GREMAN
matériaux microélectronique
acoustique nanotechnologies

Avalanches in ferroelectric and ferroelastic materials

Guillaume F. Nataf

Debrecen - 01/09/2022

UMR 7347

GREMAN | université de TOURS | INSA | cnrs

Laboratory GREMAN

50 researchers
10 postdocs
30 PhD students

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A long-term collaboration

Blai Casals
(IC2N, Barcelona)

Ekhard Salje
(University of Cambridge)

- Casals *et al.* Avalanche criticality during ferroelectric/ferroelastic switching.
  Nature Communications (2021)
- Nataf *et al.* Avalanches in ferroelectric, ferroelastic and coelastic materials: phase transition, domain switching and propagation.
  Ferroelectrics (2020)
- Casals *et al.* Avalanches from charged domain wall motion in $BaTiO_3$ during ferroelectric switching.
  APL Materials (2020)
- Nataf *et al.* Predicting failure: acoustic emission of berlinite under compression.
  Journal of Physics: Condensed Matter (2014)
- Nataf *et al.* Avalanches in compressed porous SiO_2-based materials.
  Physical Review E (2014)

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Outline

1. Introduction on ferroelectric materials and domain walls
2. How domain walls move in response to an applied electric-field?
3. How domain walls relax after an applied shear stress?

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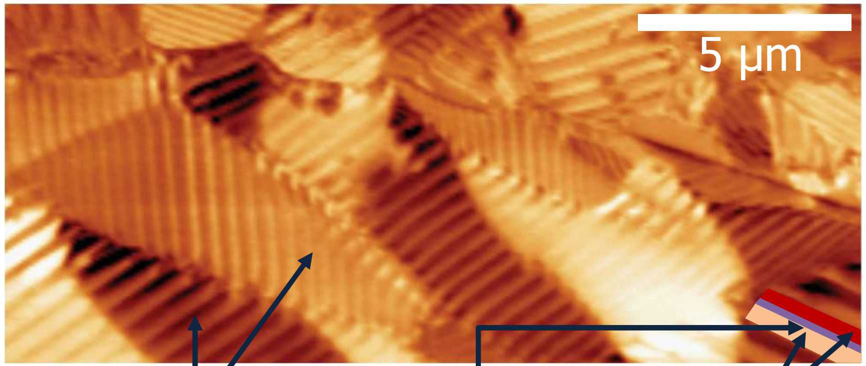
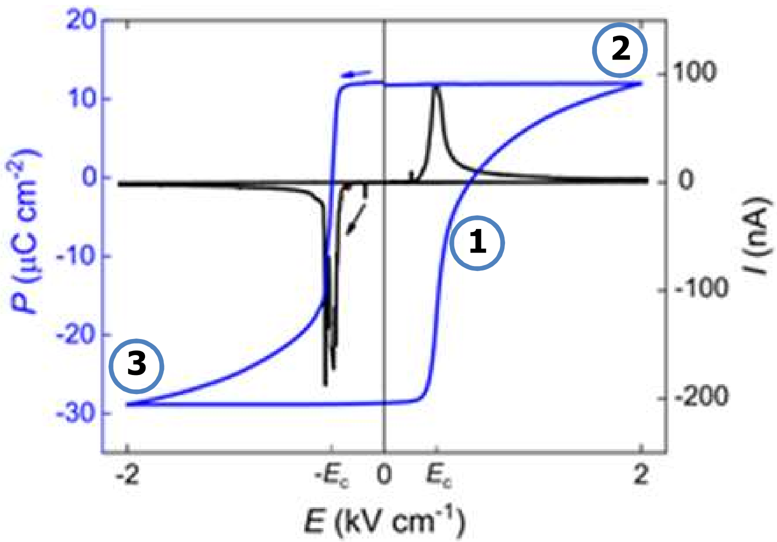
$BaTiO_3$



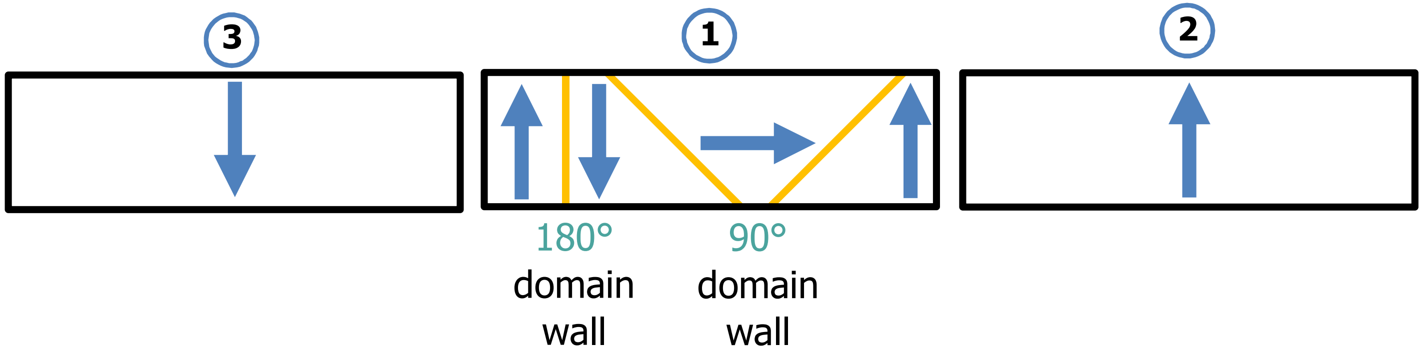
Grains
(nm - mm)

Domains (nm - mm)
Domain wall (< 2 nm)



Polarization

Domain wall



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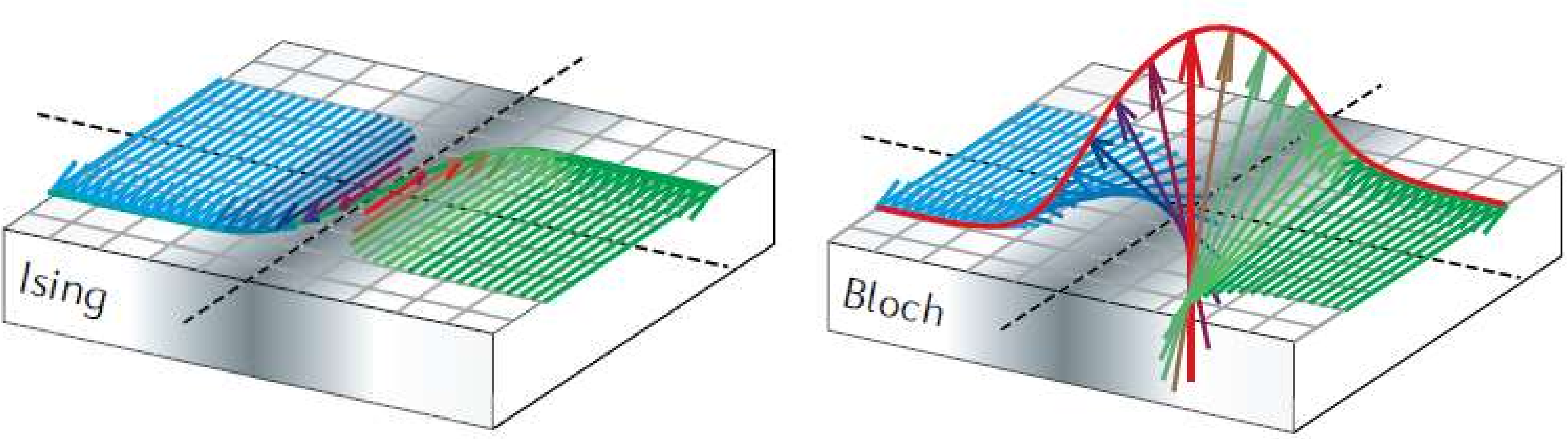
Salje, Nataf *et al.*, Phys. Rev. B. **87** (2013). Pesquera, Casals, Thompson, Nataf et *al.*, APL Mater. **7** (2019).

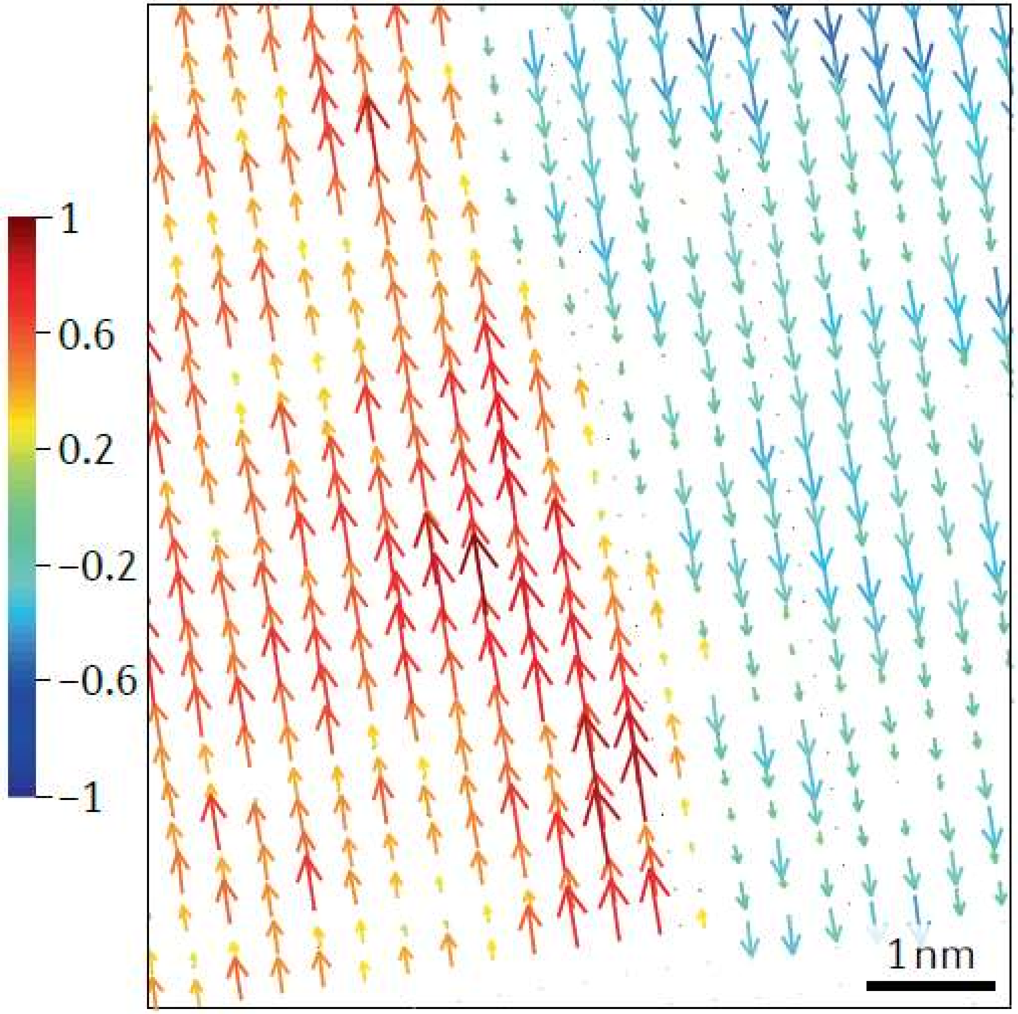
Profiles of ferroelectric domain walls



Nataf *et al.* Nat. Rev. Phys. **2** (2020).

Image of a ferroelectric domain wall

Scanning transmission electron microscopy on a 180° Ising domain wall in $LiNbO_3$



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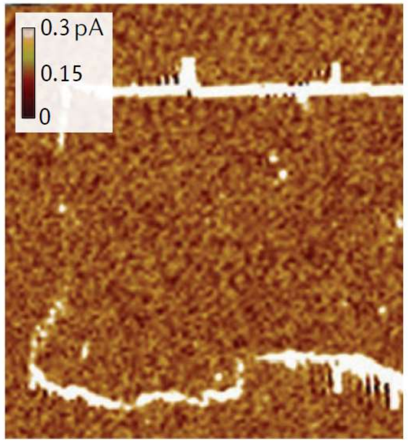
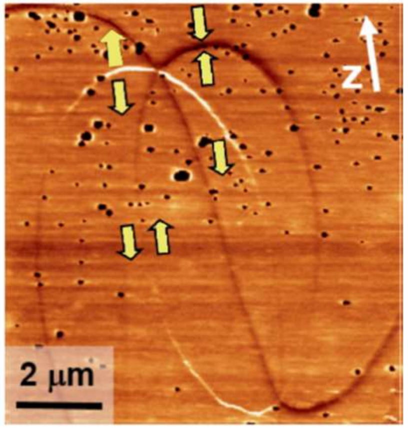
Gonnissen, Nataf *et al.*, Adv. Funct. Mater. **26** (2016).

Domain-wall engineering: electric conduction in ferroelectrics





Nataf *et al.* Nat. Rev. Phys. **2** (2020). Meier, Selbach, Nat. Rev. Mater. (2021). Sharma *et al.*, Materials **12**, 2927 (2019).

Domain-wall engineering:
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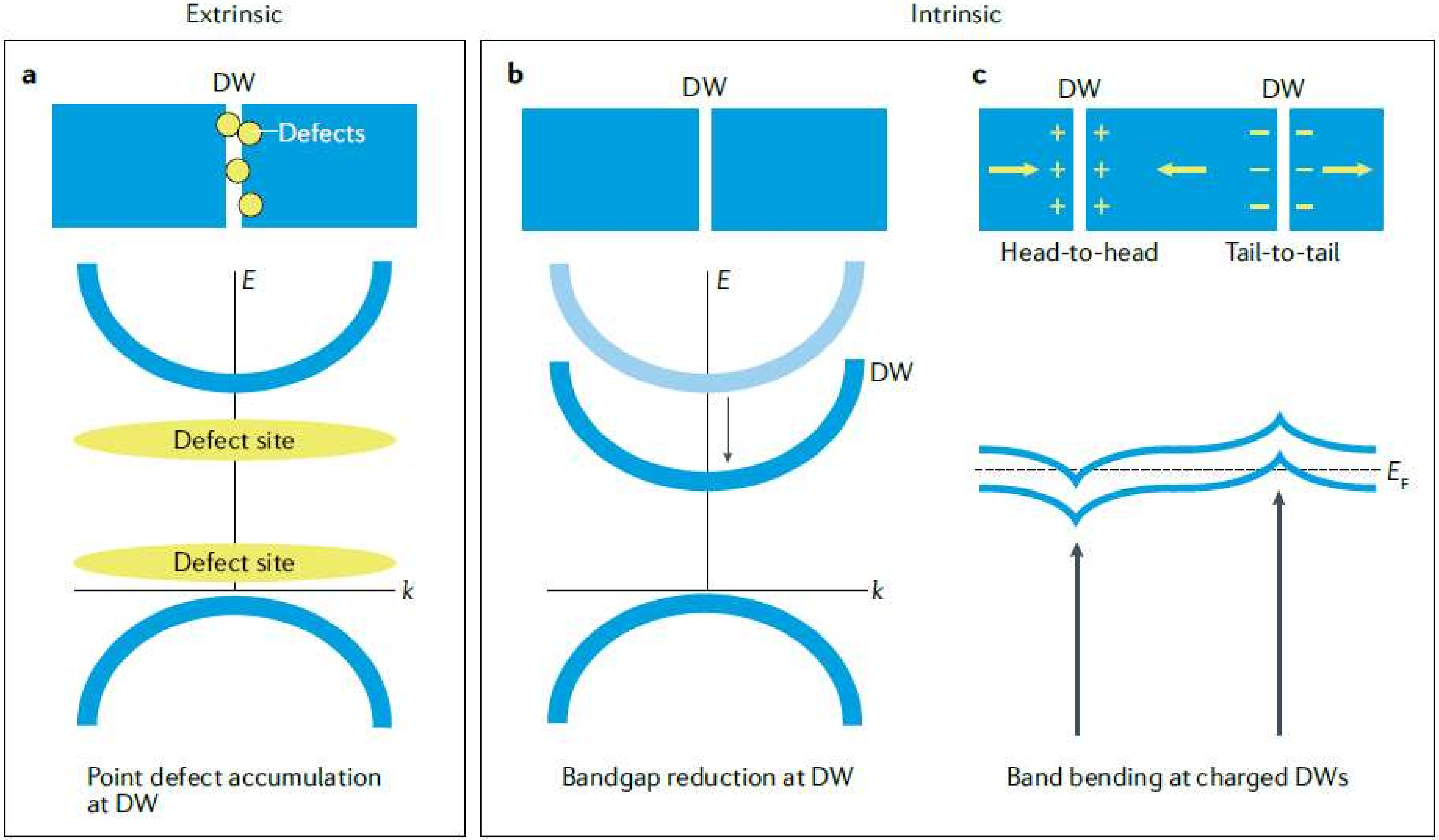
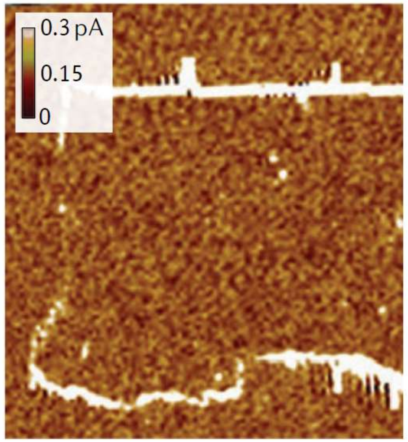
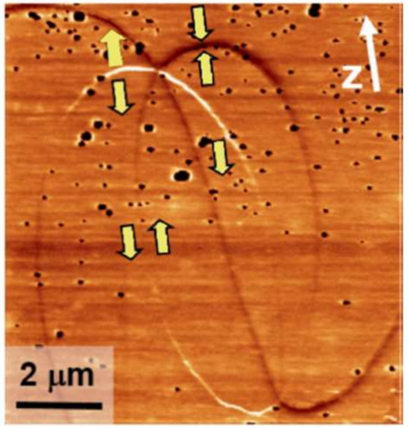
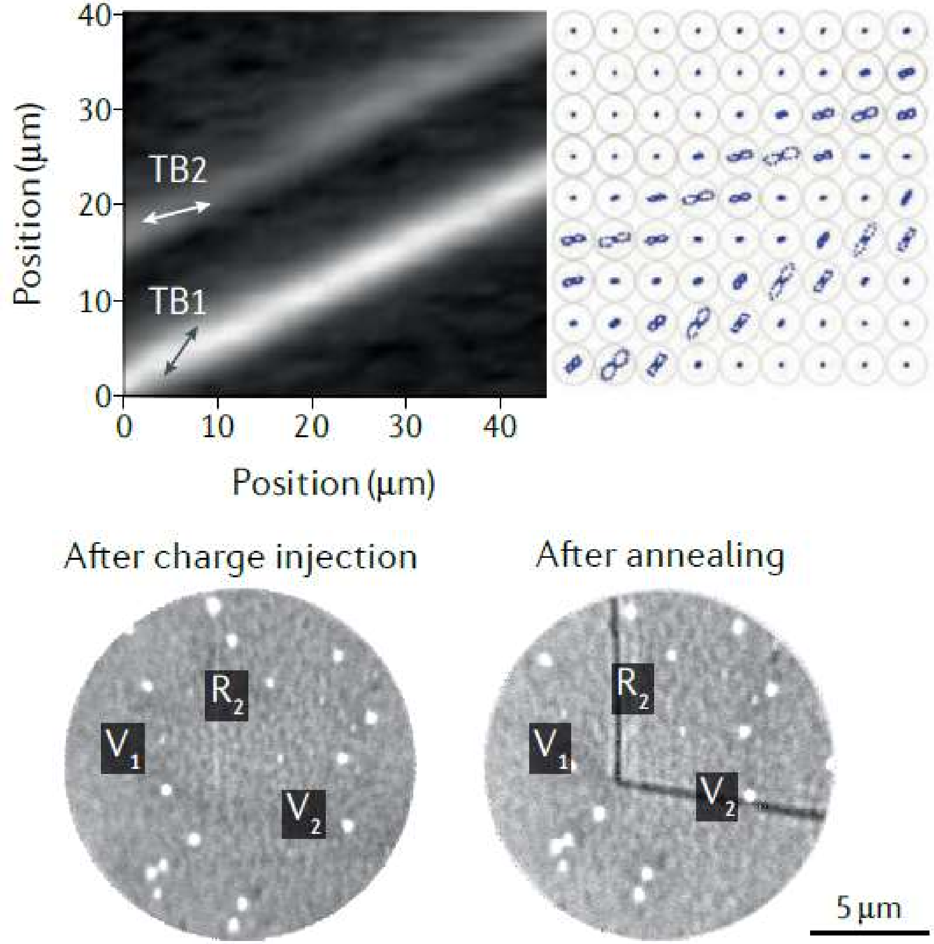






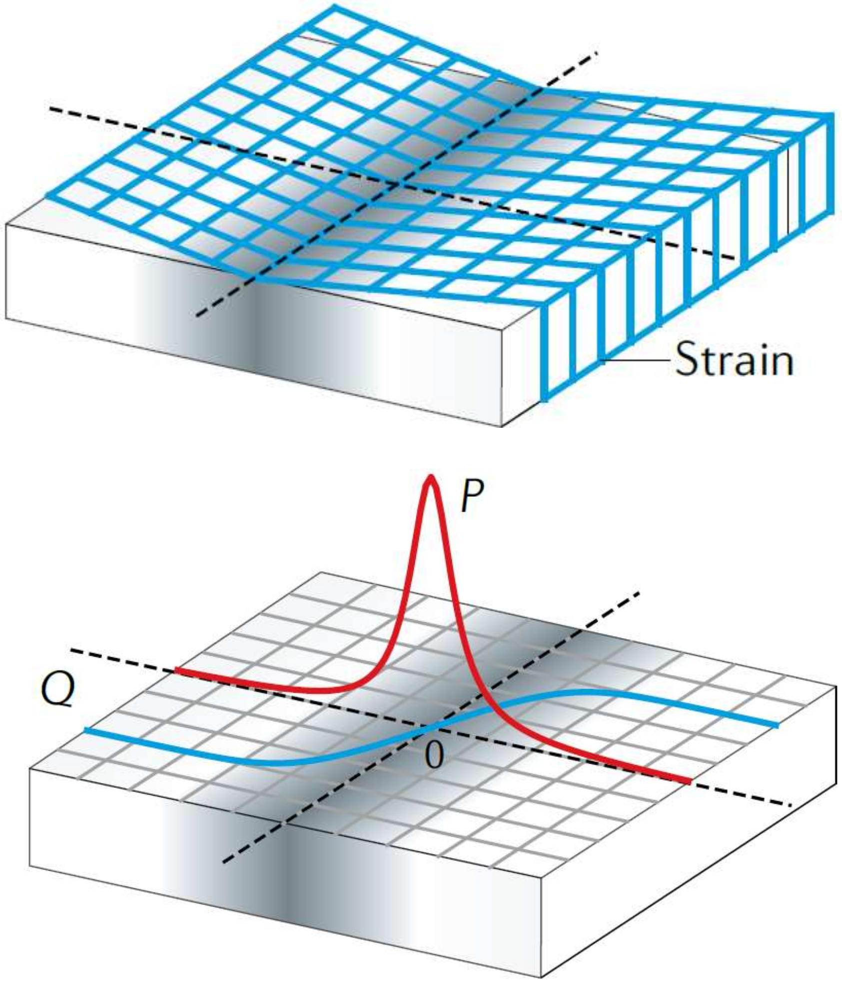
Nataf *et al.* Nat. Rev. Phys. **2** (2020). Meier, Selbach, Nat. Rev. Mater. (2021). Sharma *et al.*, Materials **12**, 2927 (2019).

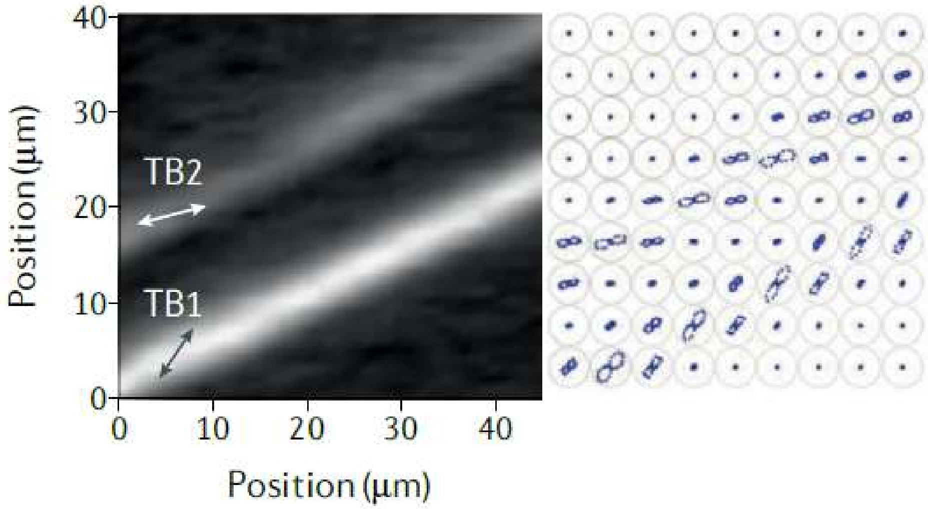
Domain-wall engineering: polarization in non-polar materials

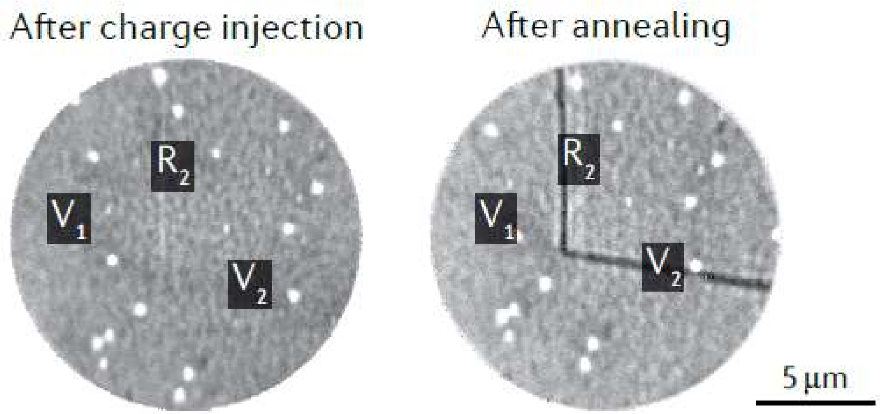


Nataf *et al.* Nat. Rev. Phys. **2** (2020). Cherifi-Hertel *et al.* J. Appl. Phys. **129** (2021).

Domain-wall engineering: polarization in non-polar materials

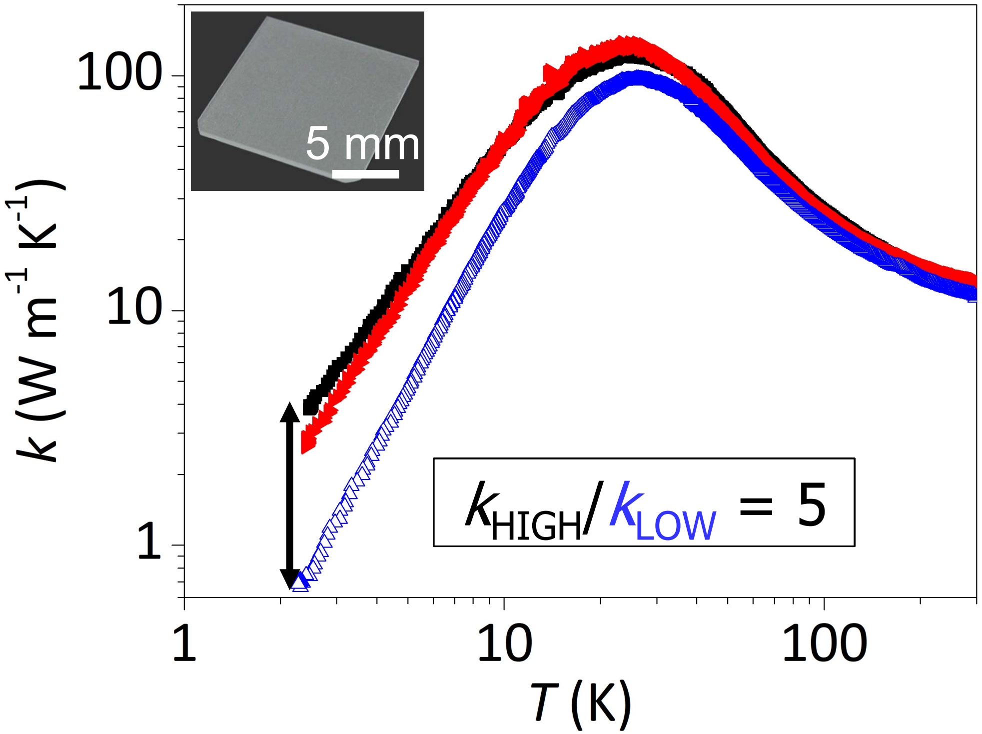


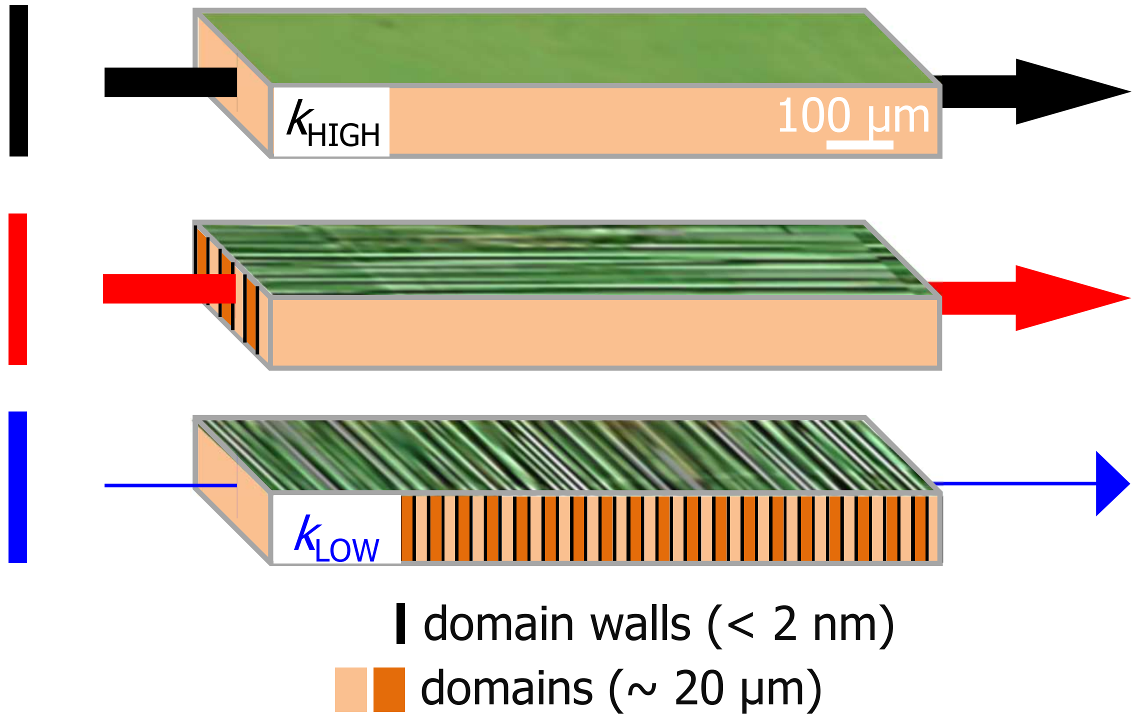




Nataf *et al.* Nat. Rev. Phys. **2** (2020). Cherifi-Hertel *et al.* J. Appl. Phys. **129** (2021).

Domain-wall engineering: thermal conduction





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El Kamily, … Nataf (submitted)

Take home message

Domain-wall engineering in ferroelectric and ferroelastic materials

Domain walls are 2D topological defects that can move in response to an electric-field or an applied pressure. When this spatial confinement is combined with observations of emergent functional properties, it becomes clear that domain walls represent new and exciting objects in matter.

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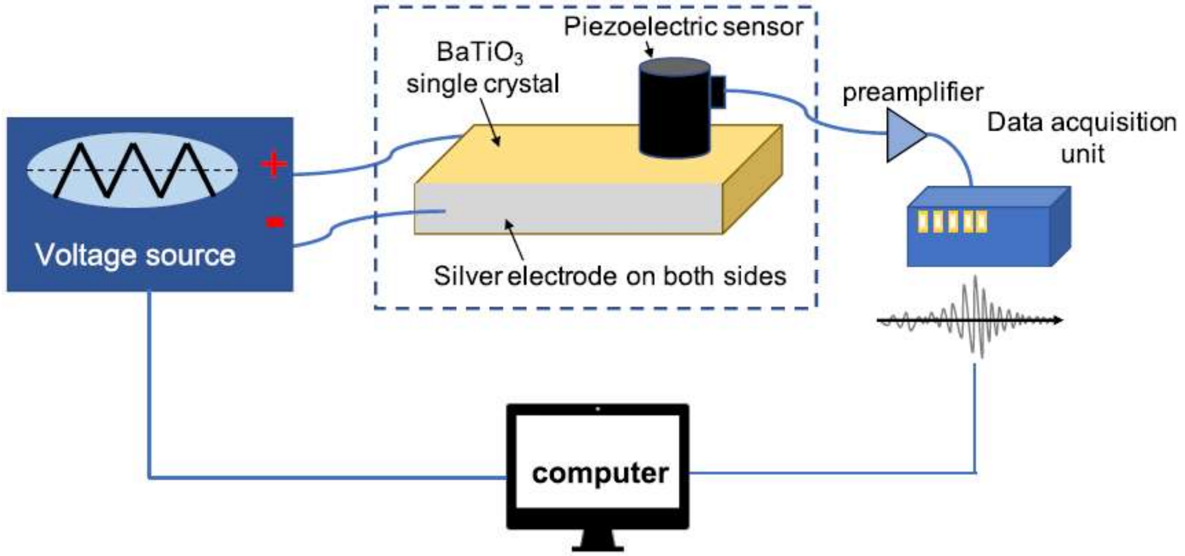
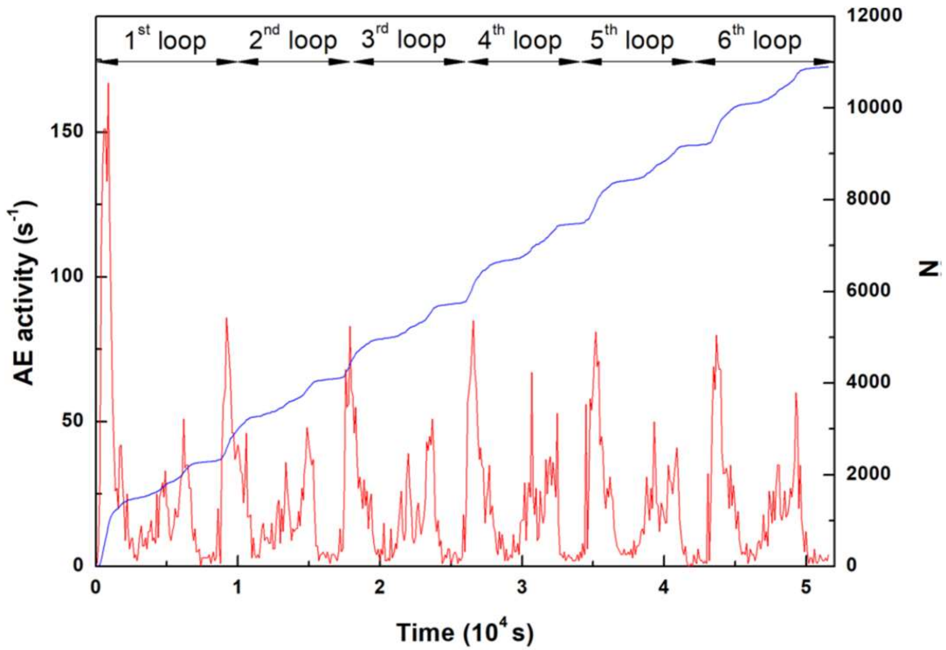
« Listen » to domain walls

Acoustic emissions under an applied voltage



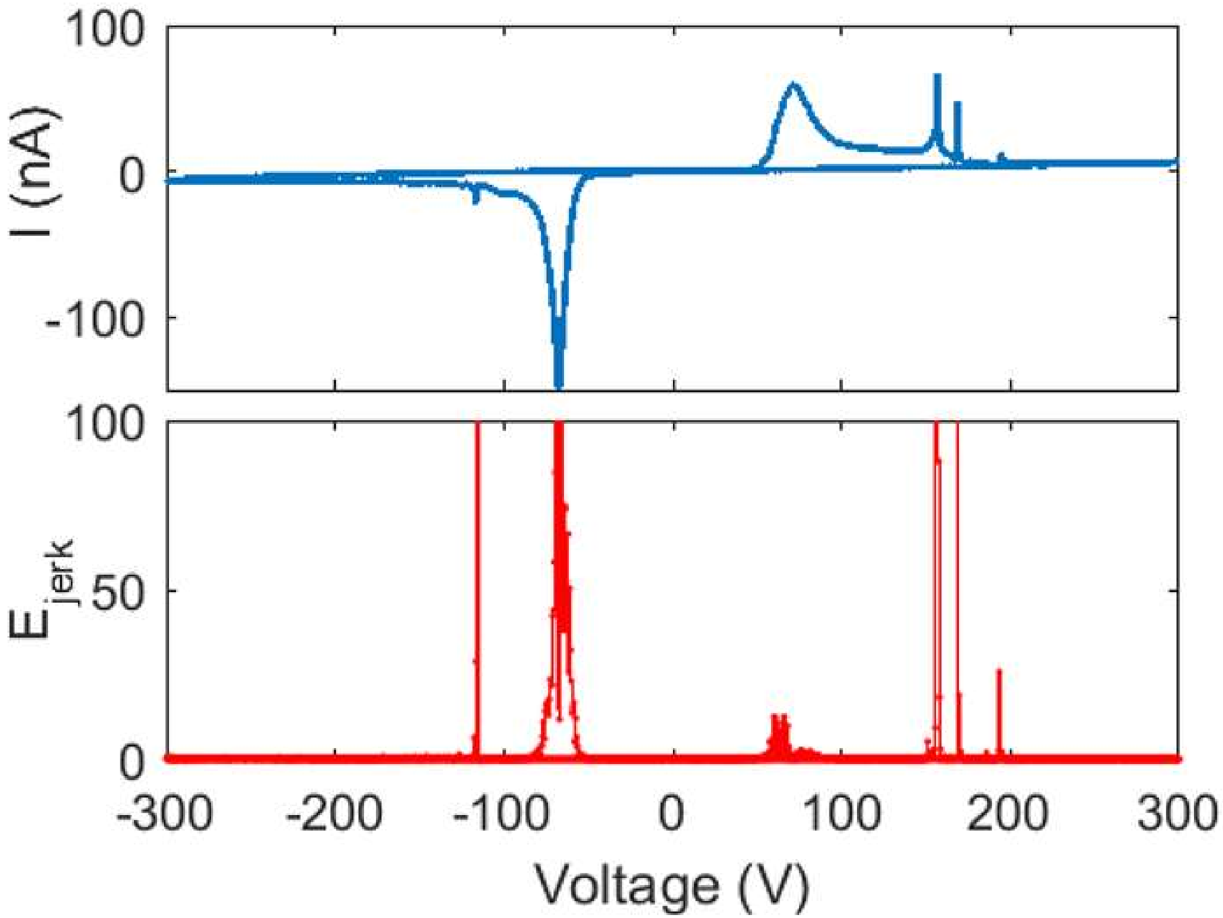


Salje *et al.* Phys. Rev. Mat. **3** (2019).

« Touch » domain walls

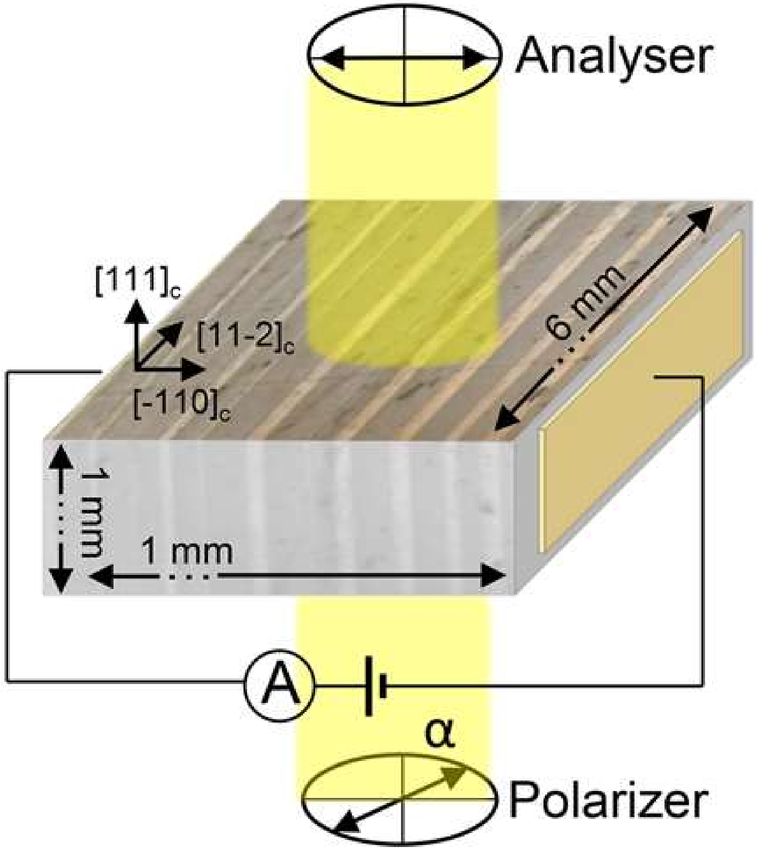
Displacement current (I) under an applied voltage (V)

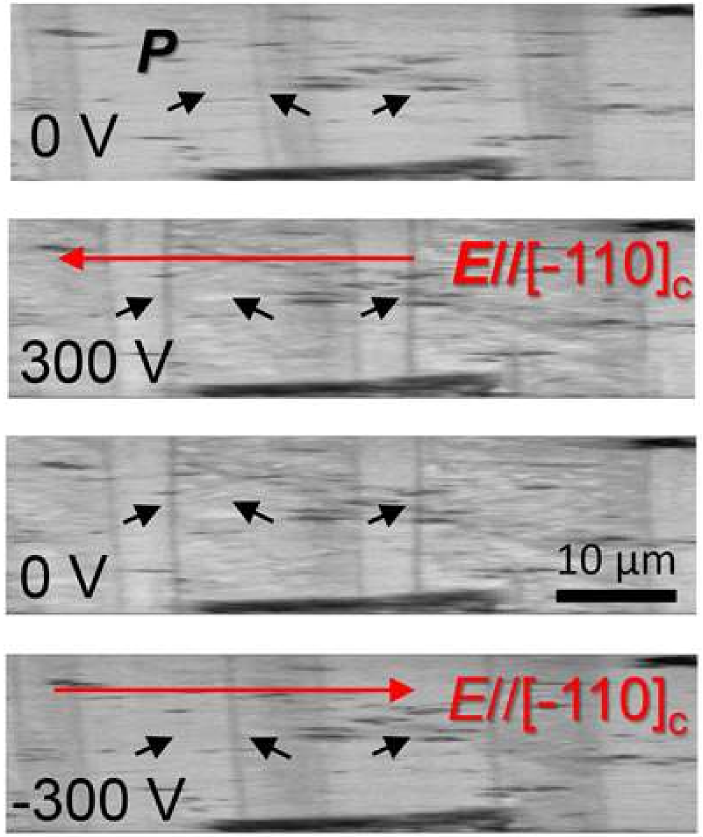
$E_{jerk} = (dI/dV)^2$



Casals *et al.* APL Mat. **8** (2020).

Optical microscopy under an applied voltage

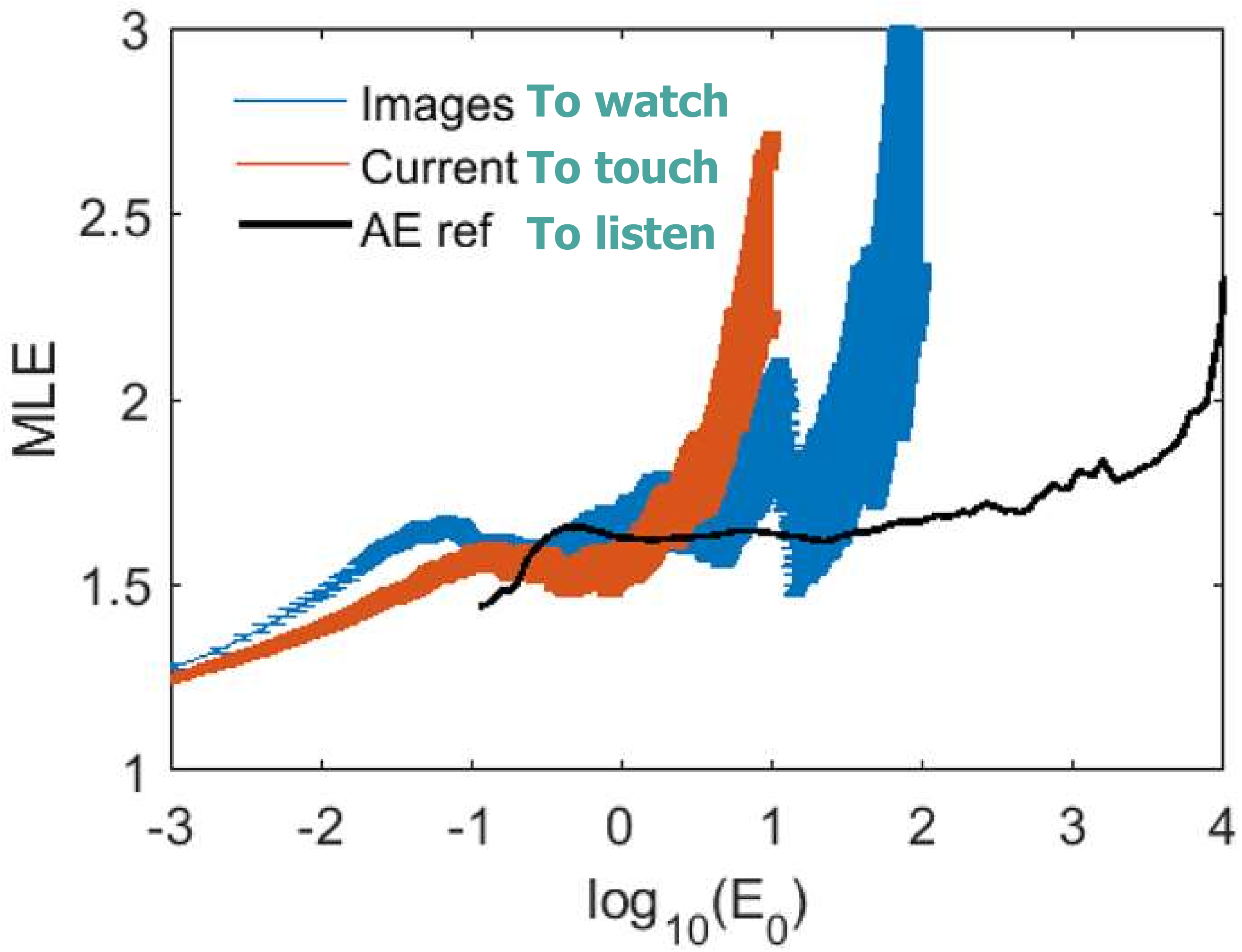




Casals *et al.* APL Mat. **8** (2020).

Measuring avalanches in ferroelectrics

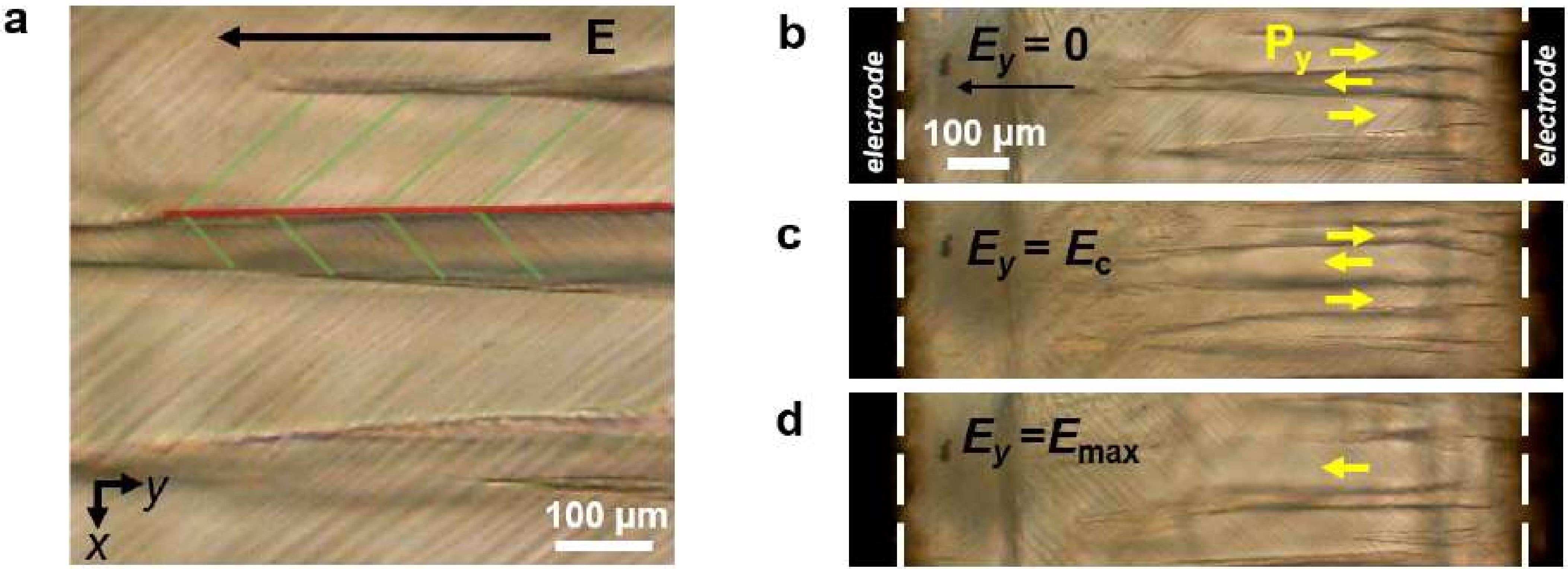
Maximum Likelihood Analysis
for the energy exponent ε



Casals *et al.* APL Mat. **8** (2020). Salje *et al.* Phys. Rev. Mat. **3** (2019).

Moving domain walls in $0.68[Pb(Mg_{1/3}Nb_{2/3})O_3]-0.32[PbTiO_3]$

- domain walls
- junctions between domain walls



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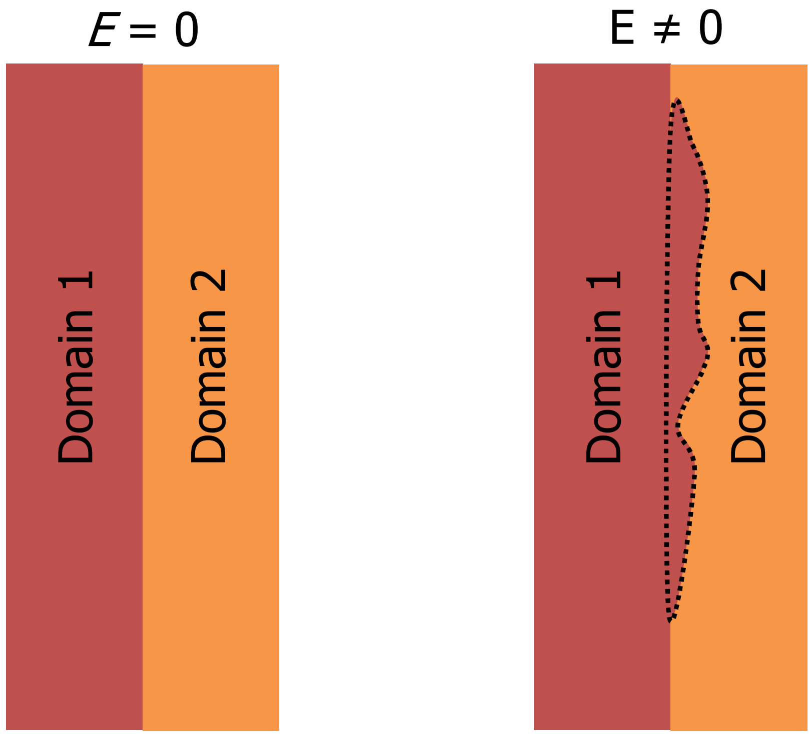
Casals, Nataf, Salje, Nat. Commun. **12** (2021).

Switched regions

Difference between consecutive images to extract regions that switched



Switched region

Perimeter P

Area A

Energy $E = A^2$

→ Hausdorff dimension: $P \propto A^{H_D/2}$

- Low roughness: $H_D \approx 1$
- High roughness: $H_D \approx 2$

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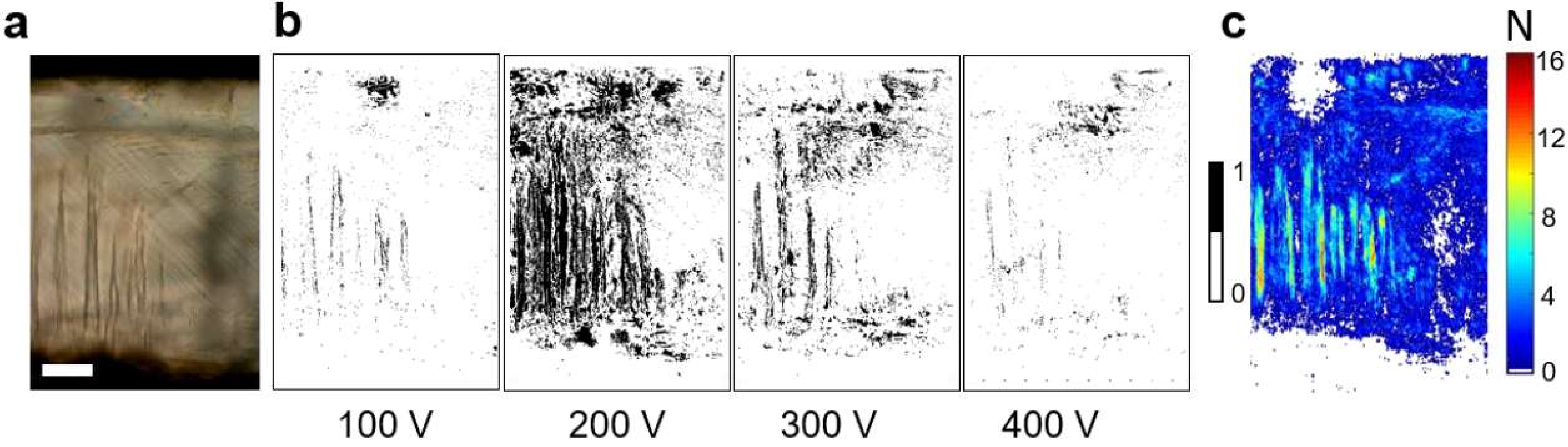
Casals, Nataf, Salje, Nat. Commun. **12** (2021).

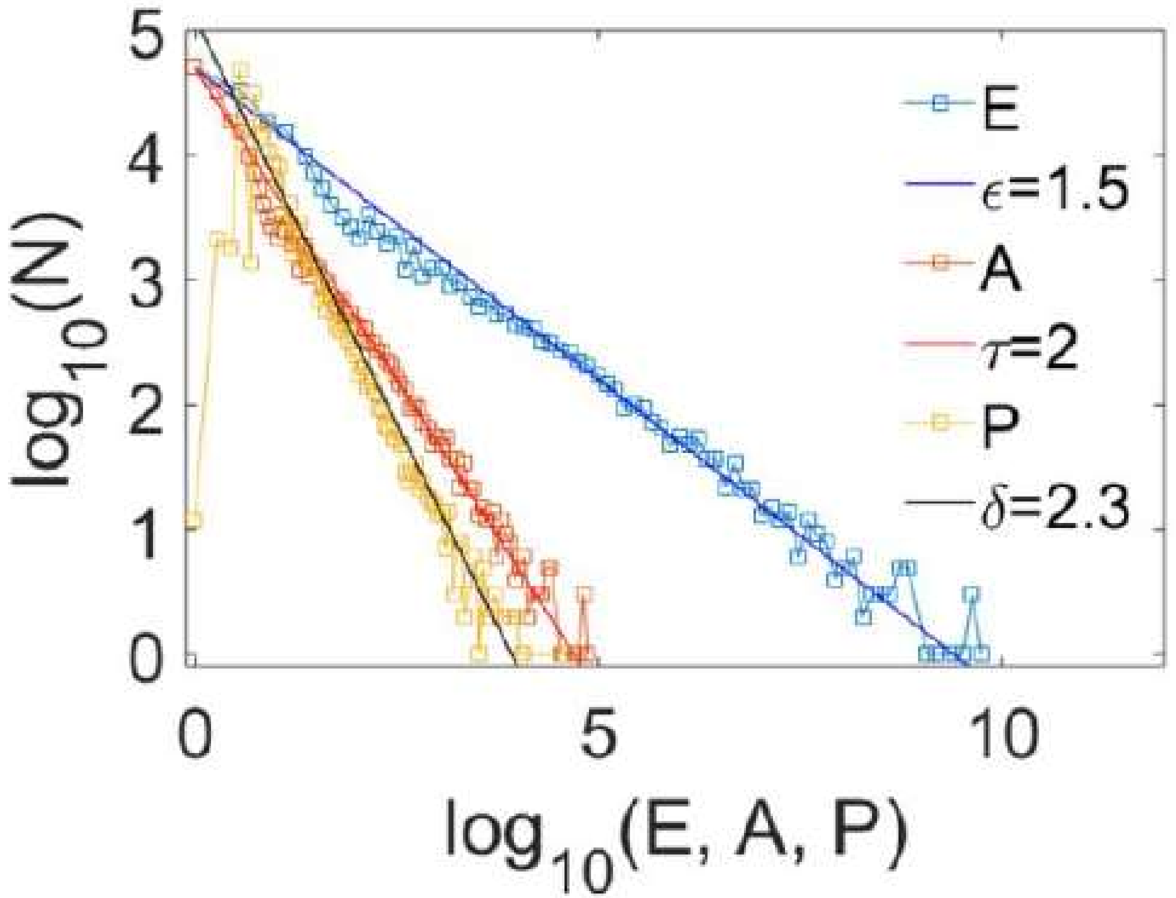
Switched regions in PMN-PT

Regions that switched are close to junctions between domain walls



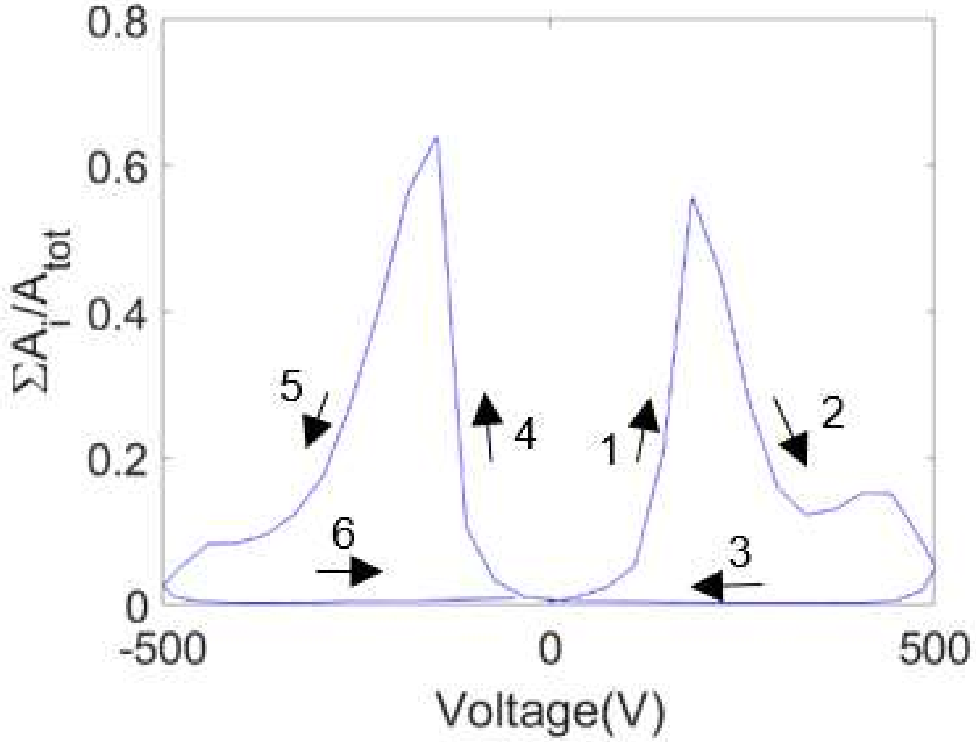
Casals, Nataf, Salje, Nat. Commun. **12** (2021).

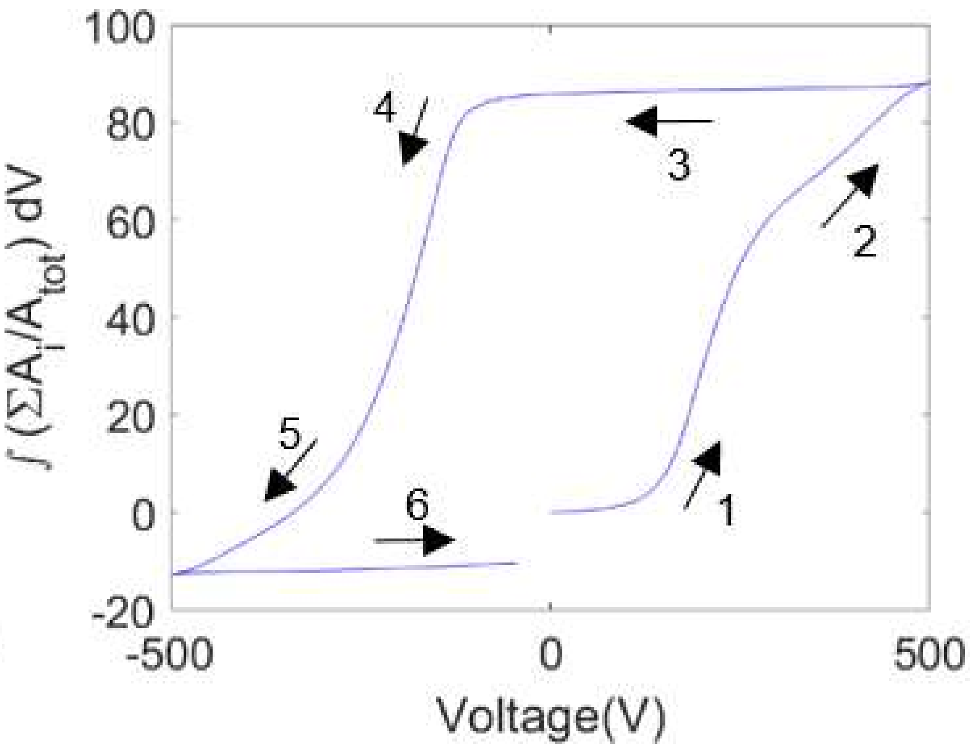
Switched regions: power law distributions



Casals, Nataf, Salje, Nat. Commun. **12** (2021).

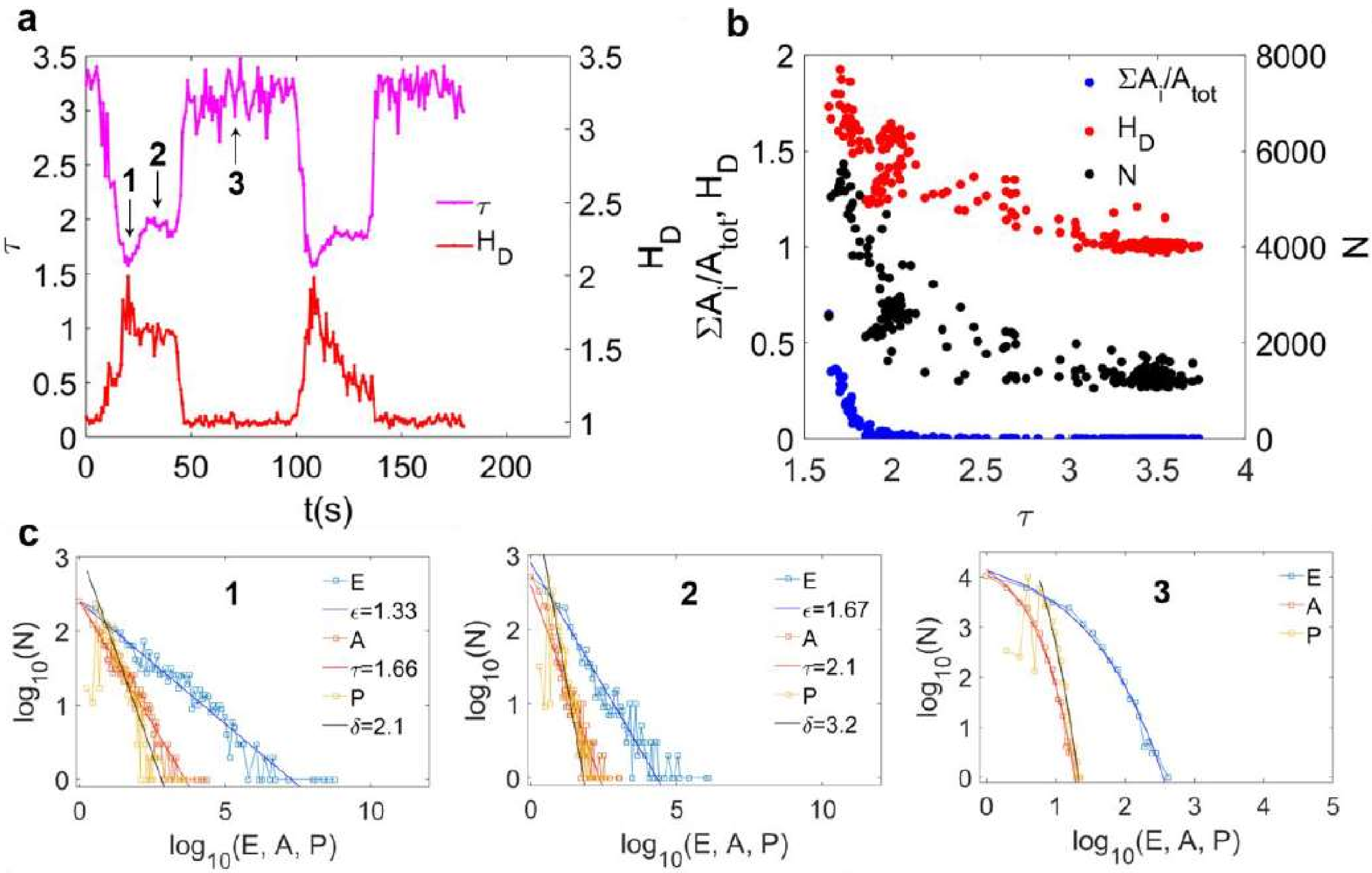
Switched regions: power law distributions





Casals, Nataf, Salje, Nat. Commun. **12** (2021).

Criticality at the coercive field



Casals, Nataf, Salje, Nat. Commun. **12** (2021).

Take home message

Ferroelectric/ferroelastic switching progresses via **avalanches**

A fine structure appears during switching:
→ At the **coercive field**, area and energy exponents correspond to unrelaxed mean-field values (ε = 1.3, τ = 1.7), while the **fractality** is maximum with H_D = 1.8
→ Elsewhere, exponents near the field integrated mean-field values with ε = 1.6 and τ~2.2

→ The **coercive field** acts as a **critical point**

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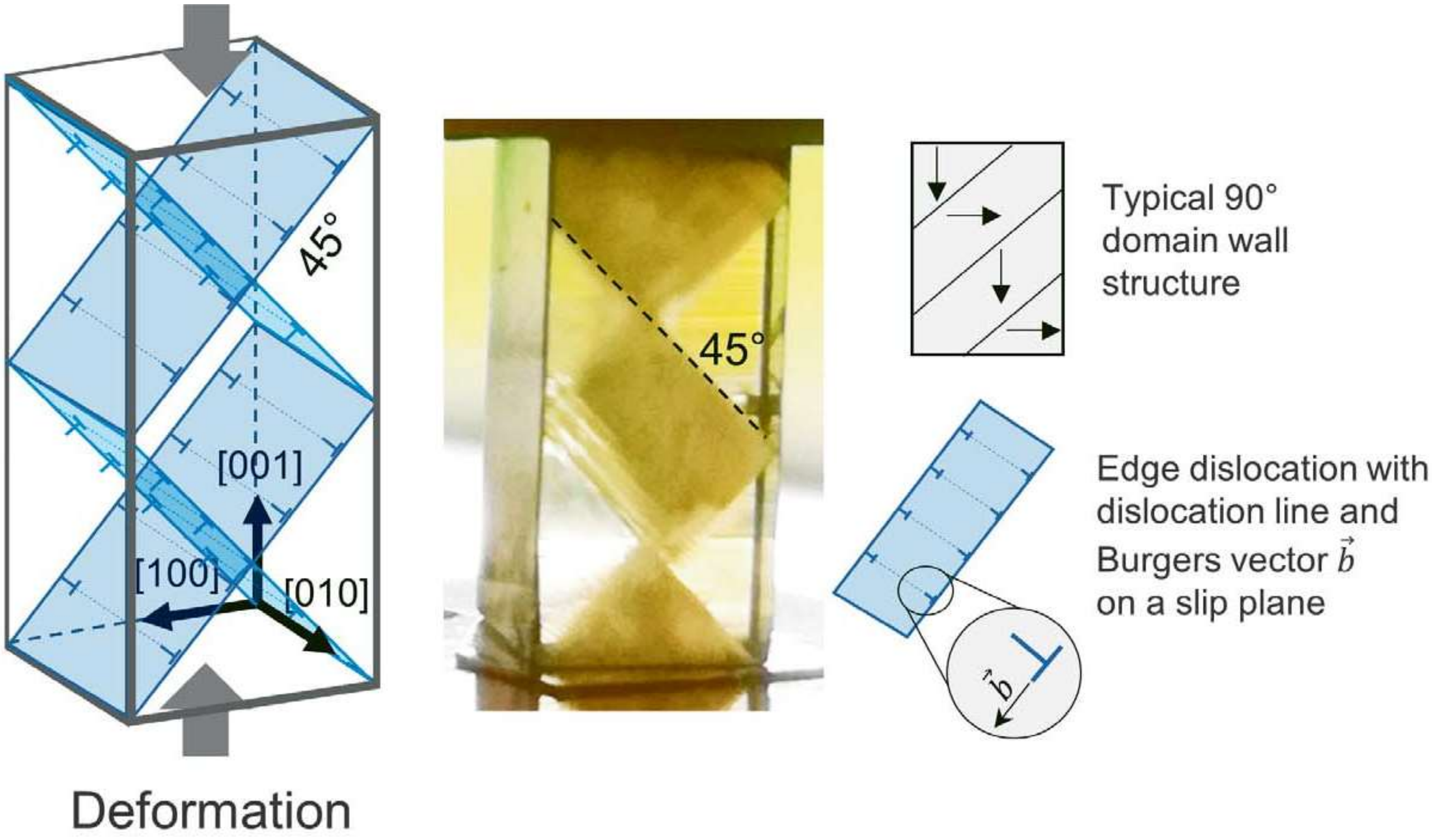
Tuning criticality with dislocations in $BaTiO_3$

Collaboration with Jürgen Rödel (Darmstadt)



Höfling *et al.*, Science **372** (2021).

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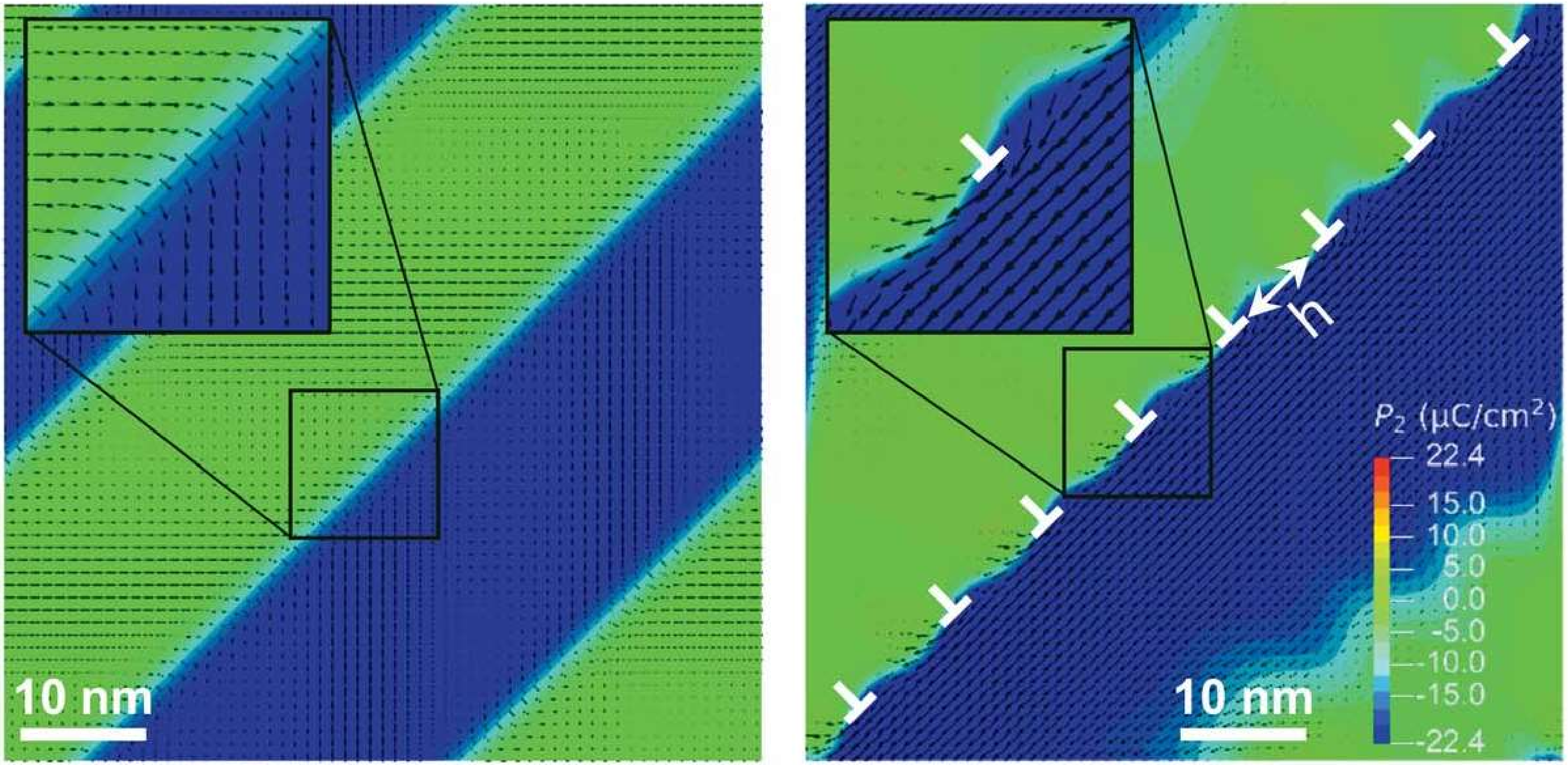

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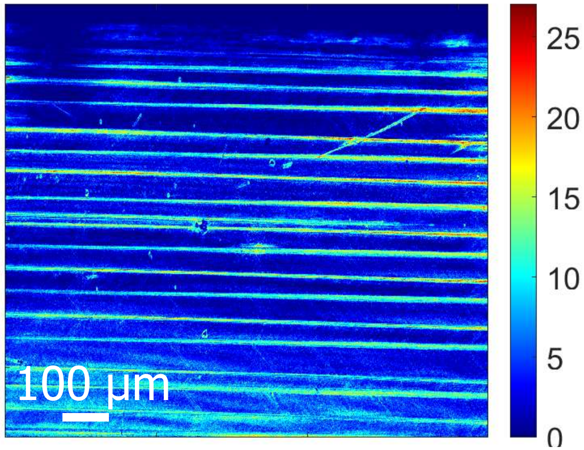
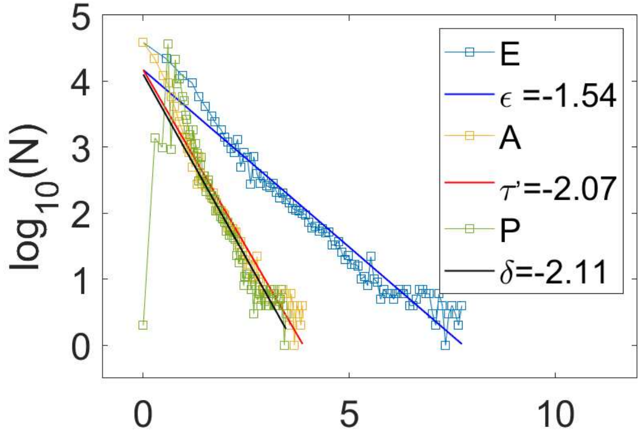
Höfling *et al.*, Science **372** (2021).

Tuning criticality with dislocations in $BaTiO_3$

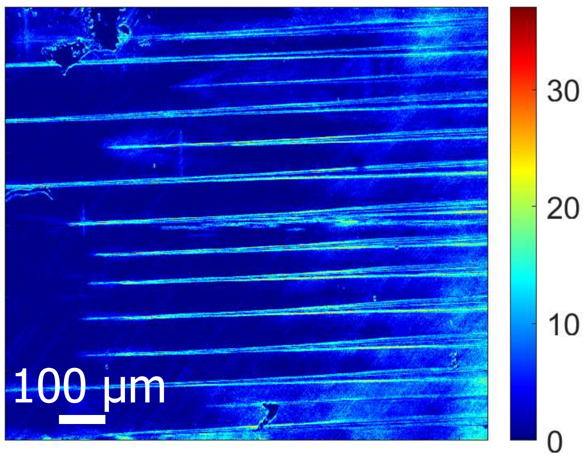
Dislocations are decreasing the energy exponent?

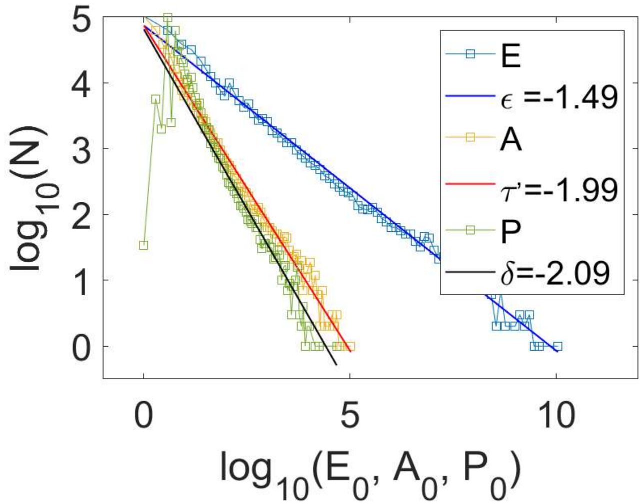
Reference





Deformed





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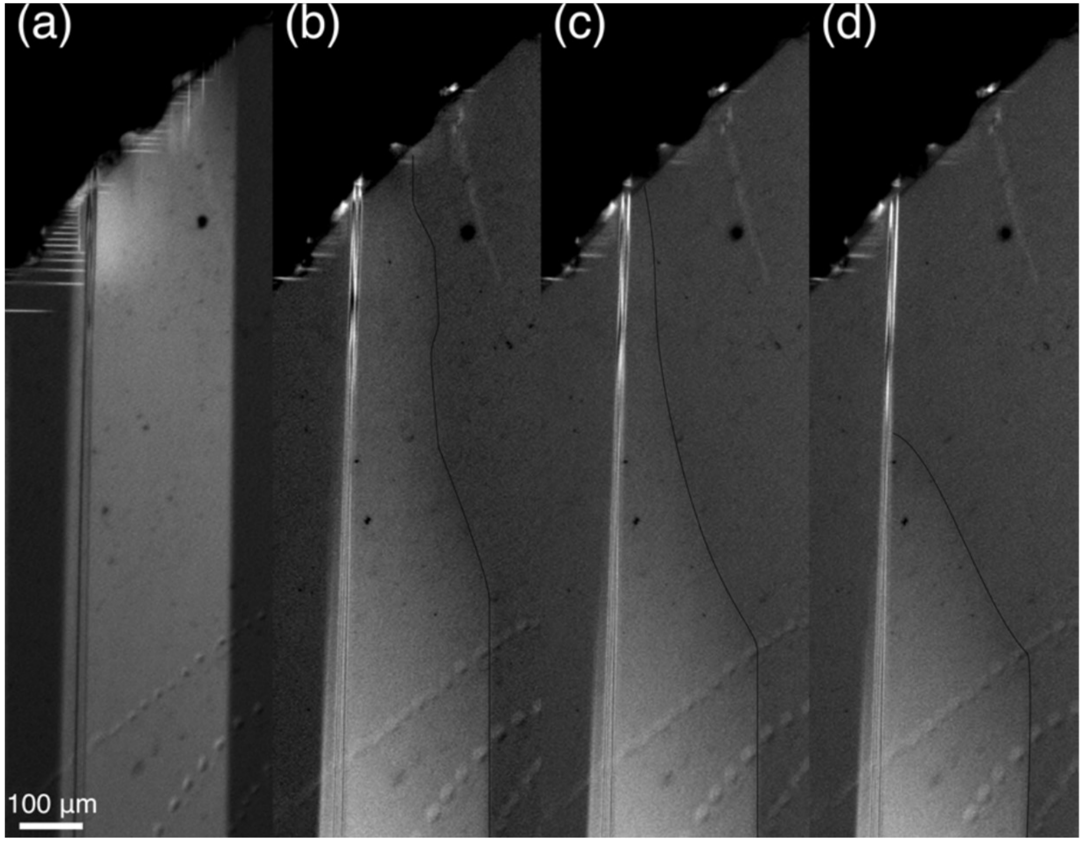
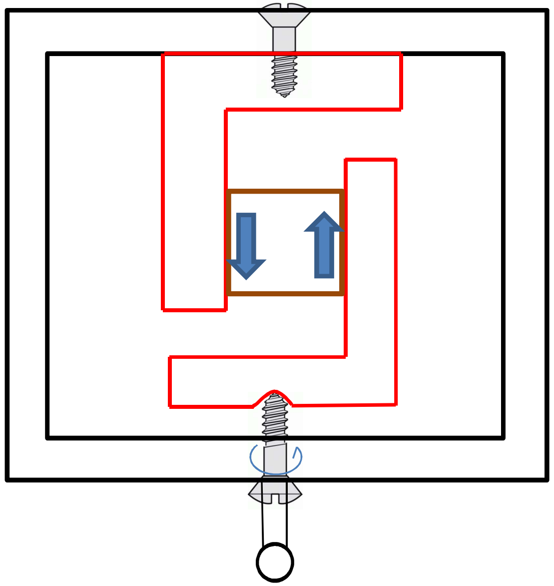
$LaAlO_3$: a prototypical system for ferroelastic avalanches



Harrison *et al.*, Appl. Phys. Lett. **99** (2011).

Applying shear stress to $LaAlO_3$

Collaboration with Nick Barret (Saclay)



1- Apply to $LaAlO_3$ single crystal a shear force
2- Keep the pressure for few seconds
3- Release the pressure
4- Take 1 image per second

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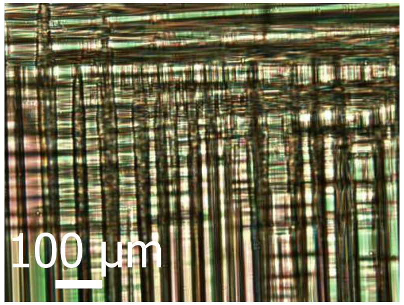
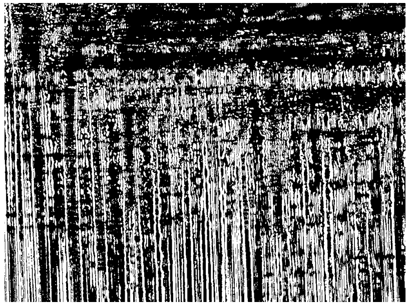
Entering a creep regime

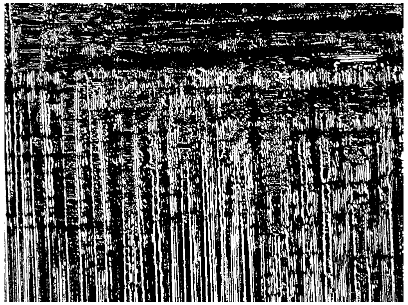
The number of switched regions decreases rapidly



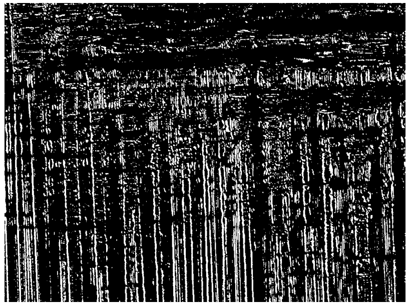
t = 0 s



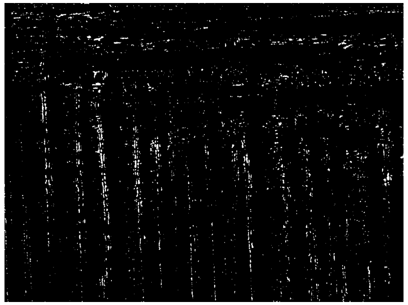
t = 1 s



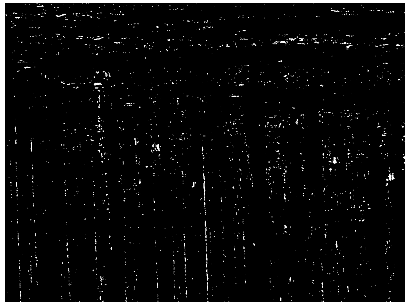
t = 2 s



t = 3 s



t = 4 s



t = 5 s

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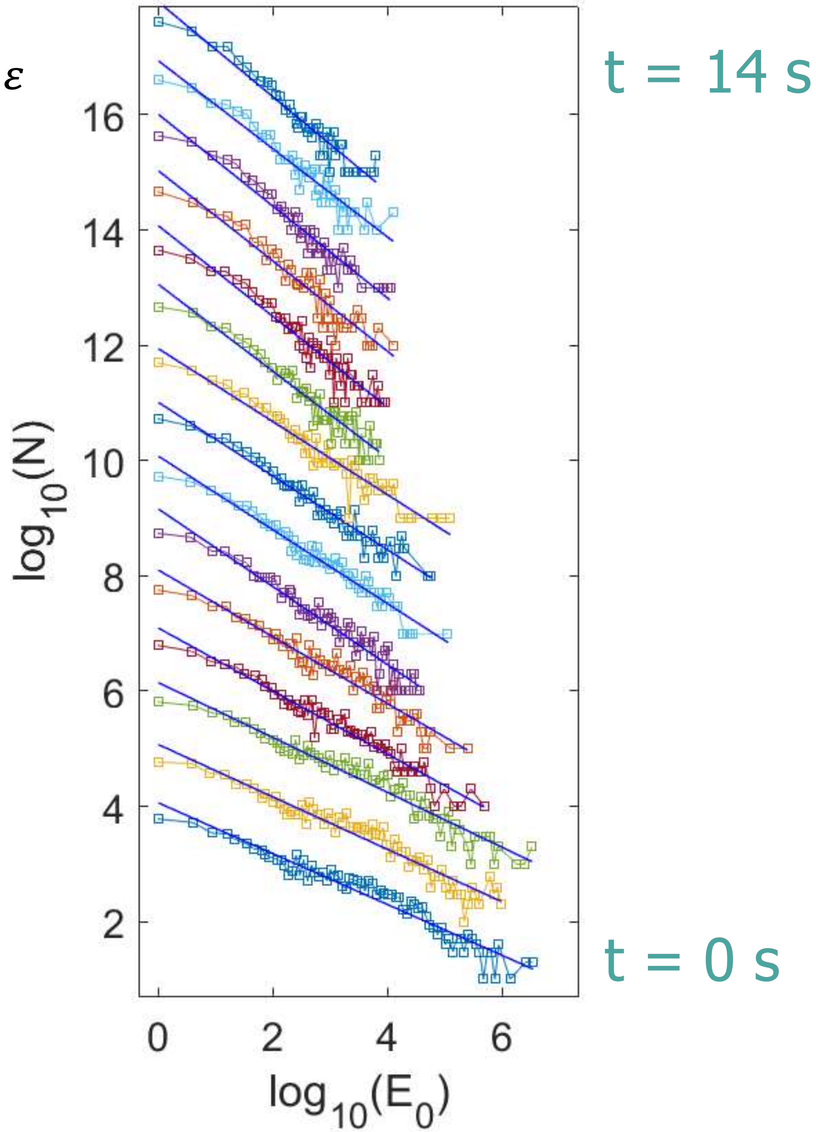
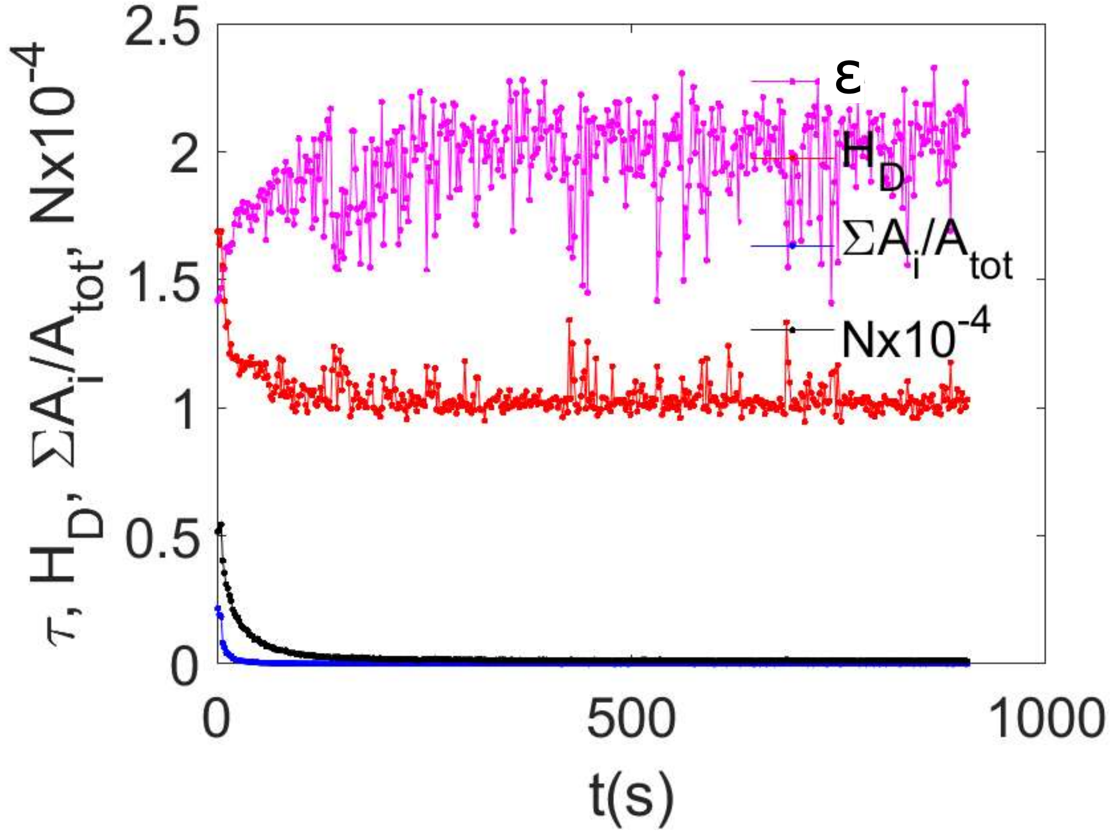
A simple power-law analysis

$N \sim E^{-\varepsilon}$





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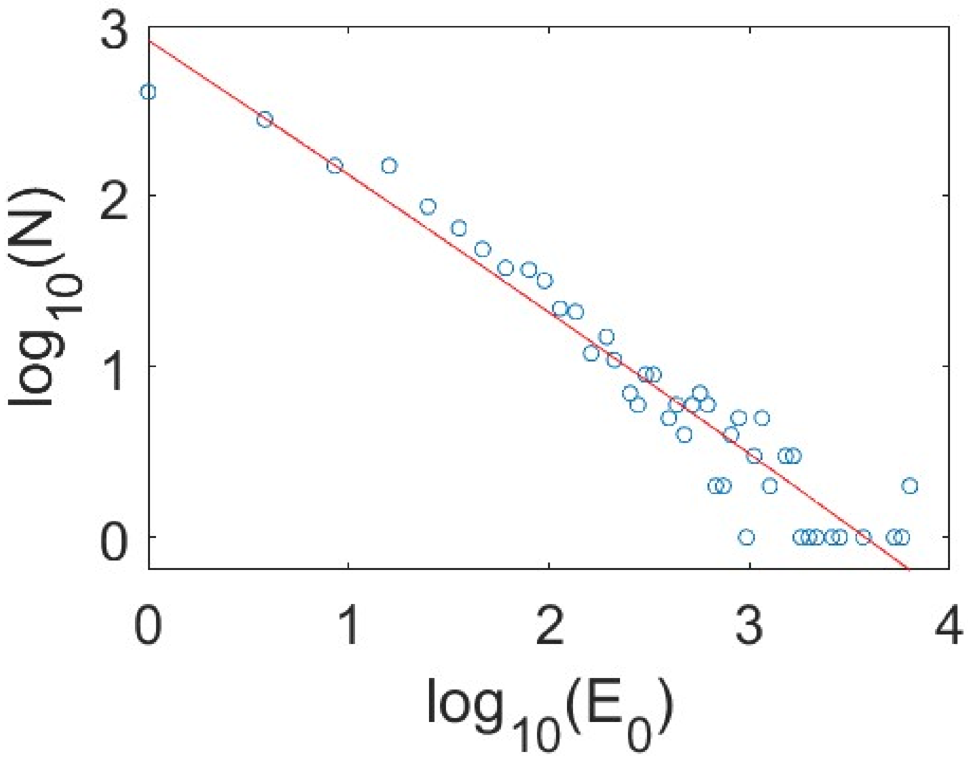
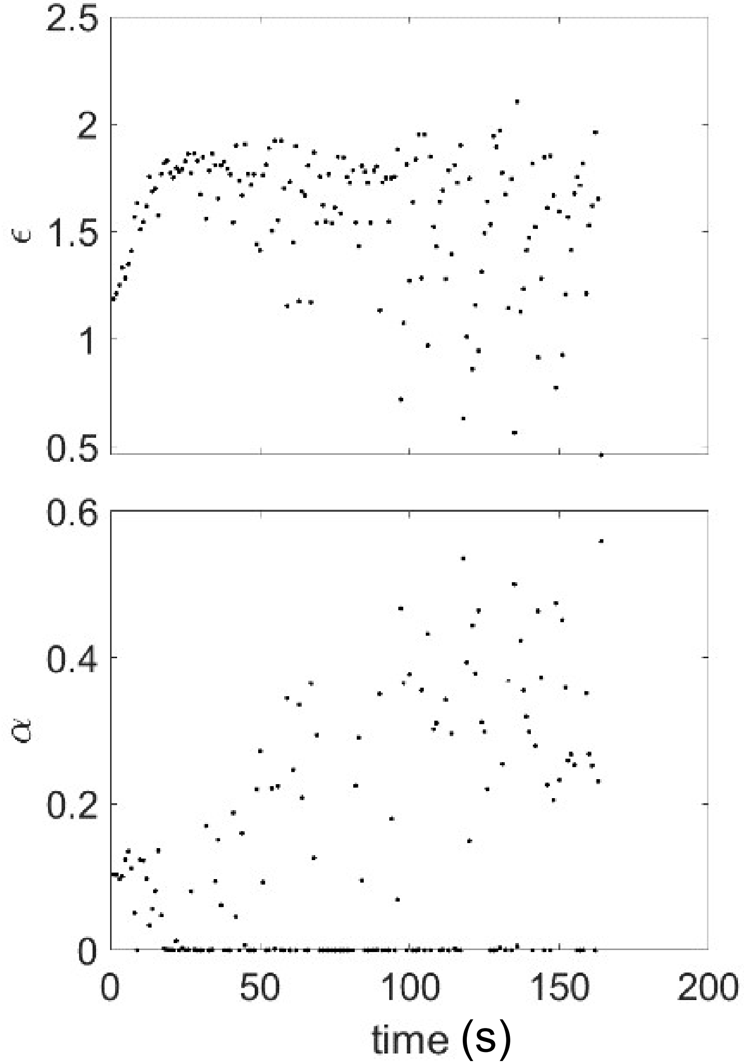
A power law with a cut-off

$N \sim E^{-\varepsilon} \exp(-E^{\alpha})$

free ε





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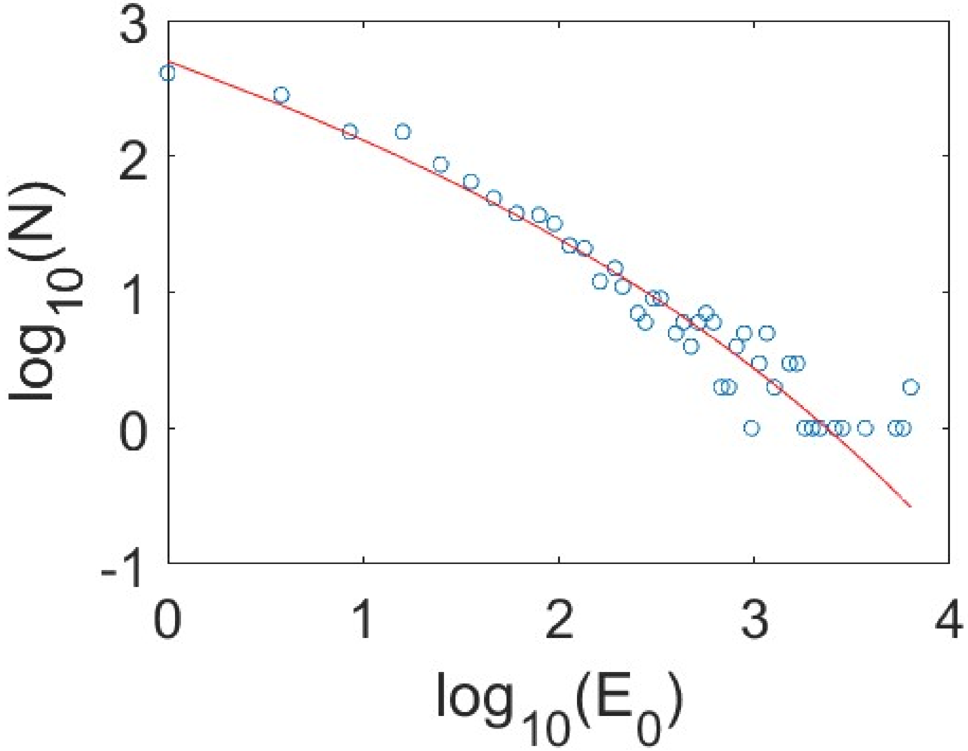
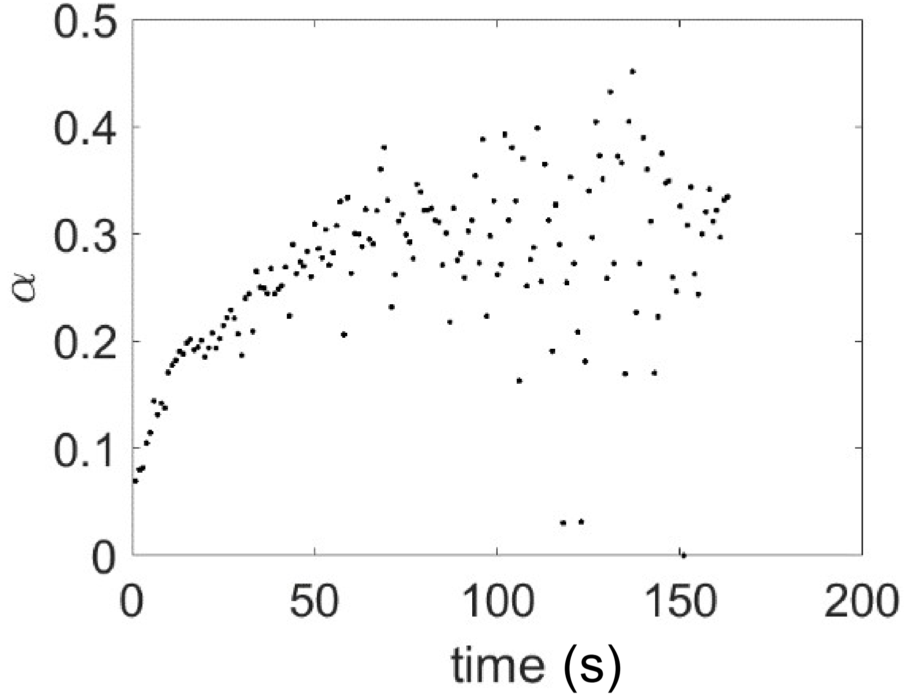
A power law with a cut-off

$N \sim E^{-\varepsilon} \exp(-E^{\alpha})$

fixed ε = 1.33





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Take home message

When releasing the shear stress applied on a ferroelastic, after a few seconds, domain walls response moves away from a power-law behaviour and exhibits a stronger exponential damping (cut-off).

Acknowledgements

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CAMBRIDGE
Ekhard Salje

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Questions?