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Novel Physical Model for DC Partial Discharge in Polymeric Insulators

Allen Andersen

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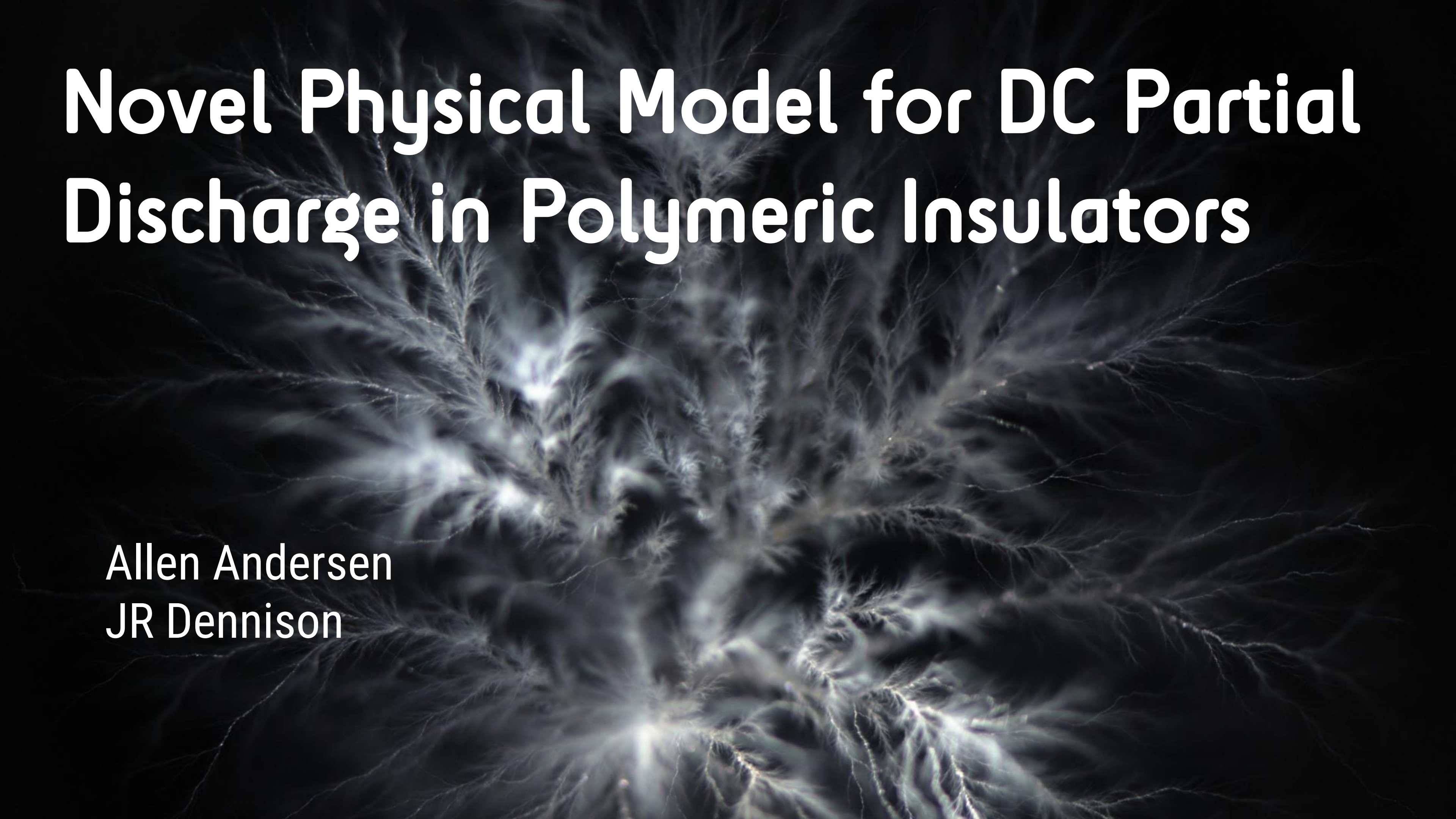


UtahStateUniversity
DEPARTMENT OF PHYSICS

MATERIALS
PHYSICS GROUP

MARCH
MEETING2017

Why study DCPD?

- There is not a widely accepted physical model of DC partial discharge (DCPD).

- DCPD is a key indicator of dielectric breakdown.

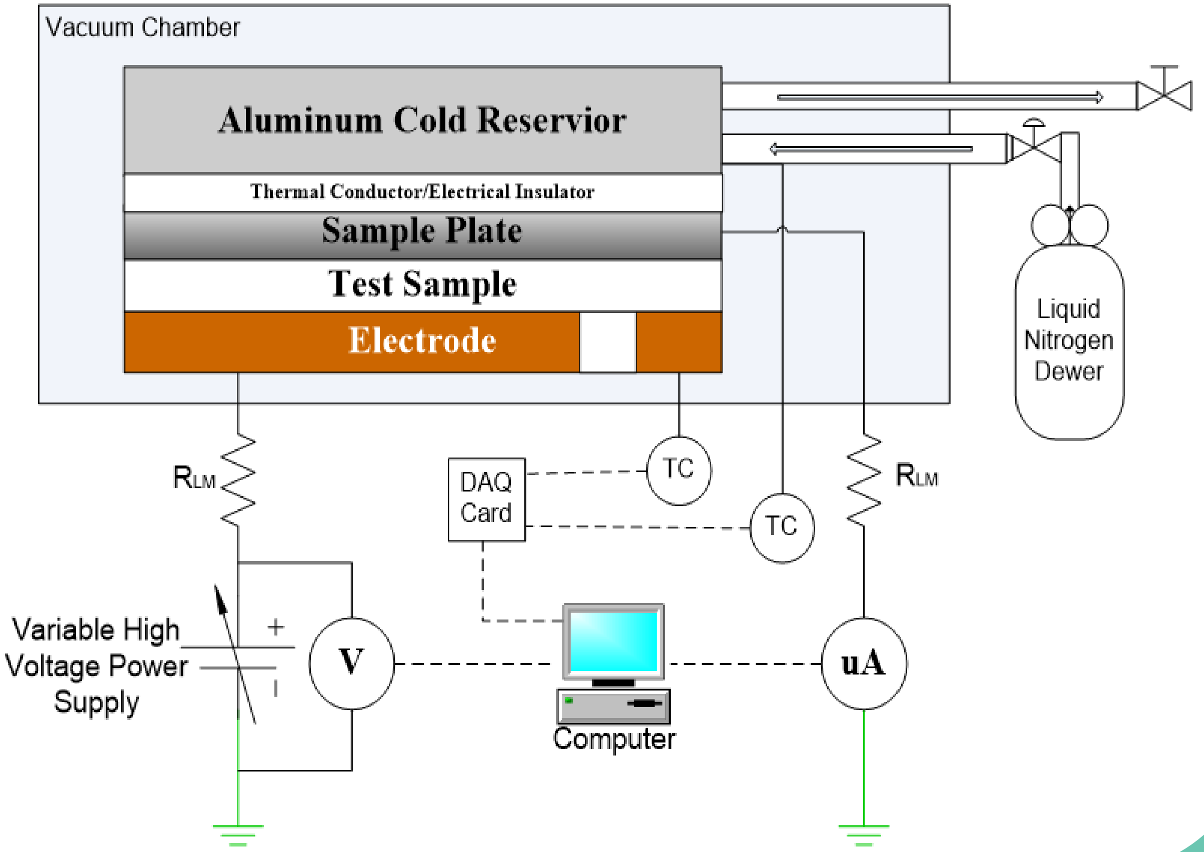
- Important DC applications include
  - HVDC power
  - Spacecraft charging
  - Microelectronics

DCPD & breakdown measurements

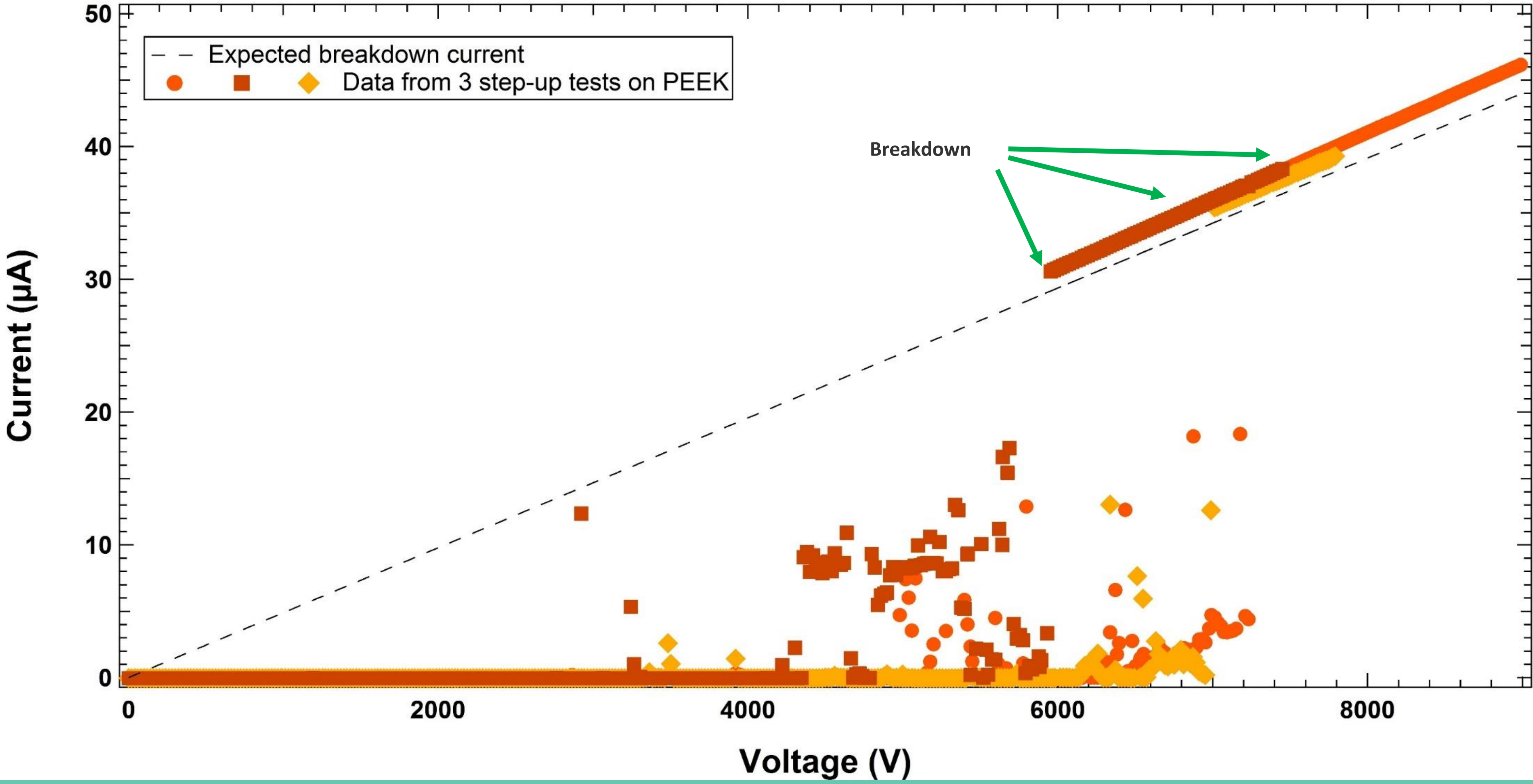
Dual-defect model of breakdown

DCPD in the context of model

Test Setup

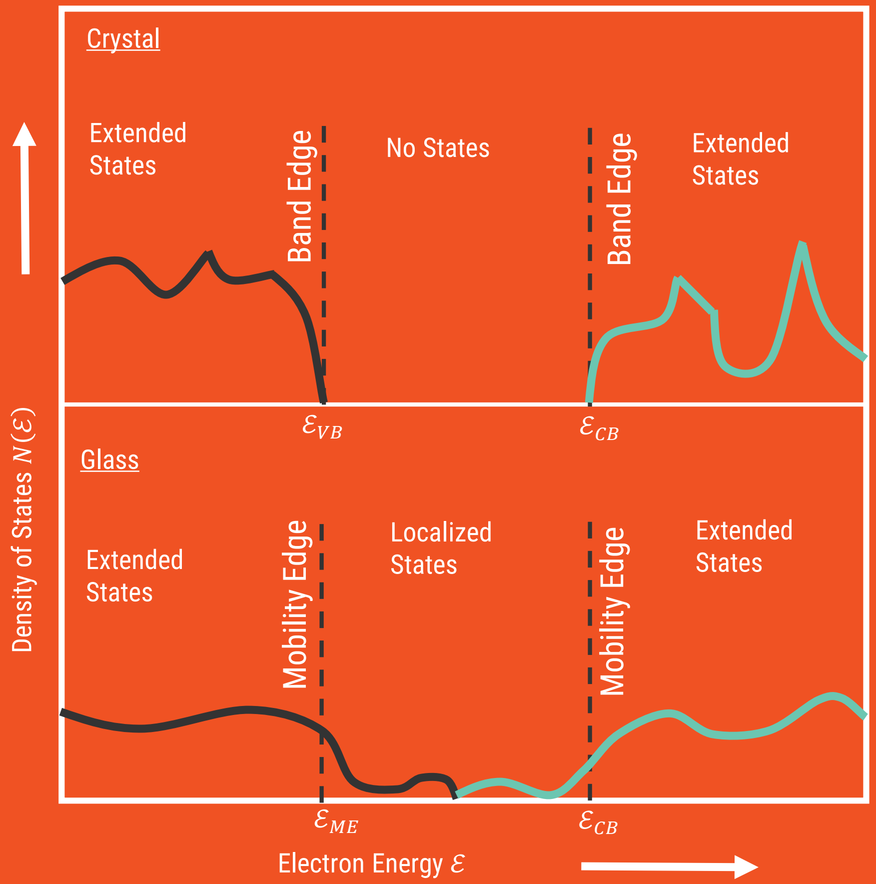


Vacuum Chamber
Aluminum Cold Reservior
Thermal Conductor/Electrical Insulator
Sample Plate
Test Sample
Electrode
Liquid Nitrogen Dewer
RLM
RLM
DAQ Card
TC
TC
Variable High Voltage Power Supply
+
V
Computer
uA



Expected breakdown current
Data from 3 step-up tests on PEEK
Breakdown
Current (μA)
Voltage (V)
0
10
20
30
40
50
0
2000
4000
6000
8000

Defect-driven model



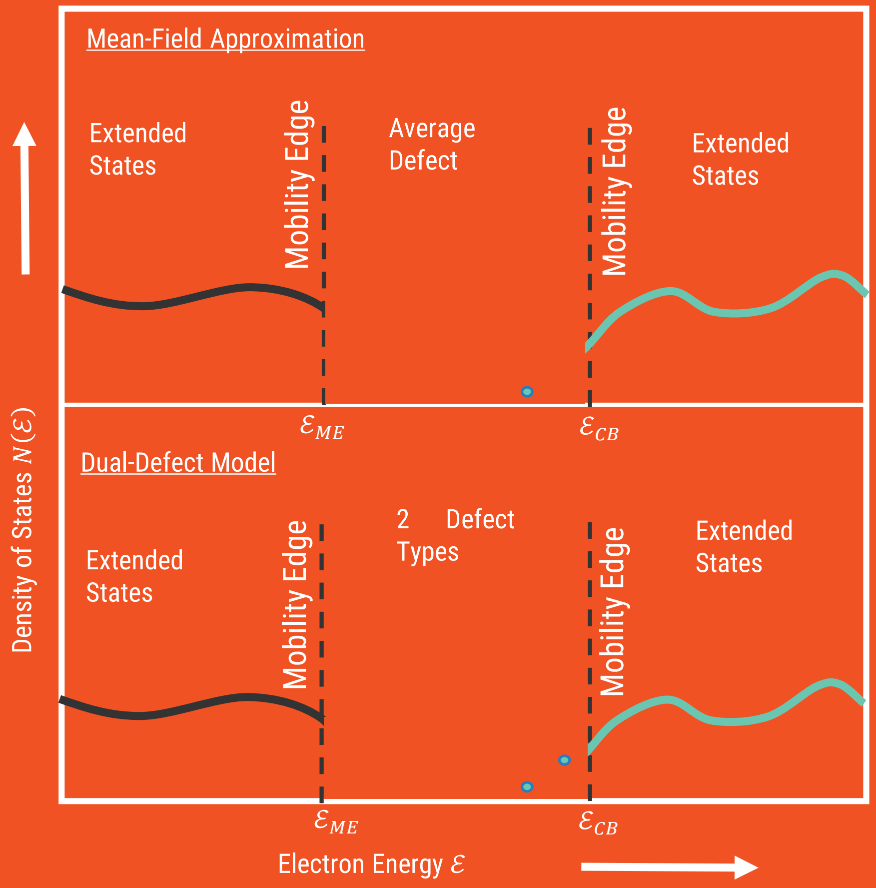
Ideal crystalline insulators

- Large band gap of forbidden energies.
- Charge transport is solvable from first principles.

Highly disordered insulators

- Spatially localized states exist in the mobility gap.
- Analytic solutions from first principles are not available.

Defect-driven model



Crine model

- Consider transport between evenly spaced defects of the same energy is a common approximation.

Dual-defect model

- Consider the average contributions of low-energy physical defects and high-energy chemical defects.
- Low-energy defects are thermally recoverable.

Mean field theory—single defect model

$$P_{def}(F,T,\Delta t) = \left(\frac{2k_b T \Delta t}{h}\right) \exp\left[\frac{-\Delta G_{def}}{k_b T}\right] \sinh\left[\frac{\epsilon F^2}{2k_b T N_{def}}\right]$$

Mean field theory—single defect model

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Probability of Breakdown

Mean field theory—single defect model

$$P_{def}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}}{k_bT}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}}\right]$$

Probability of Breakdown

Phonon Frequency

Mean field theory—single defect model

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Probability of Breakdown

Mean defect energy

Phonon Frequency

Mean field theory—single defect model

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Probability of Breakdown

Phonon Frequency

Mean defect energy

Maxwell Stress

Mean field theory—single defect model

$$P_{def}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}}{k_bT}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}}\right]$$

Probability of Breakdown

Phonon Frequency

Mean defect energy

Maxwell Stress

Mean defect density

Mean field theory—single defect model

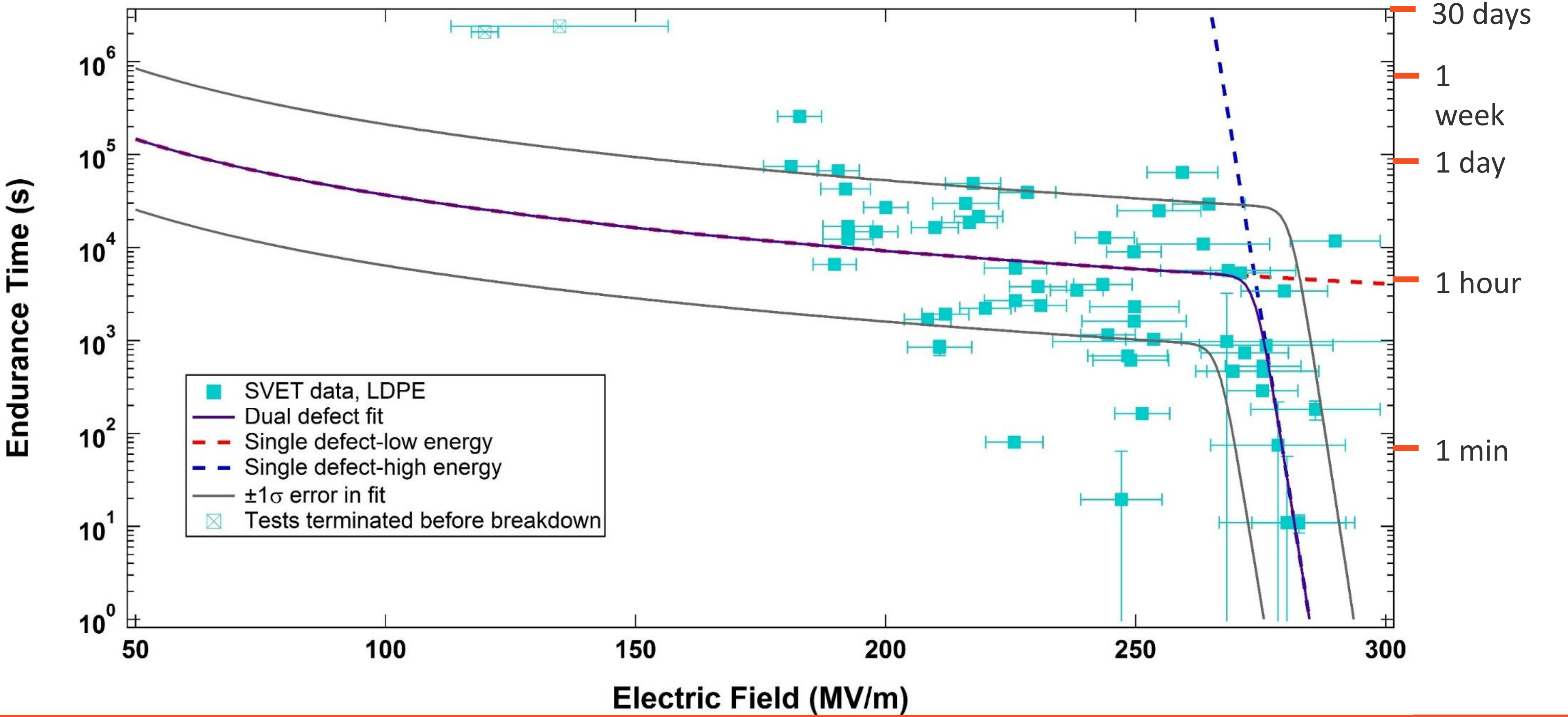
$$P_{def}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}}{k_bT}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}}\right]$$

Dual-defect model—sum of the contribution of two defect types

$$P_{def}^{tot}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\sum_{i=LO,HI}\exp\left[\frac{-\Delta G_{def}^i}{k_bT}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}^i}\right]$$

LO-type low-energy defects correspond to physical defects.
HI-type high-energy defects are high energy chemical defects.

Defect-driven model

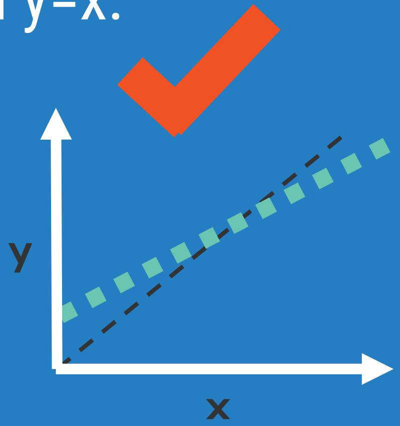


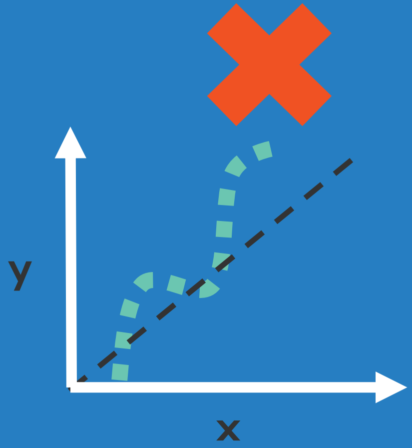
Are DCPD and Breakdown Related?

Quantile-Quantile plots compare the distributions of two observables.

If the distributions are related the plot is a linear.

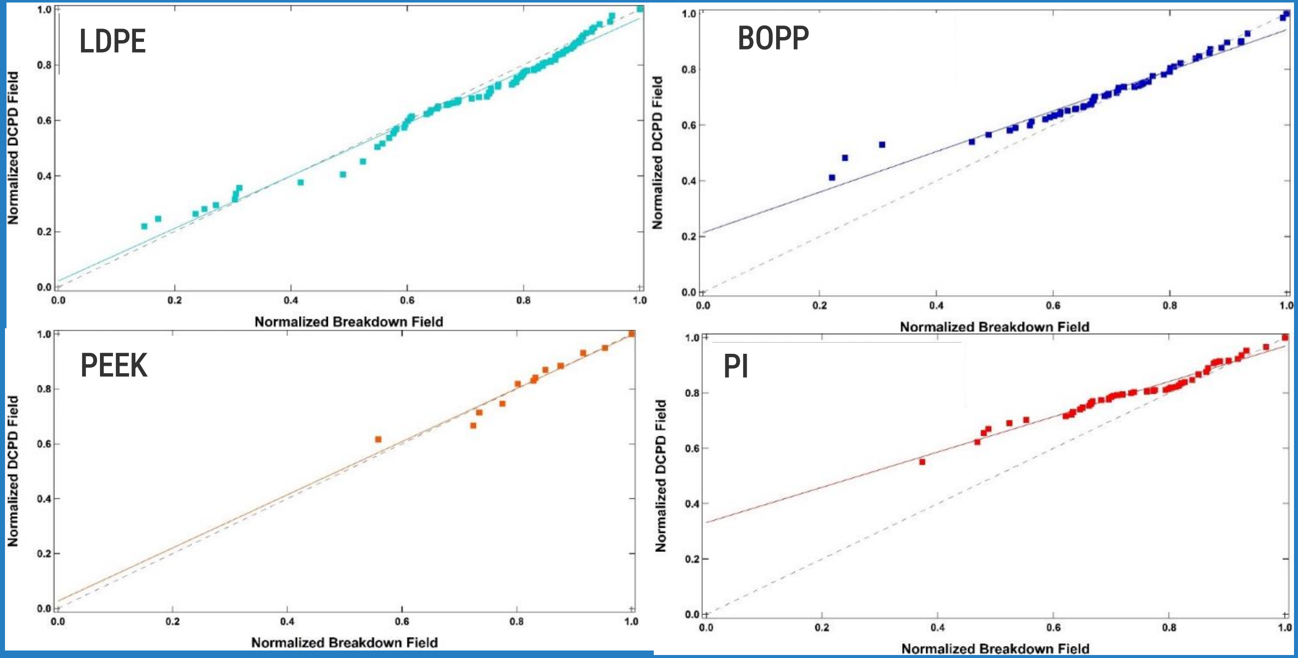
If the fields at each quantile are identical, points will lie on y=x.





Are DCPD and Breakdown Related?

Quantile-Quantile (q-q) analysis shows DCPD and breakdown are correlated!



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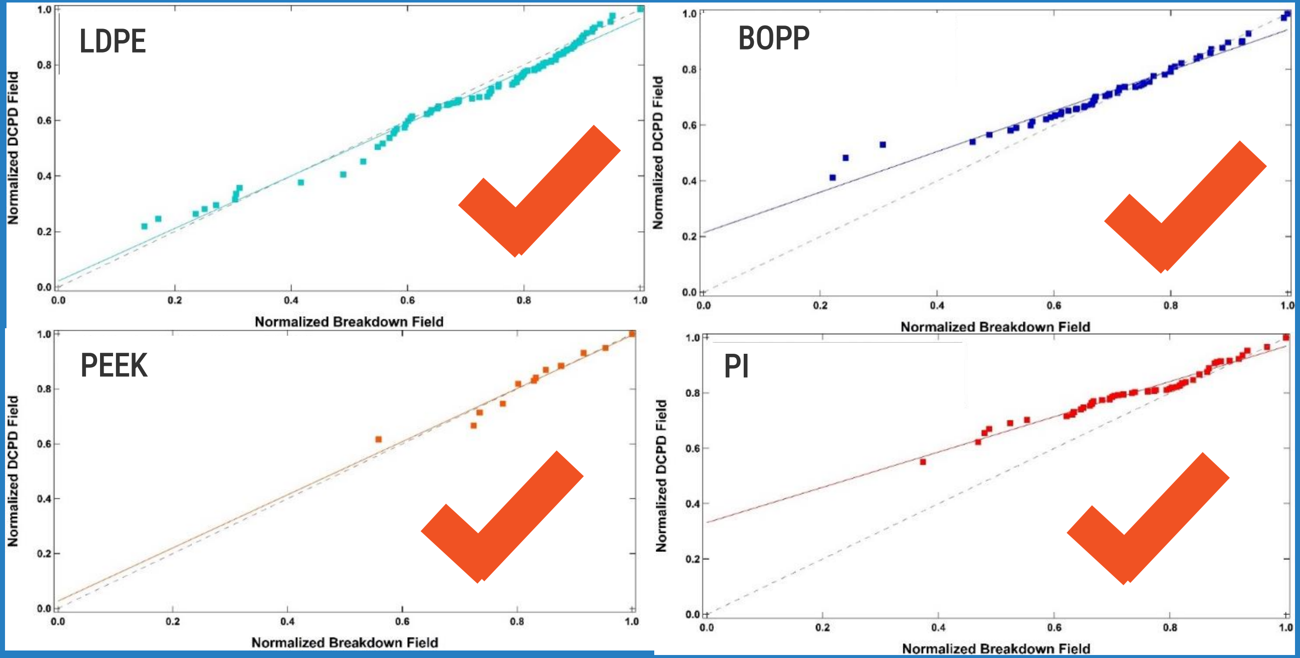
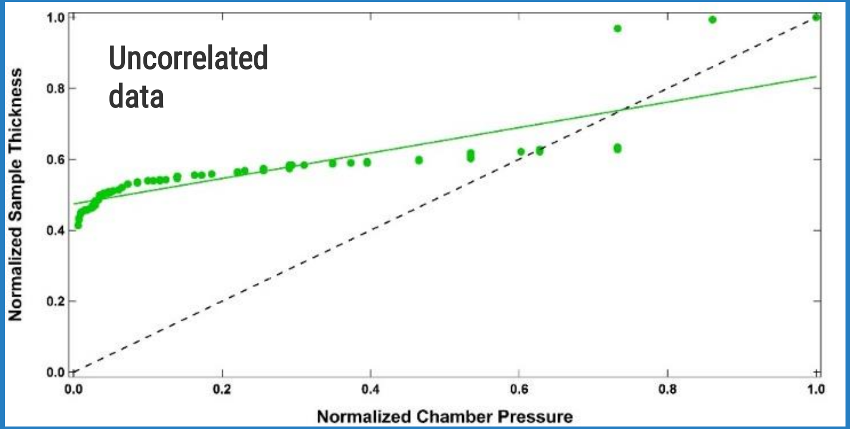
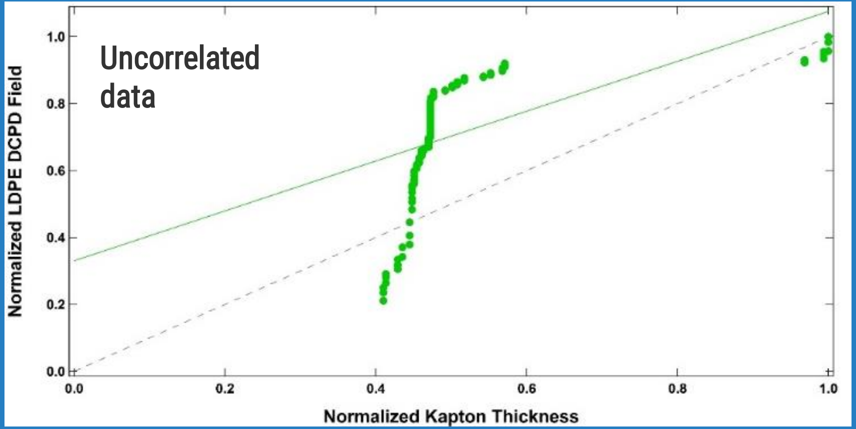


Are DCPD and Breakdown Related?

q-q plots of uncorrelated data





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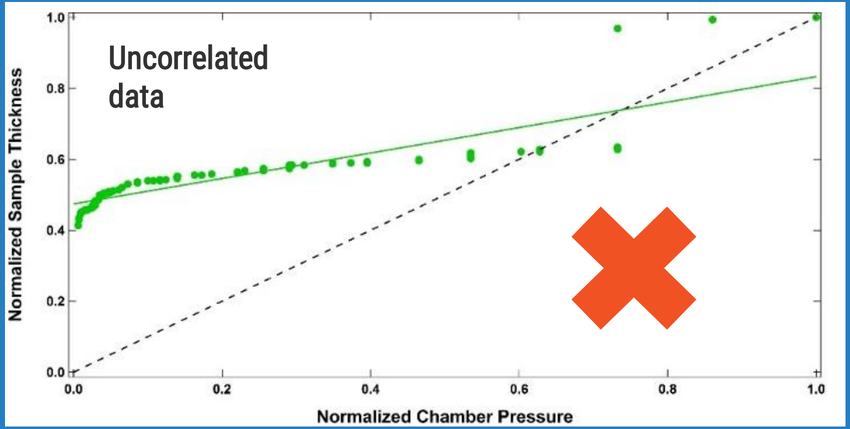
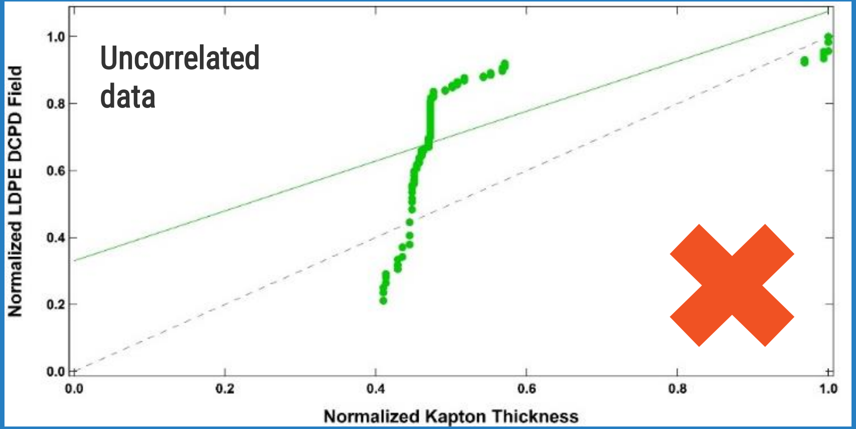
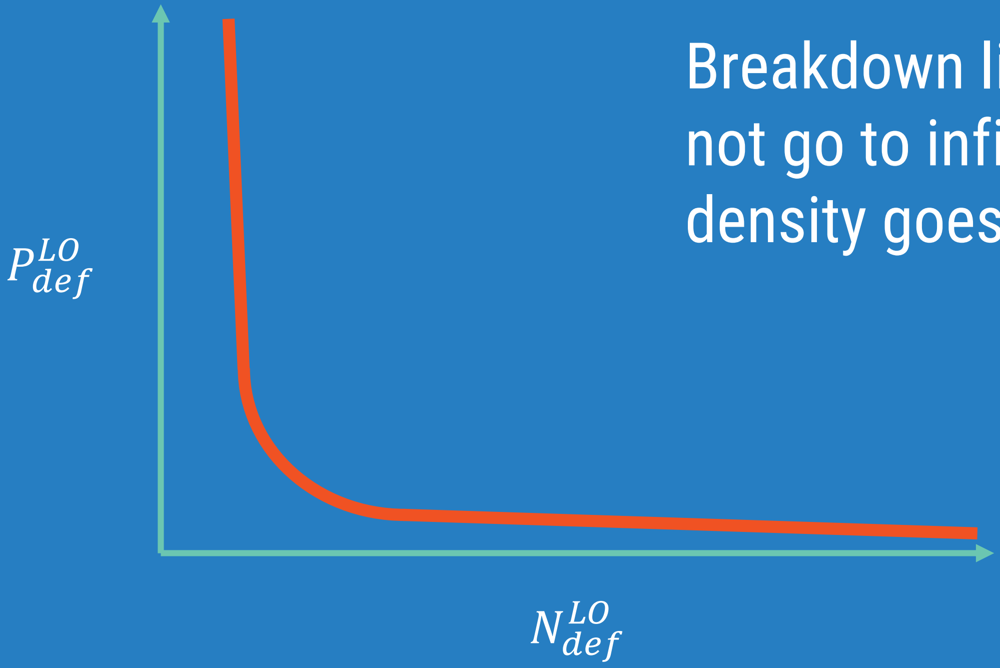




Correction to the limiting behavior

$$P_{def}^{LO}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}^{LO}}{k_bT}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}^{LO}}\right]$$

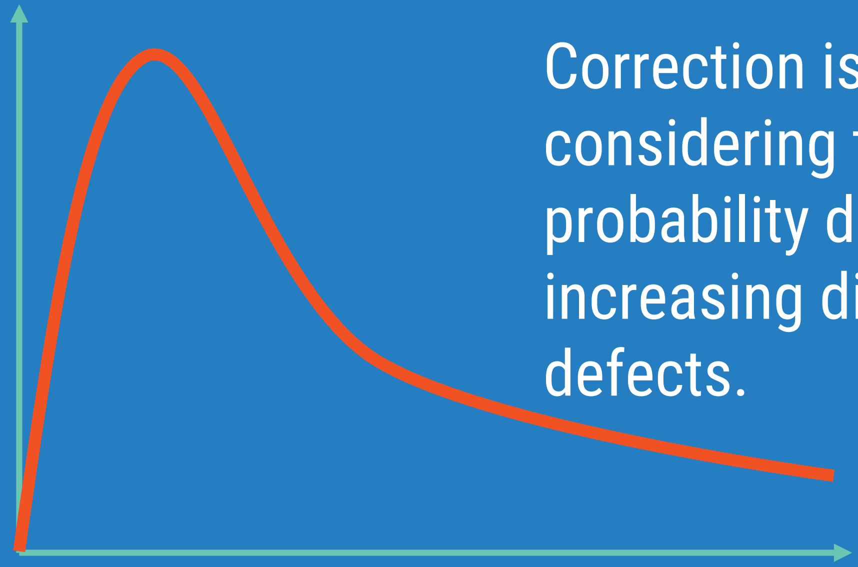


Breakdown likelihood should not go to infinity as defect density goes to zero!!!

Correction to the limiting behavior

$$P_{def}^{LO}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}^{LO}}{k_bT} - \frac{N_0^{LO}}{N_{def}^{LO}}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}^{LO}}\right]$$

P_{def}^{LO}

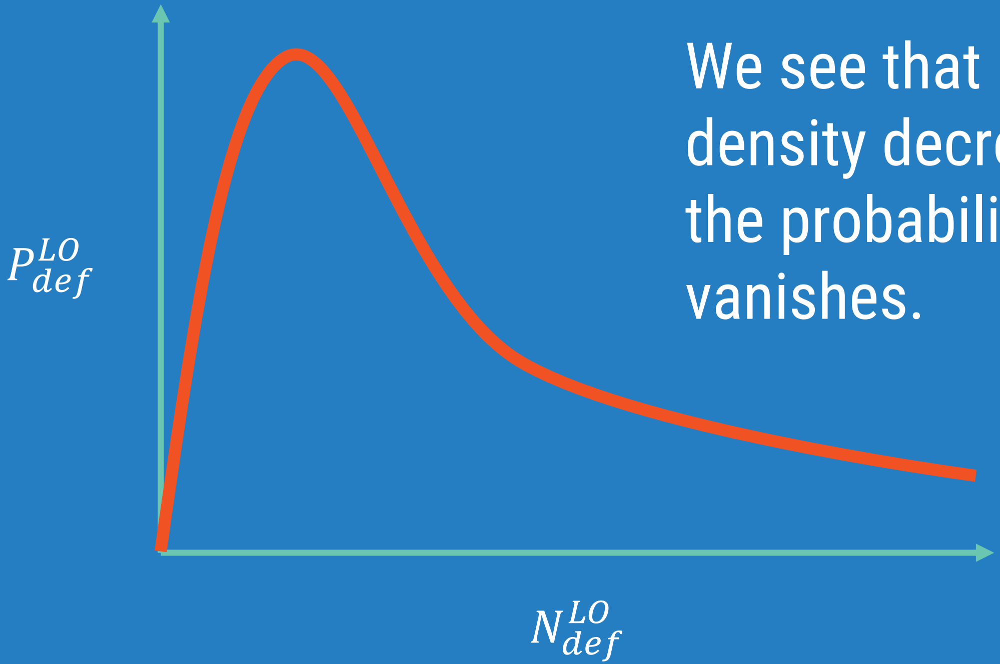


N_{def}^{LO}

Correction is analogous to considering that tunneling probability dies off with increasing distance between defects.

Correction to the limiting behavior

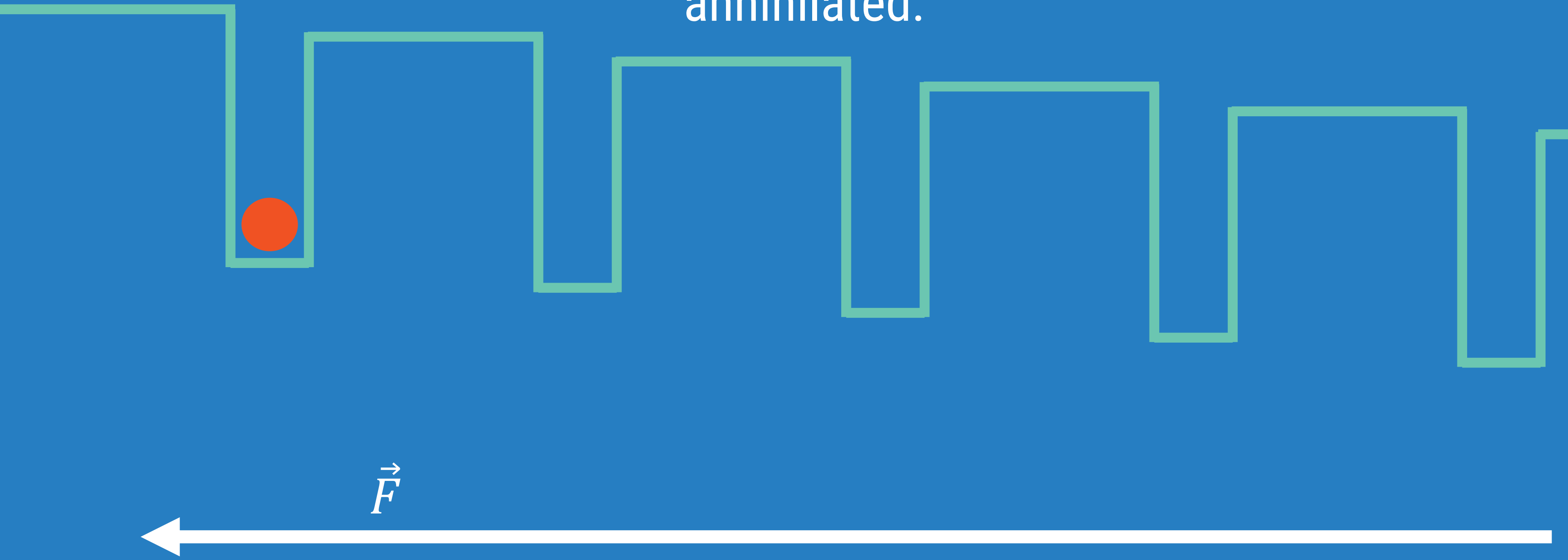
$$P_{def}^{LO}(F,T,\Delta t) = \left(\frac{2k_bT\Delta t}{h}\right)\exp\left[\frac{-\Delta G_{def}^{LO}}{k_bT} - \frac{N_0^{LO}}{N_{def}^{LO}}\right]\sinh\left[\frac{\epsilon F^2}{2k_bTN_{def}^{LO}}\right]$$



We see that if the defect density decreases sufficiently, the probability of breakdown vanishes.

Role of Recoverable Defects in DCPD

Depending on the temperature, low-energy defects an be created or annihilated.



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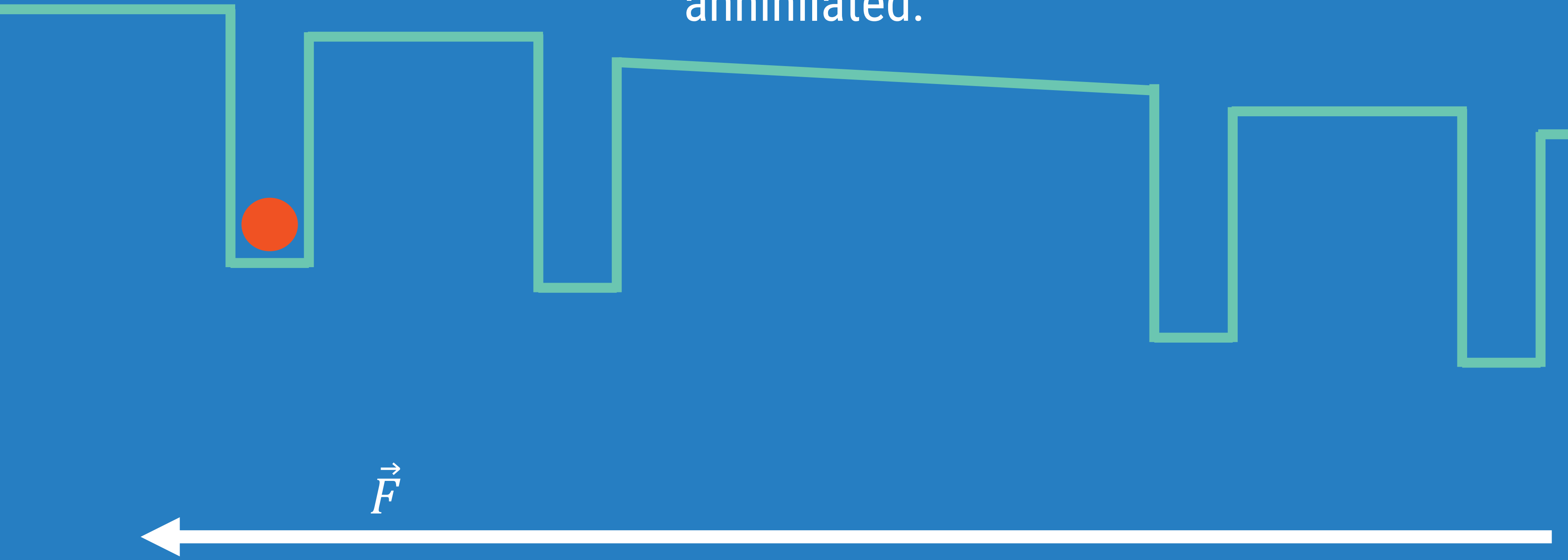

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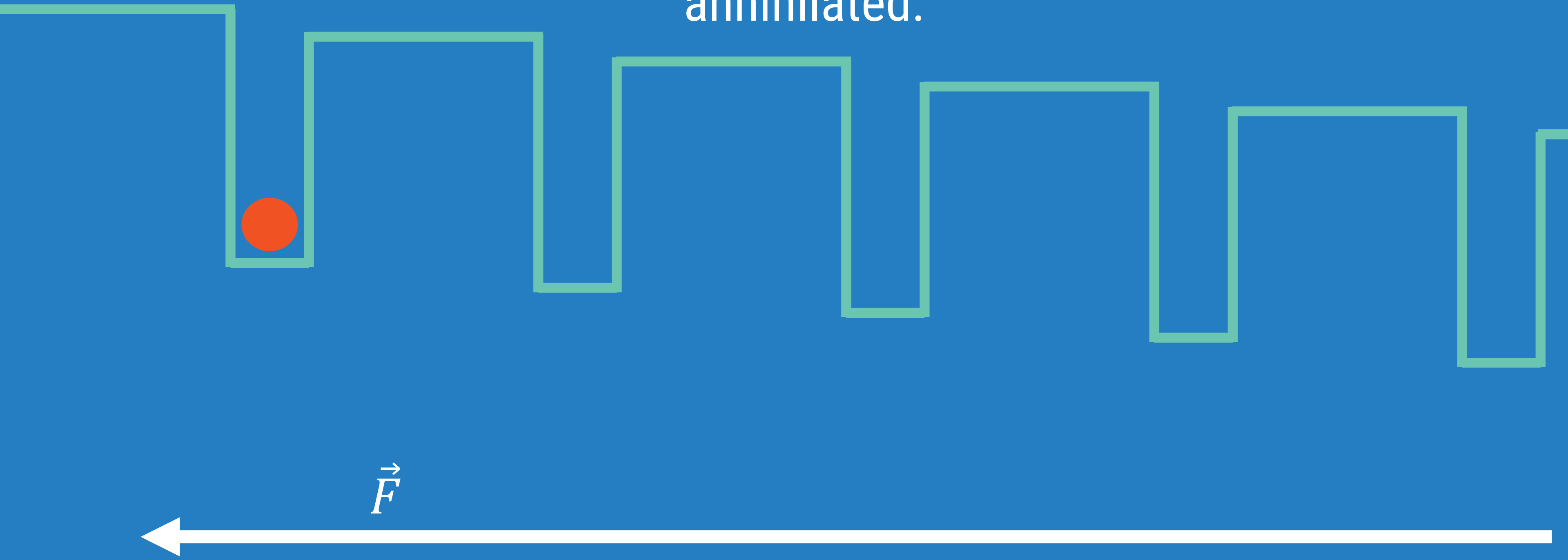
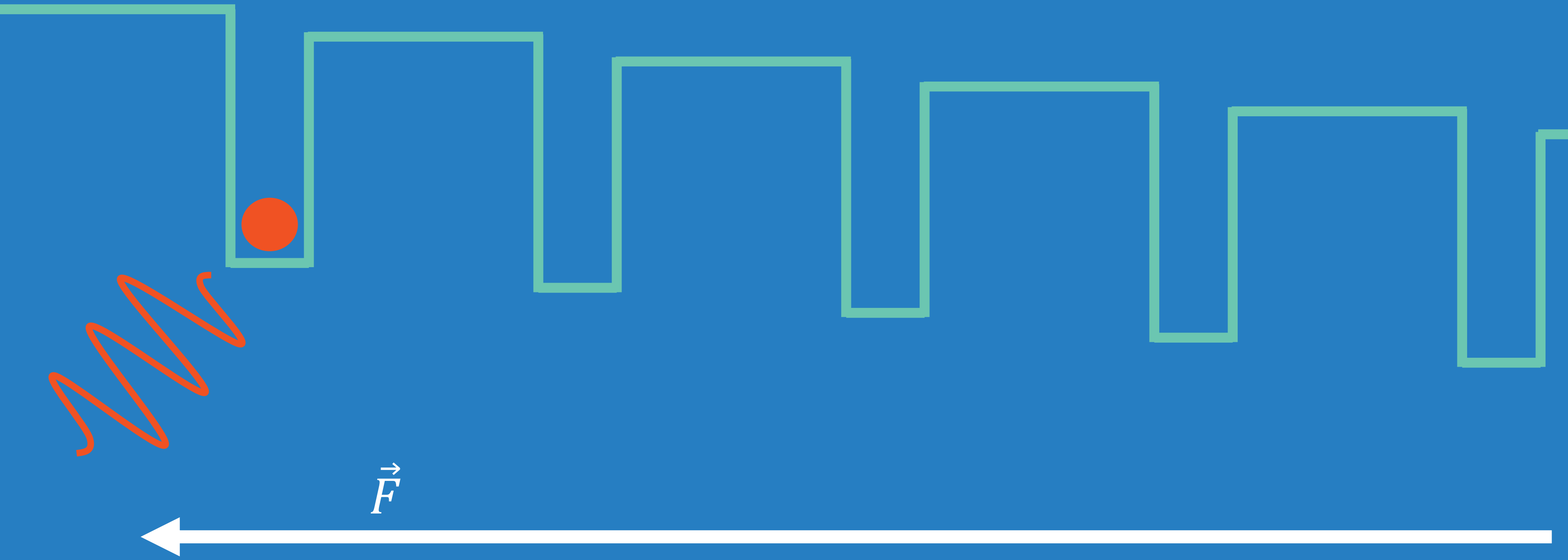


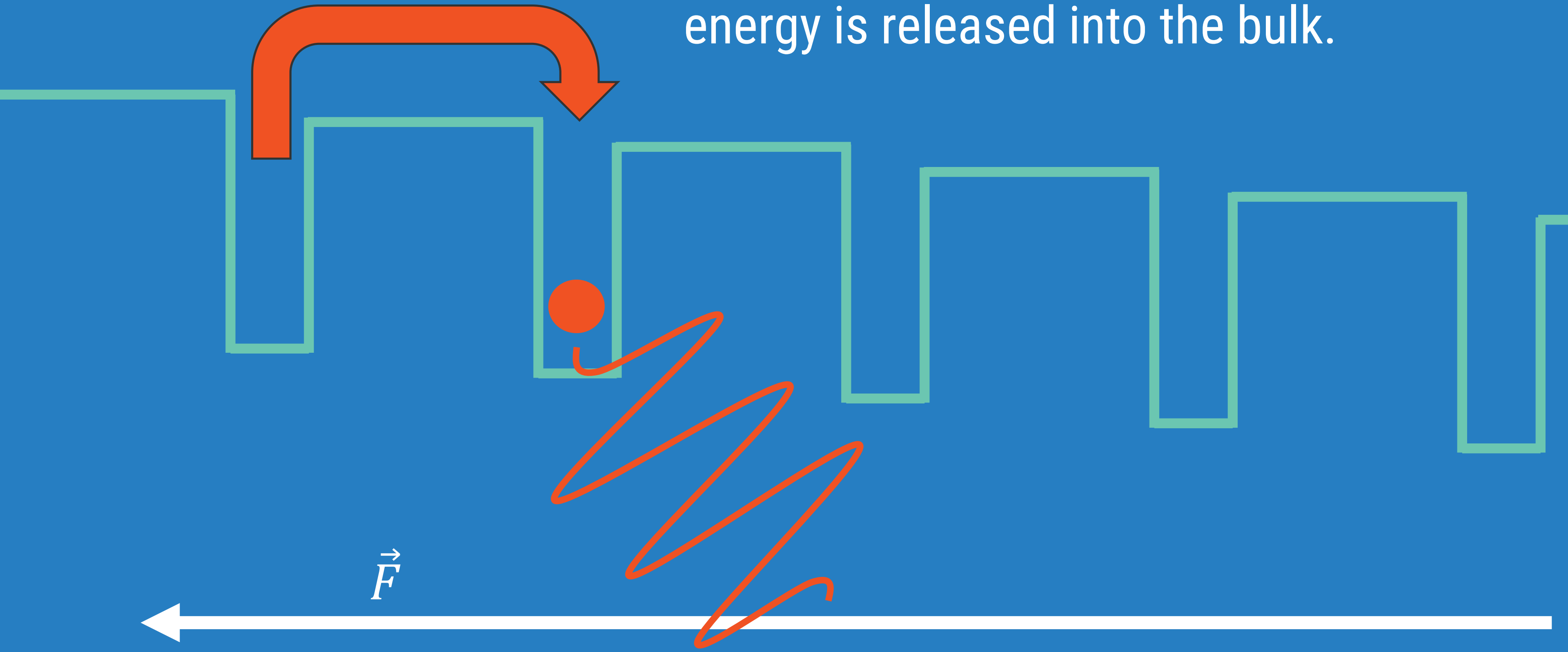
Role of Recoverable Defects in DCPD

Start with field-assisted thermally assisted hopping transport.



Role of Recoverable Defects in DCPD

As a discharge begins to form, thermal energy is released into the bulk.



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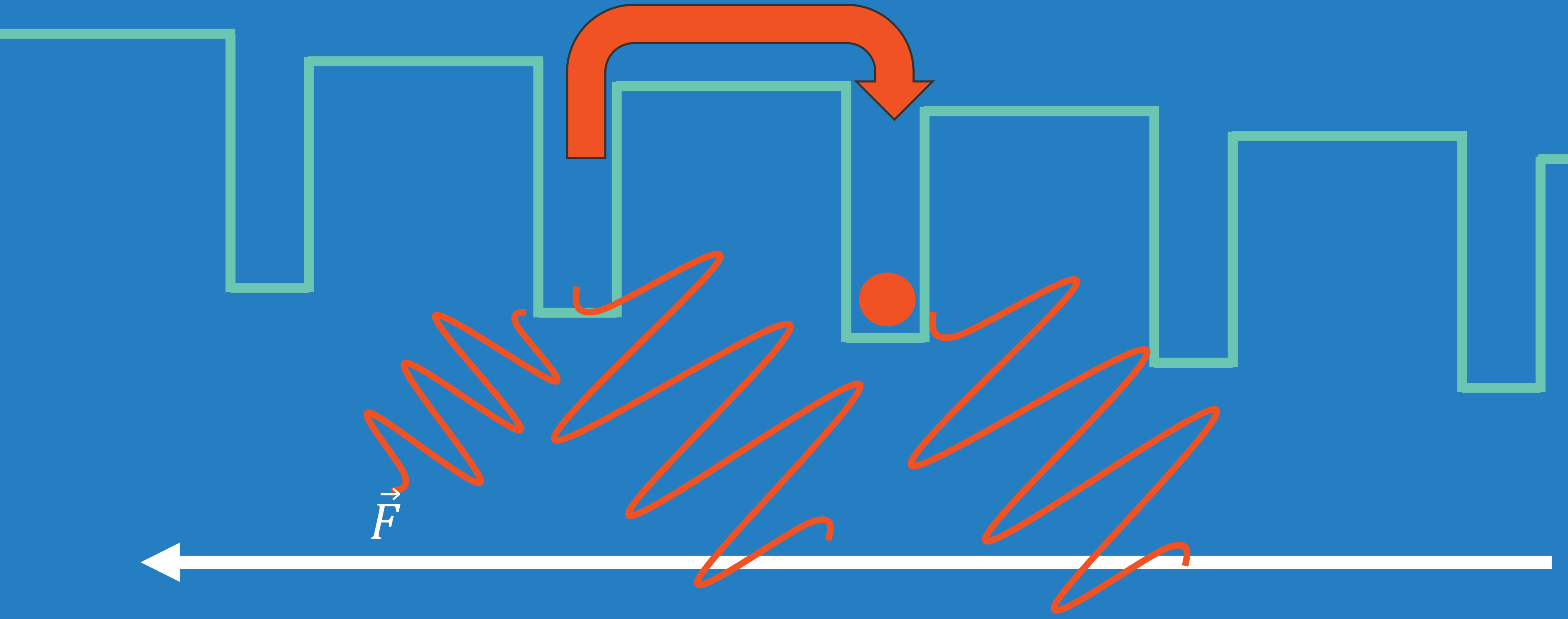
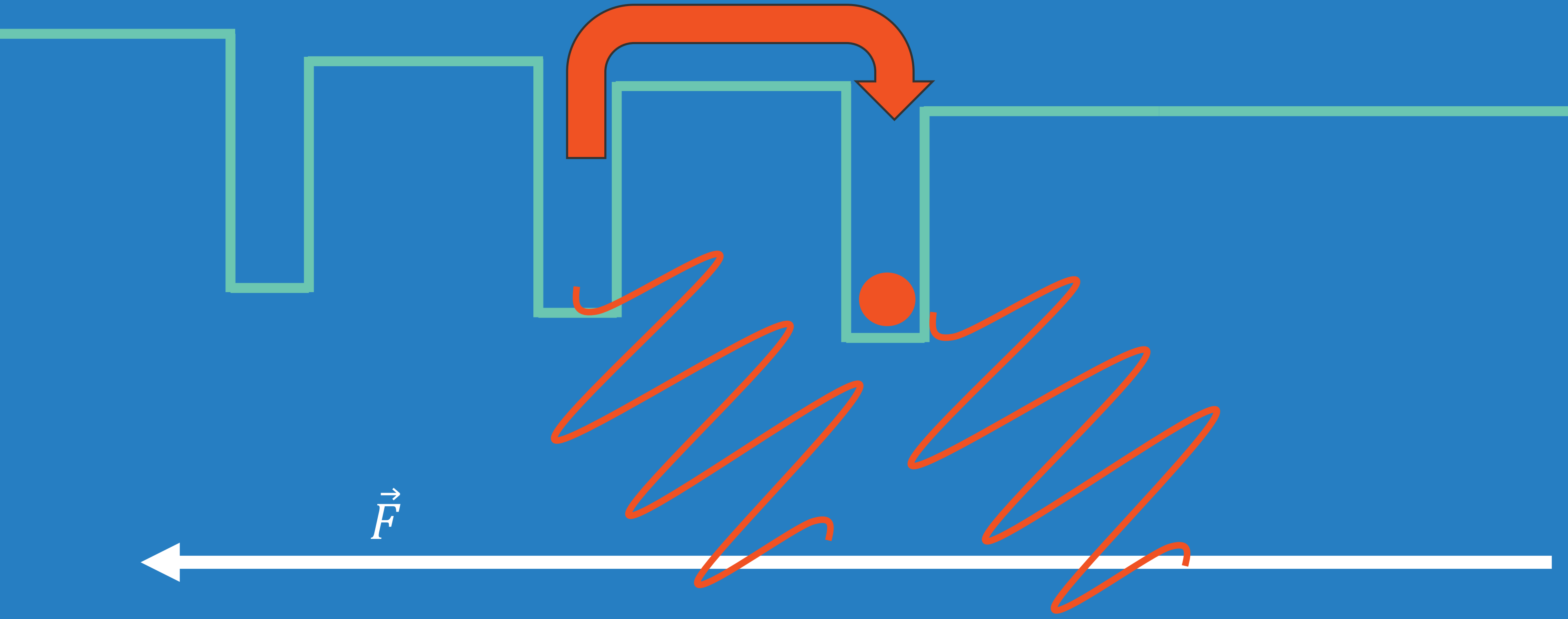


Role of Recoverable Defects in DCPD

Enough low-energy defects are thermally annealed to stop the motion of charge.



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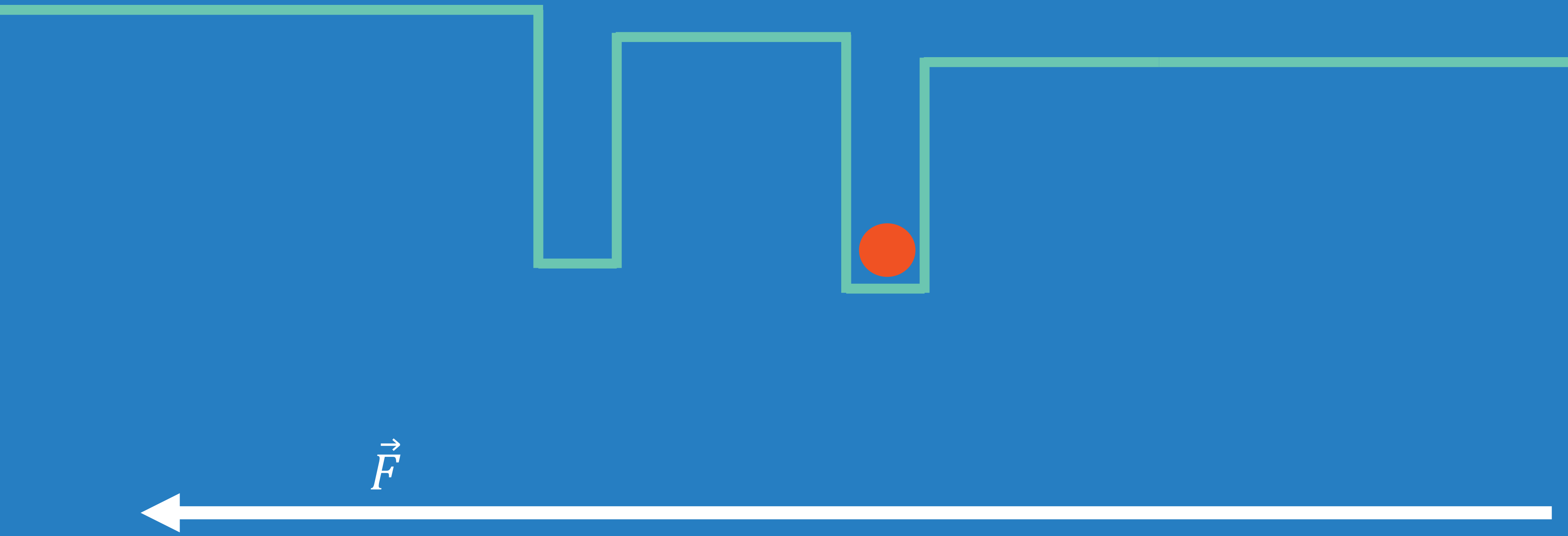
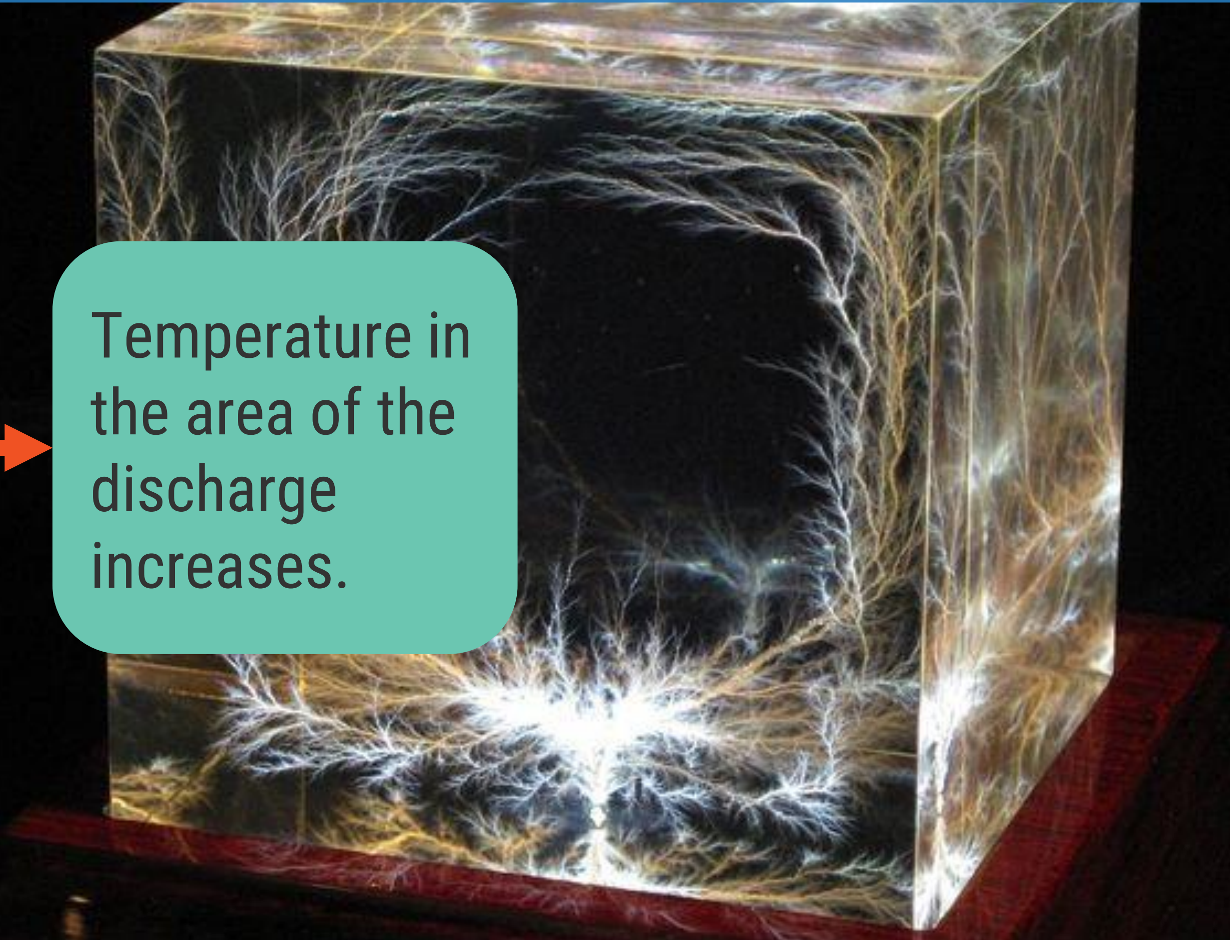


Role of Recoverable Defects in DCPD

Runaway charge motion begins under applied electric field.

Role of Recoverable Defects in DCPD

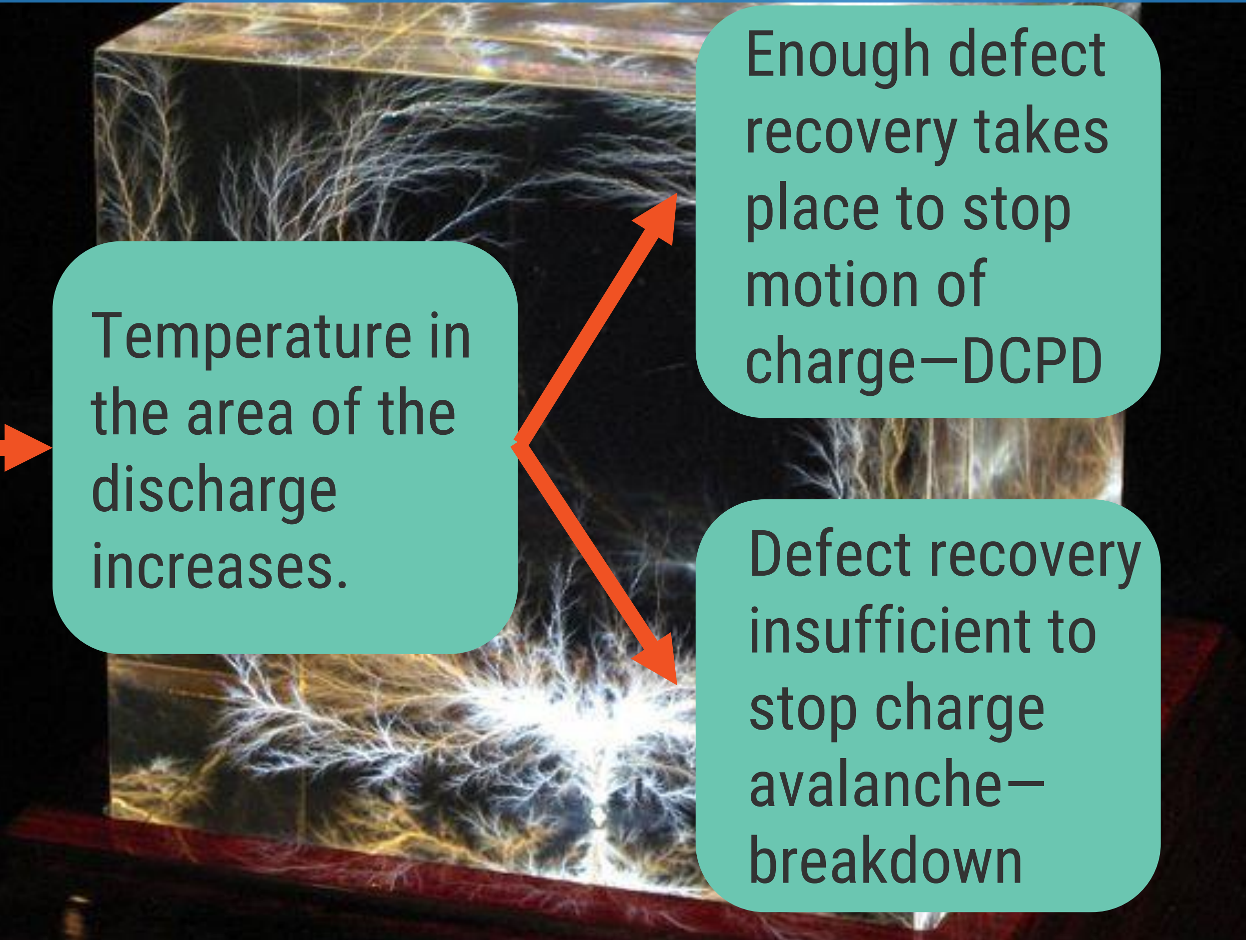


Runaway charge motion begins under applied electric field.

→

Temperature in the area of the discharge increases.

Role of Recoverable Defects in DCPD

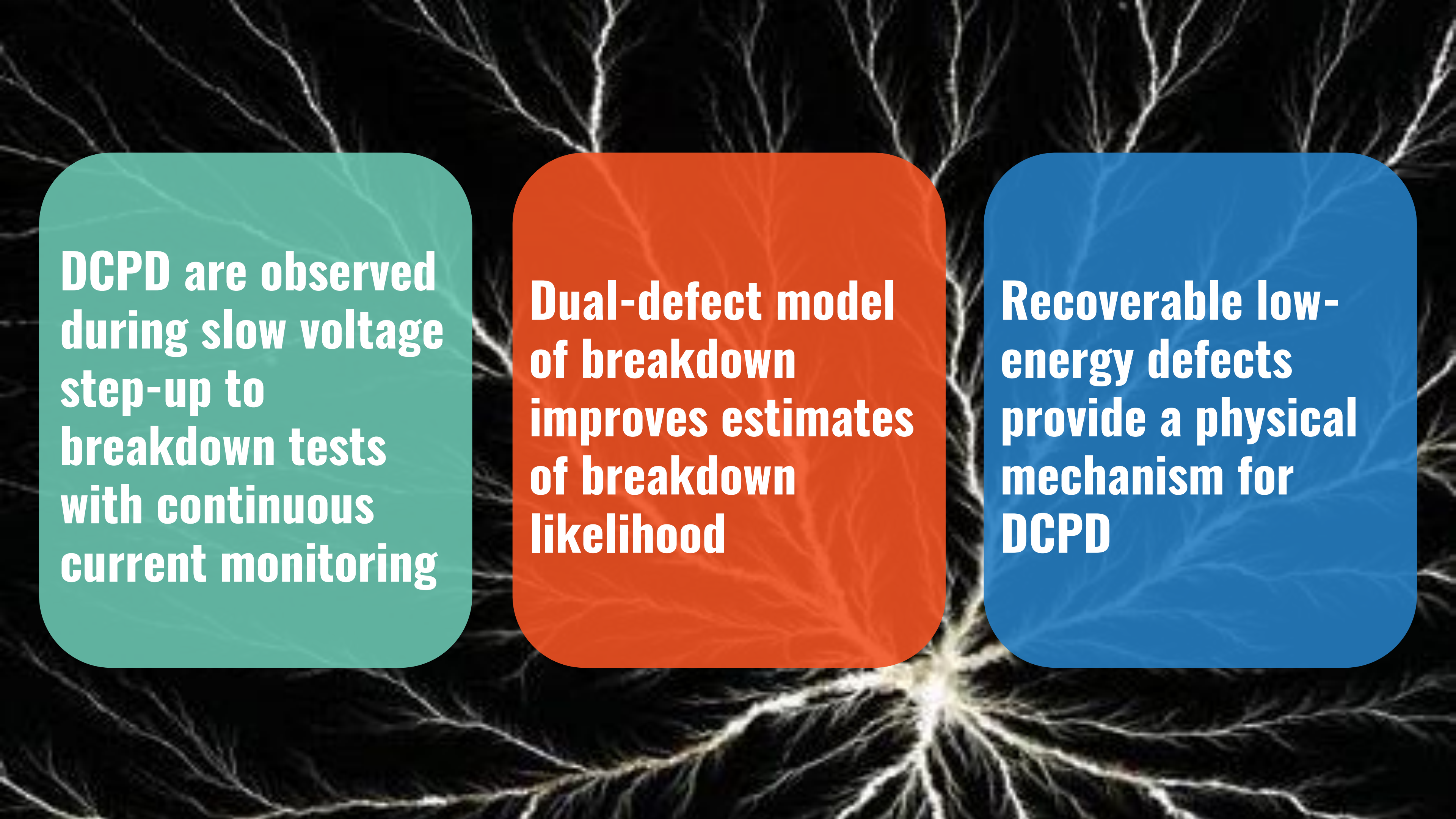


Runaway charge motion begins under applied electric field.

→ Temperature in the area of the discharge increases.

→ Enough defect recovery takes place to stop motion of charge—DCPD

→ Defect recovery insufficient to stop charge avalanche—breakdown


DCPD are observed during slow voltage step-up to breakdown tests with continuous current monitoring
Dual-defect model of breakdown improves estimates of breakdown likelihood
Recoverable low-energy defects provide a physical mechanism for DCPD