Intermittent Flow in Microcrystal Plasticity

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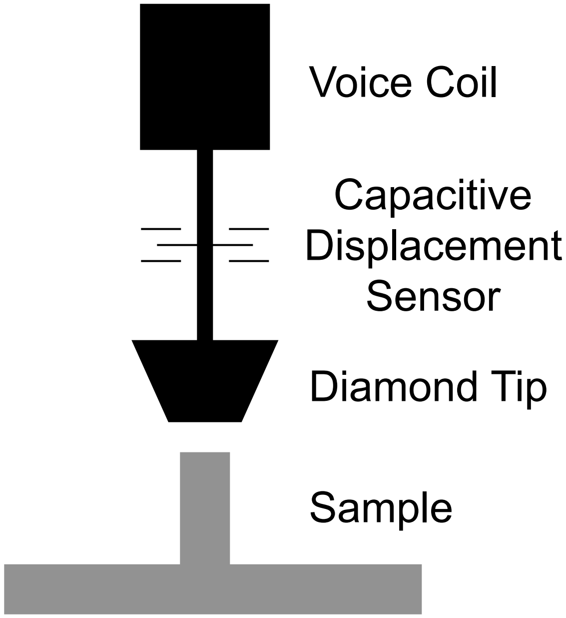
AFOSR

Outline

- Some Comments on Understanding Microcrystals
- Strain Intermittency in LiF Microcrystals (ρ_o ~$10^9/m^2$)
- Strain-Rate Effects on Intermittency in Ni Microcrystals (ρ_o ~$10^{12}/m^2$)
- Initial Studies of Strain Intermittency via 3d-DD Simulations (ρ_o ~$10^{12}/m^2$ to ρ_o ~$10^{13}/m^2$)
- Selected Current Work & Future Directions (ρ_o ~$10^{15}/m^2$)

Testing Device, Samples & Response



Attributes of Nanoindenter

Displacement range: 500 μm

" " resolution: 0.02 nm

($\Delta\varepsilon \sim 0.6\ \mu\varepsilon$)

Maximum load: 500 mN

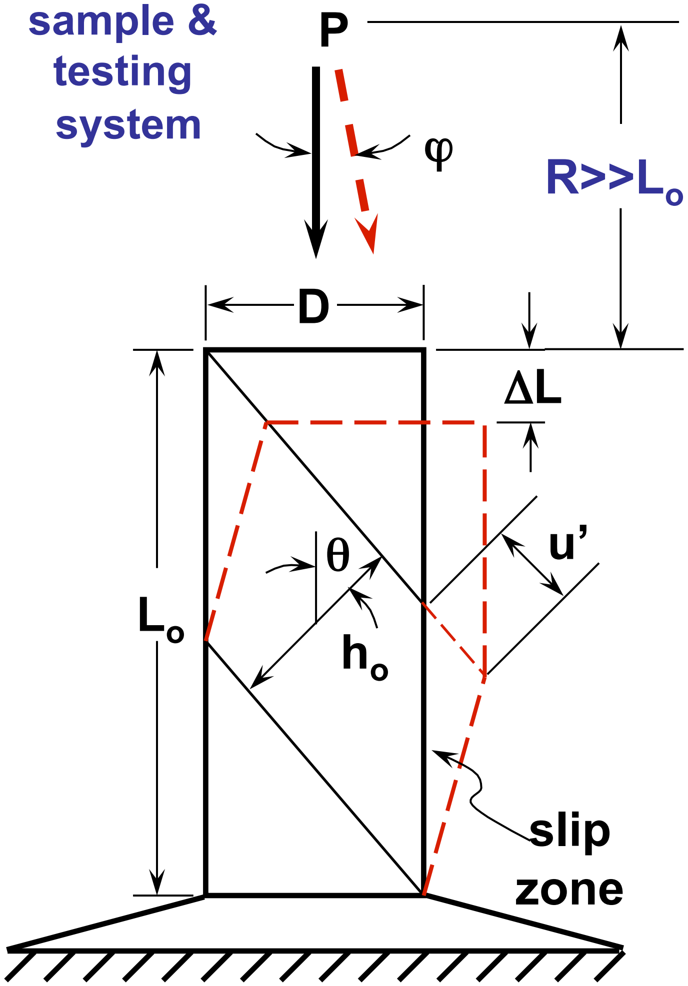
($\sigma_{max} \sim 6.3$ GPa)

Load resolution: 50 nN

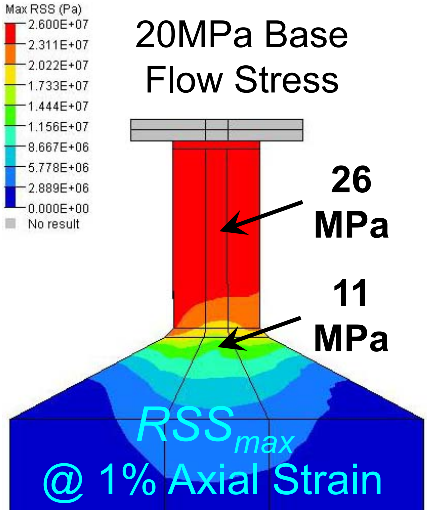
($\Delta\sigma \sim 0.0006$ MPa)

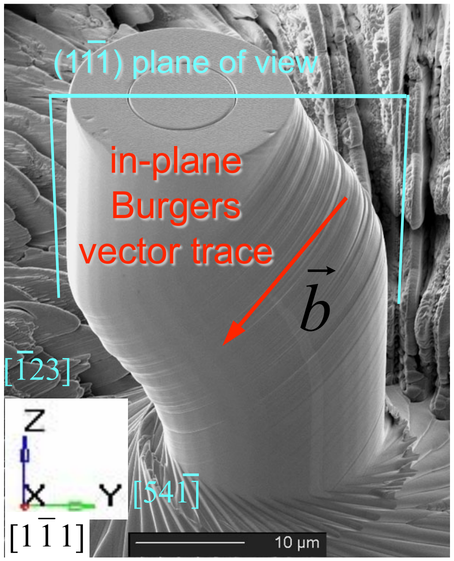
Uchic, Dimiduk, Choi, Shade, et al. (2002-present)

Schematic sample & testing system



Specimen before and after testing (2D projection)

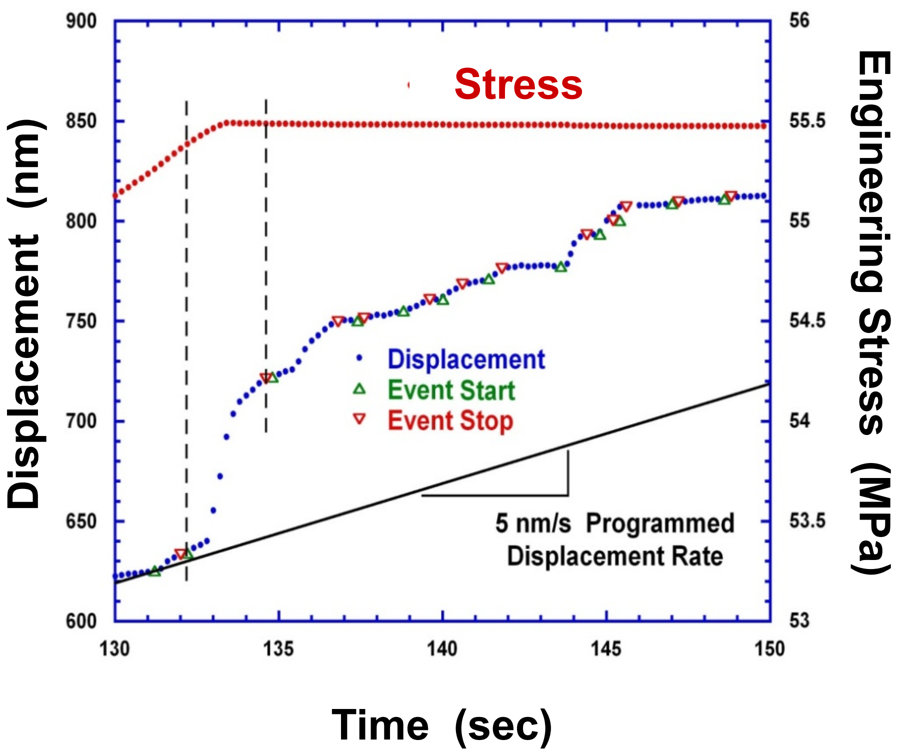


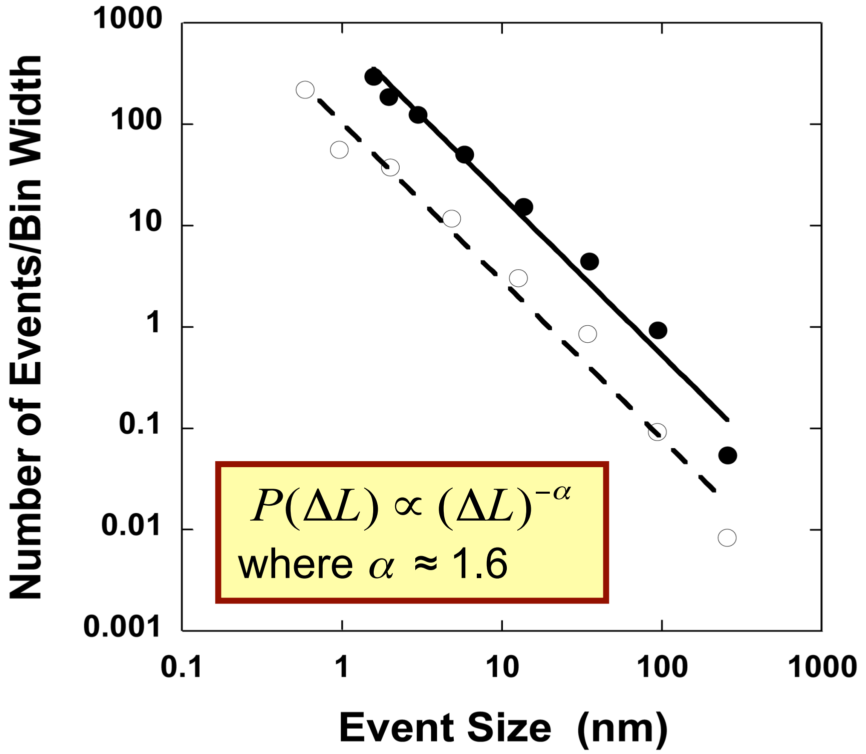


CP-FEM Simulation & SEM image 20 μm Ni sample

Intermittency & “Avalanche” Slip Events

***Pure Ni, <-269> orientation, Stage I; 9 samples, 20-30 μm dia.; $\dot{\varepsilon}$ = 1.1 x 10^{-4}/s**





- **Analysis methods somewhat ad hoc…**
- **Driving forces and control mechanisms unknown**
- **Basis for largest observed avalanche ?**
- **Temporal scaling ?**
- **Basis for stochastic plasticity framework ?**

Dimiduk, Woodward, LeSar & Uchic, *Science,* Vol. 312 (2006) 1188.

Avalanche Exponents vs Strain Rate

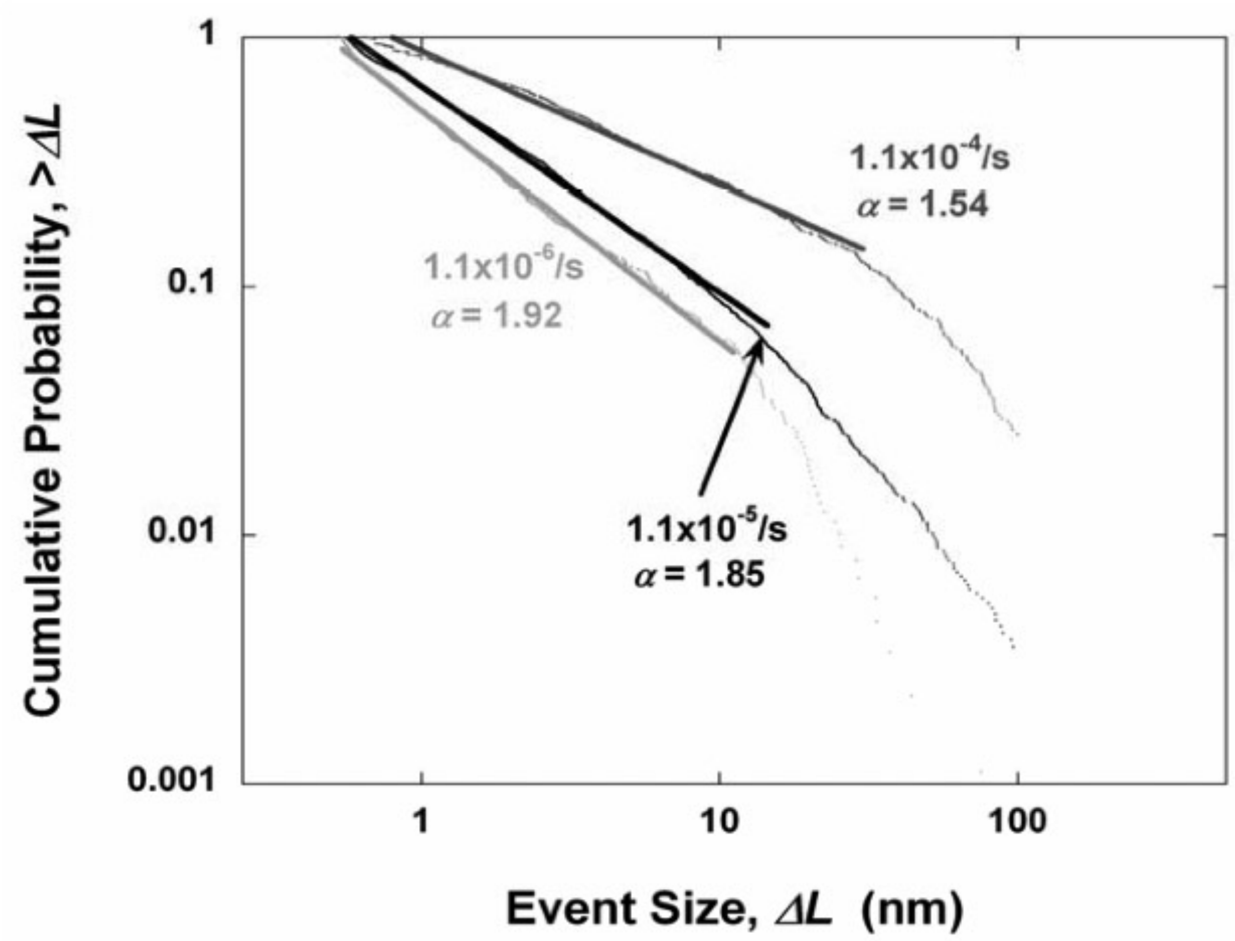


Fig. 3: Cumulative probabilities for avalanche events exceeding a given size, versus size, for three different loading rates. Data are for <-269> oriented, ~20µm diameter Ni crystals.

Dimiduk, et al., *Proc. MMM-3* (2006), *MSMSE* (2007)

Selected Issues for Dislocation Avalanches

- Large avalanches expected to contribute largest part of strain in any experiment; not seen for large specimens—why not?

- What is and what controls the avalanche cut-off (a correlation length)?
  - Zaiser, et al, (2007), Theory: X_{max} proportional to Sample 'Size' (L), Machine Stiffness (M) & Hardening Rate (Θ)
  - Weiss, et al, (2008) Experiment & Theory: X_{max} proportional to L & M; Θ does not matter

- What about other exerimental details?
  - Pole sources in microsamples (few limits on X_{max})
  - Variations in initial dislocation density?
  - Creep loading excludes M (nearly constant far-field driving force)
  - For low dislocation density, Θ tends to zero

  … X_{max} in small samples may only be limited by test boundary conditions

- Strain rate effects in 'rate-insensitive' FCC metals?

Demands better analysis methods & better models/simulations

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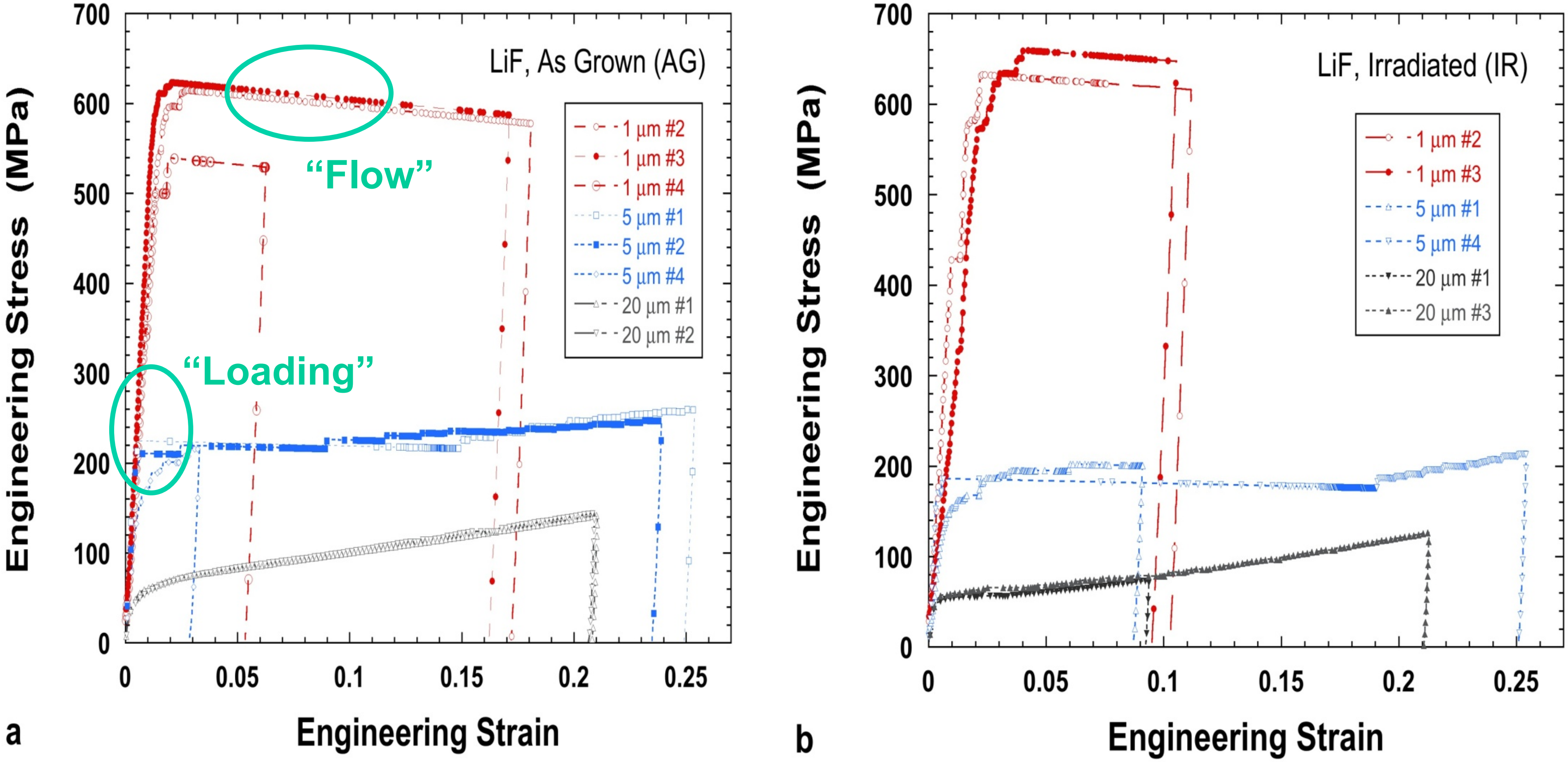
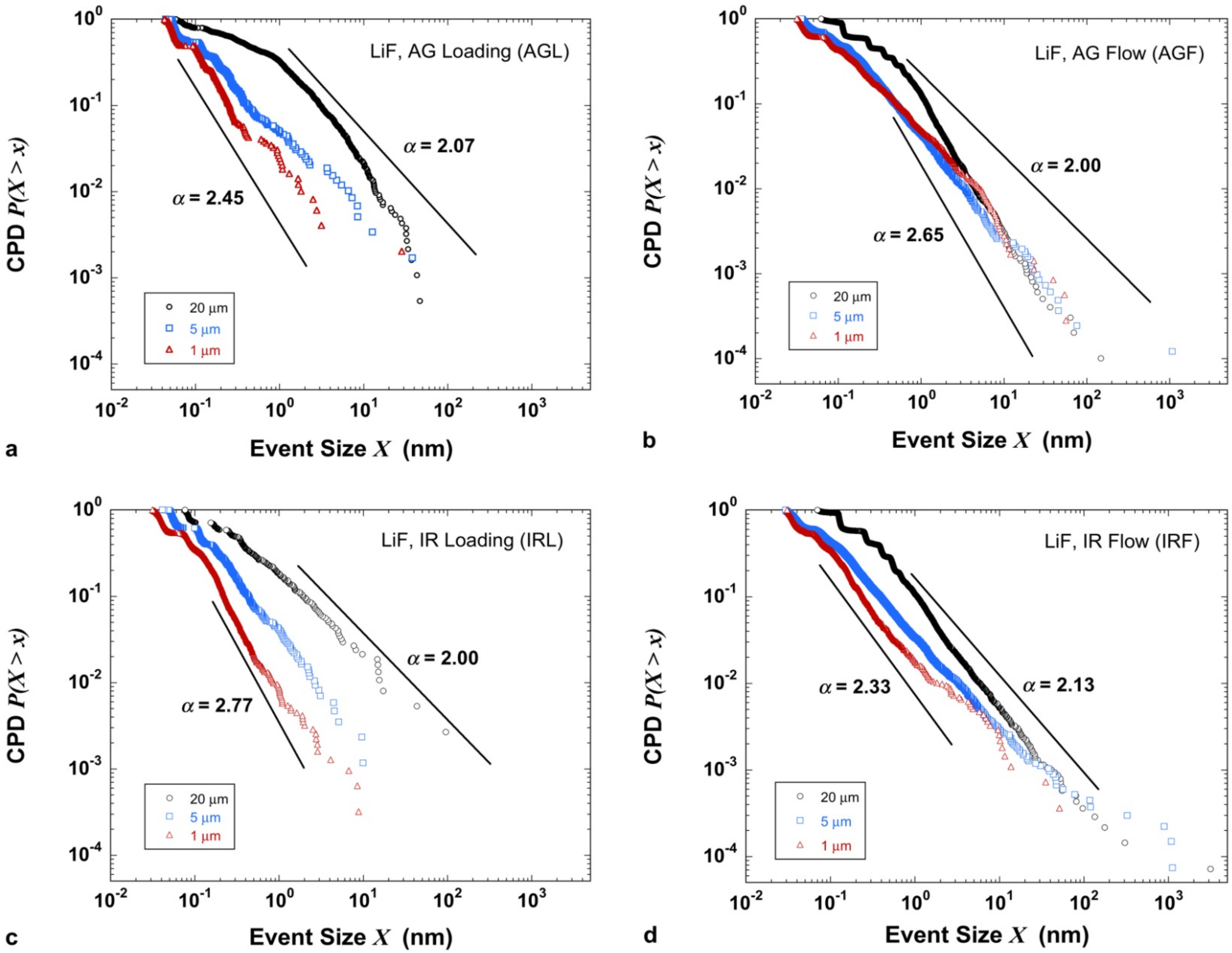
LiF Microcrystal Stress-Strain Curves



Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Platen Displacement Burst (Size) Probability

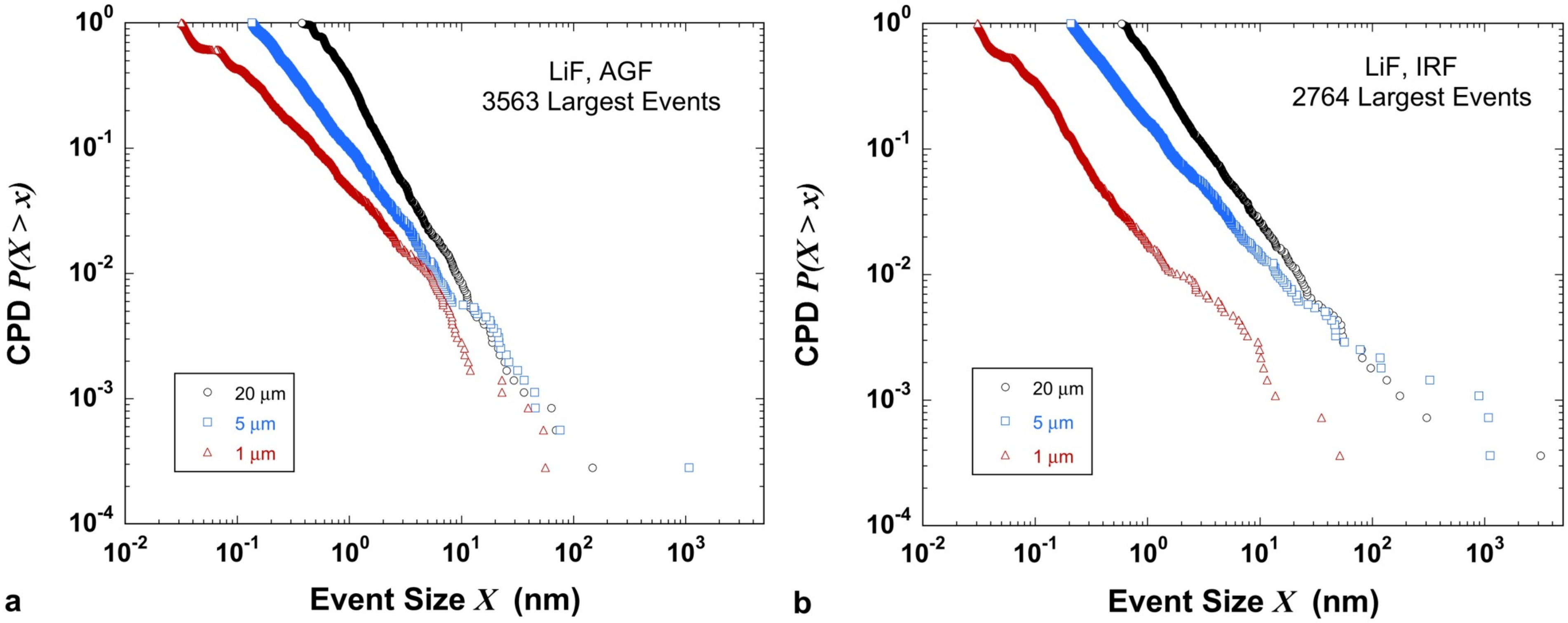


Well-behaved power laws, MLE scaling exponents consistently >1.5

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Sample Size Effect on Strain Bursts

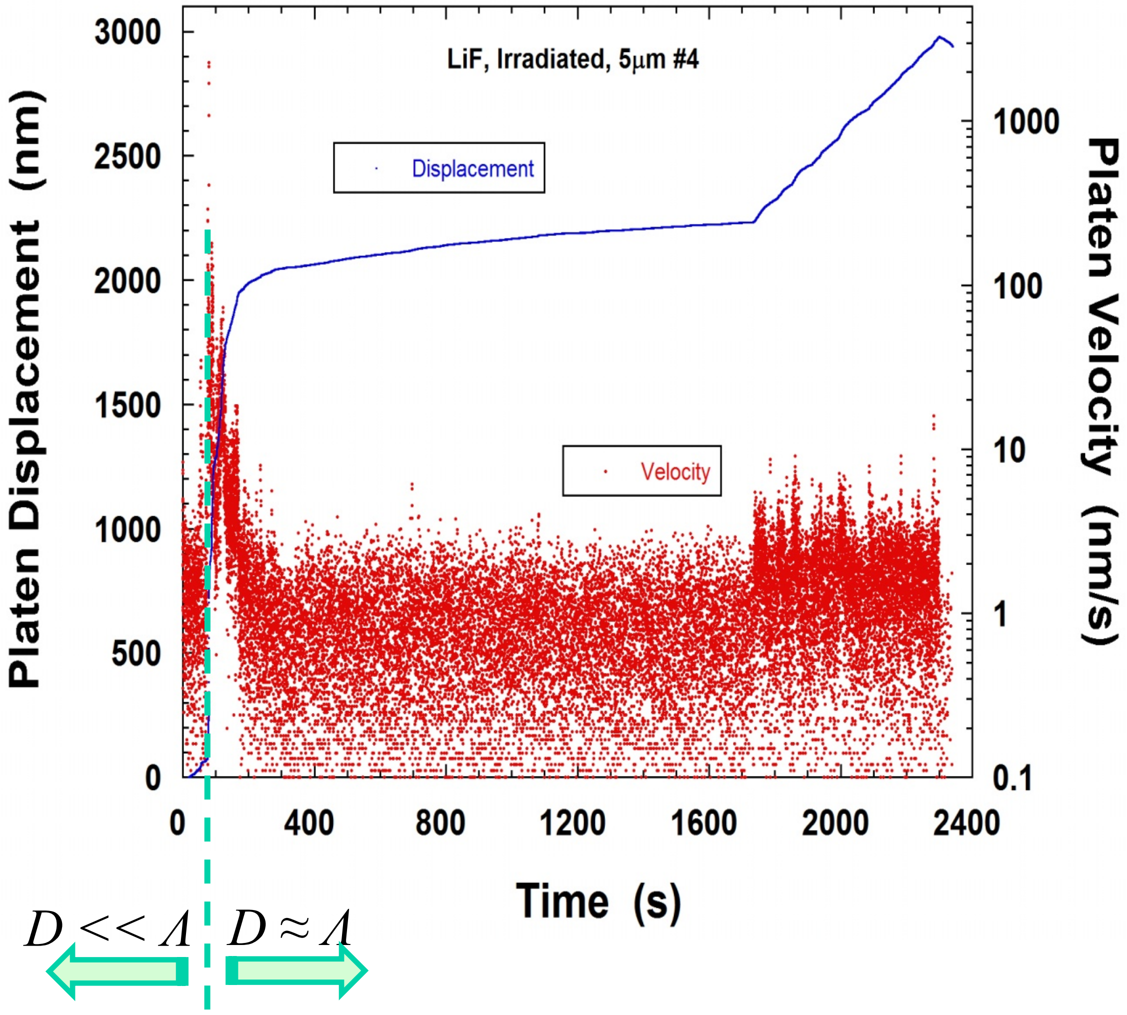
Normlized rank order statistics

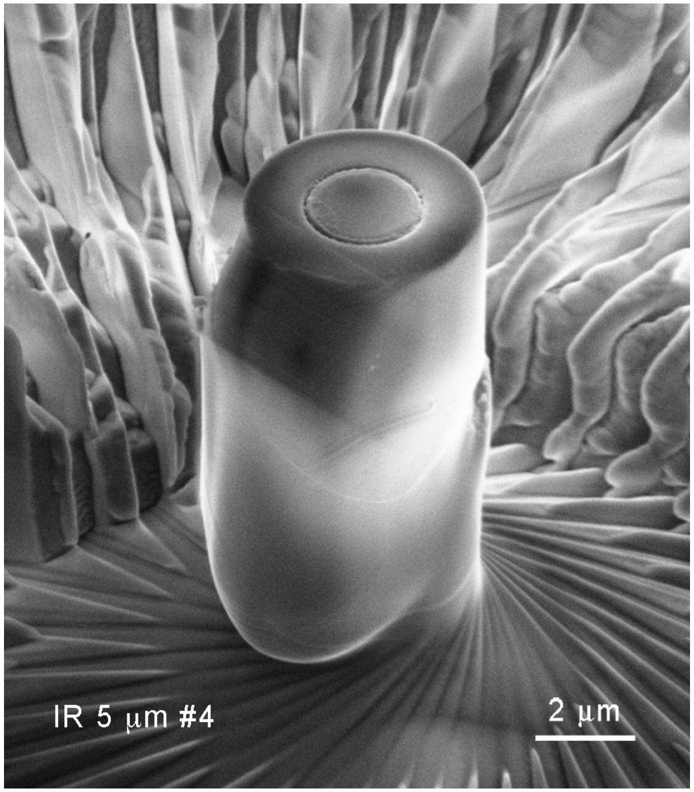


- Probability of events at a given size decreases in small samples
- Probability of maximum size not so different
- Scaling exponents tend to decrease slightly for small samples

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Largest Strain Events in LiF: $\rho_o < 10^9/m^2$



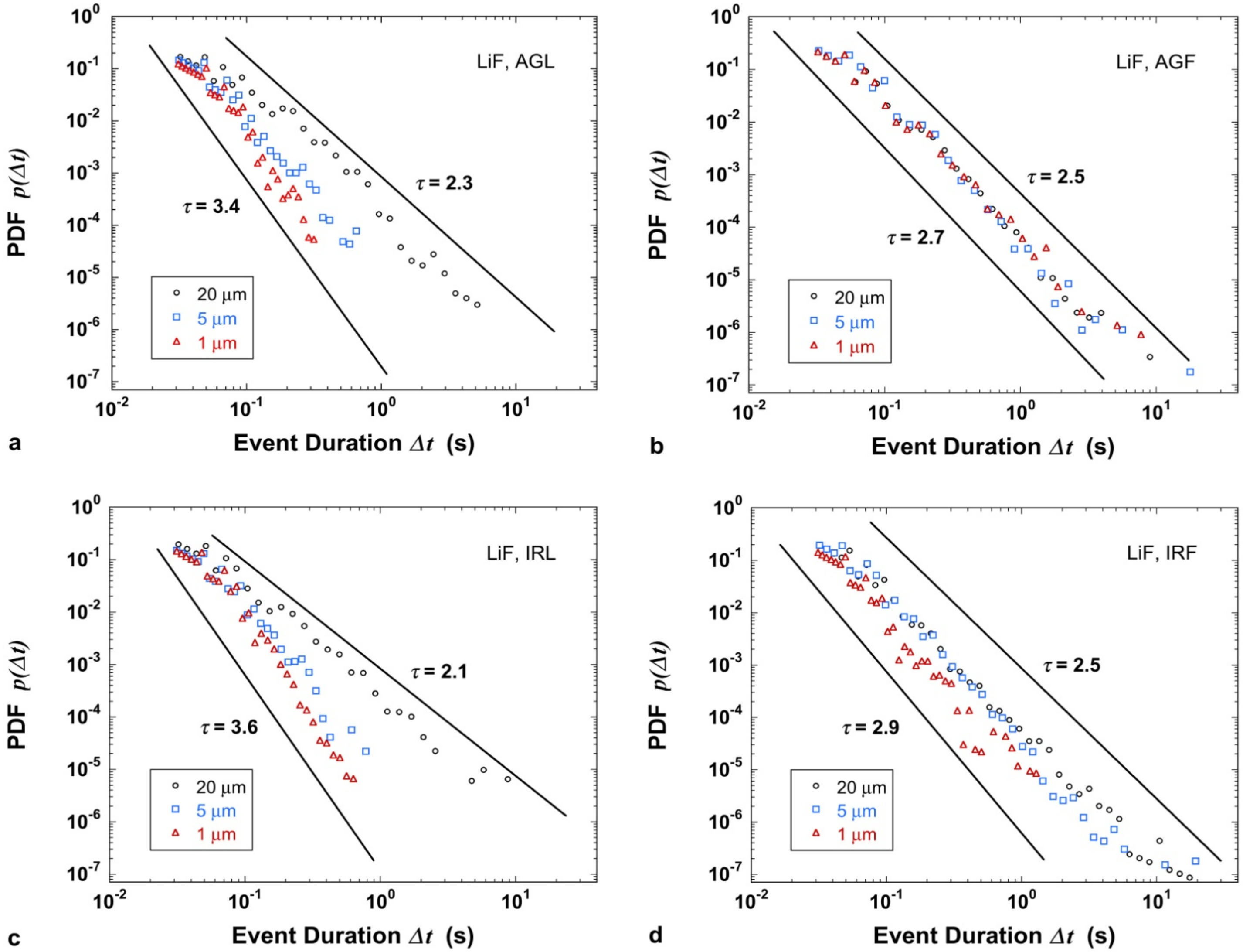


Intersecting slip zones in deformed microcrystal

Large bursts occur at transition from “multiplication limited” loading to flow

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

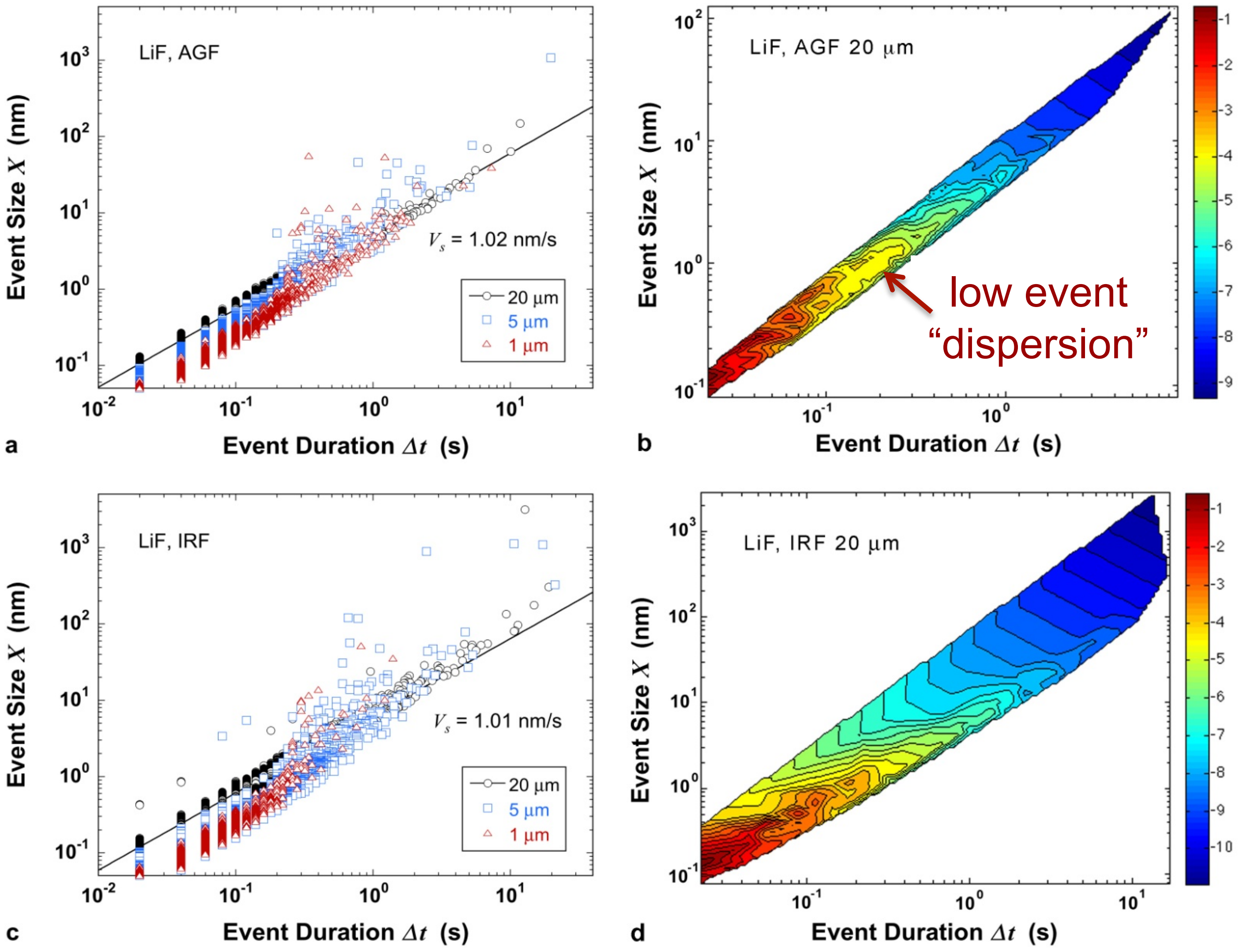
LiF Strain Burst Durations Also Show Scaling



Duration power law scaling exponents consistently >2

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Joint Burst Size – Duration Probabilities



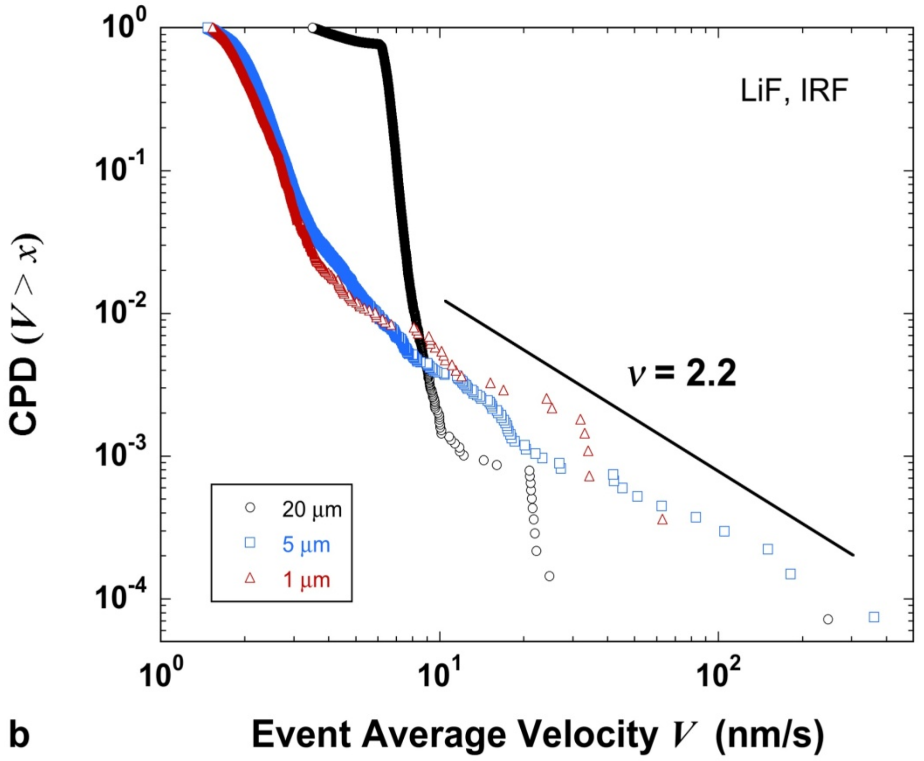
low event “dispersion”

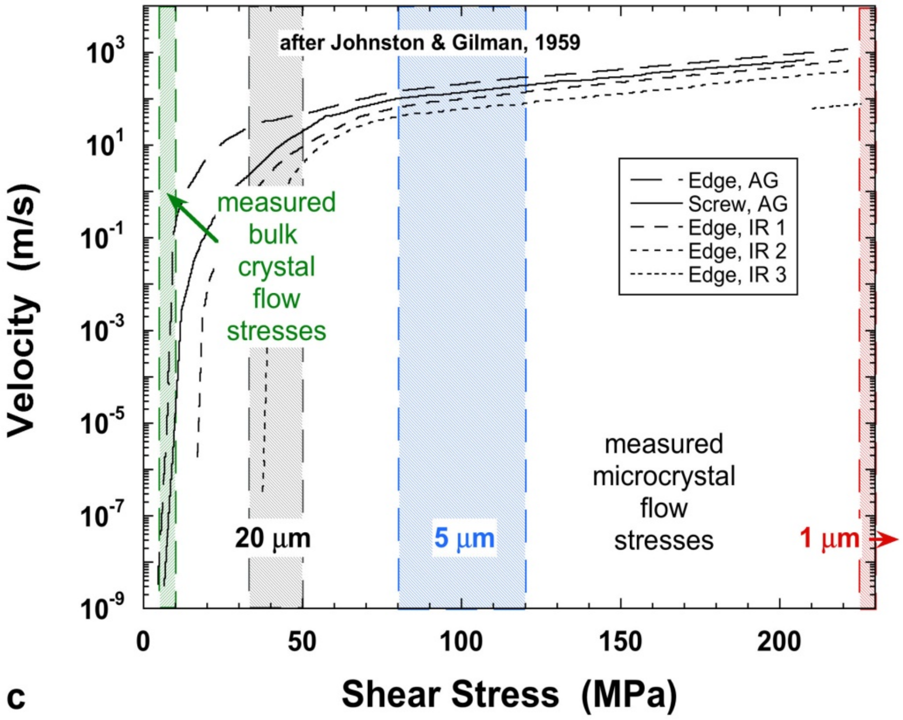
Most event sizes proportional to their duration; large events are exceptions

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Avalanche Velocity vs Dislocation Velocity

Mismatch observed between platen vs dislocation velocities

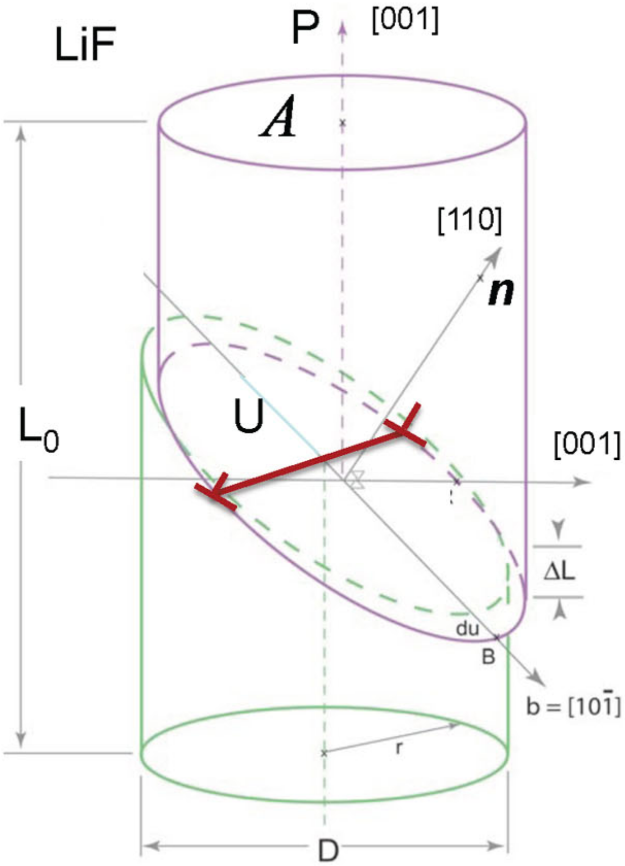




Experiments *may not* directly reveal dislocation temporal dynamics

Dimiduk, Nadgorny, Woodward, Uchic & Shade, *Philos. Mag.* (2010)

Dislocation Velocity & Platen Velocity Estimates



For single straight dislocation moving slip distance, U

$$D = 2.015 \text{ x } 10^{-6} \text{ m}$$

$$U = 2.85 \text{ x } 10^{-6} \text{ m}$$

$$dU = |b| = 2.85 \text{ x } 10^{-10} \text{ m}$$

$$\boxed{v_d = 2.85 \text{ m/s}}$$

Time for displacement ΔL

$$t_U = U / v_d = 1 \text{ x } 10^{-6} \text{ s}$$

$$\Delta L = |b| / \sqrt{2} = 2.015 \text{ x } 10^{-10} \text{ m}$$

Net platen velocity for displacement ΔL

$$v_p = \Delta L / t_U = 2.015 \text{ x } 10^{-4} \text{ m/s}$$

$$\boxed{v_p = 2.015 \text{ x } 10^{5} \text{ nm/s}}$$

For single arm source traversing circumference, C

$$C \approx 2\pi\sqrt{\frac{a^2+b^2}{2}} = 2\pi\sqrt{\frac{(2.015 \text{ x } 10^{-6})^2 + (2.85 \text{ x } 10^{-6})^2}{2}} = 1.55 \text{ x } 10^{-5}\text{m}$$

$$t_C = C / v_d = 5.44 \text{ x } 10^{-6} \text{ s}$$

$$v_p = \Delta L / t_C = 3.704 \text{ x } 10^{-5} \text{ m/s}$$

$$\boxed{v_p \approx 3.7 \text{ x } 10^{4} \text{ nm/s}}$$

Maximum measured platen velocity for 1 & 5 μm samples (50 Hz data) : ~3.7 x 10^2 nm/s

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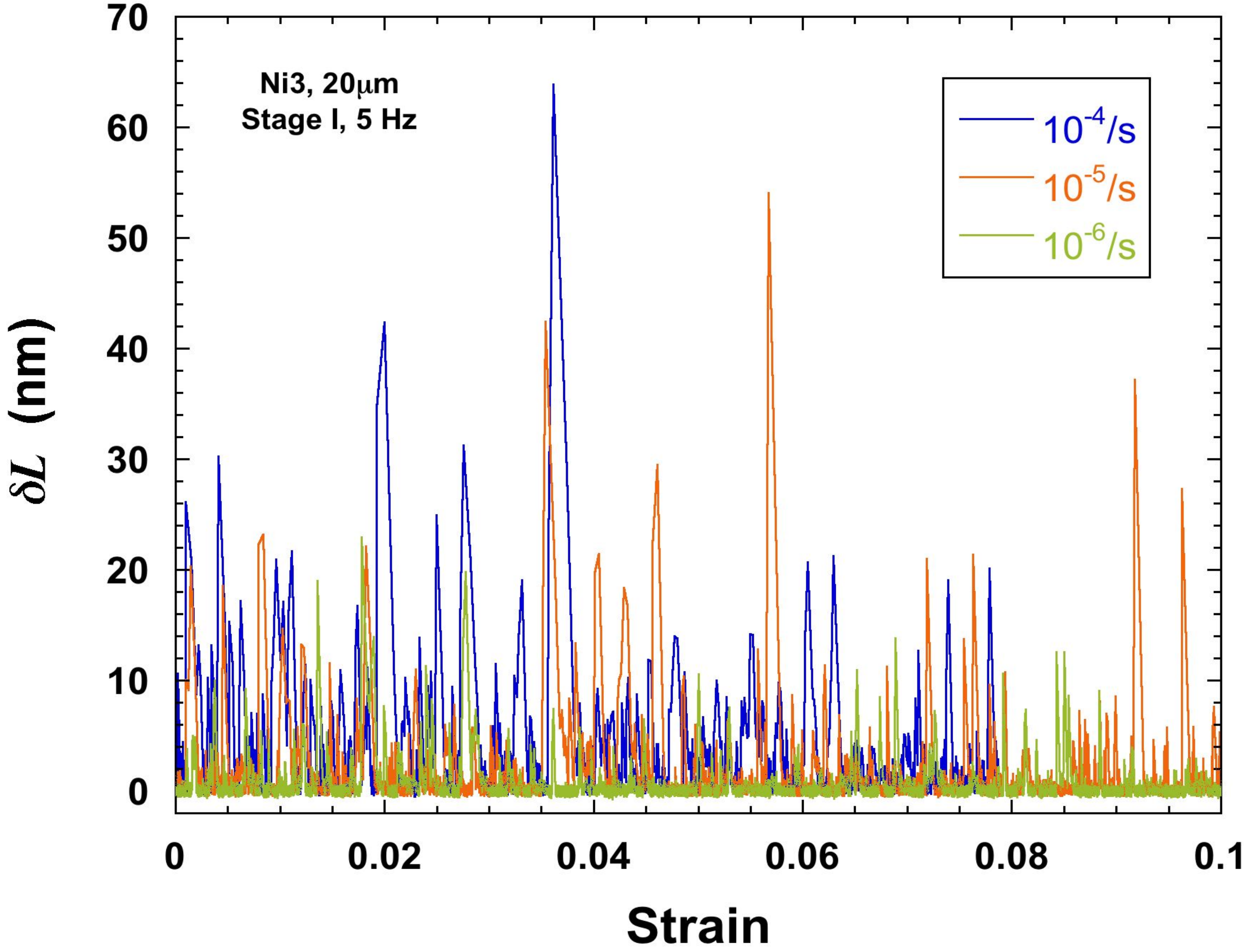
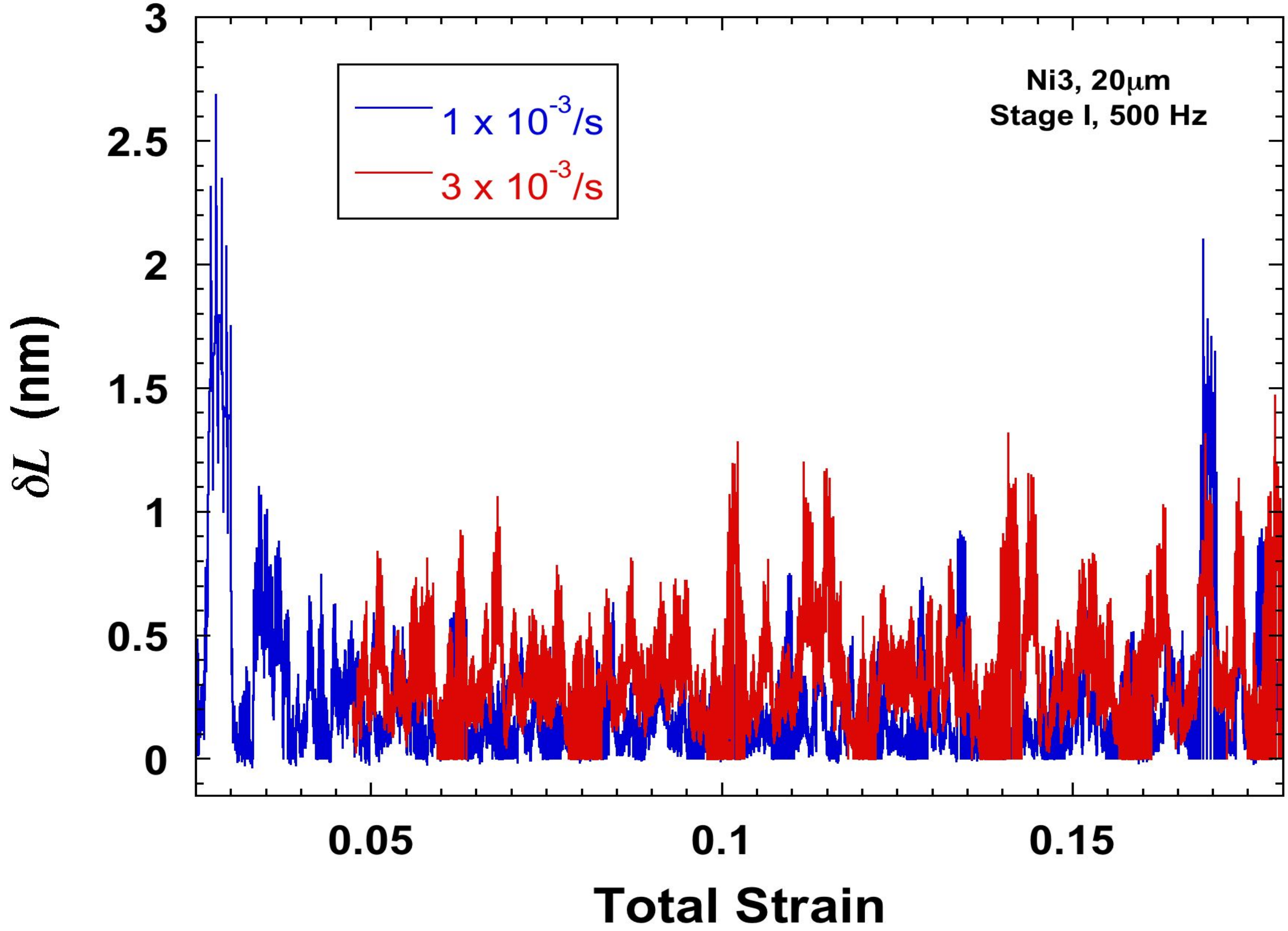
Ni Strain (Time) Series Comparisons



Qualitative differences in average & largest sizes; frequency per unit strain

Dimiduk, Nadgorny, Papanikolaou, et al. (2010) unpublished research

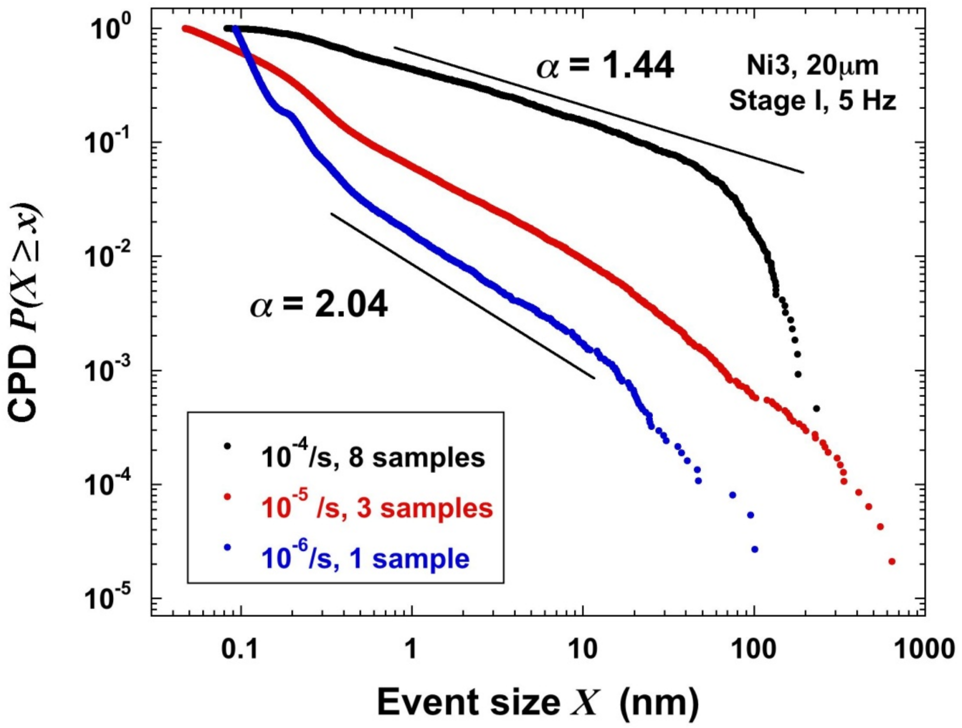
Ni Strain (Time) Series for High Strain Rates

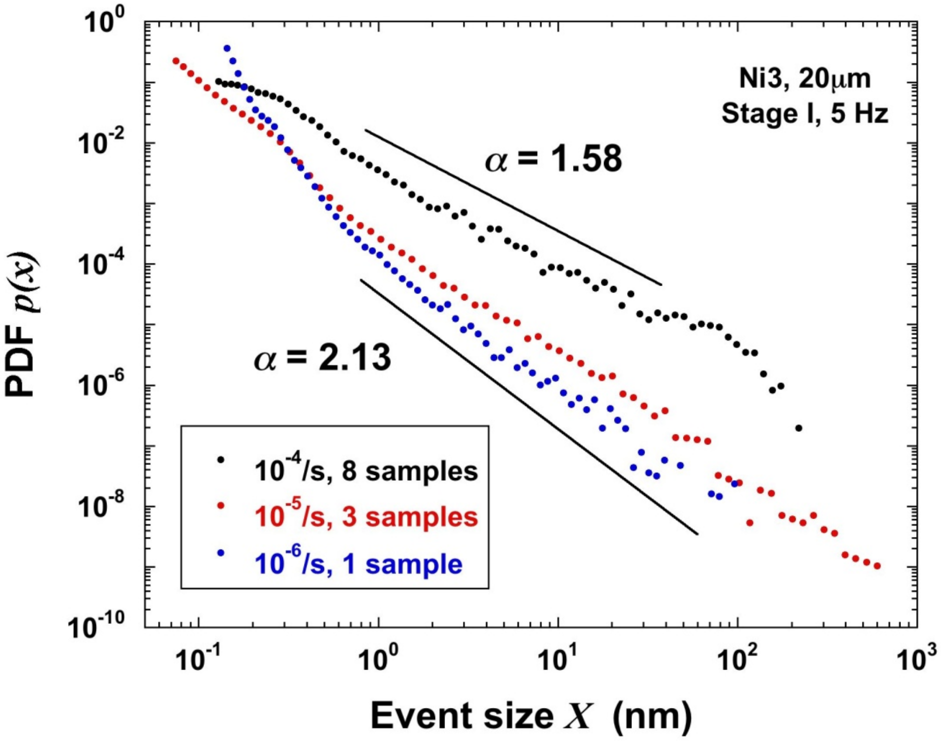


Overlapping avalanches for both strain rates

Dimiduk, Nadgorny, Papanikolaou, et al. (2010) unpublished research

Pure Ni: Effect of Strain Rate on Burst Size Scaling

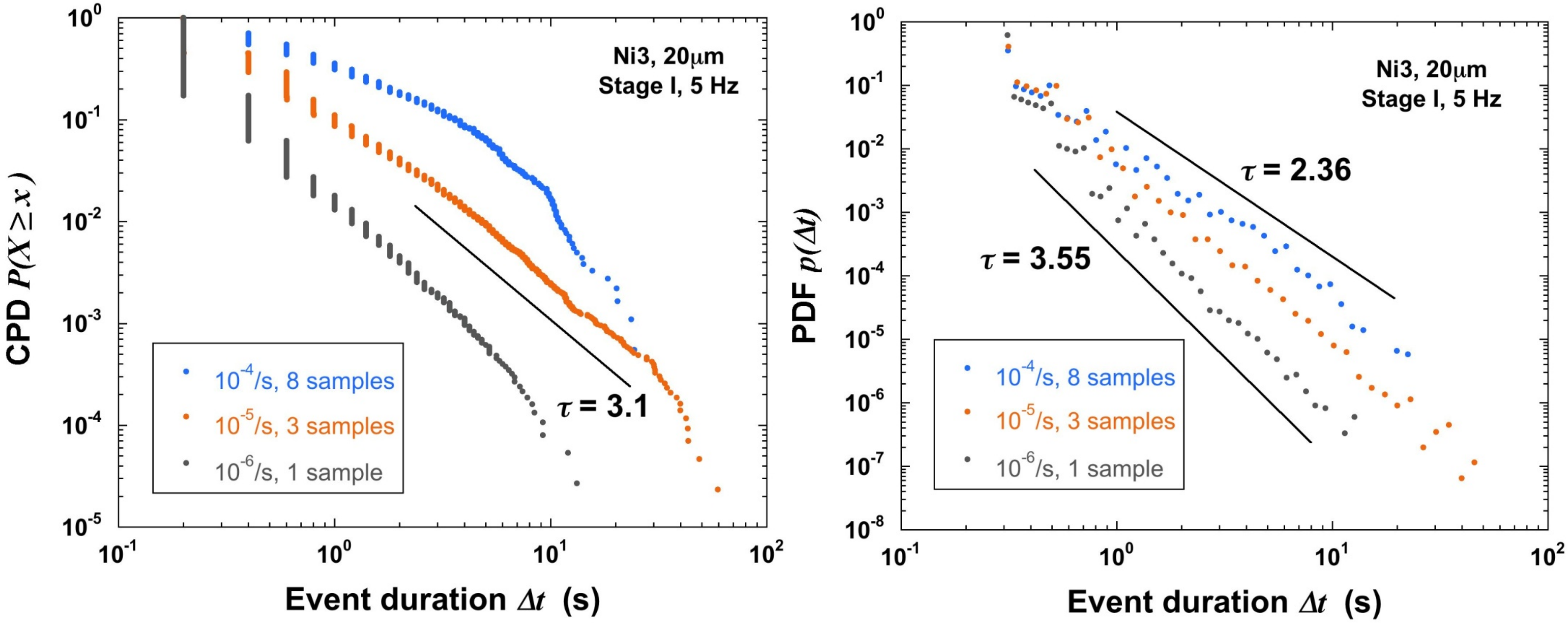




Avalanche size scaling exponents clearly rise above 1.5 at low strain rates

Dimiduk, Nadgorny, Papanikolaou, et al. (2010) unpublished research

Pure Ni: Effect of Strain Rate on Burst Durations

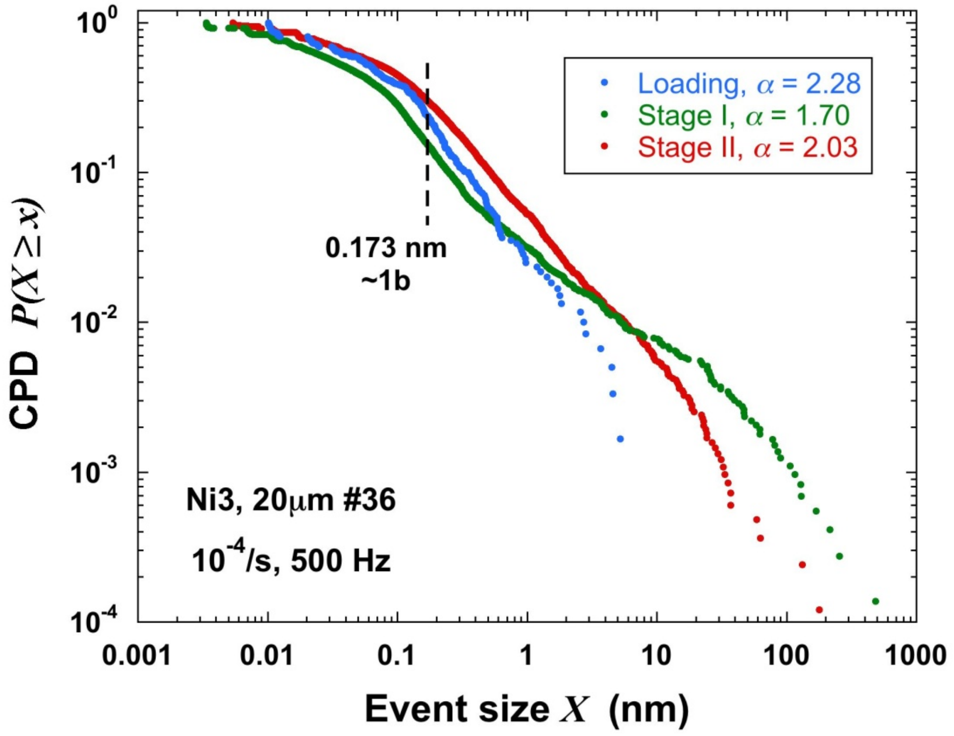


Avalanche duration scaling exponents clearly rise above 2.0 at low strain rates

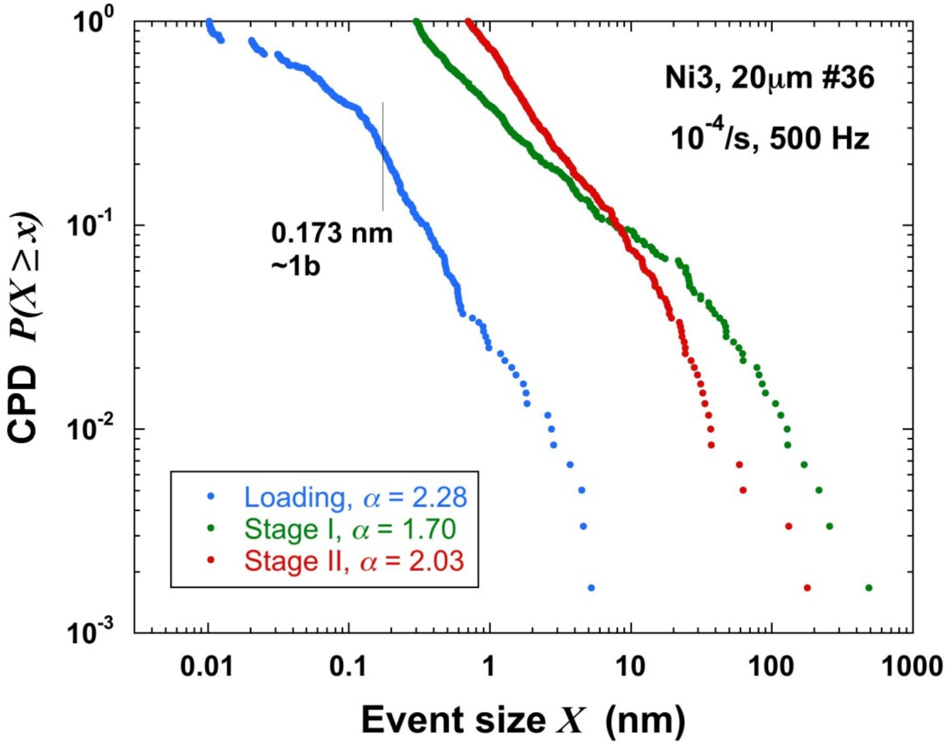
Dimiduk, Nadgorny, Papanikolaou, et al. (2010) unpublished research

Effect of Deformation Stage of Ni on Size Scaling

All avalanche events



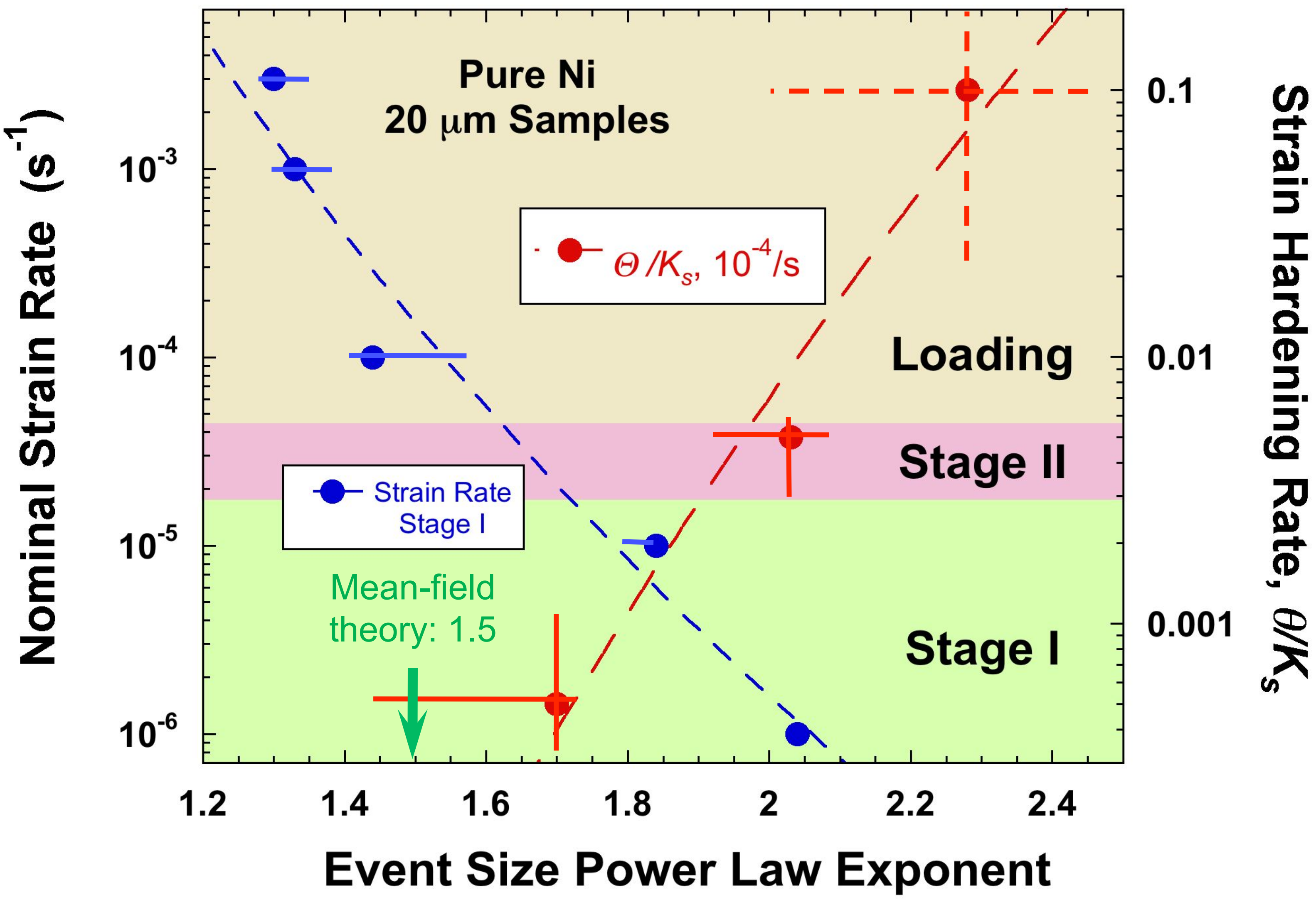
Constant N, starting from largest



Avalanche scaling exponent depends upon deformation regime

Dimiduk, Nadgorny, Papanikolaou, et al. (2010) unpublished research

Scaling Exponent vs Strain Rate & Hardening Rate



Significant deviations from mean-field theory of scale-invariance

Dimiduk, et. al., (2008-10) unpublished research

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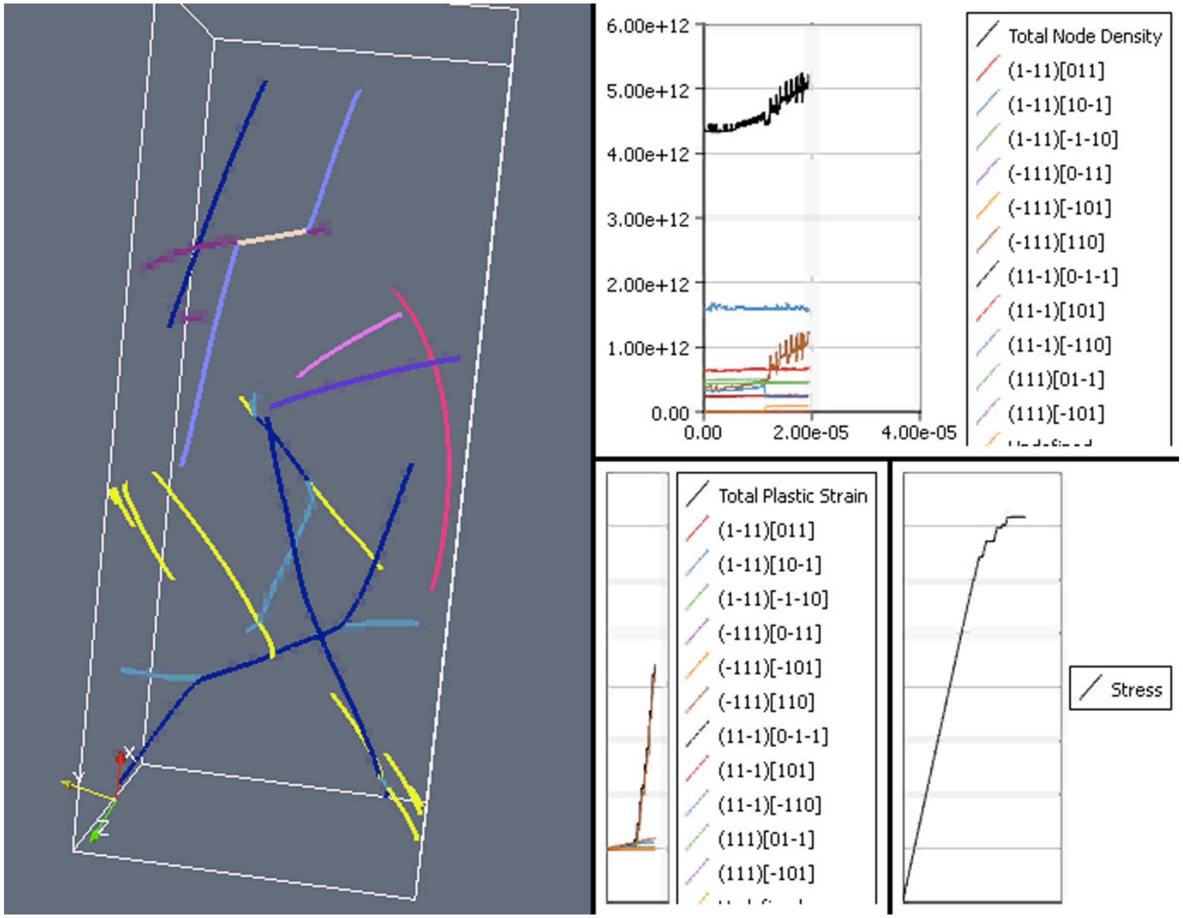
3d Dislocation Dynamics Simulations of 1μm Cells



<001>-type, 1μm cell faces, $L_o/D = 2.5$

Loading is “experimental mode” along [4-13]

Schmid factor is m = 0.471 for primary (111)[1-10]

Starting dislocation density ρ_o = ~2 x 10^{12}/m^2

$\dot{\varepsilon}$ = 50/s, parameters for Ni

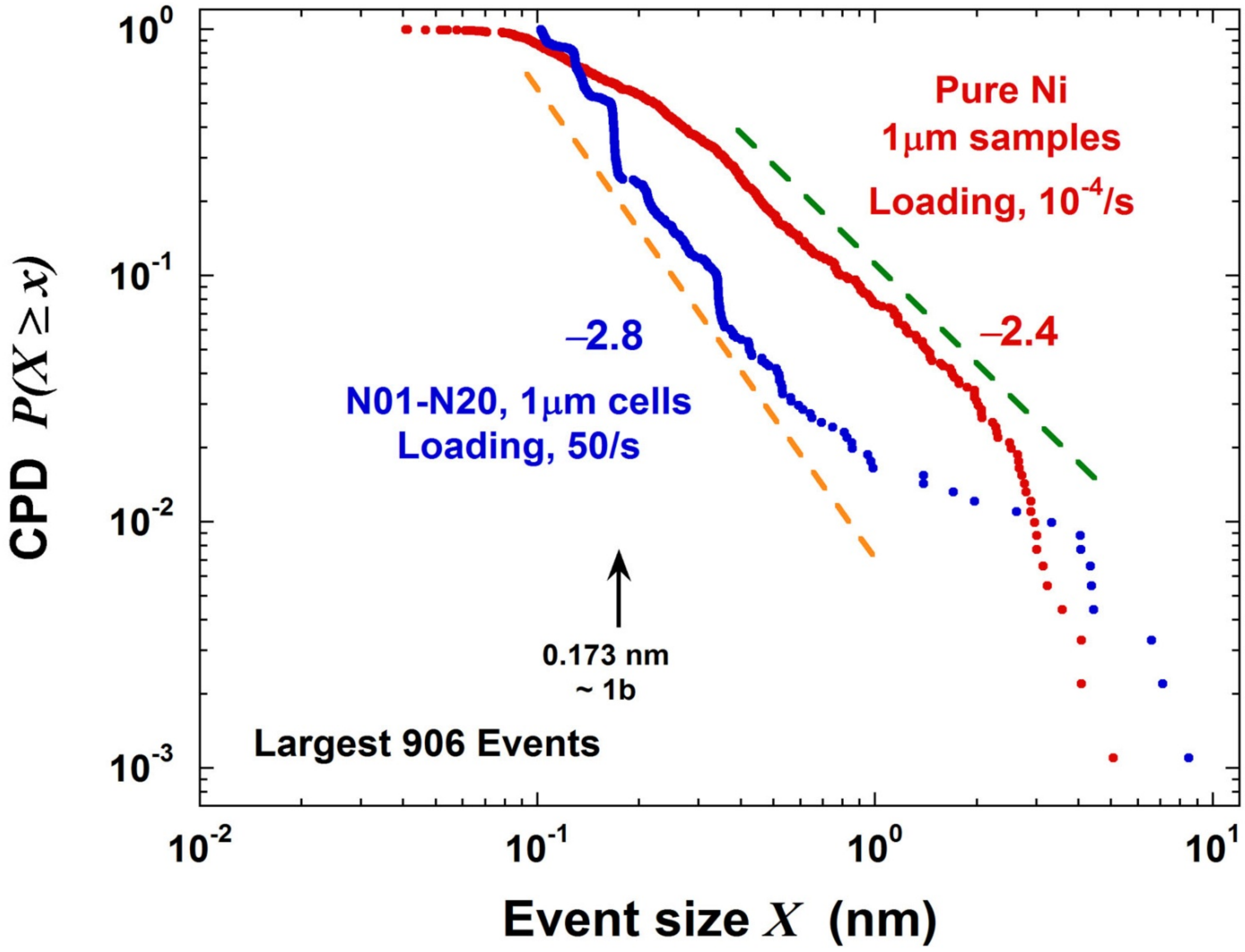
20 random instantiations

How best to “integrate” avalanche events remains an open question
Also strain rates, cross-slip models (thermal activation), strains, densities, patterns…

Rao, El-Awady, et al. (2008-11) unpublished research

3d DD Simulation & Experiment Comparison

Loading Stage (≤ ~1% Strain) Simulations & Experiment



Exponent for strain burst size compares well to experiment for loading regime

Dimiduk, Rao, etal. (2010) unpublished research

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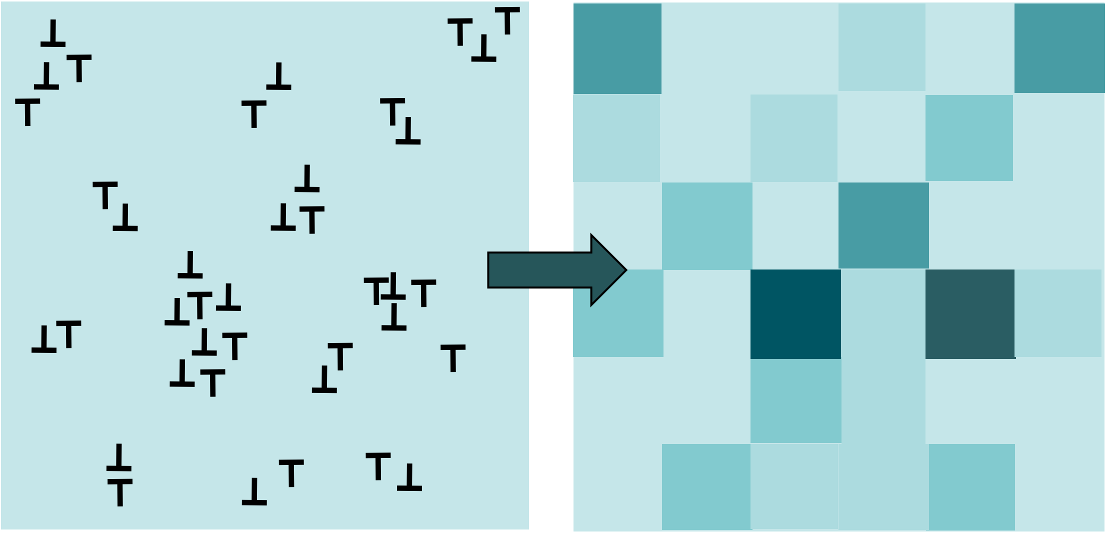
Continuum Mean Field Avalanche Theory



2d dislocation array

Continuum representation

local flow condition of element

$$\tau(\mathbf{r}) \le \tau_f(\mathbf{r},\gamma(\mathbf{r}))$$

stress outside of element

$$\tau(\mathbf{r}) = \tau_{ext} + \tau_{\text{int}}(\mathbf{r})$$

τ_{ext} = far-field applied stress

τ_{int} = long-range internal stress

Each element an “Eshlby inclusion”

Element flow stress: $\tau_f(\mathbf{r},\gamma(\mathbf{r})) = \delta\tau(\mathbf{r},\gamma) + \tau_p(\mathbf{r})$ i.e. fluctuations & ‘pile-up’ stress

Correlation function of fluctuations: $\langle \delta\tau(\mathbf{r},\gamma)\delta\tau(\mathbf{r}+\mathbf{r}',\gamma+\gamma')\rangle = \langle \delta\tau(\mathbf{r})^2 \rangle h(\mathbf{r}'/\xi) g(\gamma/\gamma_{corr})$

correlation lengths where $\xi \approx 1/\sqrt{\rho}$ & $\gamma_{corr} = b\rho\xi \approx b/\sqrt{\rho}$

Element flow condition:

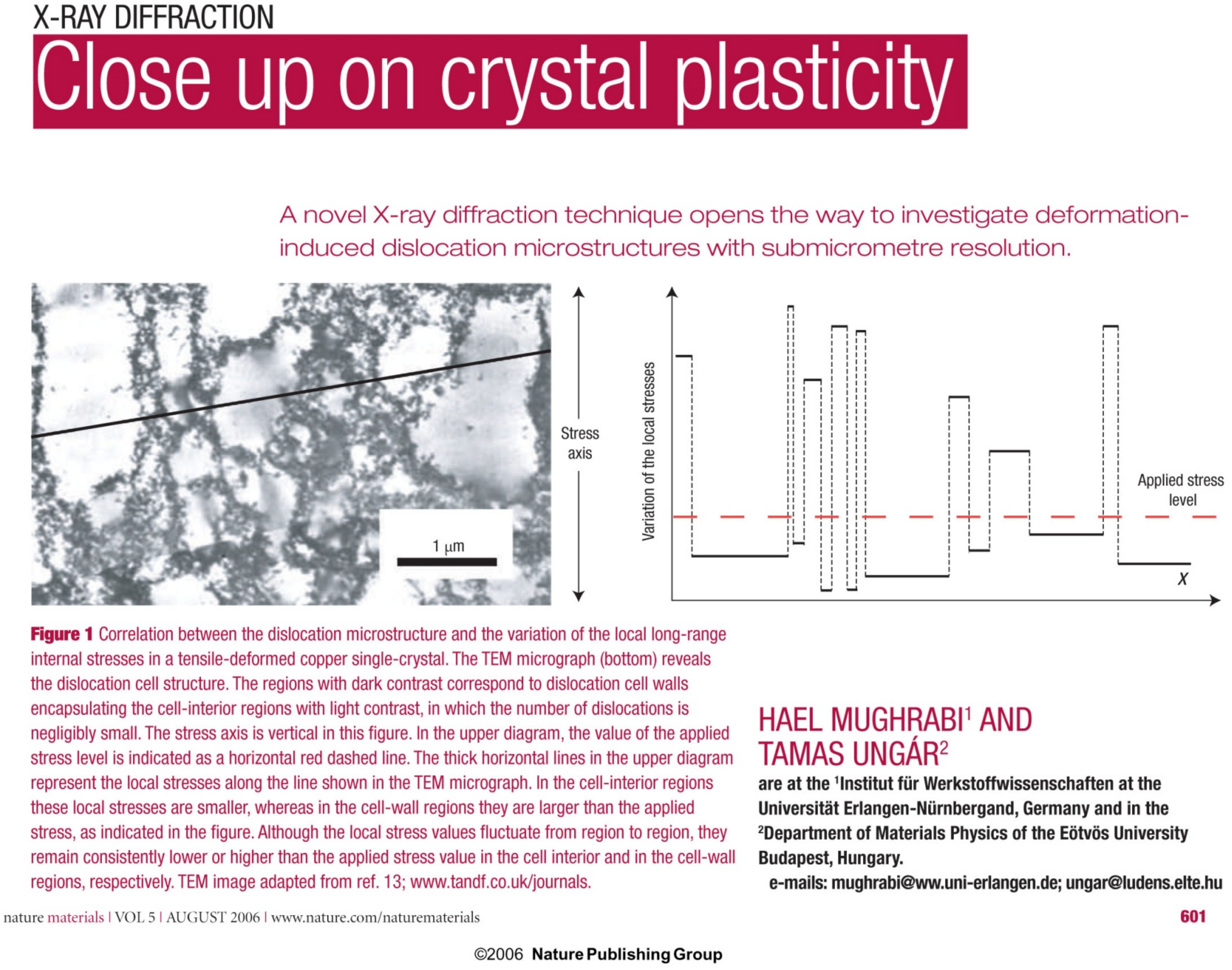
$$\tau_{ext} + \tau_{\text{int}}(\mathbf{r}) + {}^{DG}\!/_{\rho}\left[\gamma_{xx} + \gamma_{yy}\right] + \delta\tau(\mathbf{r},\gamma) > 0$$

External Long-range internal Pile-ups Fluctuations (local density)

Solved via CA simulation
assumed Gaussian

Zaiser & Moretti, J. Stat. Mech. (2005)

Stress Fluctuations and Scales



X-RAY DIFFRACTION

Close up on crystal plasticity

A novel X-ray diffraction technique opens the way to investigate deformation-induced dislocation microstructures with submicrometre resolution.

Figure 1 Correlation between the dislocation microstructure and the variation of the local long-range internal stresses in a tensile-deformed copper single-crystal. The TEM micrograph (bottom) reveals the dislocation cell structure. The regions with dark contrast correspond to dislocation cell walls encapsulating the cell-interior regions with light contrast, in which the number of dislocations is negligibly small. The stress axis is vertical in this figure. In the upper diagram, the value of the applied stress level is indicated as a horizontal red dashed line. The thick horizontal lines in the upper diagram represent the local stresses along the line shown in the TEM micrograph. In the cell-interior regions these local stresses are smaller, whereas in the cell-wall regions they are larger than the applied stress, as indicated in the figure. Although the local stress values fluctuate from region to region, they remain consistently lower or higher than the applied stress value in the cell interior and in the cell-wall regions, respectively. TEM image adapted from ref. 13; www.tandf.co.uk/journals.

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nature materials | VOL 5 | AUGUST 2006 | www.nature.com/naturematerials 601

Mean Free Path or correlation length, multiple ‘cells’ ?

$$\sim 10/\sqrt{\rho}$$

Characteristic length or ‘cell’ size ?

$$1/\sqrt{\rho}$$

‘Short Range’ Interactions, ‘cell’ wall dimensions down to atomic (thermal activation)

Stress fluctuations on the order of the applied stress
Also at least 3 relevant length scales, at least 2 time scales…

Continuum Mean Field Avalanche Theory

- 2d (infinite-line) Mean Field theory yields avalanche size probability scaling exponent of 1.5 & avalanche duration probability exponent of 2.0

- However, need studies of at least three lengths scales:
  - Effects of thermal activation & rate dependence (short-range effects)
  - 3d dislocation mechanisms (need to understand screening, interactions, anelastic effects, etc.)
  - Local dislocation statistics & their tie to screening & multiplication

    $\xi \approx 1/\sqrt{\rho}$, but $\xi \approx 10/\sqrt{\rho}$ estimate from *weak link* & classical theory

    similar issue with γ_{corr}, should tie to trapping ('mean-free-path')

    $\delta\tau(\mathbf{r},\gamma)$ may be power law, not Gaussian, but strain dependent

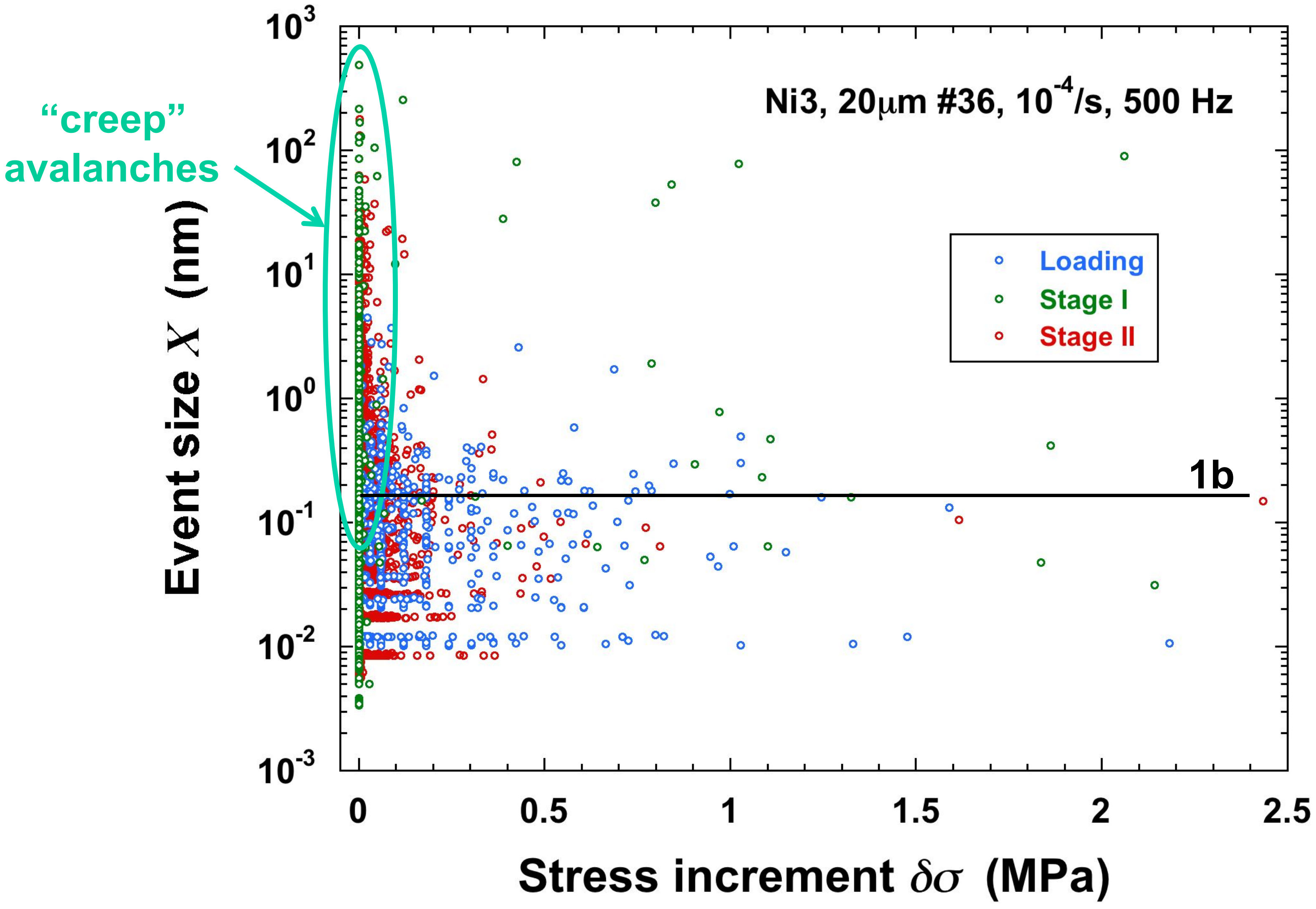
    need to reconcile with Zaiser, Bay & Hahner, PRL (1998), Acta Mater. (1999) showing fractal substructure size distribution
  - Avalanches reflect dislocation multiplication (and hardening), i.e.

    time dependence & trapping probability

    $X_i \propto \delta(\rho_m v) \propto f(\tau_{loc}, \gamma_{loc})$cross-slip probability, surface sources, etc.
  - Need to better understand temporal aspects of experimental methods

Dimiduk, et al., unpublished research

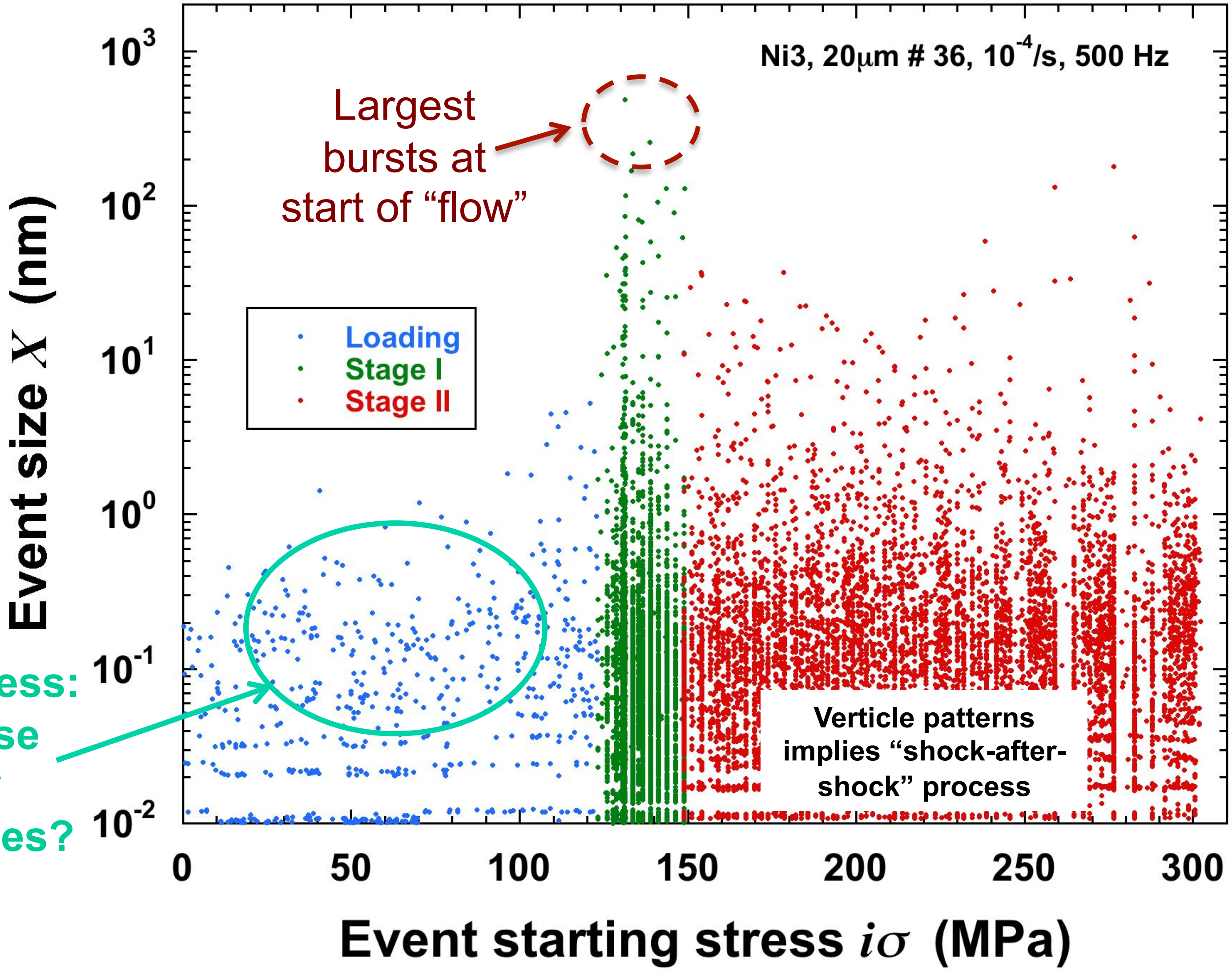
Stress change & burst size not well related



Many "creep" avalanches; dominated by internal stresses

Dimiduk, Nadgorny, Papanikolaou, et al. (2010-) unpublished research

Stress Level & Burst Size: Ni, ρ_o ~$10^{12}/m^2$



Largest bursts at start of "flow"

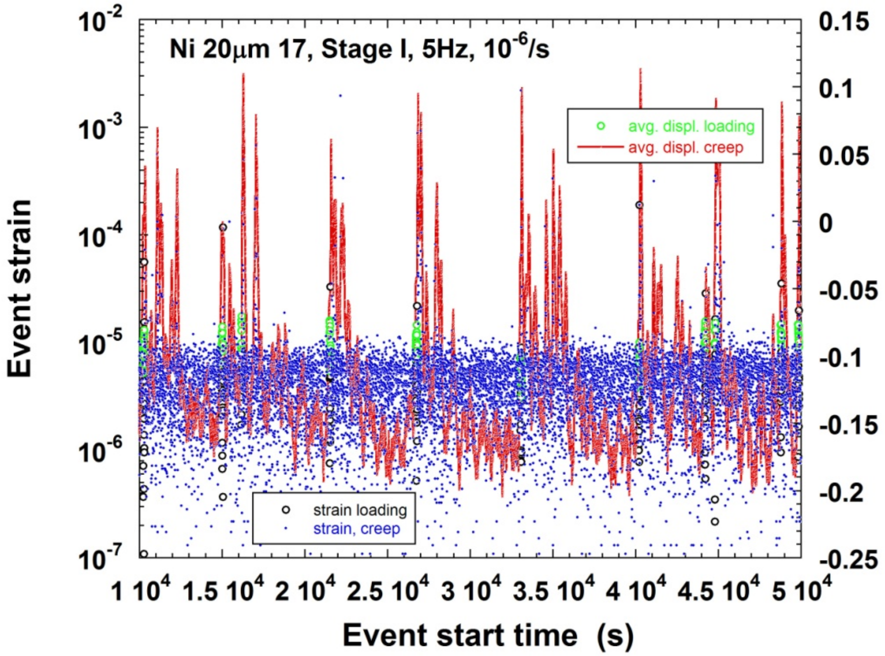
randomness: are these really avalanches?

Verticle patterns implies "shock-after-shock" process

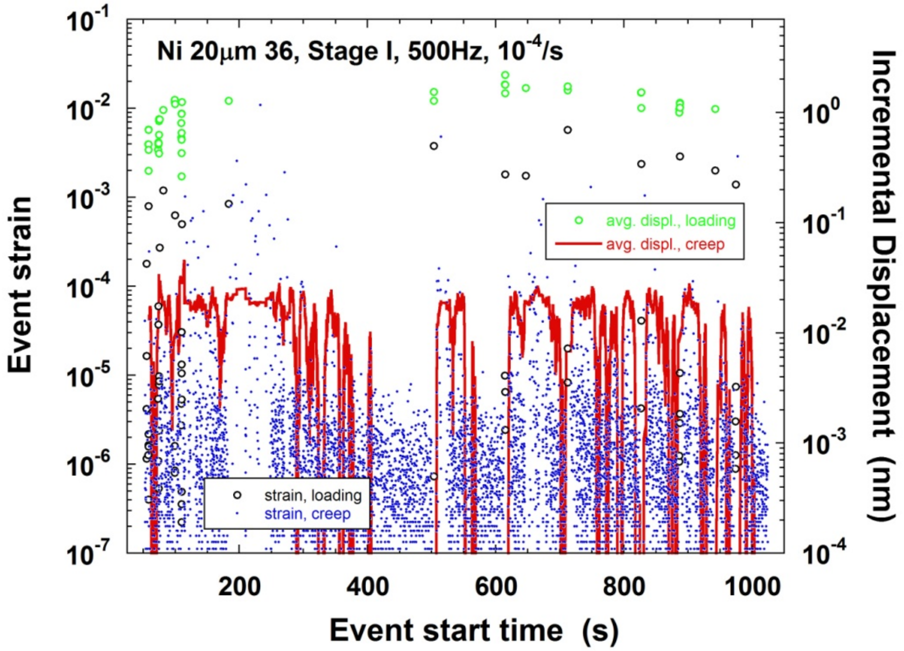
Clear influence of 'multiplication stress' & "trapping" probability (substructure)

Dimiduk, Nadgorny, Papanikolaou, et al. (2010-) unpublished research

Pure Ni: Displacements Between Strain Bursts



10^{-6}/s; Shock-Aftershock



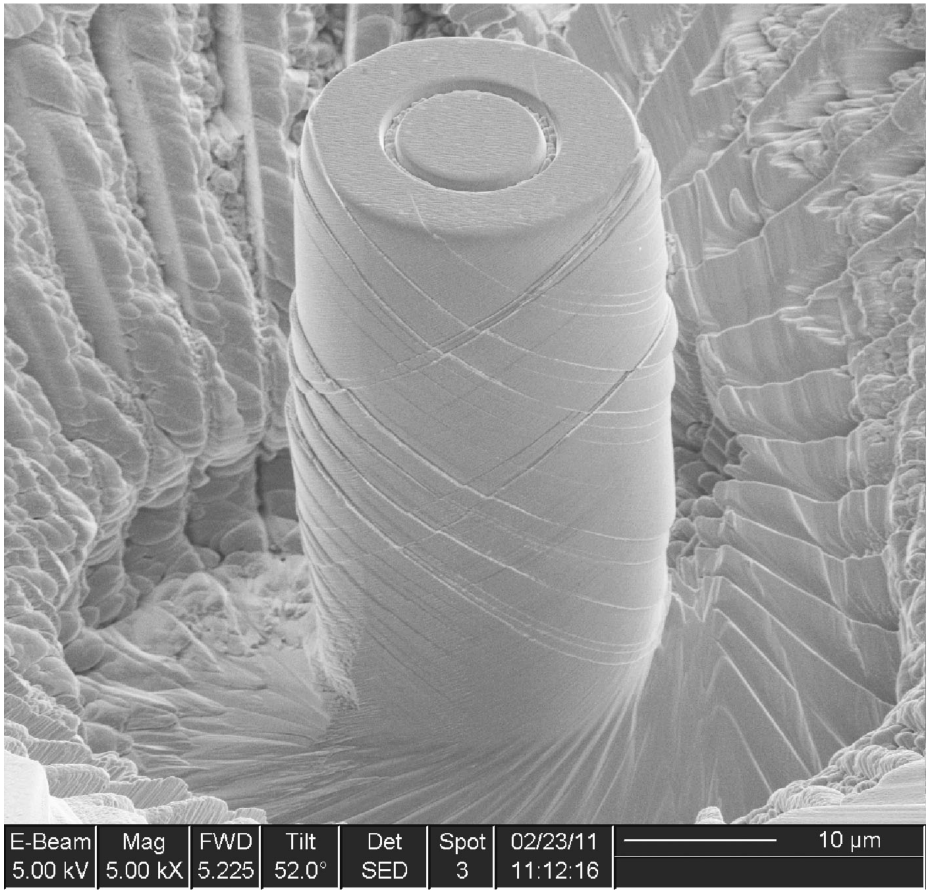
10^{-4}/s; Driven System

Perhaps only 10^{-6}/s testing has sufficient separation of driving - response scales

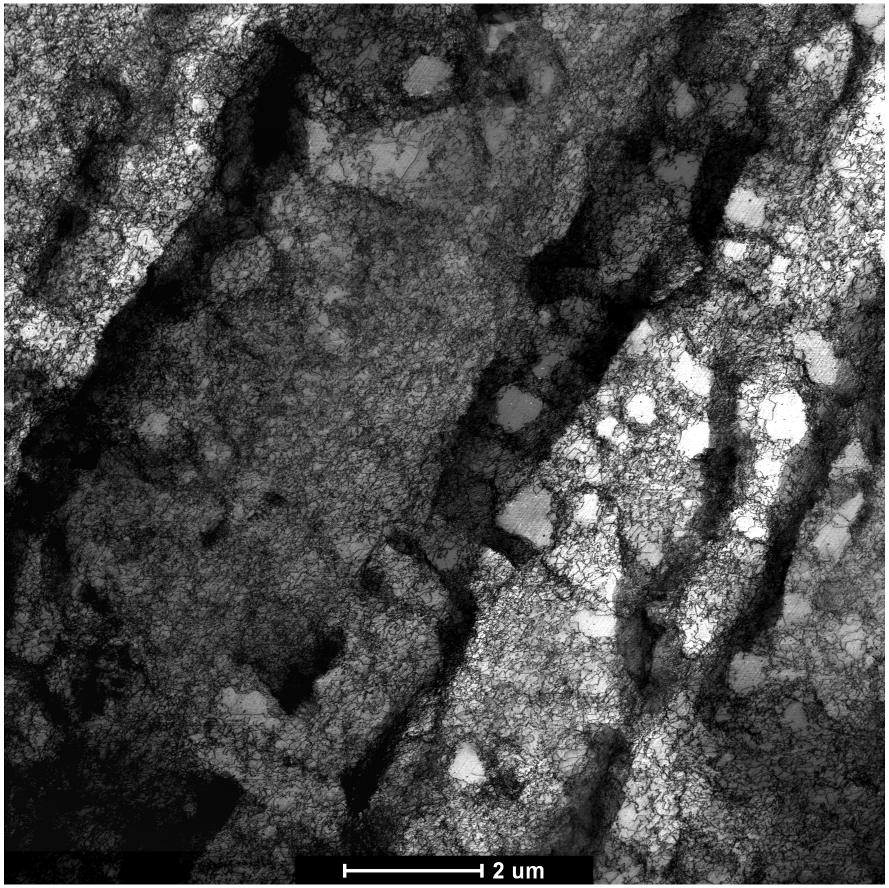
Dimiduk, Papanikolaou, et al. (2011-) unpublished research

Other Current Studies

Pure Ni, <110> Oriented Bulk Crystal
Pre-Strained 26% into Stage III Flow



Additionally-strained
20μm microsample



Bulk Crystal Dislocations After Pre-Straining; ~ρ_o ~10^{15}/m^2

El-Awady, Uchic, Dimiduk, et al. (2011) unpublished research

Synopsis About Intermittency

- *Loading Stage* (pre-yielding) and *Flow Stage* (large strain bursts)
- *Dislocation "multiplication" distinguishes the stages, strengthening & stress-sensitivity of mobile density*

- *Driving forces* are *likely internal & long range*
- *"Control" (& and scaling?) likely short range…*

- Largest observed "event" most affected by *strain hardening state*
  - The spatial-temporal aspects of the dislocation density (kinetics of weakest links)
  - The resolution of the measurement device relative to the obstacle landscape
  - Whiskers show huge events, LiF and Ni Stage I smaller, Ni Stage II smaller still, Stage 0 smallest, macroscopic stress-strain curves almost none at all…

- The *observed* power law *exponents are not universal*
  - Likely over-lapping avalanches for test conditions when mean-field value observed
  - Likely material & testing state parameter affected by multiplication & strain-hardening parameters; *stress sensitivity of mobile density*
  - Extensions to mean-field theory (dynamic, multiscale theory) required

- Strong correlation between size and duration implies *need for time resolution*
  - Need an *experimental system model*

Dimiduk, Nadgorny, Papanikolaou, et al. (2011) unpublished research