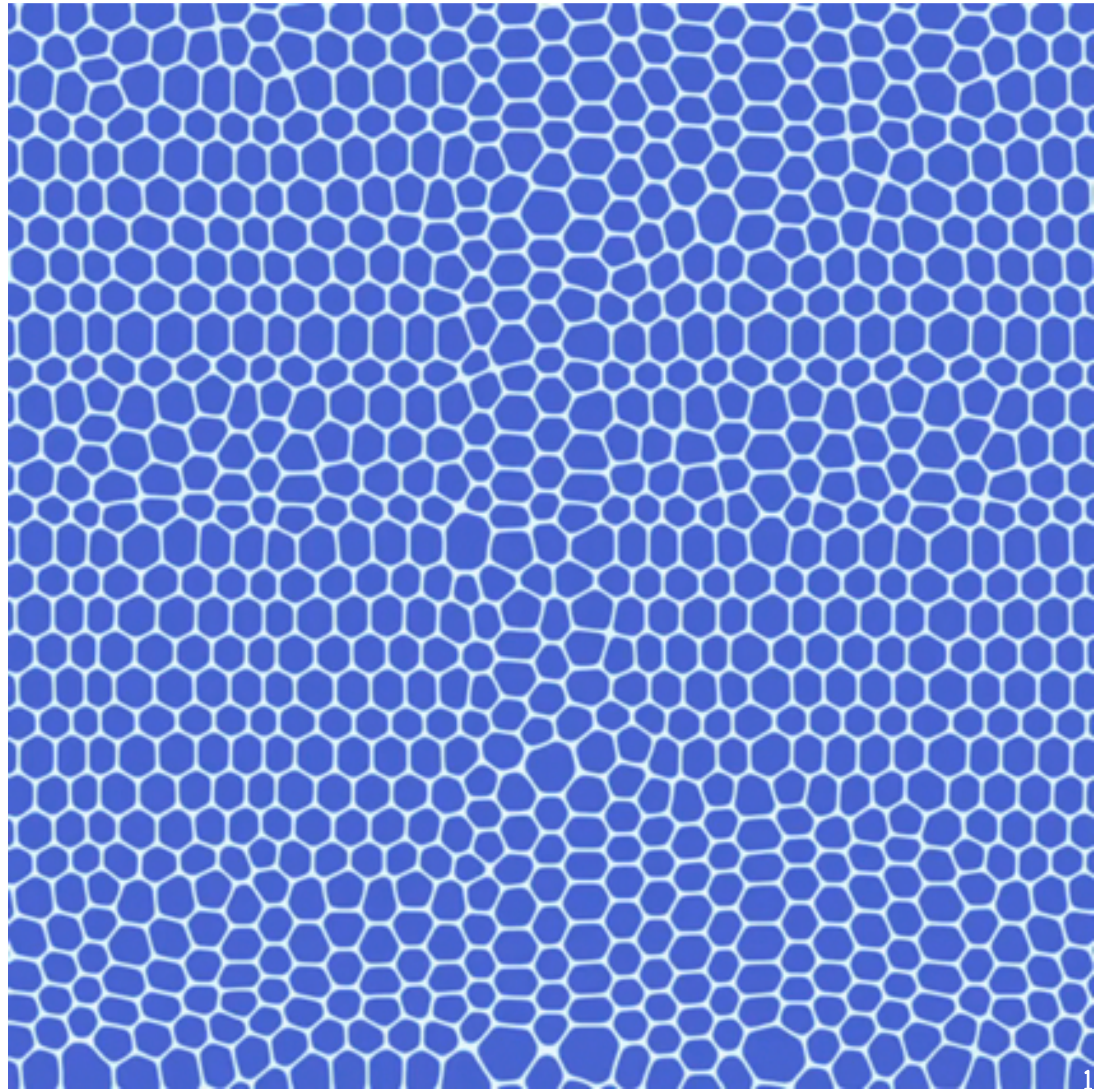
Force $> F_c \Rightarrow$ the system flows $\rightarrow$ liquid

<u>$F_c$ is known as yield stress</u>



Forcing

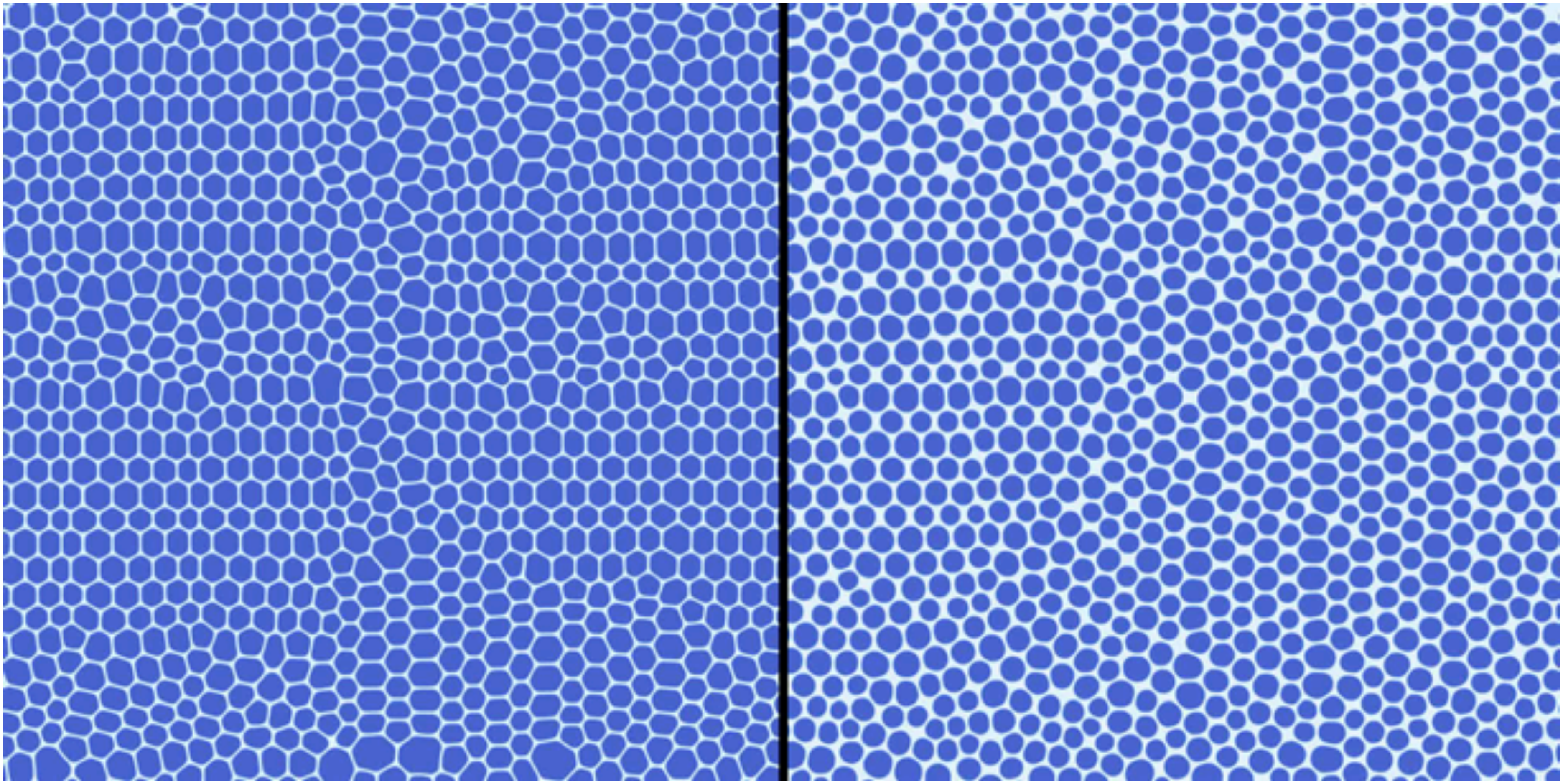
# Kolmogorov flow

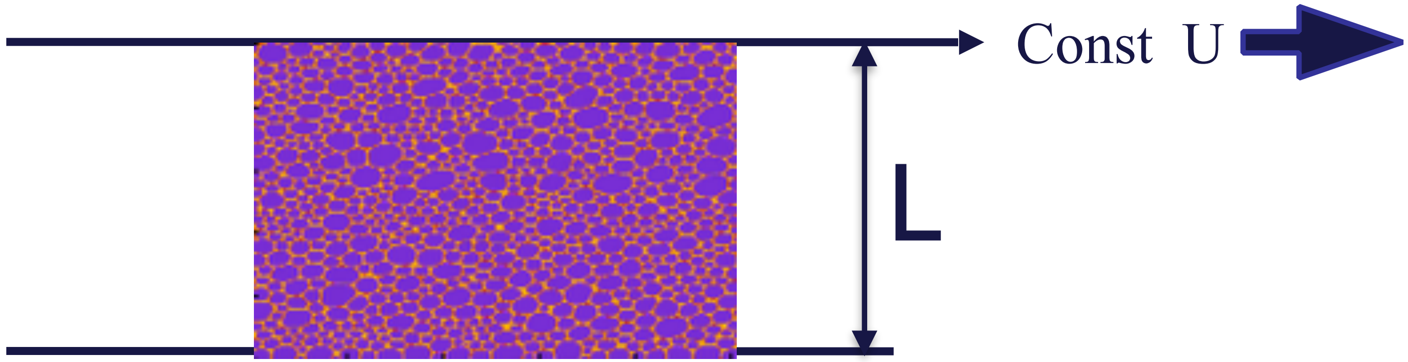


*RB, M. Sbragaglia, S. Succi, M. Bernaschi, S. Chibbaro,*
J.Chem. Phys. 2009
PRL 2009
*RB, M. Sbragaglia, P. Perlekar, M. Bernaschi, S. Succi, F.Toschi*
Soft Matter, 2014
Soft Matter, 2015

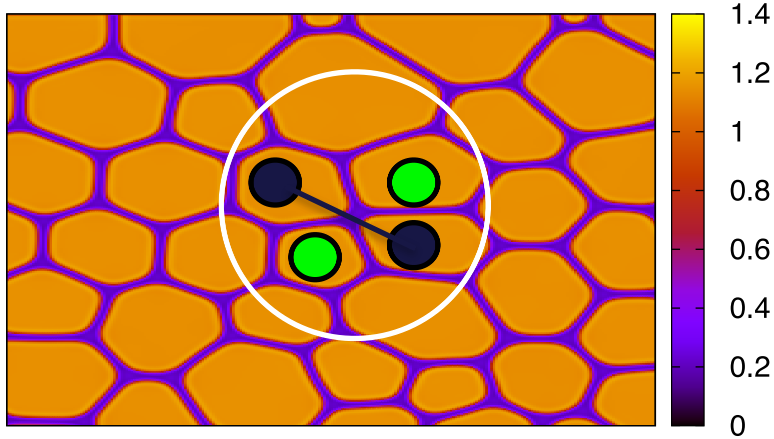
high packing fraction
yield stress

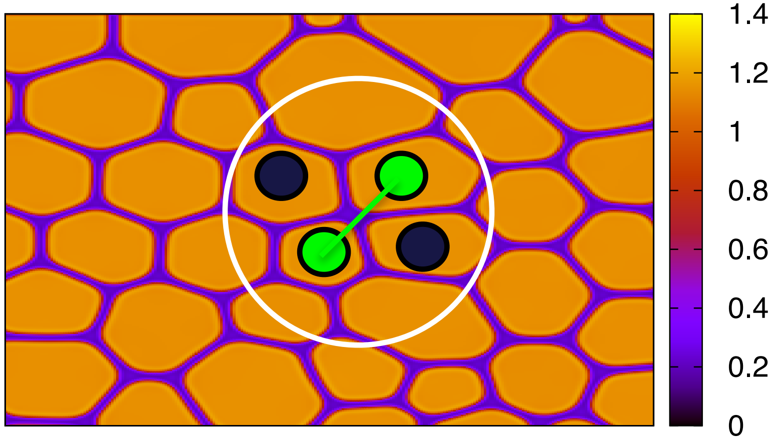
low packing fraction
no yield stress



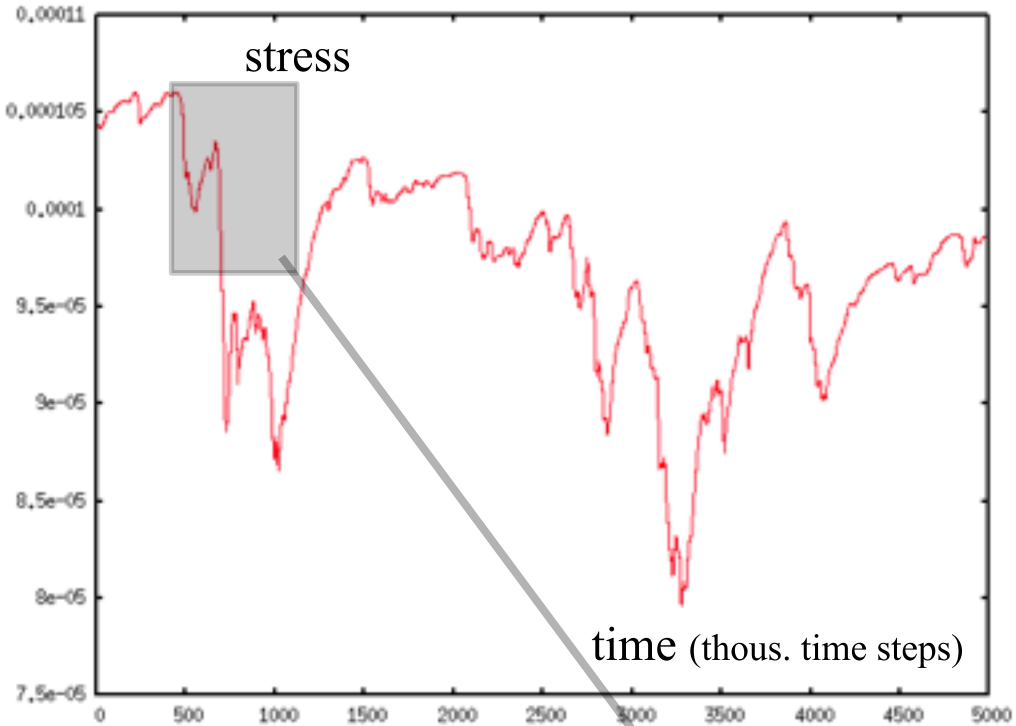



Plastic events are irreversible topological changes of the interface

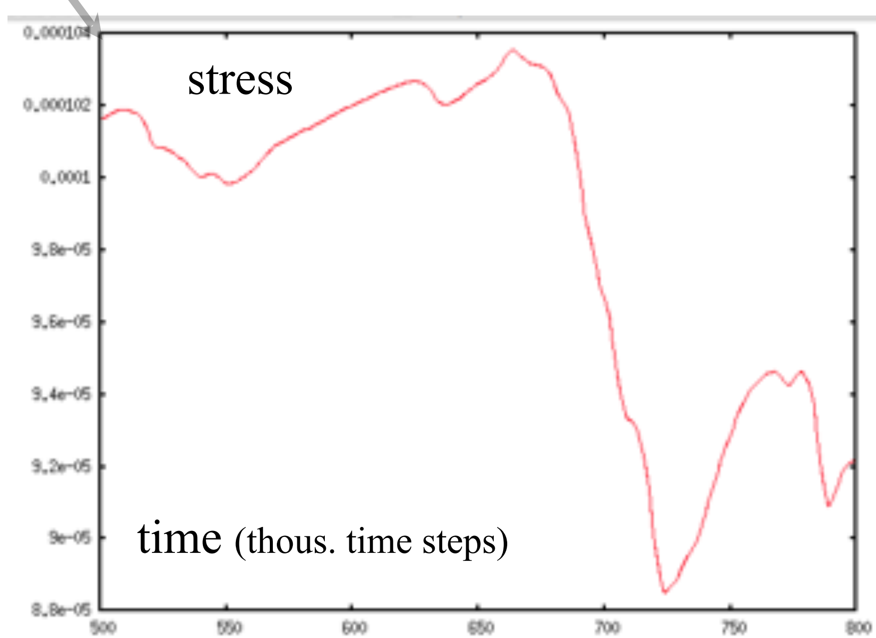


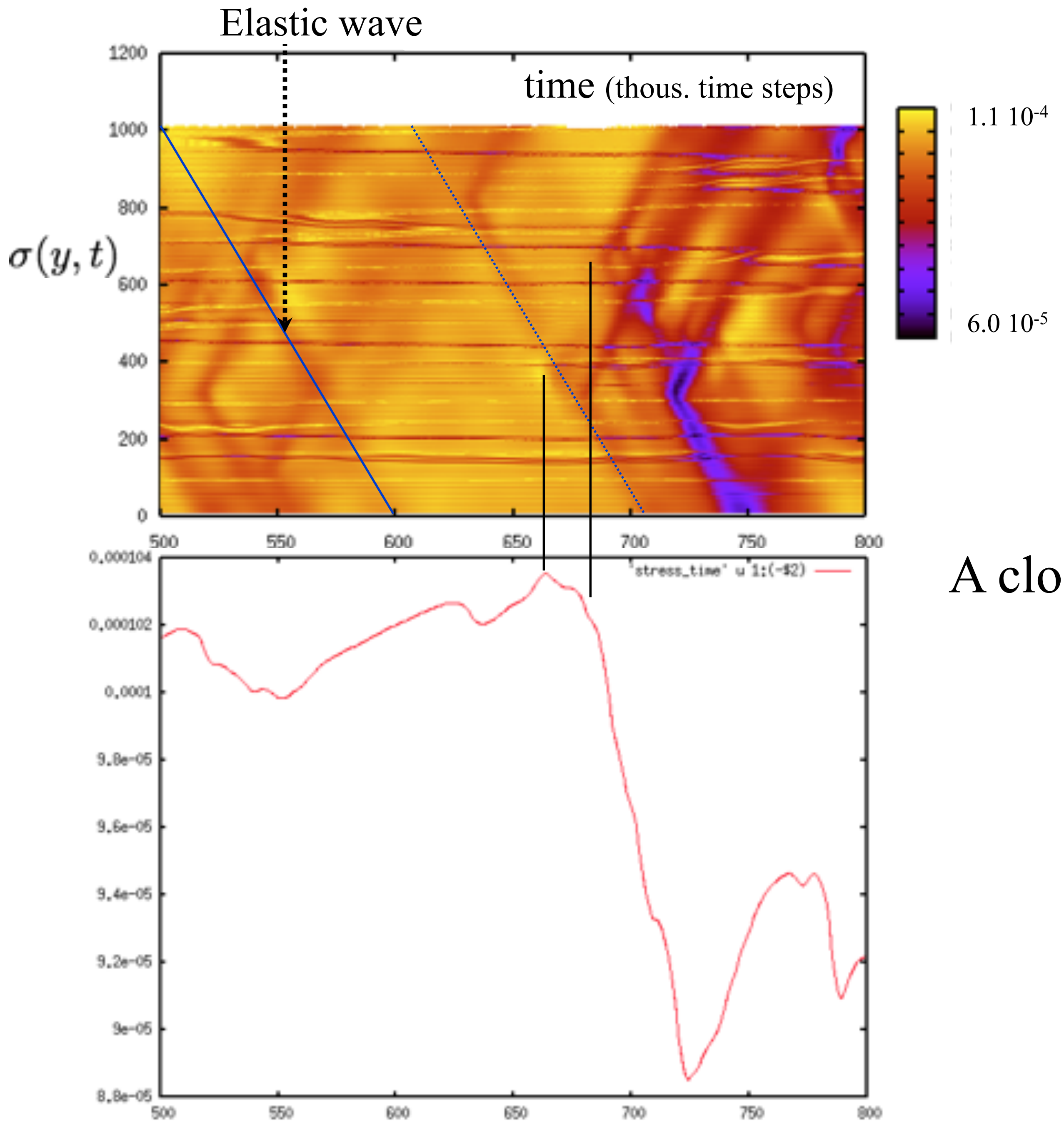
Plastic events are responsible of sharp decreases in stress




A closer look

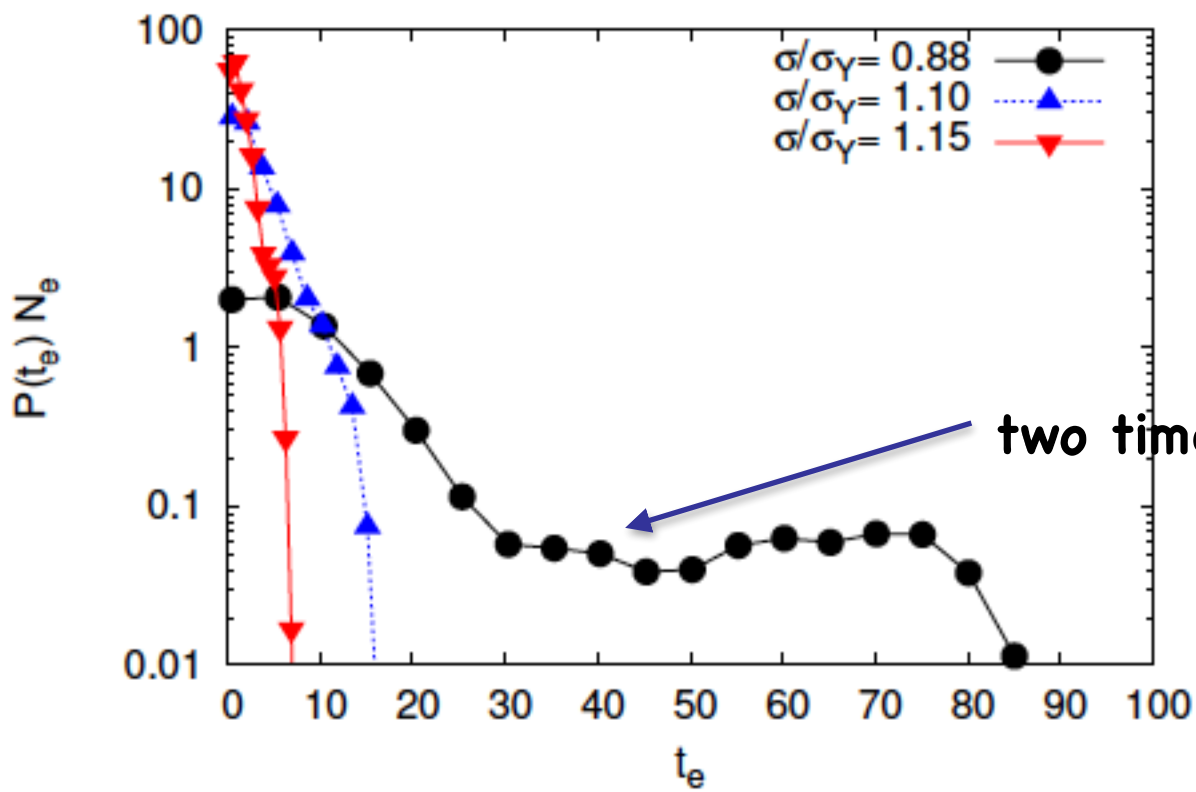


# Time-space view




# A closer look

Probability distribution of the time interval $t_e$ between two consecutive plastic events.

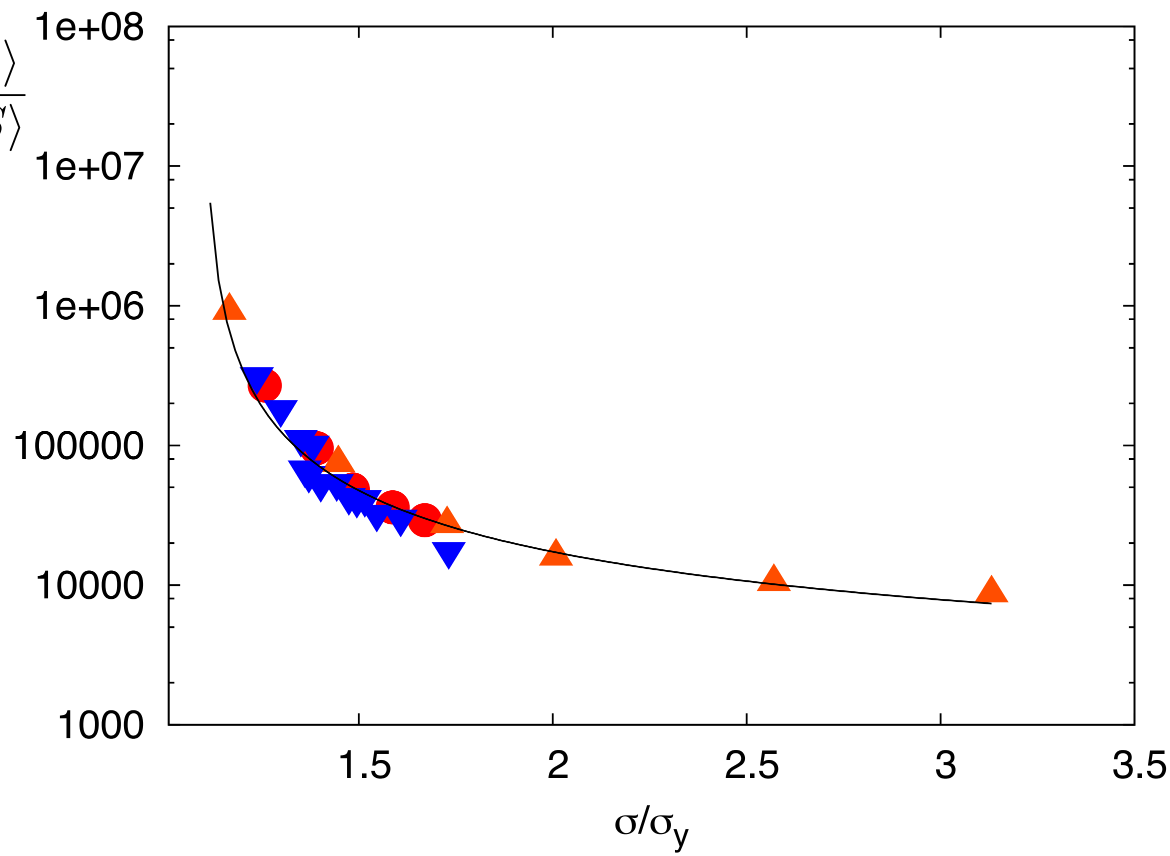



**two time scales !!**

$\sigma \equiv stress \quad \sigma_y \equiv yield\ \ stress$

Statistical mechanics tells us that the relaxation time $\tau$ is proportional to viscosity. This implies that $lim_{\sigma \to \sigma_y} \tau(\sigma) \to \infty$

$$\tau = \frac{elastic\ energy}{rate\ energy\ input} = \frac{\langle \sigma^2 \rangle}{\langle \sigma S \rangle}$$




Remark:
Different kind of forcing mechanisms gives gives the same behavior !!

## Solid/Liquid transition at the yield stress

The transition is not order/disorder!

Yet, if the relaxation time grows to $\infty$ below the yield stress, than we should expect some characteristic scale to become very large.

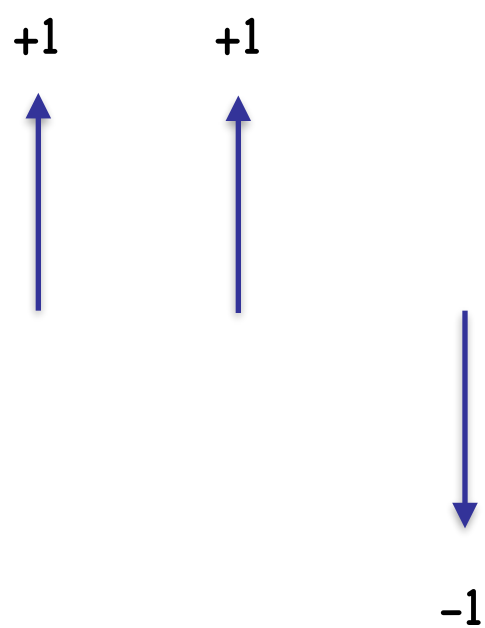
Density-density correlation function does not change at the transition (disorder/disorder transition)

We need something else!!

# Time-space correlation function of interface

Let us use the analogy with spins for the Ising model

We compute the motion of each piece of material between time t and t + T, and we assign +1 when it moves or -1 when it does not move.




The correlation functions of "spins" are usually called

DYNAMIC HETEREOGENITY

# Computing Dynamic heterogeneity

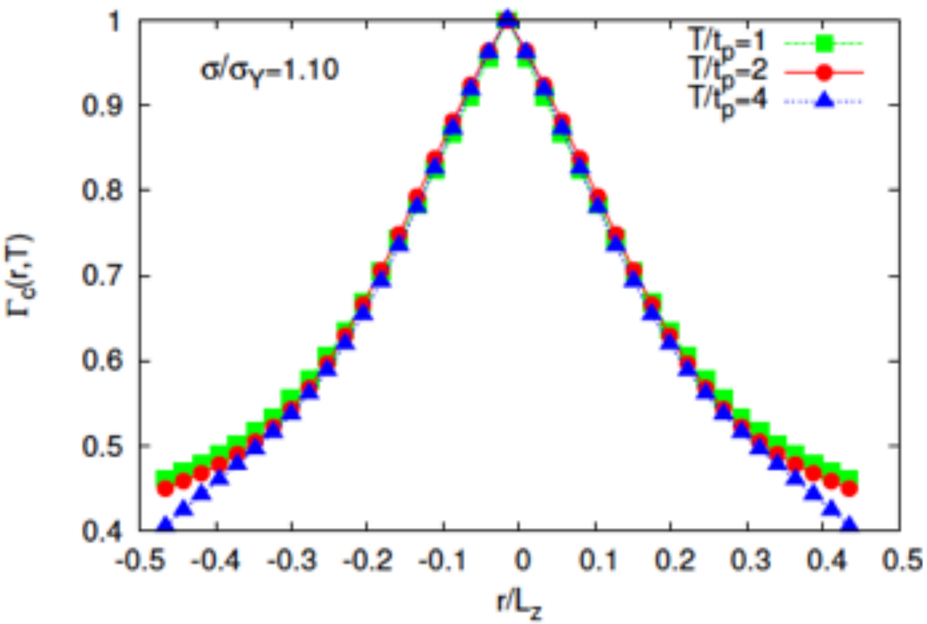
phase field $$\phi(x,z;t) \equiv \rho_A(x,z;t) - \rho_B(x,z;t) - \langle(\rho_A - \rho_B)\rangle_{x,z}$$

overlap
$$\left\{\begin{array}{l} q(x,z;t,t+T) = \dfrac{\phi(x,z;t)\phi(x,z;t+T)}{\bar{\phi}(t)\bar{\phi}(t+T)} \\ \bar{\phi}^2(t) \equiv \langle\phi^2(x,z;t)\rangle_{x,z} \end{array}\right.$$

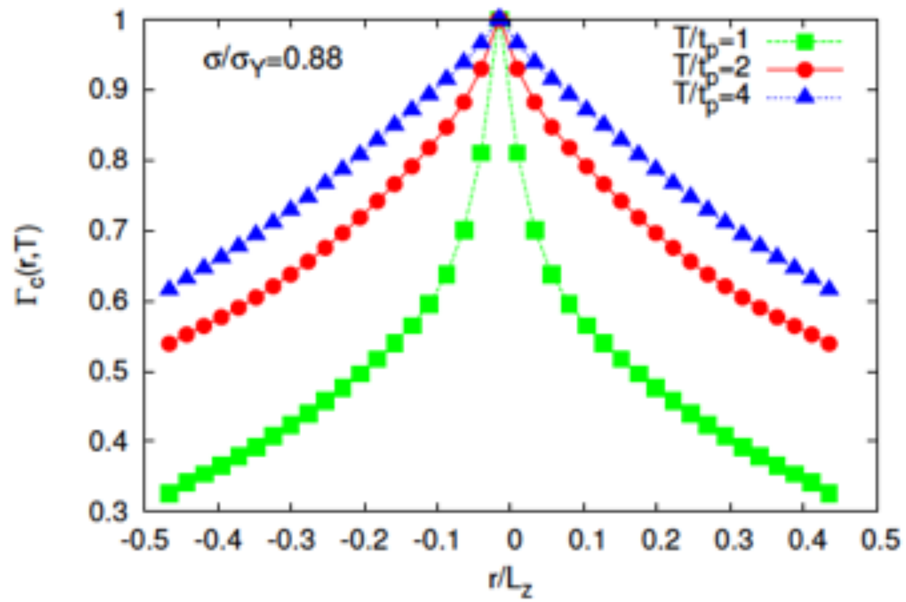
overlap correlation
$$\Gamma(r,T) = \langle q(x,z+r;t,t+T)q(x,z;t,t+T) + q(x+r,z;t,t+T)q(x,z;t,t+T)\rangle_{x,z,t}$$

The concept of Dynamic Heterogeneity was introduced for the glass transition in several papers, see Binder&Young 1986, Dasgupta et.al. 1991, Kirkpatrick&Thirumalai 1988, Franz&Parisi 2000

Above the yield stress

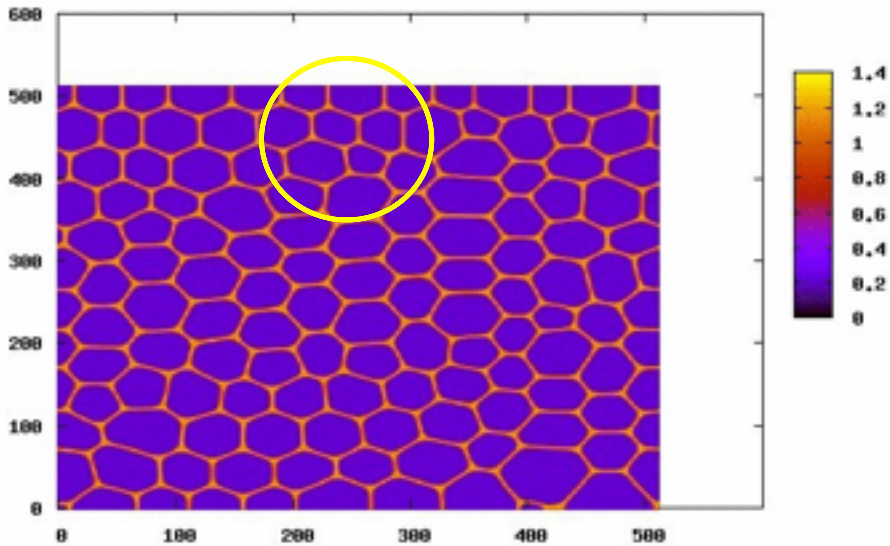



Below the yield stress

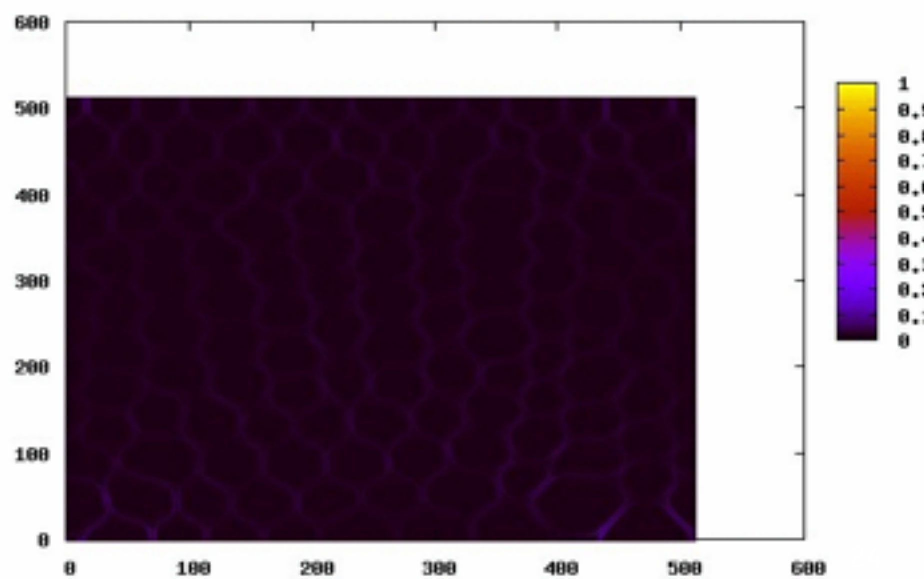


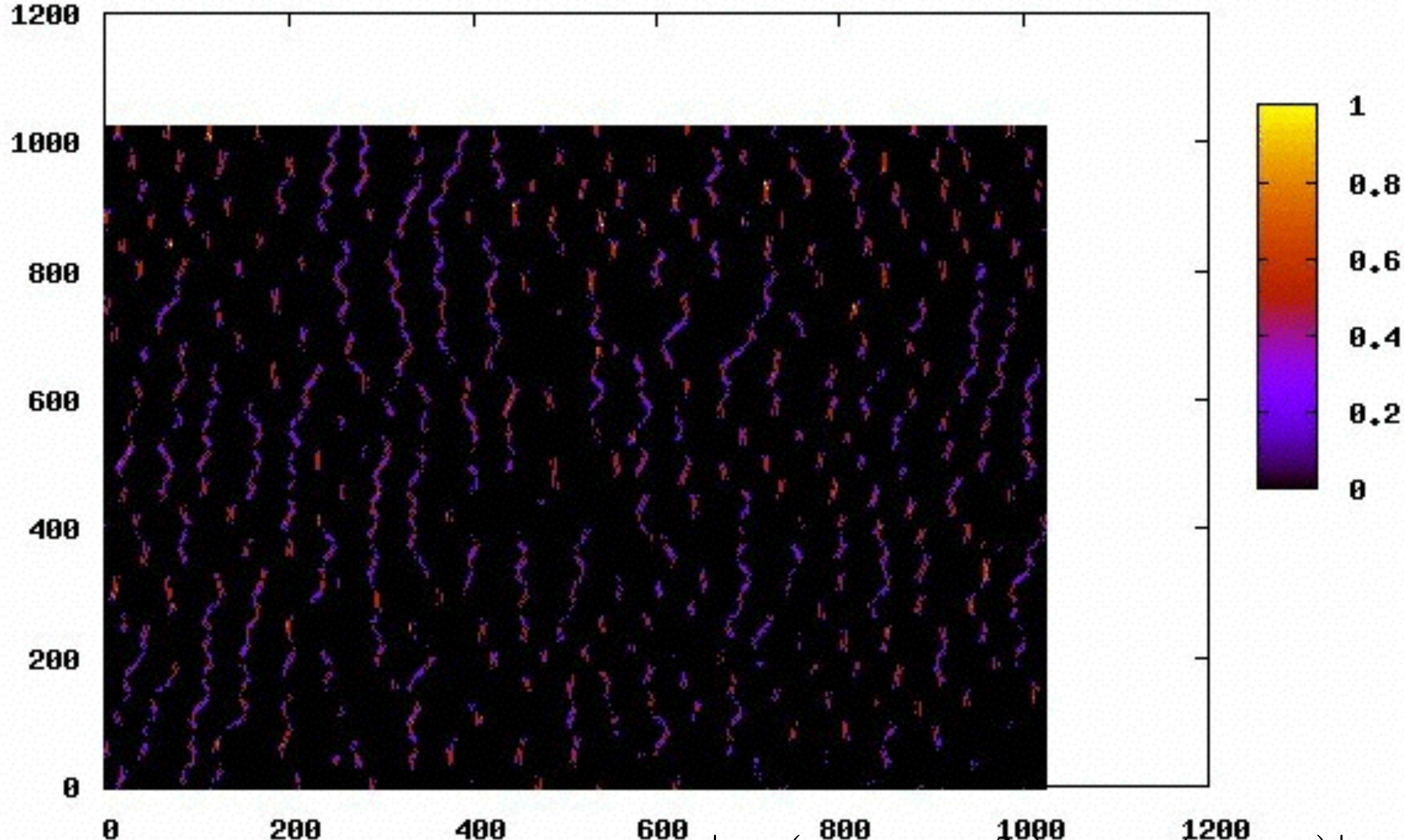

Correlations grow as the system size !

resolution $512^2$ one single event

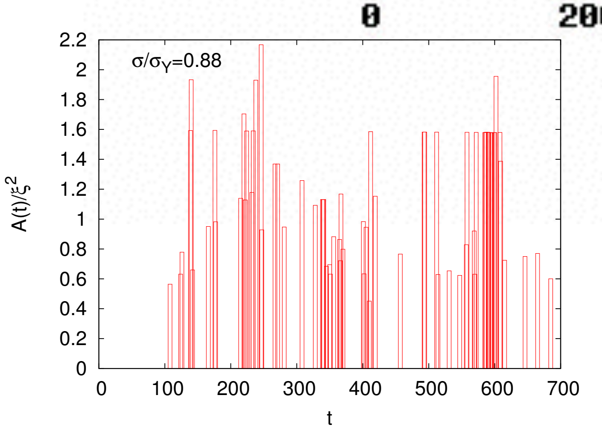



$$|\rho_A(x,y,t+\delta t) - \rho_A(x,y,t)|$$



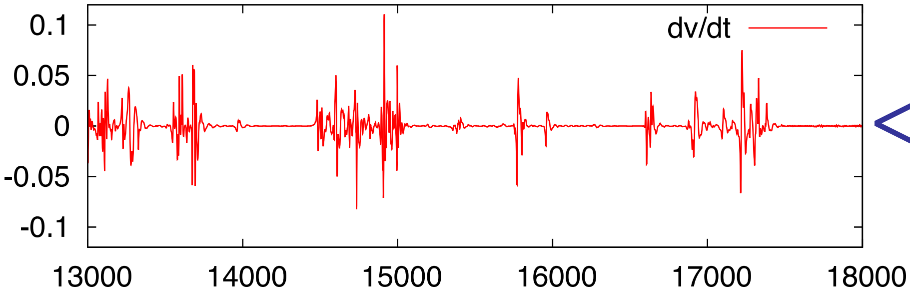



$$|\rho_A(x,y,t+\delta t)-\rho_A(x,y,t)|$$

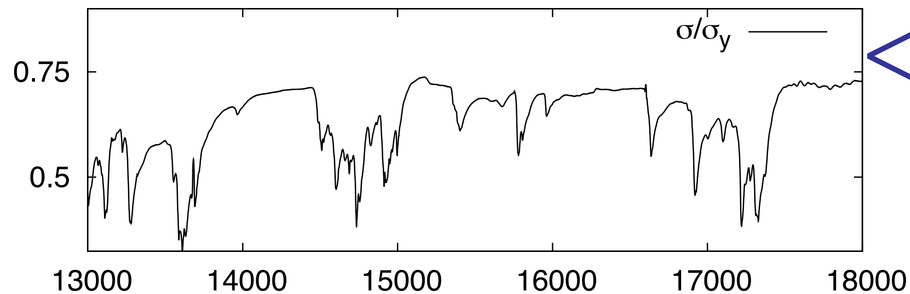


# Scaling at the transition?
# Analogy with earthquake dynamics

*RB, F, Toschi and J. Trampert in prep.*




Acceleration in a single point

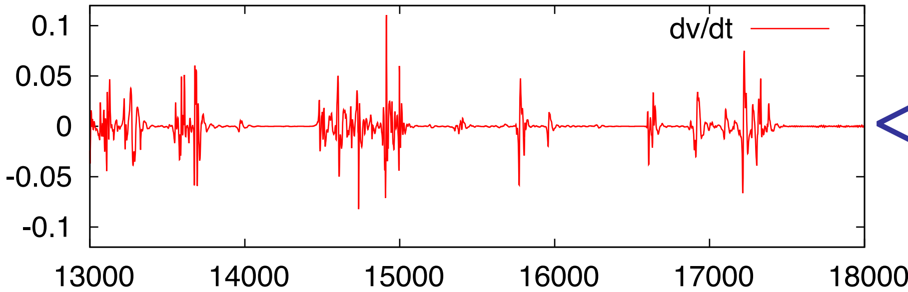



Sharp decrease in stress

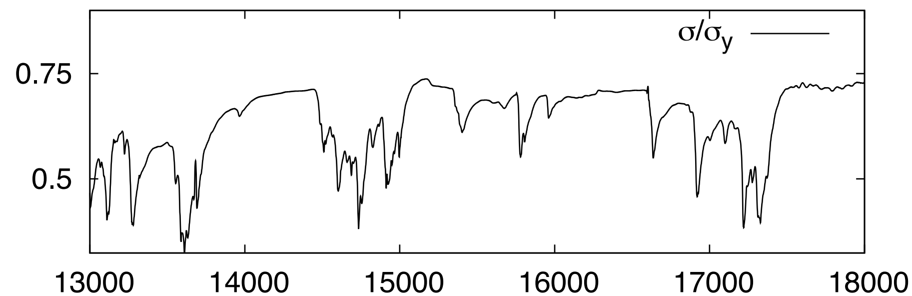
Stick-slip behavior for earthquake have been investigated by several authors:

*Stuart and Mavko, 1979;*
*Sieh, 1978;*
*Choi and Huberrnan, 1984*
*Kagan and Knopoff, 1987,*
*P Bak  C. Tang 1989,*
*Carlson and Langer, 1989*

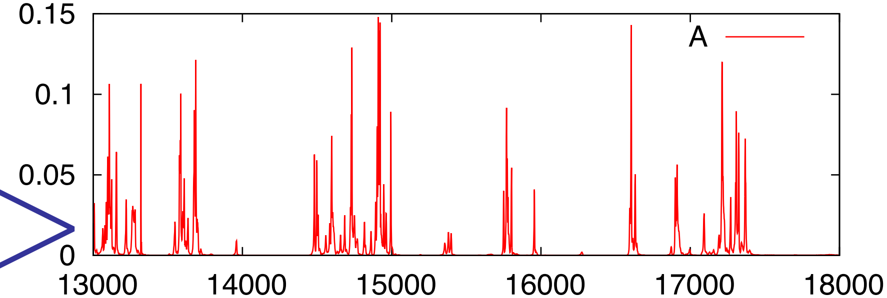
# Scaling at the transition?
# Analogy with earthquake dynamics

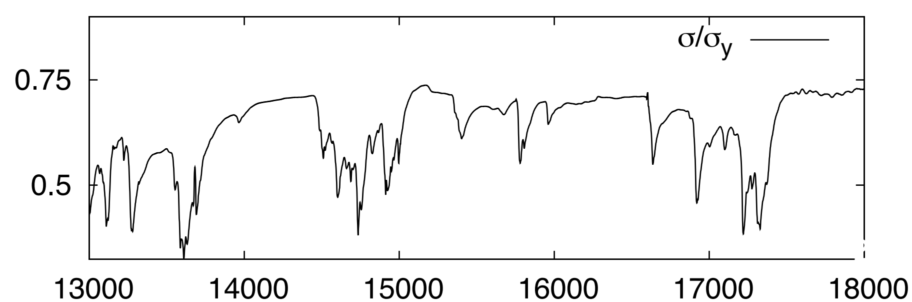



Acceleration in a single point
strong intermittency in time!

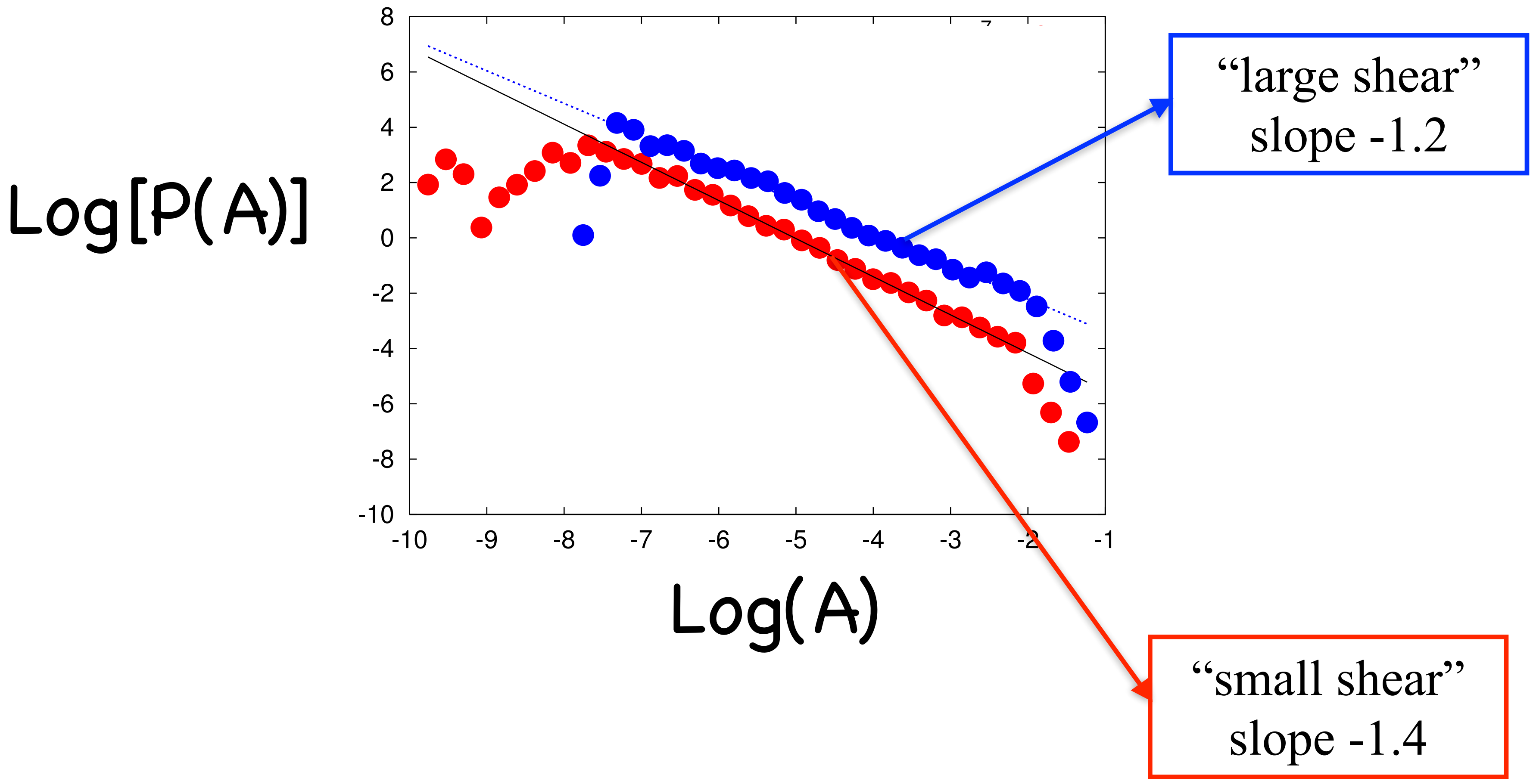



**A**=maximum displacement
during a single event.



# Gutenberg - Richter law



# Conclusions

- We have a method to simulate soft glass dynamics (two liquids + frustration = emulsion)
  agreement with experimental finding (linear-nonlinear rheology),
  agreement with non local rheology;
  viscoelastic behavior, stick-slip behavior ......

- Rigidity (glassiness) is induced by the interface;

- Below the yield stress, plastic events introduce correlations all over the interface (both local and global features of system dynamics);

- Gutenberg Richter scaling is recovered near the transition

- New physics?

# Thanks