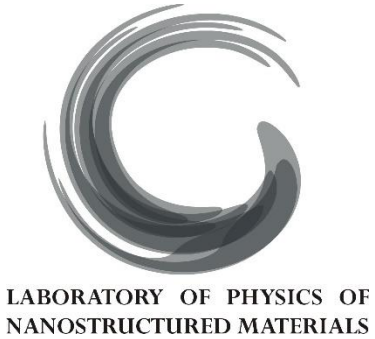
# Superconducting weak links created by electromigration

Alejandro V. Silhanek

*Experimental Physics of Nanostructured Materials*
*Physics Department, University of Liège*
*BELGIUM*

# Collaborators

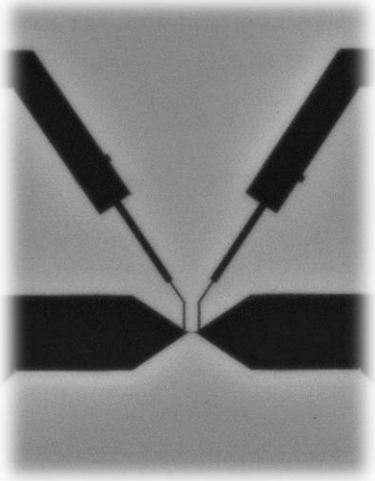
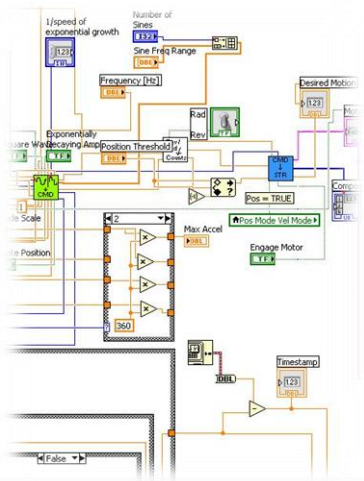
X. D.A. Baumans, J. Lombardo, J. Brisbois, G. Shaw, S. Blanco Alvarez (ULg)

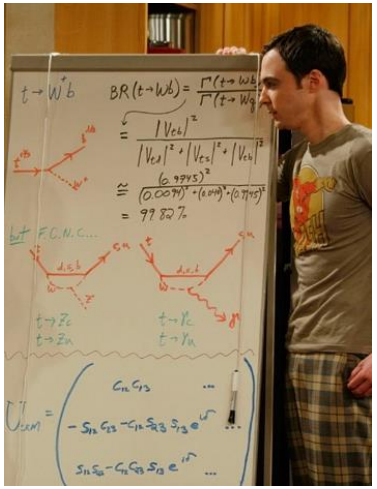
V. S. Zharinov, J. E. Scheerder, V. V. Moshchalkov, J. Van de Vondel (KULeuven)

R.B.G. Kramer (Univ. Grenoble Alpes, Institut NEEL, Grenoble)

D. Massarotti, F. Tafuri (U. Federico II and CNR-SPIN, Naples)

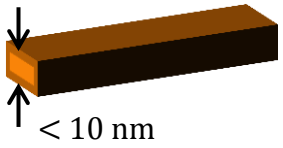
Ge He, Heshan S. Yu, Jie Yuan, Beiyi Zhu, Kui Jin (IOP-CAS, Beijing)

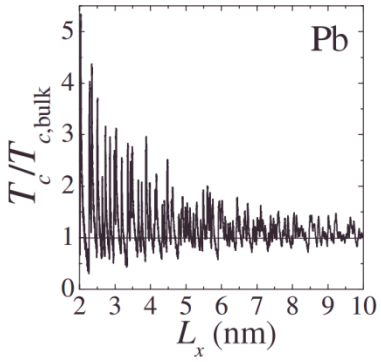



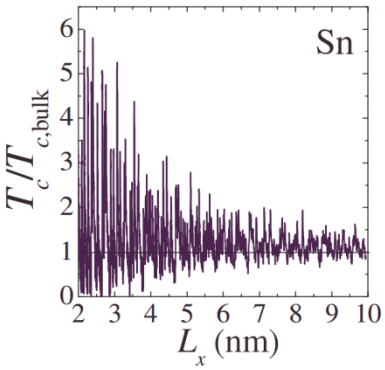



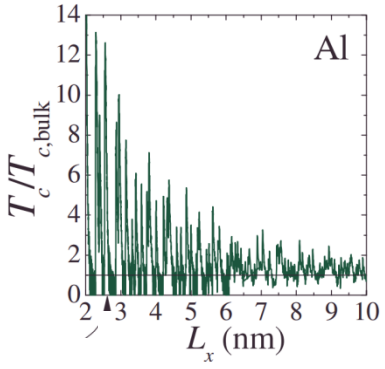

# Context and Motivation

Promising future for nanoscale superconductors …

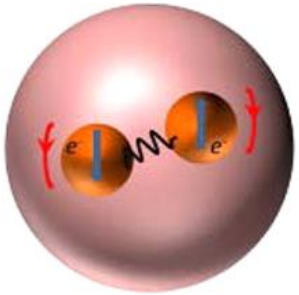



[1]




High temperature superconducting state with $T_C \gtrsim 100$ K in Al nanoclusters [2]

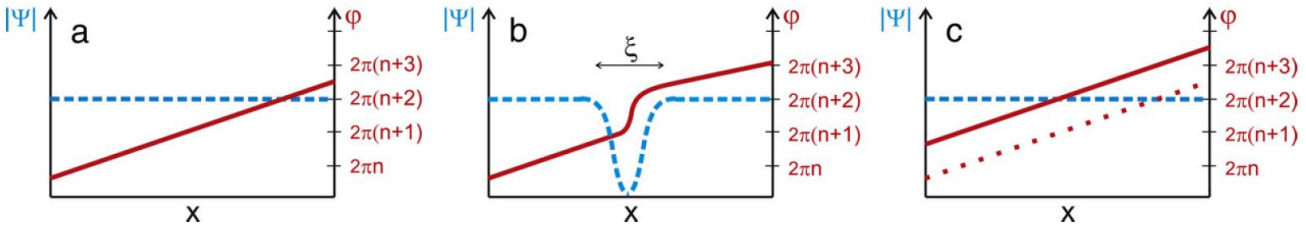


[1] Croitoru *et al.*, Phys. Rev. B 76, 024511 (2007) | [2] Halder *et al.*, Nano Lett. 15, 1410 (2015)

# Context and Motivation

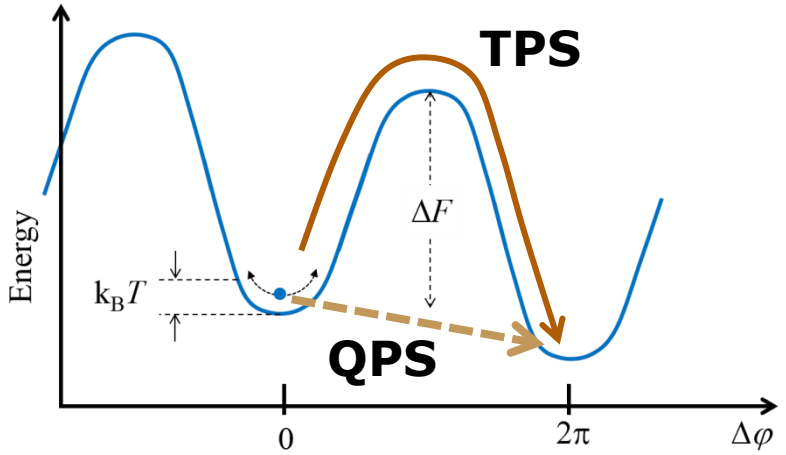
Threaten by fluctuations …

$$\psi = |\psi| e^{i\varphi}$$




$$I_{sc} \approx |\psi|^2 \nabla\varphi$$

$$V = \frac{\hbar\dot{\varphi}}{2e}$$



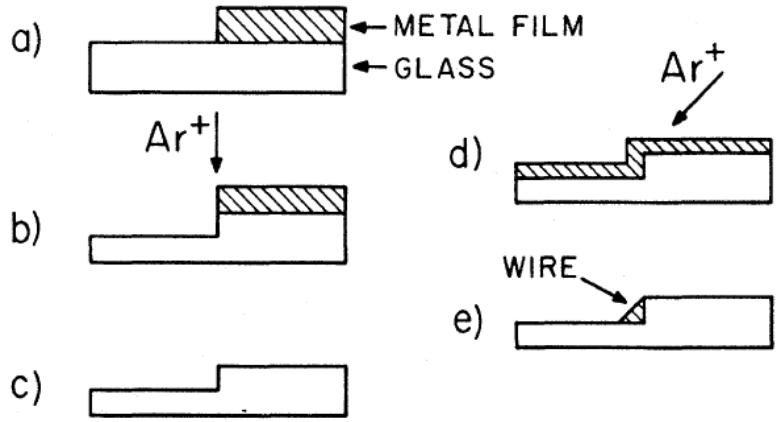

$$\Delta F \approx H_c^2 \xi\sigma - \Phi_0 J\sigma$$

$$R(T) \propto \exp(-\Delta F / T)$$

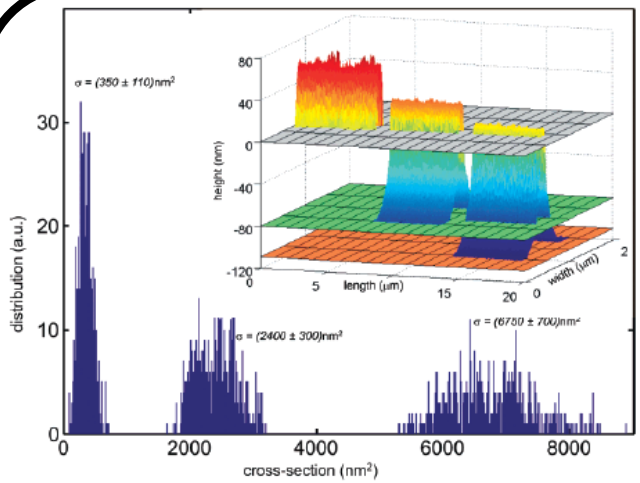


Arutyunov, Golubev, Zaikin, Physics Reports 464, 1 (2008)

# Evidence of TPS to QPS transition requires going beyond EBL resolution…

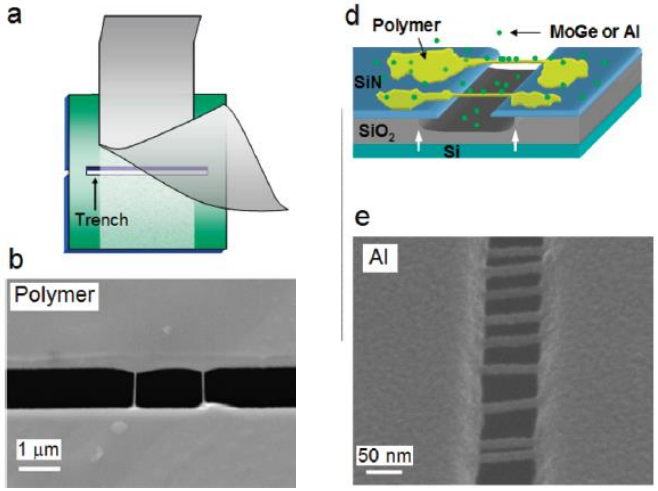



Giordano *et al.*, Phys. Rev. Lett. **43**, (1979)




Ar⁺ ion sputtering for progressive reduction of an Al nanowire effective cross section down to few nm

Zgirski *et al.*, Nanoletters **5**, 1029 (2005)




Tape peel-off technique
Al and MoGe

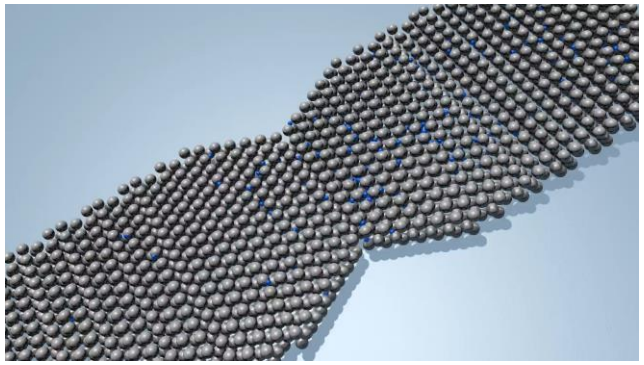
w=20 nm and L > 80 nm

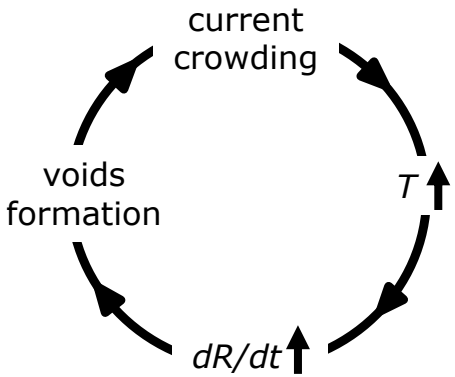
Bae *et al.*,
Nanoletters **9**, 1889 (2009)

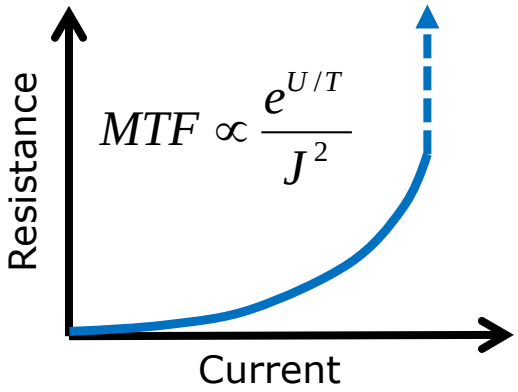
DNA, CNT, etc.

See also Altomare *et al.*, Appl. Phys. Lett. **86**, 172501 (2005)

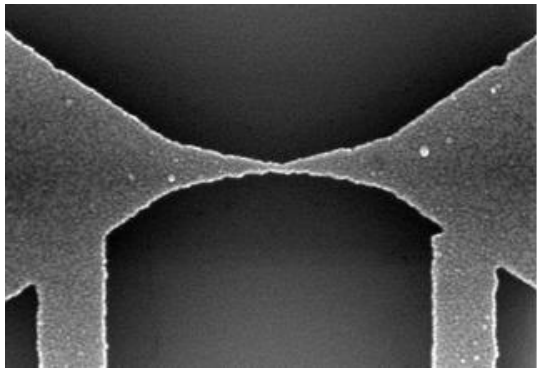
# An alternative technique: electromigration

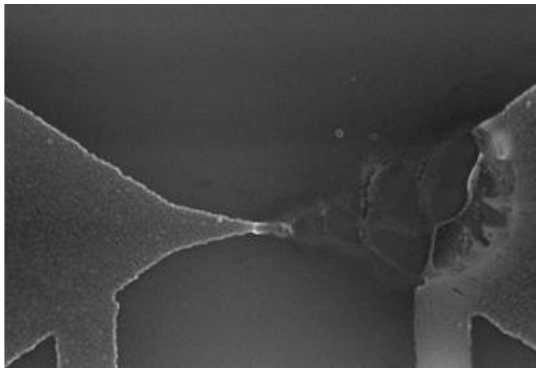


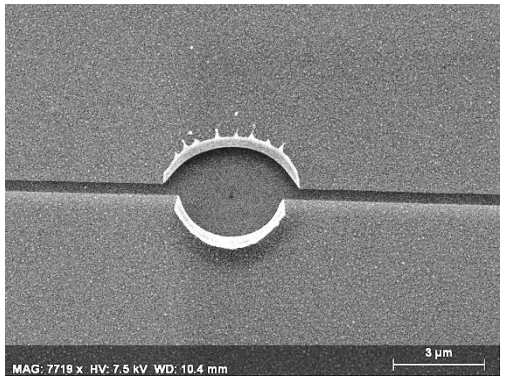



Uncontrolled electromigration



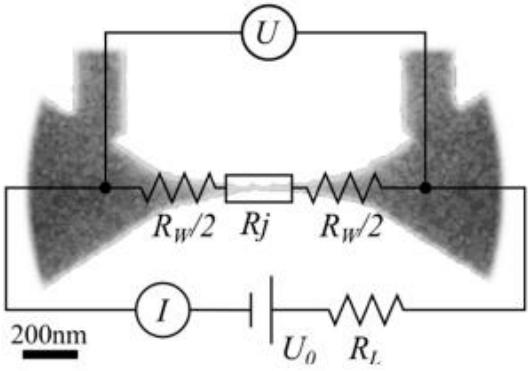


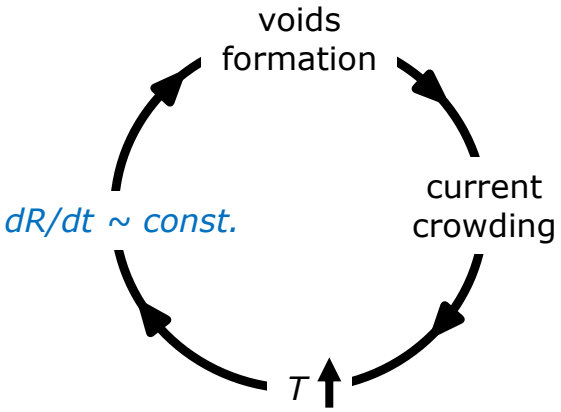


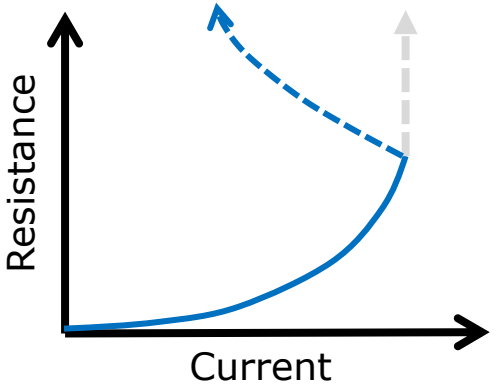


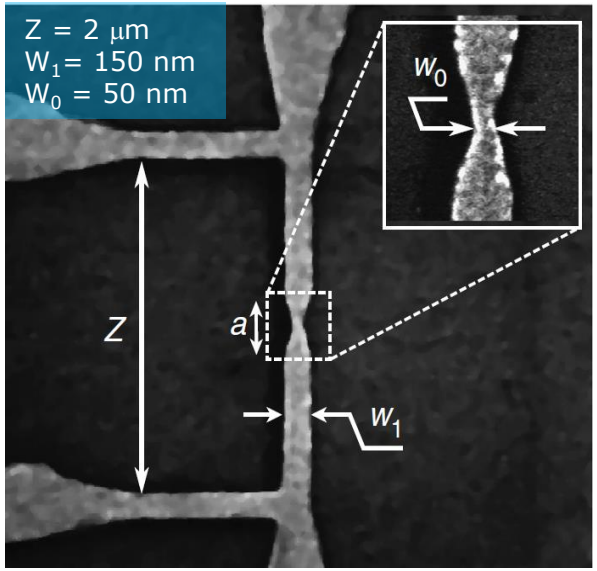

Ho & Kwok, Rep. Prog. Phys (1981)

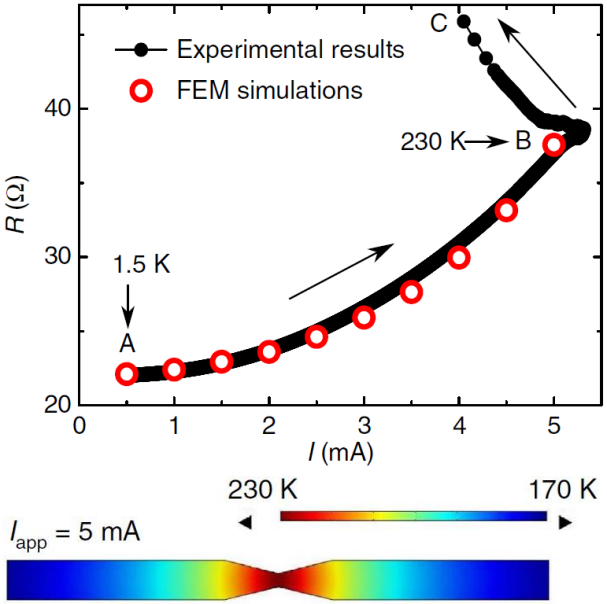
# Controlled electromigration in Al



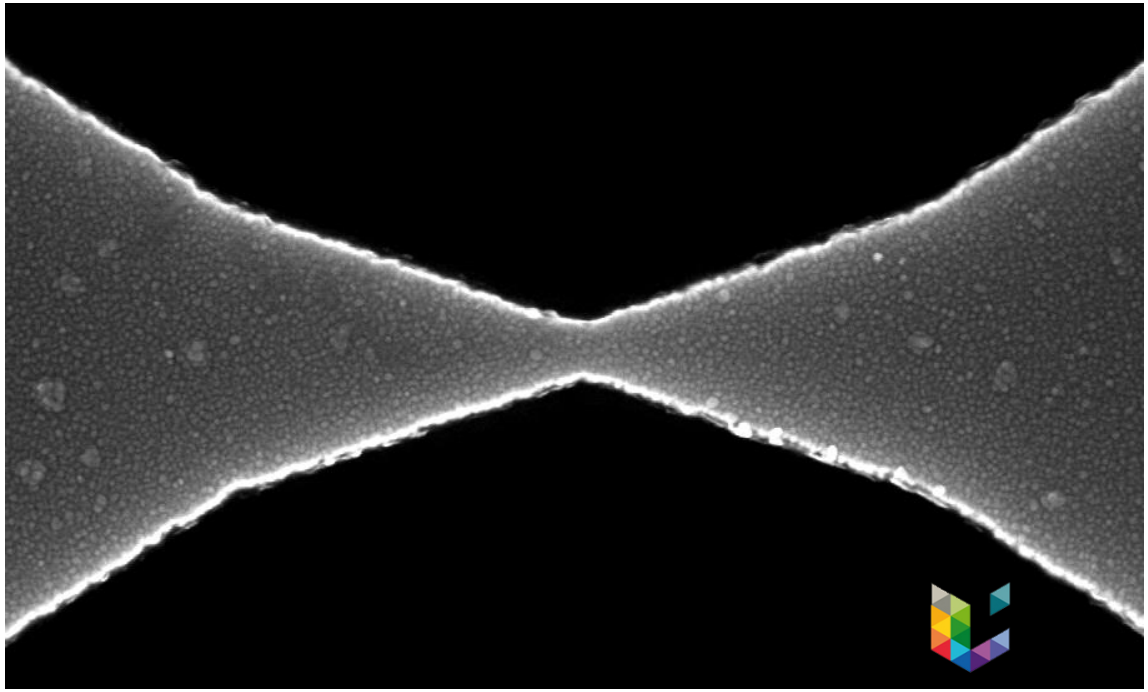



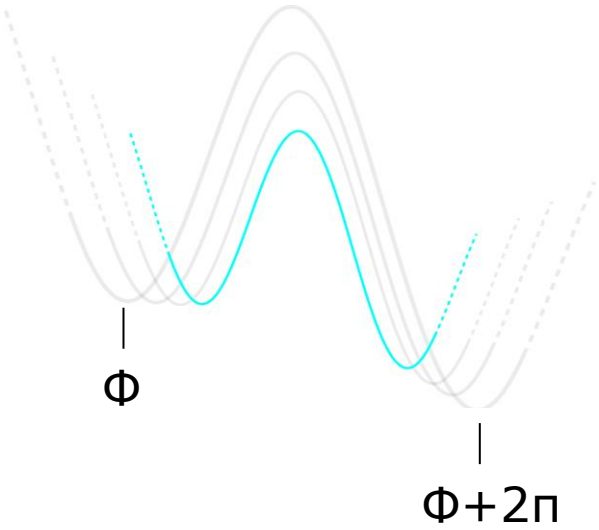

See Campbell, J. M. & Knobel, R. G. Appl. Phys. Lett. **102**, 023105 (2013)

# In-situ visualization of the electromigration process

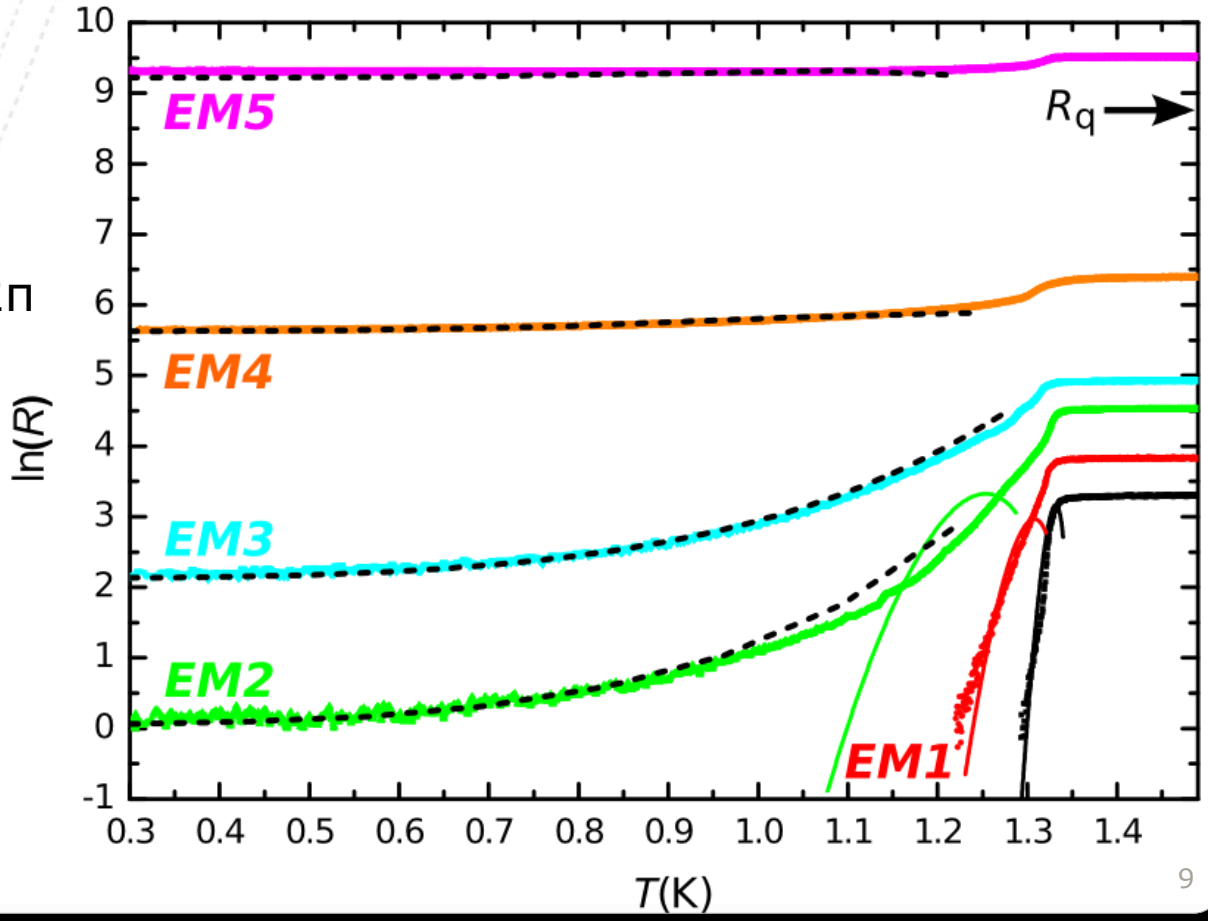


Baumans et al.

# *R*(*T*) evidence the TPS to QPS transition



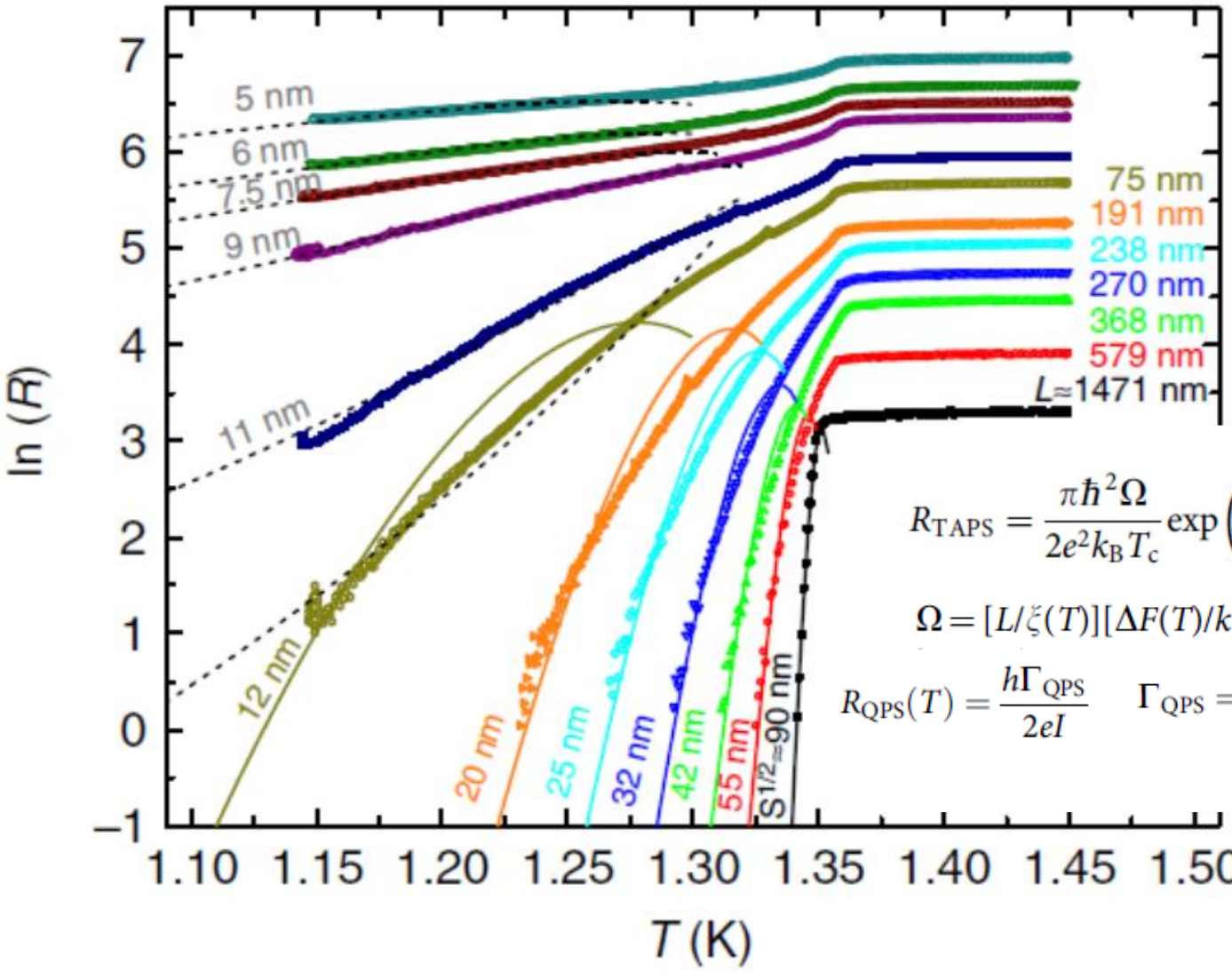

$$\Delta F \approx H_c^2 \xi \sigma - \Phi_0 J \sigma$$






X. D. A. Baumans *et al.*, Nat. Commun. **7**, 10560 (2016)

# $R(T)$ evidence the TPS to QPS transition




$$R_{\mathrm{TAPS}} = \frac{\pi\hbar^2\Omega}{2e^2 k_B T_c}\exp\left(-\frac{\Delta F(T)}{k_B T}\right)$$

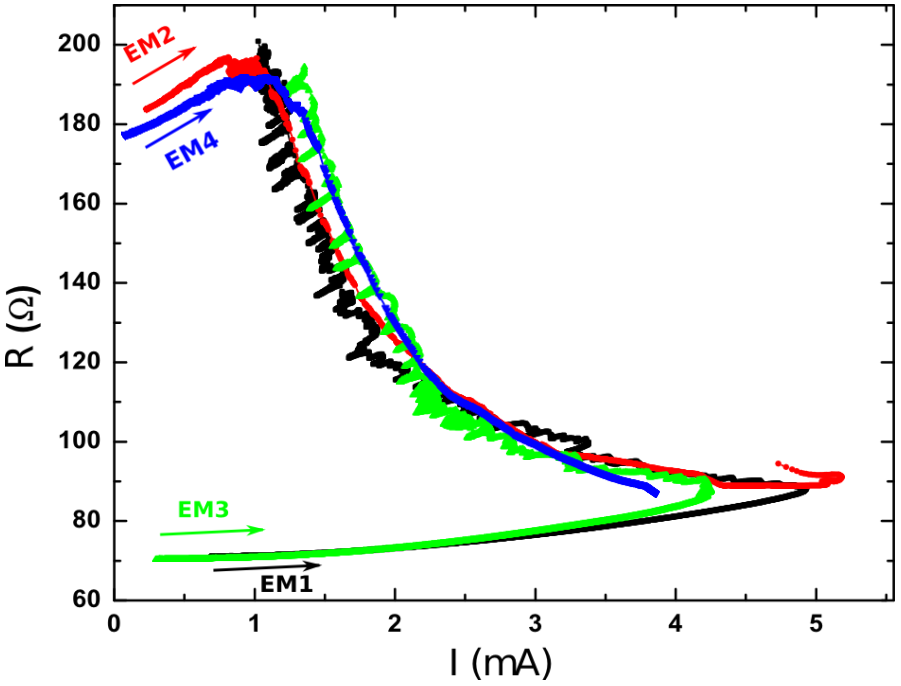
$$\Omega = [L/\xi(T)][\Delta F(T)/k_B T]^{1/2}[1/\tau_{GL}]$$

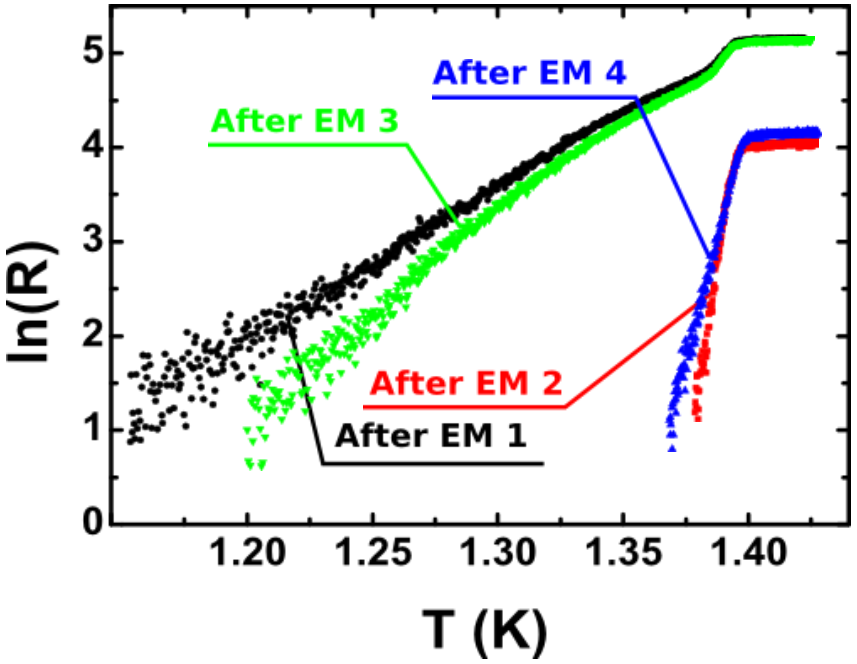
$$R_{\mathrm{QPS}}(T) = \frac{h\Gamma_{\mathrm{QPS}}}{2eI} \qquad \Gamma_{\mathrm{QPS}} = \frac{S_{\mathrm{QPS}}}{\tau_0}\frac{L}{\xi(T)}\exp(-S_{\mathrm{QPS}})$$

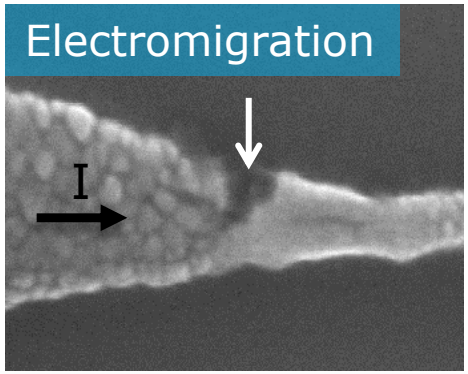


Golubev, D. S. & Zaikin, A. D. Phys. Rev. B 64, 014504 (2001)

# Healing via anti-electromigration



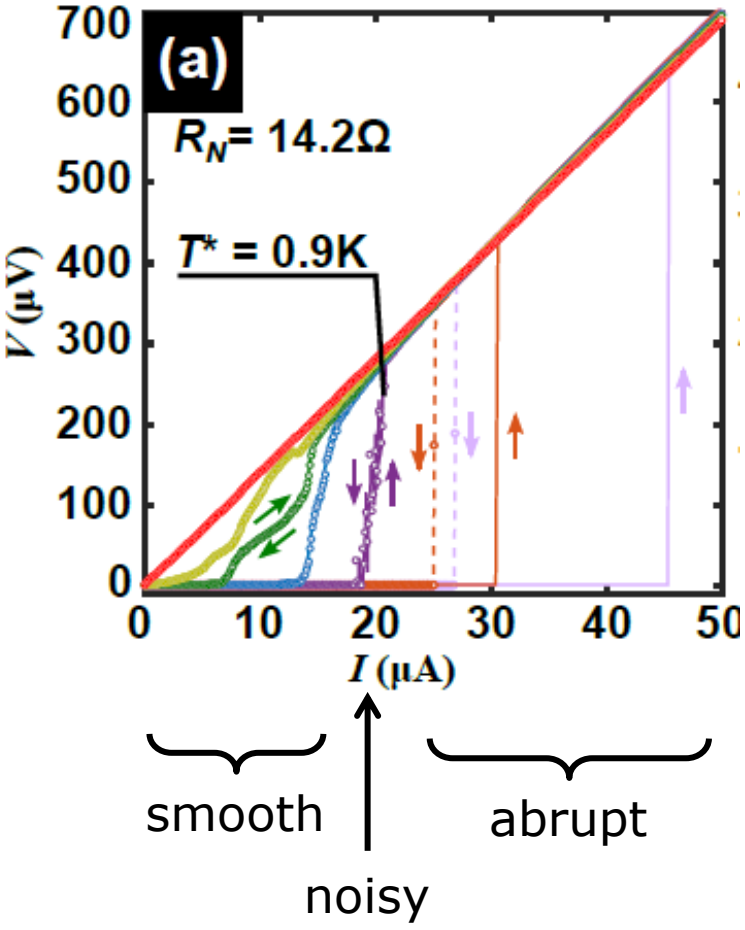



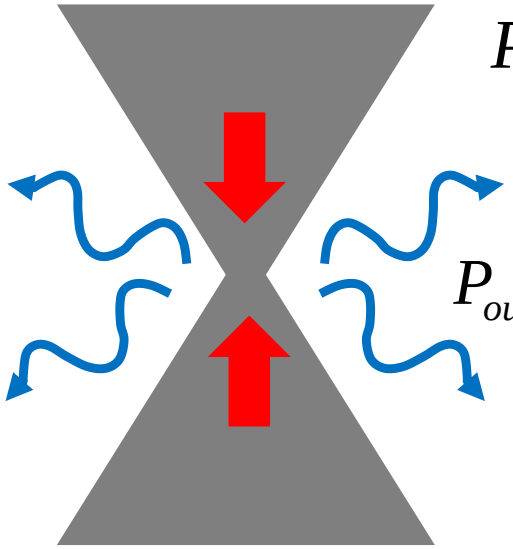



X.D.A. Baumans, Small (2017)

# Voltage-current characteristics

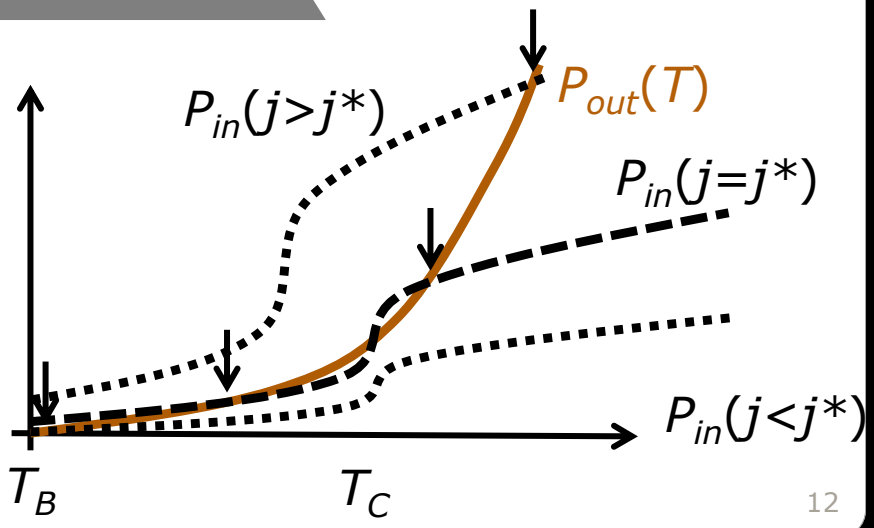



$$\alpha = \rho J_c^2 r / h(T_c - T_B)$$



$$P_{in} = \rho(J,T)J^2$$

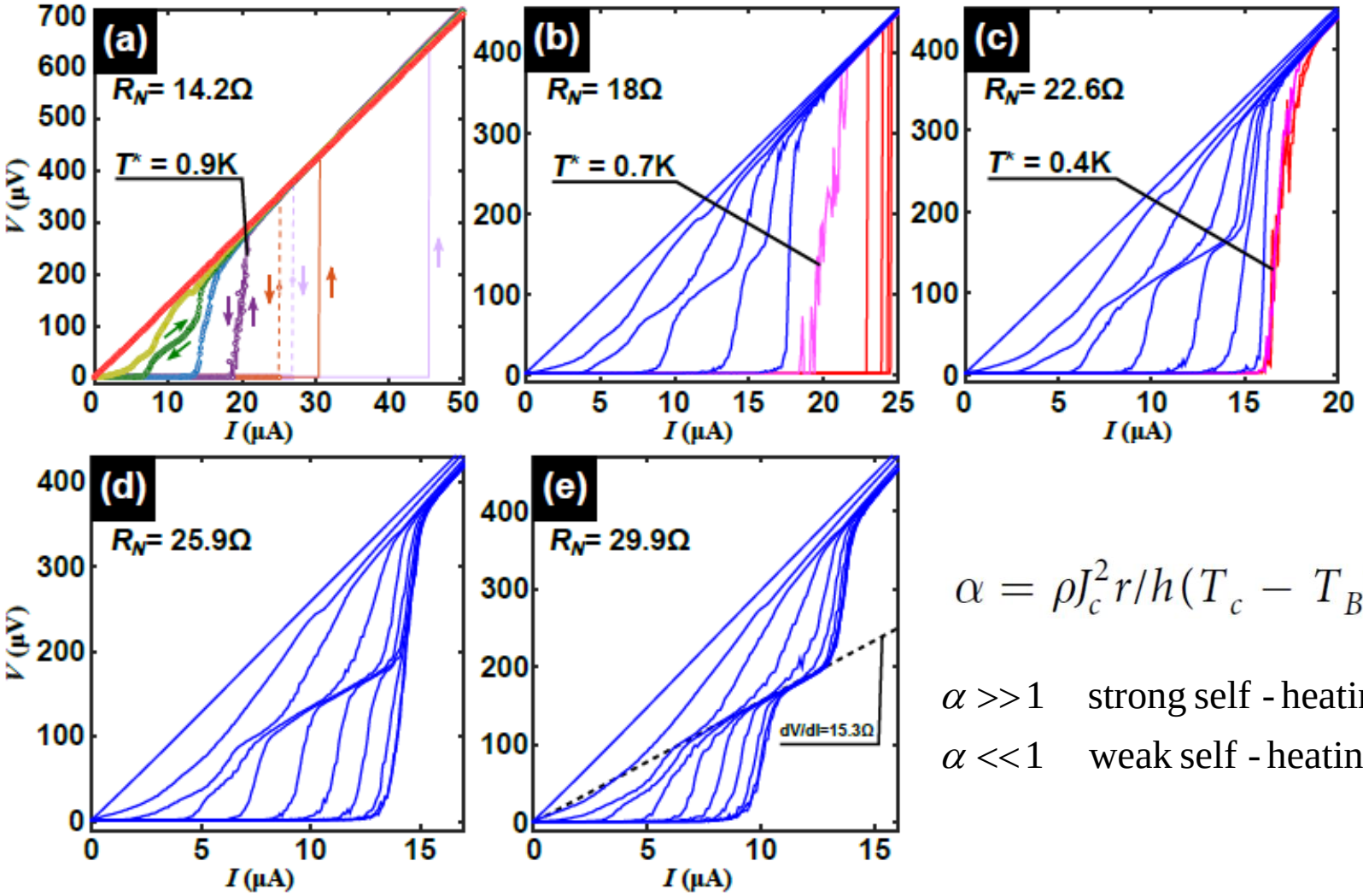
$$P_{out} = \frac{h(T)(T - T_B)}{r}$$






A. V. Gurevich and R. G. Mints, *Rev. Mod. Phys.* **59**, 941 (1987)

# Evidence of two thermal regimes




$$\alpha = \rho J_c^2 r / h(T_c - T_B)$$

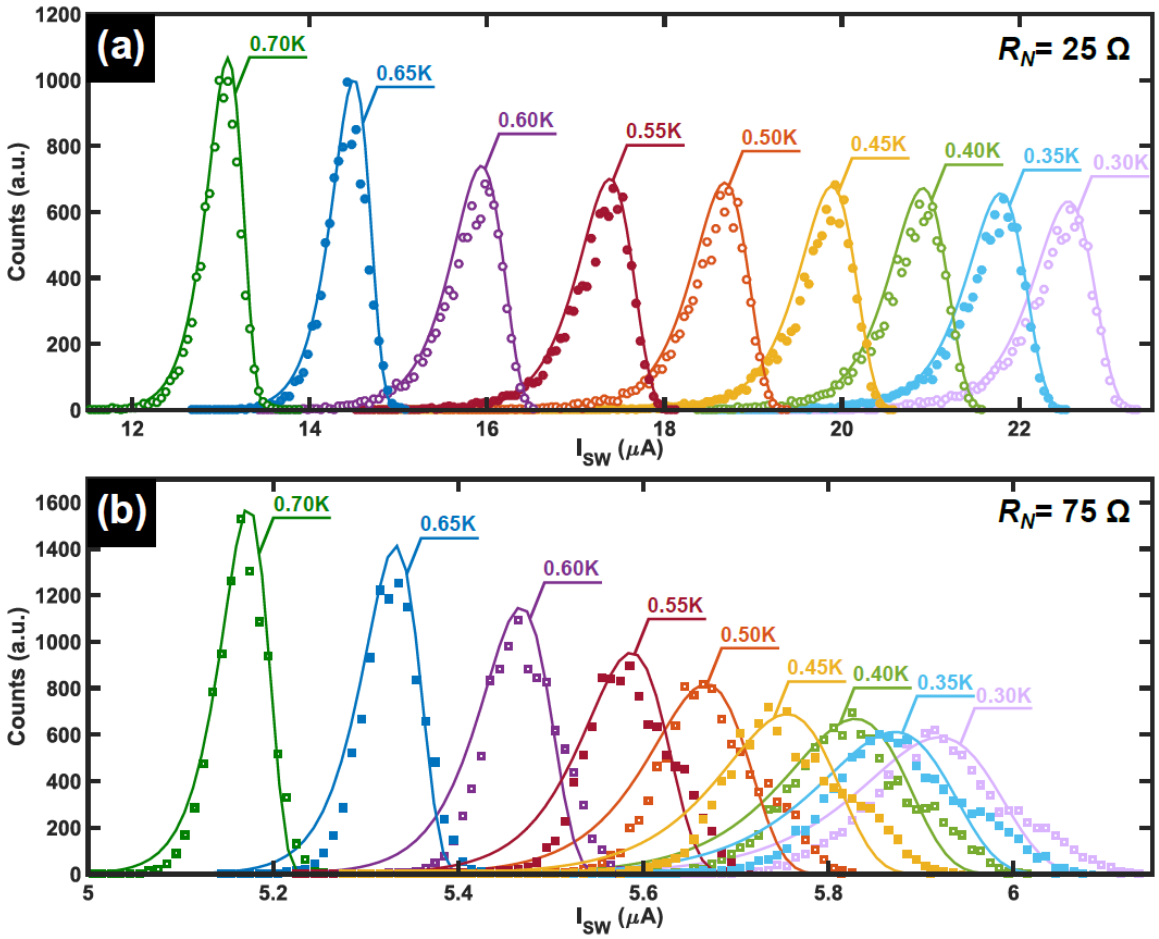
$\alpha >> 1$ strong self - heating

$\alpha << 1$ weak self - heating



X.D.A. Baumans *et al.*, *Sci. Rep.* (2017)

# Statistics of the switching current

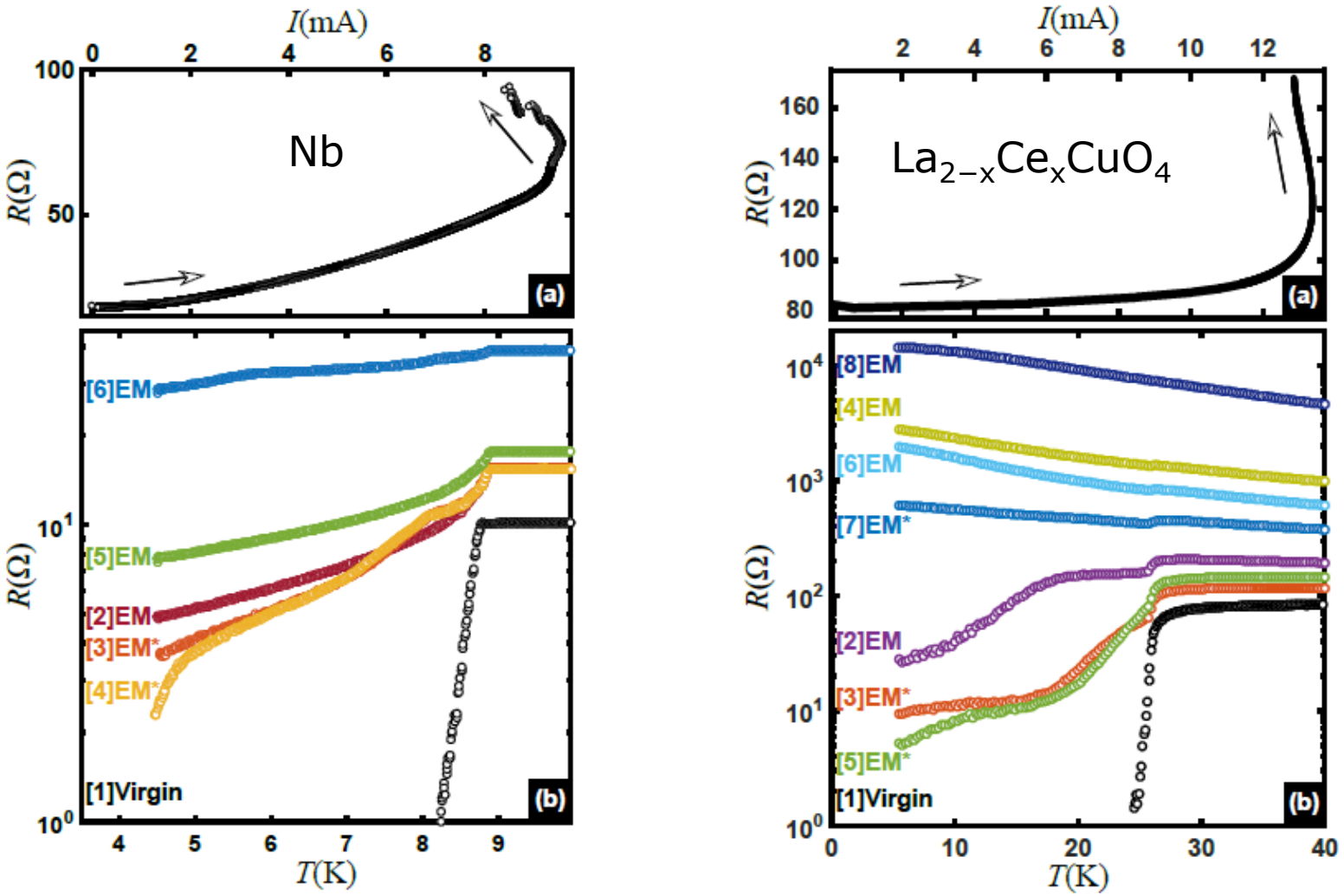



$T \downarrow$ $I_{sw} \uparrow$ $\kappa \downarrow$ $C \downarrow$



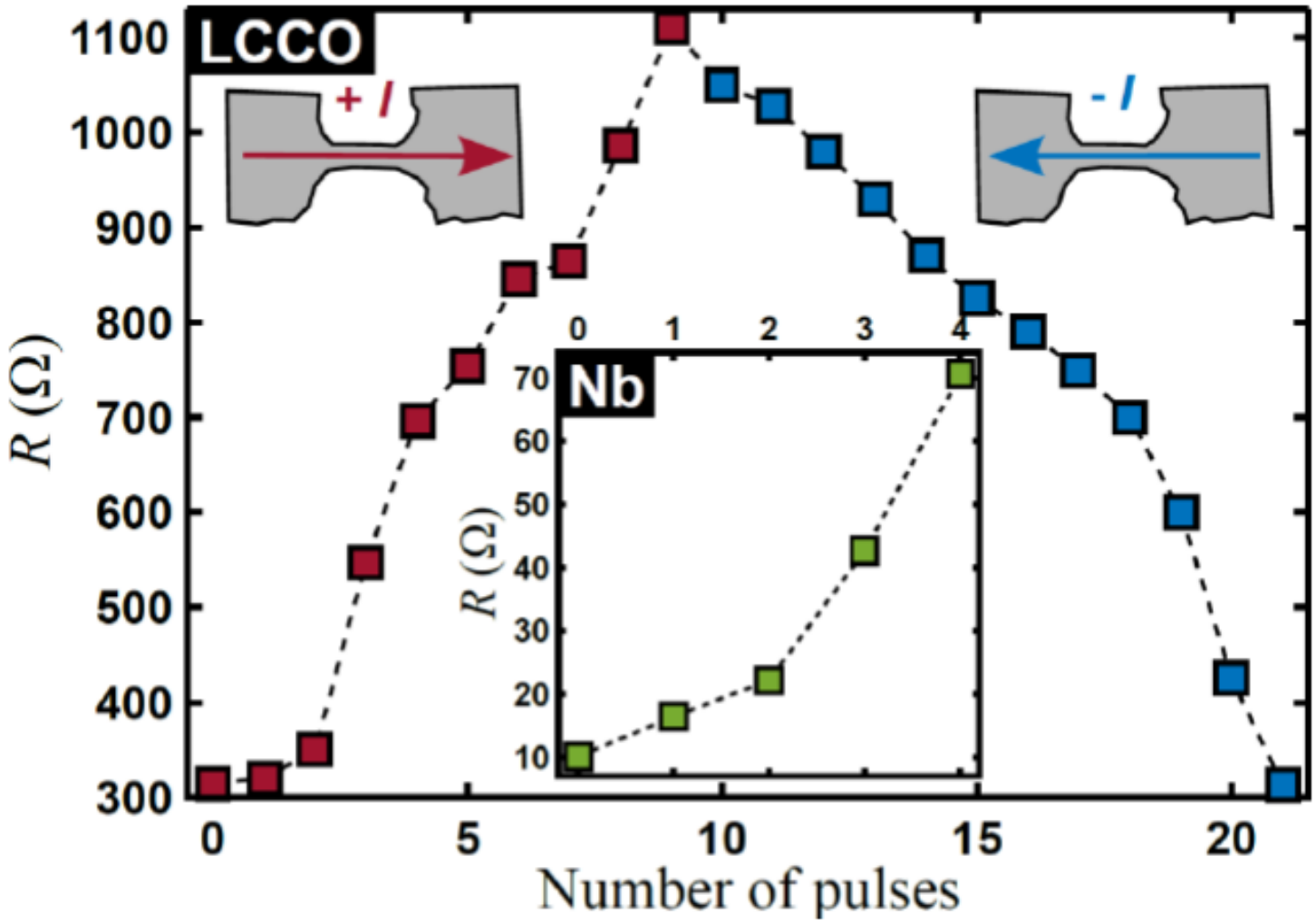
X.D.A. Baumans *et al.*, *Sci. Rep.* (2017)

# Does it work in other superconductors?




X.D.A. Baumans *et al.*, *Small* (2017)

# Is there a way to avoid the feedback control?



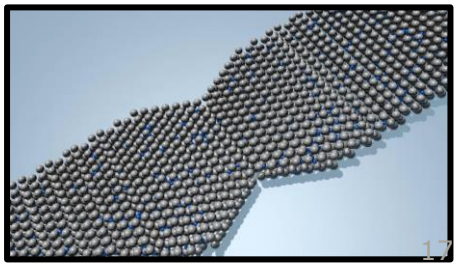



X.D.A. Baumans *et al.*, *Small* (2017)

# Conclusion

- Electromigration is a promising method for carving Al superconducting nanostructures beyond EBL resolution
- R(T) show some hints of the transition from TPS to QPS
- Evidence of two thermal regimes
- Statistics of switching current provides evidence that multiple TPS participate in the switching to the normal state
- Reversible change of oxygen doping in high temperature superconductors without the need to fabricate different samples
- Superconductor-semiconductor-like transition induced by electromigration

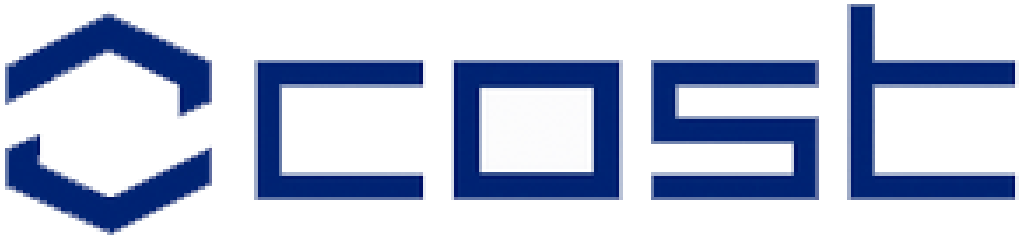
**Interested? Try it yourself!**
**We offer you a starter kit**



# Acknowledgements





# Physics of nanostructured materials


http://www.mate.ulg.ac.be/