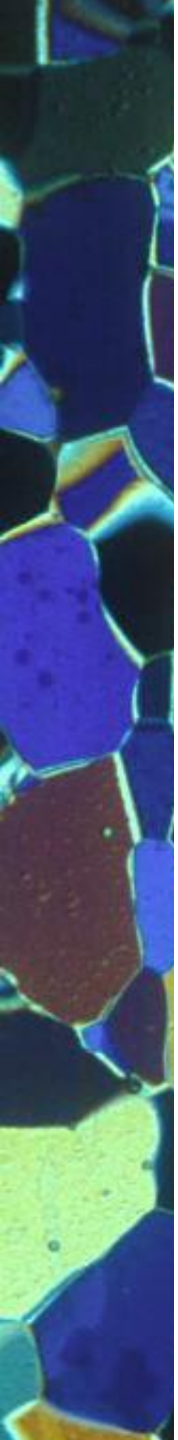
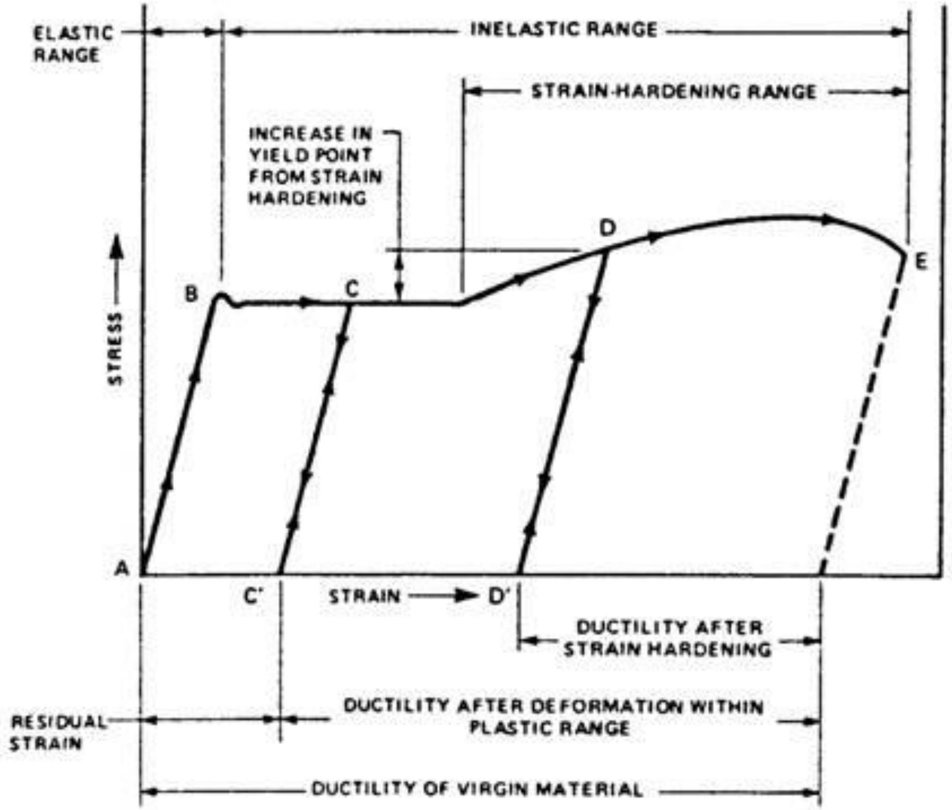


From continuous to crackling plasticity

Jérôme Weiss

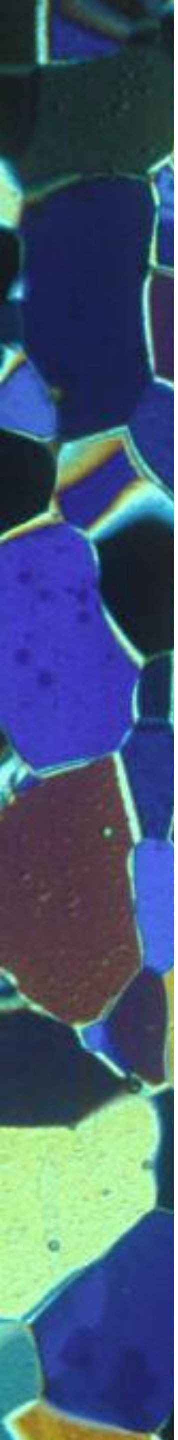
IsTerre/CNRS, Grenoble
with:

W. Ben Rhouma
T. Richeton
S. Deschanel
F. Louchet
L. Truskinovsky



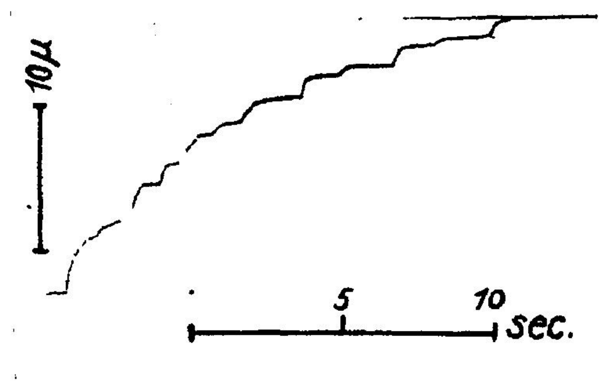
The classical view of plastic *flow* in textbooks:
Smooth and homogeneous

Fluctuations are assumed to be *mild*



Jerkyness of plastic « flow »

(Becker and Orowan, *Z. Phys*., 1932)

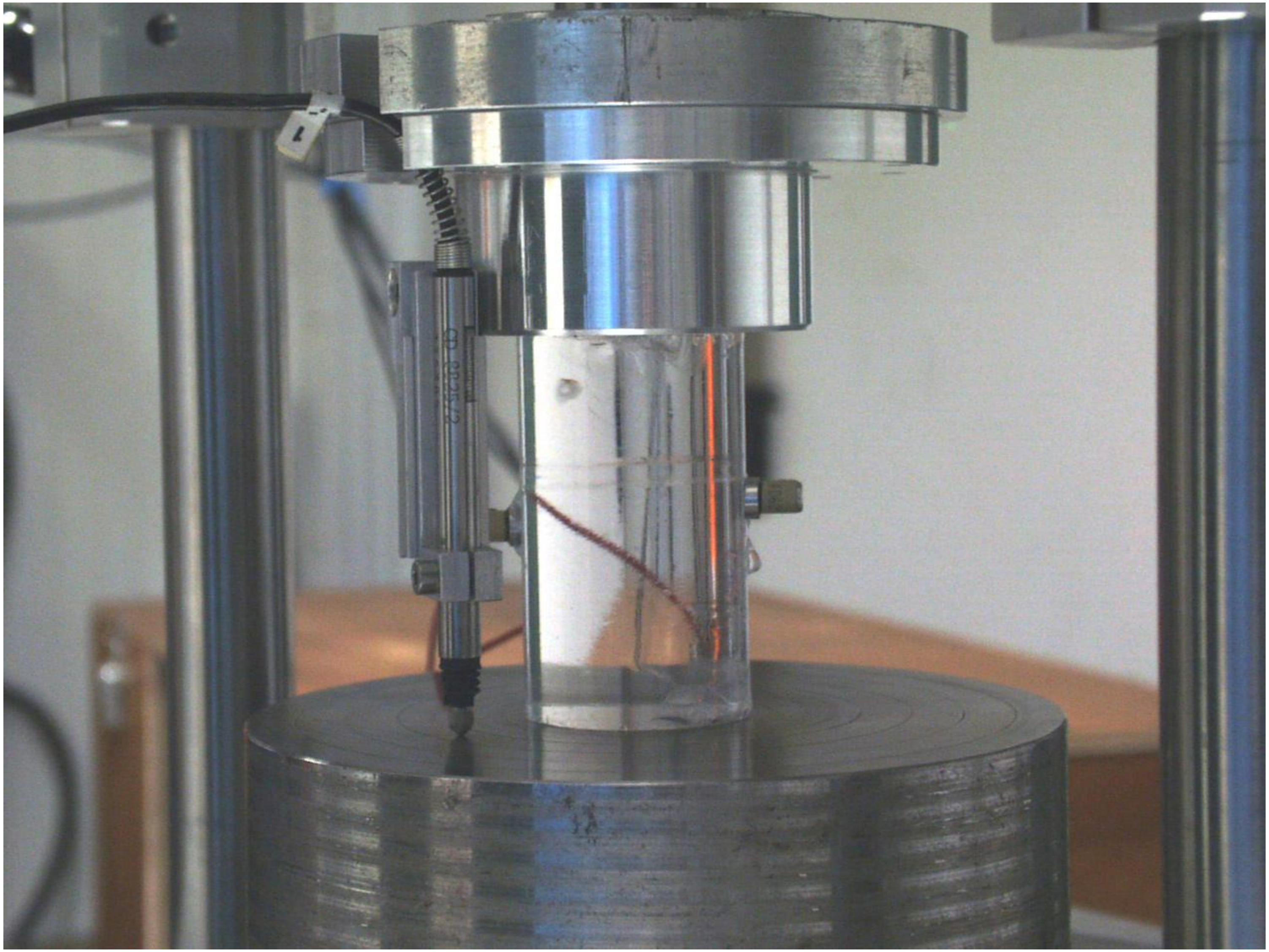


« The jerky extension of Zinc single crystals »

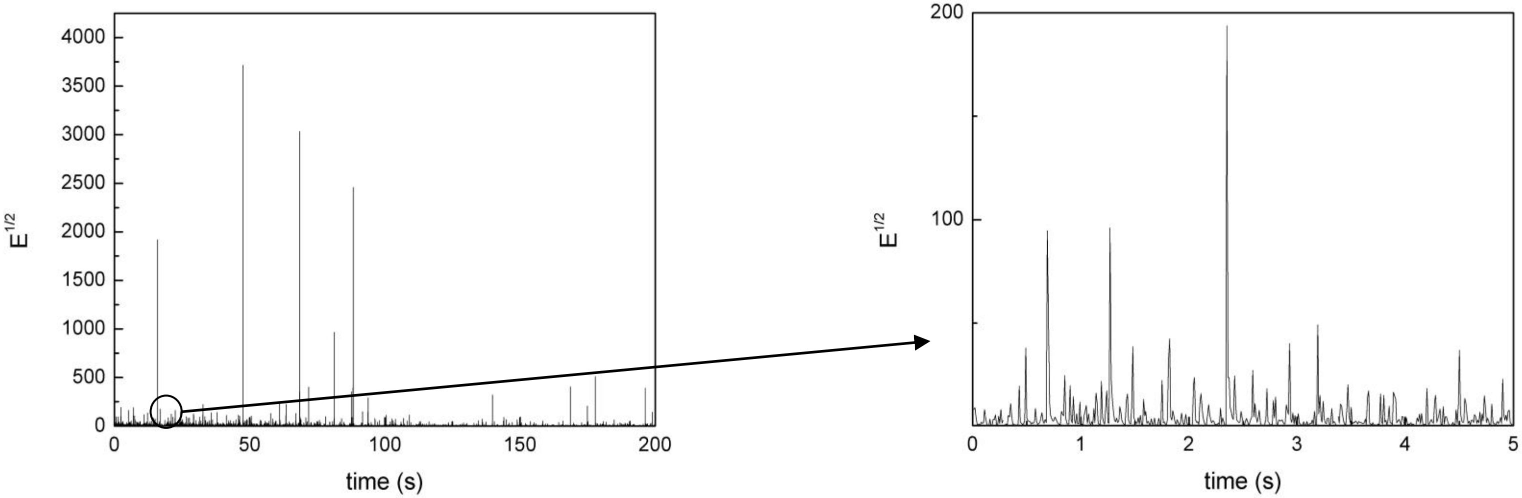
« A single glide process, started obviously from one point in the crystal, produces gliding by thousands or even millions of atomic distances; in other words, a first impulse gives rise to a whole avalanche of dislocations »

"Crackling" plasticity: single crystals of ice

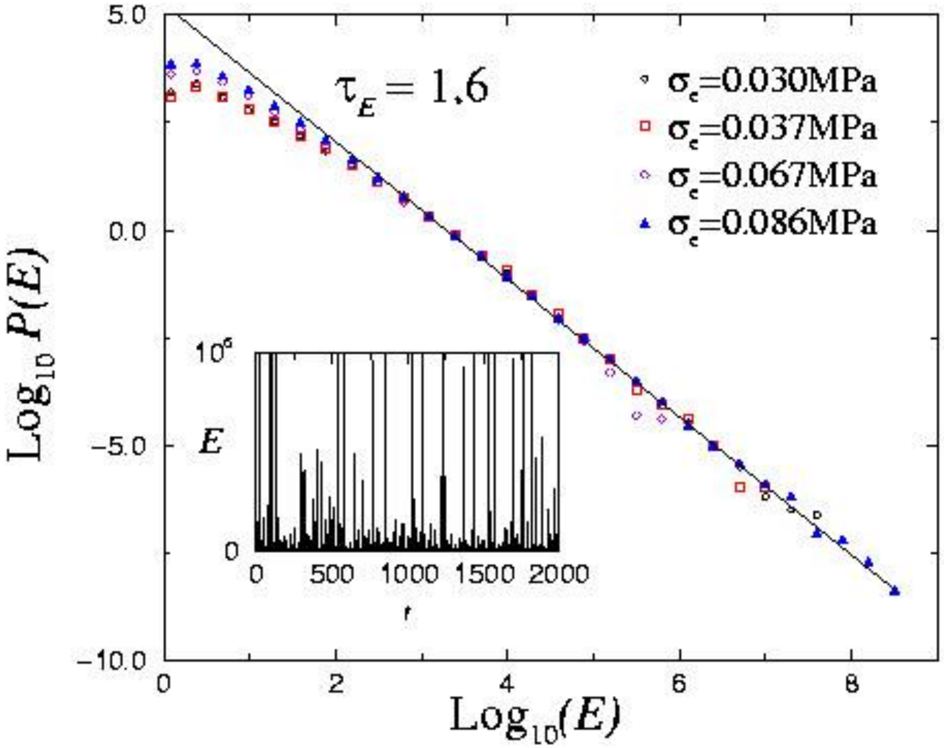
(Weiss and Grasso, *J. Phys. Chem.*, 1997
Miguel et al., *Nature*, 2001)



“Crackling” plasticity: single crystals of ice



“Crackling” plasticity: single crystals of ice

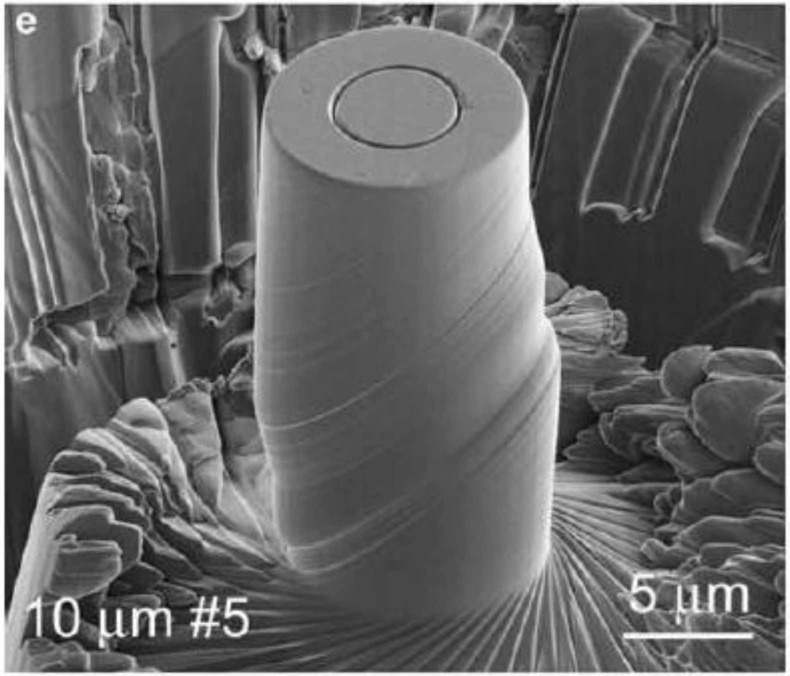


Power law distribution of avalanche amplitudes and energies, $p(E) \sim E^{-\tau_E}$

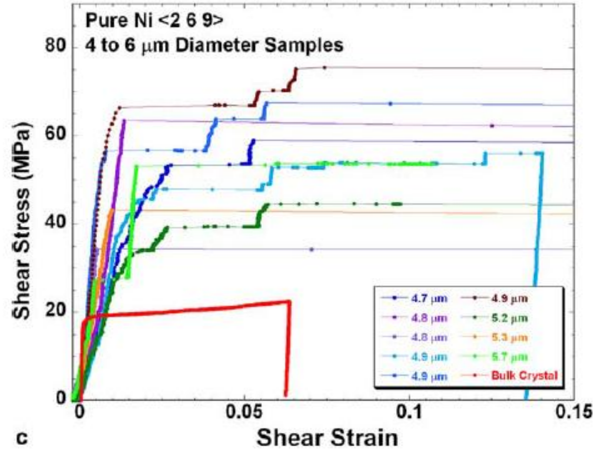
Fluctuations are *wild*

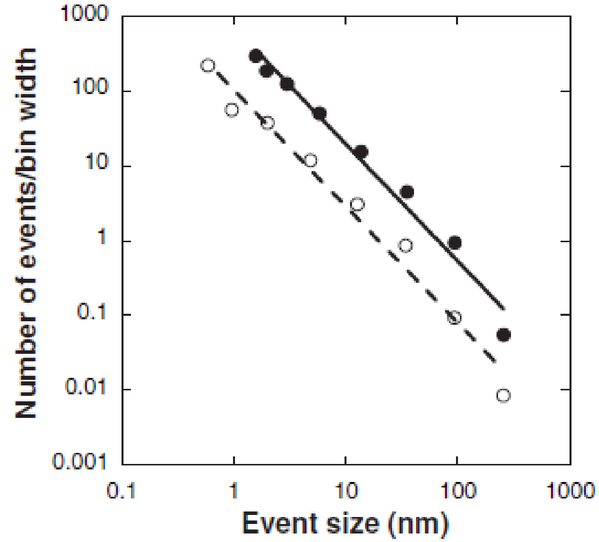
Micro- and nano-pillars

(Dimiduk et al., 2006) and many others

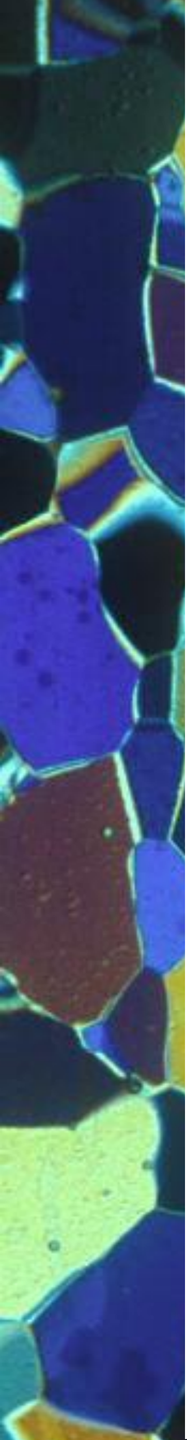


Nickel single crystals





Fluctuations are *wild*



Classical vs Crackling plasticity

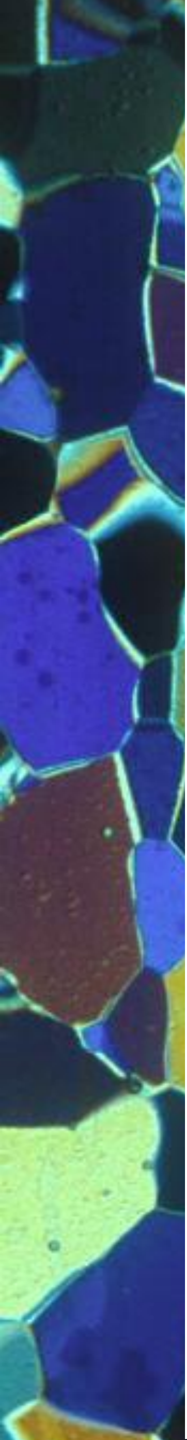
Classical view of plasticity

Mild fluctuations

Scale-free, intermittent plasticity

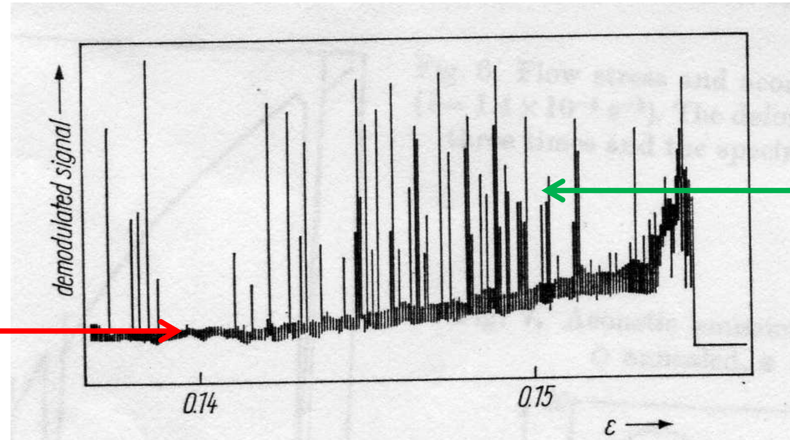
Wild fluctuations

Are they compatible ?



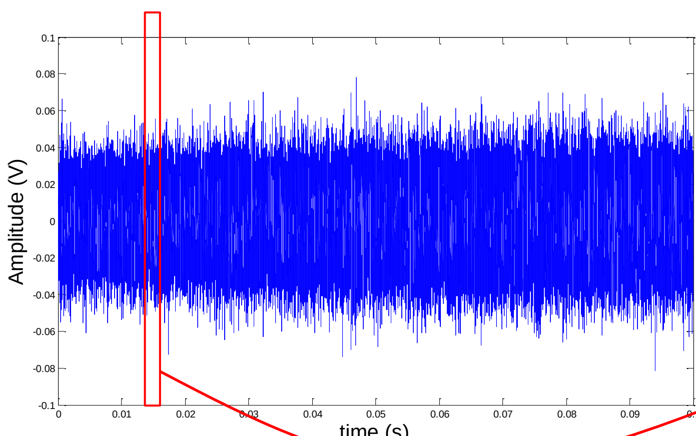
Acoustic emission from dislocation motion:
« Continuous » vs « discrete » AE

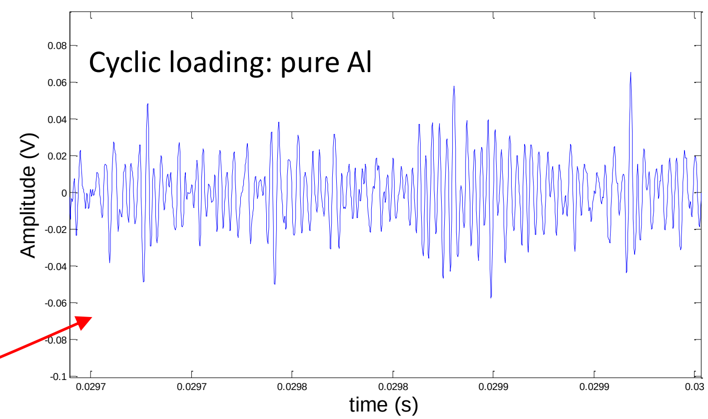
Continuous AE
=
« classical noise »



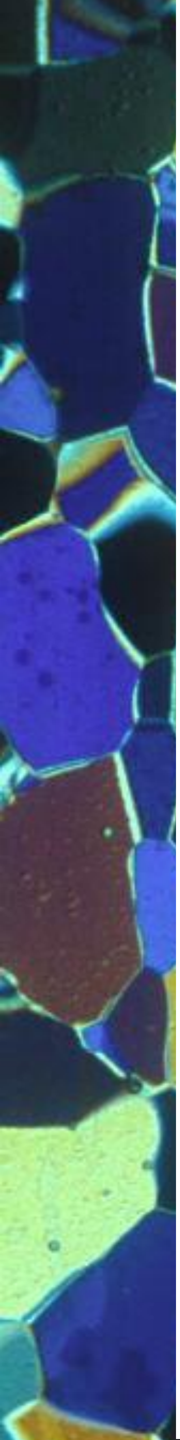
Discrete AE
=
« Crackling noise »

AE recorded during the plastic deformation of Al
(*Imanaka et al.*, 1973)

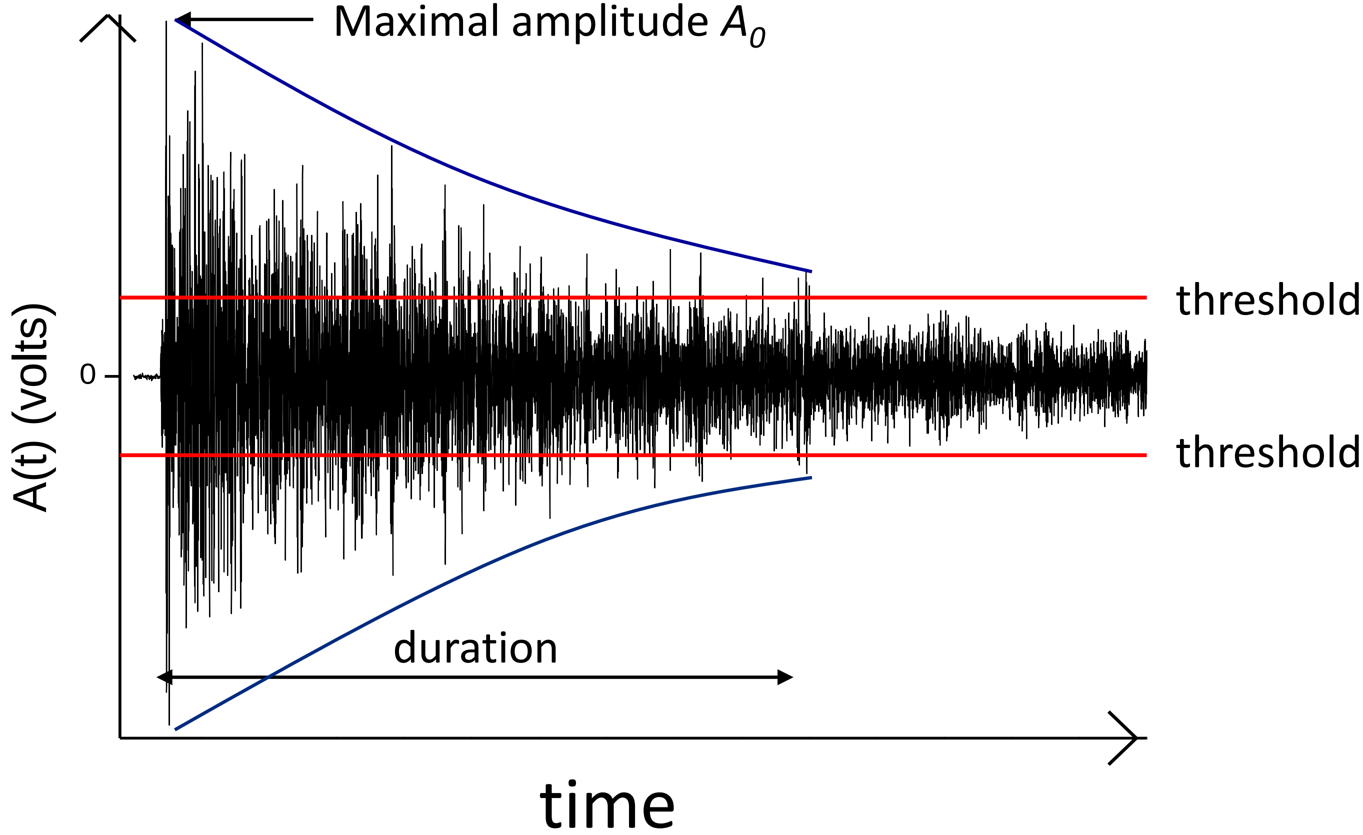




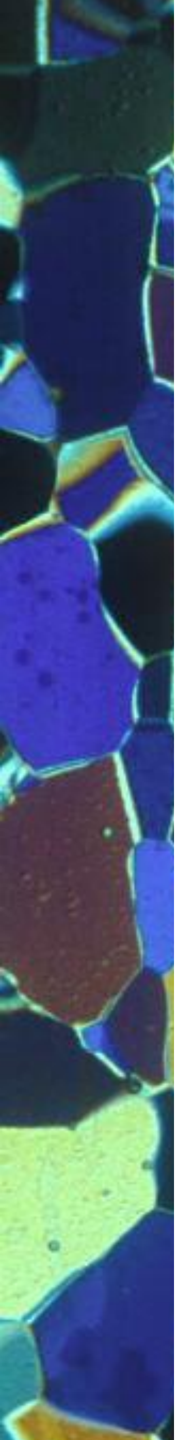
« Datastreaming »: full signal sampled at 5 MHz



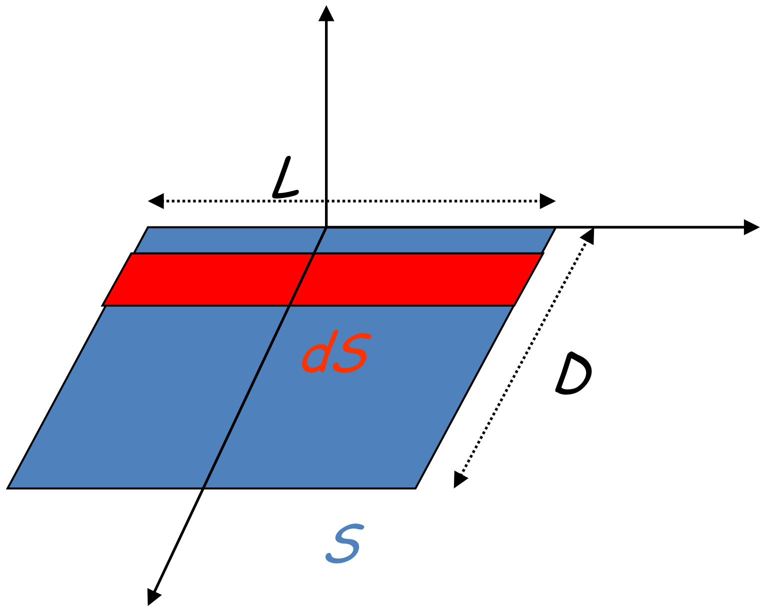
AE burst



- AE maximal amplitude A_0
- Duration δt
- AE energy $E = \int_{\delta t} A^2(t)dt$



Discrete AE: Source model (Rouby et al., 1983)
Collective dislocation motion: Avalanches



- velocity sensors

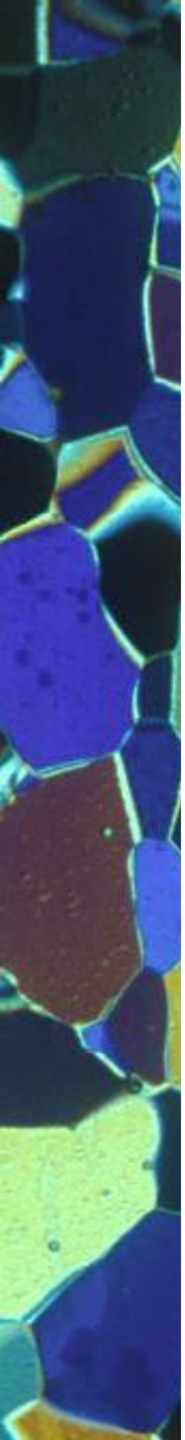
$$A(t) \sim b\, n(t)\, L\, v(t) \sim b \frac{dS}{dt}$$

- *b*: Burger's vector
- *n*: number of dislocations
- *v*: dislocations velocity

Decay hypothesis: $v(t) = v(t_0)\, exp[-\alpha(t - t_0)]$

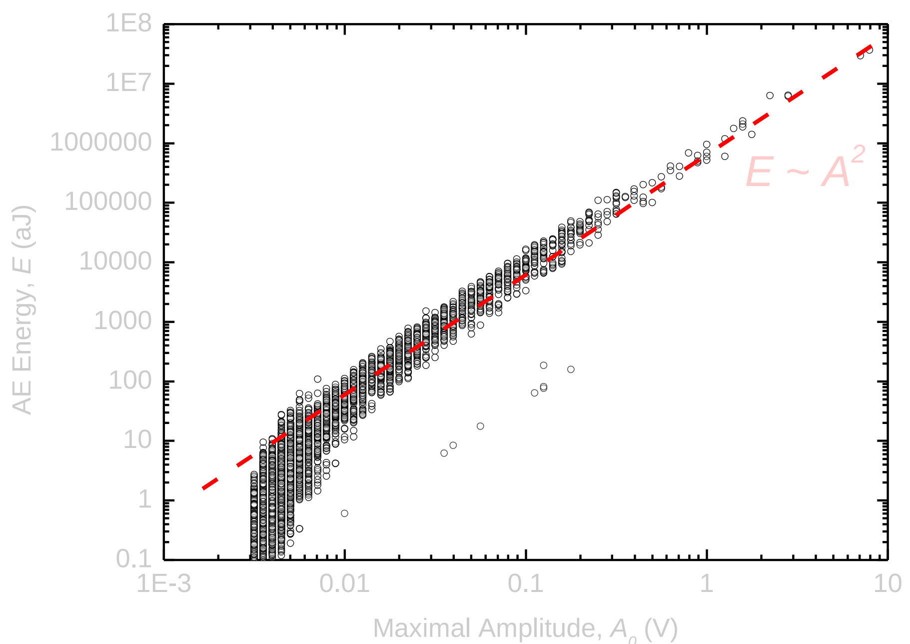
$$\Rightarrow A_0 \sim S \sim \varepsilon_p$$

$$\Rightarrow E \sim {A_0}^2 \sim {\varepsilon_p}^2$$



Discrete AE: Source model (Rouby et al., 1983)
Collective dislocation motion: Avalanches

$$E \sim {A_0}^2 \sim {\varepsilon_p}^2$$



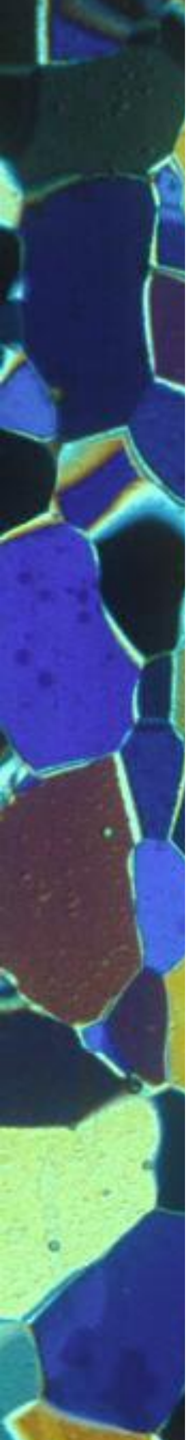
Continuous AE as the result of classical plasticity

(Rouby et al., 1983; Slimani et al., 1992)

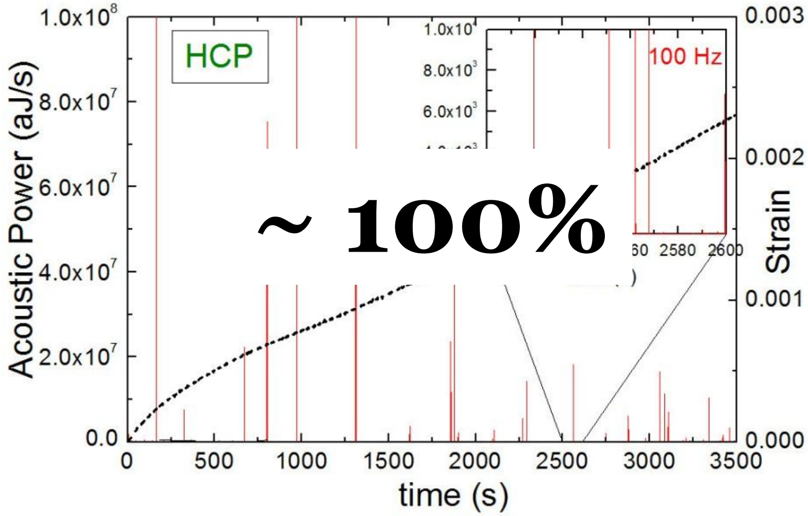
Acoustic power = sum of numerous, small, and uncorrelated motions
(**mild fluctuations**)

⇒ Energies (instead of amplitudes) add up

$$\frac{dE}{dt} \sim \dot{\varepsilon}_p$$

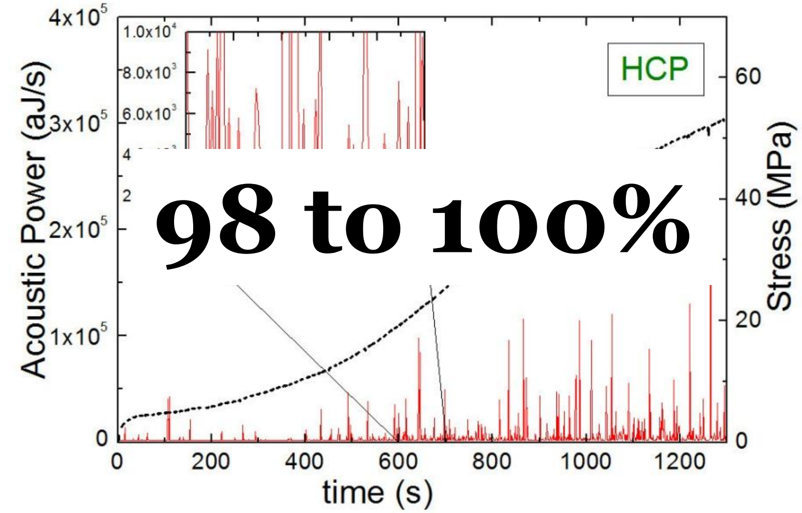


Ice

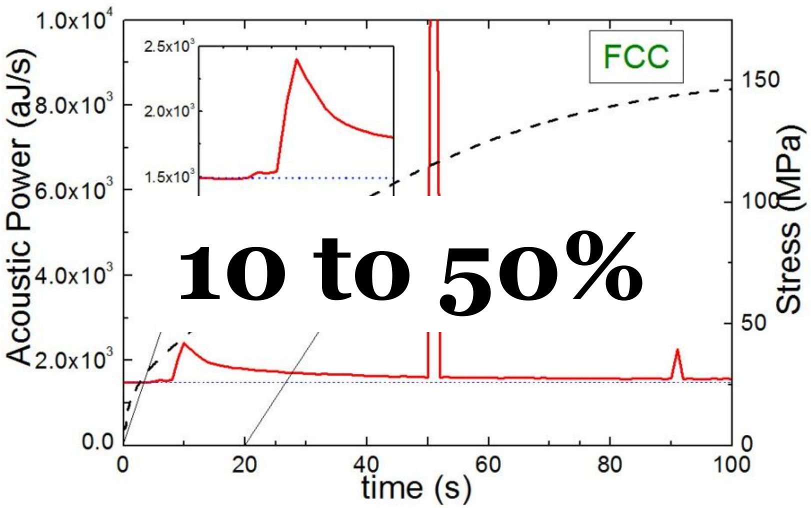


~ 100%

Cadmium

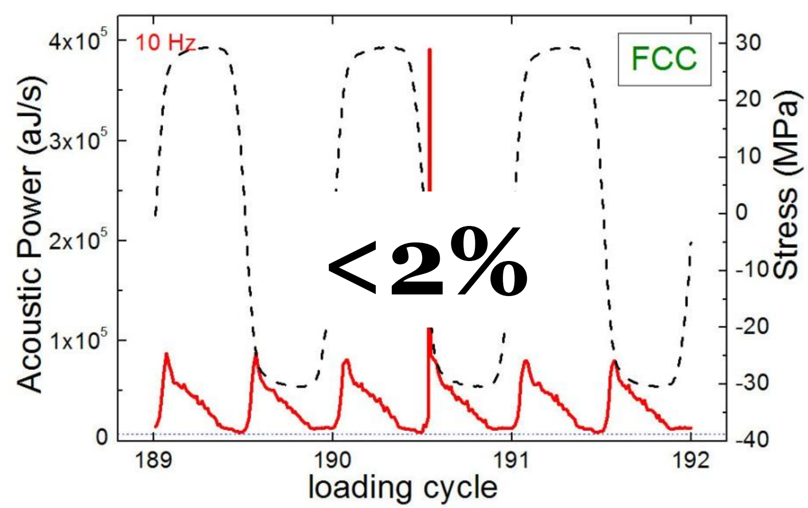


98 to 100%



10 to 50%

Copper



<2%

Aluminum

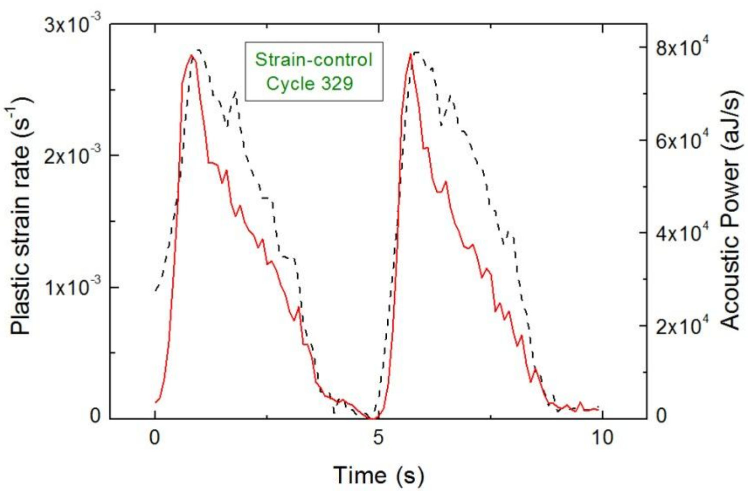
Is continuous AE the signature of **mild** fluctuations ?

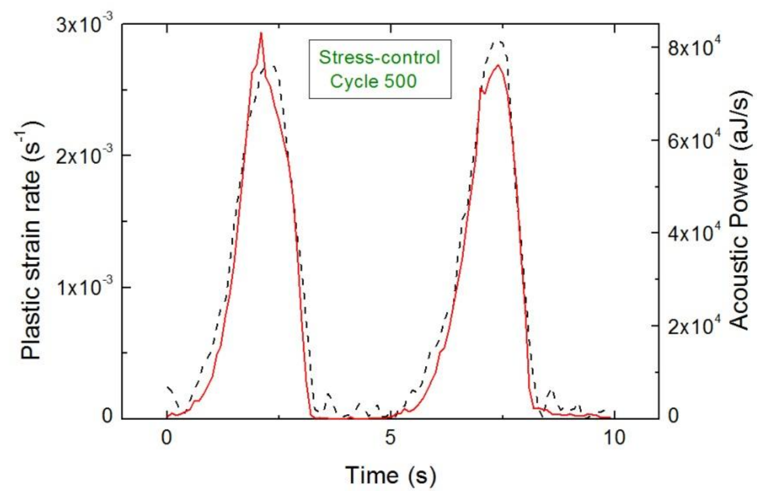
Continuous AE as the result of classical plasticity

(Rouby et al., 1983; Slimani et al., 1992)

Acoustic power = sum of numerous, small, and uncorrelated motions
(**mild fluctuations**)

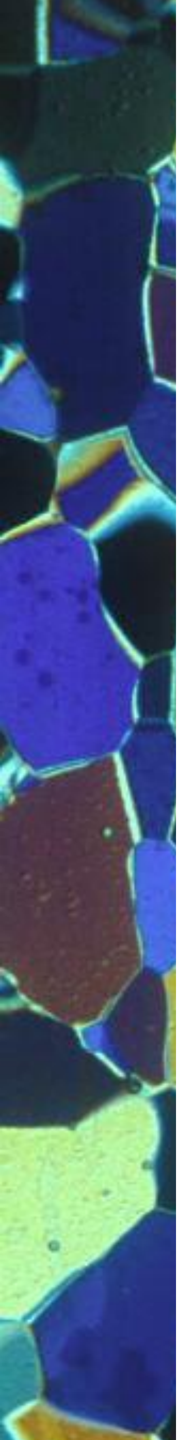
$$\frac{dE}{dt} \sim \dot{\varepsilon}_p$$

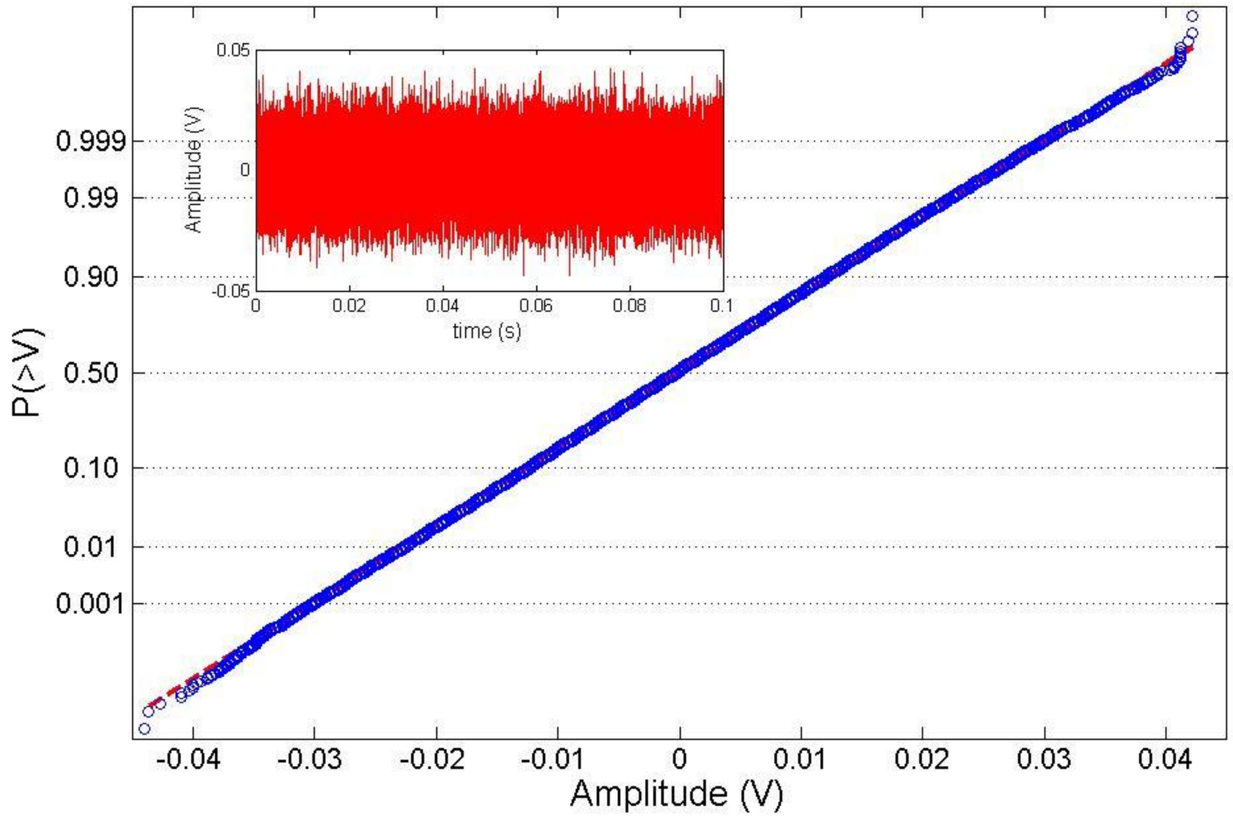




Cyclic loading of Aluminum

Acoustic "noise" analysis



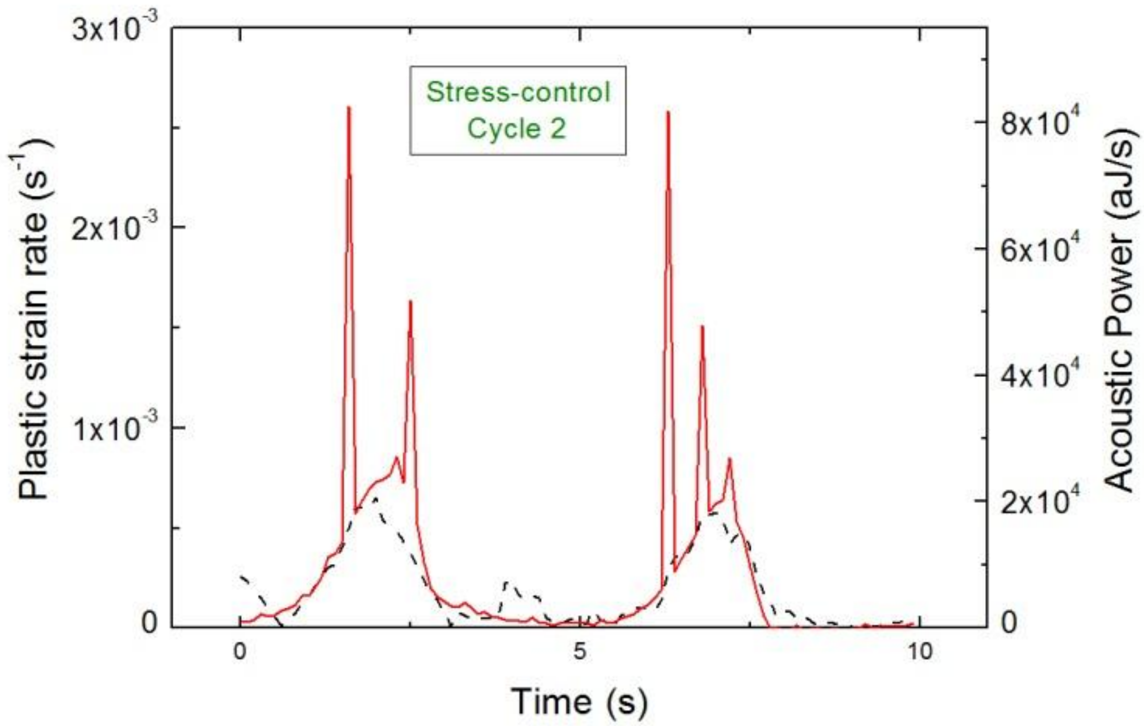


- Gaussian distribution of local maxima
  (skewness $\zeta = 0.02$, excess kurtosis $\kappa = -0.27$)

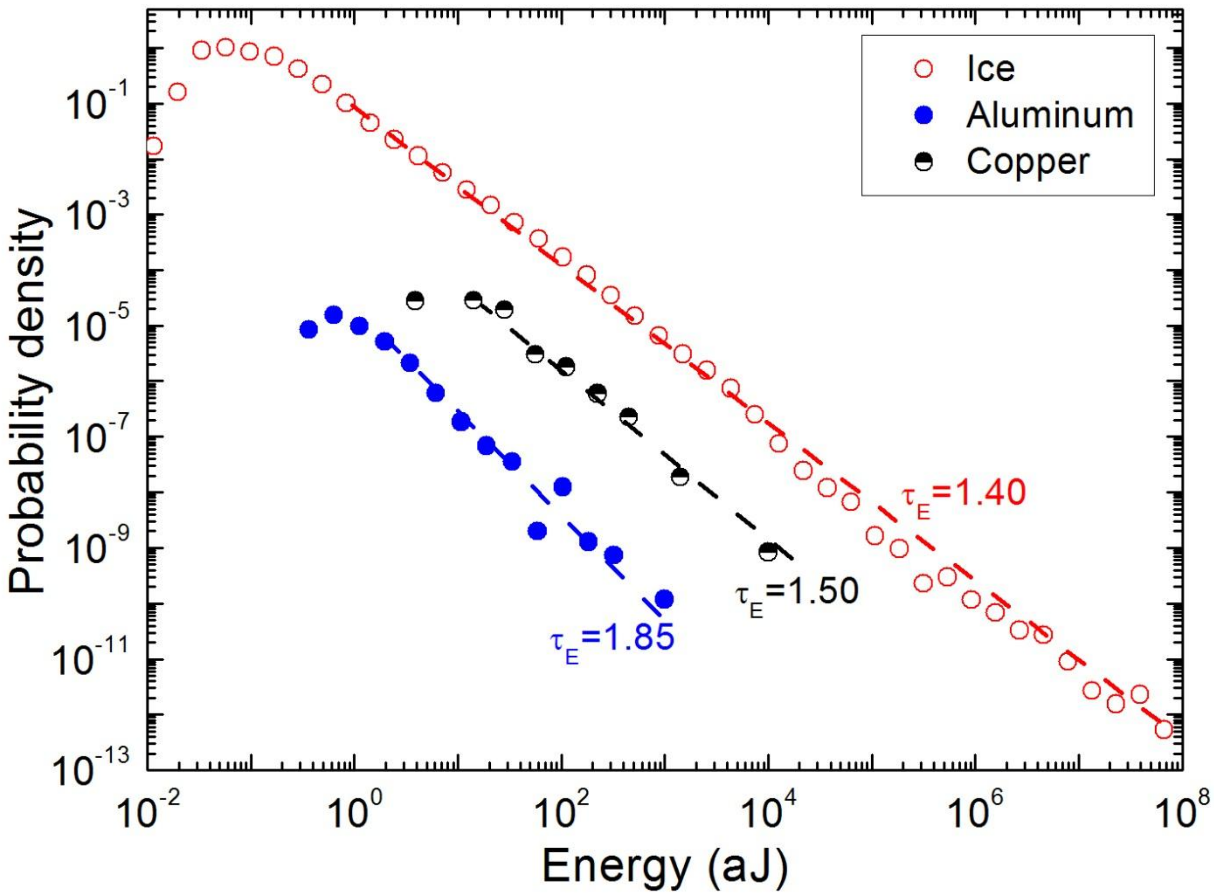
- Multifractal analysis → No significant intermittency

⇒ All the attributes of gaussian noise

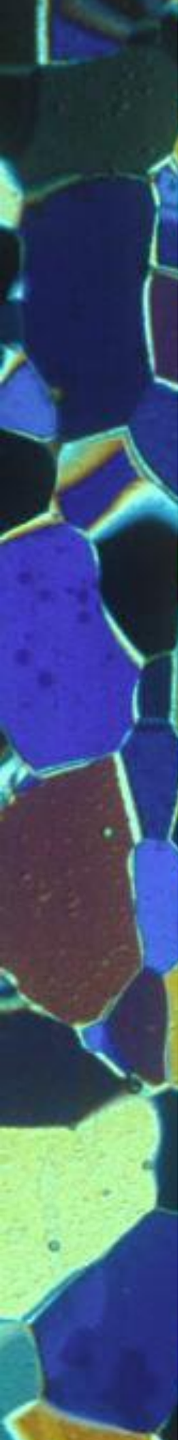
Coexistence of continuous emission and acoustic bursts



Power law statistics of avalanches

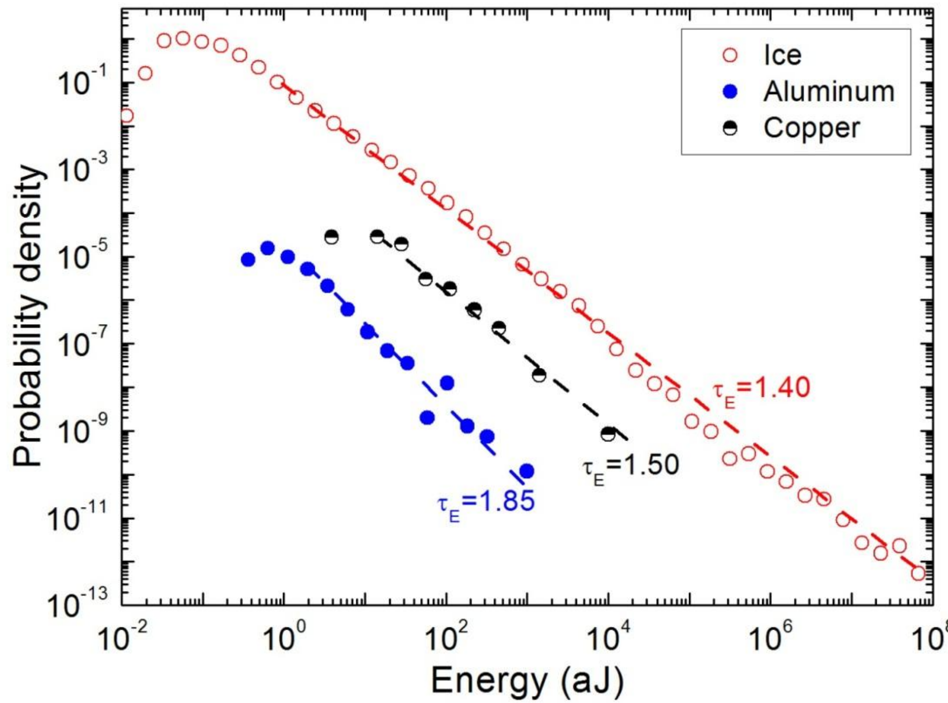


→ Wild and mild fluctuations can coexist



Non universal exponent

(determined from a maximum likelyhood method; Clauset et al., 2009)



Ice → Cadmium → Copper → Aluminum

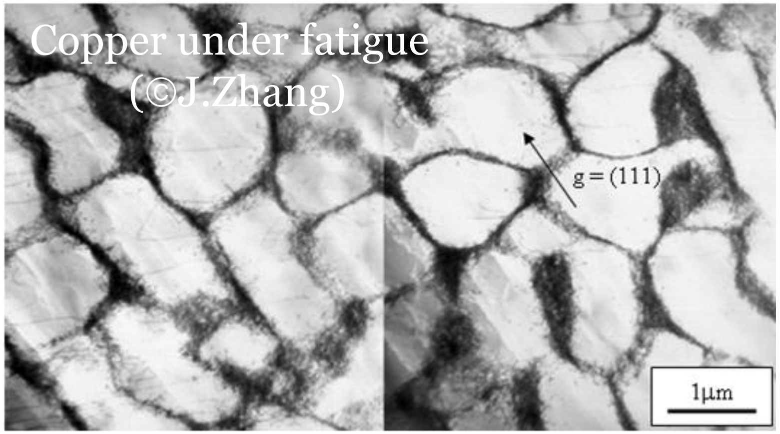
$<\tau_E>$ = 1.4±0.03 → 1.45 ±0.05 → 1.55 ±0.08 → 2.0 ±0.05

Hexagonal *vs* Face Centered Cubic

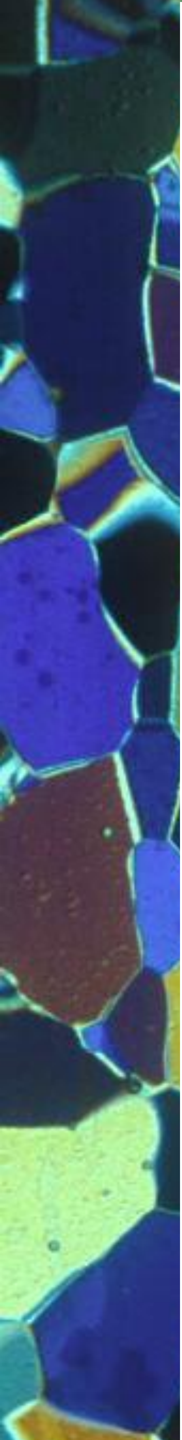
- Anisotropic glide (single-slip)
- Long-range elastic interactions dominate
- Kinematic hardening

Crackling plasticity favoured

- Isotropic glide (multi-slip)
- Short-range interactions
- Isotropic hardening
- Pattern formation



« Gaussian » plasticity favoured



A simple model

Deterministic equation: $d\rho_m/d\gamma = a - c\rho_m$

a: nucleation rate
c: multiplication / annihilation rate
γ: controlled strain

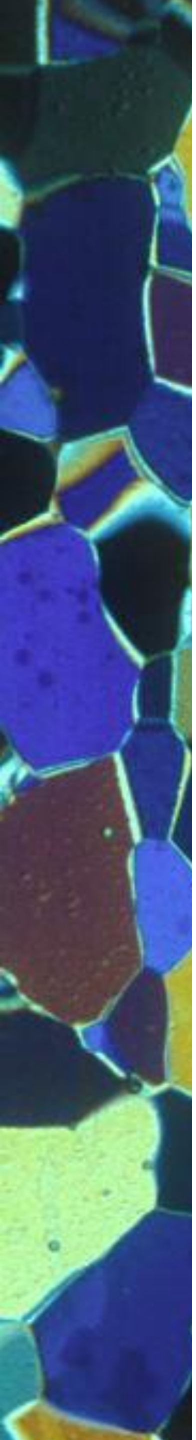
→ Evolution towards an equilibrium density $\rho_c = a/c$

Stochastic equation:

$$\frac{d\rho_m}{d\gamma} = a - c\rho_m + \sqrt{2D}\,\xi(\gamma)$$

ξ: internal "noise" $\langle \xi(\gamma) \rangle = 0, \langle \xi(\gamma_1), \xi(\gamma_2) \rangle = \delta(\gamma_1 - \gamma_2)$
D: intensity parameter ("effective temperature")

→ Gaussian fluctuations only



A simple model

Starting point: $d\rho_m/d\gamma = a - c\rho_m$

Gaussian fluctuations only: $\dfrac{d\rho_m}{d\gamma} = a - c\rho_m + \sqrt{2D}\,\xi(\gamma)$

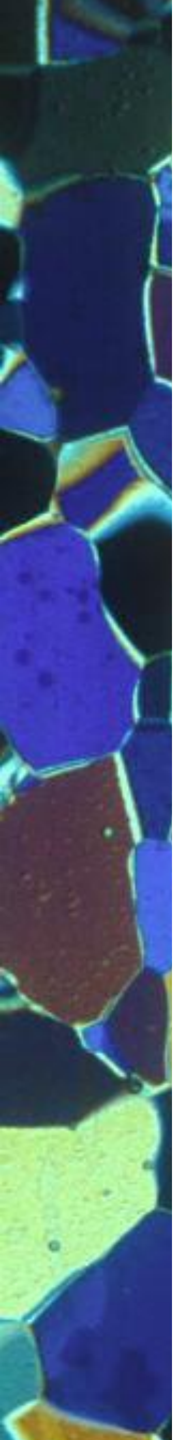
Multiplicative noise: dislocations react *collectively* to perturbations

$$\frac{d\rho_m}{d\gamma} = a - c\rho_m + \sqrt{2D}\rho_m\xi(\gamma)$$

$$p(\rho_m) \sim exp\left(-\frac{a}{D\rho_m}\right){\rho_m}^{-\left(1+\frac{c}{D}\right)}$$

Power law tail + gaussian-like distribution at small scales

The power law exponent depends on *c/D*



Interpretation of data

Exponent from the model

$$\alpha = 1 + c/D$$

Link with acoustic emission exponent

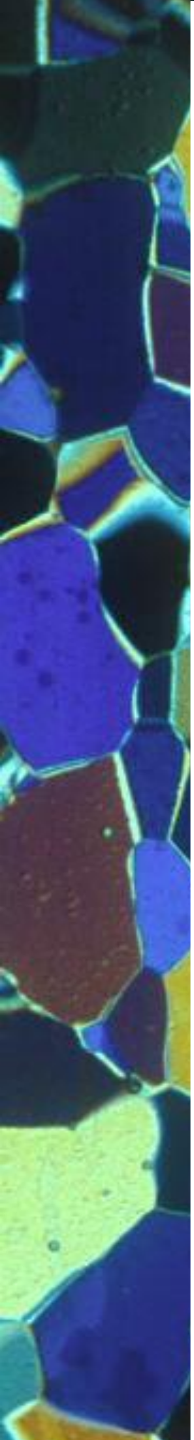
$$\alpha = \tau_A$$

Avalanche structure

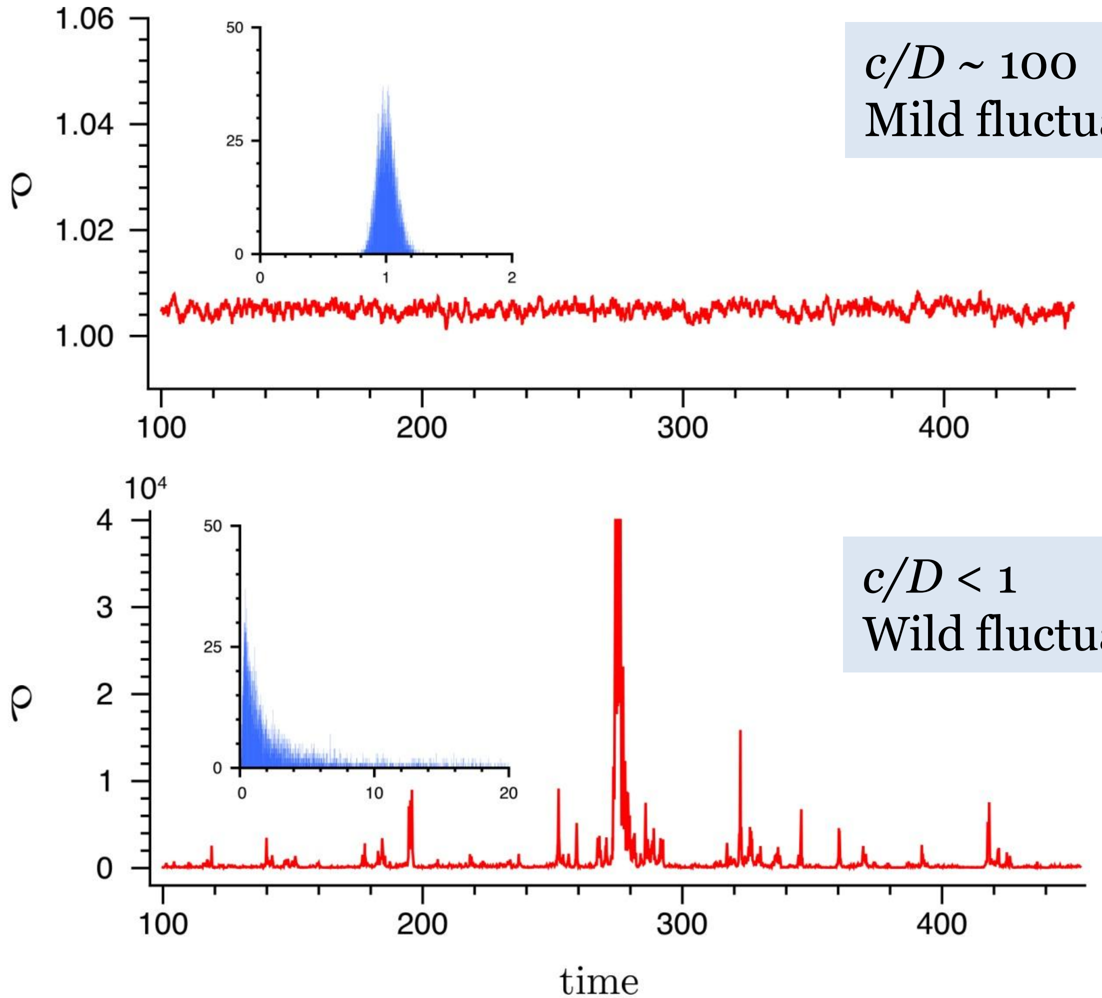
$$A_0 \sim E^{1/2}$$

$$\tau_A = 2\tau_E - 1$$

For Ice c/D is smaller than for Al



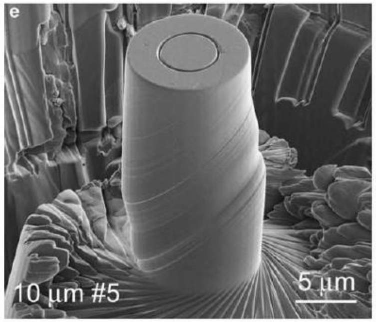
A simple model



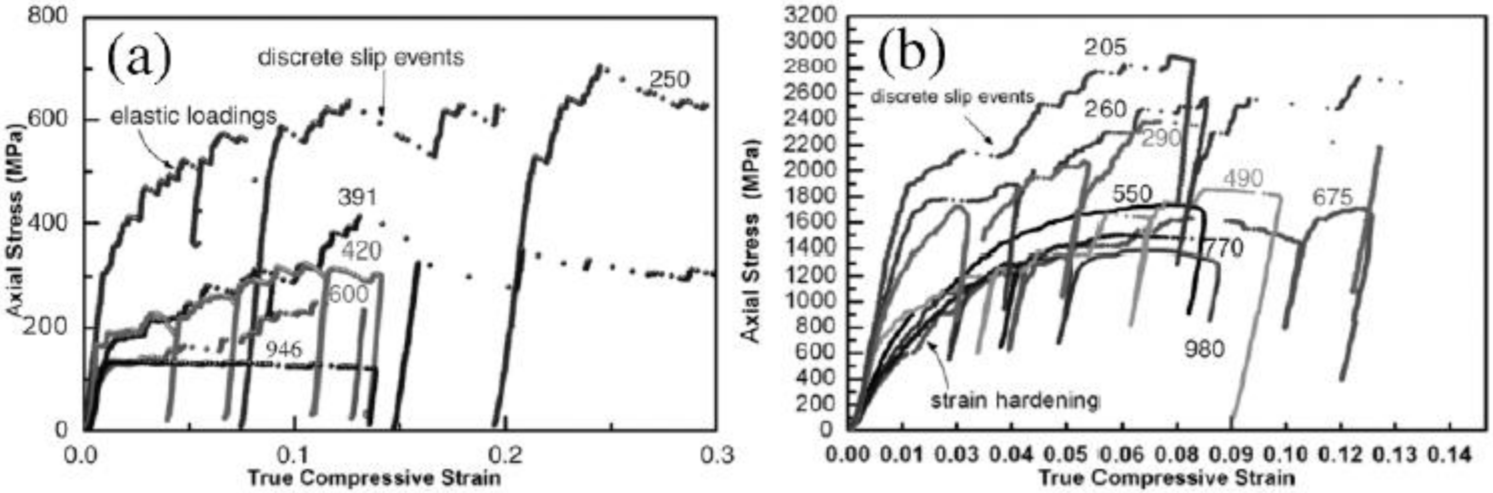
c/D ~ 100
Mild fluctuations dominate

c/D < 1
Wild fluctuations dominate

Micro- and nano-pillars



(From Brinckmann, PRL, 2008)



For non-bulk crystals $c/D \ll 1$

$\rightarrow$ intermittent plasticity even for FCC

Smaller is wilder!