# Plasticity and memory effects in glasses

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PMMH, CNRS/ESPCI Paris

Memory Formation in Matter
KITP, UC Santa Barbara, 05 february 2018

# Credits

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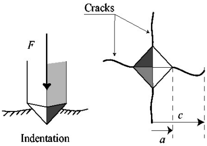
- Mehdi Talamali, Botond Tyukodi, Armand Barbot, Matthias Lerbinger (PMMH, ESPCI)
- Antoine Perriot, Etienne Barthel (CNRS/Saint-Gobain)
- Cindy L. Rountree, Elisabeth Bouchaud (CEA Saclay/ESPCI)
- Craig Maloney (NorthEastern University, Boston)
- Michael L. Falk (Johns Hopkins University, Baltimore)

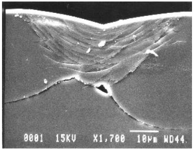
# Introduction: Plasticity and memory

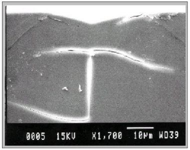
# Mechanical memory effects in bulk amorphous silica

# Plasticity of oxide glasses

- **Indentation induces plastic imprints** No crack under low enough loading. Plastic deformation confined at micro-scale
- **Permanent densification** under indentation or hydrostatic test, amplitude depends on glass nature, up to 20 % in the case of silica glass ; strong coupling shear/pressure ;

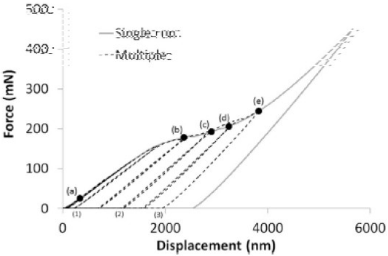


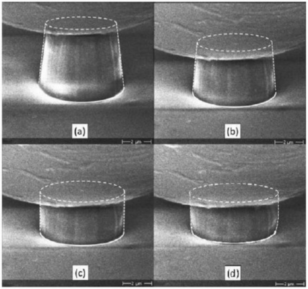



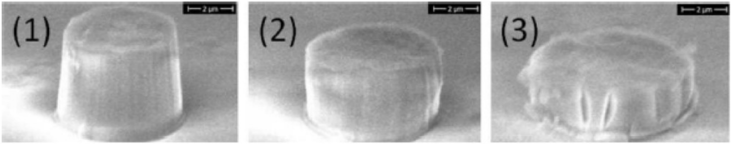




G. Kermouche et al. Acta Mat. **56**, 3222 (2008)

# Compression of micro-pillars of silica glass

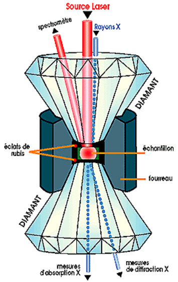


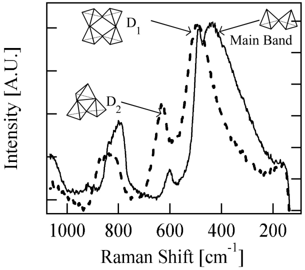




C. Kermouche et al. et al. Acta Mater. **114** 146 (2016)

# Raman spectroscopy as a probe of glass density



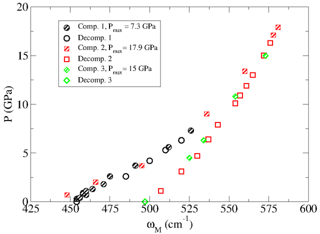

Diamond Anvil Cell – Pressure up to 18-20 GPa

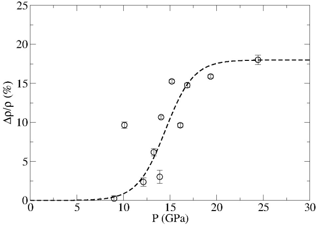



Raman spectrum of normal and densified silica

A. Perriot et al. J. Am. Ceram Soc **89**, 596 (2006)

# Amorphous silica under cycles of increasing pressure




Beyond $P_Y \approx 10GPa$, the Raman shift is no longer reversible: densification is permanent.

The higher $P_{Max}$ the higher the final density. Saturation at $\Delta\rho/\rho \approx 20\%$ for $P_{Max} > 20GPa$

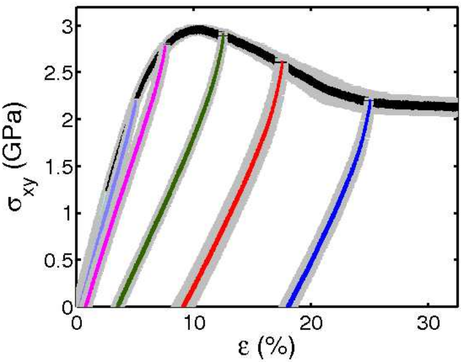
Amorphous silica keeps memory of the highest Pressure level experienced in the past.

D. Vandembroucq et al. J. Phys. Cond. Mat. **20**, 485221 (2008)

# Pressure induced permanent densification of amorphous silica

- Amorphous silica keeps memory of the highest Pressure level experienced in the past $\Delta\rho/\rho = f(P_{Max})$
- The higher $P_{Max}$ the higher the final density. Saturation at $\Delta\rho/\rho \approx 20\%$ for $P_{Max} \approx 20$ GPa
- Below 20 GPa, amorphous silica = network of tetrahedra $SiO_4$ connected by their vertices (4-fold coordination)
- Above 20 GPa, *reversible* transition to 6-fold coordination
- **Question:** Can we compute the maximum density of a packing of tetrahedra connected by their vertices only ?

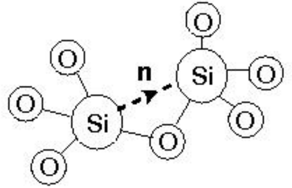
# Amorphous silica under cycles of increasing shear strain




A molecular dynamic study of a model silica glass (3-body potential, Vashishta et al PRB 90)

C.L. Rountree, DV, M. Talamali, E. Bouchaud, S. Roux, PRL 09

# A probe of structural anisotropy at medium range order

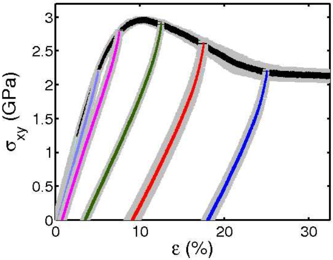


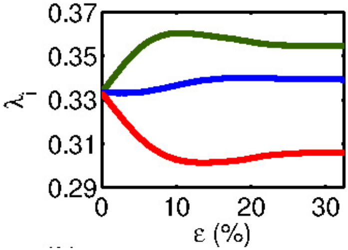

- Analogy with the fabric tensor in granular materials
- $F = \langle \vec{n} \otimes \vec{n} \rangle$ is the tensor of "contacts" between neighboring Si atoms, Eigenvalues $\lambda_i$
- $\lambda_i = \{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$ : Isotropy
- $\lambda_i = \{1, 0, 0\}$ : Full Anisotropy

Anisotropy parameter:

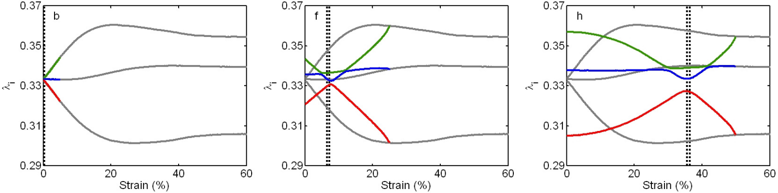
$$\alpha = \frac{3}{2}\sqrt{\sum_i \left(\lambda_i - \frac{1}{3}\right)^2}$$

# Shear strain induces structural anisotropy



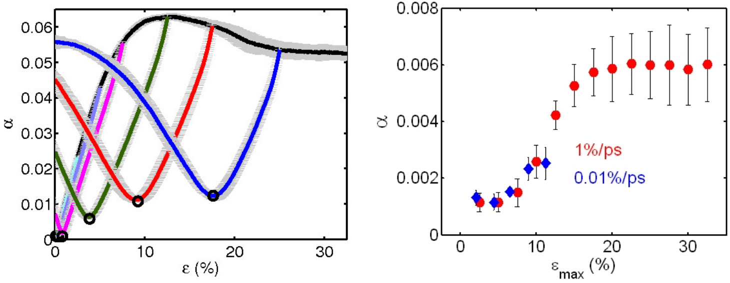



# Plasticity induces *persistent* structural anisotropy




Isotropy is not recovered after unloading at zero shear stress

# An orientational memory of amorphous silica




Experimental confirmation: Sato et al. JAP 13, PRB 15

# Ultrafast laser photo inscripion in amorphous silica

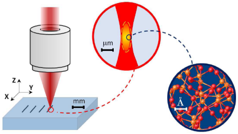
JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 3 1 AUGUST 2003

**Demonstration of high-density three-dimensional storage in fused silica by femtosecond laser pulses**

Guanghua Cheng,[a)] Yishan Wang, J. D. White, Qing Liu, Wei Zhao, and Guofu Chen
*State Key Laboratory of Transient Optics and Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710068, China*

(Received 16 December 2002; accepted 13 May 2003)

Three-dimensional optical recording of high contrast spherical bits (diameter<300 nm) at a density of 500 G/cm$^3$ in fused silica using a Ti:sapphire femtosecond laser is demonstrated. Bits are optically read out using both a confocal and a phase-contrast scheme. The recording density for different materials and recording mechanisms are discussed. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1589596]




N. Shcheblanov et al, PRB 2018

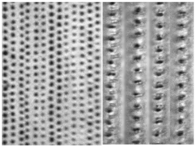


FIG. 2. Optical image of bits written inside fused silica as viewed parallel to the 400 nJ 200 fs excitation pulse. Light is focused by a NA=0.85 objective. In-plane bit separation is 1 $\mu$m and the layer separation is 2 $\mu$m. (Left) bits as viewed parallel to the excitation. (Right) bits as viewed orthogonal to the excitation pulse.

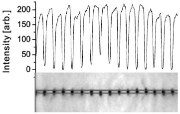
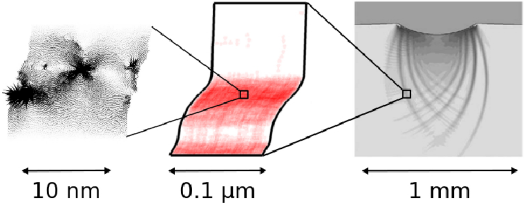



FIG. 4. Read out of data through a phase-contrast microscope. The upper part of the figure is the signal recorded by a single row of the CCD camera. The pits being imaged are shown in the bottom portion, with the two lines denoting the edges of the row. High contrast is evident even for those bits not perfectly centered.

# Mesoscopic models of amorphous plasticity

# Lattice models of amorphous plasticity



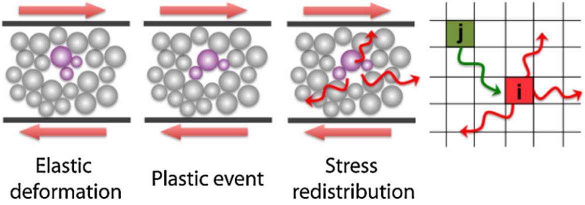

**Can we build at mesoscopic scale a *minimal* model** that reproduces at large scale the important features of amorphous plasticity ?

**Two main ingredients:**

- Local threshold dynamics
- Elastic interactions

$$\mu \frac{\partial \varepsilon_p}{\partial t} = \Sigma^{ext} + \sigma^{el}\left[\mathbf{x}, \{\varepsilon_p(\mathbf{x})\}\right] - \sigma^Y\left[\mathbf{x}, \varepsilon_p(\mathbf{x})\right]$$

# Lattice models of amorphous plasticity

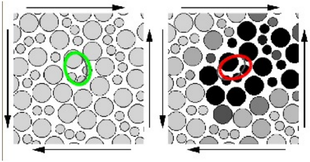



Bocquet et al. PRL 2009

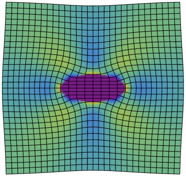
Various implementations: Boston, Erlangen, Grenoble, Helsinki, Lausanne, Milano, Paris...

Recent review: A. Nicolas et al. arxiv:1708.09194

# Local reorganizations and anisotropic elastic interactions



Local rearrangement induced by shear stress, Falk and Langer PRE 98



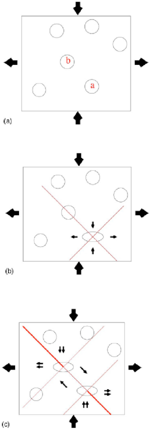
Quadrupolar stress field induced by a plastic event

The (far field) internal stress induced by a plastic reorganization obeys a quadrupolar symmetry (Eshelby):

$$\sigma_{xy}(0,0) = -\mu^*\gamma_p \; ; \quad \sigma_{xy}(r,\theta) = A\frac{\cos 4\theta}{r^2} \; ; \quad A = \frac{2\mu^*}{\pi}\mathcal{S}\gamma_p$$

Potential Energy Landscape: distribution of random barriers

# Internal stress induces avalanches and cascades of plastic events



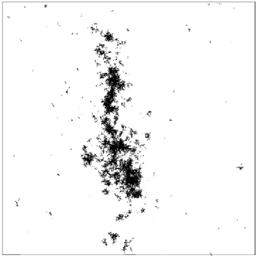



FIG. 16. Local slip (as defined in the text) which occurs during the entire plastic event. Arrow lengths are equal to the magnitude of the particular slip scaled by a factor of 10. Slips of amplitude less than $10^{-3}$ are not shown for clarity.

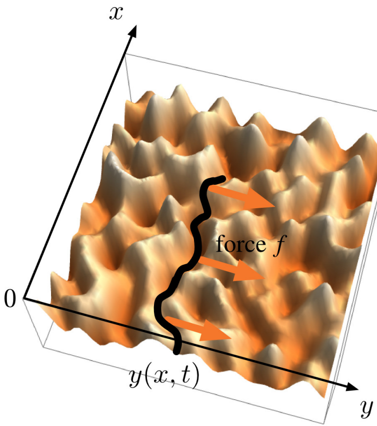
Maloney and Lemaitre PRE 06

# A cellular automaton for amorphous plasticity

- Discretization on a lattice at mesoscopic scale
- A scalar plastic criterion $\sigma > \sigma_Y$
- Structural disorder Local criterion : $\sigma(i,j) > \overline{\sigma_Y} + \delta\sigma_Y(i,j)$
- Local reorganization local slip increment $\delta\gamma$ and **update** of local plastic threshold: $\delta\sigma_Y$ is **renewed** after slip
- Anisotropic elastic response A local slip induces a stress redistribution $\sigma^{el}$ all over the system, $\sigma^{el} \propto \mu\delta\gamma\cos 4\theta/r^2$
- Evolution rule: extremal dynamics, stress or strain control...
- Parameters of the model: $\mu = 1$, $\delta\sigma_Y \in rand[0,1]$, $\delta\gamma \in rand[0,\mathbf{d}]$; $\mathbf{d}$ = coupling parameter

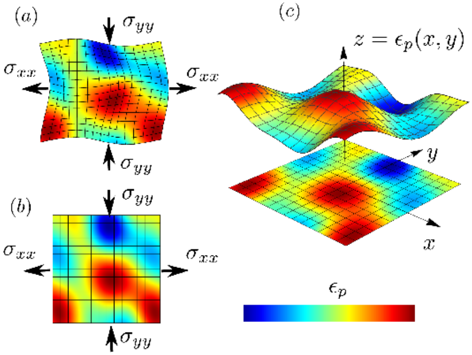
Baret et al. PRL 2002, Talamali et al. PRE 2011, C.R. Mecanique 2012

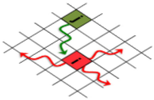
# Depinning of an elastic line/manifold

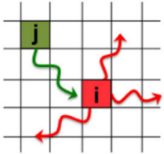



$$\mu \frac{\partial h}{\partial t} = f^{ext} + f^{el}\left[\mathbf{x}, \{h(\mathbf{x})\}\right] - \frac{\partial V}{\partial h}\left[\mathbf{x}, h(\mathbf{x})\right]$$

# Amorphous plasticity as an elastic manifold: Depinning

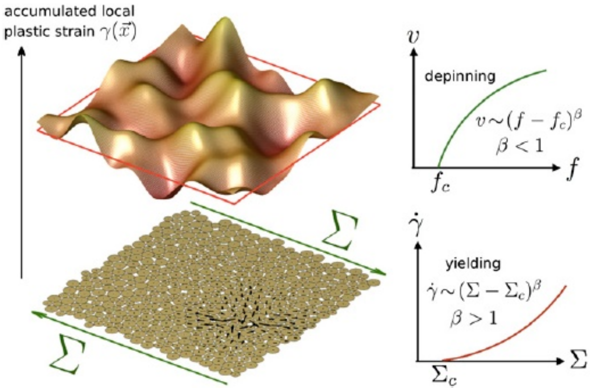



$$\mu \frac{\partial \varepsilon_p}{\partial t} = \sigma^{ext} + \sigma^{el}[\mathbf{x}, \{\varepsilon_p(\mathbf{x})\}] - \sigma^{Y}[\mathbf{x}, \varepsilon_p(\mathbf{x})]$$

# Depinning vs Plastic yielding: scaling properties

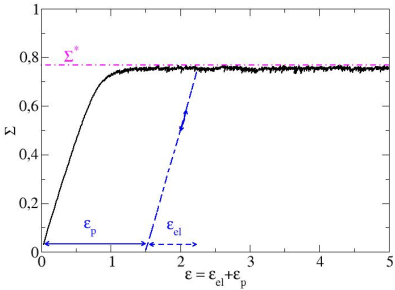



J. Lin, E. Lerner, A. Rosso and M. Wyart, PNAS **111**, 40 (2014)

# Transient hardening: a mechanically induced aging process

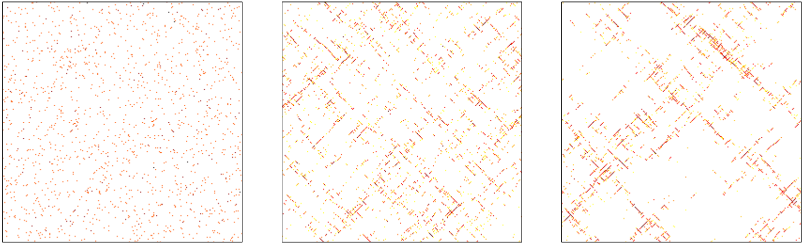
# A transient "hardening" stage precedes a stress plateau

The macroscopic flow stress $\Sigma^*$ can be interpreted as a **depinning threshold** :



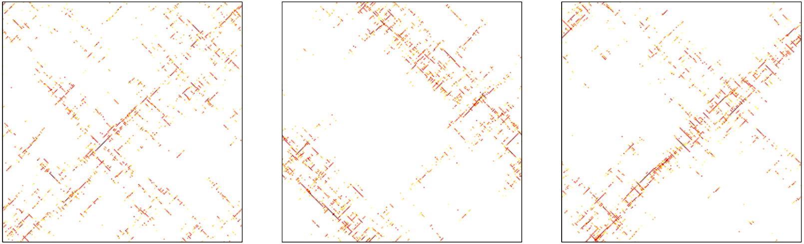

Below $\Sigma^*$ the material starts deforming and eventually stops ;
Above $\Sigma^*$ it flows indefinetely.

# Elastic interactions matter: strain localization



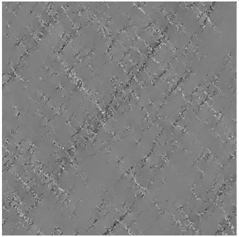
During the transient/hardening stage, plastic deformation gets graduallly more correlated with the same quadrupolar symmetry as the elastic interaction.

# Localization *vs* diffusion



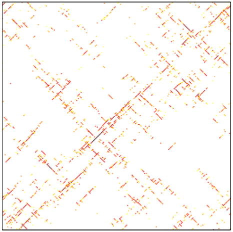
In the stationary regime, plastic deformation remains localized but, localization patterns are not persistent, rather they diffuse throughout the system.

# Localization *vs* diffusion



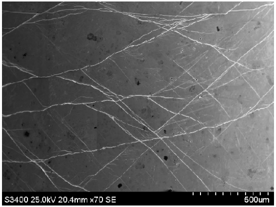
Atomistic scale

Maloney & Robbins, PRL 09



Mesoscopic Scale

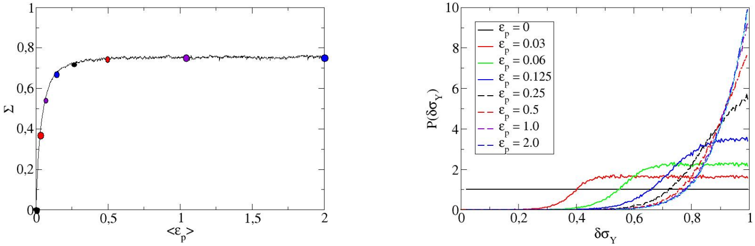
Talamali et al, PRE 11




Experimental Results

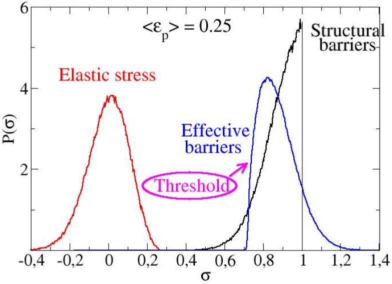
Zhang et al, Scripta Mat. 09

# Exhaustion of low barriers induces transient hardening




**Hardening:** the plastic yield stress gets higher whith deformation.
**Interpretation:** "Darwinian" or SOC-like dynamics; progressive exhaustion of the weakest sites during the transient stage induces a systematic bias in the distribution of local plastic thresholds.

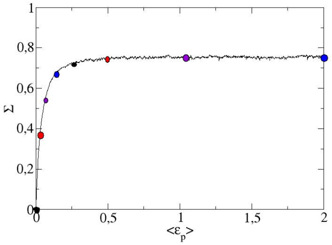
# Elastic interactions matter: effective barriers

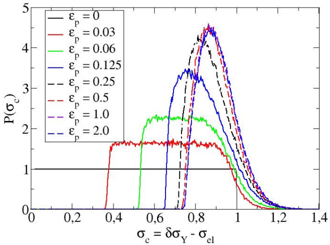



Local effective barriers: $\sigma_c(i,j) = \delta\sigma_Y(i,j) - \sigma^{el}(i,j)$

A well defined stress threshold bounds the distribution of effective barriers: yield stress

# Exhaustion of effective barriers




Exhaustion induces a progressive increase of yield stress: transient hardening

Again a "mechanical memory": dependence on the past maximum stress

Talamali et al, C.R. Mecanique 2012

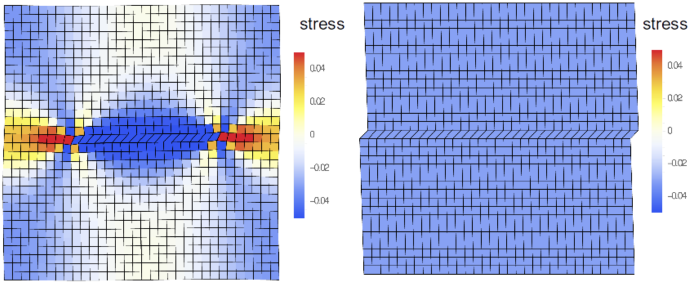
# Plasticity vs Depinning

- **Depinning**: Any fluctuation of the line/manifold induces a restoring force
- **Plasticity**: Any unit shear-band in a maximum shear stress direction induces no elastic stress

Specific features of plastic yielding models: anisotropic strain fluctuations, localization, shear-banding

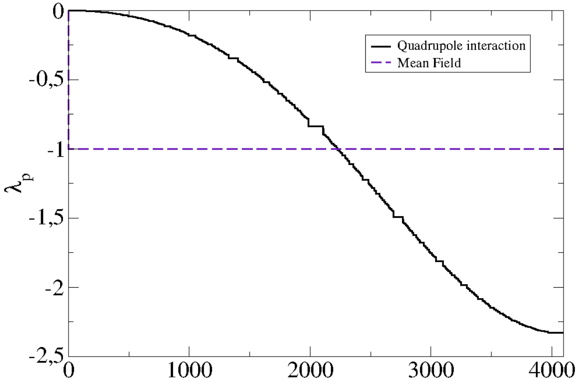
Tyukodi et al, PRE **93**, 063005 (2016)

# Spanning shear-bands induce no stress

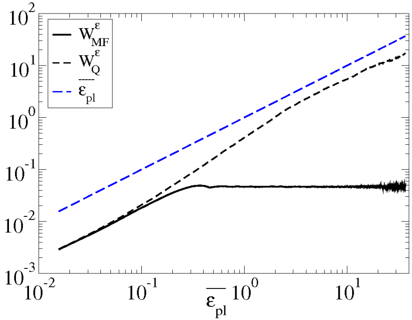



**partial shear band** **full shear band**

# Spectrum of eigenvalues: quadrupolar vs Mean Field interaction

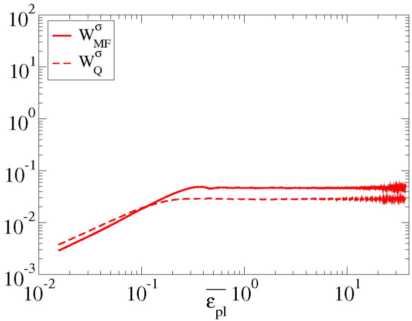


# Family-Vicsek scaling vs diffusive regime




**Depinning**: Variance of interface fluctuation saturates when correlation length reaches system size
**Plasticity**: Variance of strain fluctuations <u>does not saturate</u>, diffusive regime

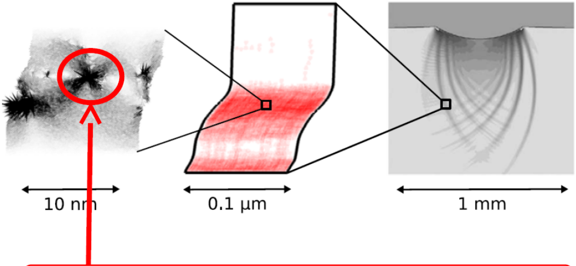
# Family-Vicsek scaling vs diffusive regime




**Depinning**: Variance of elastic force fluctuation saturates when correlation length reaches system size
**Plasticity**: Variance of stress fluctuations saturates, soft modes prevents divergence of stress fluctuations

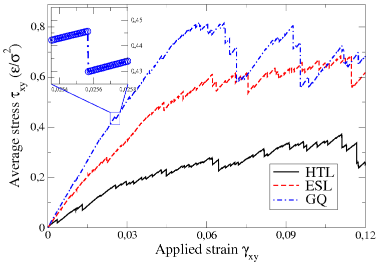
# Yield stress disorder under the mesoscope

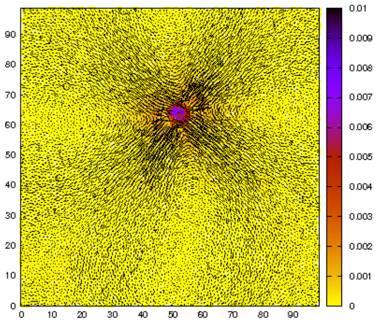
# Characterization of local plastic thresholds




**Question:** how to localize *(before plastic deformation)* and characterize the population of STZ at the atomistic scale ?

# AQS simulations of a 2D LJ model glass

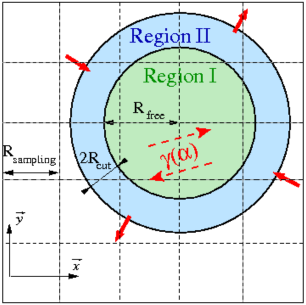



Three protocols of preparation:

- HTL "liquid-like"
- ESL: "fast quench"
- GQ: "slow quench"

# A mesoscopic probe of local yield stress



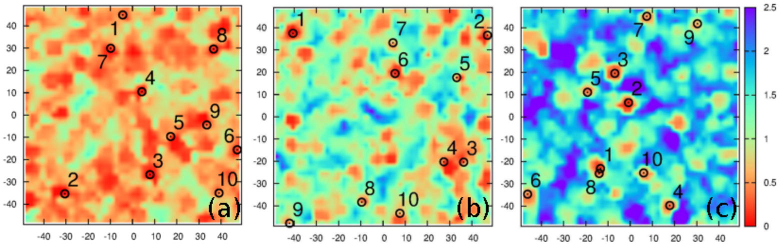

- Shear along direction $\alpha$
- Initial shear stress along $\alpha$: $\tau^0(\alpha)$
- Local shear stress at the onset of the instability: $\tau^{inst}(\alpha)$
- Shear stress threshold along $\alpha$: $\Delta\tau^C(\alpha) = \tau^{inst}(\alpha) - \tau^0(\alpha)$

Projected yield stress along $\alpha_\ell$:

$$\Delta\tau^Y(\alpha_\ell) = \min_\alpha \frac{\Delta\tau^C(\alpha)}{2\cos(\alpha_\ell - \alpha)}$$

S. Patinet, DV, M.L. Falk PRL16, Barbot et al submitted 2017

# Dependence on thermal history




HTL-"liquid-like" ESL-"fast quench" GQ-"slow quench"

The more equilibrated the glass, the larger the local yield stresses

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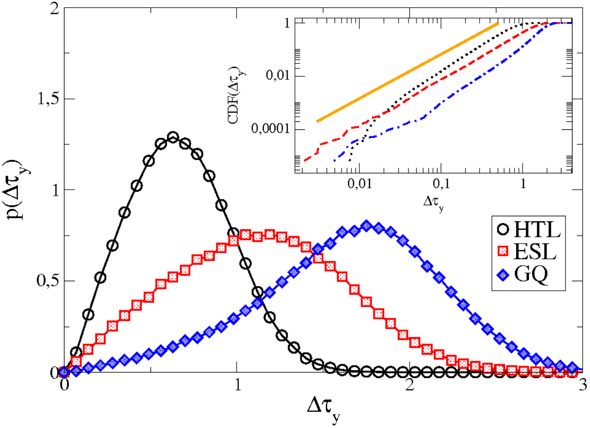
# Distributions of local yield stress

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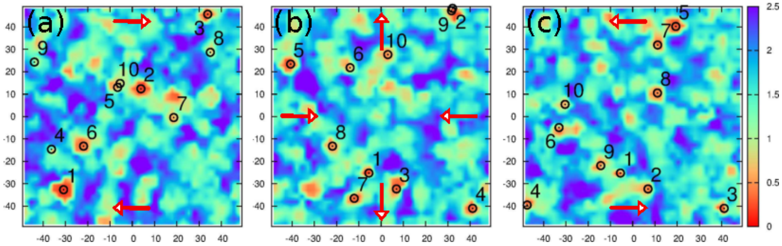
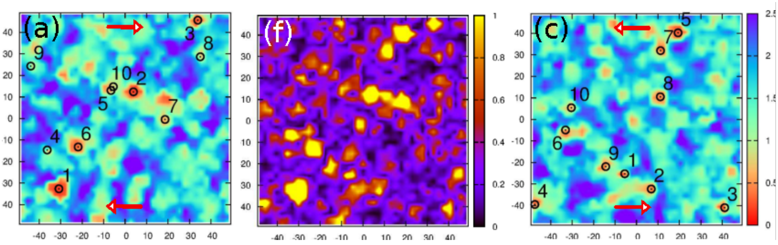
# Anisotropy of yield stress disorder




Simple Shear "Forward" Pure Shear Simple Shear "Backward"

The location of the weakest sites is highly dependent on the orientation of the remote applied stress.




Forward threholds $\Delta\sigma_+^Y$ $\Delta\sigma_\pm^Y = \Delta\sigma_+^Y - \Delta\sigma_-^Y$ Backward thresholds $\Delta\sigma_-^Y$

A tool to study memory effects in glasses ?