Investigation of avalanche phenomena by simultaneous measurements of different variables

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Avalanche

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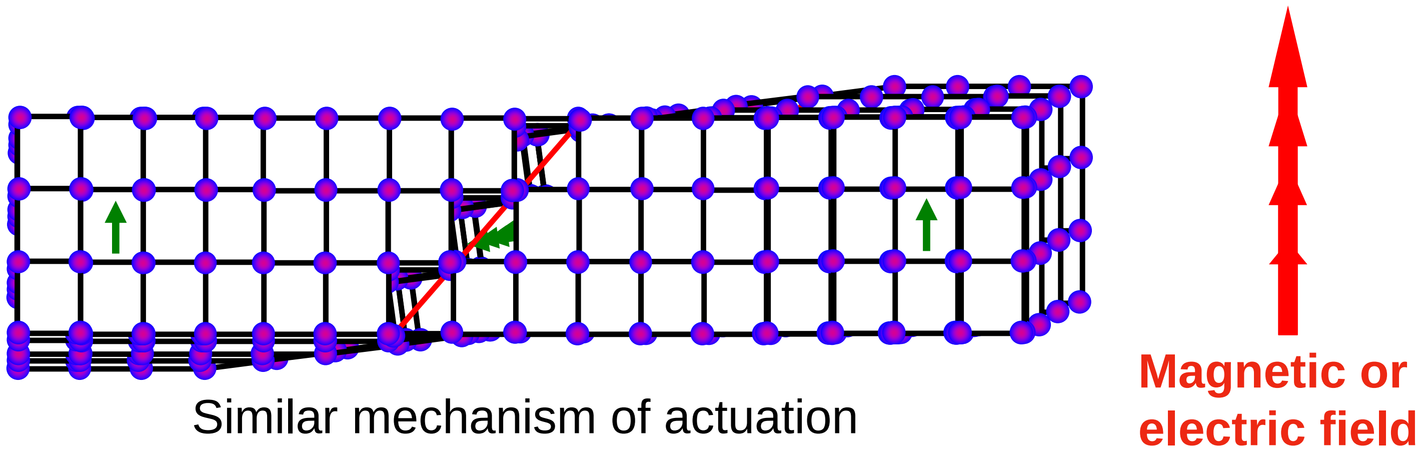
הטכניון מכון טכנולוגי לישראל TECHNION Israel Institute of Technology

Twin boundary motion

- A crystal/grain can be separated into domains/twins that have different orientation of the unit cell.
- The interfaces between domain/twins are called twin boundaries.
- Mechanical stress / electric field / magnetic field ⇨ Expansion of the favored domain/twin-variant on the expense of other domains/twin-variants.

Examples:

- Domain switching in ferroelectric materials
- Twinning reorientation in ferromagnetic shape memory alloy (FSMA) NiMnGa

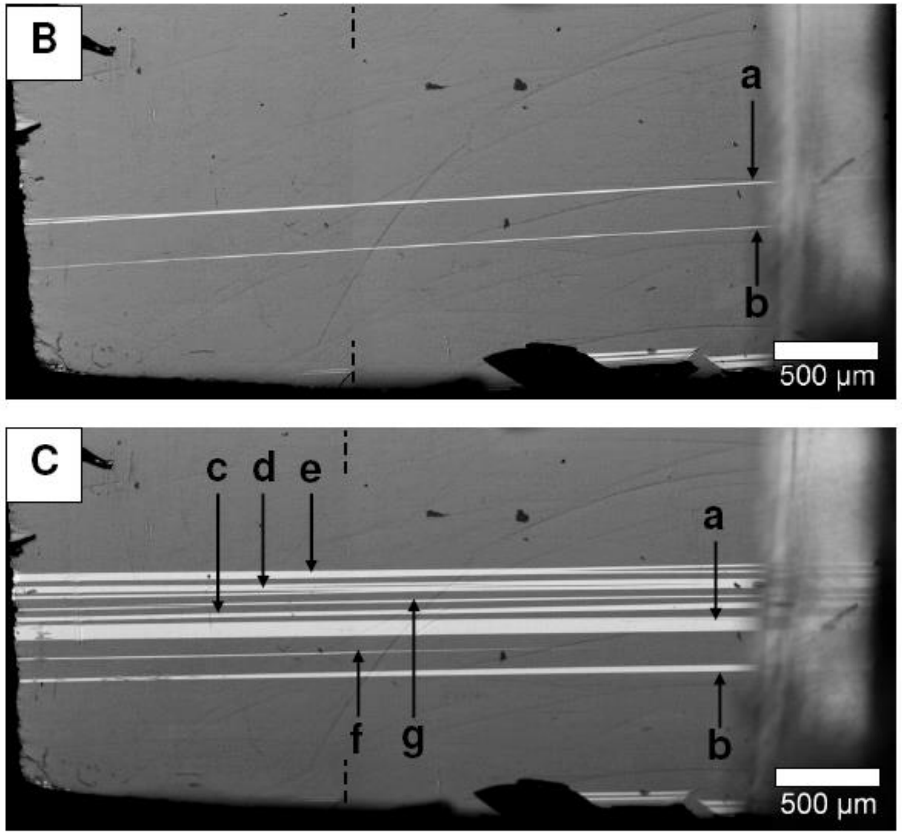


Similar mechanism of actuation

Example: Domain switching in ferroelectric $BaTiO_3$

Time: *t*

Time: *t* + 0.6 μs

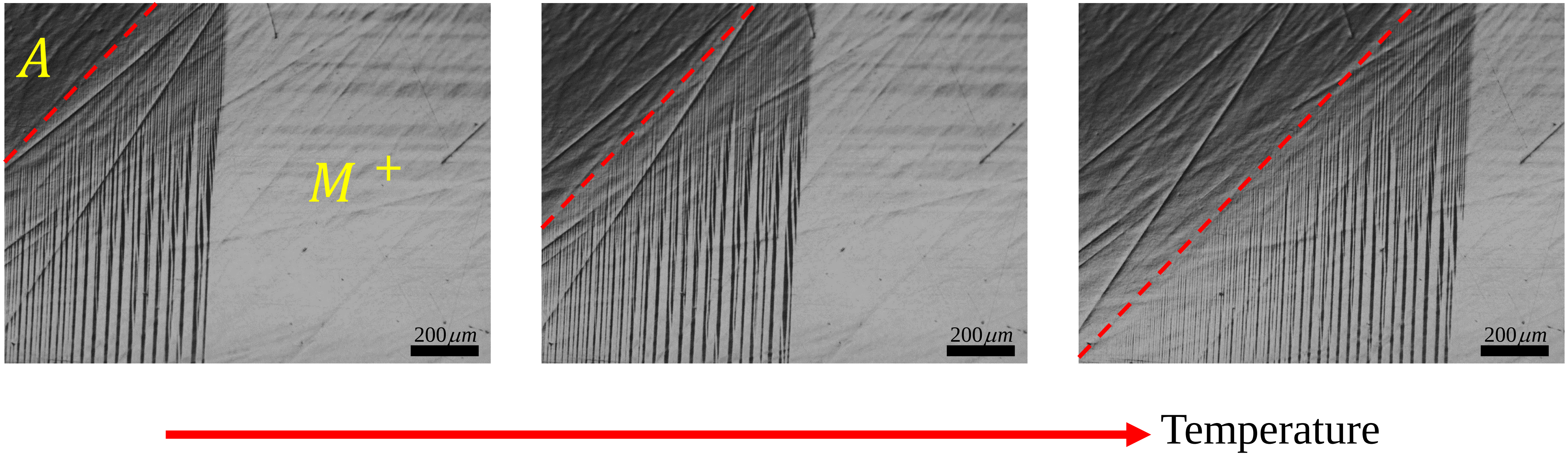


Twin Motion Faster than the Speed of Sound

Faran and Shilo, PRL, (2010).

Example: Phase transformation in SMA

Self similar propagation of the phase boundary and twinning microstructure

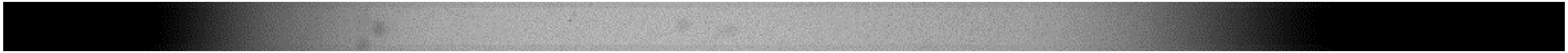


Analysis of austenite-martensite phase boundary and twinned microstructure in SMA

Bronstein, Faran, and Shilo, Acta Mater, (2019).

Example: Plastic deformation in magnesium

100,000 Frames Per Second

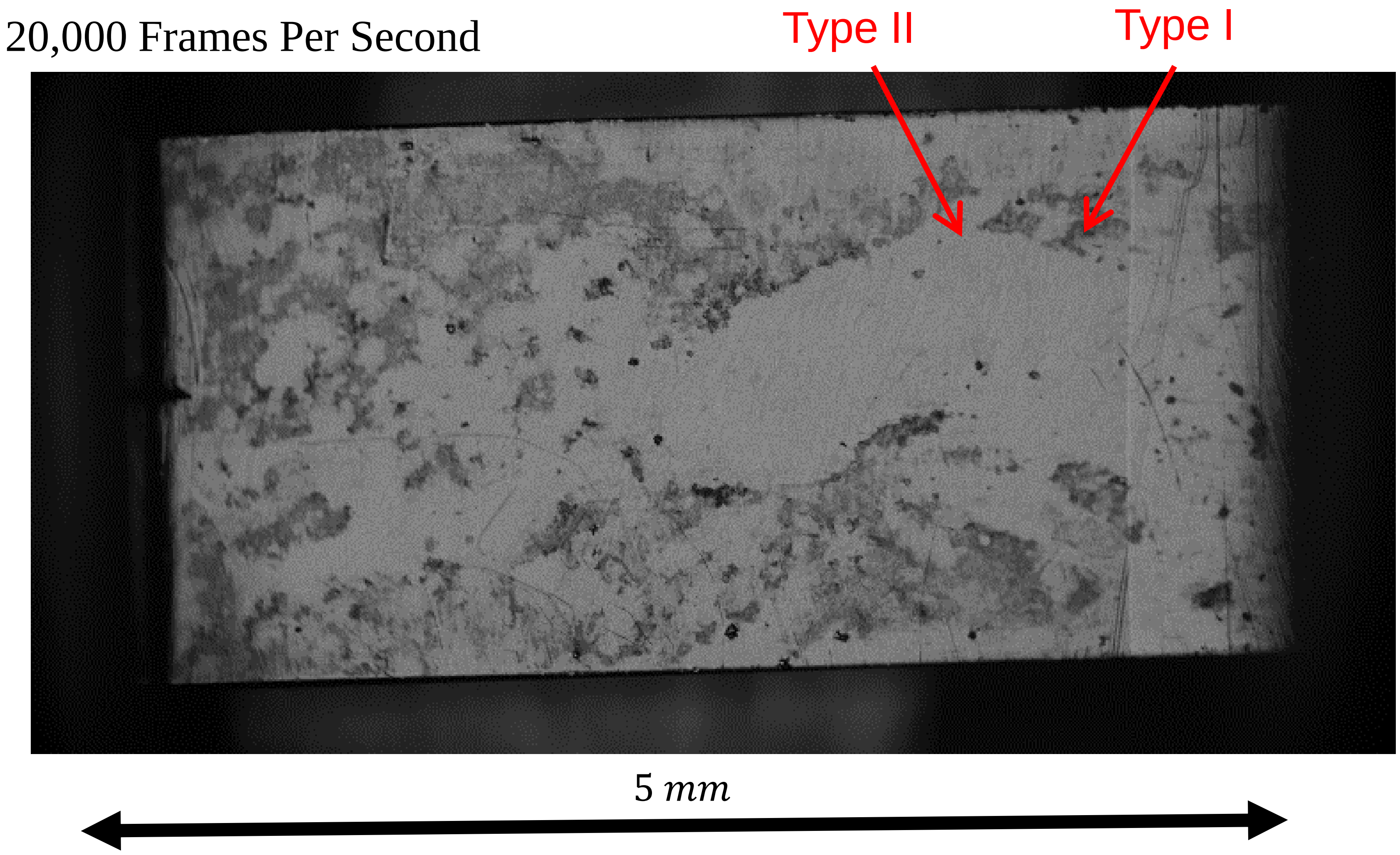


$4\ mm$

High-rate nucleation and motion of twin boundaries in Mg single crystals

Faran and Shilo, to be published.

Example: Twinning reorientation in FSMA Ni-Mn-Ga



Variability of twin boundary velocities in 10M Ni-Mn-Ga measured under μs-scale force pulses

Mizrahi, Shilo, and Faran, SMS, (2020).

Many studies reported power law distributions of avalanches during the motion of twin boundaries in different materials

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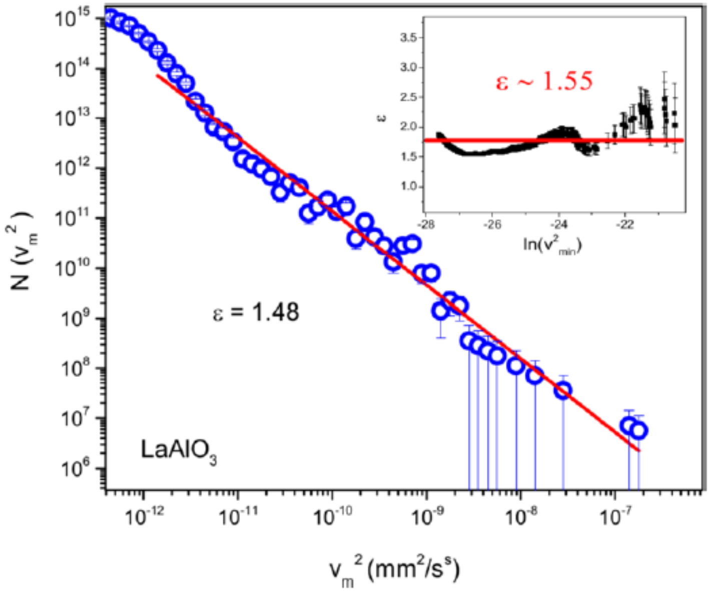
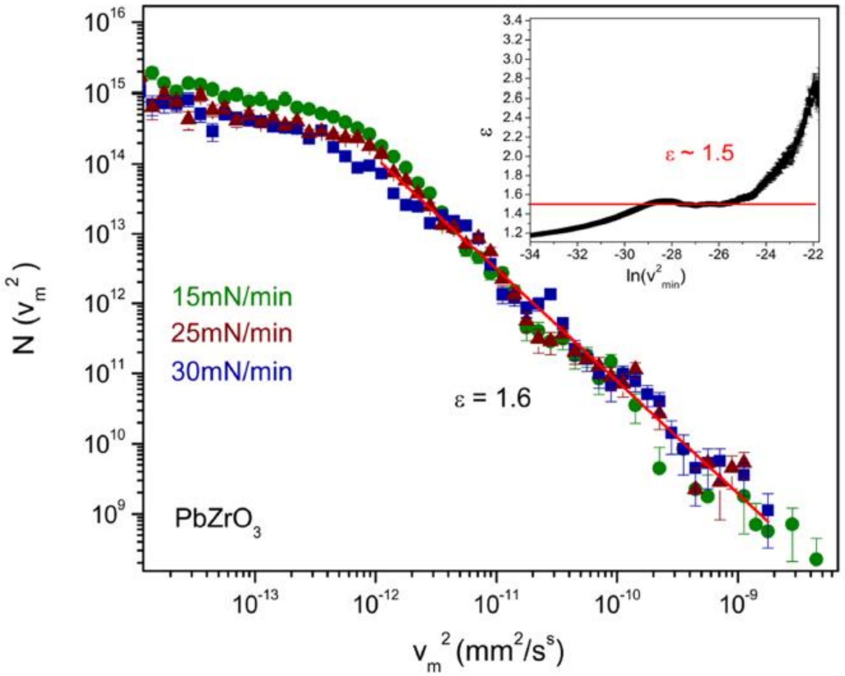
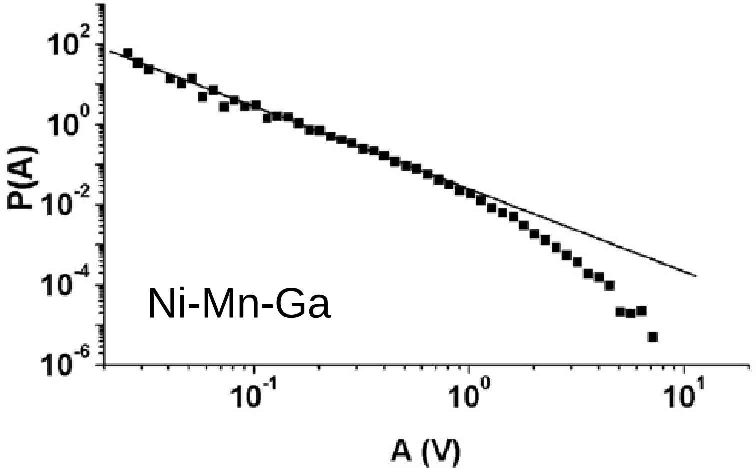


V. Soprunyuk, S. Puchberger, A. Tröster, E. Vives, E. K. H. Salje, W. Schranz,
J. Phys. Condens. Matter. **29** (2017) 224002.



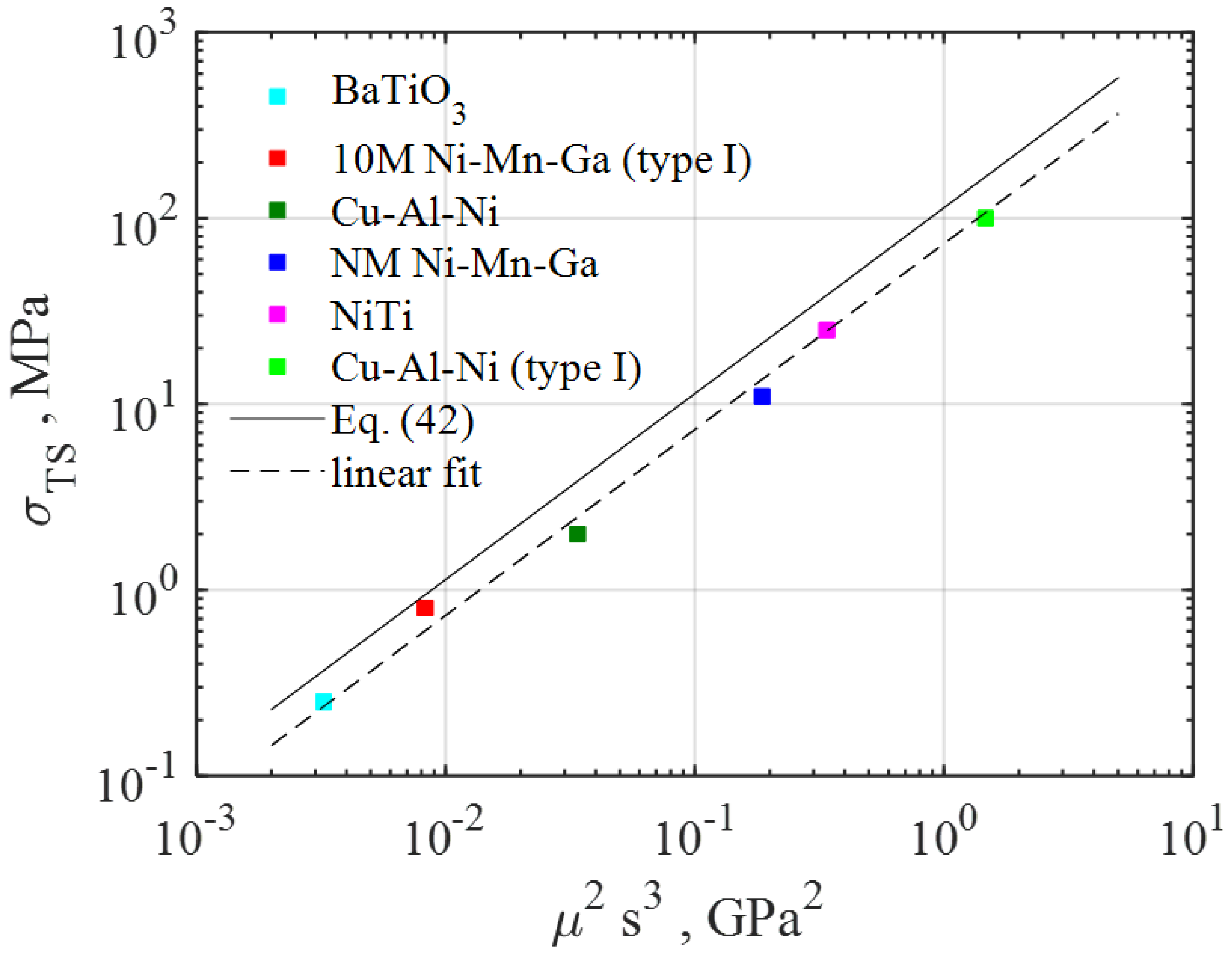
S. Puchberger *et al.*,
APL Materials **5** (2017) 046102.



L. Daróczi, E. Piros, L.Z. Tóth, D.L. Beke,
Phys. Rev. B **96** (2017) 014416.

The characteristics and kinetic laws for twin boundary motion can be accurately modeled and predicted

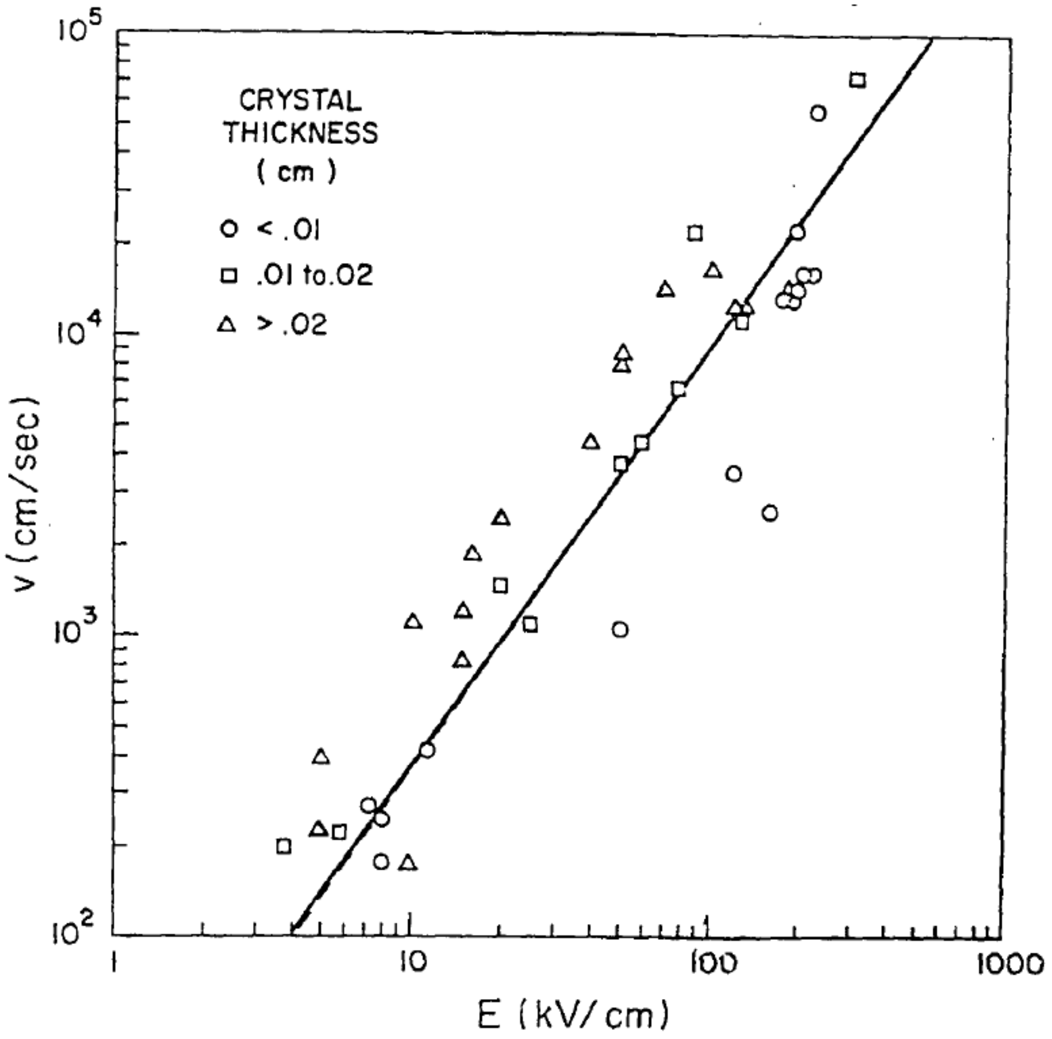
Example: The twinning stress in various materials



Twin Boundary Structure and Mobility

Shilo, Faran, Karki, Müllner, Acta Mater, (2021).

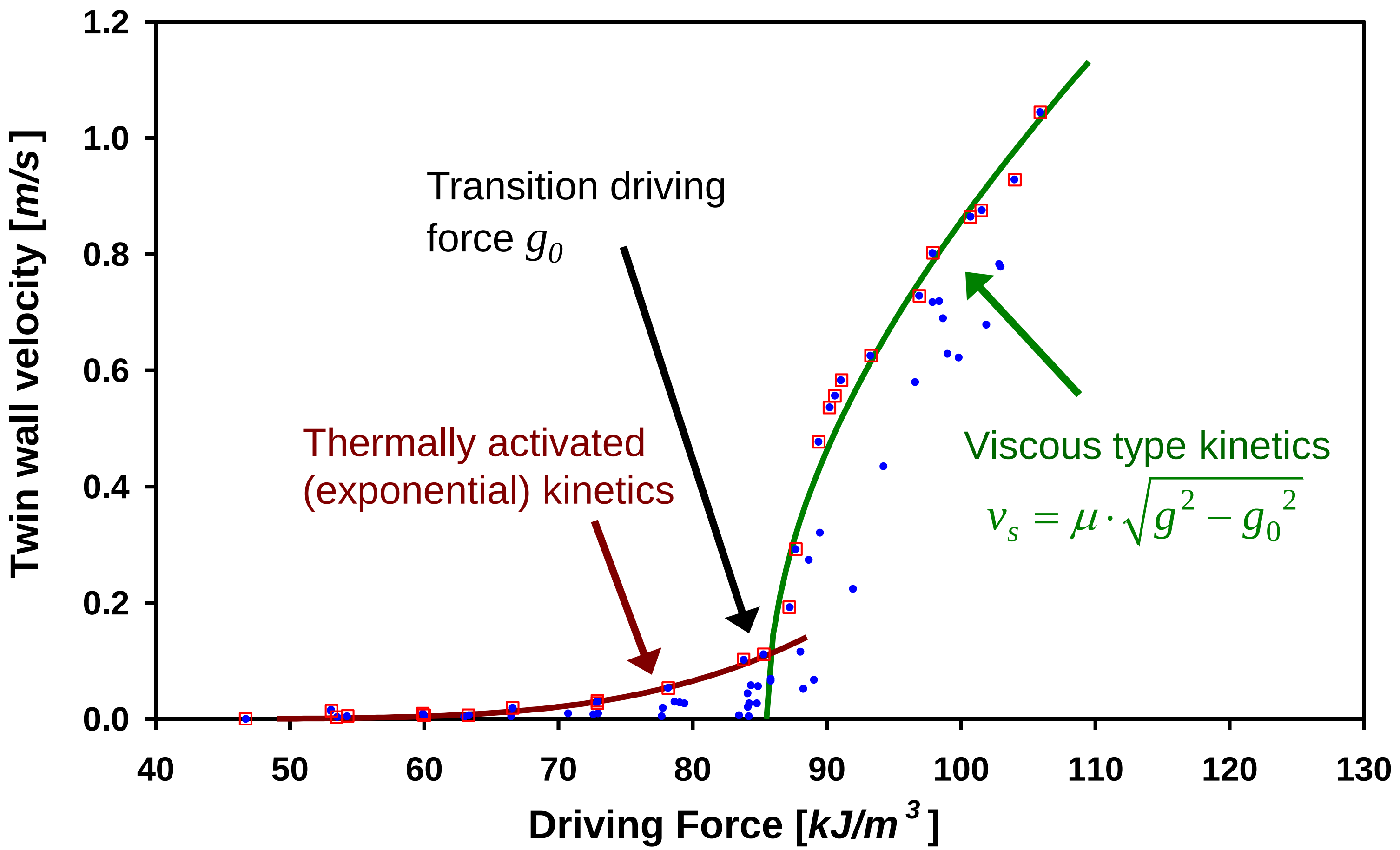
Example: Twin boundary velocity vs. electric field in ferroelectrics

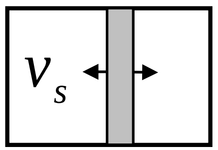


Kinetics of domain wall motion in ferroelectric switching

Hayashi, J. Phys. Soc. Japan, (1973).

Example: Kinetic relations for twin boundary motion in FSMA



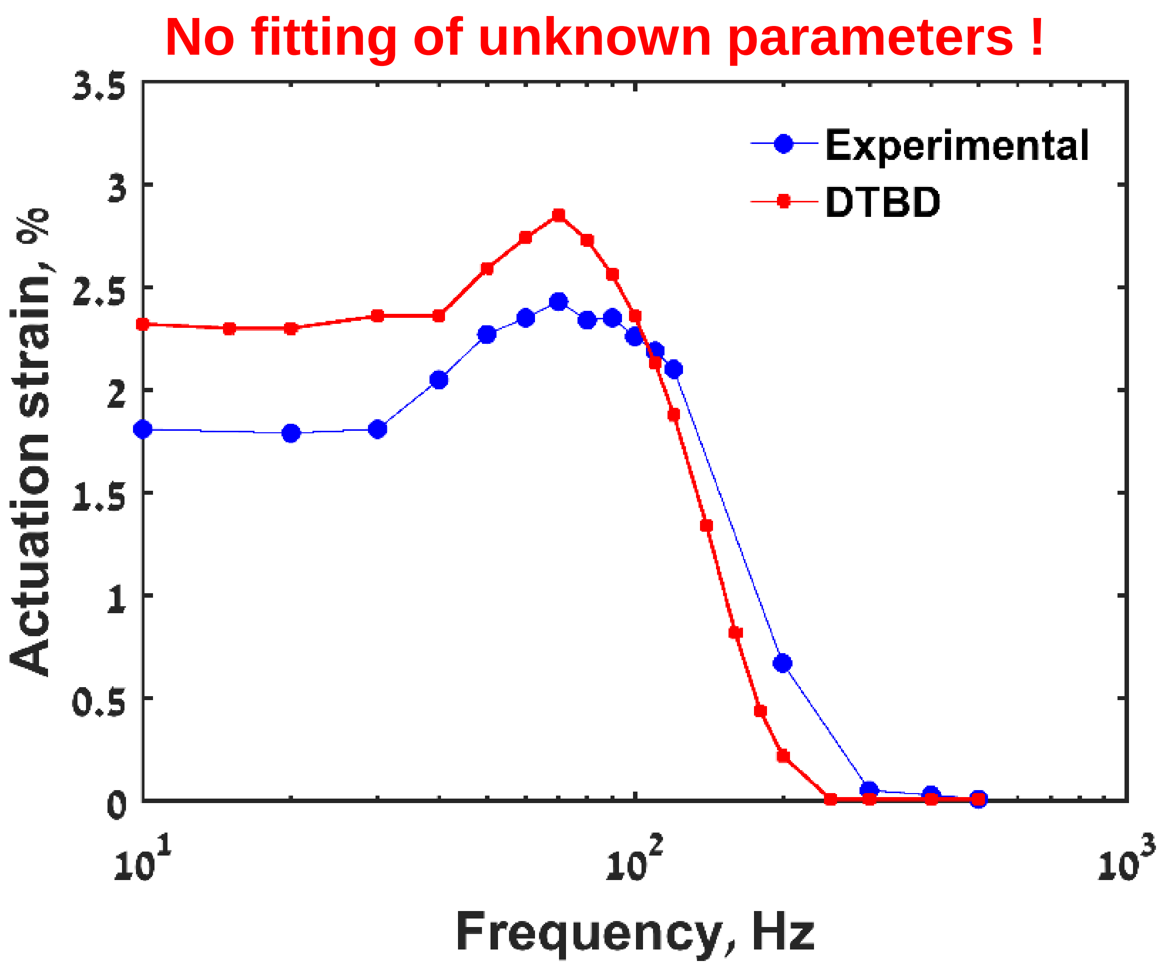


The kinetic relation for twin wall motion in NiMnGa

Part I: Faran and Shilo, J. Mech. Phys. Solids (2011)

Part II: Faran and Shilo, J. Mech. Phys. Solids (2013)

Example: Discrete twin boundary dynamic simulations



Inertia controlled twinning in Ni-Mn-Ga actuators: a discrete twin boundary dynamics study

Faran, Riccardi, Shilo, SMS, (2017).

The enigma of twin boundary motion

Power law distributions of avalanche events

- The average and STD of a power law distribution are undefined or do not represent a typical (most probable) value.
- Avalanches are not governed by characteristic properties or kinetic laws.

Well predicted twinning stress and kinetic laws

- Some variables that characterize the twin boundary motion display a characteristic value or follow a kinetic law.

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Calls for measuring different variables during avalanche events

Variables involved in the physical process

Apply: controlled external/average strain

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{ct}{L_0}$$

c – applied displacement rate

L_0 - Sample's length

Measure: stress (σ) vs. time (t)

Variables involved in the physical process

Applied strain: $$\varepsilon = \frac{ct}{L_0} = \frac{\sigma}{Y} + \varepsilon_{trans}$$

c – displacement rate
Y – effective modulus (stiffness)

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Strain due to twin boundary motion: $$\varepsilon_{trans} = \frac{x_{TB}}{L_0} \varepsilon_T$$

x_{TB} – twin boundary displacement
$\varepsilon_T = 0.06$ – twinning strain

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Variable 1: Twill boundary displacement during an avalanche event: $$\Delta x_{TB} = \frac{c\Delta t}{\varepsilon_T} - \frac{L_0}{\varepsilon_T Y}\Delta\sigma$$

Released potential (elastic) energy during an avalanche event: $$\Delta U_P \cong -A\sigma\varepsilon_T \cdot \Delta x_{TB}$$

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<u>Variable 2:</u> Temporary twin boundary velocity: $$v_{TB} = \frac{c}{\varepsilon_T} - \frac{L_0}{\varepsilon_T Y}\dot{\sigma}$$

Potential energy release rate: $$\dot{U}_P \cong -A\sigma\varepsilon_T \cdot v_{TB}$$

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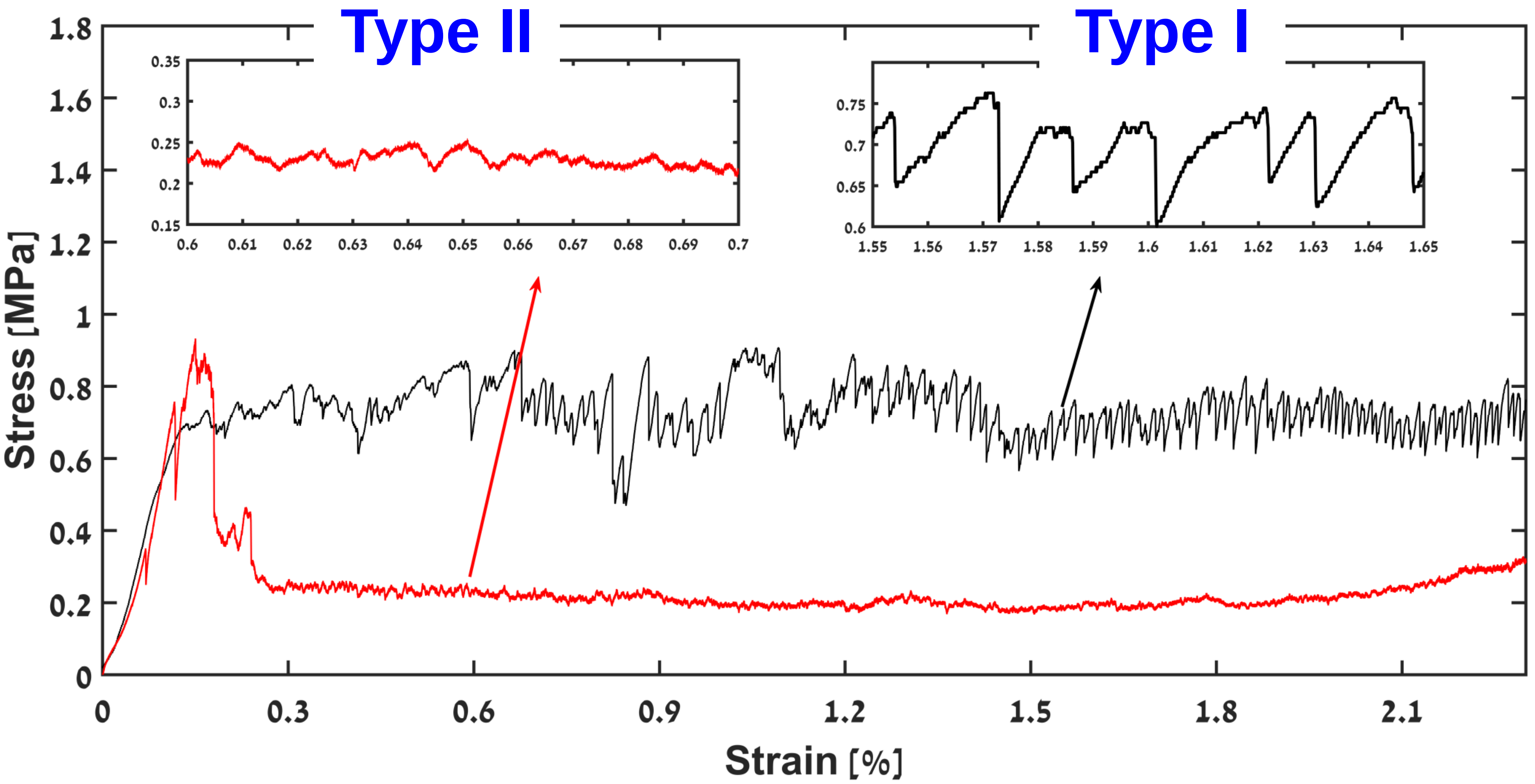
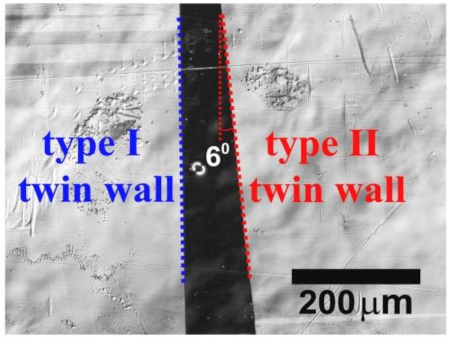
Variable 3: Total acoustic emission energy during an event: $$E_{AE}$$

Two types of twin boundaries in Ni-Mn-Ga





$$\dot{\sigma} = \frac{Y}{L_0}(c - \varepsilon_T v_{TB})$$

Results for type II twin boundaries

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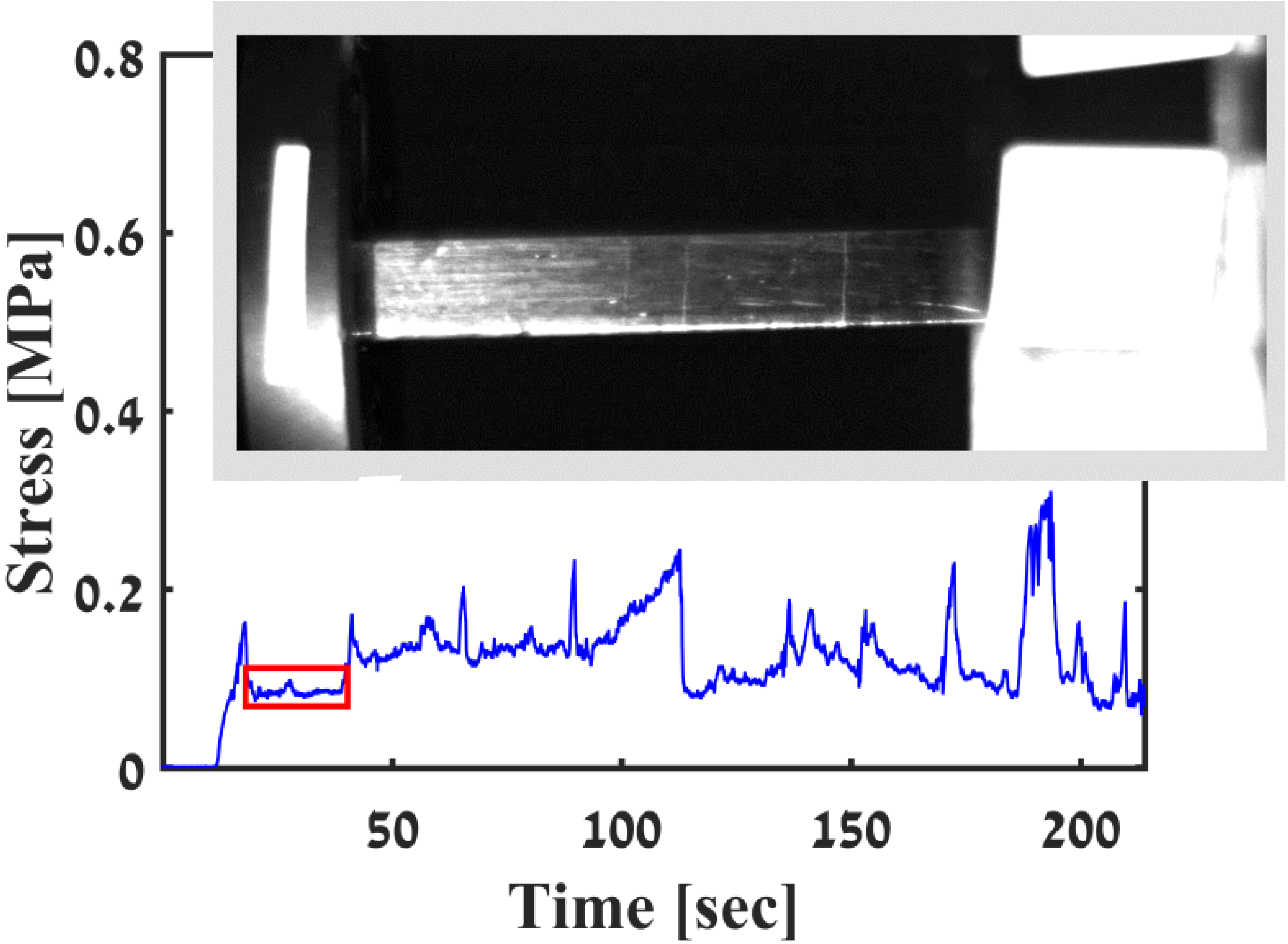

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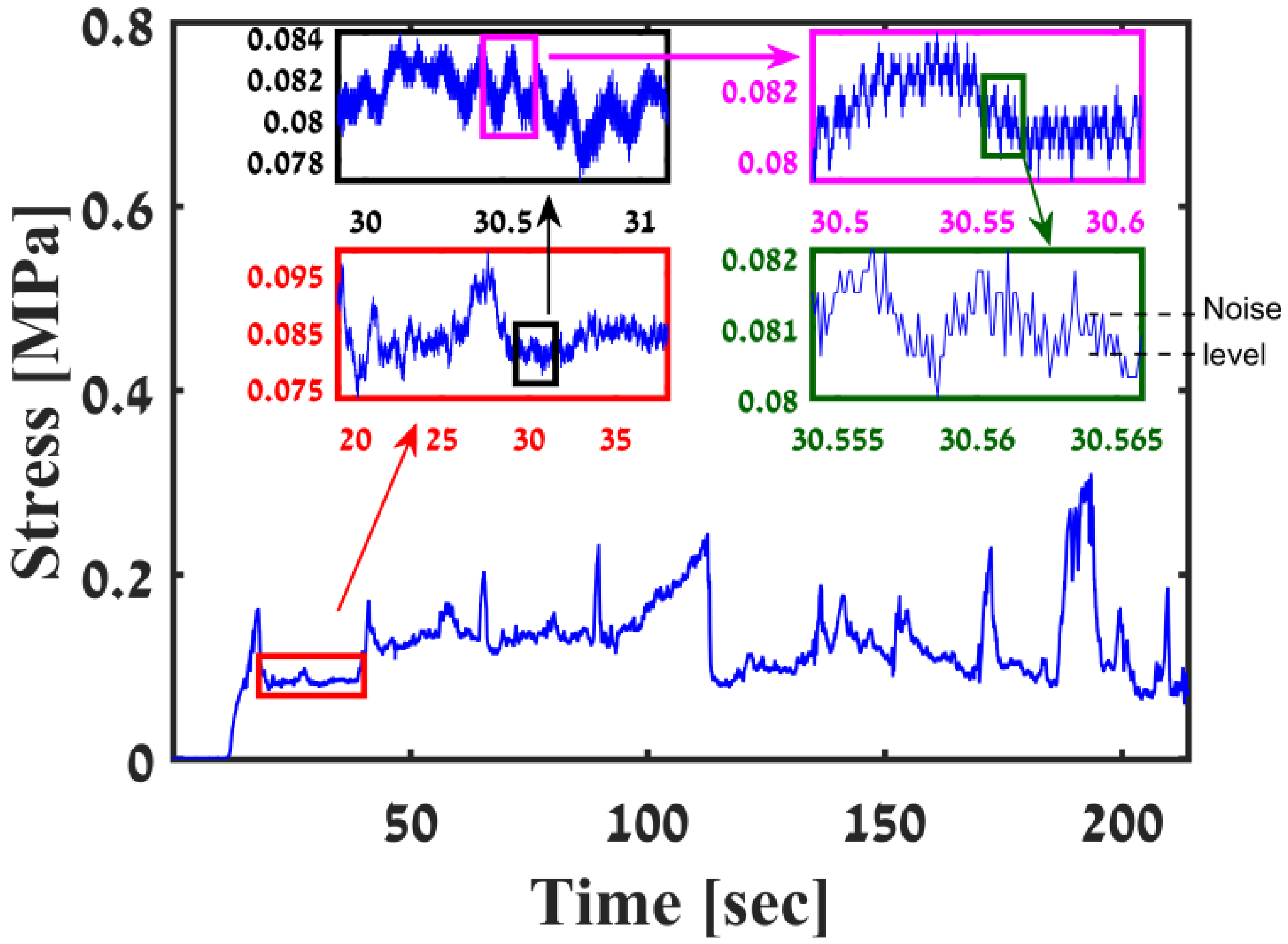

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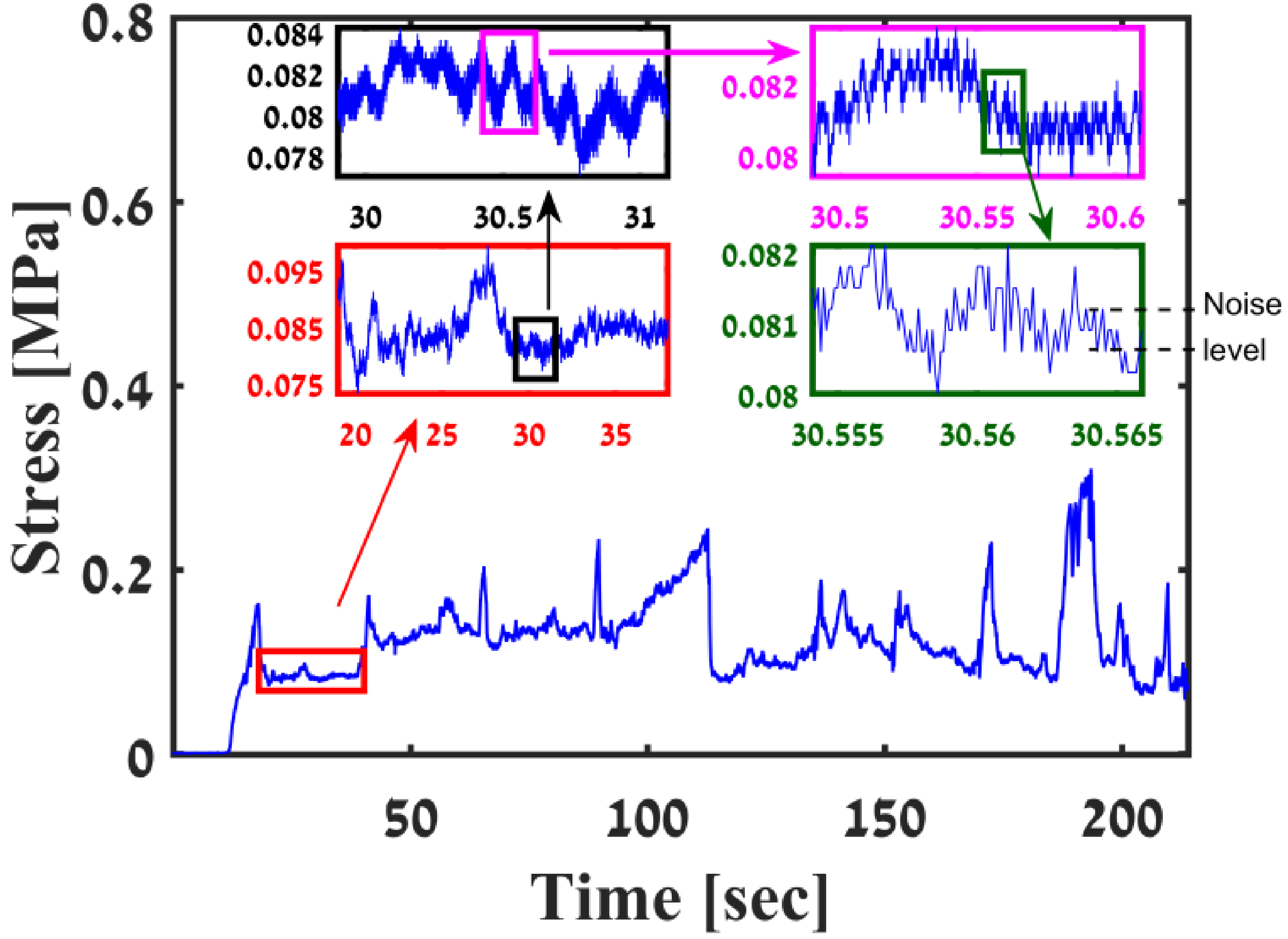

$$v_{TB} = \frac{c}{\varepsilon_T} - \frac{\dot{\sigma} L_0}{Y \varepsilon_T}$$

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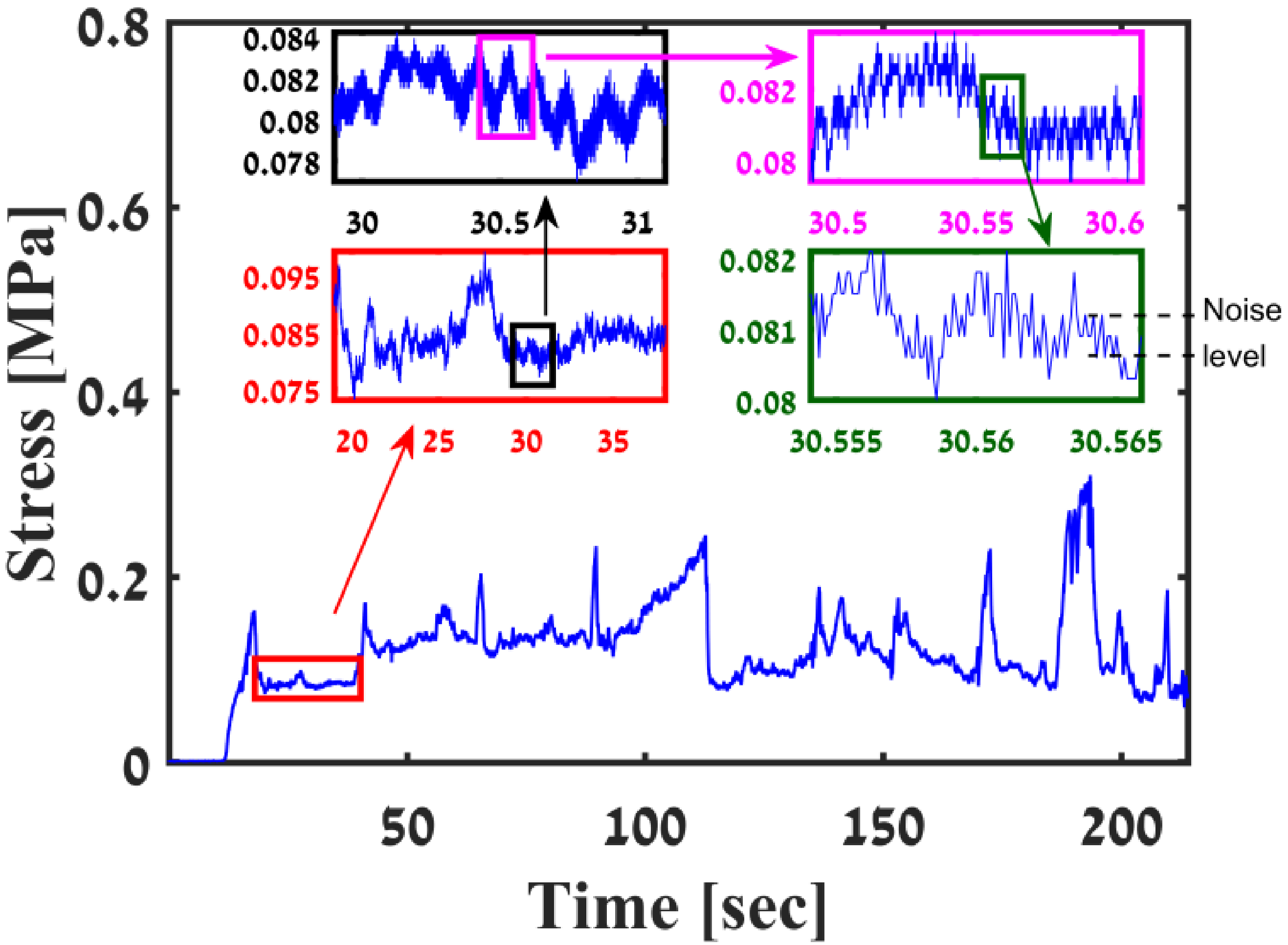
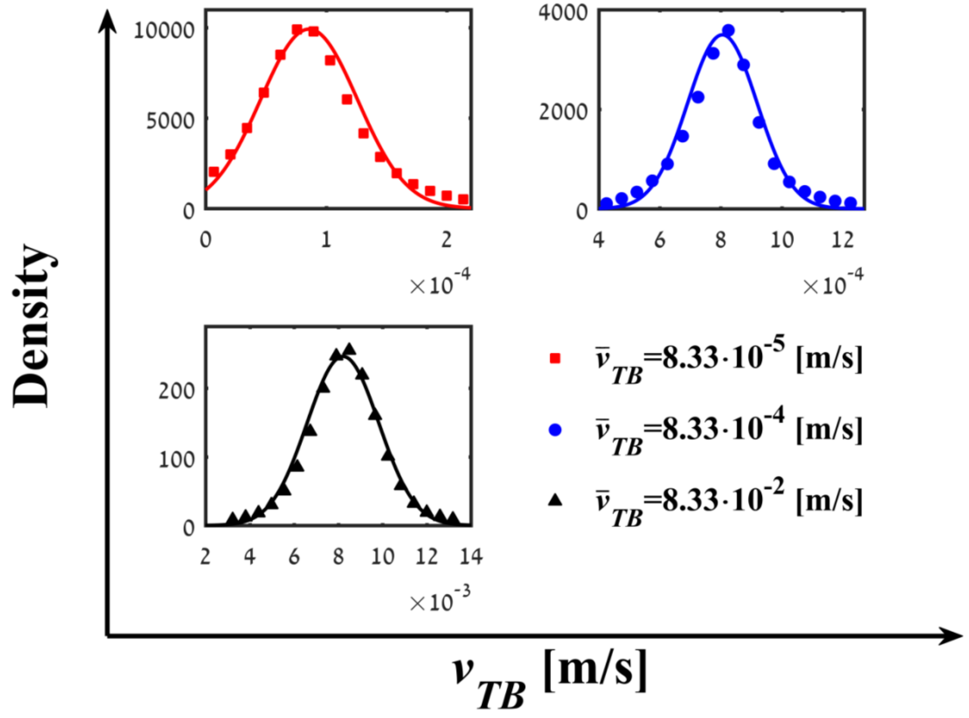


$$v_{TB} = \frac{c}{\varepsilon_T} - \frac{\dot{\sigma} L_0}{Y \varepsilon_T}$$

- There are no time intervals during which the twin boundary motion stops.
- The twin boundary moves during all time but with different velocities.

Statistical distributions of AE and twin boundary velocity during mechanical tests

Velocity - Gaussian distribution



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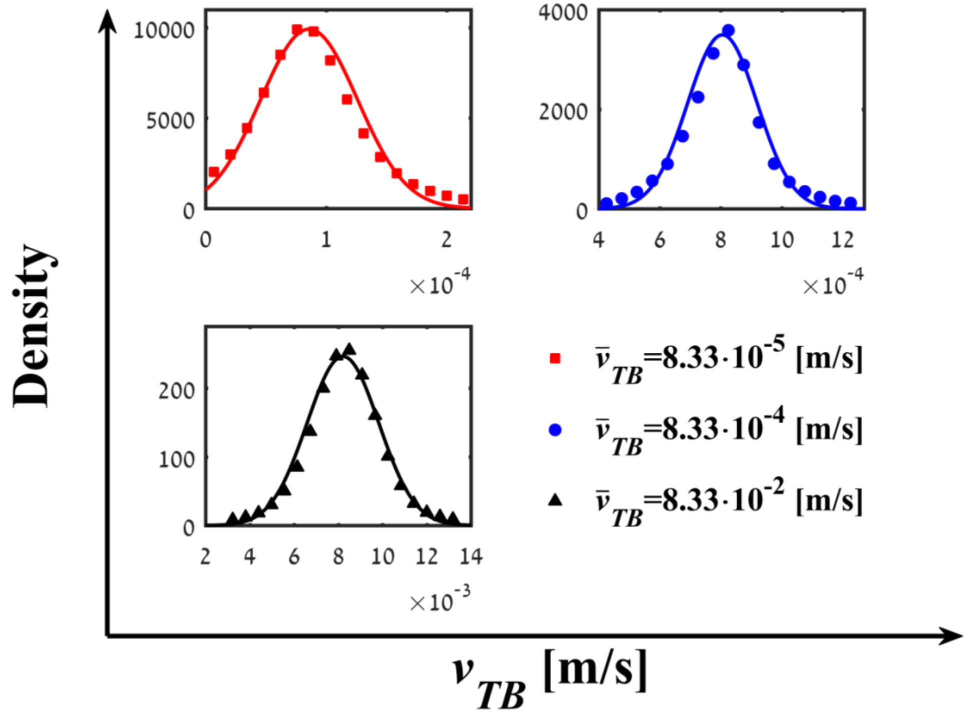

- The average value of the normal distribution is determined by the material's kinetic relation.
- The distribution width scales with the average velocity.

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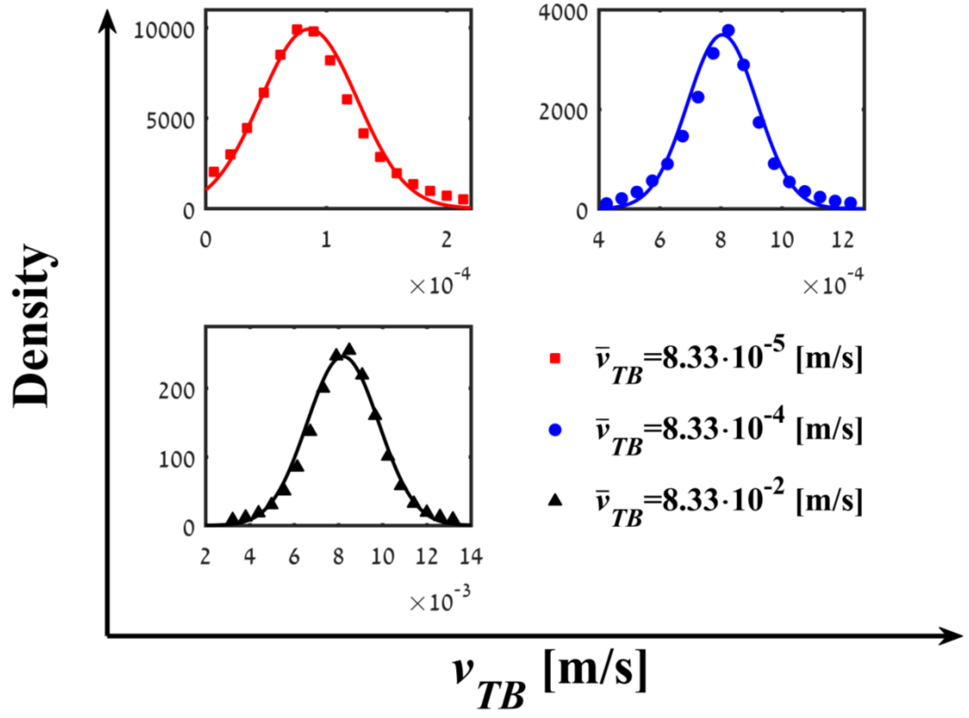

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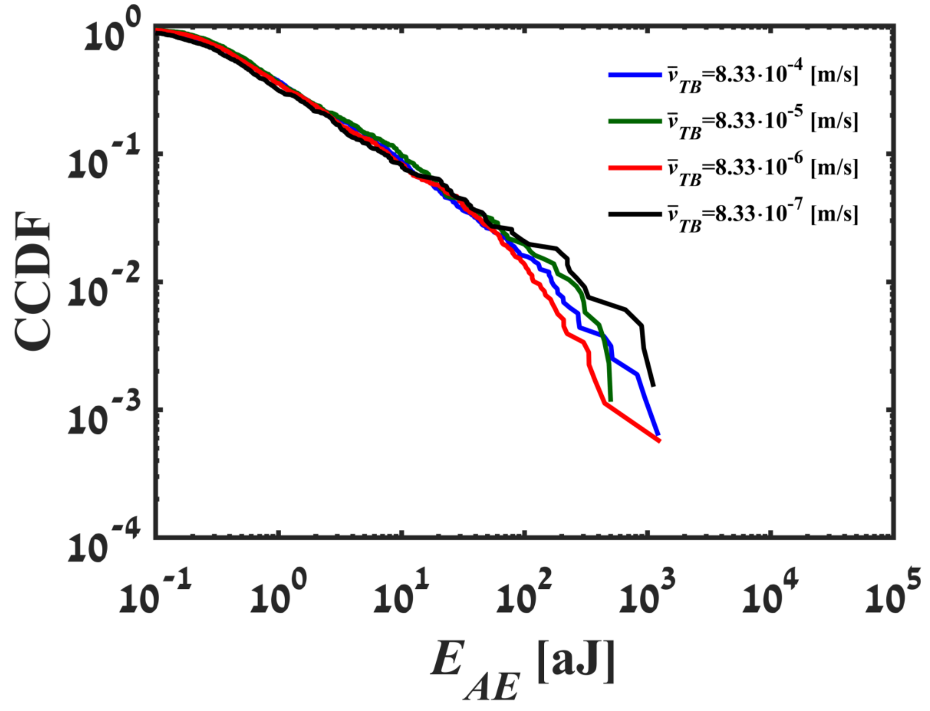
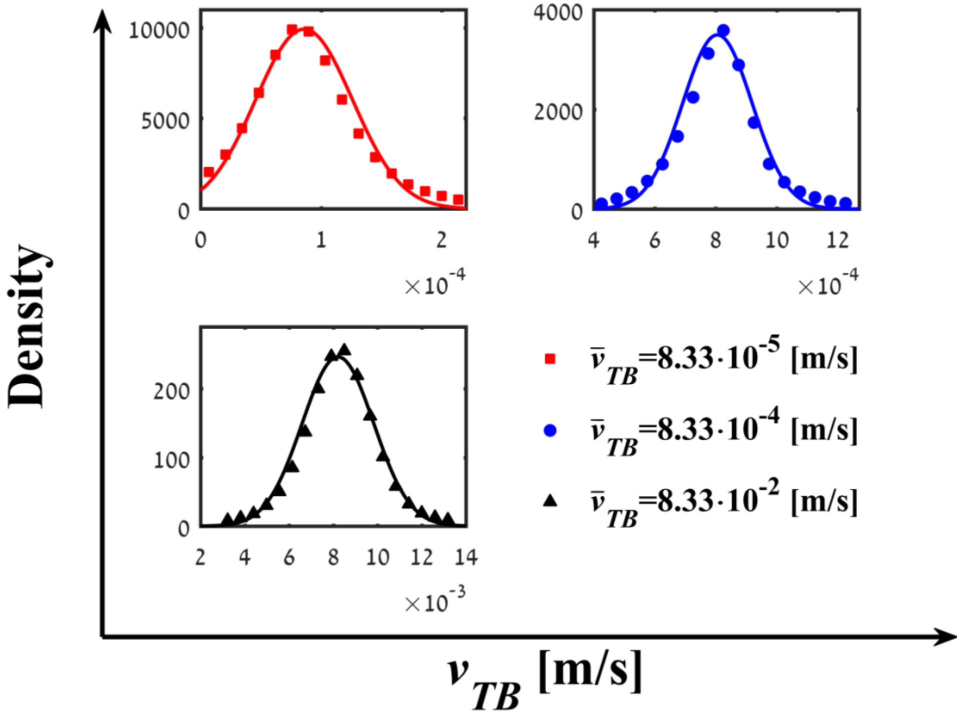
AE - Power law distribution



- Dynamic criticality: a state at which the dynamics of the process is unpredictable

Statistical distributions of AE and twin boundary velocity during mechanical tests

Velocity - Gaussian distribution



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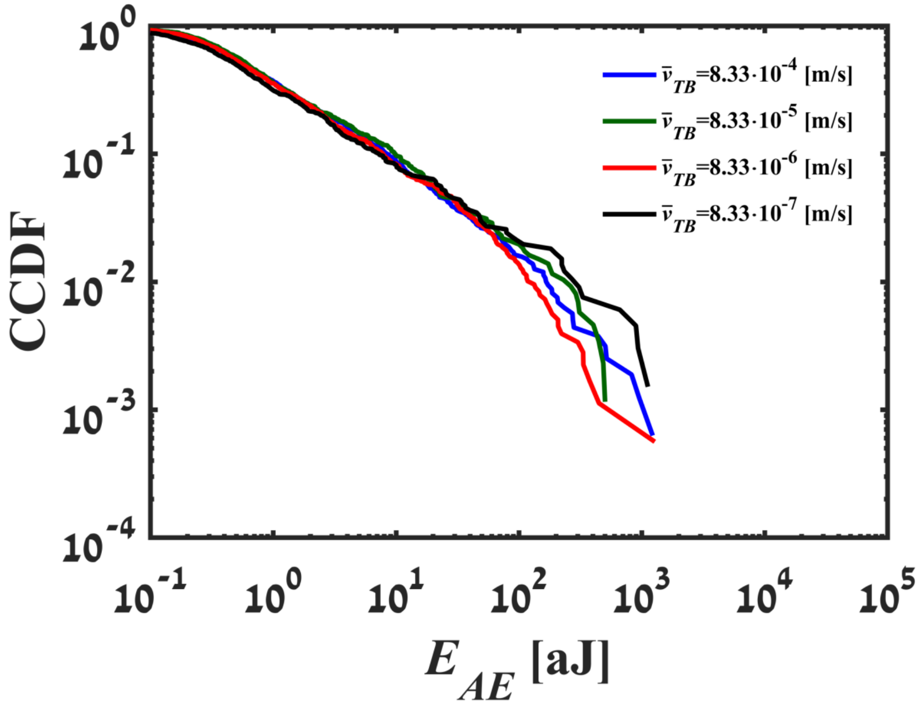
Enigma

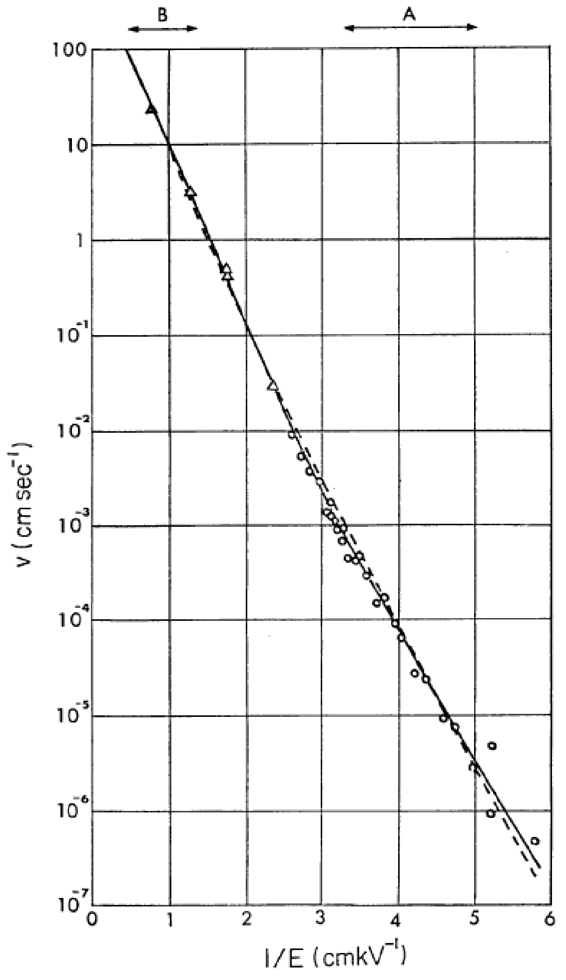
AE - Power law distribution



- Dynamic criticality: a state at which the dynamics of the process is unpredictable

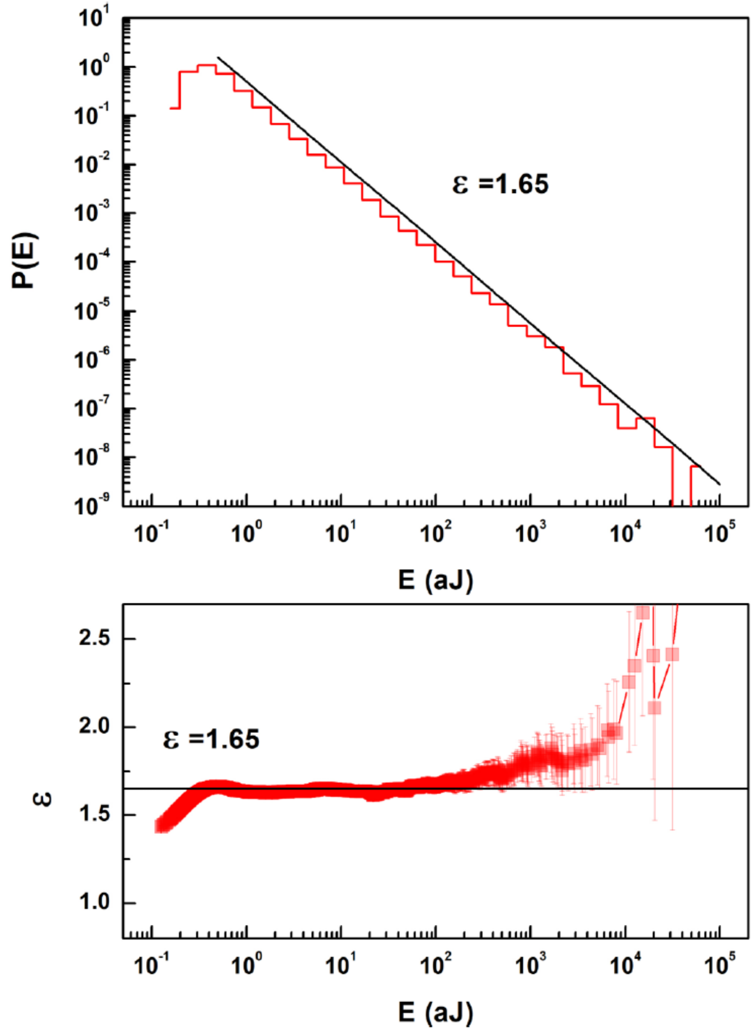
A similar enigma for 90° domain wall motion in ferroelectric $BaTiO_3$

Domain wall velocity



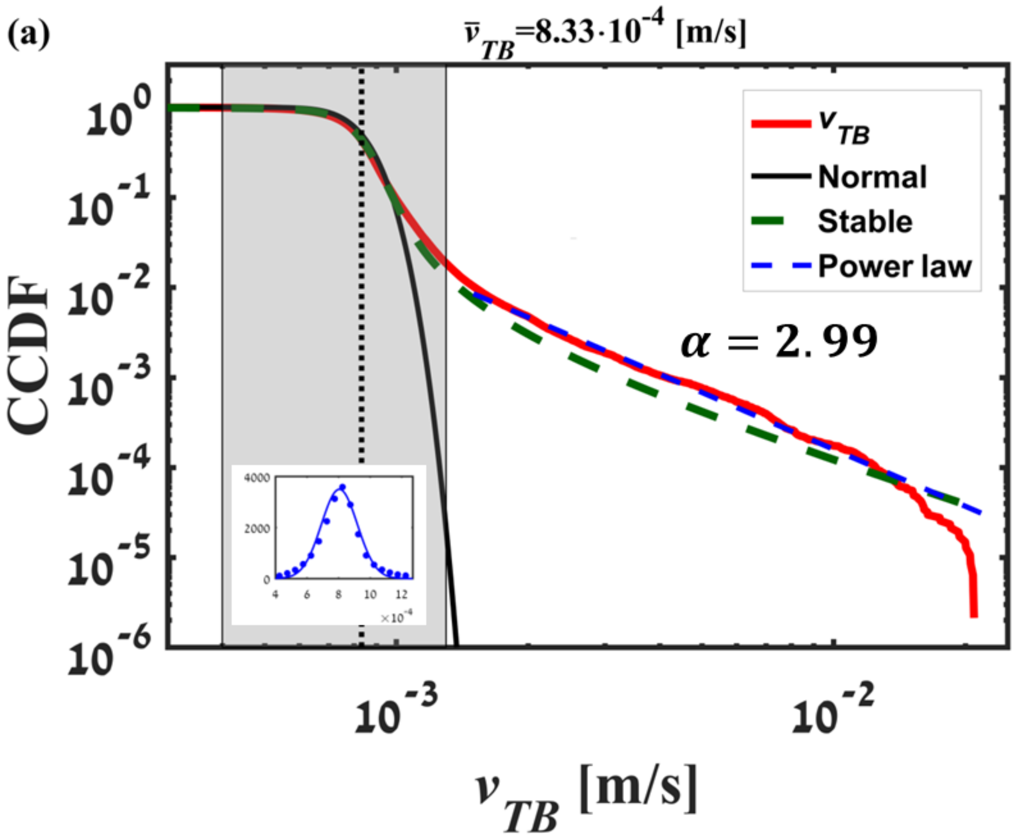
- Well determined kinetic law

AE energy



- Power law distribution

Coexistence of a well-determined kinetic law and a scale-invariant power law during the same physical process



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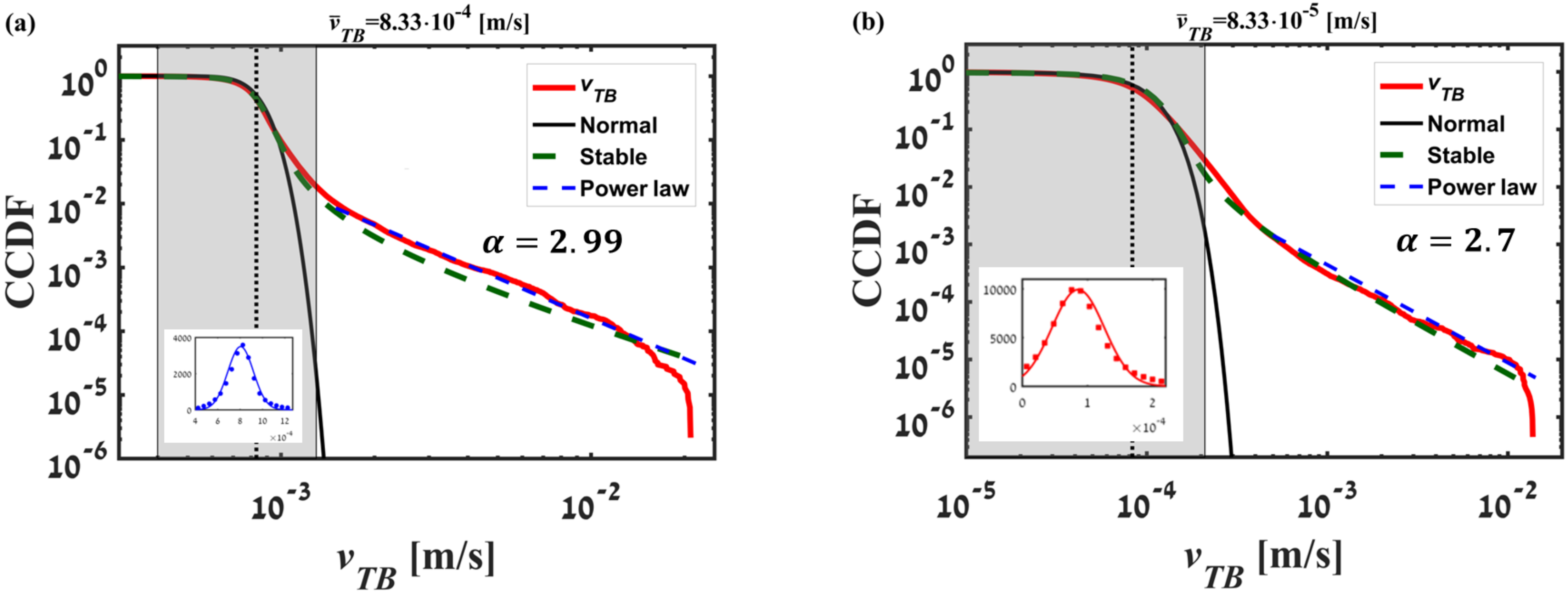

Conclusions for type II twin boundaries

The two different statistical behaviors reflect the mixing of different types of fluctuations:

<u>During most of the twin boundary motion:</u>

Slow and mild non-critical fluctuations about an average value, predicted by a kinetic law.

<u>During short times:</u>

Fast and abrupt avalanches that display a power law distribution.

Results for type I twin boundaries

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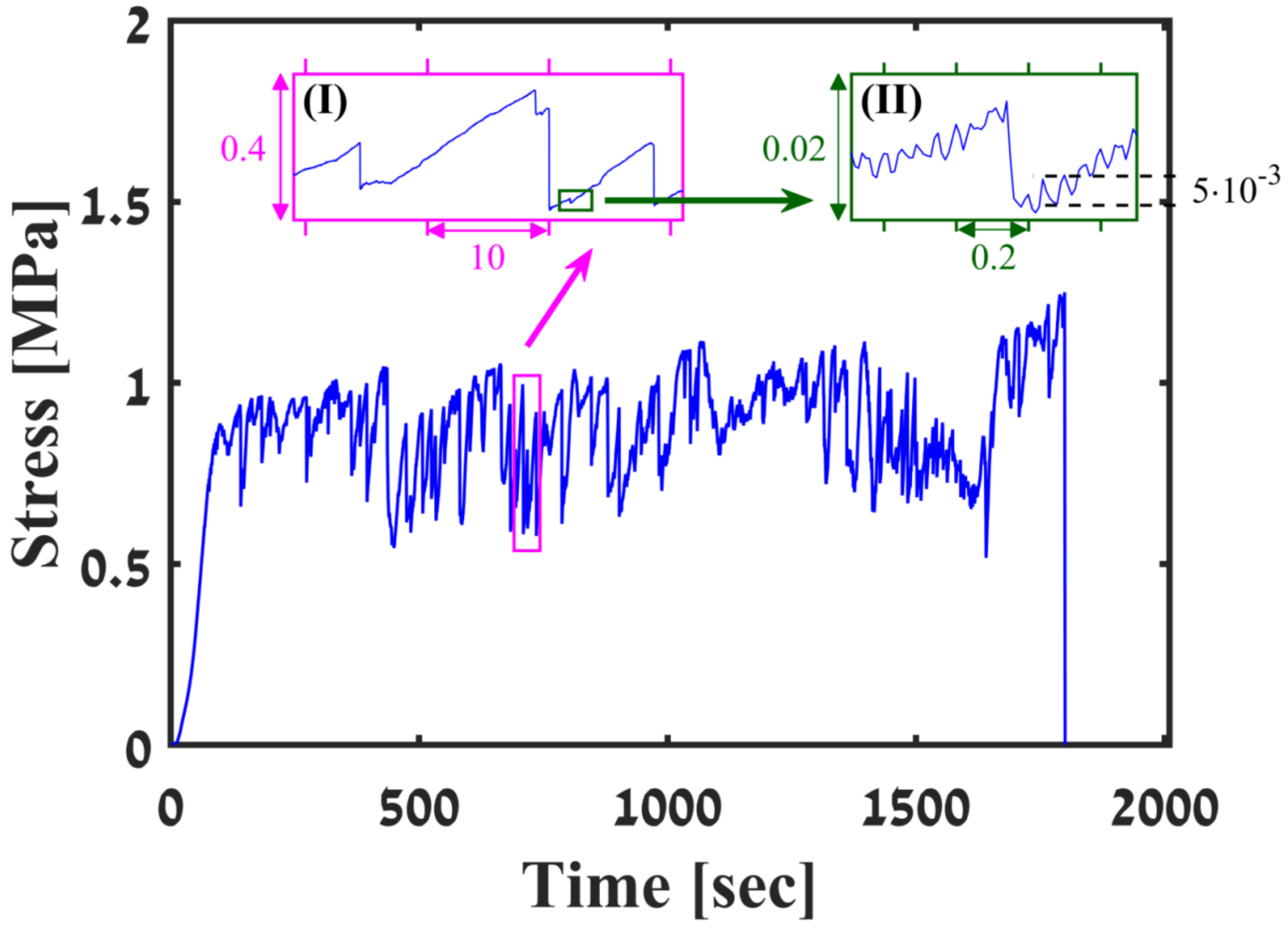
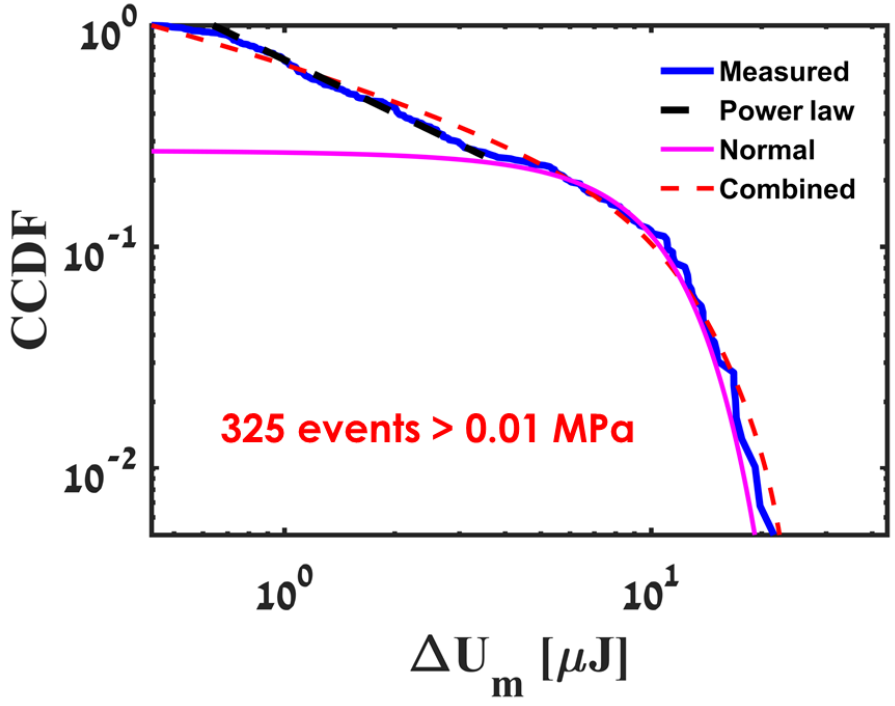


$$\dot{\sigma} = \frac{Y}{L_0}(c - \varepsilon_T v_{TB})$$

- Time intervals during which the stress increases linearly, indicating that the twin boundary doesn’t move.
- Distinct abrupt stress drops that occur during twin boundary motion.

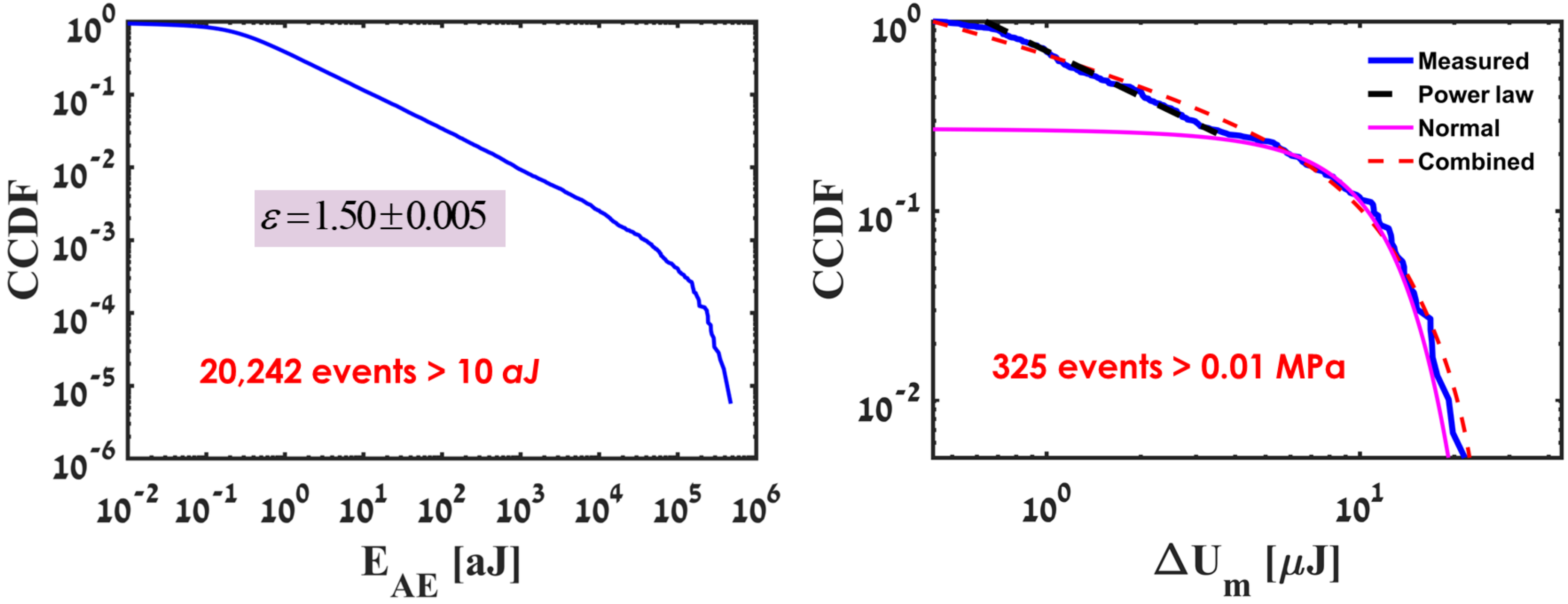
Statistical distributions



Mechanical energy released during an avalanche:

$$\Delta U_m = \frac{F_{up}^{\ 2} - F_{down}^{\ 2}}{2k}$$

Statistical distributions



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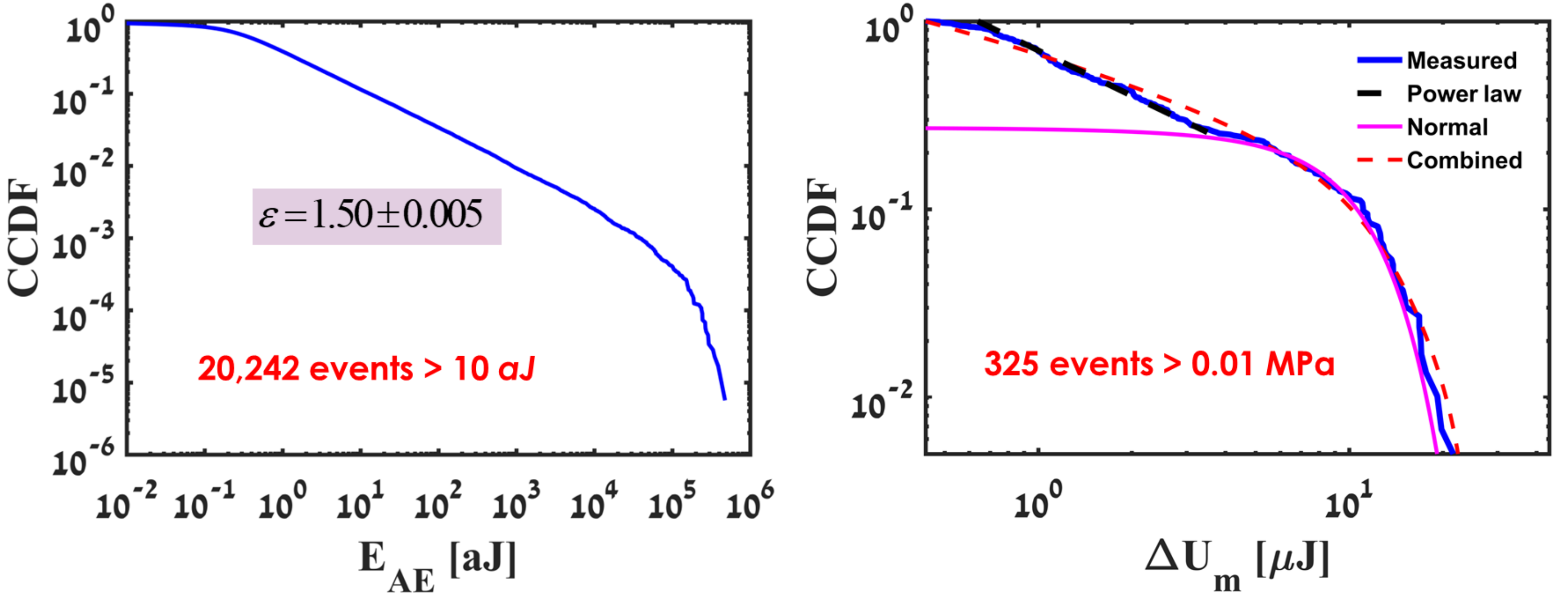

Mechanical energy released during an avalanche:

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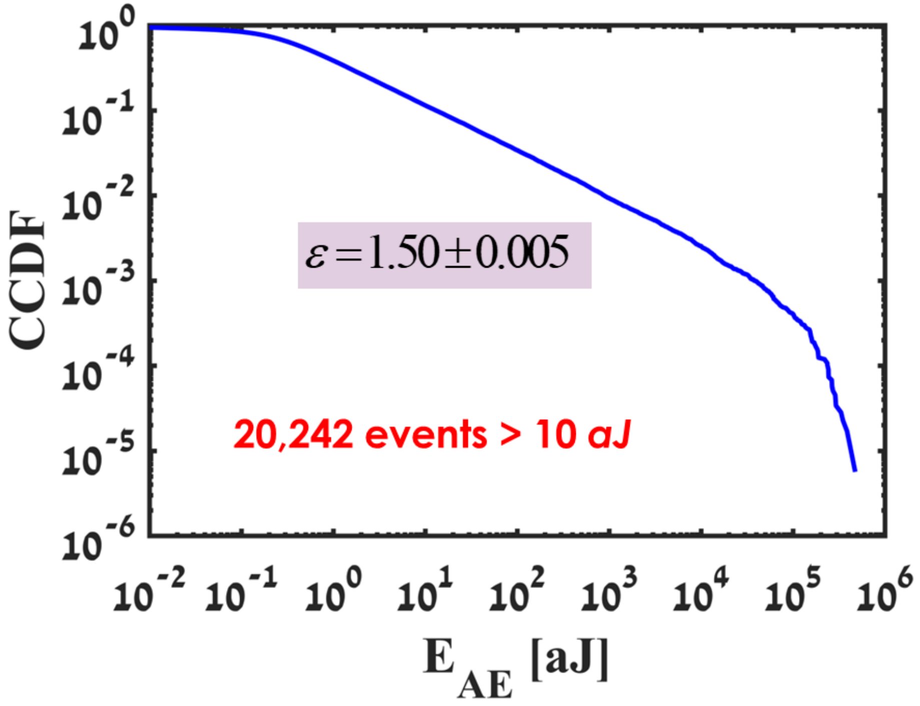
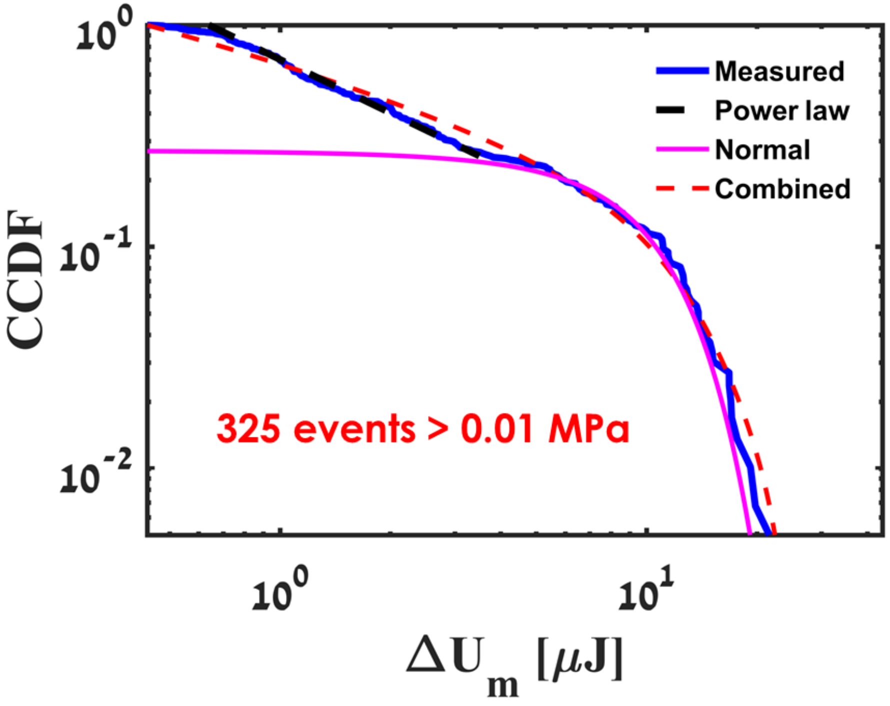
- **98.5% of the AE signals with an energy larger than 10 *aJ* were not associated with any detectable stress drop event.**

Statistical distributions





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- **All values of E_{AE} are smaller by at least 7 orders of magnitude than the corresponding value of ΔU_m .**

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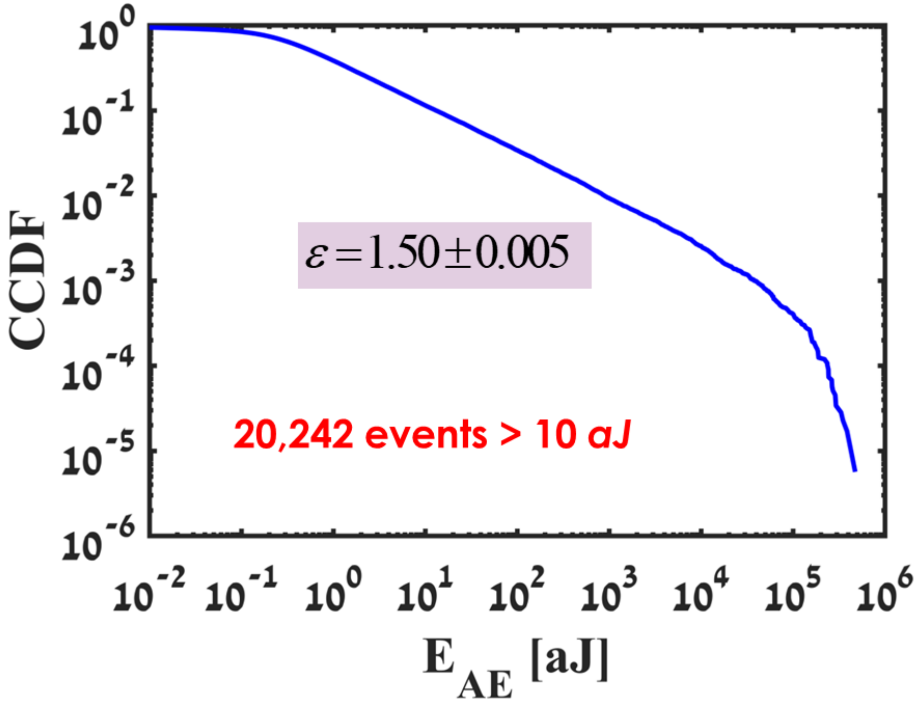

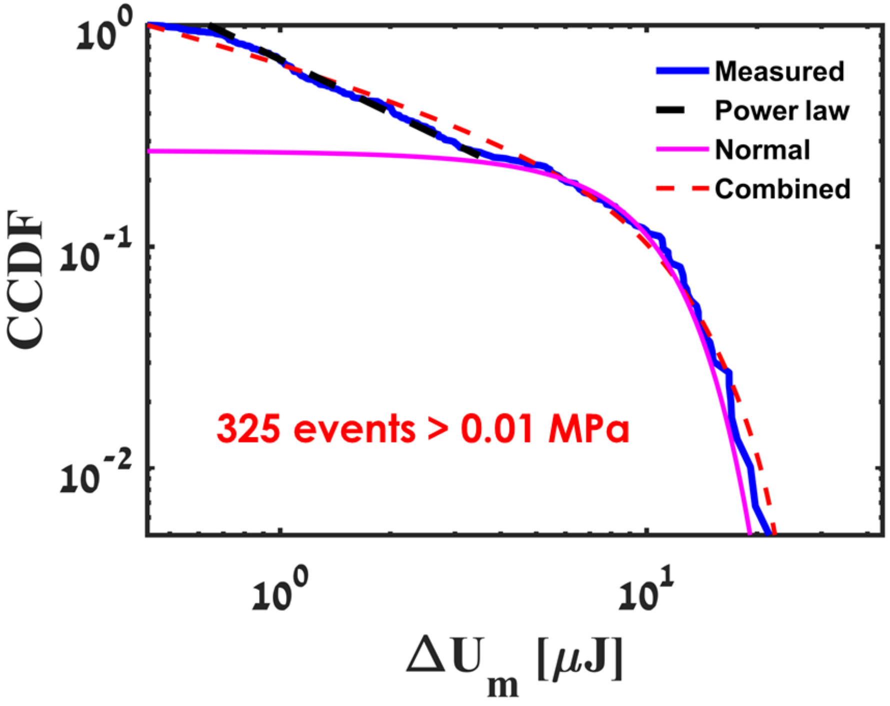

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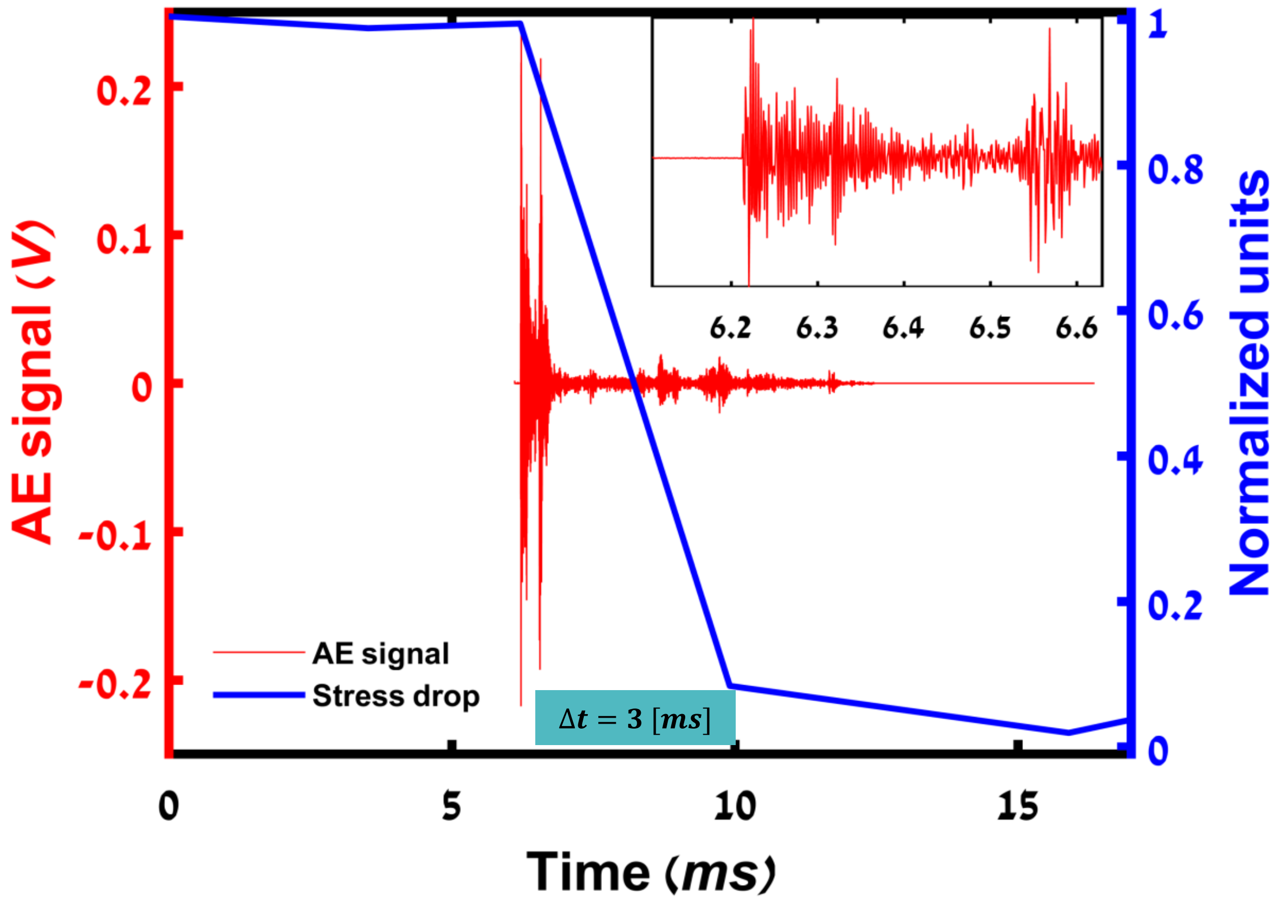
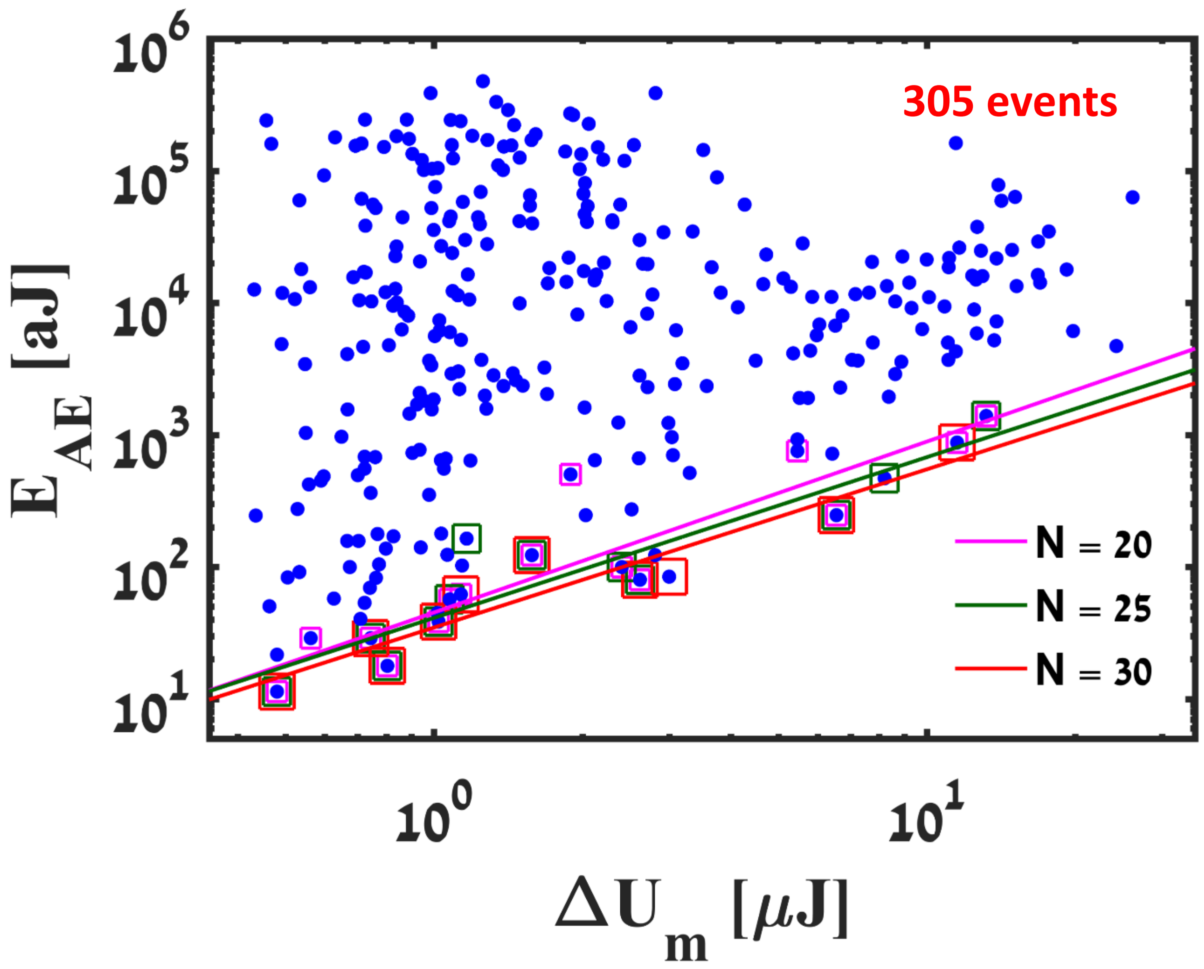
- **98.5% of the AE signals with an energy larger than 10 *aJ* were not associated with any detectable stress drop event.**
- **All values of E_{AE} are smaller by at least 7 orders of magnitude than the corresponding value of ΔU_m .**
- **The overall AE energy is smaller by 8 orders of magnitude than the overall released mechanical energy.**

Relations between stress drops and AE on the level of individual events



- 94% of the stress drop events were accompanied by an AE signal with an energy larger than 10 aJ.
- The probability of finding an AE event during a stress drop is ~ 100 times higher than between stress drops.

Stress drops vs AE signals on the level of individual events



Lower bound:

$$\min(E_{AE}) = E_{LB}$$

$$E_{LB} = C \cdot \Delta U_m^{\,1.24}$$

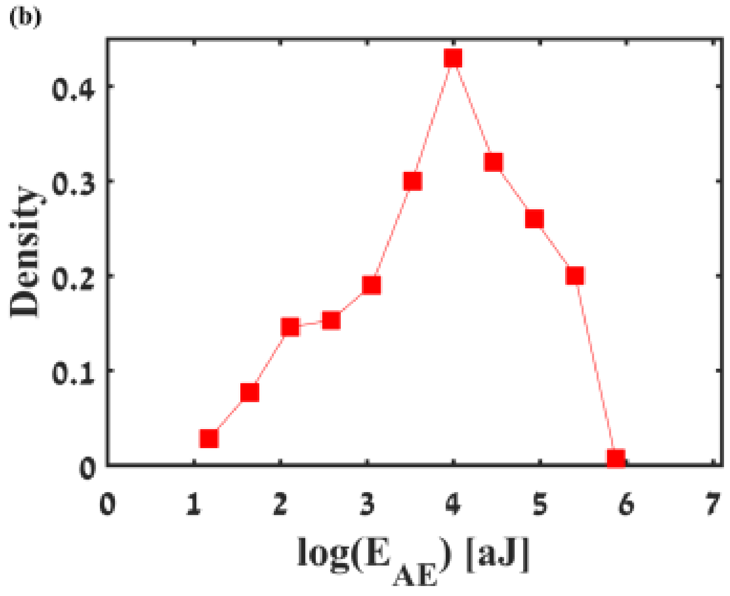
$$E_{AE} = E_{LB} + \Delta E$$

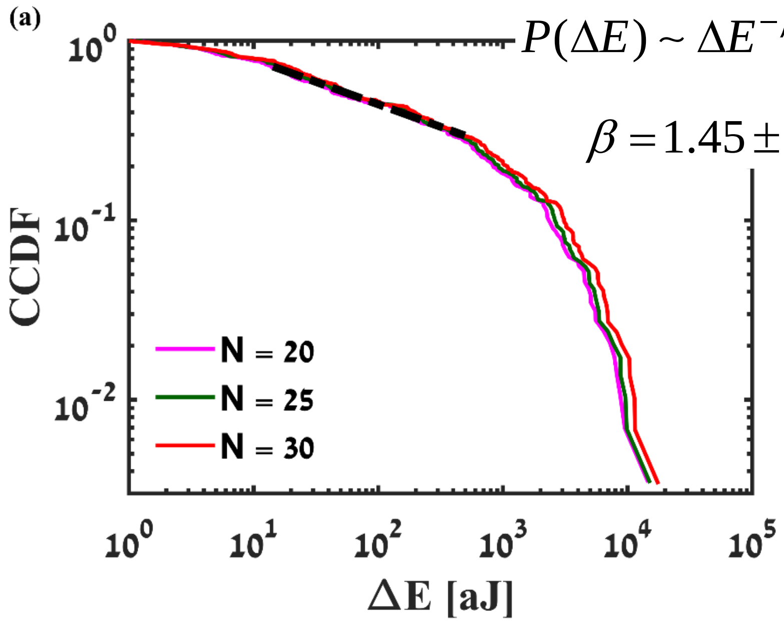
- E_{LB} is associated with macroscopic stress changes.

Analysis of AE events occurring during stress drops

* Only 305 events

$$E_{AE} = E_{LB} + \Delta E$$





$$P(\Delta E) \sim \Delta E^{-\beta} \cdot \exp\left(-\frac{\Delta E}{\Delta E_{cutoff}}\right)$$

$$\beta = 1.45 \pm 0.05$$

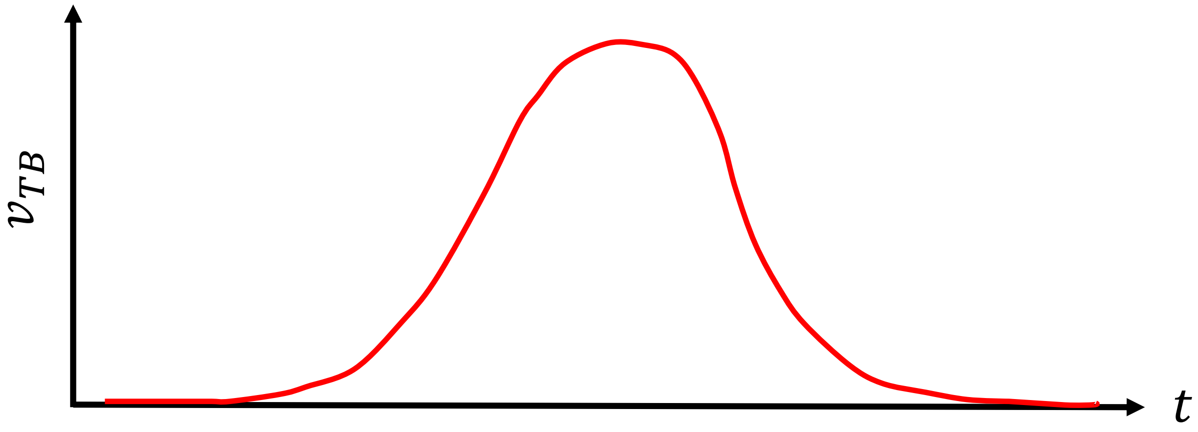
The distribution of E_{AE} is centered about a peak that represents a typical value.

The distribution of ΔE has a power law segment

The process that contributes to ΔE is close to dynamic criticality.

Discussion

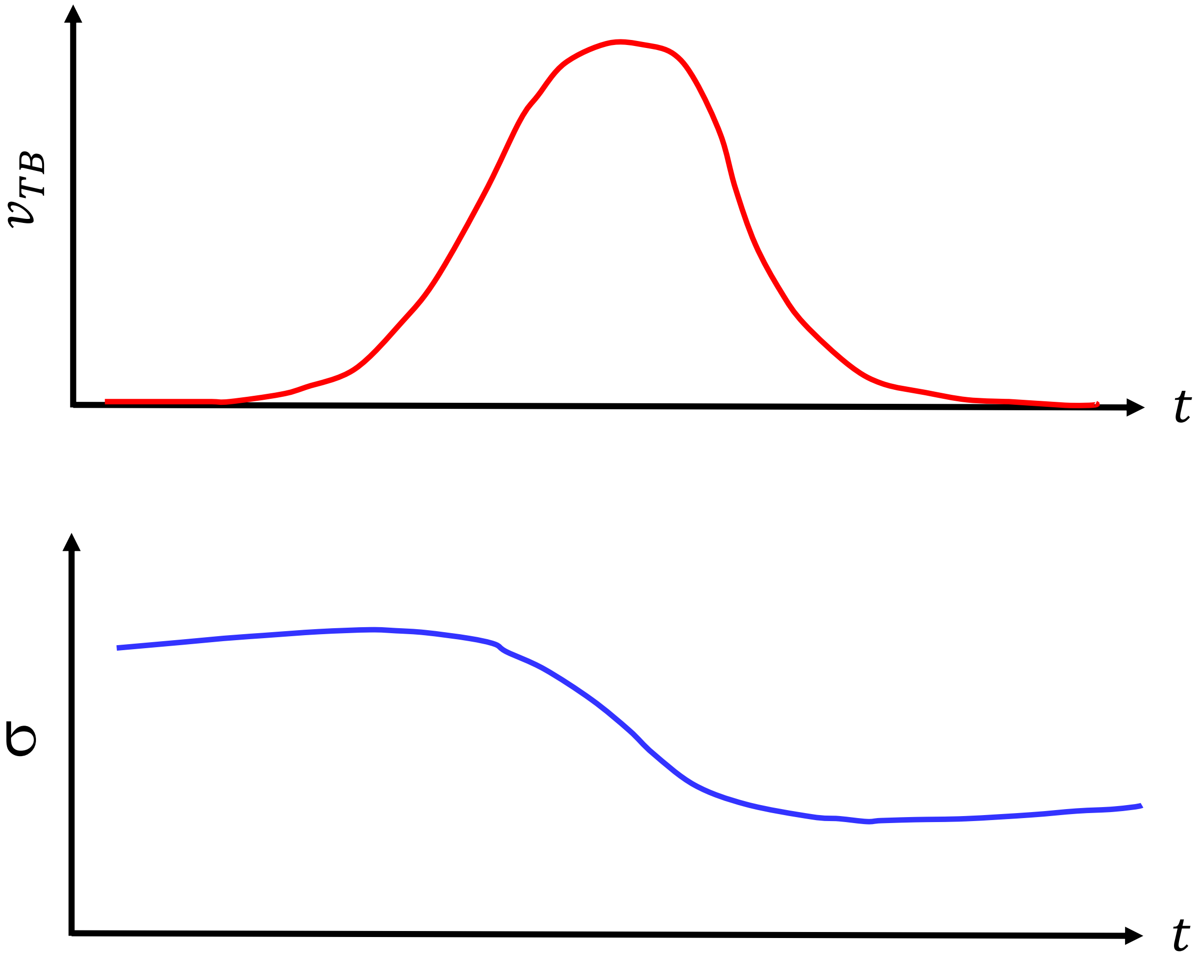
Avalanche is manifested by a burst of twin boundary velocity



Discussion

Stress drop:

$$\dot{\sigma} = \frac{Y}{L_0}(c - \varepsilon_s v_{TB})$$



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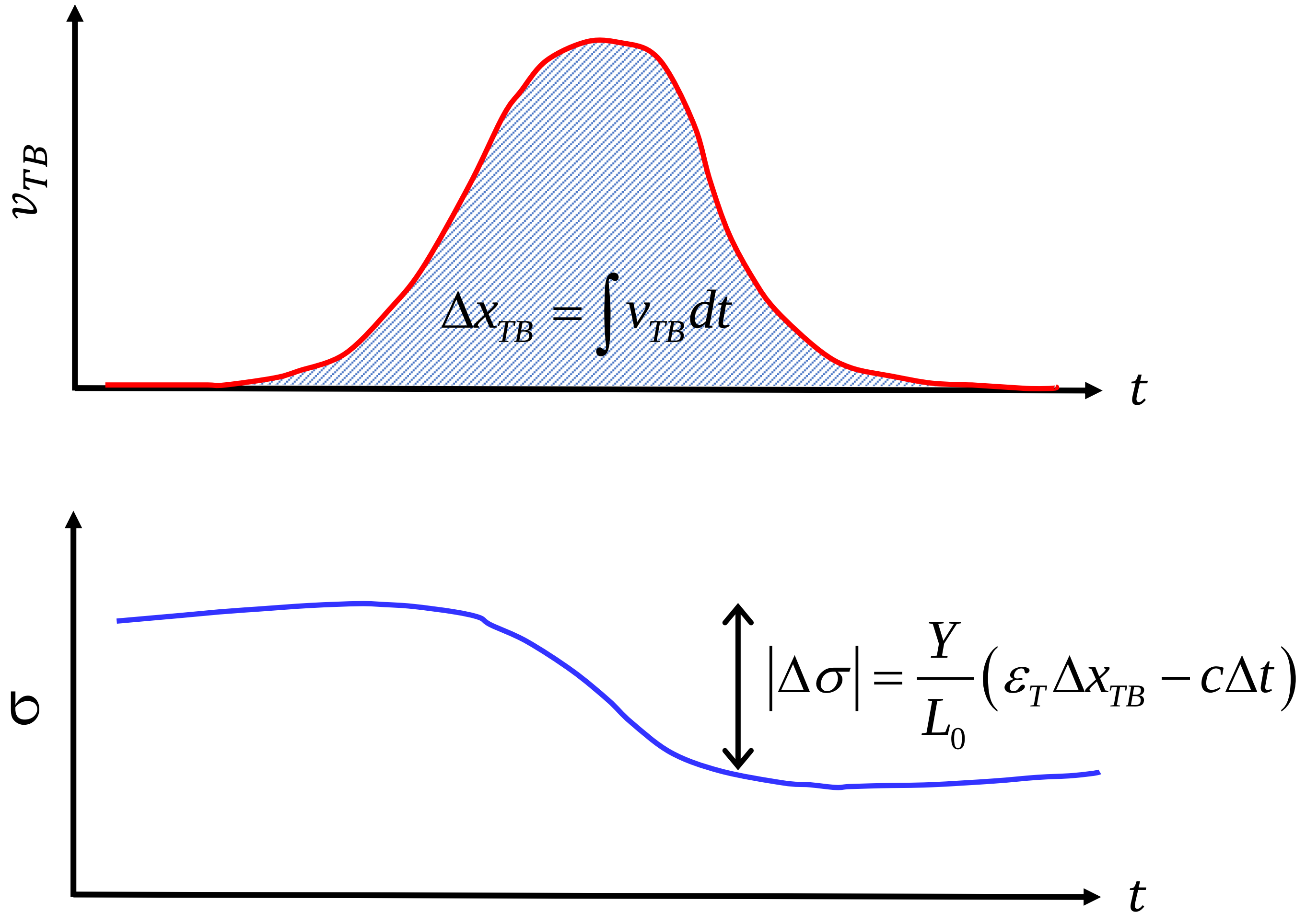
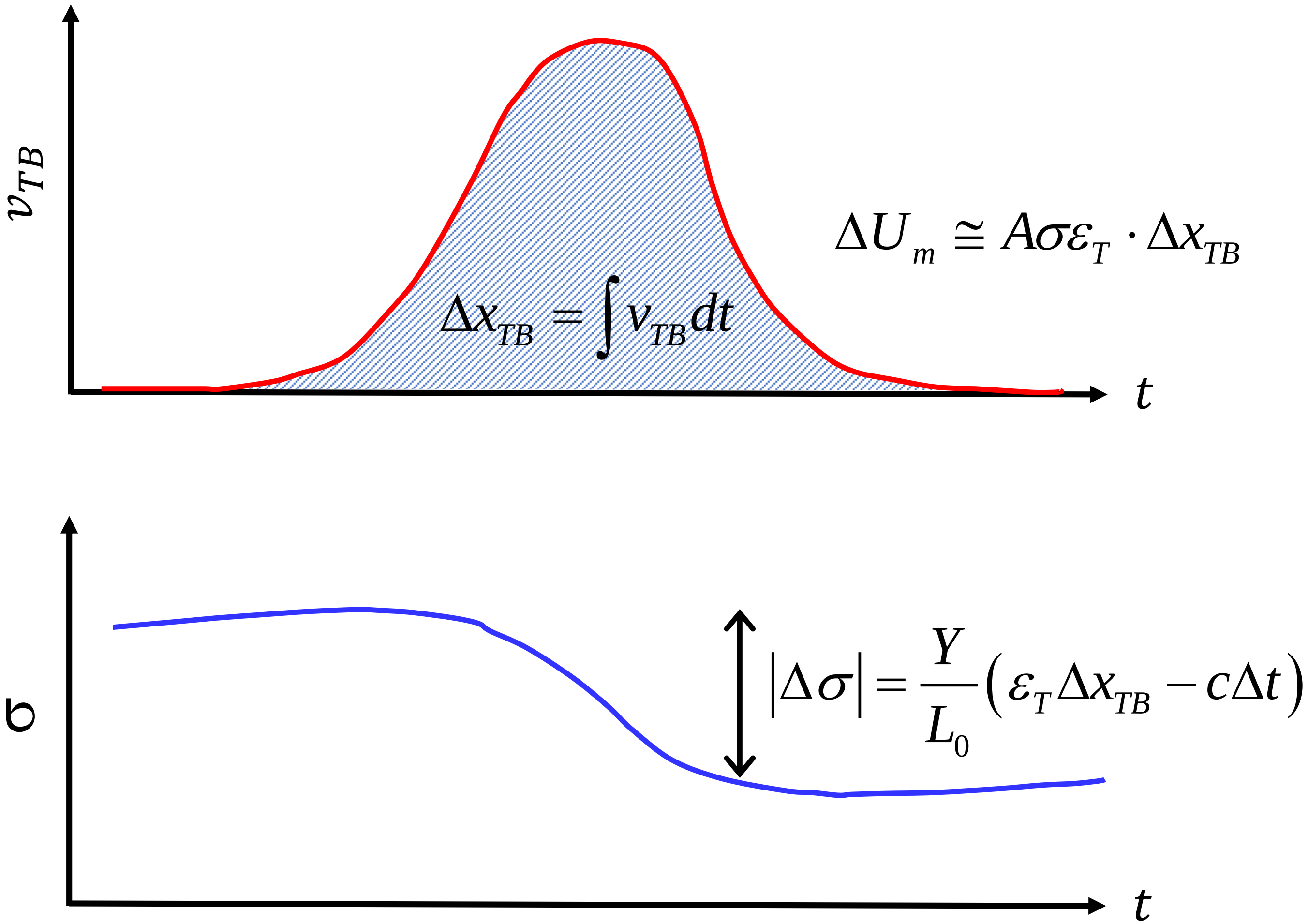


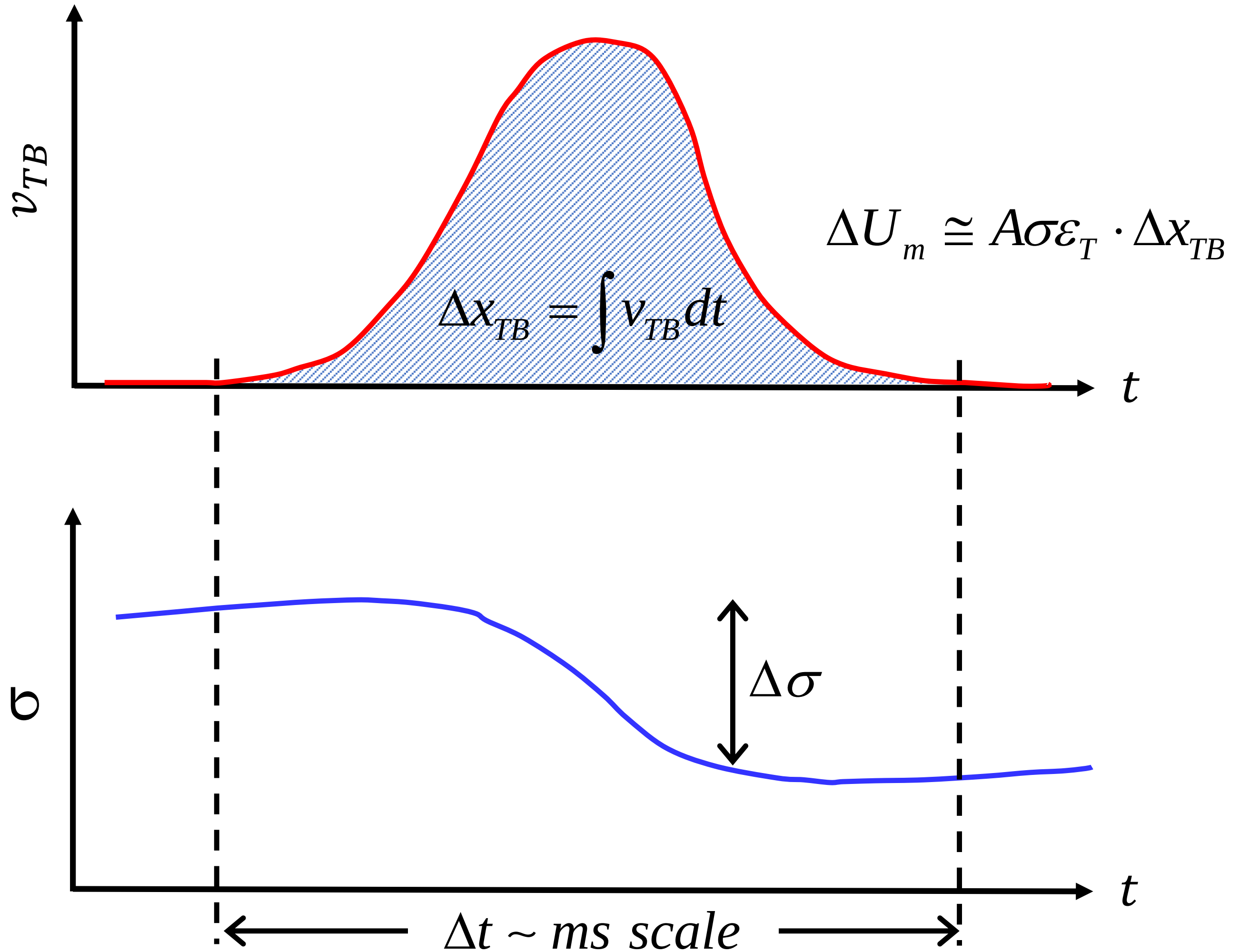
v_{TB}
$\Delta x_{TB} = \int v_{TB} dt$
t
σ
$|\Delta\sigma| = \frac{Y}{L_0}(\varepsilon_T \Delta x_{TB} - c\Delta t)$
t

Discussion



v_{TB}
$\Delta U_m \cong A\sigma\varepsilon_T \cdot \Delta x_{TB}$
$\Delta x_{TB} = \int v_{TB} dt$
t
σ
$|\Delta\sigma| = \frac{Y}{L_0}(\varepsilon_T \Delta x_{TB} - c\Delta t)$
t

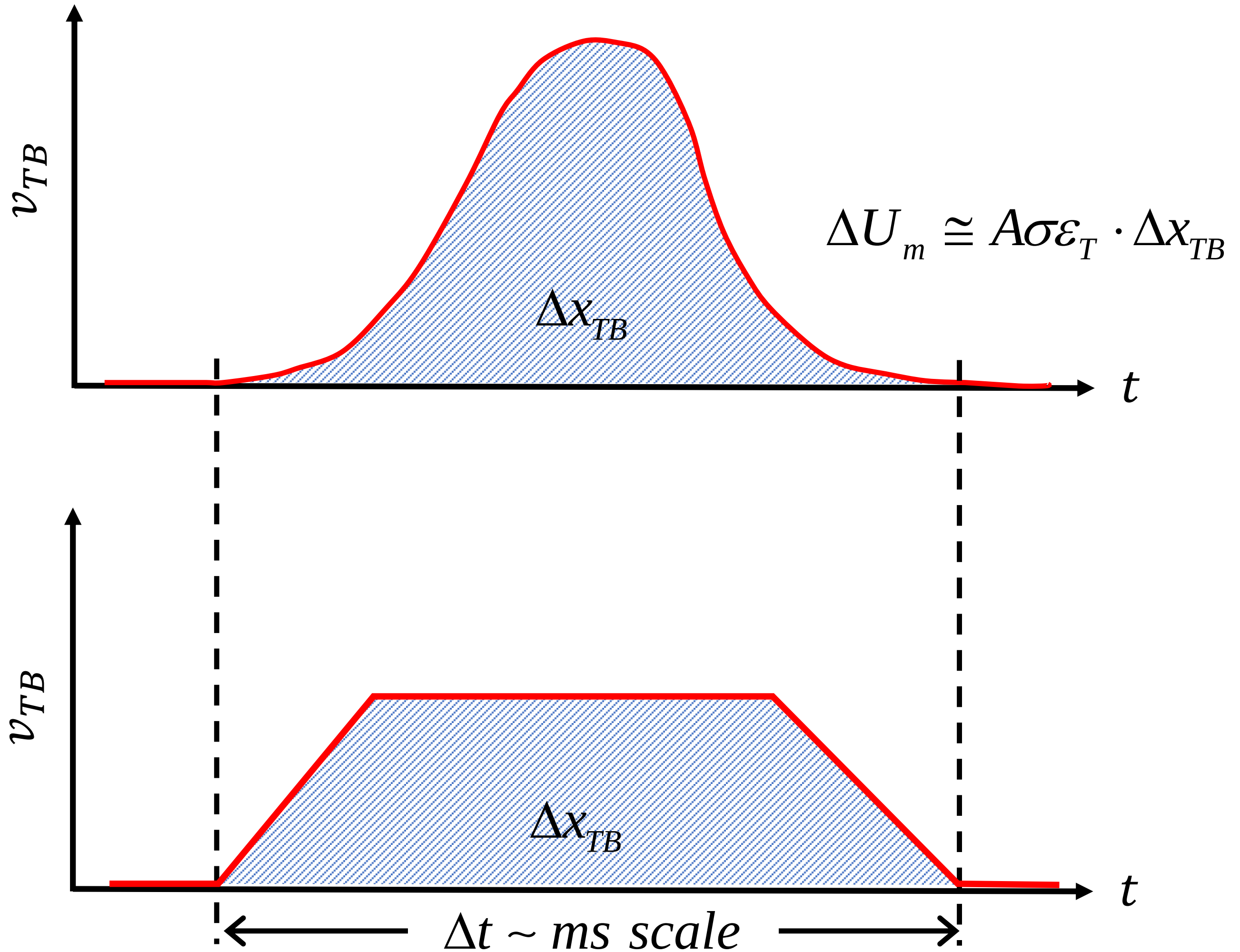
Discussion



- **The stress drop generates a wide band of acoustic waves, most of them with frequencies that scale as 1/Δt (sub kHz range) and are much lower than the frequency range captured by the AE transducer (above 100 kHz).**

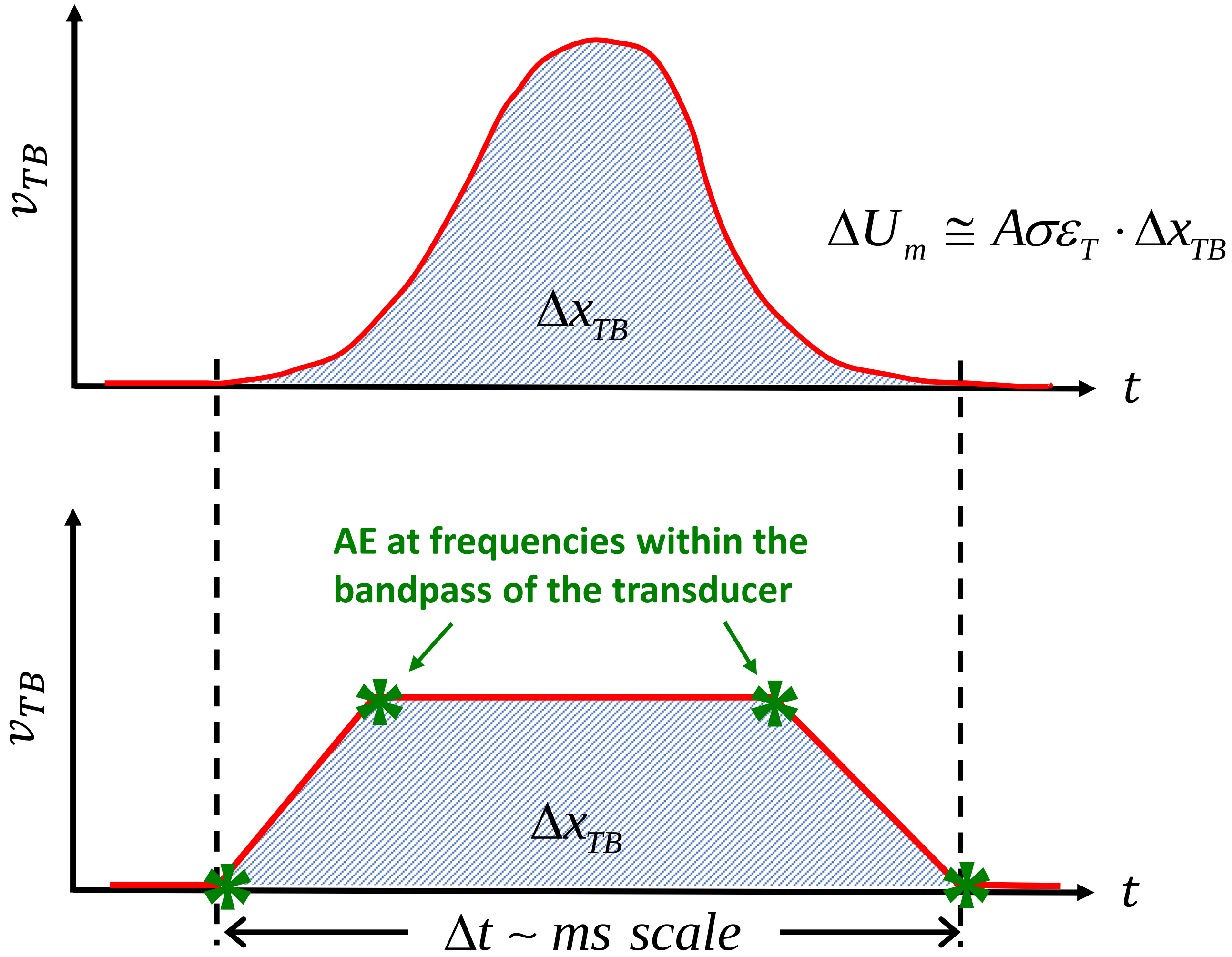
Therefore: $\boldsymbol{\Delta U_m \gg E_{AE}}$

Shape of the v_{TB} vs. t avalanche



- **The same values of Δx_{TB} , Δt , $\Delta \sigma$, and ΔU_m.**

Shape of the v_{TB} vs. t avalanche



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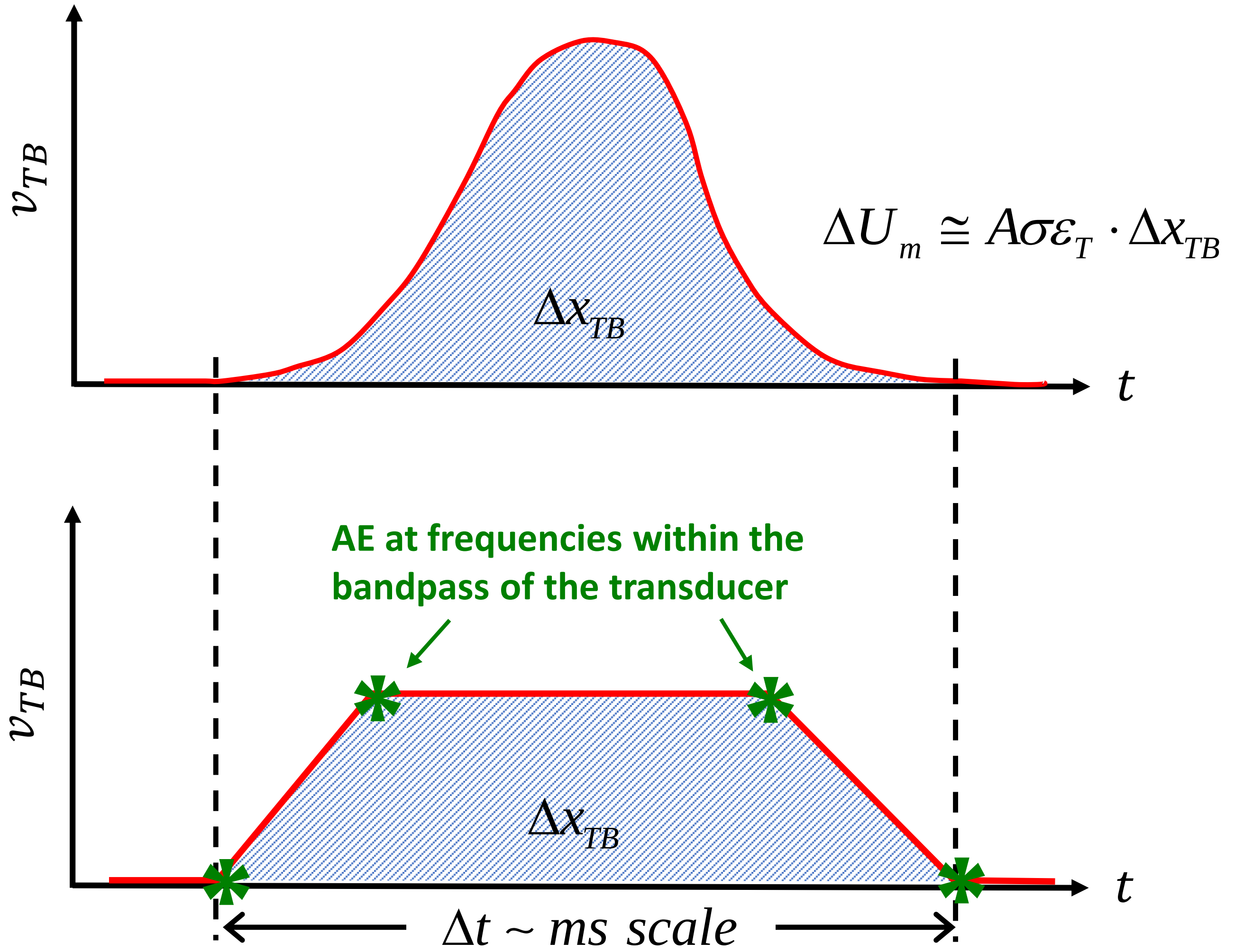
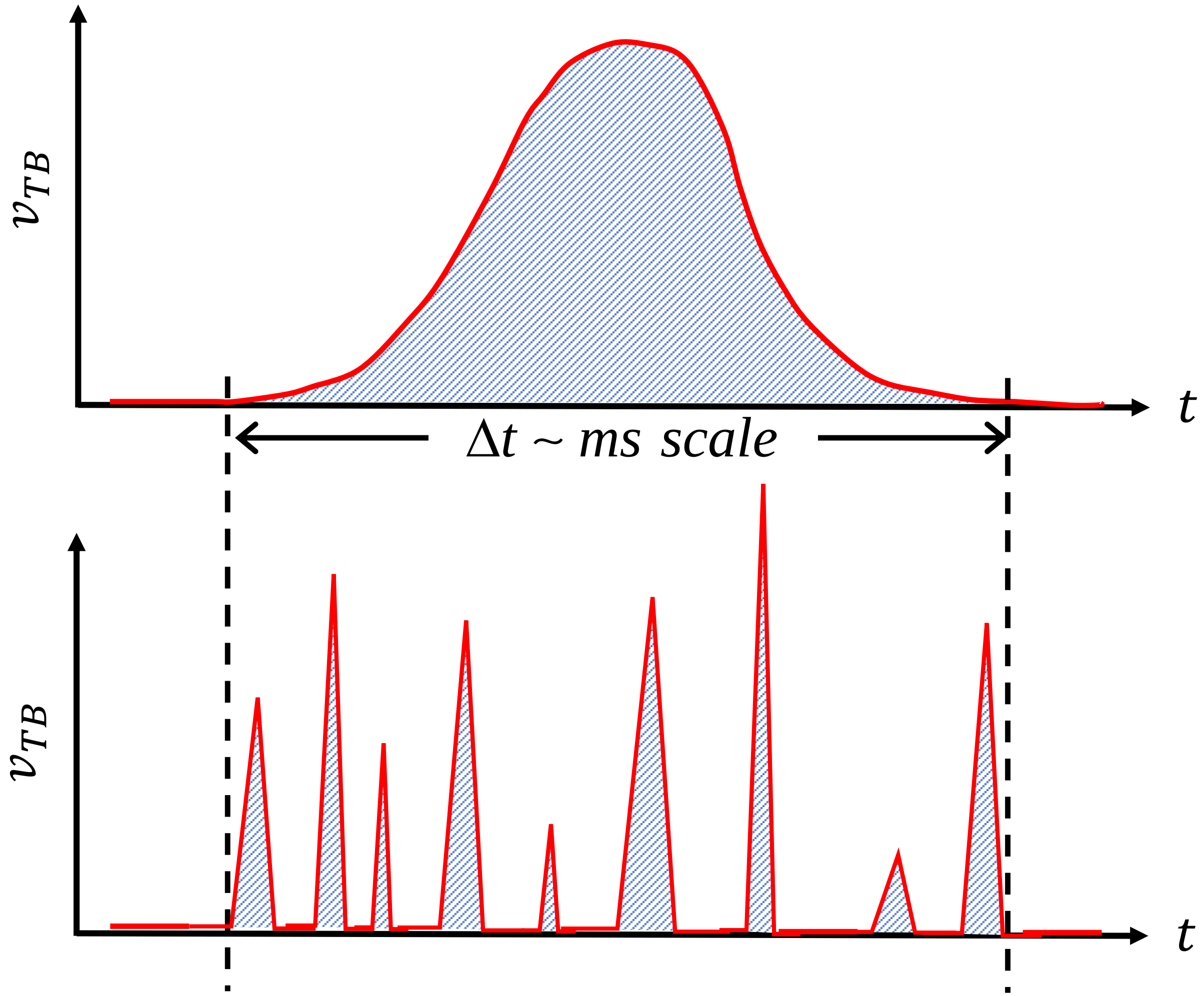
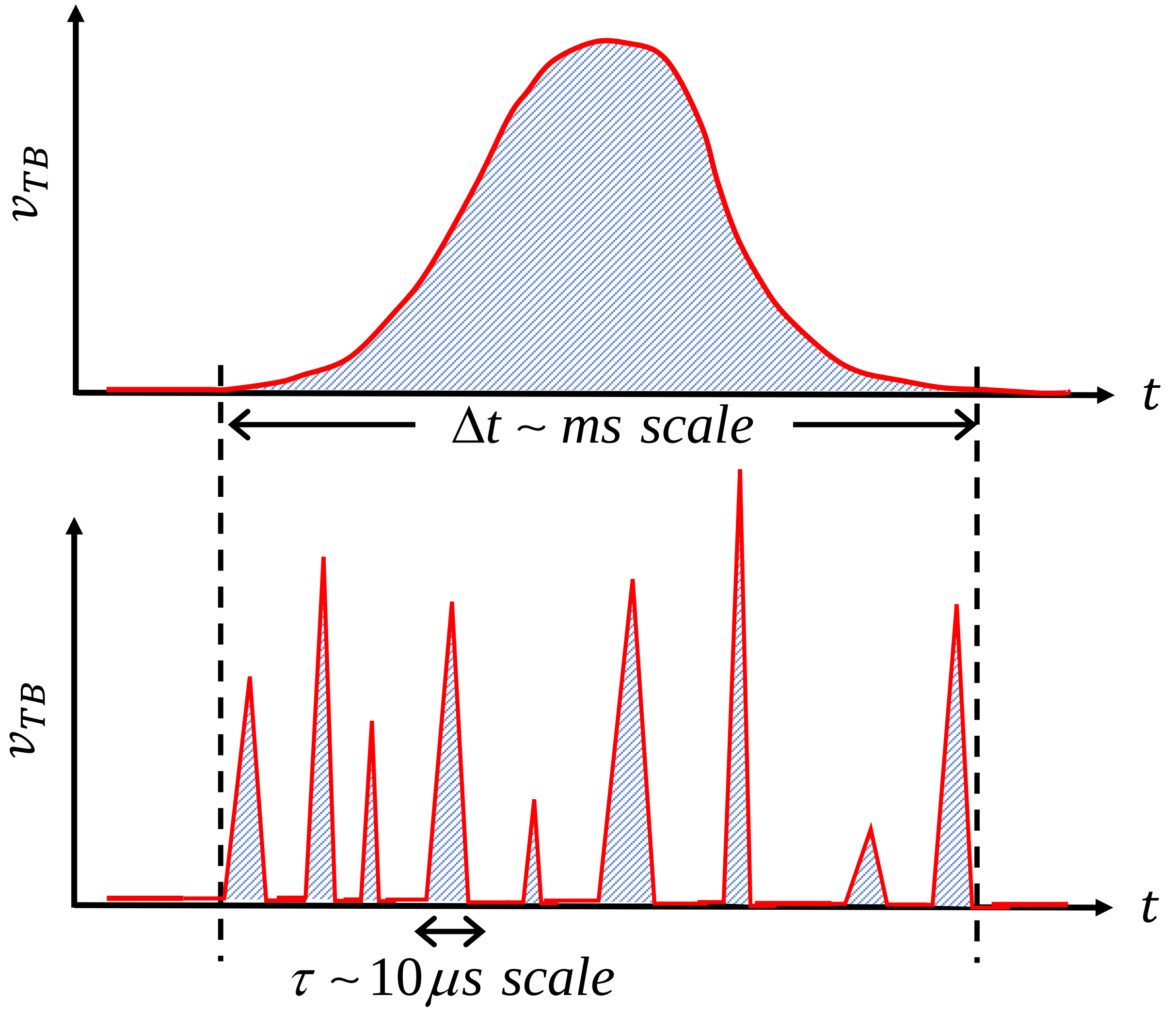


- **The same values of Δx_{TB} , Δt , $\Delta\sigma$, and ΔU_m.**
- **But a different E_{AE}.**

A more complex shape of the v_{TB} vs. t avalanche

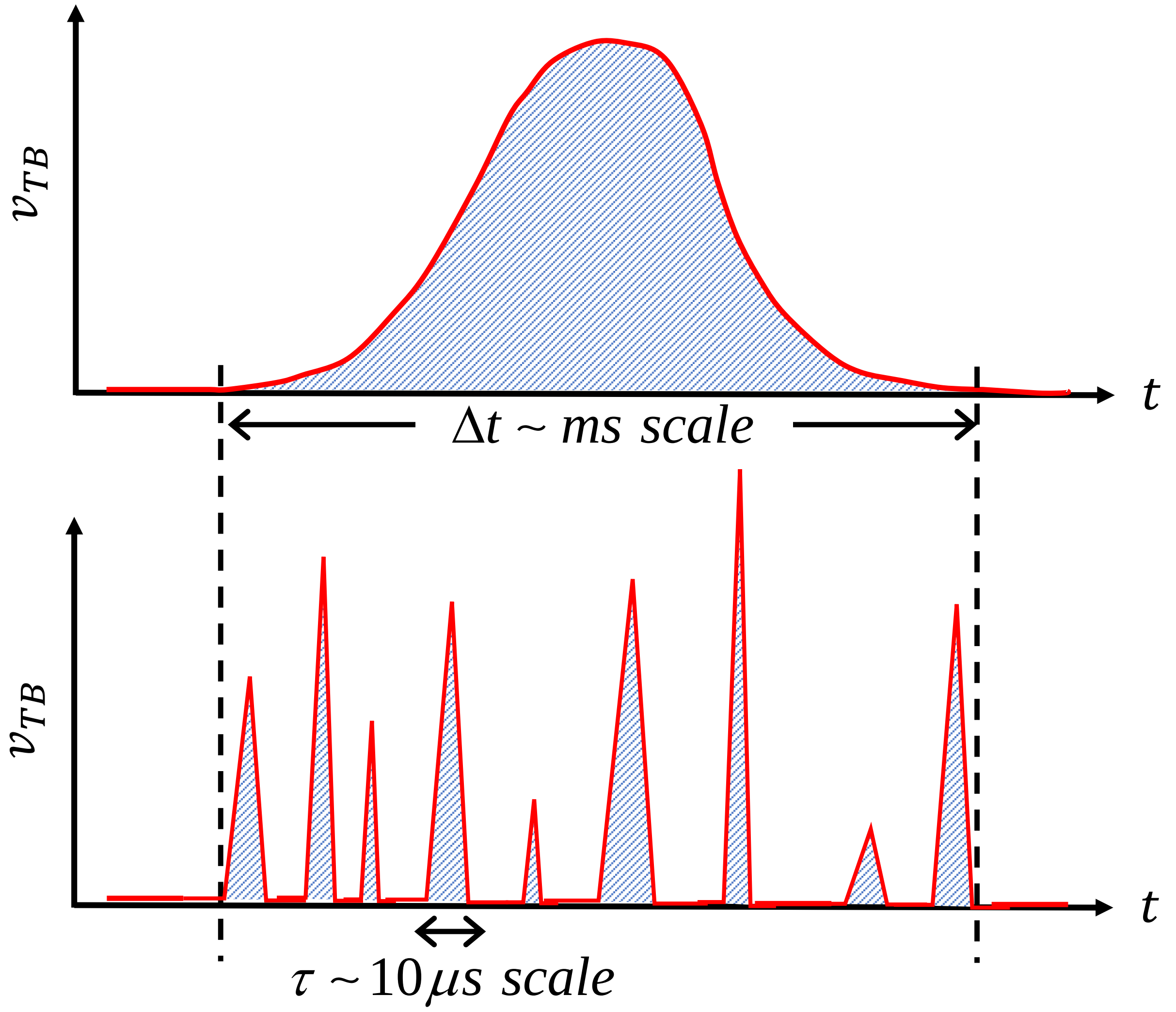


A more complex shape of the v_{TB} vs. t avalanche



$1/\tau$ - within the bandpass of the transducer.

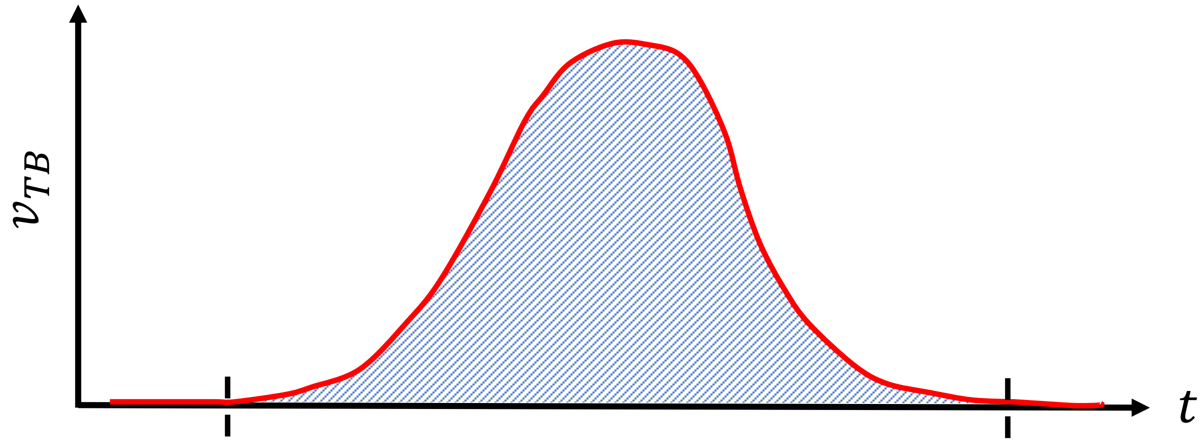
A more complex shape of the v_{TB} vs. t avalanche



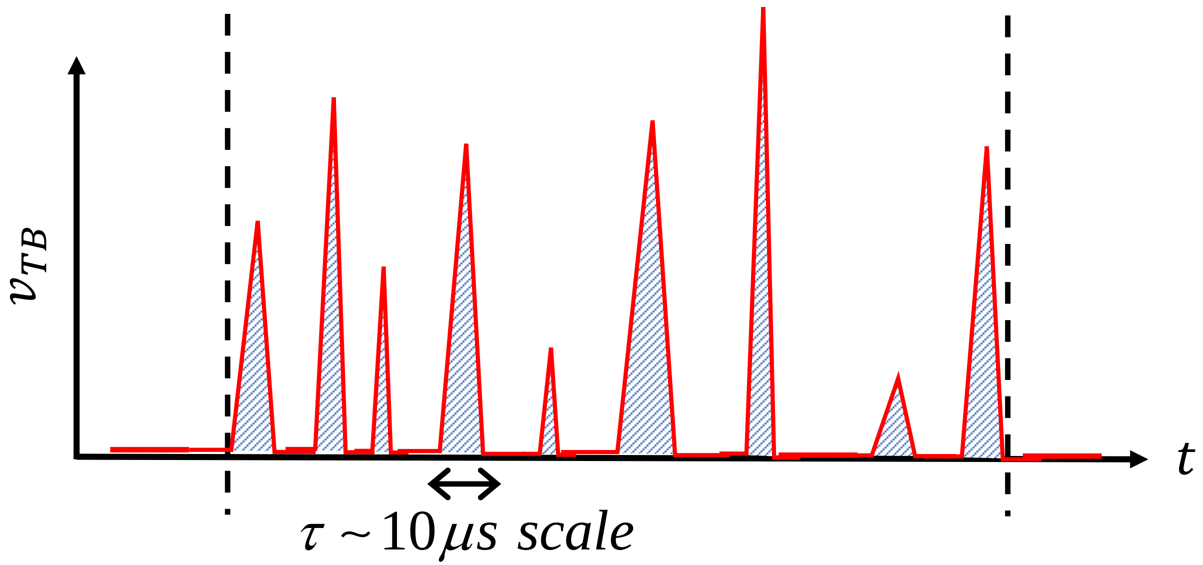
$1/\tau$ - within the bandpass of the transducer.

AE signals generated by the μs scale velocity burst may overlap.

A more complex shape of the v_{TB} vs. t avalanche



The real behavior of type I twin boundaries in Ni-Mn-Ga



$1/\tau$ - within the bandpass of the transducer.

AE signals generated by the μs scale velocity burst may overlap.

Conclusions for type I twin boundary

- There is no direct correlation between parameters measured by the force sensor (Δx_{TB}, $\Delta\sigma$, and ΔU_m) and the AE sensor during the same events.

- There is a lower bound for E_{AE}, which is approximately proportional to ΔU_m.

- The additional AE energy, above the lower bound, display a power law distribution, indicating that this contribution comes from local events that occur at much smaller scales (nm length scale and μs time scale).

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- **Unified theories that explain both avalanche statistics and kinetic laws are highly desired.**
- **A first step toward obtaining such theories is to take simultaneous measurements of different variables.**