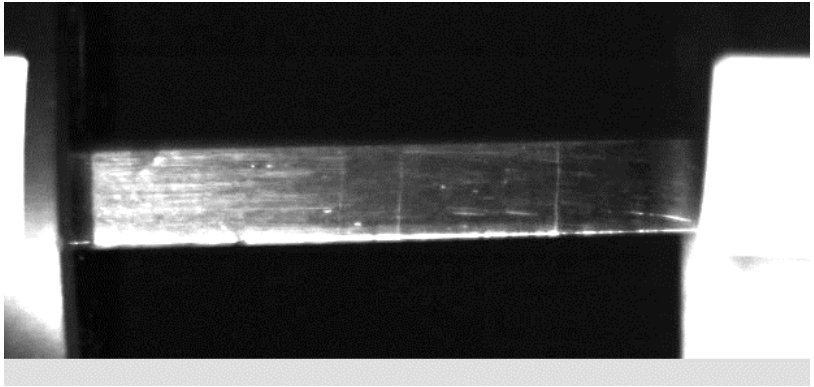
# Tracking twin boundary jerky motion at nanometer and microsecond scales

**Emil Bronstein**, László Z. Tóth, Lajos Daróczi, Dezsö L. Beke,
Ronen Talmon, and Doron Shilo.

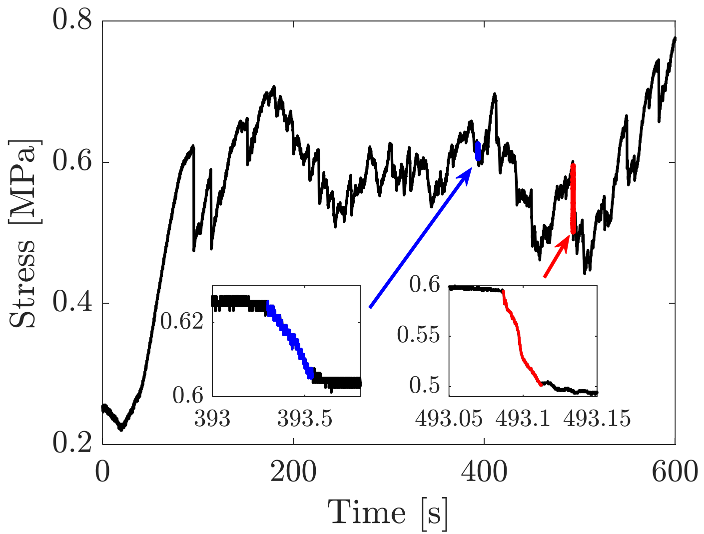
# Introduction and motivation

- **Twin boundary motion** governs the plastic deformation of a variety of materials (e.g., Mg, Ti, shape memory alloys, ferroelastics, ferroelectrics).
- Twin boundary motion is studied at both **slow** and **high loading rates**.



# Slow-rate tests

Twin boundary motion occurs via discrete and impulsive events called ‘avalanches’.

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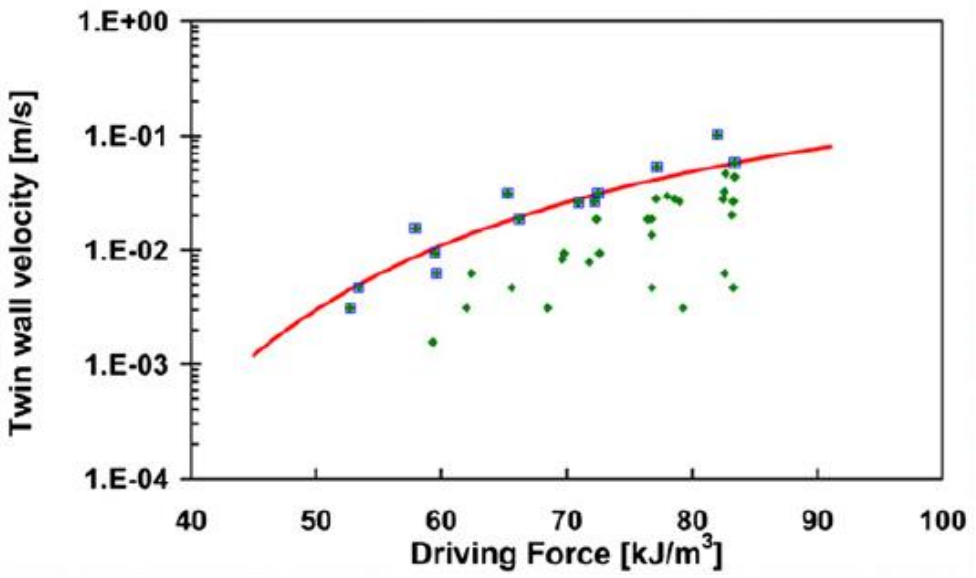
# High-rate tests

Twin boundary velocity changes were found to be bounded from above by a **kinetic law** in a **defect free crystal**.




E. Faran, D. Shilo, *Journal of the Mechanics and Physics of Solids* **61** (2013) 726–741.

# Knowledge gap

## Slow-rates

- Avalanches
- Kinetic laws have not been discussed

?

## High-rates

- Kinetic laws
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# Knowledge gap

**Slow-rates** ? **High-rates**

**Slow-rates**

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**High-rates**

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# Research goal and methodology

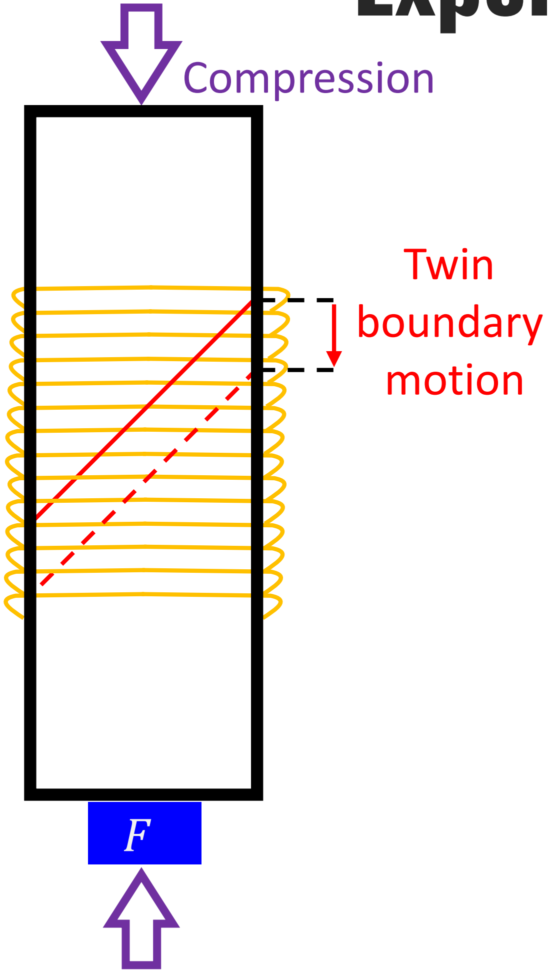
## Goal

Investigate twin boundary motion at **nanometer** and **microsecond** scales via **direct** measurements during slow-rate loading.

## Methodology


Measure the **force** (stress) and **magnetic emission** (ME) of NiMnGa during twin boundary motion.

# Experimental setup

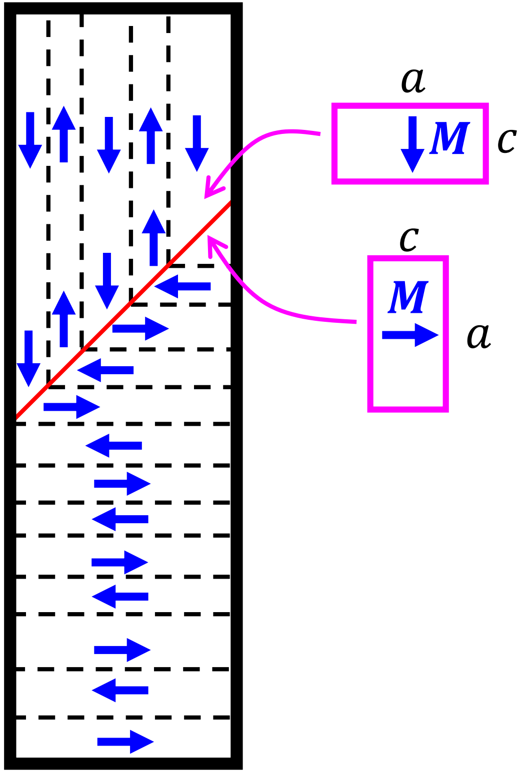



**Goal**

Measure simultaneously:

- Force
- Magnetization changes **only** due to twin boundary motion.

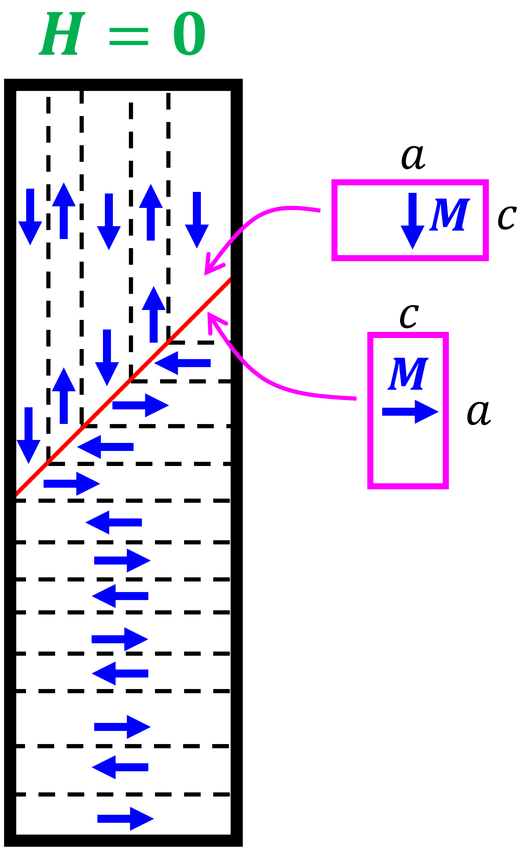
# Magneto-mechanical microstructure

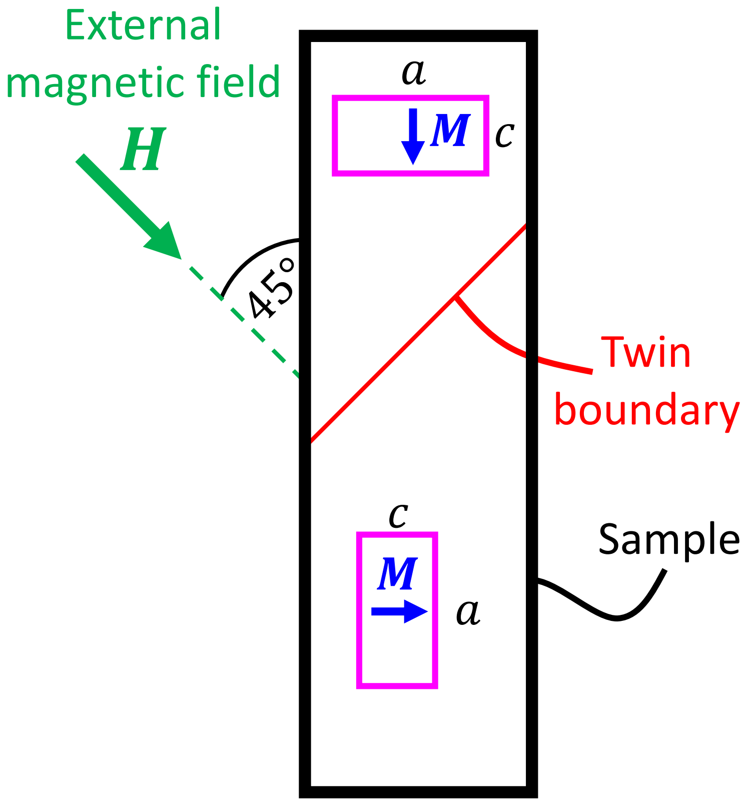



Magnetic emission due to:

- Twin boundary motion
- Magnetic domain switching

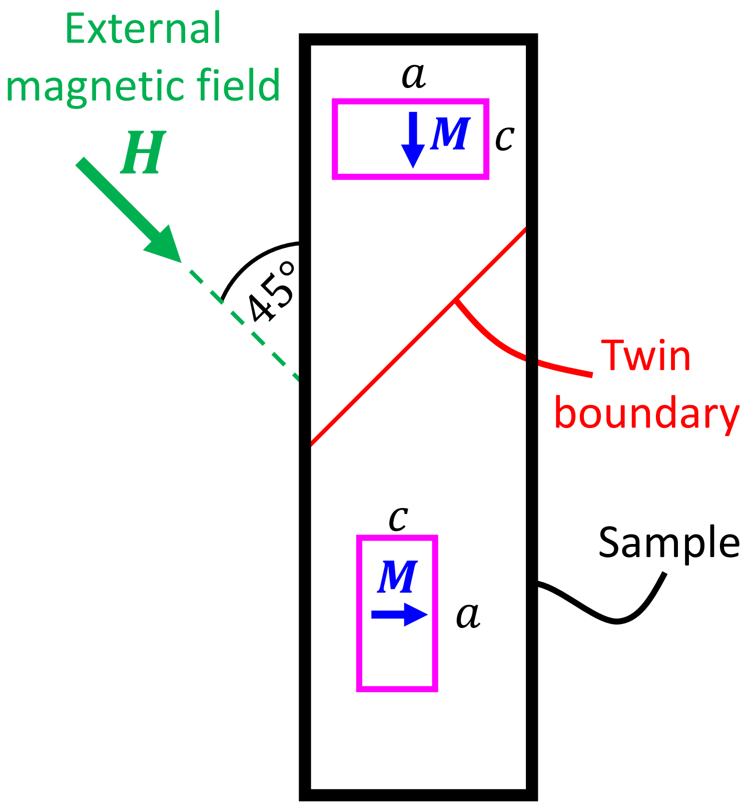
# Magneto-mechanical microstructure



# Magneto-mechanical microstructure

Magnetic emission (ME) **only** due to twin boundary motion



# Force and ME measurements

## Force measurements

- **Advantage:** **Directly** related to features of the twin boundary motion.

$$x_{TB} = \frac{1}{\varepsilon_T}\left(c\Delta t - \ell_0 \frac{\Delta\sigma}{Y}\right)$$

# Force and ME measurements

## Force measurements

- **Advantage:** **Directly** related to features of the twin boundary motion.

$$V_T = \frac{1}{\varepsilon_T}\left(Ac\Delta t - V_0\frac{\Delta\sigma}{Y}\right)$$

Measured stress

Volumes undergoing twinning transformation during avalanches

- **Limitation:** Capture **slow** (ms scale) and **large** ($\mu$m scale) events.

## ME measurements

- **Advantage:** ME measurements are capable of detecting **small** (nm scale) and **rapid** ($\mu$s scale) events.

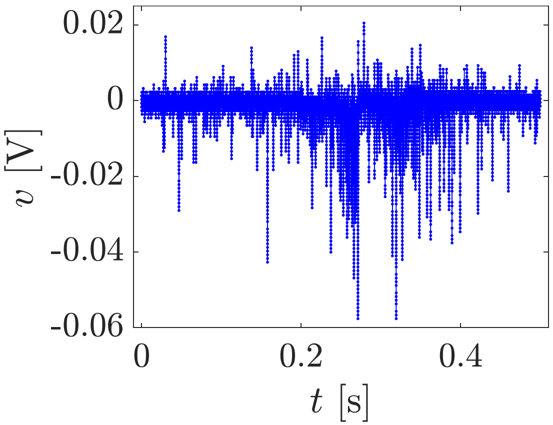
$$\dot{V}_T \overset{?}{=} \frac{\ell_{coil}}{N\mu_0 M_s}v$$

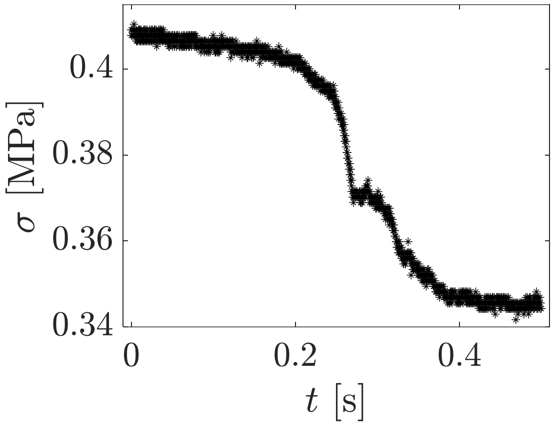
Measured ME voltage

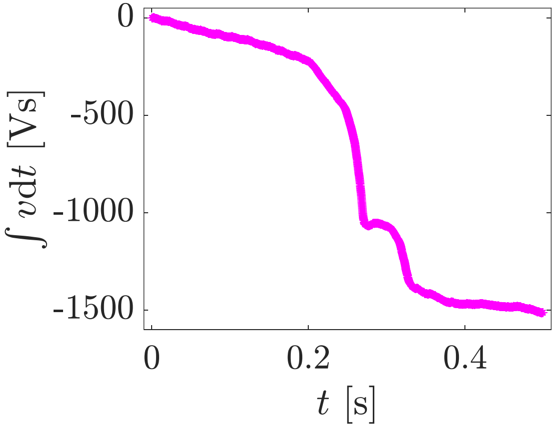
Rate of change of volumes undergoing twinning transformation

- **Limitation:** Valid under specific experimental conditions.

# Validation of the relation between $\dot{V}_T$ and $v$



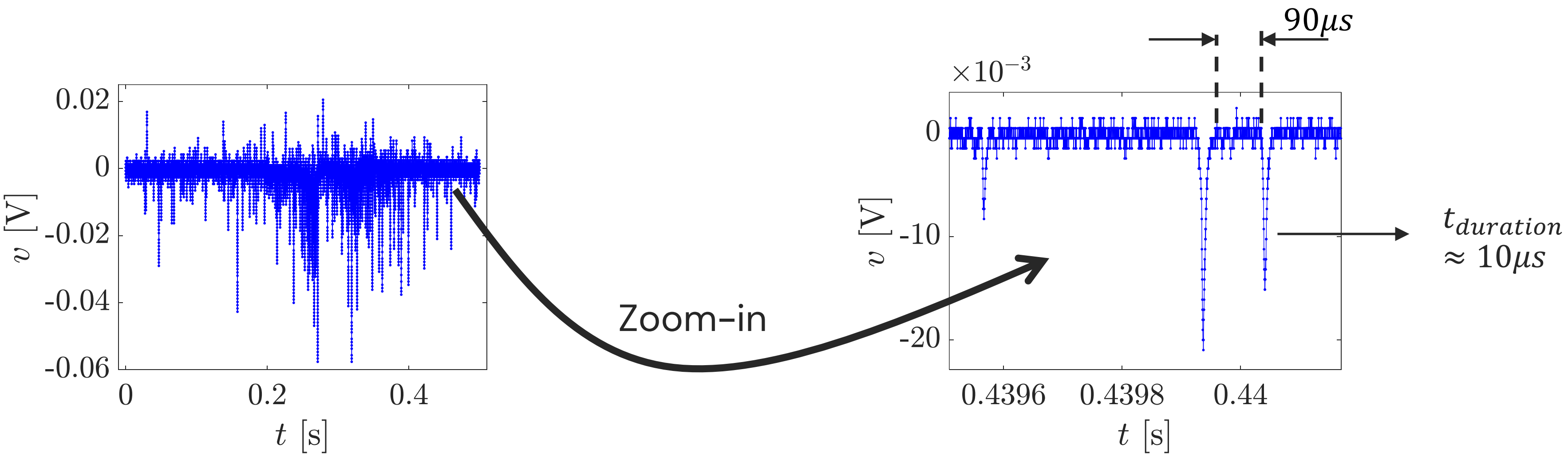



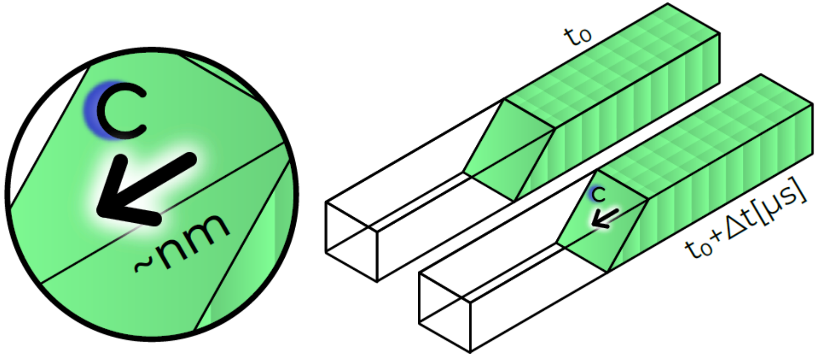

- **Results:** **Over 97%** (210 out of 216) stress drops detected in 9 experiments have $\mathbf{PCC > 0.9}$.

- **Conclusion:** Using our developed method, twin boundary motion can be **directly** studied at **nanometer** and **microsecond scales**.

# Nanometer and microsecond scales



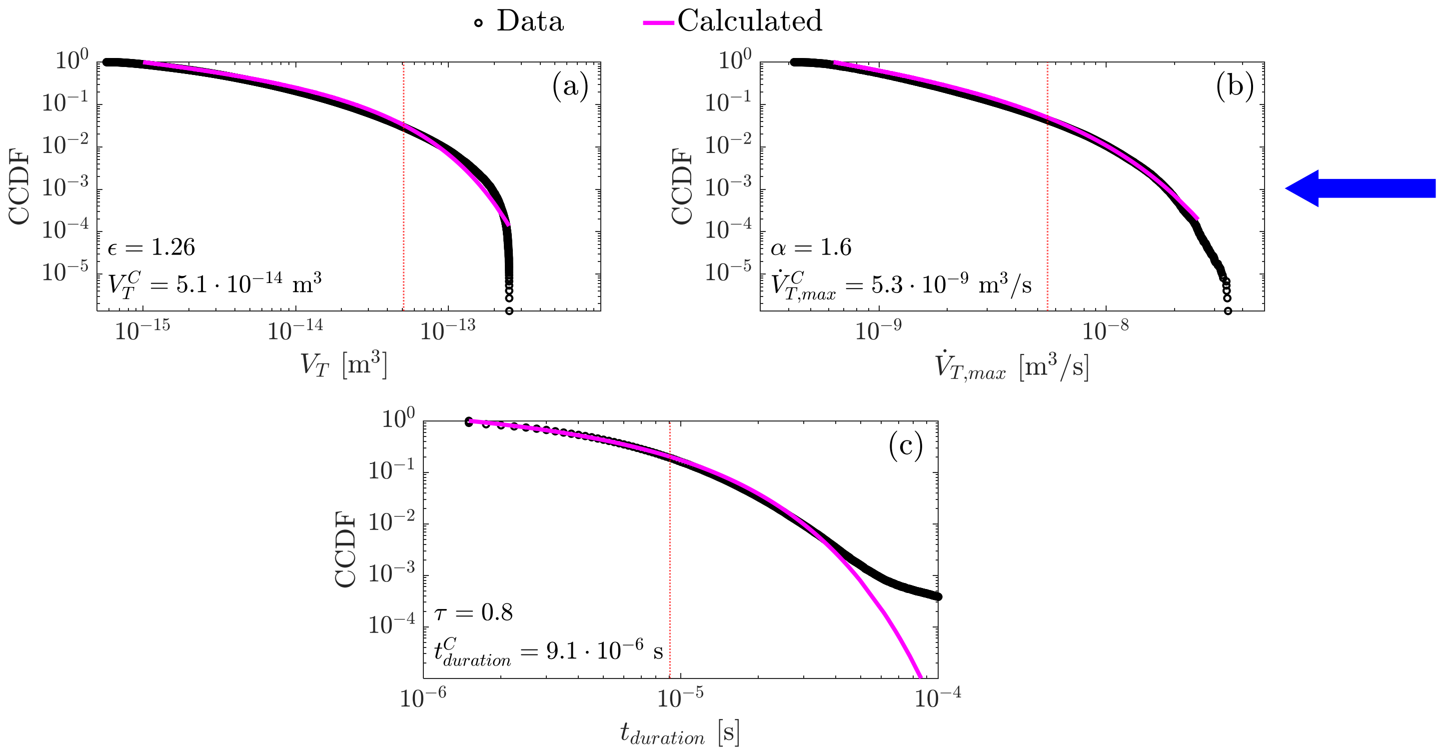
# Nanometer and microsecond scales




60% of the events correspond to twin boundary displacement **smaller** than a single lattice spacing.

# Results

# Statistical analysis

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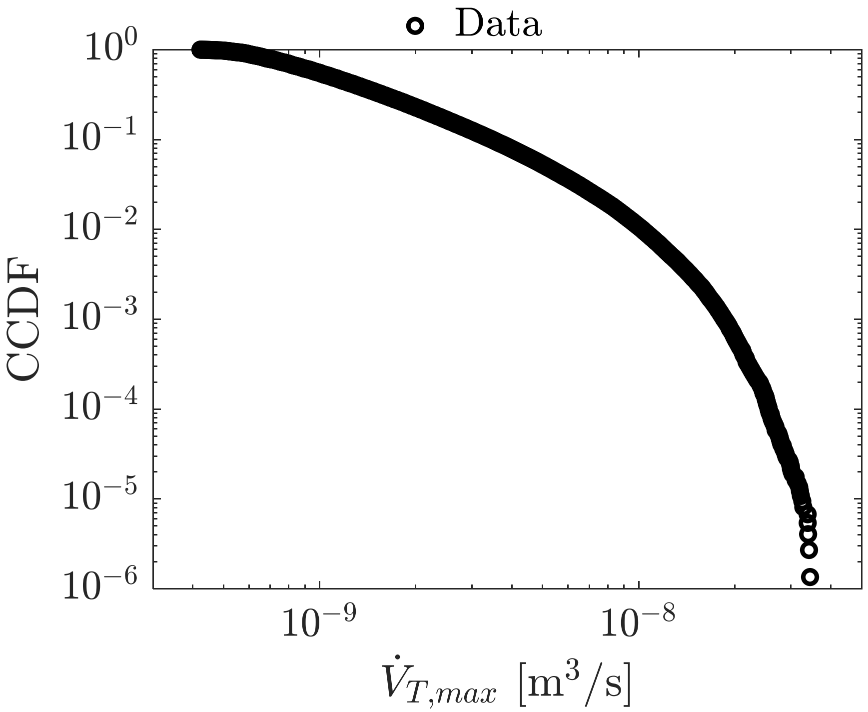
# Statistical analysis

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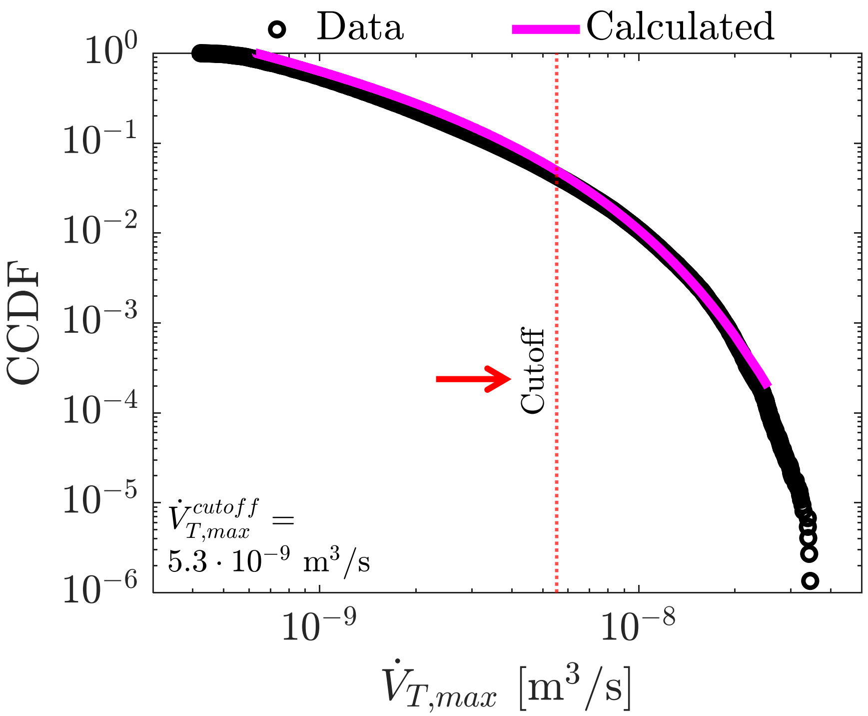
# Statistical analysis




**Proposed distribution:**

$$p(\dot{V}_{T,max}) \propto (\dot{V}_{T,max})^{-\alpha} \exp\left(-\frac{\dot{V}_{T,max}}{\dot{V}_{T,max}^{cutoff}}\right)$$

The cutoffs are in the middle of the variables' range, indicating on **limits related to the physical process**.

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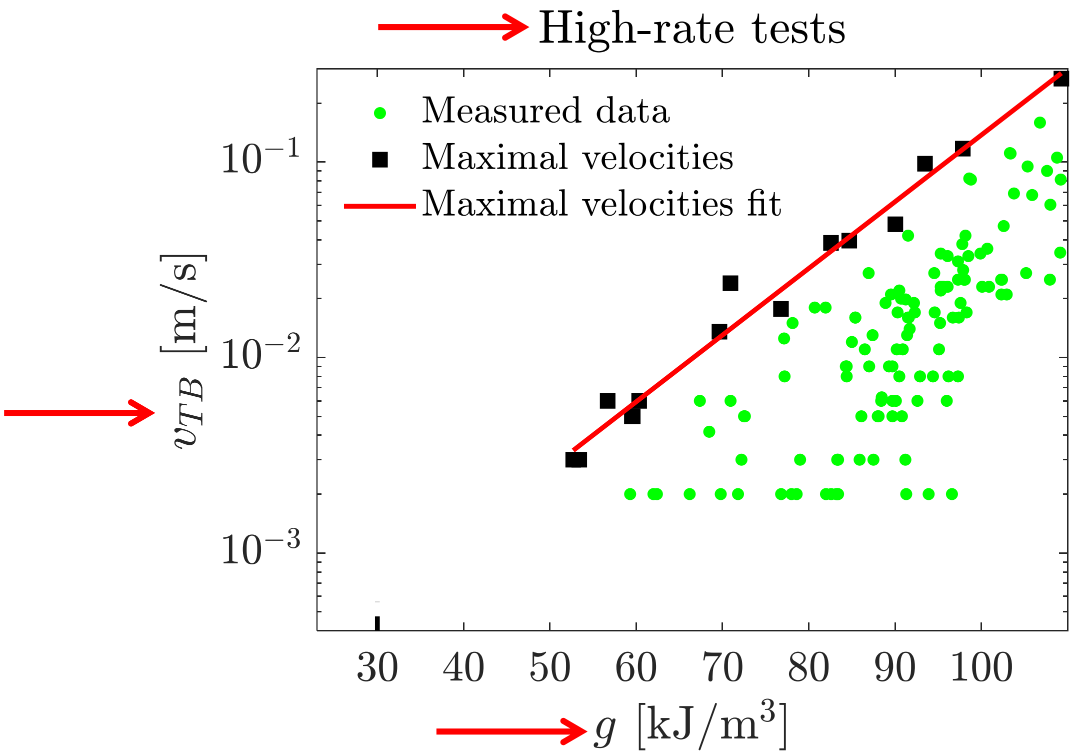
# Physical meaning of $\dot{V}_{T,max}^{cutoff}$

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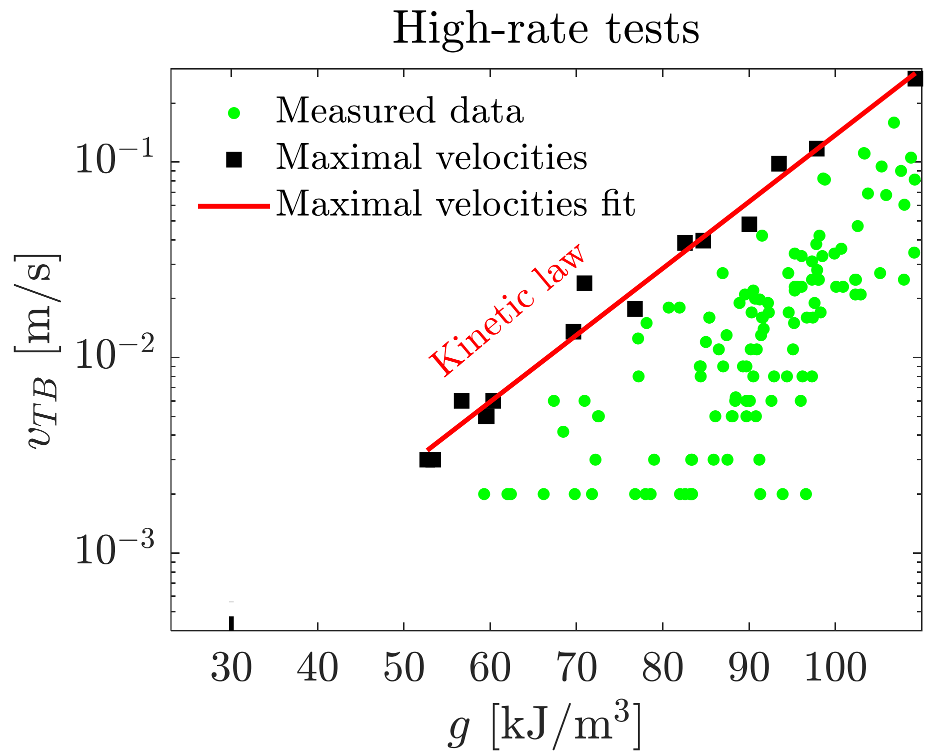


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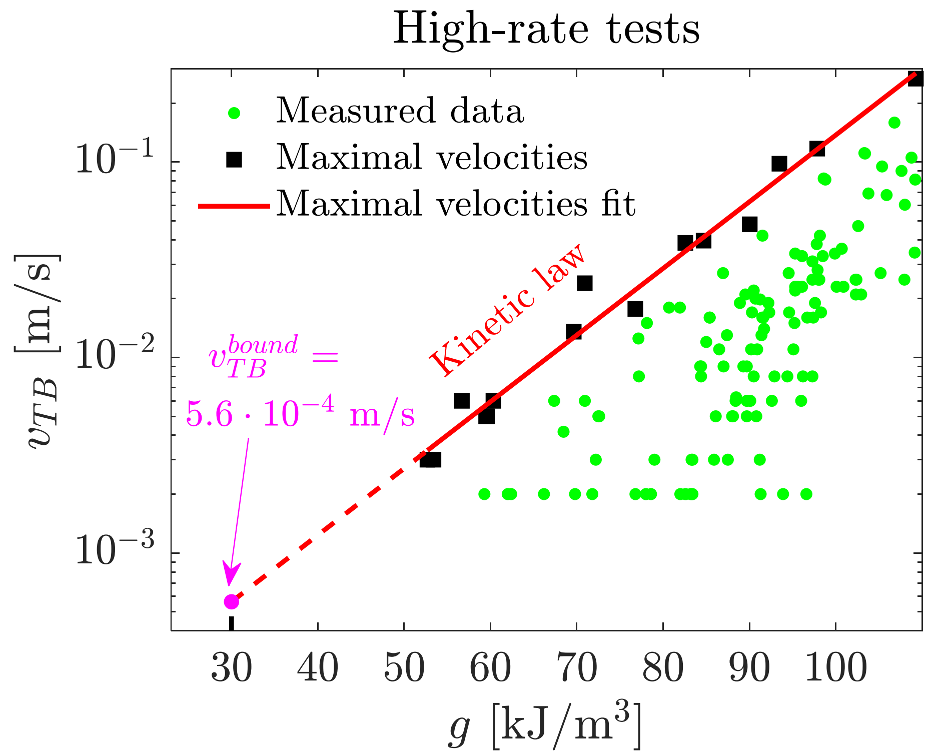

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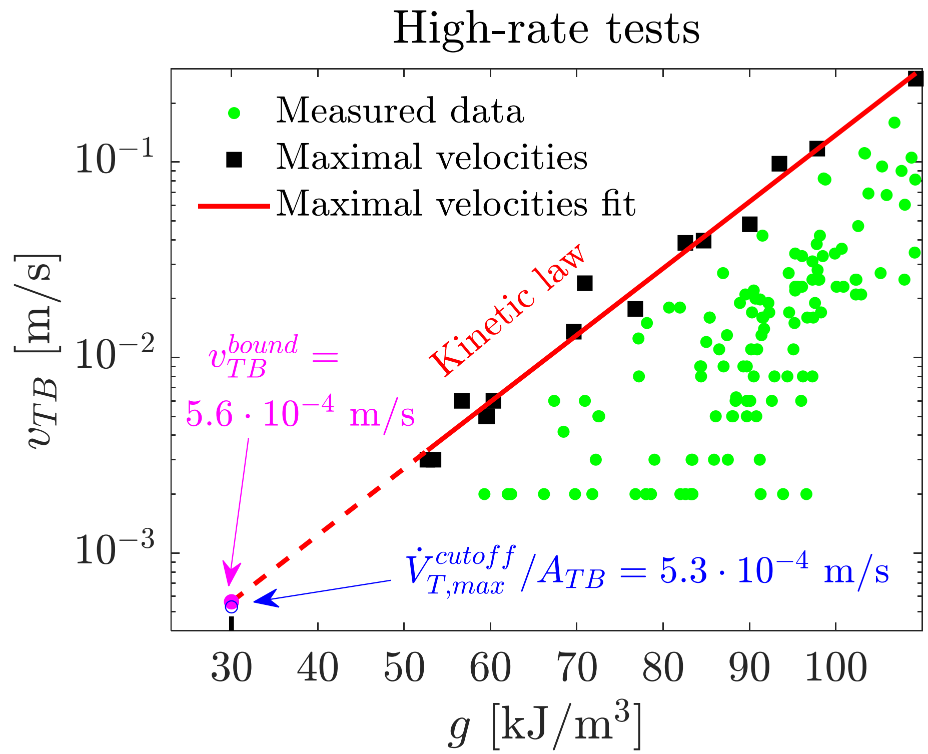
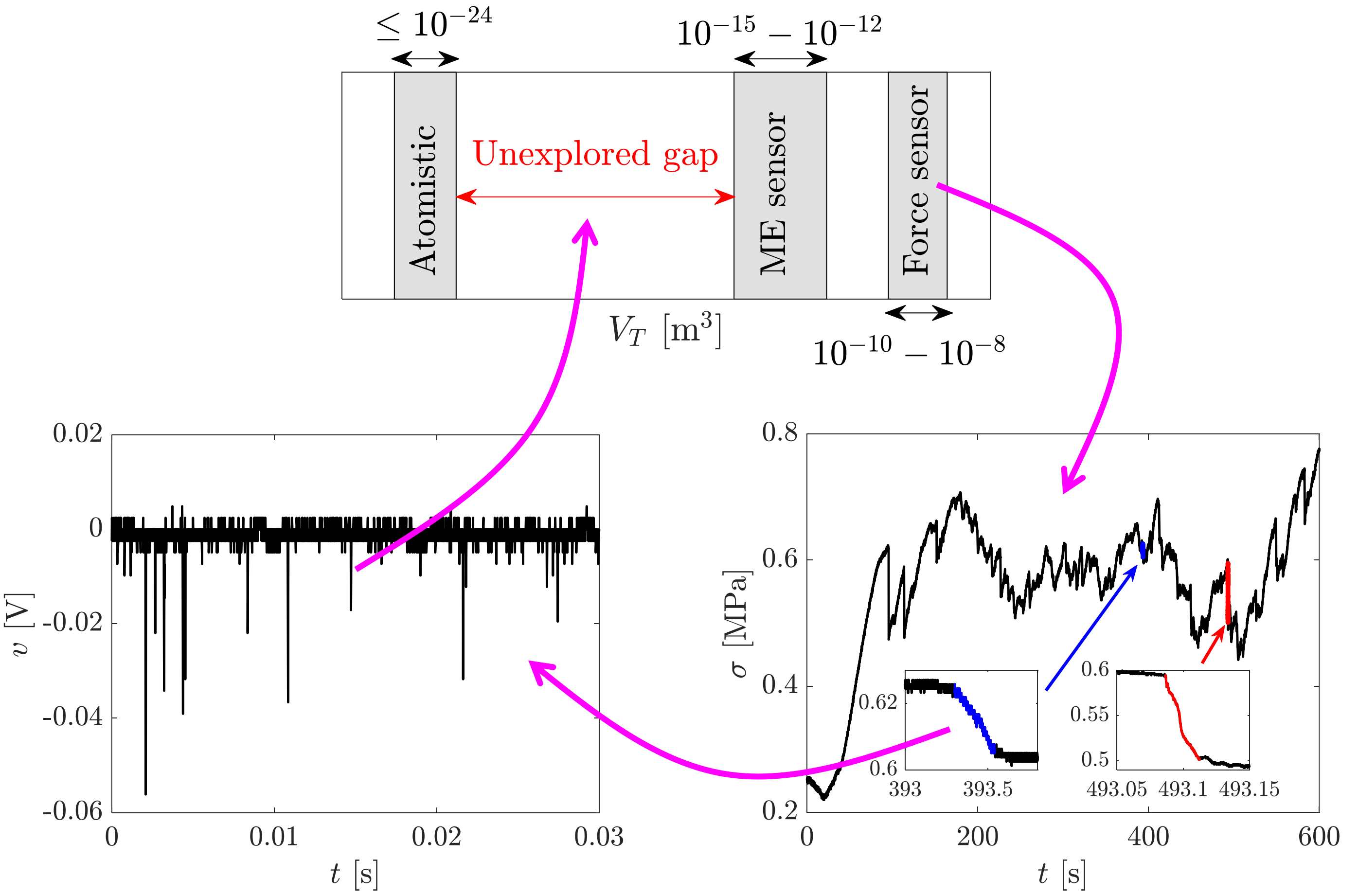



**Finding:** $\dot{V}_{T,max}^{cutoff}$ obtained from **slow-rate** tests matches the upper bound **predicted** by the kinetic law ($v_{TB}^{bound}(g)$) obtained from **high-rate** magnetic pulse tests.

# Avalanche hierarchies



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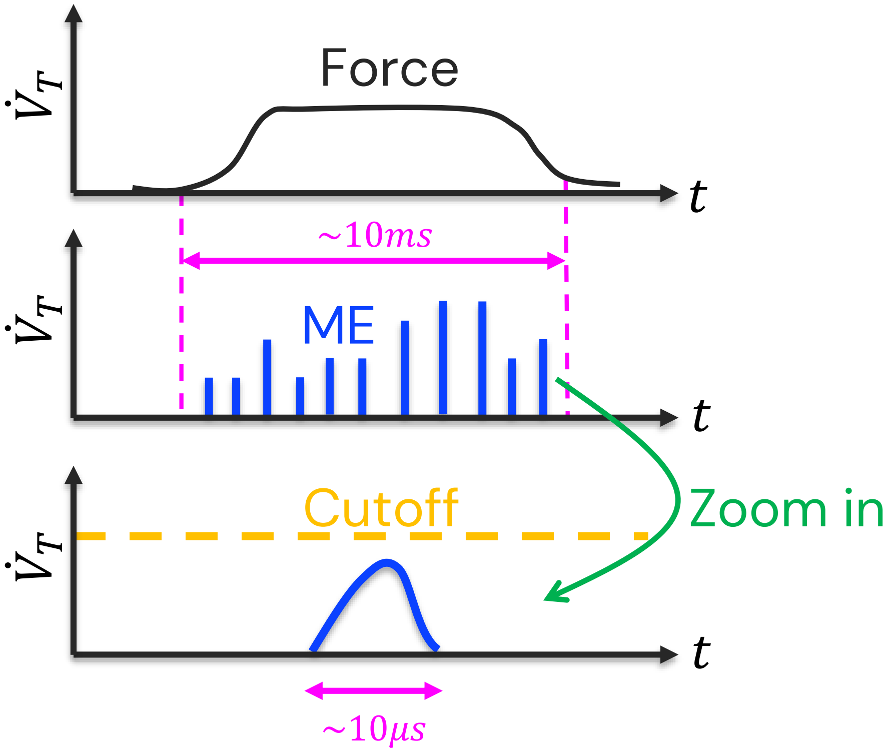

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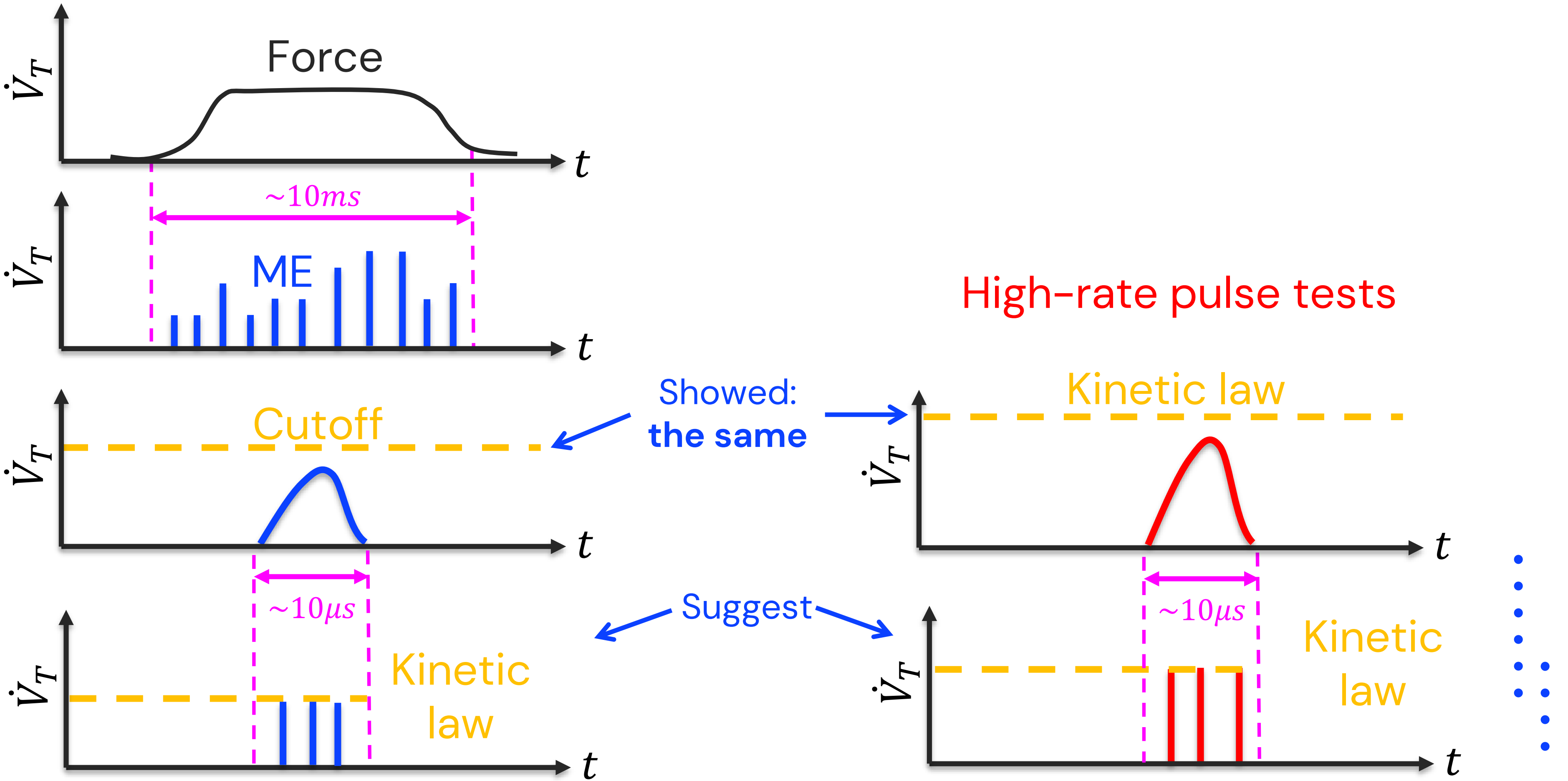

# Summary and conclusions

- A **novel** experimental method, in which the measured ME is **directly related** to twin boundary motions at **nanometer** and **microsecond** scales, has been **developed**.

- We showed that the source of the **cutoff** value $\dot{V}_{T,max}^{cutoff}$ is the **kinetic law** in a defect free crystal.

- We suggested that there are additional **unexplored hierarchies** of avalanches with **sizes** and **durations** that are **smaller** than the detection capabilities of the ME sensor. These avalanches are small enough to follow the kinetic law.

- The **same** behavior of twin boundary motion occurs both at **high-rate** and **slow-rate** tests; therefore, it can be described by the **same theory**.

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# Thank you

E. Bronstein, L. Z. Tóth, L. Daróczi,  D. L. Beke, R. Talmon, and D. Shilo, "Tracking Twin Boundary Jerky Motion at Nanometer and Microsecond Scales." *Advanced Functional Materials* **31** (2021) 2106573.

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