PLASTICITY AND FRACTURE IN GLASSES AND CRYSTALS

CENTER FOR COMPLEXITY & BIOSYSTEMS
University of Milan

22 October 2018
ENS-Paris

Stefano Zapperi
Department of Physics
University of Milan

erc

sizeffects

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CRACKING GLASS

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BRITTLE DUCTILE TRANSITION

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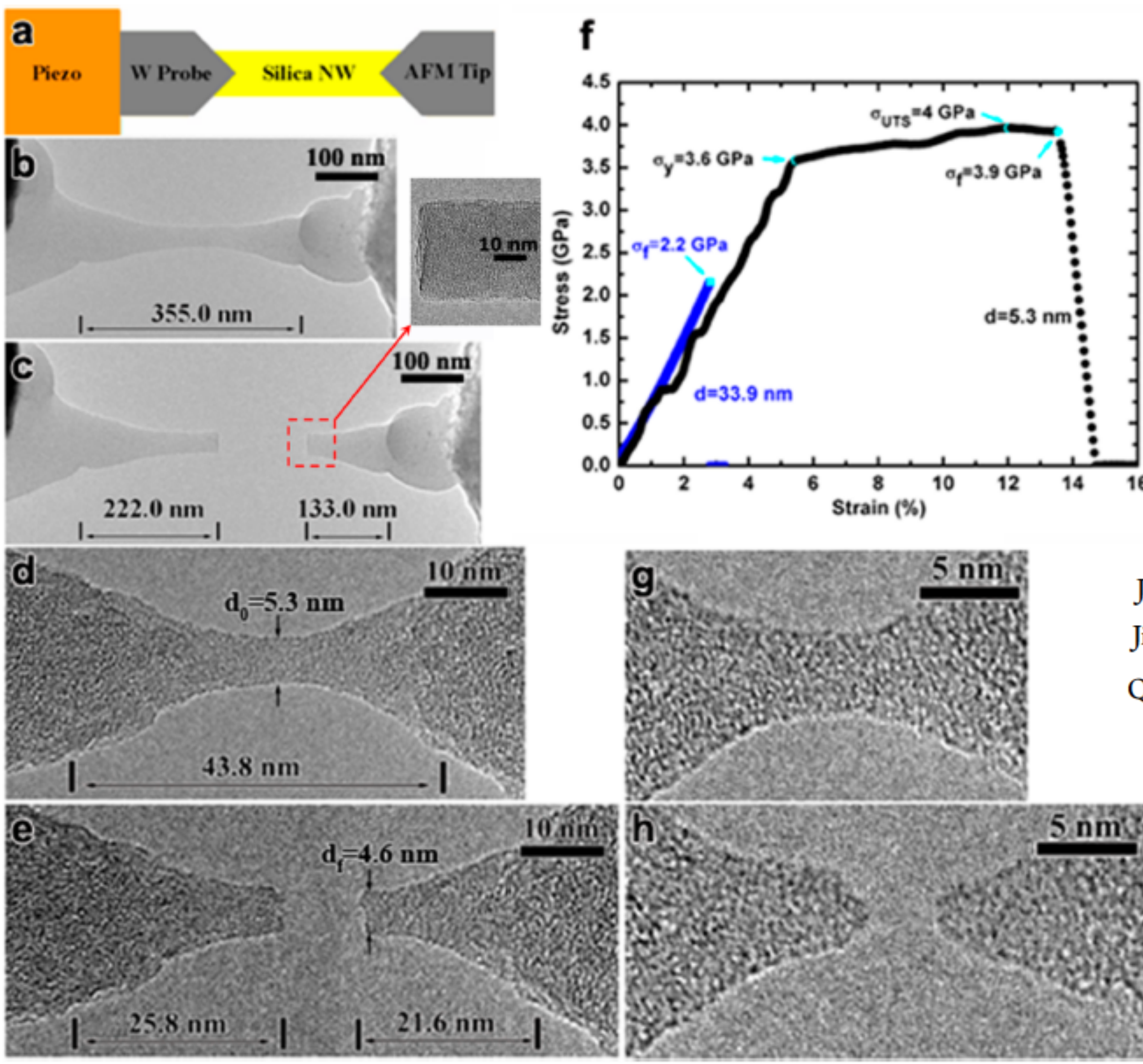
SIZE-DEPENDENT BRITTLE DUCTILE TRANSITION



Junhang Luo,[†,#] Jiangwei Wang,[†,#] Erik Bitzek,[‡,§,#]
Jian Yu Huang,[‖] He Zheng,[†] Limin Tong,[⊥]
Qing Yang,[⊥] Ju Li,[*,∓] and Scott X. Mao[*]

NANO LETTERS 2016

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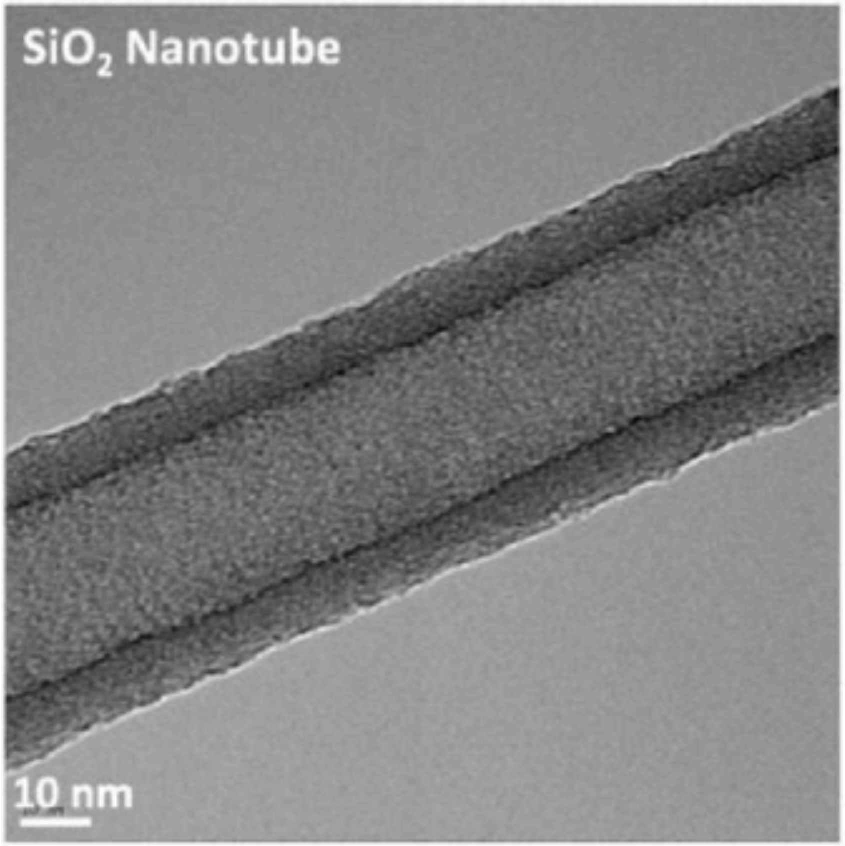
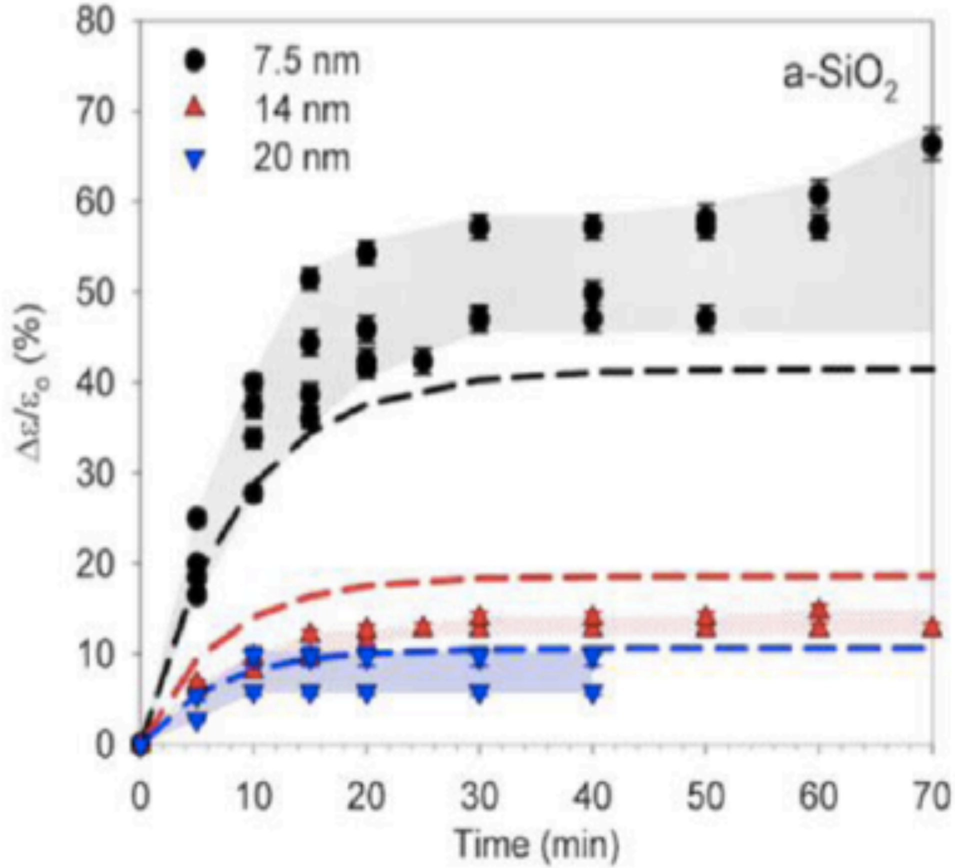
FLUID-LIKE SURFACE LAYER



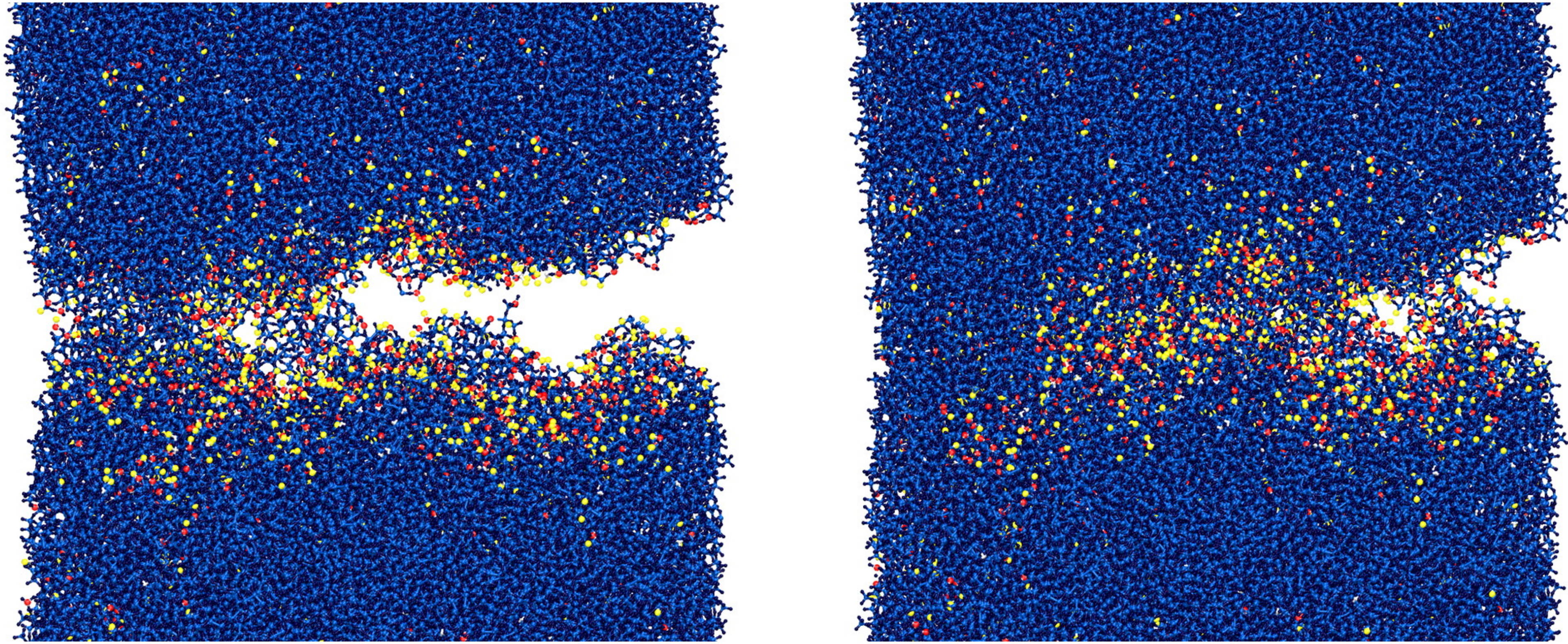


Nanotubes

Matthew C. Wingert,[†] Soonshin Kwon,[†] Shengqiang Cai,[*,†] and Renkun Chen[*,†]

NANO LETTERS 2016

MOLECULAR DYNAMICS
SiO_2 glass deformation



Bonfanti et al.

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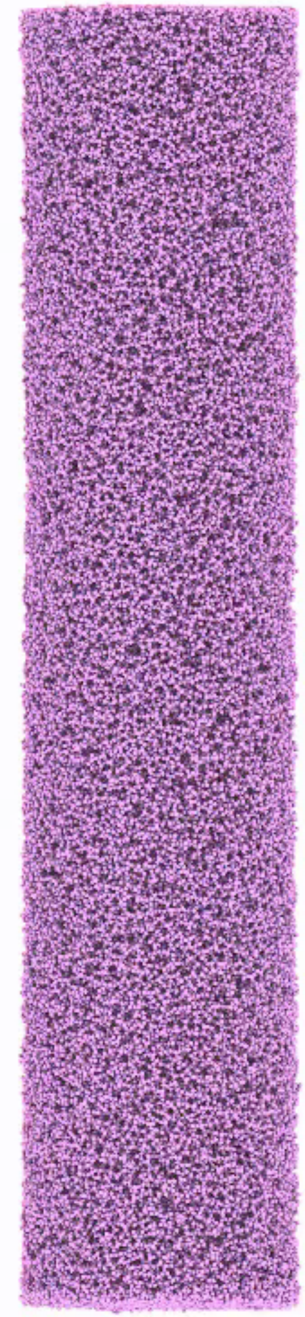
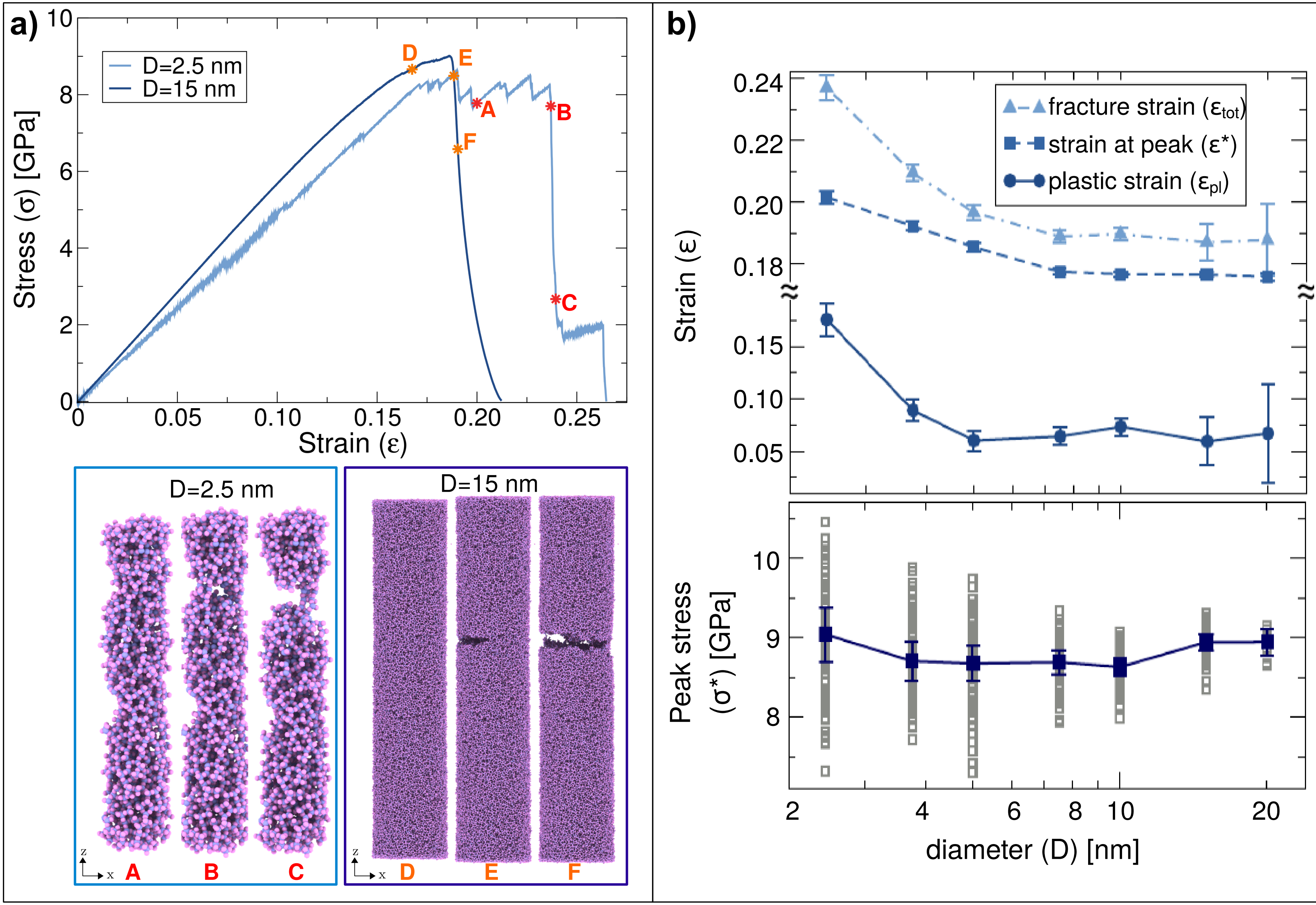
D= 2.5 nm

D= 12.5 nm





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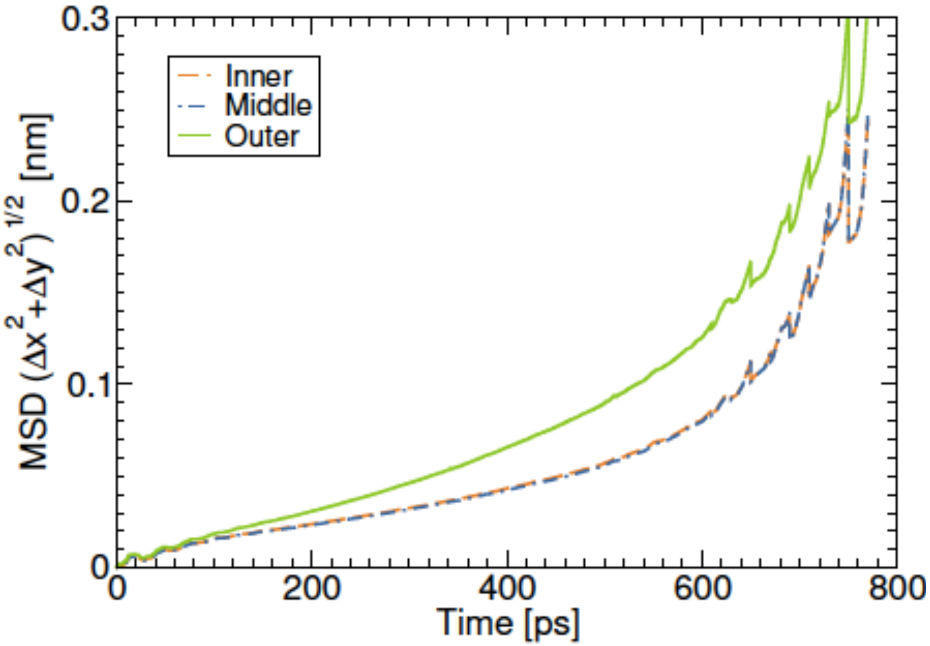
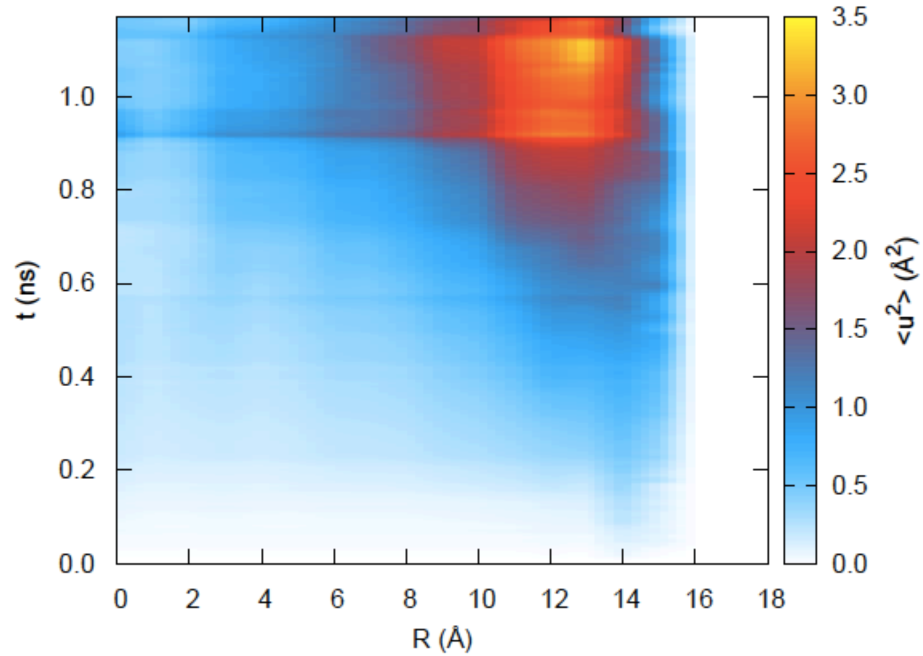
EDGE EFFECTS





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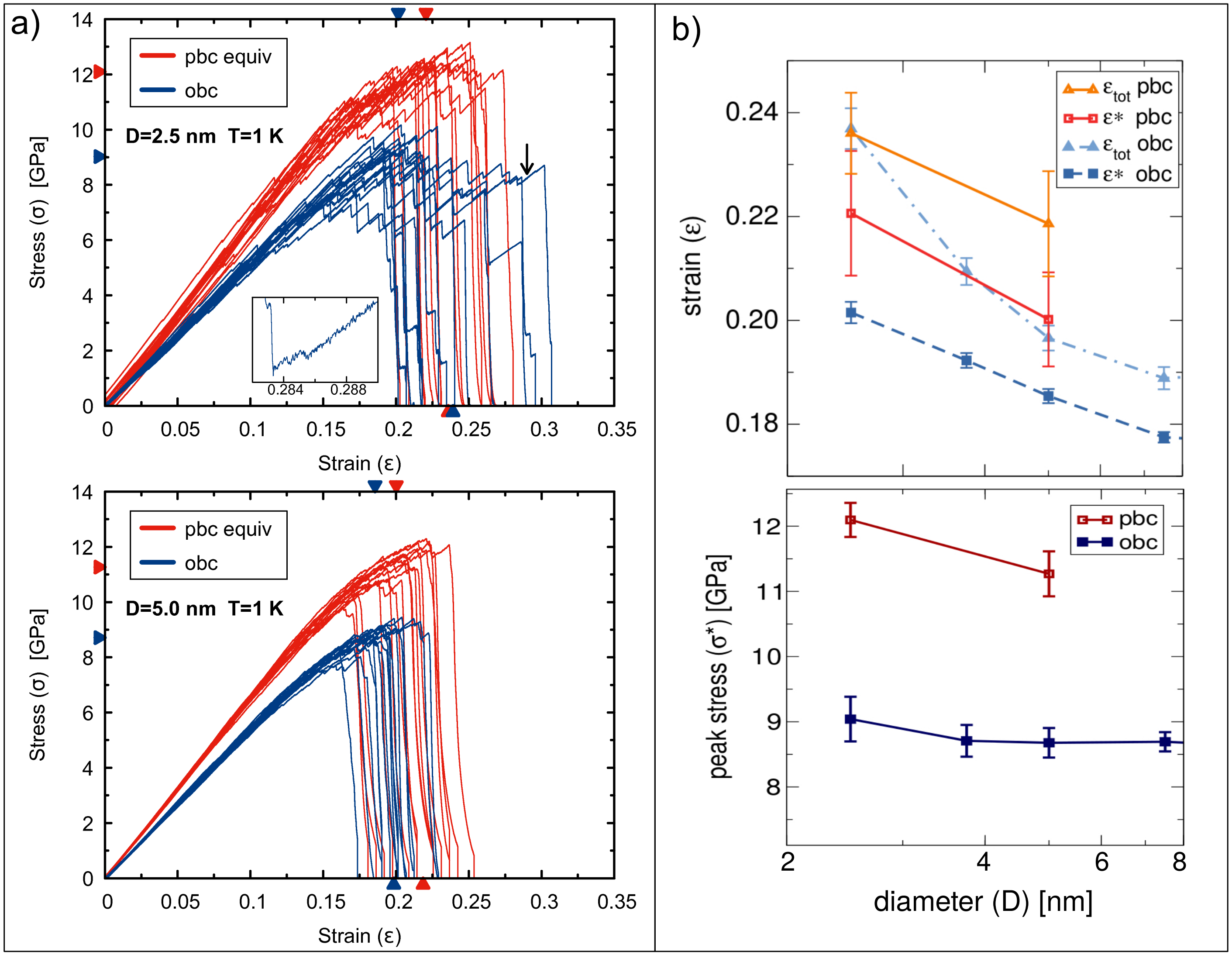
OPEN AND CLOSED BC



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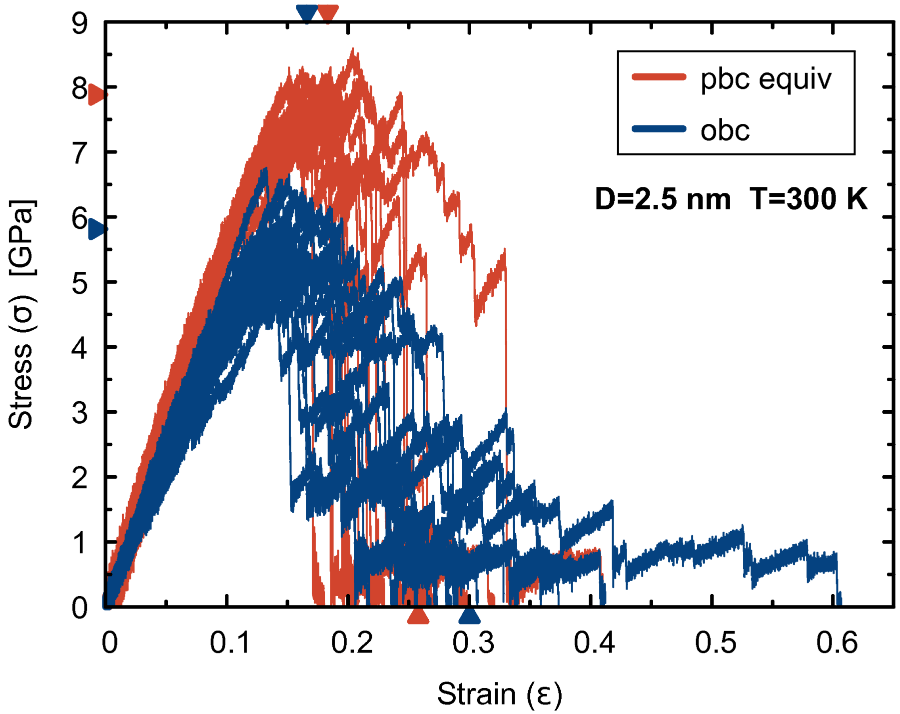
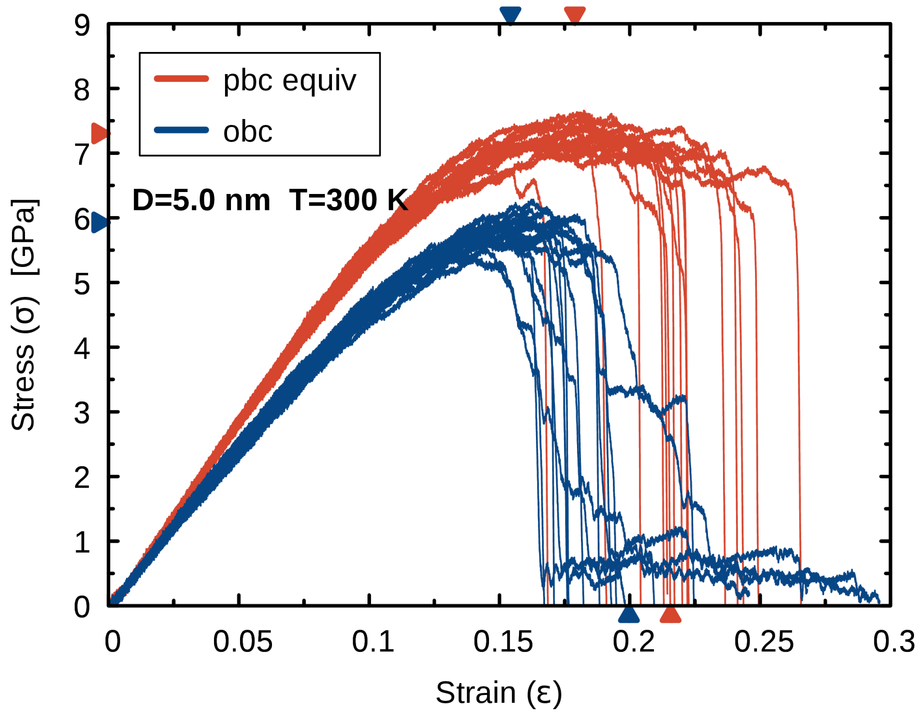
THERMAL EFFECTS





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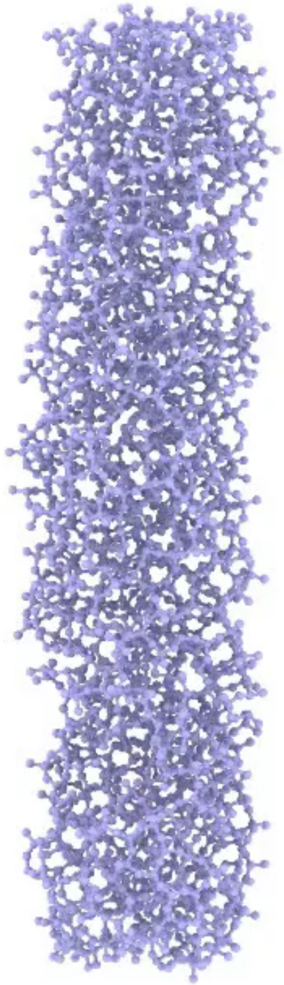
DAMAGE ACCUMULATION

D= 2.5 nm



D= 15 nm

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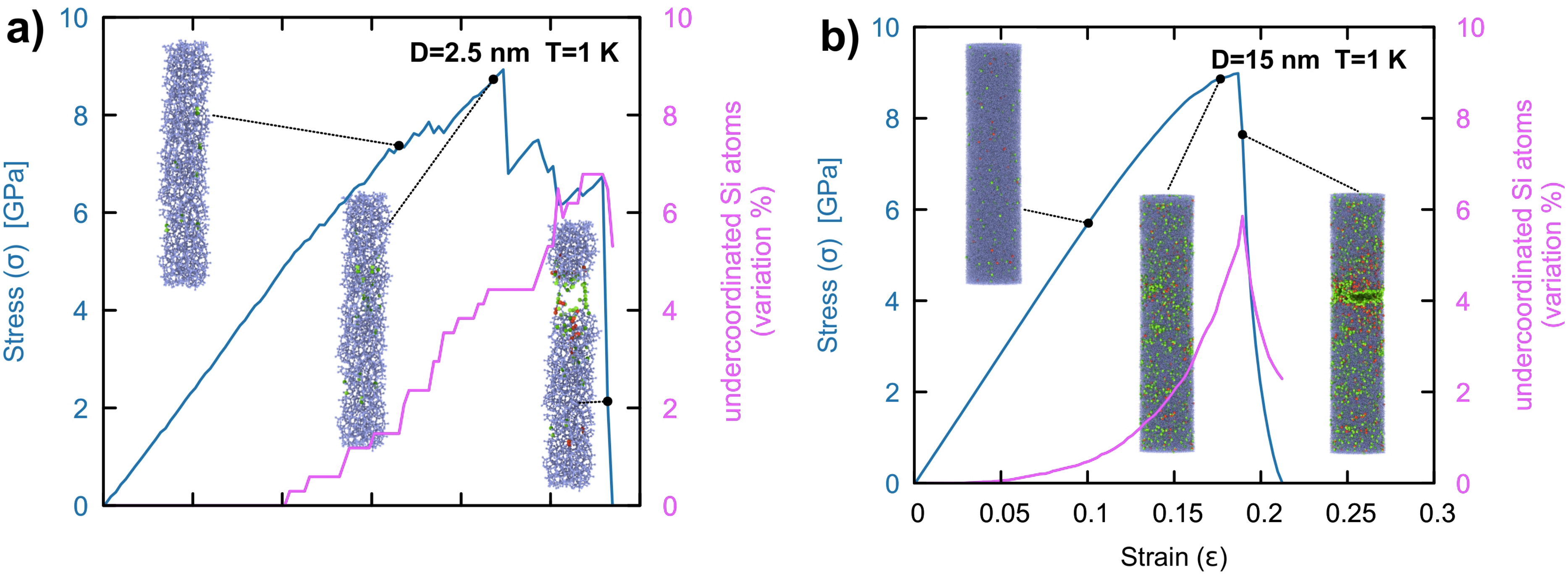
DAMAGE ACCUMULATION



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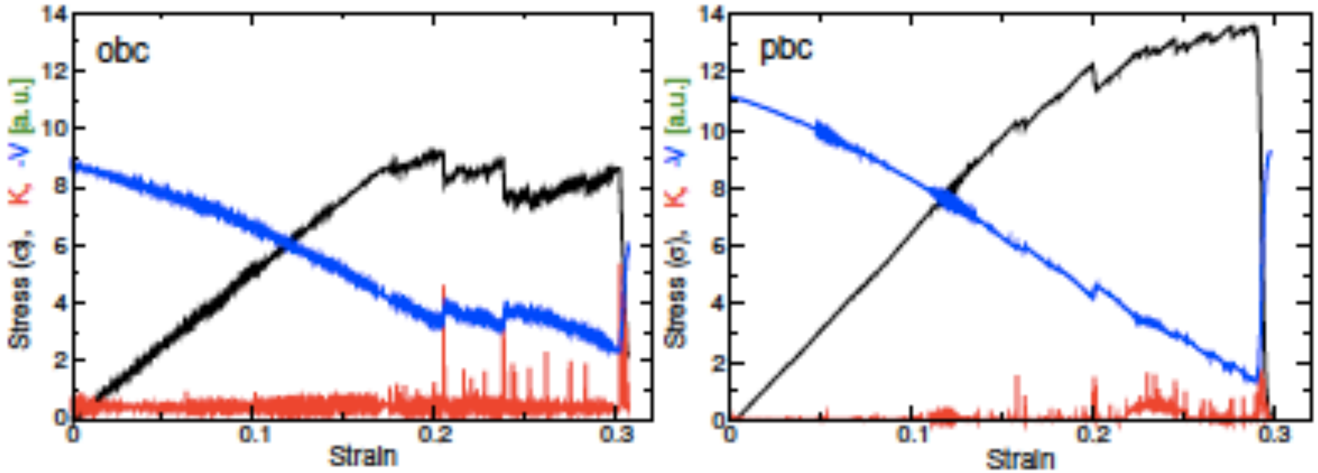
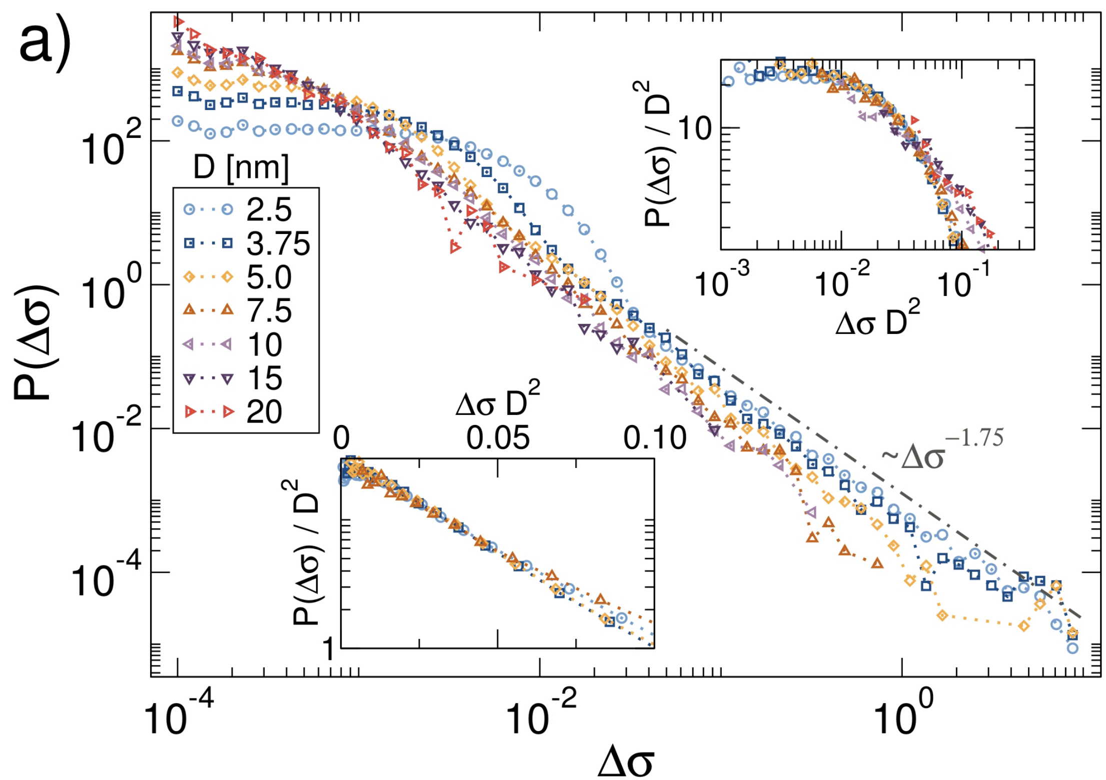
AVALANCHES AND STRESS DROPS





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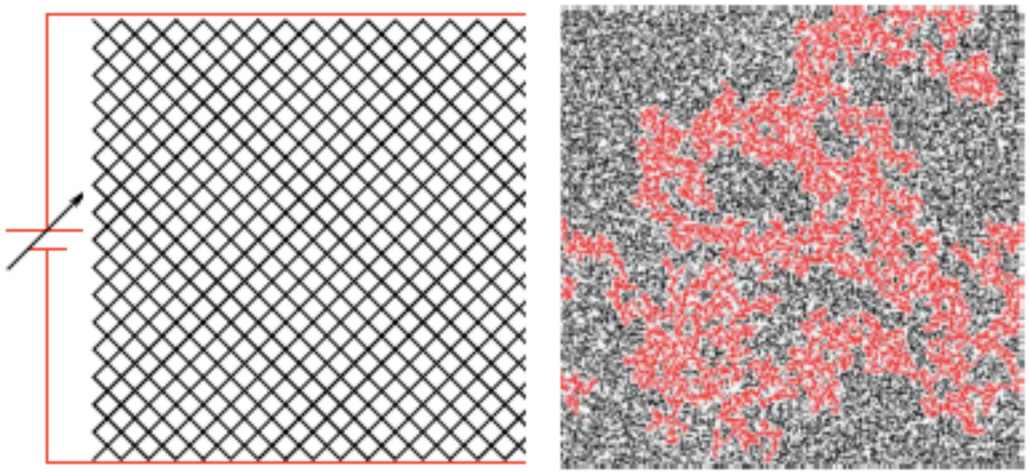
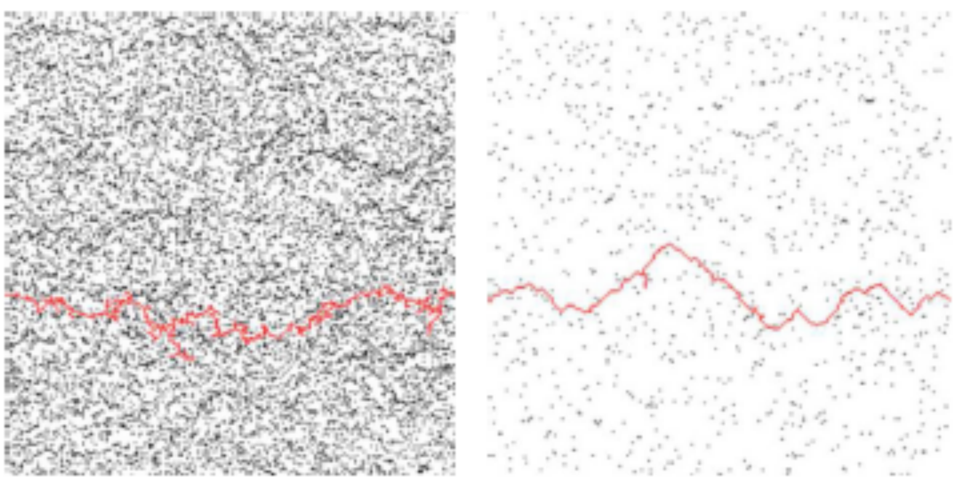
DISORDER AND DAMAGE IN FRACTURE



(a) A fuse network

(b) $\beta = 0.03$



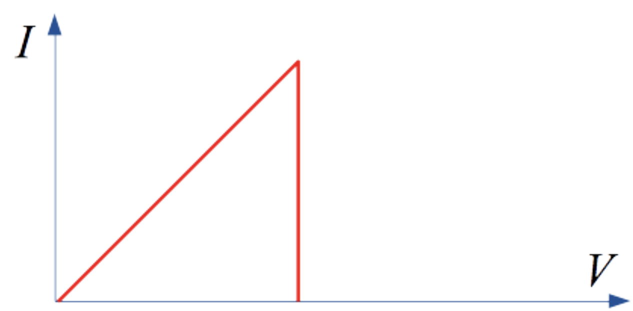
(c) $\beta = 0.5$

(d) $\beta = 3.0$

- External current is applied through the bus bars to a a resistor network
- Local current are obtained solving Kirchhoff equations

$$\sum_i \sigma_{ij}(V_i - V_j) = 0$$

- Fuses have unit conductivity and disordered thresholds.



$$F(x) = x^{\beta},\ \beta > 0.$$

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Ashivni Shekhawat,[1] Stefano Zapperi,[2,3] and James P. Sethna[1] PRL **110**, 185505 (2013)

PERCOLATION SCALING

In the limit β =0 the model fails as a percolation process

Clusters:

$$P_c(s|\beta, L) = s^{-\tau_c}\mathcal{F}_c(\beta L^{1/\nu_f}, sL^{-1/\sigma_c\nu_f}, uL^{-\Delta_f/\nu_f}).$$

$$\langle s_c^n\rangle = L^{(n+1-\tau_c)/\sigma_c\nu_f}(\mathcal{J}_n^c(\beta L^{1/\nu_f}) + L^{-\Delta_f/\nu_f}\mathcal{K}_n^c(\beta L^{1/\nu_f})),$$

$$\tau_c = 187/91 = 2.0549,$$

$$\sigma_c\nu_f = 48/91 = 0.5275,$$

$$\Delta_f/\nu_f = 72/48 = 1.5$$

Avalanches:

$$P_a(s|\beta, L) = s^{-\tau_a}\mathcal{F}_a(\beta L^{1/\nu_f}, sL^{-1/\sigma_a\nu_f}, uL^{-\Delta_f/\nu_f}),$$

$$\langle s_a^n\rangle = L^{(n+1-\tau_a)/\sigma_a\nu_f}(\mathcal{J}_n^a(\beta L^{1/\nu_f}) + L^{-\Delta_f/\nu_f}\mathcal{K}_n^a(\beta L^{1/\nu_f})),$$

PRL **110**, 185505 (2013)

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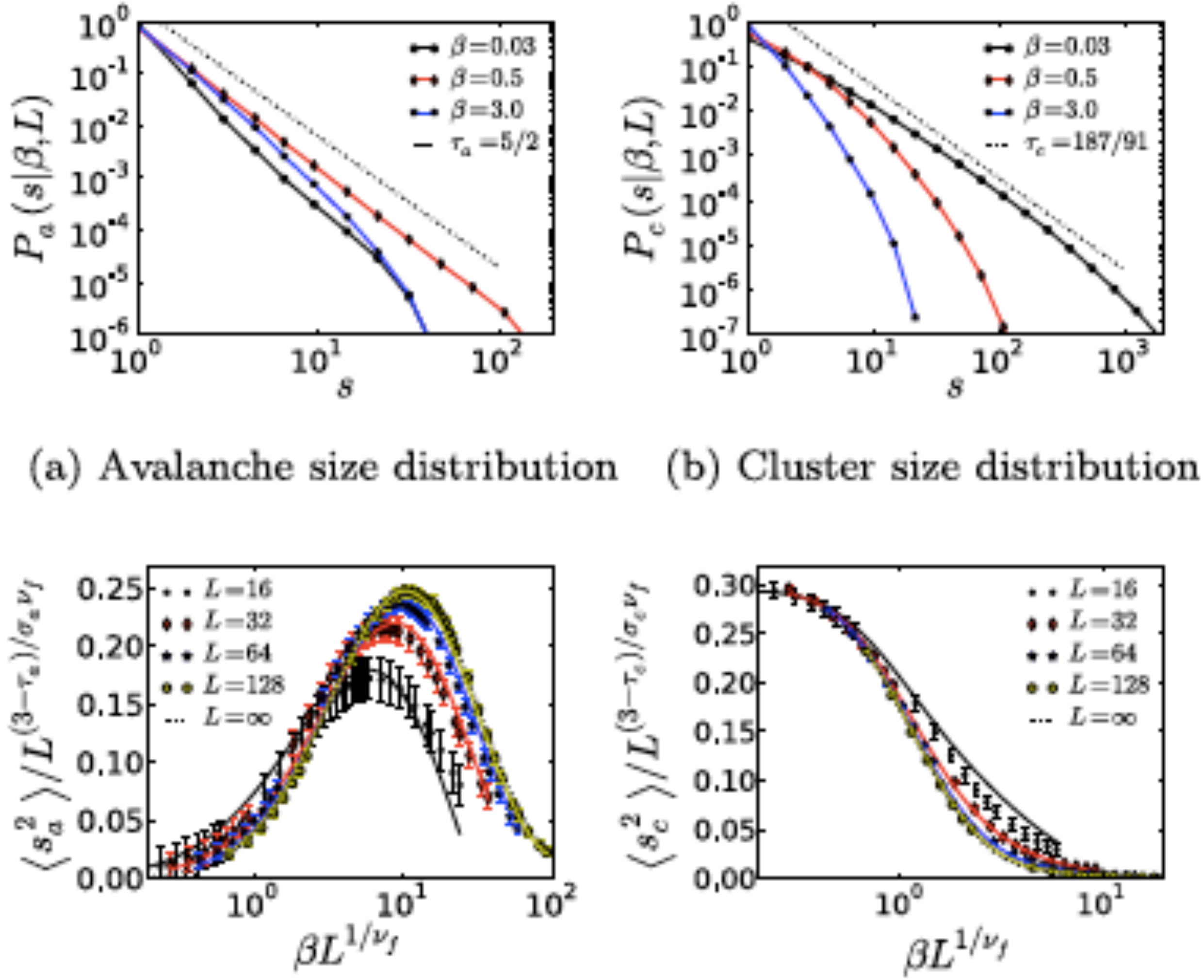
PERCOLATION SCALING



(a) Avalanche size distribution (b) Cluster size distribution

(c) Scaling collapse of $\langle s_a^2\rangle$ (d) Scaling collapse of $\langle s_c^2\rangle$

PRL **110**, 185505 (2013)

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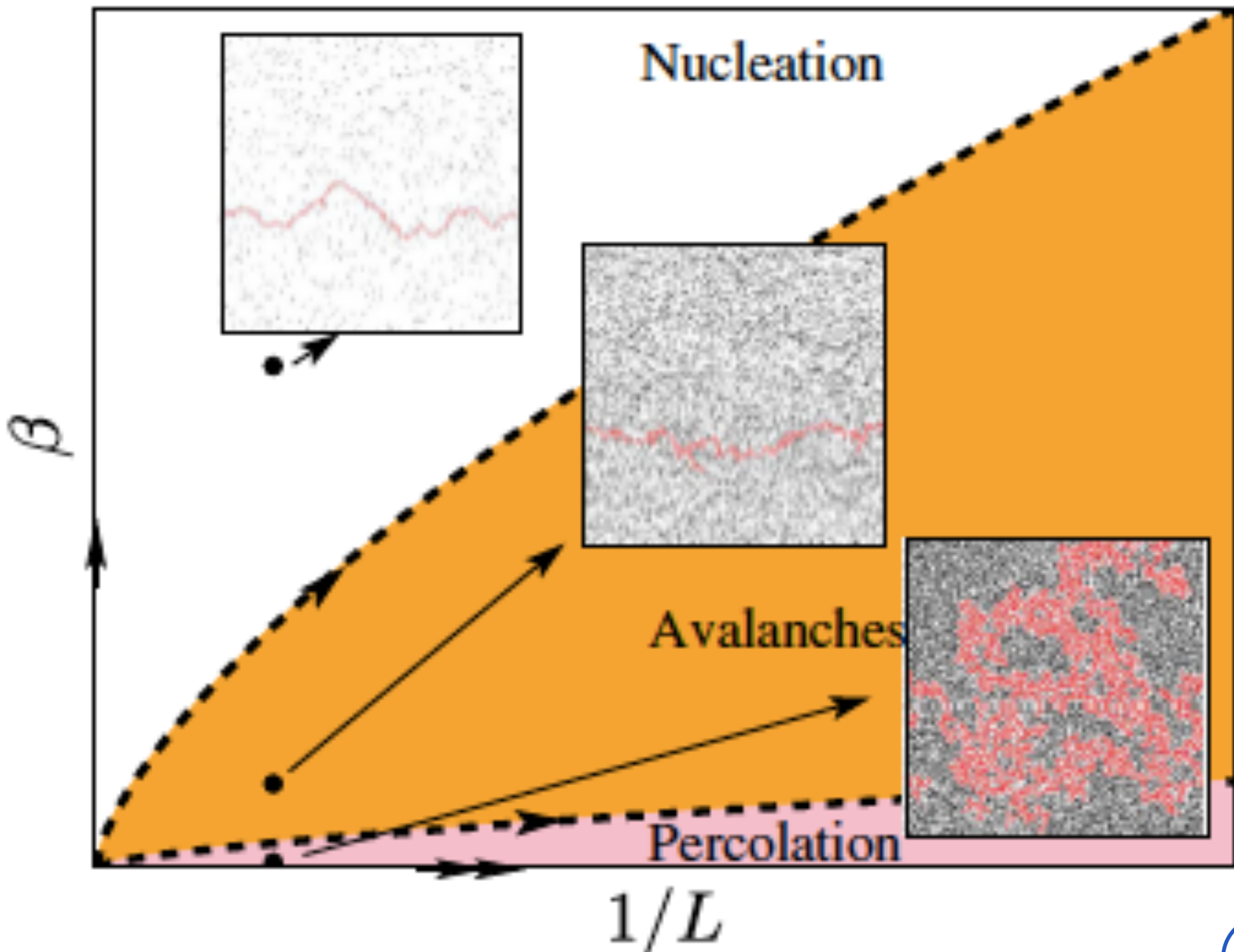
FINITE-SIZE CRITICALITY



PRL 110, 185505 (2013)

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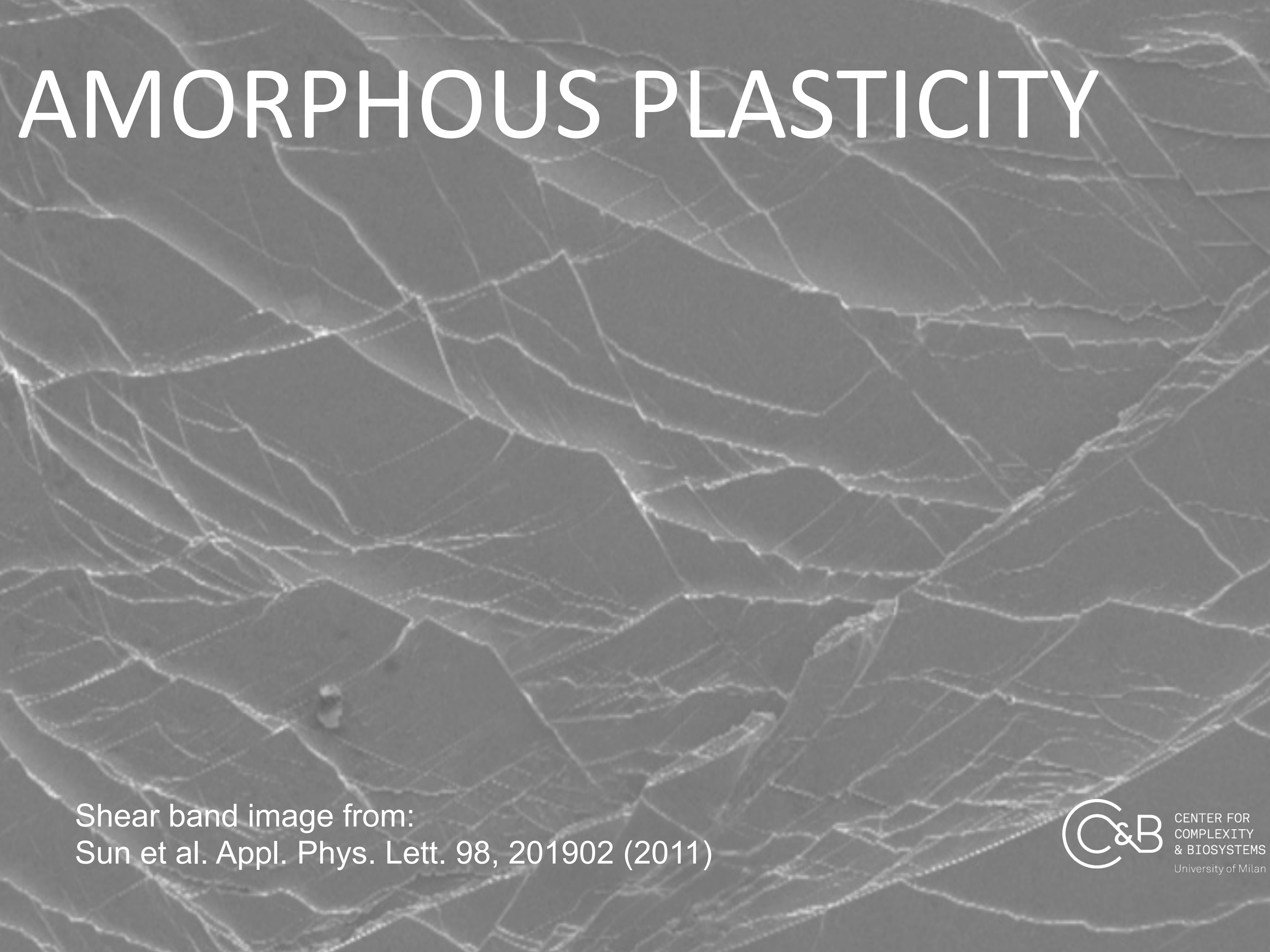
AMORPHOUS PLASTICITY



Shear band image from:
Sun et al. Appl. Phys. Lett. 98, 201902 (2011)

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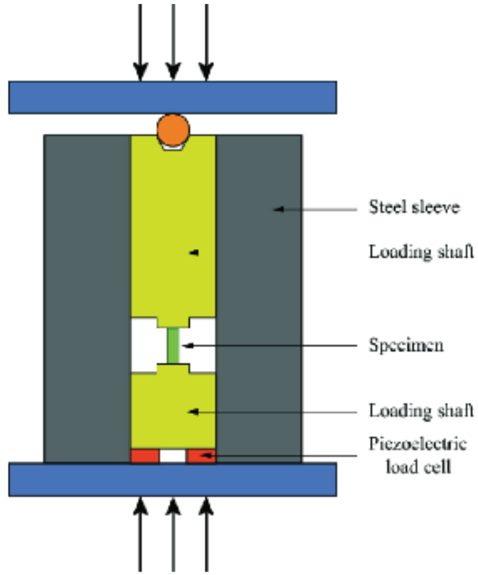
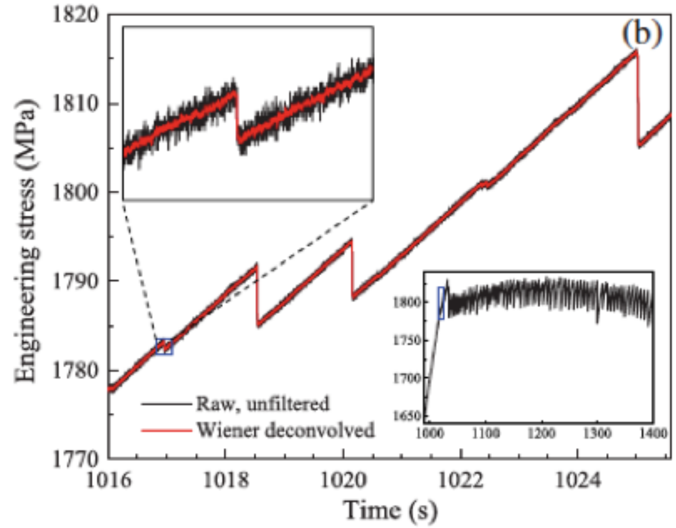
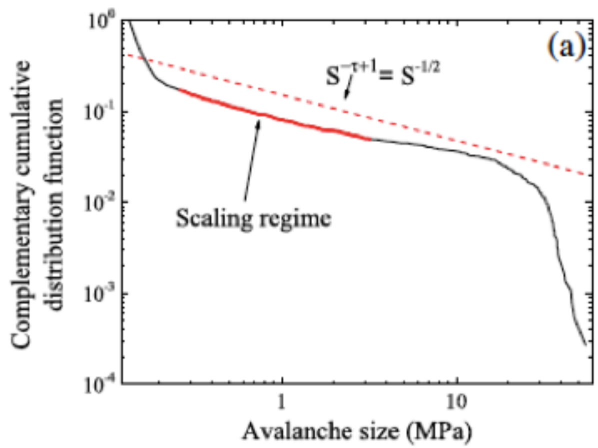
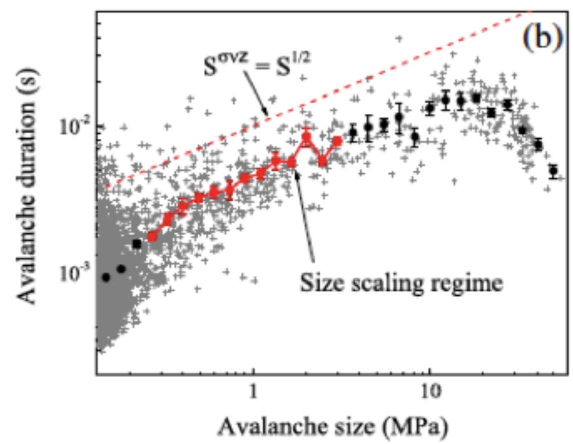
AVALANCHES IN METALLIC GLASSES









James Antonaglia, Wendelin J. Wright, Xiaojun Gu, Rachel R. Byer, Todd C. Hufnagel, Michael LeBlanc, Jonathan T. Uhl, and Karin A. DahmenPhys. Rev. Lett. 112, 155501 – 2014

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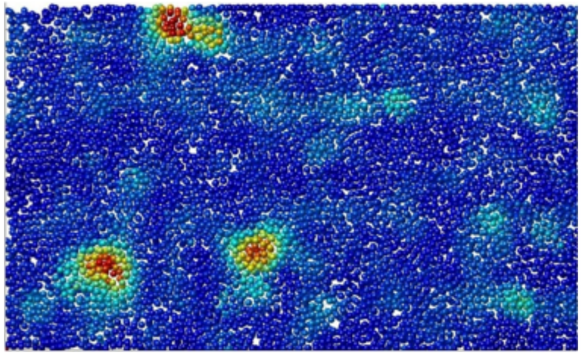
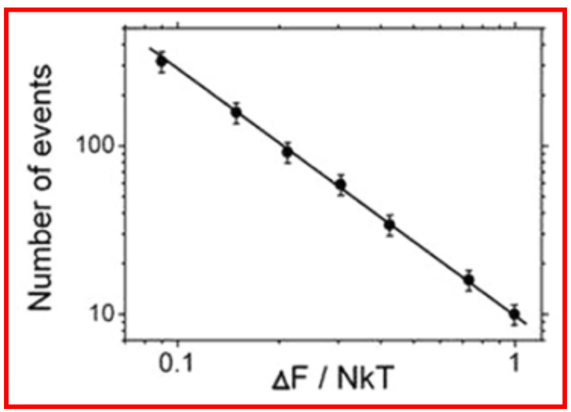
AVALANCHES IN COLLOIDAL GLASSES

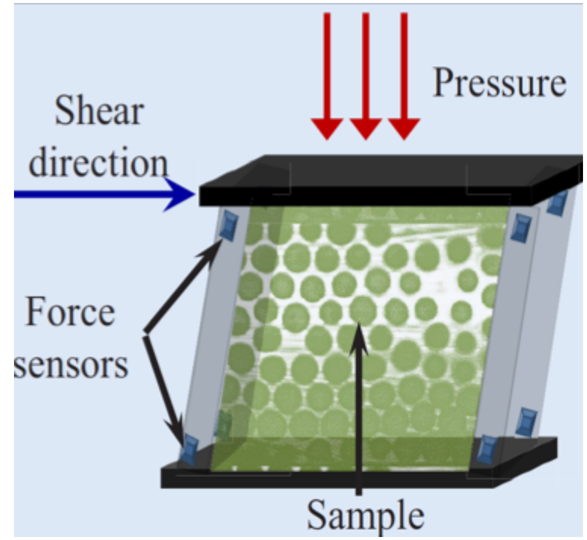


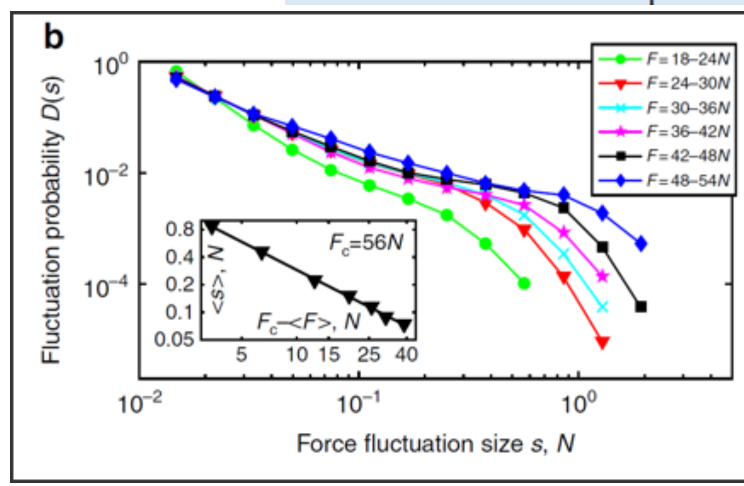
Non affine deformations
(Chikkadi PRL 2011)



Free energy drops during aging
(Zagar PRL 2014)

Shear of granular packings
(Denisov et al. Nat. comm 2016)





Images thanks to: Peter Schall

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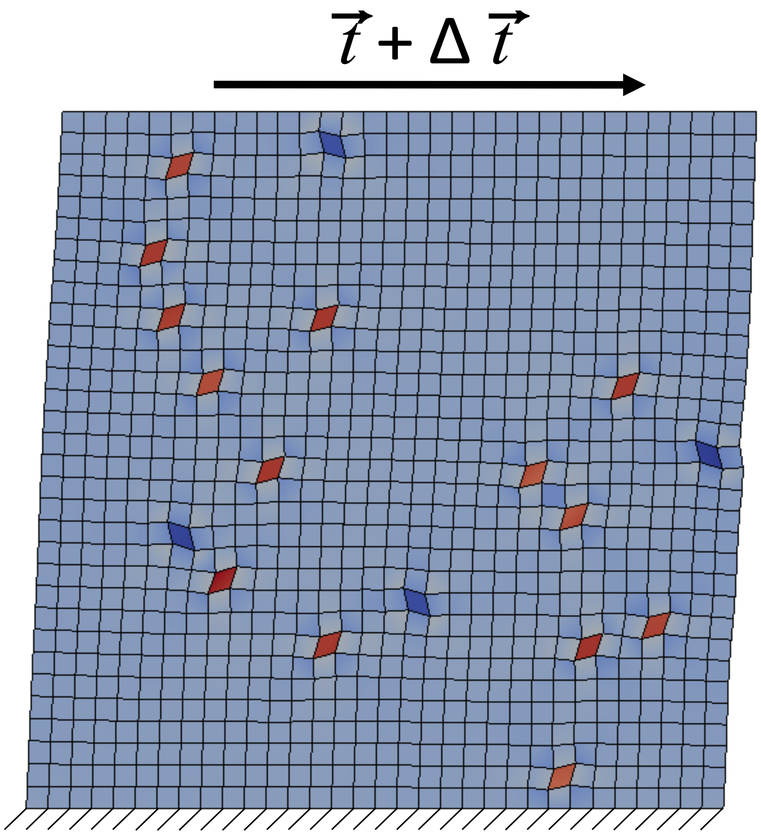
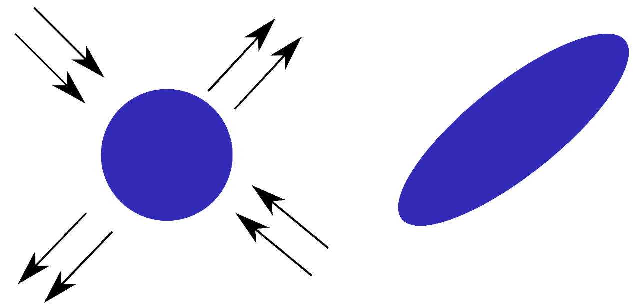
Mesoscale tensorial model for amorphous plasticity in 2D and 3D





Eshelby inclusions

$$\Sigma_{ij}(\vec{r}) = \int \sigma_{ij}(\vec{r}\,')\, G_{\xi}(\vec{r} - \vec{r}\,')\, d^3 r'$$

$$\hat{\Sigma} > \Sigma_T$$

Barriers for slip

$$\hat{\Sigma} = \sqrt{\frac{3}{2}\Sigma_{ij}^{dev}\Sigma_{ij}^{dev}}$$

nature COMMUNICATIONS

Z. Budrikis, D. Fernandez-Castellanos, S. Sandfeld, M. Zaiser, SZ

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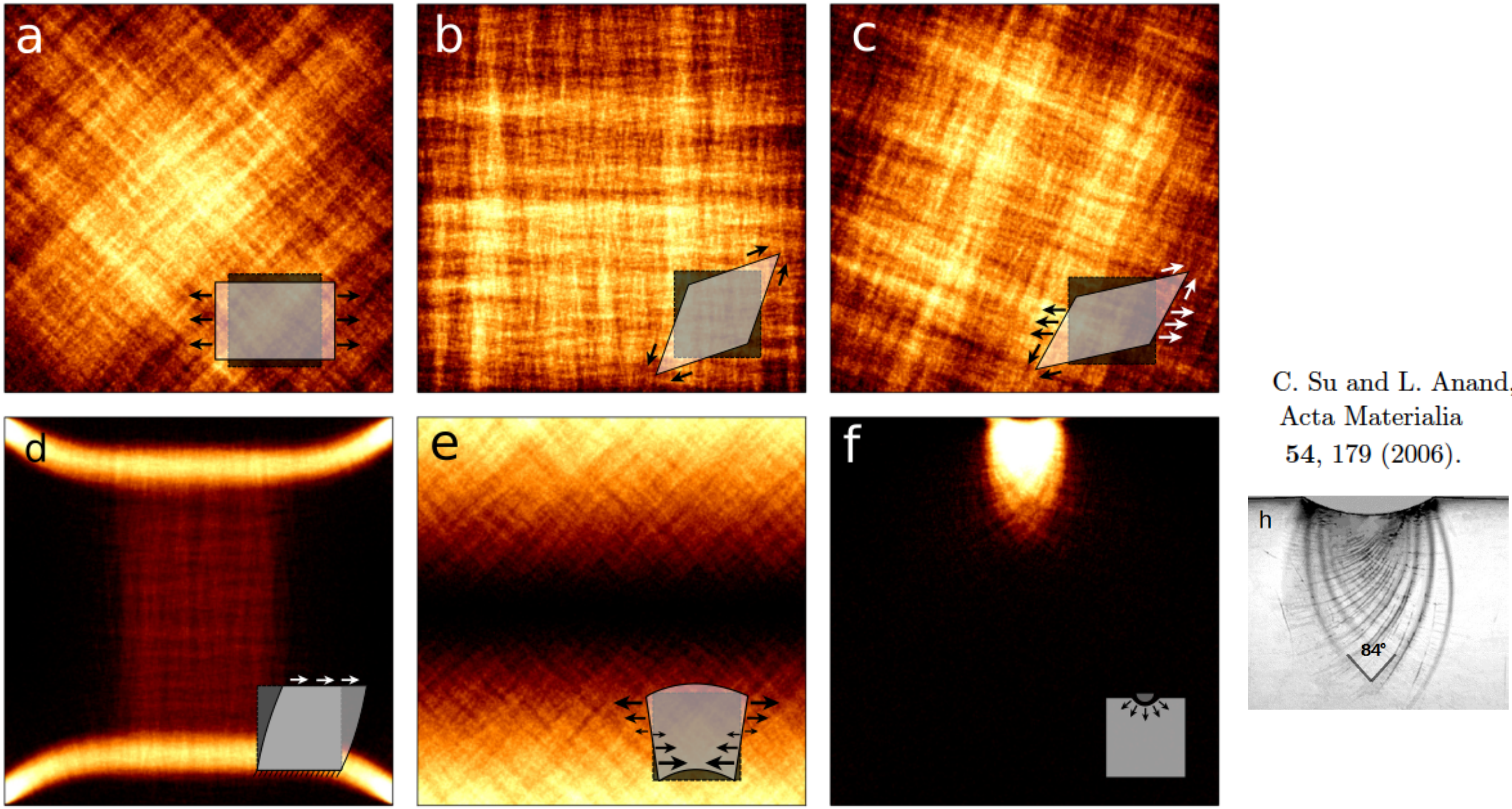
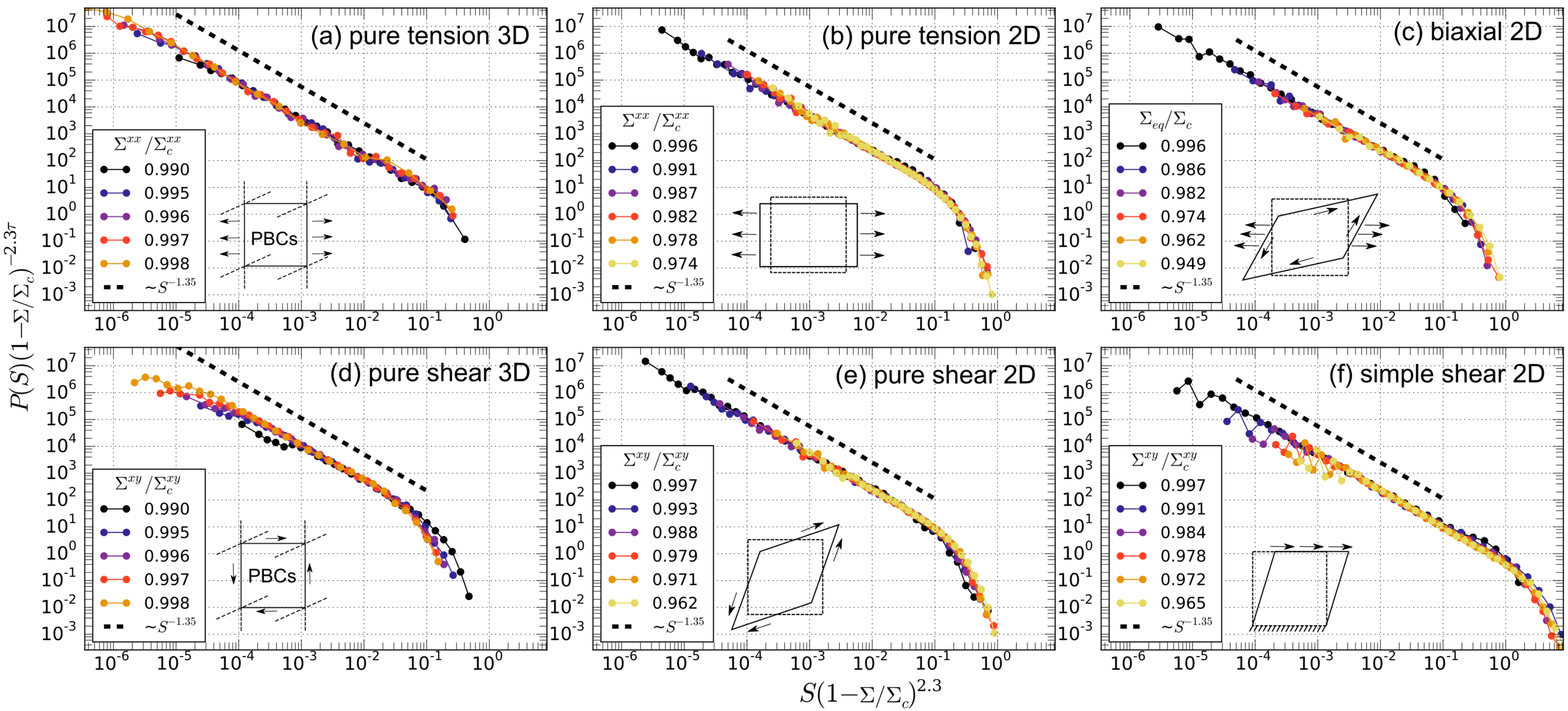
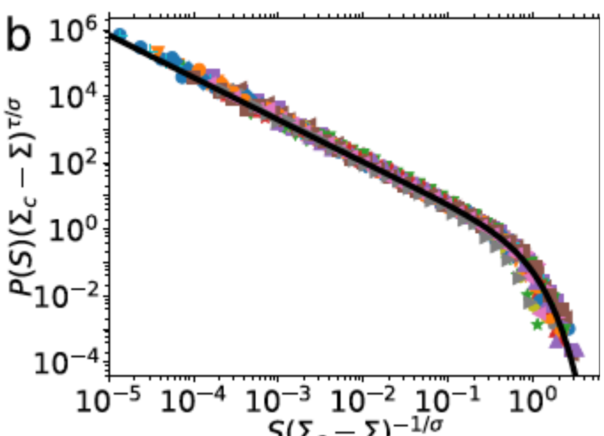
Shear bands depend on loading

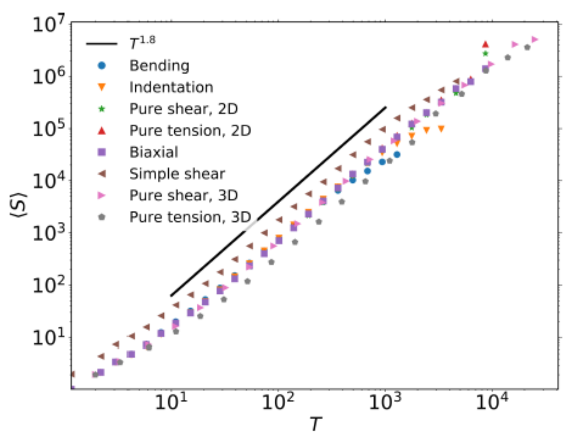


C. Su and L. Anand, Acta Materialia 54, 179 (2006).

Universal (non MF!) avalanches







$$\tau = 1.28 \pm 0.003 \text{ and } 1/\sigma = 1.95 \pm 0.01.$$

$$\gamma = 1.8 \pm 0.1$$

$$P(S) = \frac{A}{2\sqrt{\pi}} S^{-\tau} \exp\left(C\sqrt{u} - \frac{B}{4}u^{\delta}\right).$$

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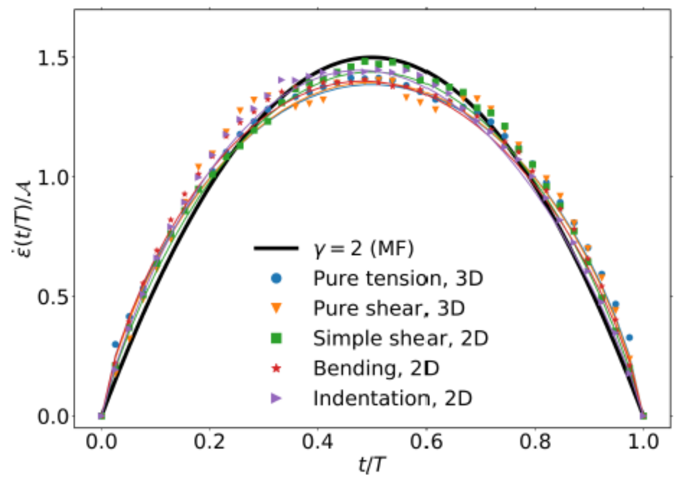
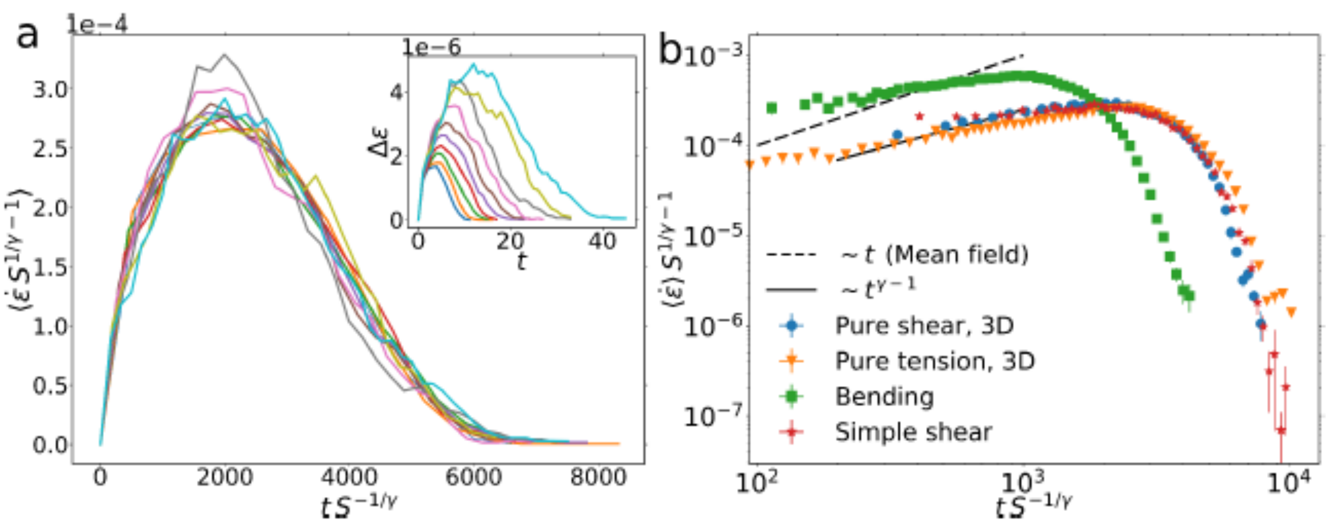
Scaling functions



$$\langle \dot{\epsilon}(t') \rangle = (t'(1-t'))^{1-\gamma}(1-a(t'-1/2))\frac{\Gamma(2\gamma)}{(\Gamma(\gamma))^2},$$

$$\langle \dot{\epsilon} \rangle_S = \frac{S}{\tau_{\mathrm{m}}}\left(\frac{S_{\mathrm{m}}}{S}\right)^{1/\gamma} f\left(\left(\frac{S_{\mathrm{m}}}{S}\right)^{1/\gamma}\frac{t}{\tau_m}\right)$$



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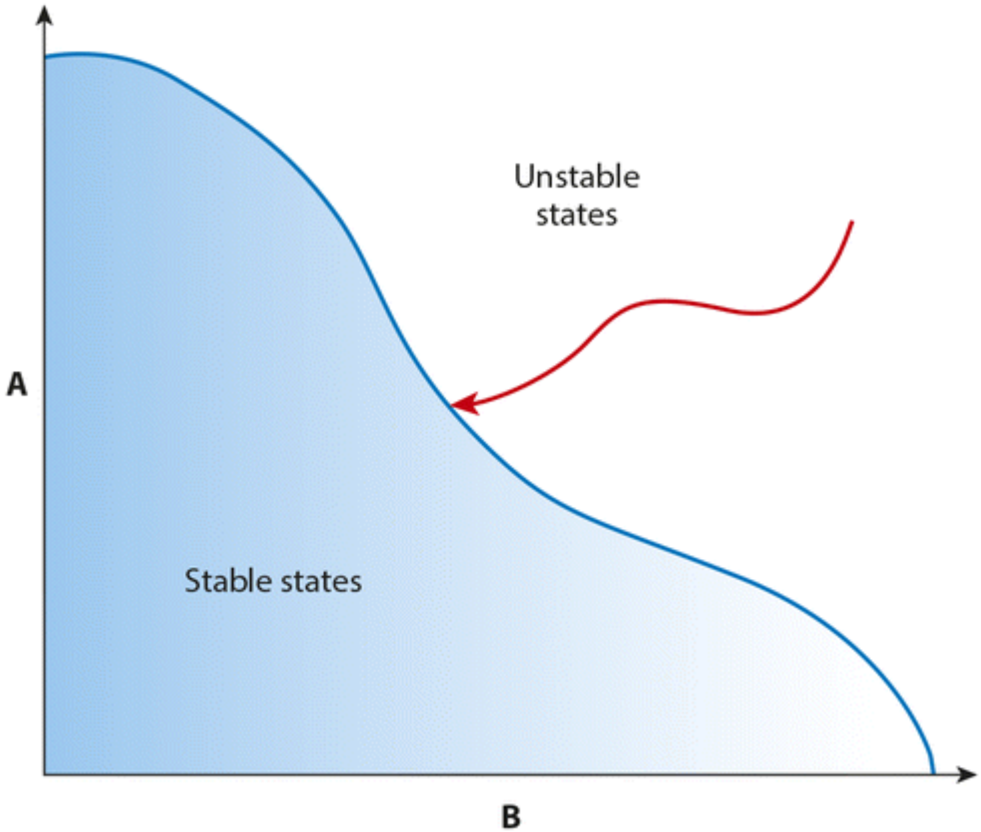
MARGINAL STABILITY AND EXCITATION SPECTRA



$$P(X) \propto X^{\theta}$$

$$X \to 0$$

Müller M, Wyart M. 2015.
Annu. Rev. Condens. Matter Phys. 6:177–200

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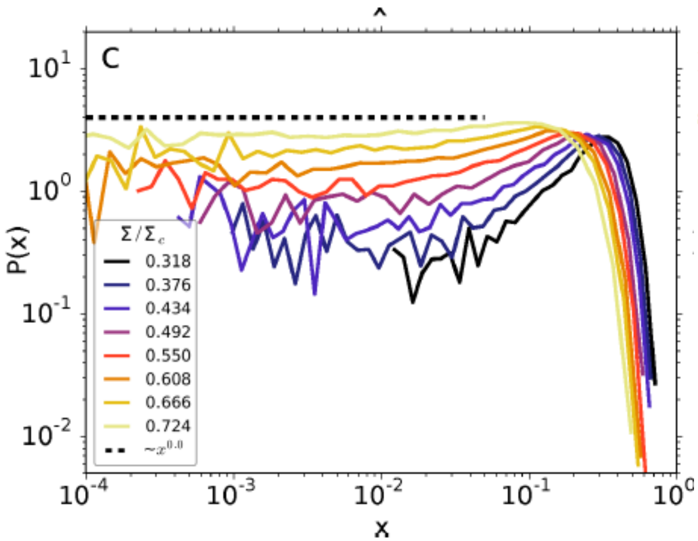
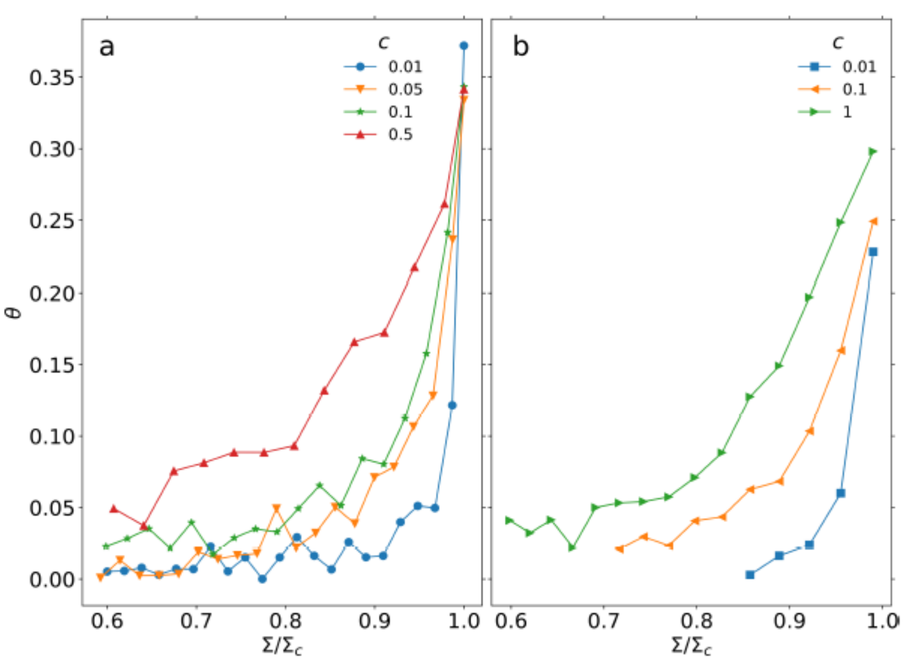
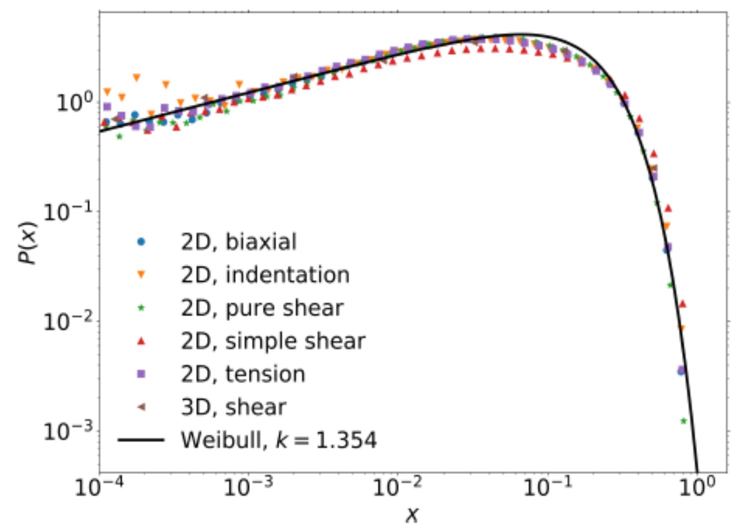
Excitation spectrum



Lin, J., Lerner, E., Rosso, A., and Wyart, M. Scaling description of the yielding transition in soft amorphous solids at zero temperature. *Proceedings of the National Academy of Sciences* **111**(40), 14382–14387 (2014).

$$P(X) \propto X^{\theta}$$





$$\mathcal{C} = \frac{E\Delta\epsilon}{\langle\Sigma_{\mathrm{t}}\rangle} = \frac{E\epsilon_{\mathrm{st}}}{\langle\Sigma_{\mathrm{t}}\rangle}\frac{V_{\mathrm{st}}}{V_{\mathrm{el}}}.$$

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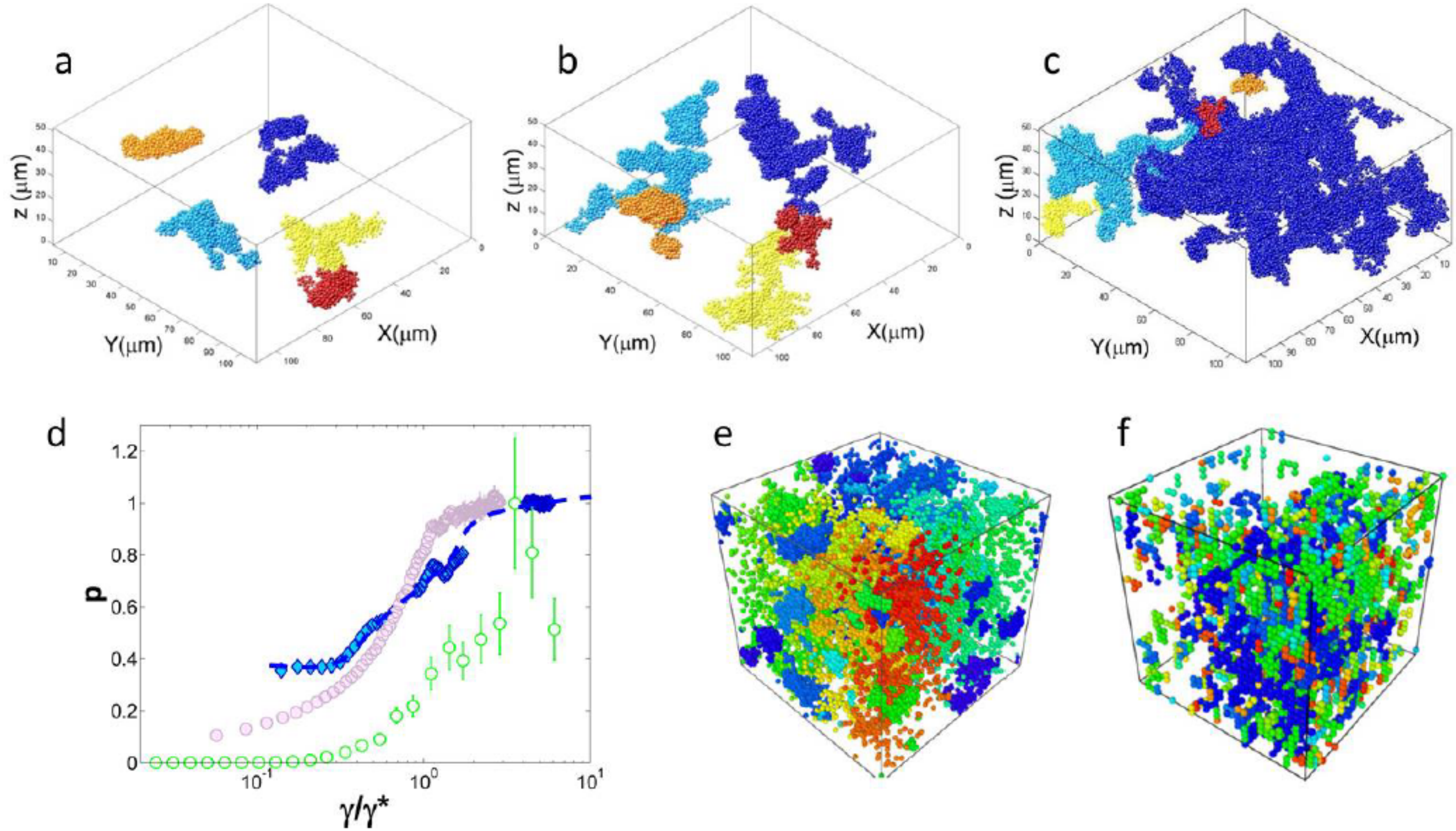
Clusters of activity

Experiments: Colloidal glasses



MD simulations

Mesoscale model

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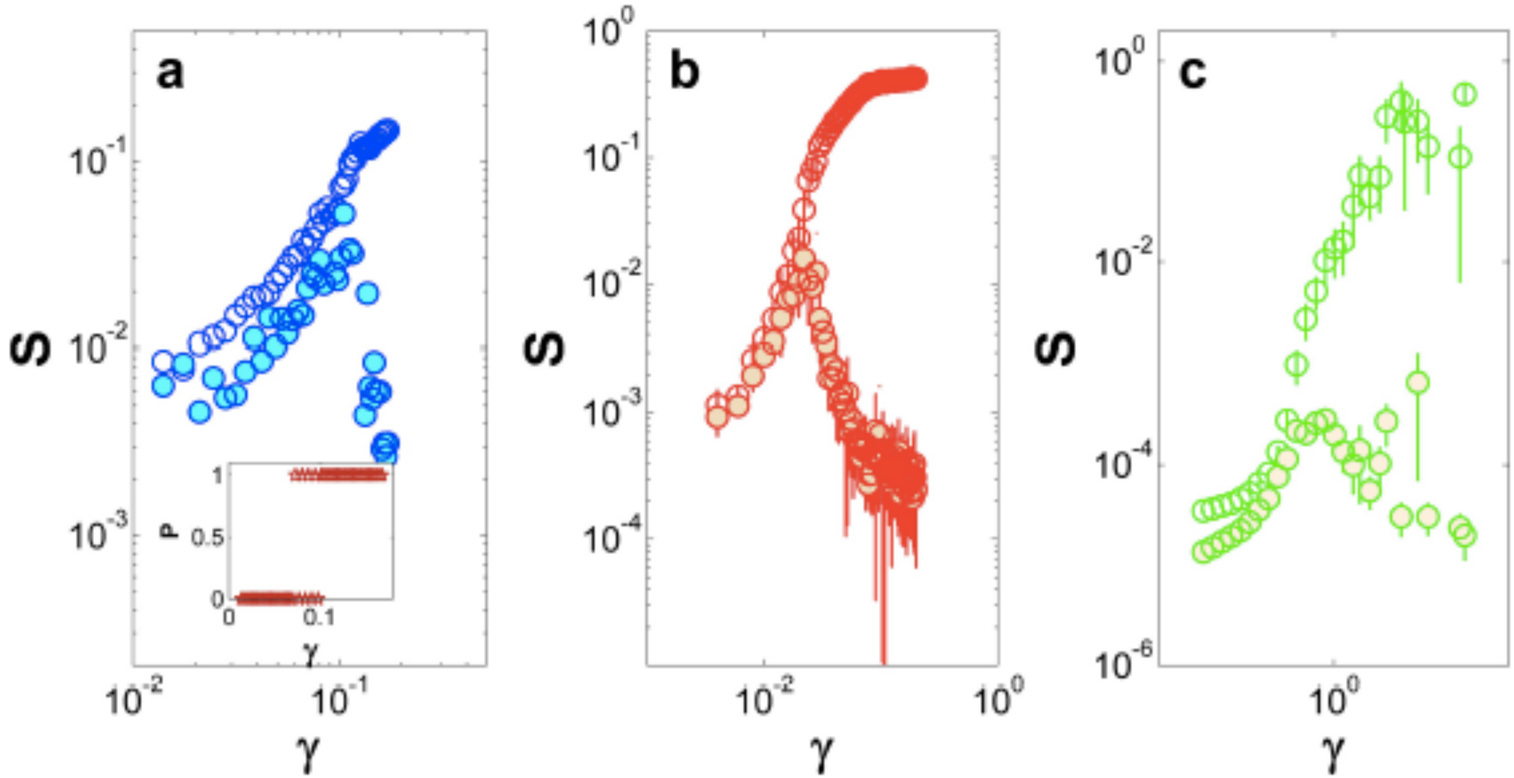
A Ghosh, Z Budrikis, V Chikkadi, A Sellerio. SZ, P. Schall PRL 2017

Clusters of activity



Experiments MD simulations Mesoscale model

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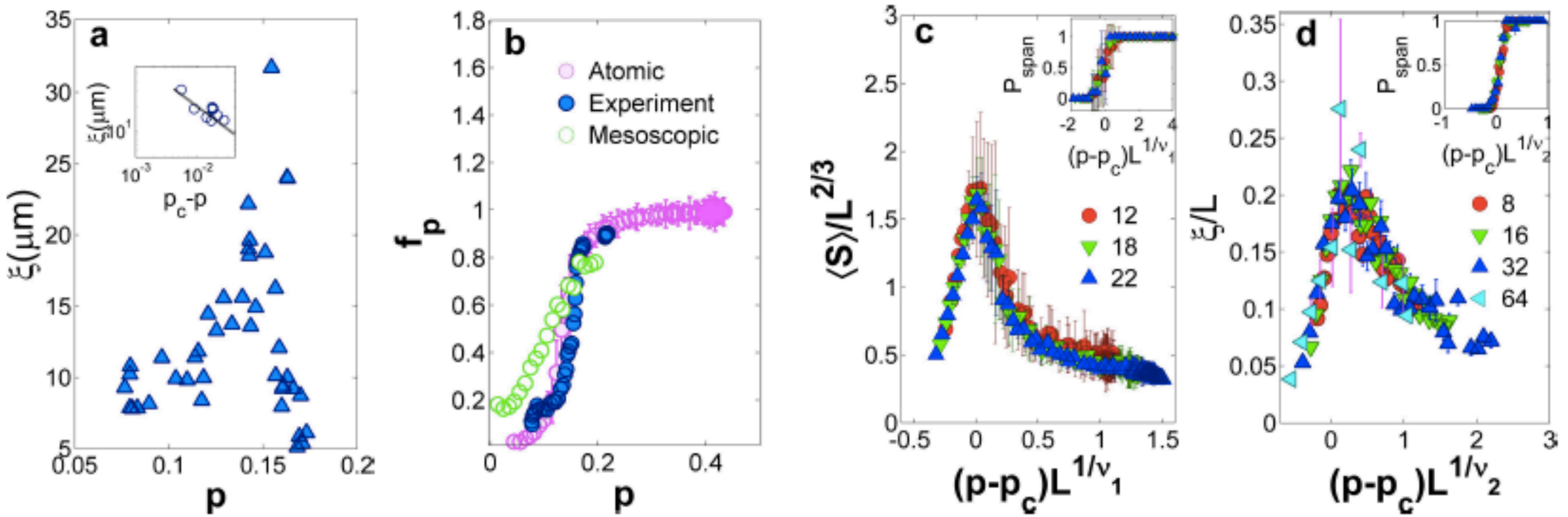
Percolation Scaling



Experiments

MD simulations

Mesoscale model

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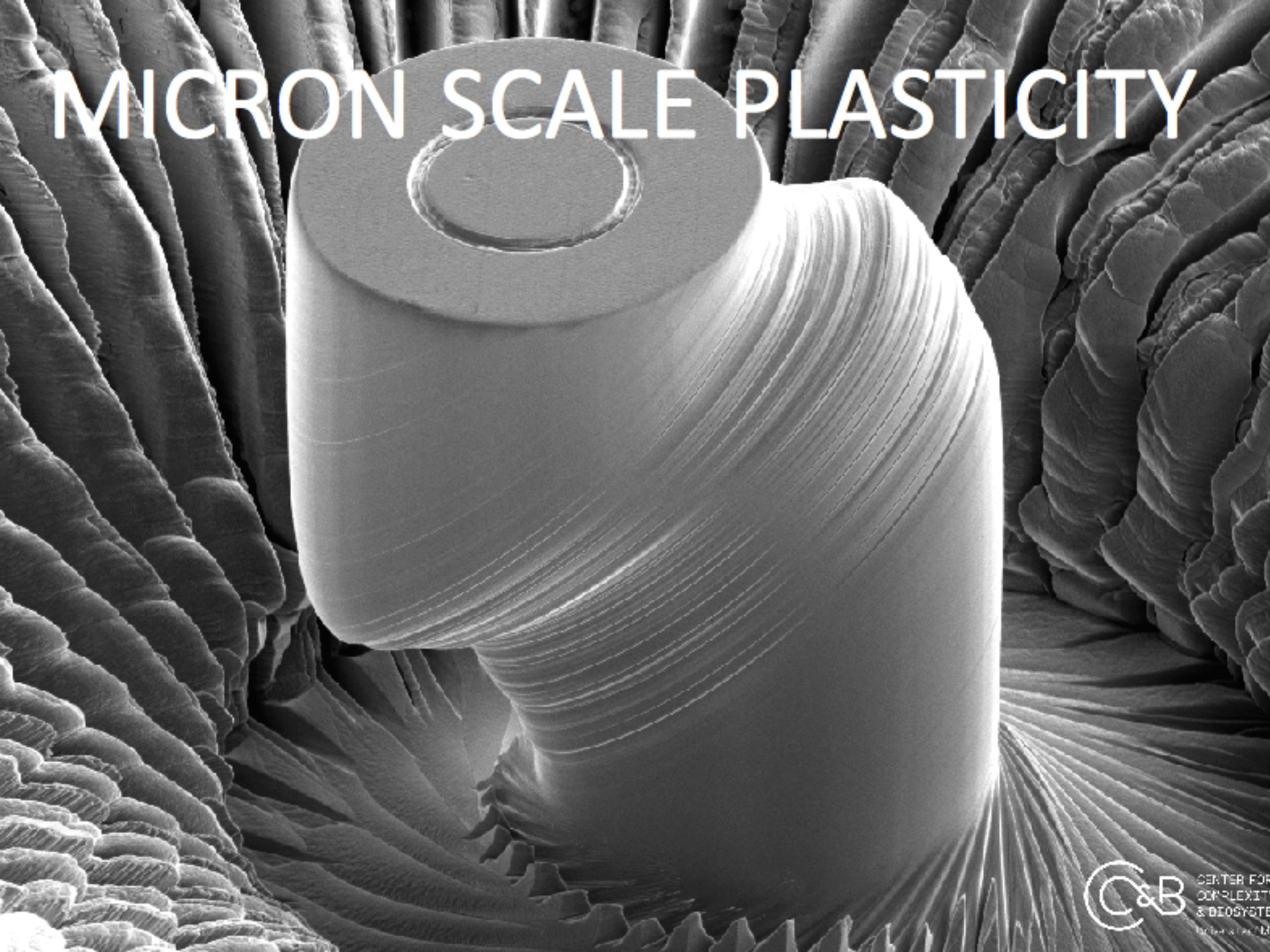
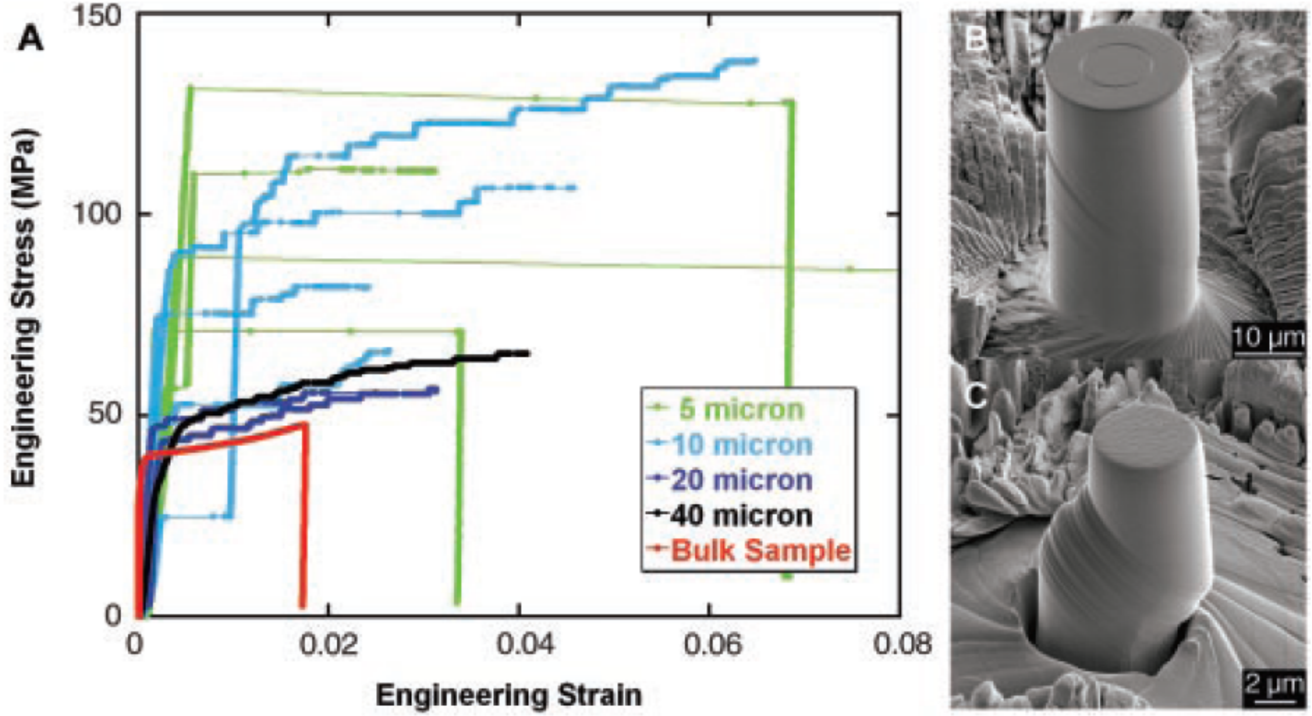
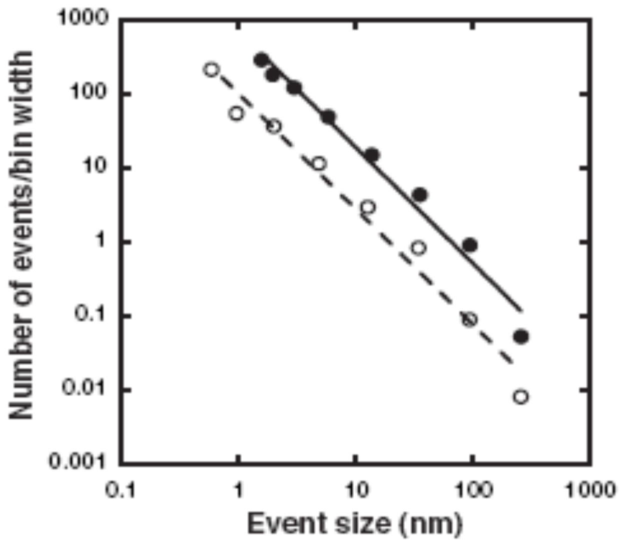
MICRON SCALE PLASTICITY







D. M. Dimiduk et al.,
Science 312, 1188 (2006).

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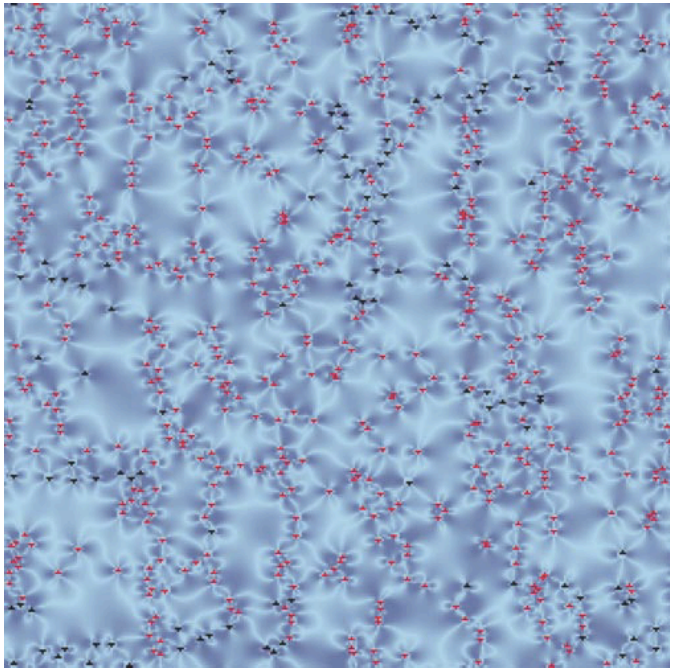
DISLOCATION DYNAMICS

2D

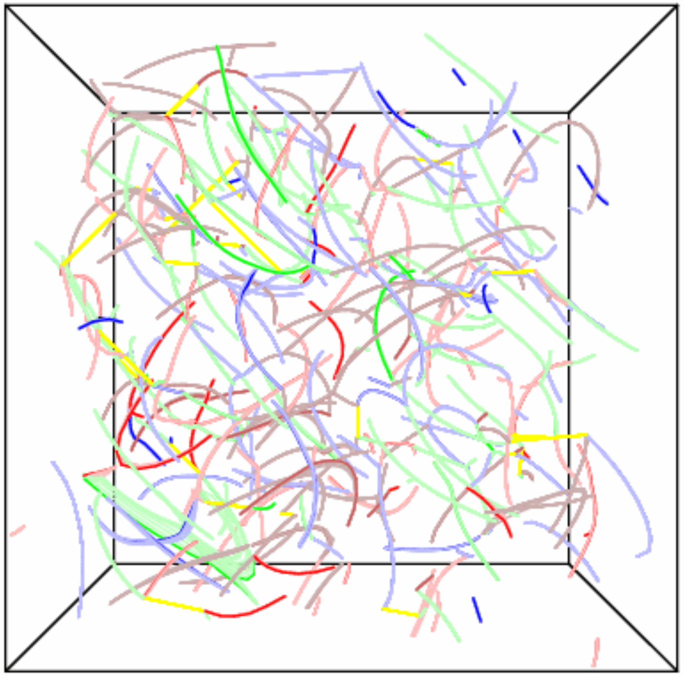
3D



Intermittent dislocation flow in viscoplastic deformation

M.-Carmen Miguel*†, Alessandro Vespignani*, Stefano Zapperi‡, Jérôme Weiss§ & Jean-Robert Grasso||

nature



Dislocation Avalanches, Strain Bursts, and the Problem of Plastic Forming at the Micrometer Scale

Ferenc F. Csikor,[1,2] Christian Motz,[3] Daniel Weygand,[3] Michael Zaiser,[2] Stefano Zapperi[4,5]*

Science

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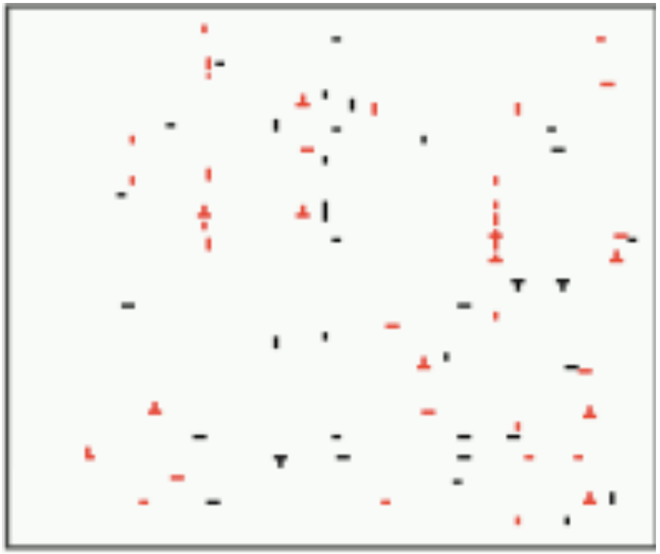
2D DISLOCATION DYNAMICS



$$\sigma_{ij} = \frac{b\mu x_{ij}}{2\pi(1-\nu)} \frac{(x_{ij}^2 - z_{ij}^2)}{(x_{ij}^2 + z_{ij}^2)^2}$$

MODEL VARIANTS:

1) Continuum time model

$$\gamma v_i = b_i (\sum_j \sigma_{ij} - \sigma_e)$$

2) Cellular automaton: extremal update

3) Cellular automaton: random update

$$v_i = \text{sign}(b_i (\sum_j \sigma_{ij} - \sigma_e))$$

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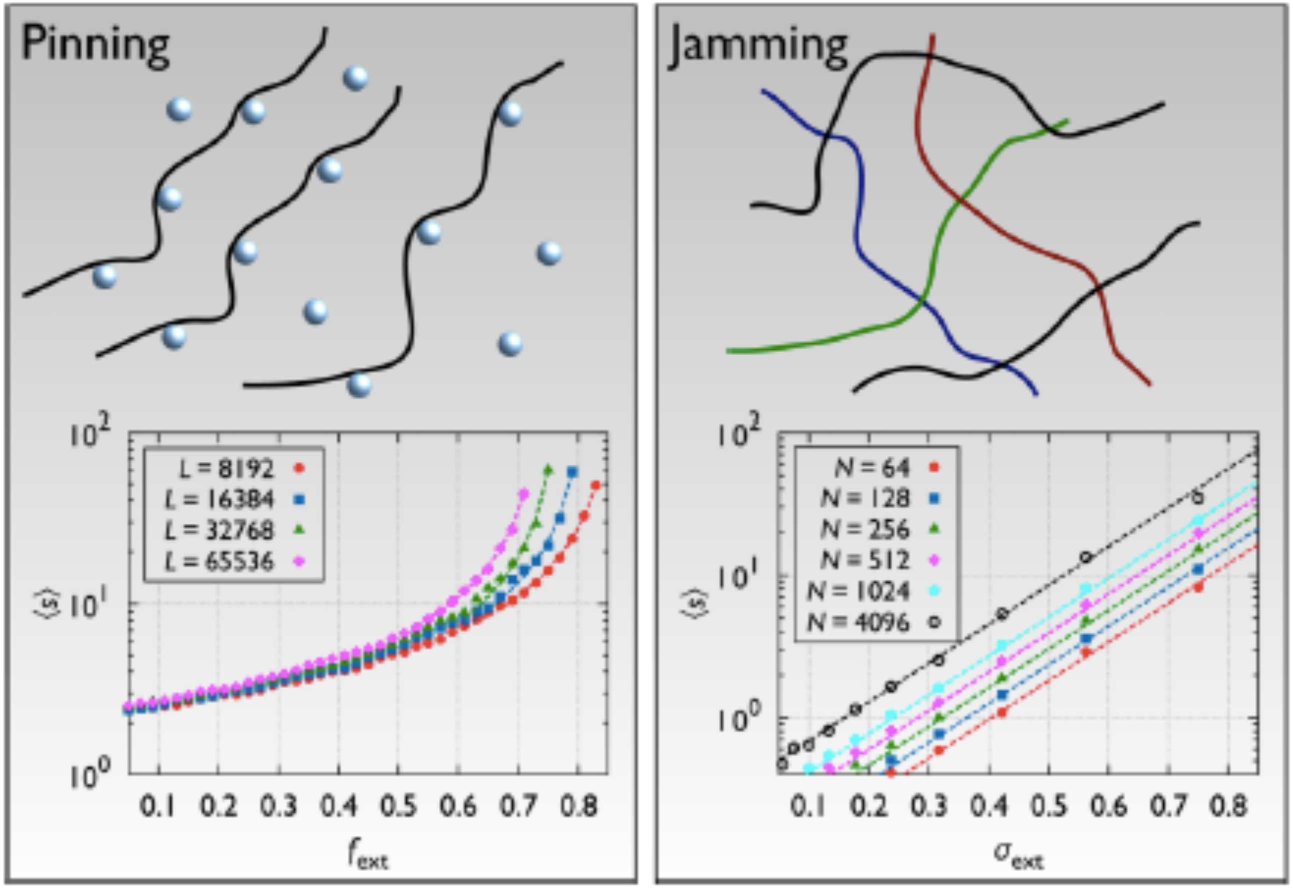
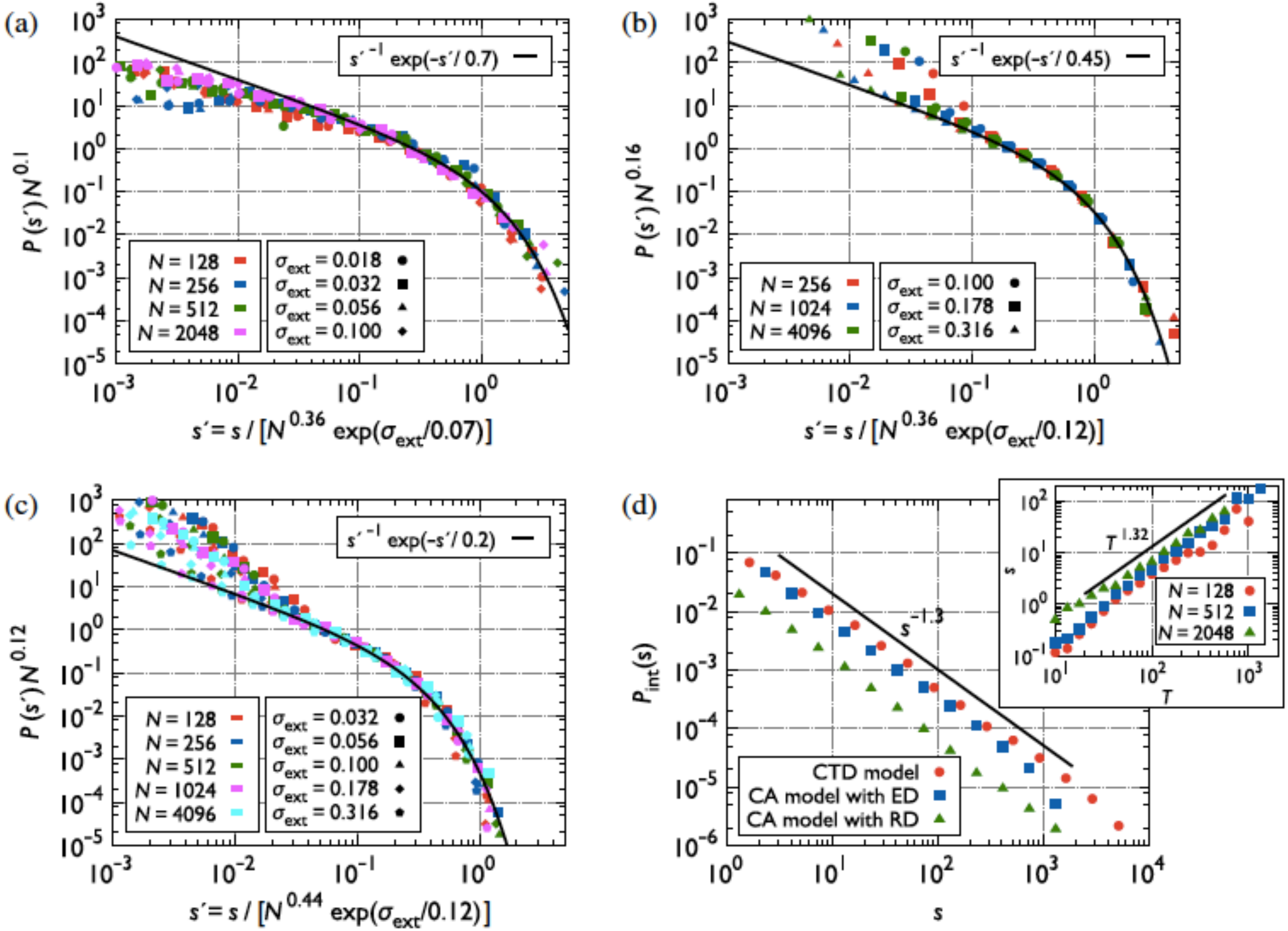
PRL 112, 235501 (2014) PHYSICAL REVIEW LETTERS week ending 13 JUNE 2014

Avalanches in 2D Dislocation Systems: Plastic Yielding Is Not Depinning

Péter Dusán Ispánovity,[1,*] Lasse Laurson,[2] Michael Zaiser,[3] István Groma,[1] Stefano Zapperi,[4] and Mikko J. Alava[2]





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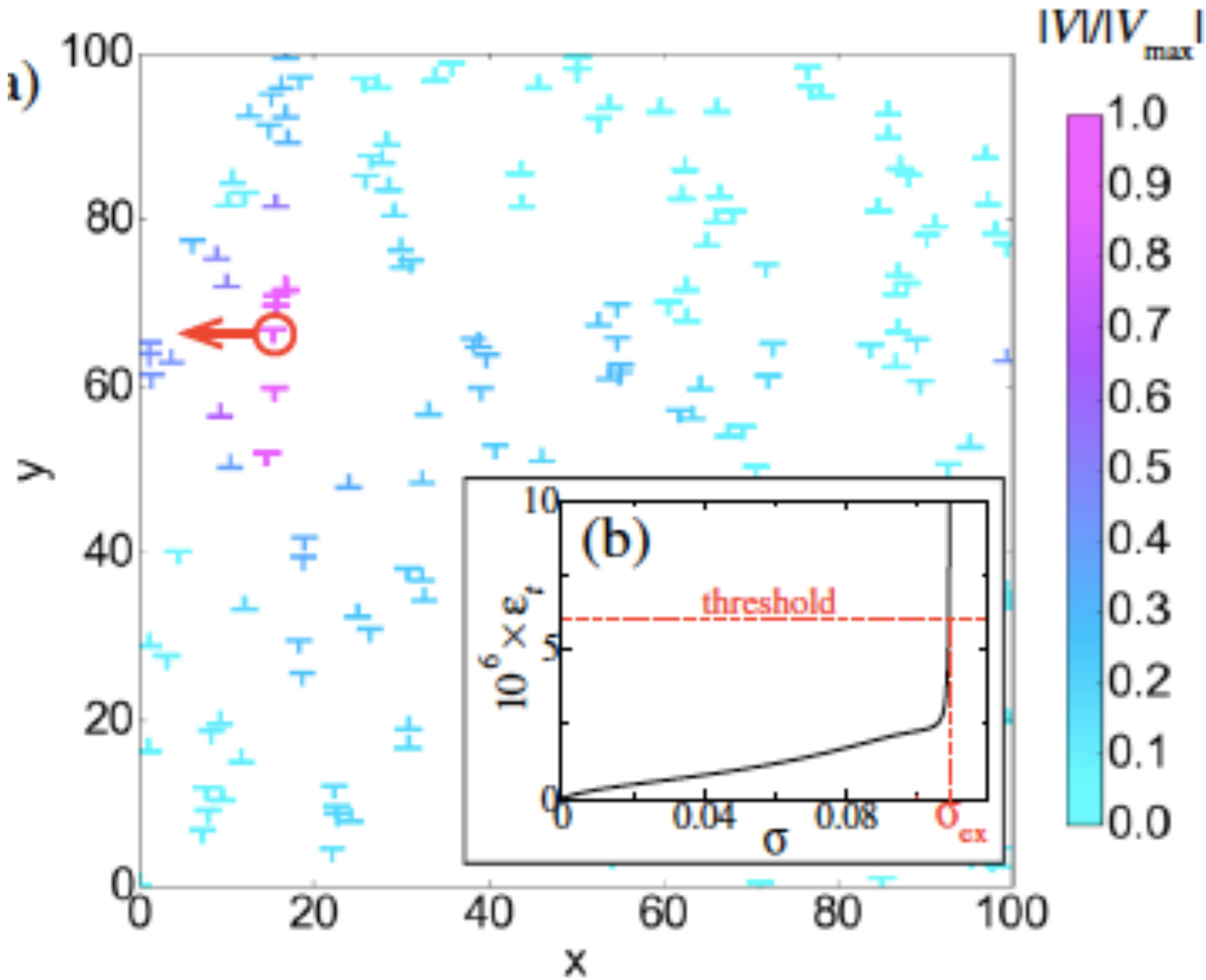
EXTRACTING SPECTRA FROM DISLOCATION DYNAMICS (2D)



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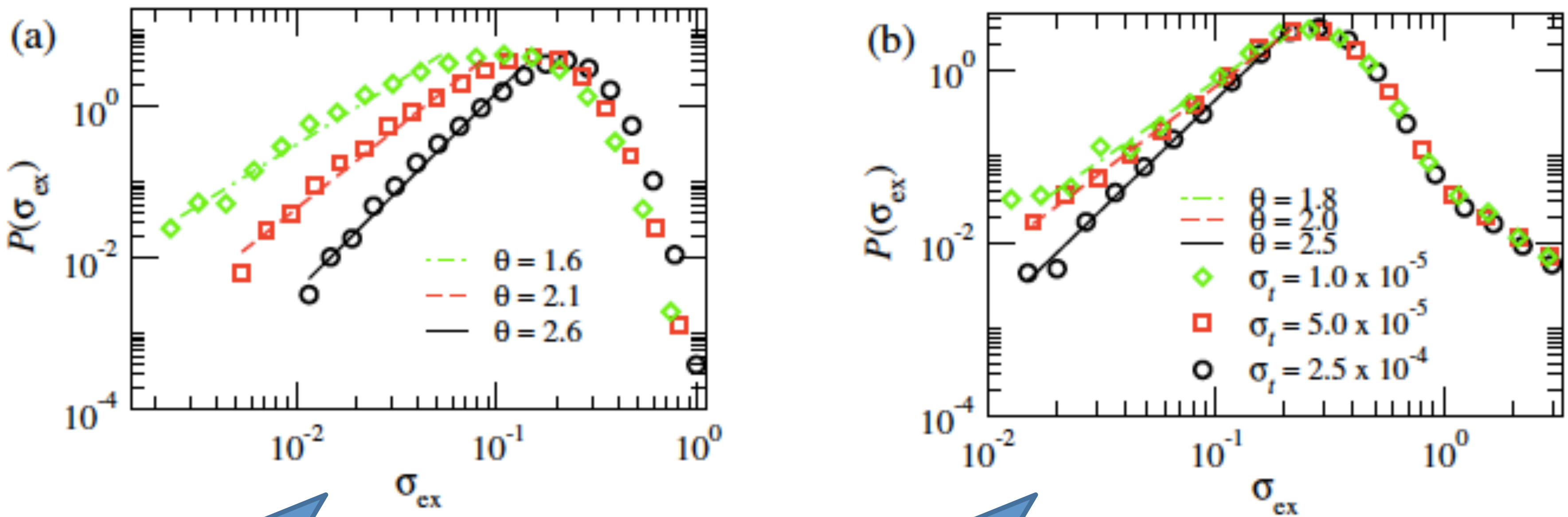
2D EXCITATION SPECTRA



All dislocations mobile

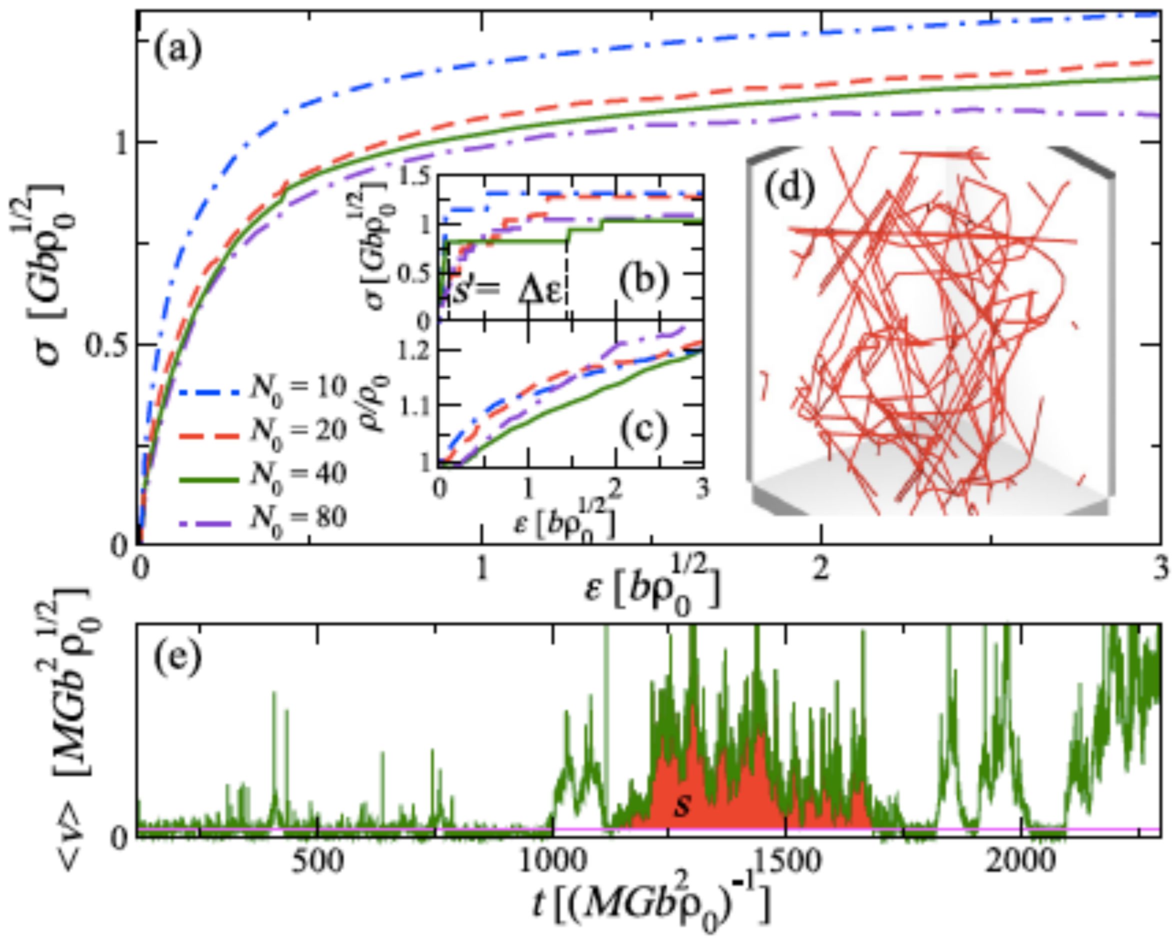
one dislocation mobile

PRL 119, 265501 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

Excitation Spectra in Crystal Plasticity

Markus Ovaska,[1] Arttu Lehtinen,[1] Mikko J. Alava,[1] Lasse Laurson,[1] and Stefano Zapperi[1,2,3]

3D AVALANCHES



Lehtinen, A., Costăntini, G., Alava, M. J., Zapperi, S., & Laurson, L. (2016). Glassy features of crystal plasticity. PHYSICAL REVIEW B, 94(6), 1-5. [064101]. DOI: 10.1103/PhysRevB.94.064101

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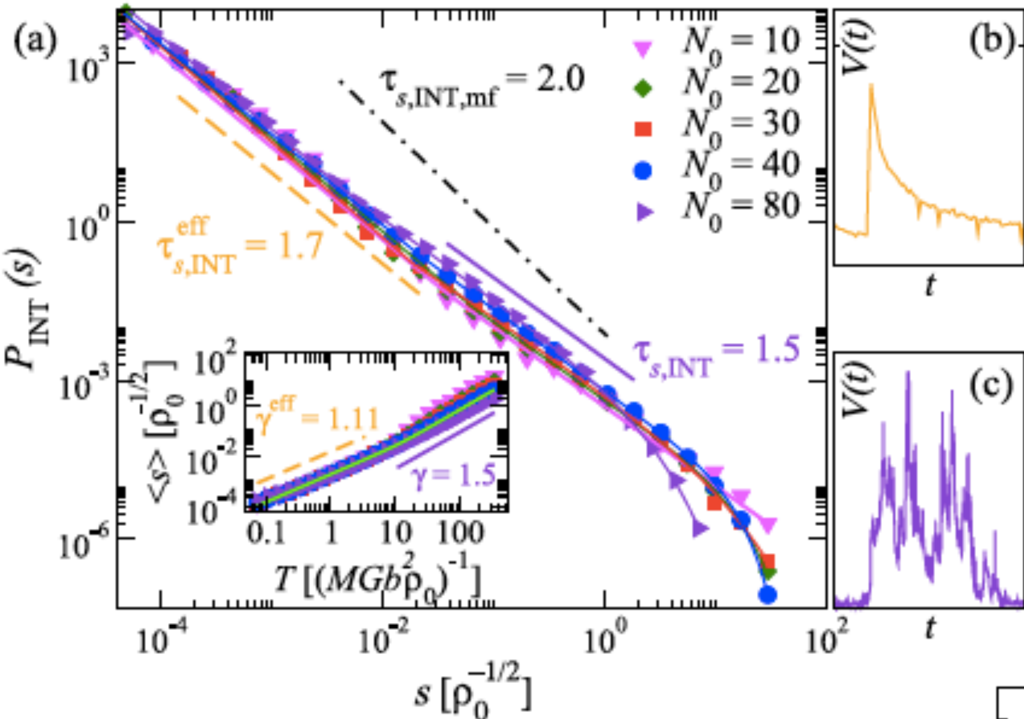
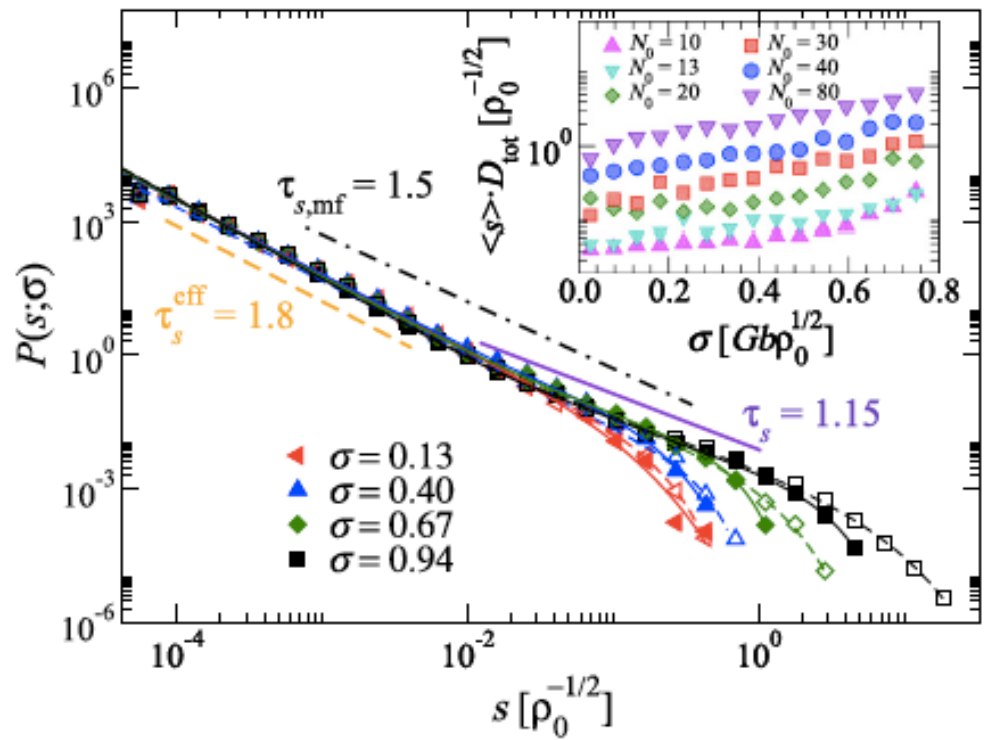
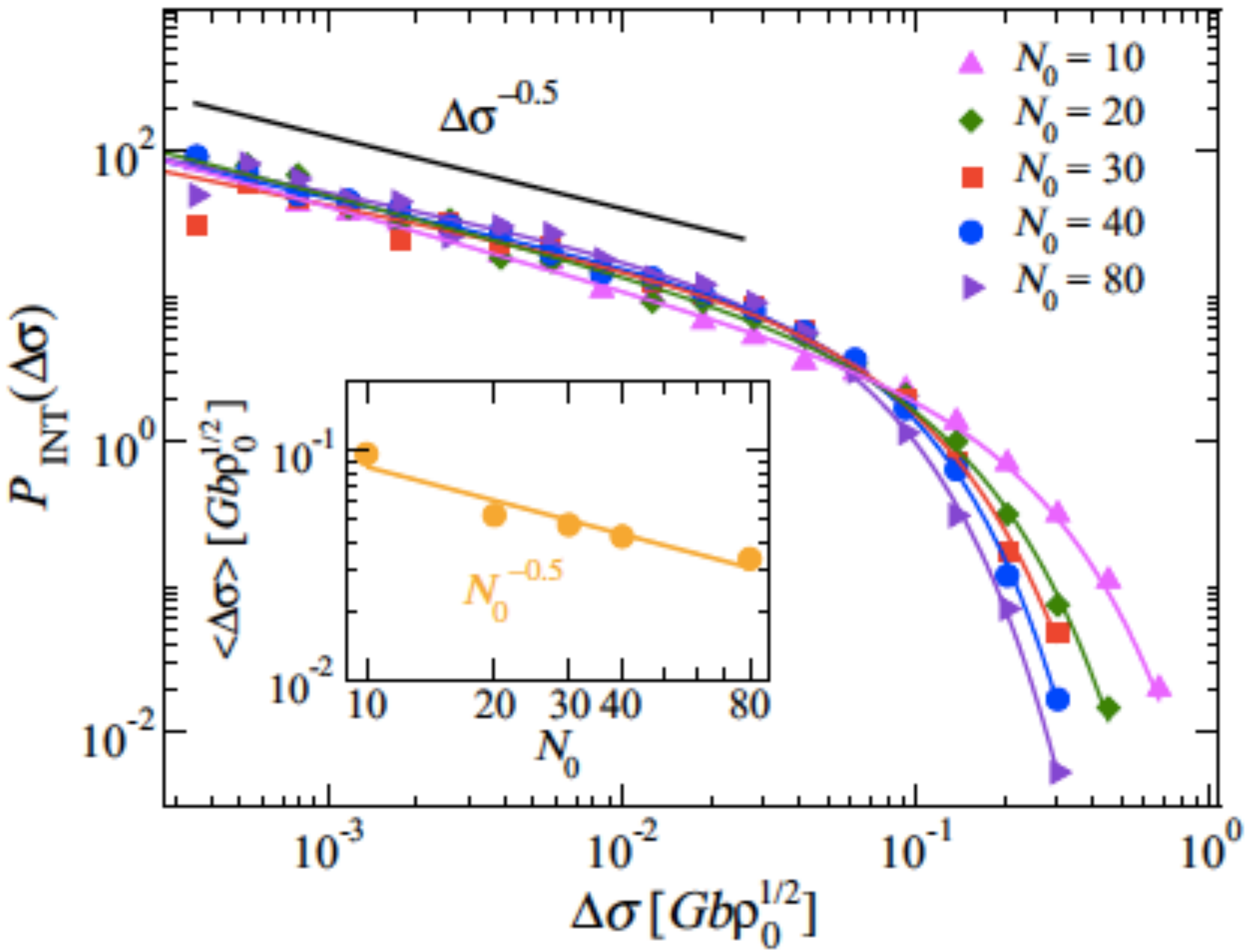


INTEGRATED DISTRIBUTIONS

STRESS RESOLVED DISTRIBUTIONS



STRESS INCREMENTS



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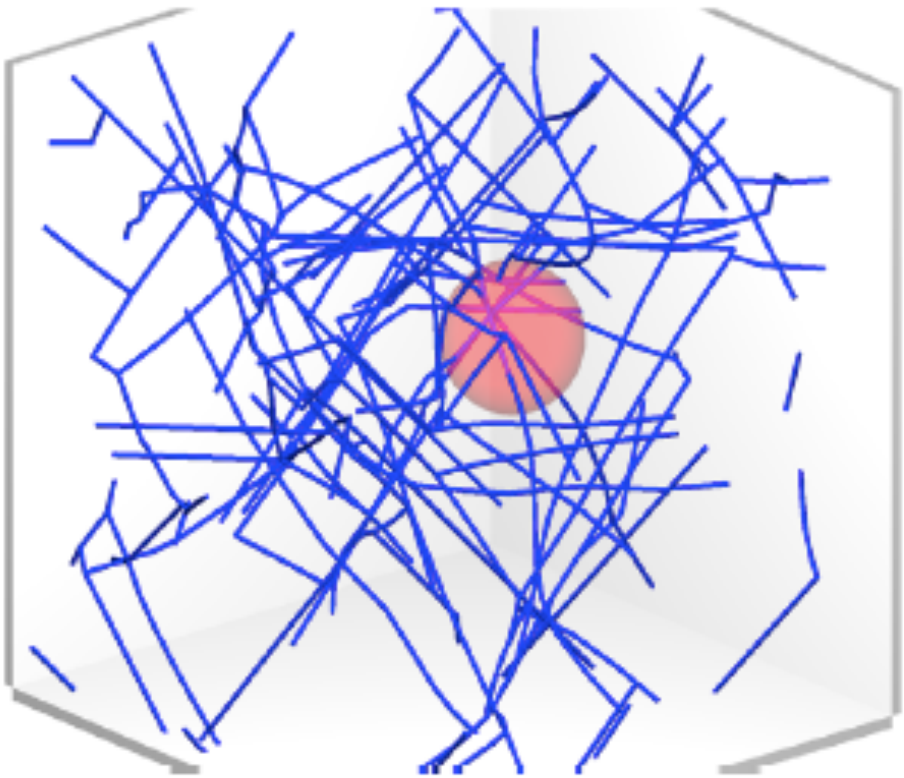
EXTRACTING SPECTRA FROM DISLOCATION DYNAMICS (3D)



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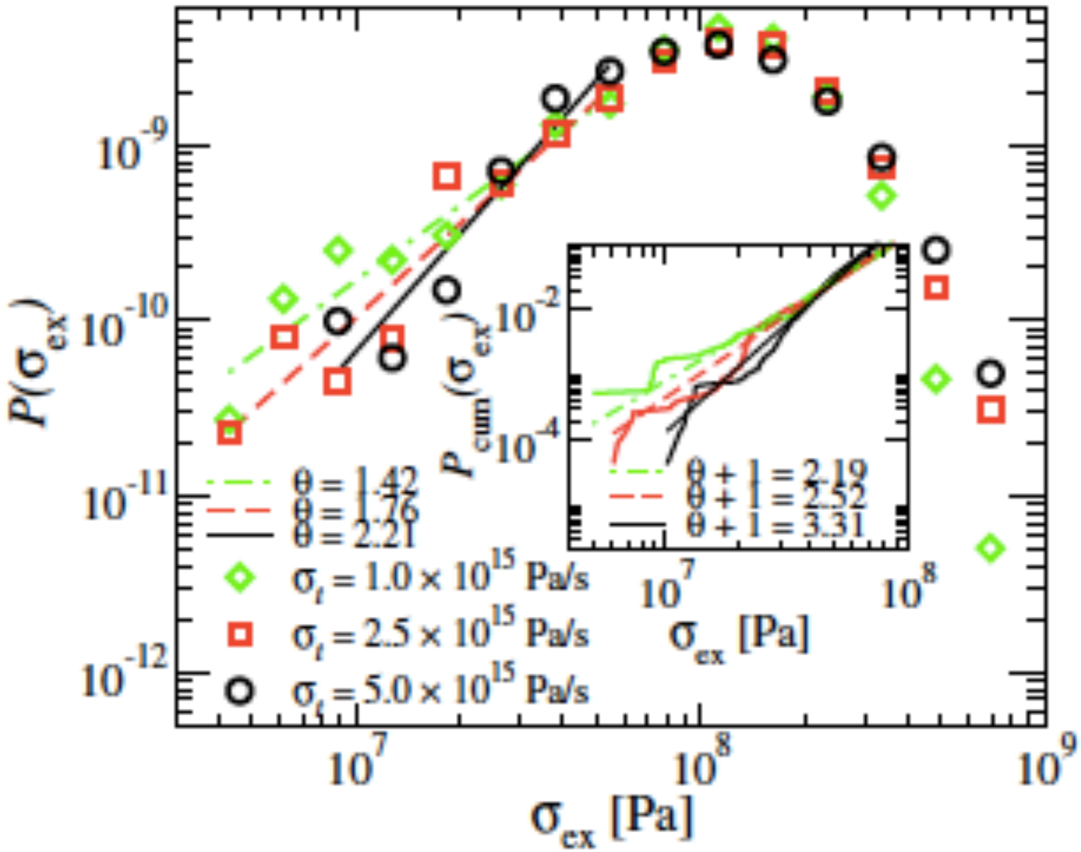
3D EXCITATION SPECTRA



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Excitation Spectra in Crystal Plasticity

Markus Ovaska,[1] Arttu Lehtinen,[1] Mikko J. Alava,[1] Lasse Laurson,[1] and Stefano Zapperi[1,2,3]

SUMMARY

deformation
yielding
amorphous
avalanche
results
stress
dislocation
dynamics
plastic
critical
size
strain
transition
models
loading
powerlaw
exhibit
stresscontrolled
sample
similar
bursts
crystal
occurs
study
suggest
model
point
show
motion
observed
yield
allow
elastic
make
slip
flow
still

Thanks

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Zoe Budrikis

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Silvia Bonfanti

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