UNIVERSITY OF BIRMINGHAM
School of Physics
& Astronomy

EPSRC

Does a bad metal become "superinsulator"?

Giant jumps in *I-V* characteristics in 2D films (near a superconductor-insulator transition)

Boris Altshuler, Vladimir Kravtsov, I.L., Igor Aleiner

Columbia U., NY

ICTP

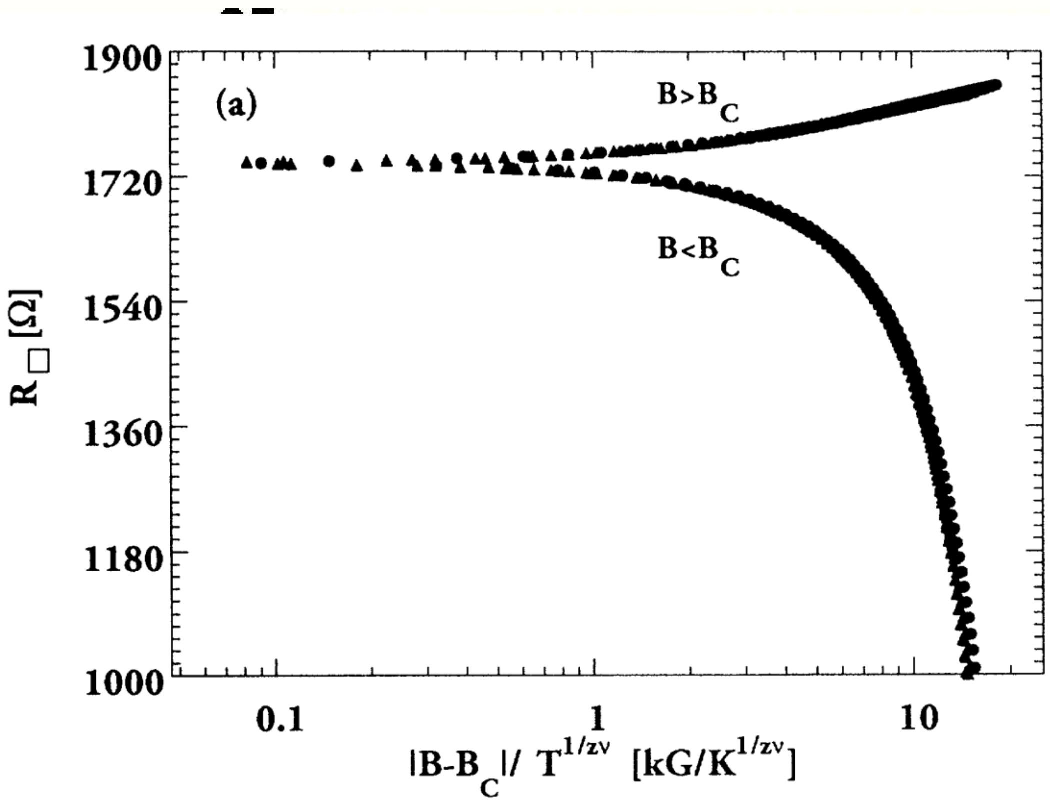
Columbia U., NY

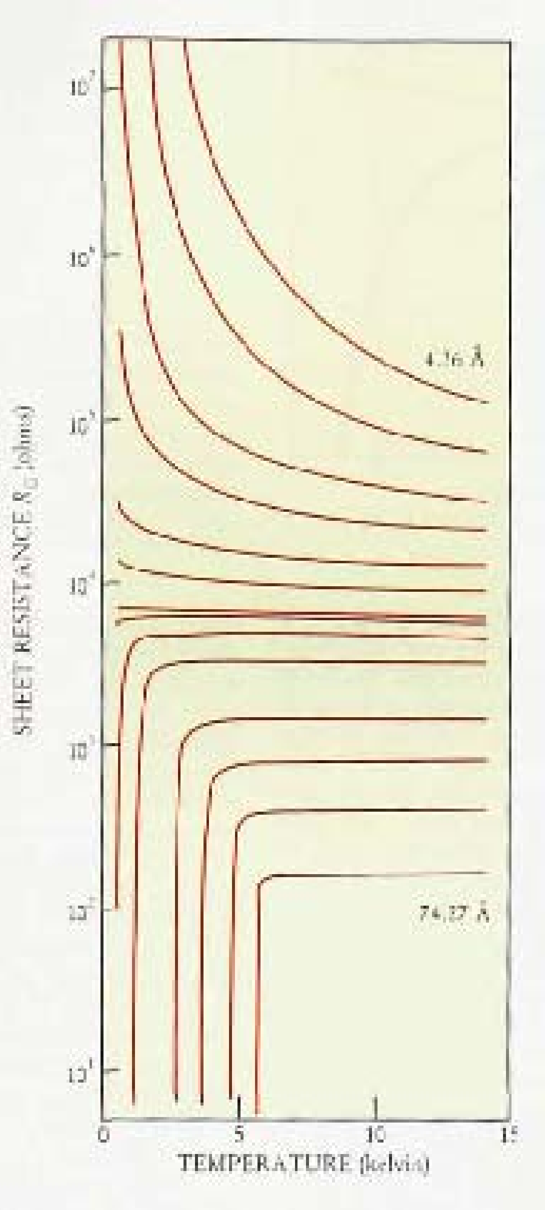
PRL, 102, 176803 (2009)

(also Ovadia, Sacepe, Shahar, *ibid*, 176802)

Low-Dimensional Electronic Systems,
KITP, UCSB, May 2009

Superconductor-Insulator Transition

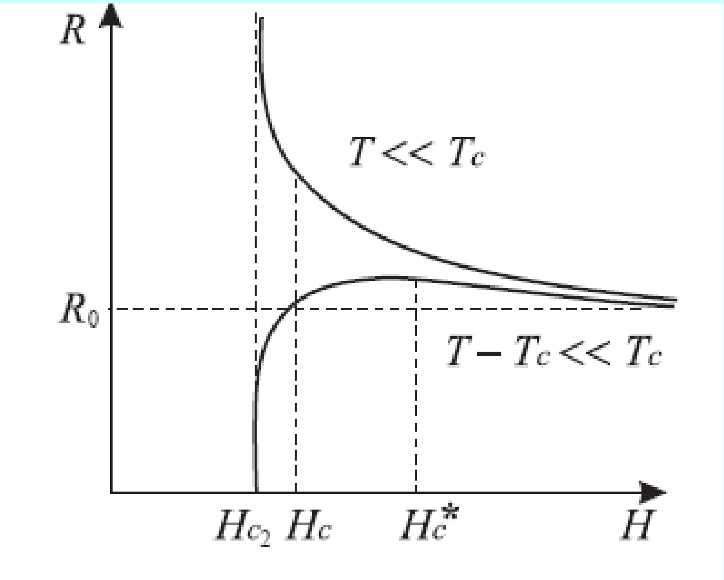




Goldman et al; Kapitulnik et al; Paalanen et al.,
Hsu et al, Ovidiyahu et al, ..., 1989-till now

Physics behind

- At T=0, QPT from superconductor to insulator: |D| survives but phase correlations are destroyed: a clear cut for granular systems.
- Near $T_c{}^{1}0$, suppression of & fluctuations in |D| are probably also relevant...



Skrynski, Beloborodov, Efetov, 2001; Varlamov, I.L., Vinokur, 2007

but today's story is not about this.

Subject of the talk:

Highly unusual
nonlinear electronic transport
on the insulating side of SIT in
disordered thin films of
InO and TiN,
and also in other materials

Linear regime: Arrhenius law at low T

is also rather unusual, but observed in numerous experiments, e.g. in InO amorphous films and elsewhere

$$R(T) = R_0 \mathrm{e}^{(\Delta/T)^\gamma}$$

$$\gamma \approx 1\,, \Delta \sim 1\mathrm{K}$$

instead of Mott's VRH, g=1/d+1, or Efros-Shklovskii g=½

This was always considered as a puzzle and doesn't have a satisfactory theoretical explanation

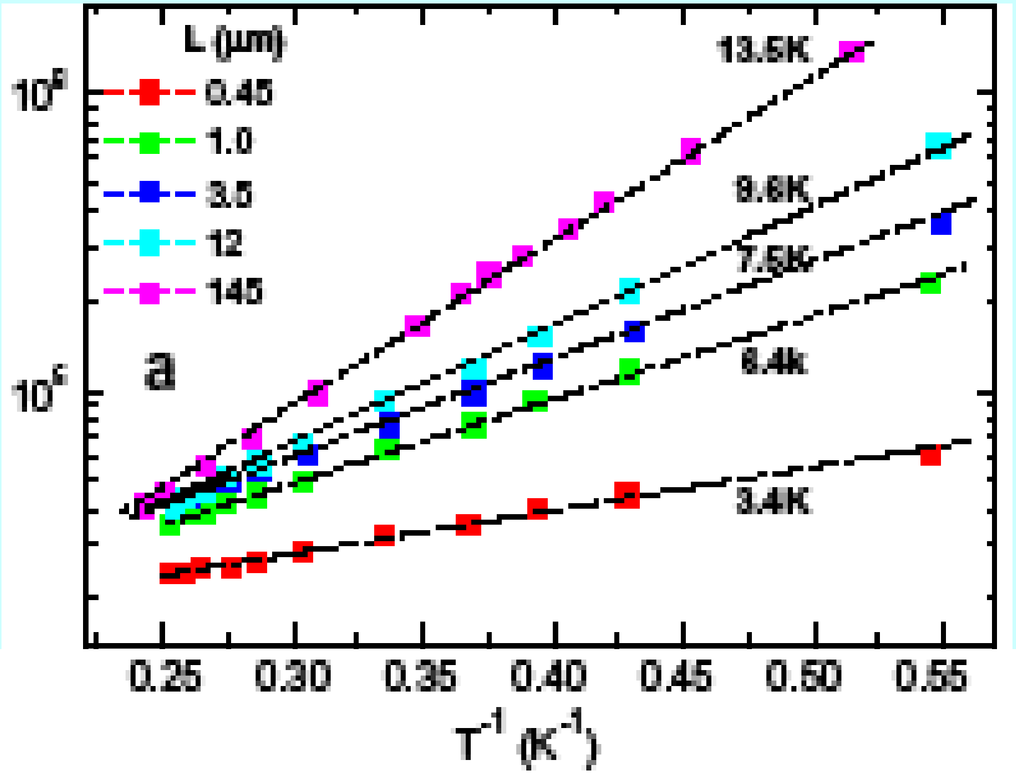
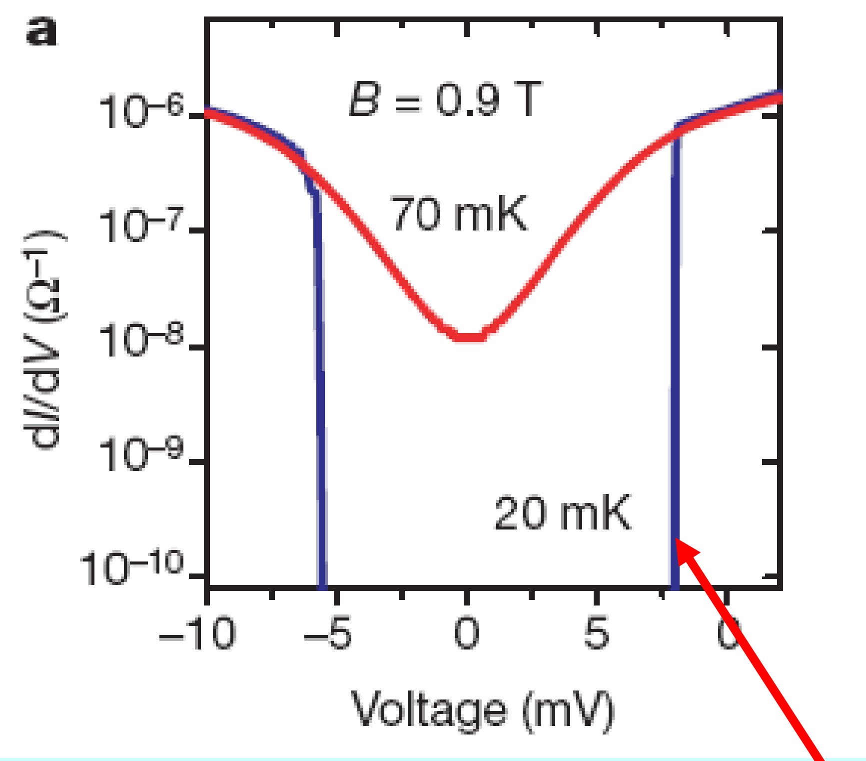


Fig. 4. (a) Resistance vs. temperature for a single batch of In$_x$O film with a common width of 500 μm and length as shown. Each sub-sample is

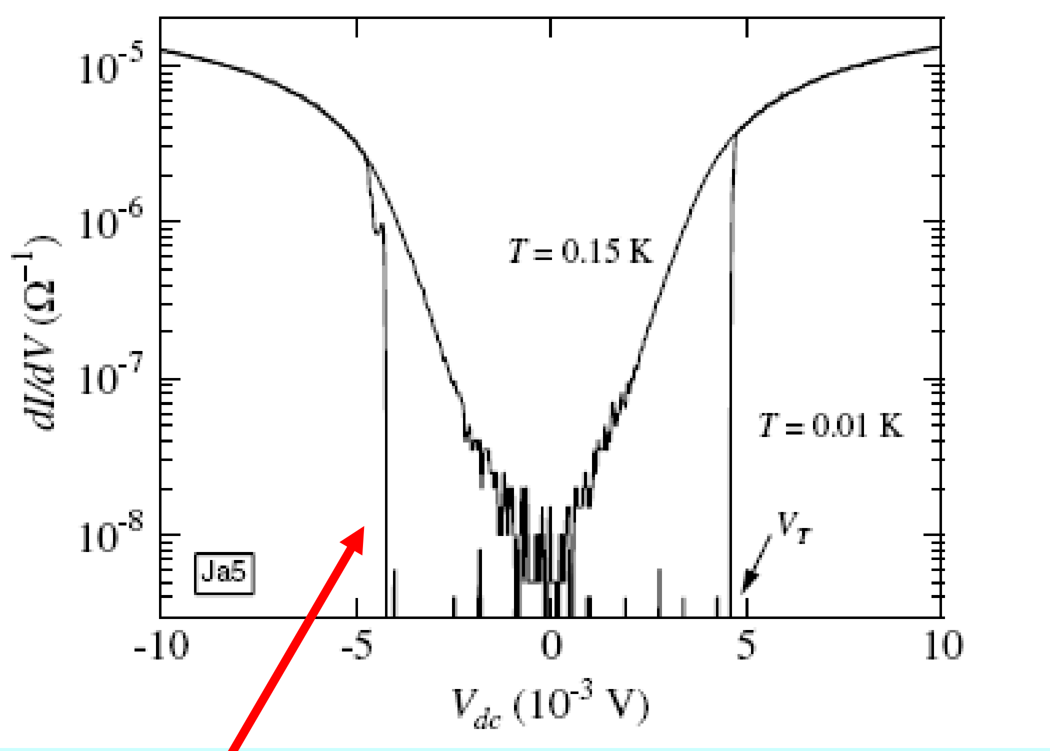
Shahar, Ovadyahu, '92
Kowal, Ovadyahu, '94
Gantmakher, Golubkov, Lok, Geim, '96
Sambandamurthy, Engel, Johansson, Shahar, '04
Lin, Goldman '09

Giant jumps in I-V characteristics

TiN films



InO films



Baturina, Mironov, Vinokur, Baklanov, Strunk,'07

Sambandamurthy, Engel, Johansson, Peled, Shahar, '05

Giant jumps in resistance
from kΩ to GΩ regime

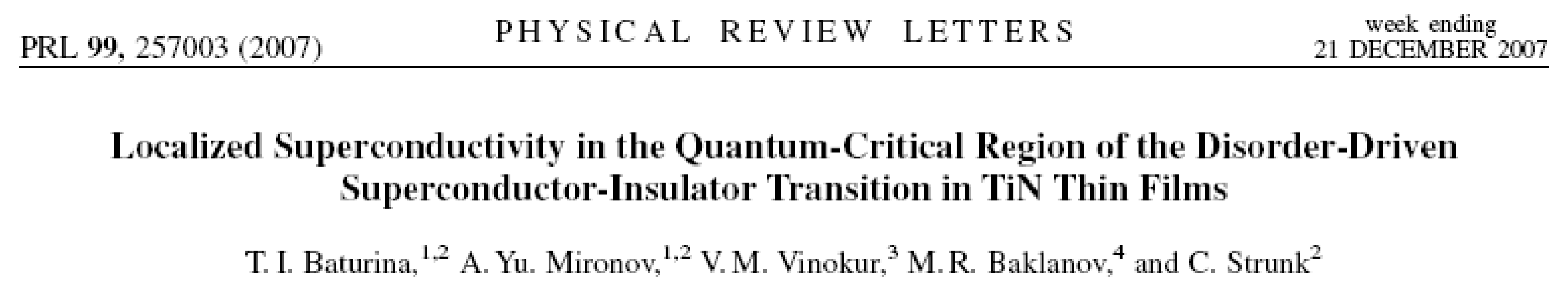
in systems tantalizingly
close to superconductors

From a superconductor to a super-insulator?


PRL **94,** 017003 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

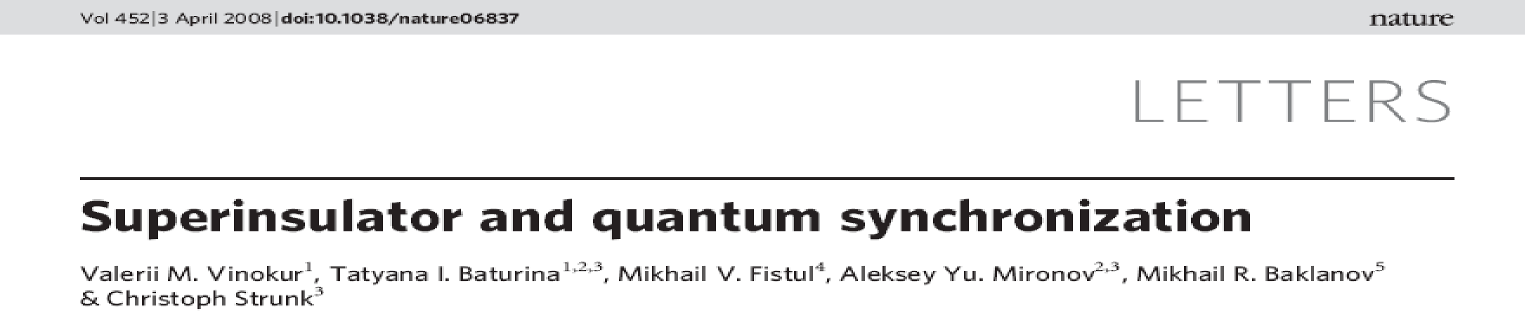
Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors

G. Sambandamurthy,[1] L. W. Engel,[2] A. Johansson,[1] E. Peled,[1] and D. Shahar[1]


PRL **99,** 257003 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

Localized Superconductivity in the Quantum-Critical Region of the Disorder-Driven Superconductor-Insulator Transition in TiN Thin Films

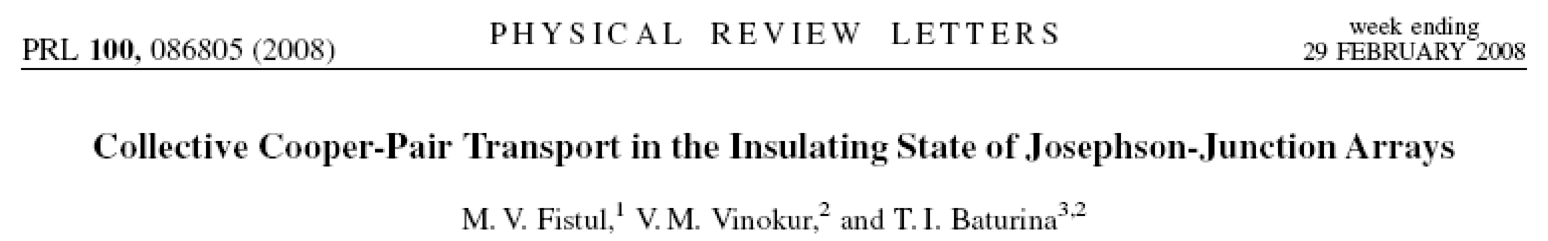
T. I. Baturina,[1,2] A. Yu. Mironov,[1,2] V. M. Vinokur,[3] M. R. Baklanov,[4] and C. Strunk[2]


Vol 452 | 3 April 2008 | **doi:10.1038/nature06837** nature

LETTERS

Superinsulator and quantum synchronization

Valerii M. Vinokur[1], Tatyana I. Baturina[1,2,3], Mikhail V. Fistul[4], Aleksey Yu. Mironov[2,3], Mikhail R. Baklanov[5] & Christoph Strunk[3]


PRL **100,** 086805 (2008) PHYSICAL REVIEW LETTERS week ending 29 FEBRUARY 2008

Collective Cooper-Pair Transport in the Insulating State of Josephson-Junction Arrays

M. V. Fistul,[1] V. M. Vinokur,[2] and T. I. Baturina[3,2]

Jumps in *I-V* characteristics: old data

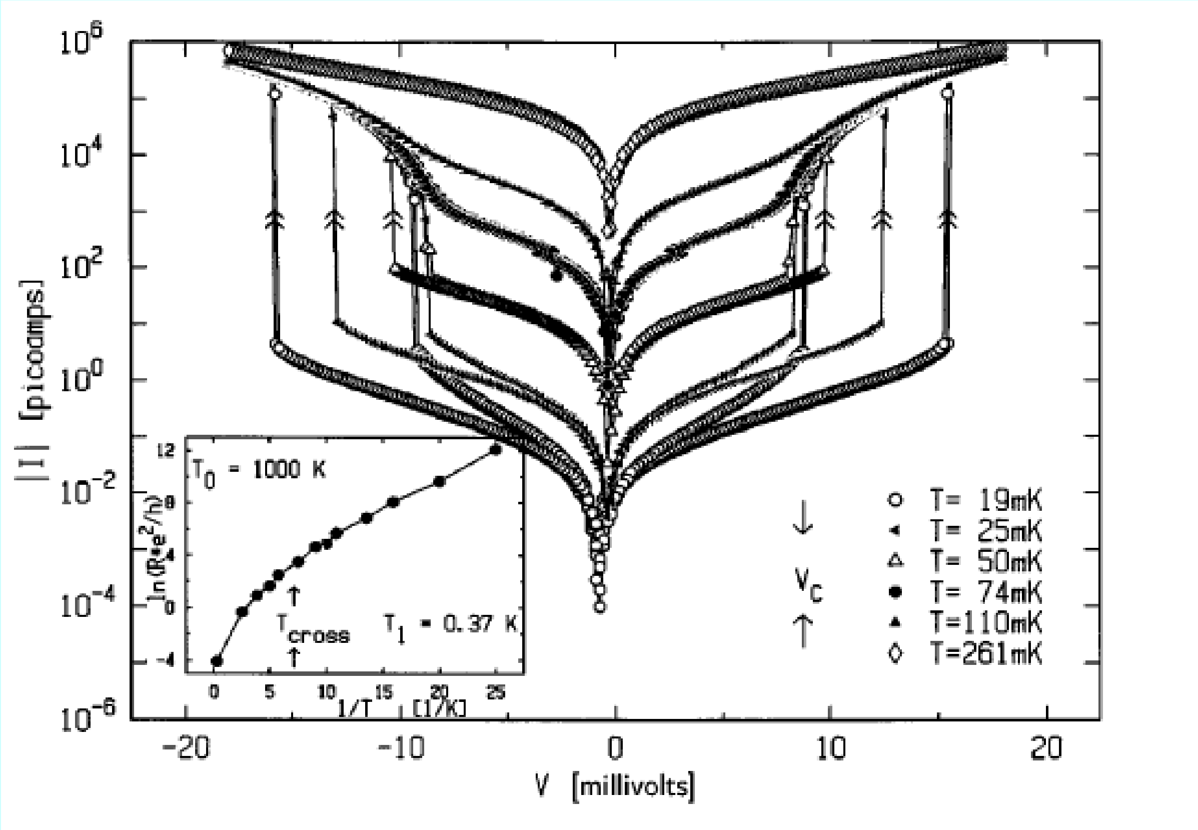
PHYSICAL REVIEW B VOLUME 53, NUMBER 3 15 JANUARY 1996-I

Depinning transition in Mott-Anderson insulators

F. Ladieu, M. Sanquer, and J. P. Bouchaud

YSi films

A few orders in magnitude current jumps increasing with lowering temperature **not in the vicinity of the SIT transition**



Something else?

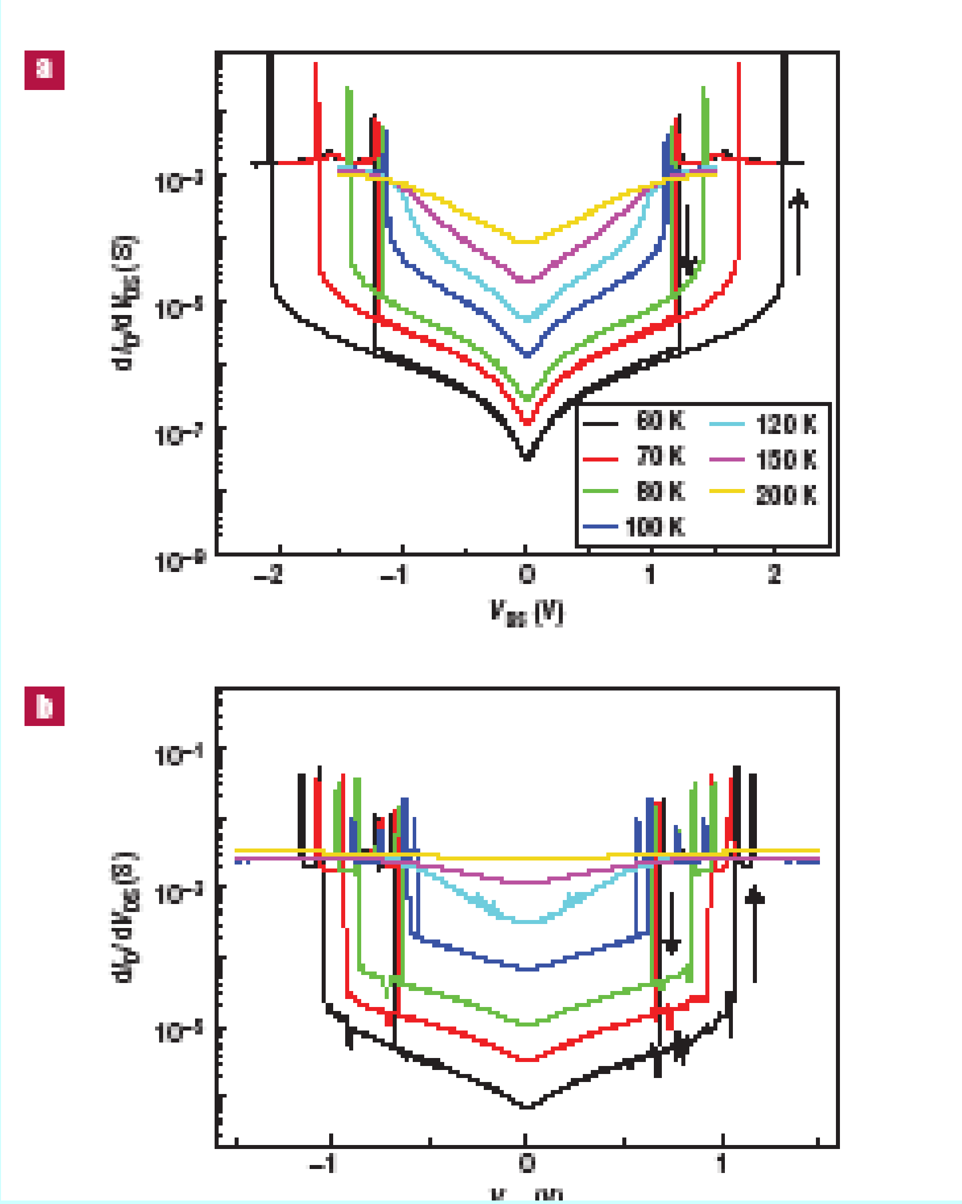
LETTERS

Electrically driven phase transition in magnetite nanostructures

SUNGBAE LEE[1], ALEXANDRA FURSINA[2], JOHN T. MAYO[2], CAFER T. YAVUZ[2], VICKI L. COLVIN[2], R. G. SUMESH SOFIN[3], IGOR V. SHVETS[3] AND DOUGLAS NATELSON[1,4]*

nature materials | VOL 7 | FEBRUARY 2008 |

Magnetite (Fe_3O_4) nanostructures



Common features

- Strong disorder: $R_0 = \frac{2h}{e^2}\frac{1}{g}, \; g \sim 1 \text{ in low-}R\text{ state}$
- Arrhenius law for linear (V→0) resistance at low T - *pseudo-gap*

$$\boxed{R(T) = R_0 \mathrm{e}^{\Delta/T}}$$

- VRH ($\gamma \leq ½$) is not observed at low T – no electron-phonon thermalization?

$$\cancel{R(T) \propto e^{(\Delta/T)^\gamma}}$$

- Voltage threshold eV (at which jumps occurs) increases with increasing Δ much faster than Δ itself

Phenomenological explanation?

No single microscopic approach can possibly explain so similar behaviour in so different systems...

Our main idea: bi-stability due to (over)heating is the main cause of giant resistance jumps

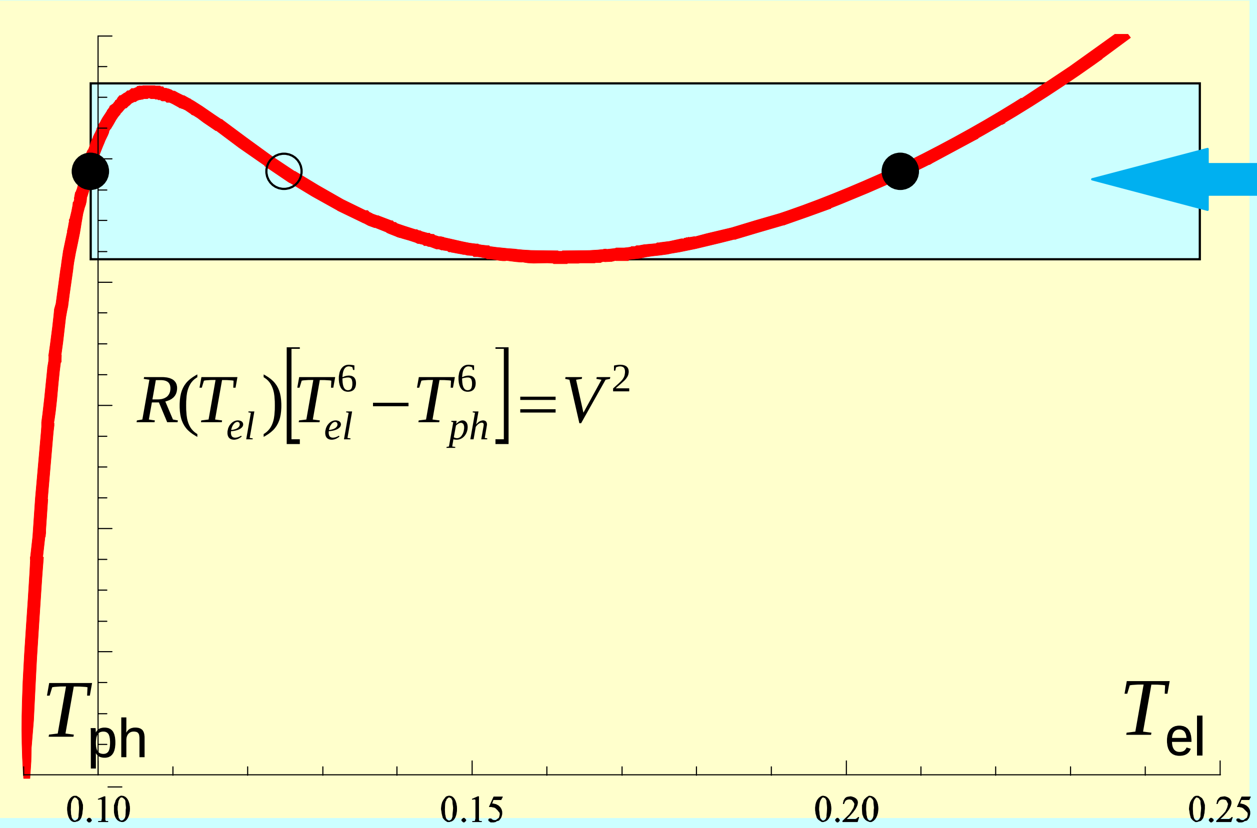
Not normally expected for hopping conductivity in the insulating regime – in contrast to the metallic one...

Assumptions

- Electron-electron interaction is strong enough: electrons are mutually thermalized with $T_{\rm el}$
- Cooling is mainly due to electron-phonon interaction which is, however, inefficient: electrons can be joule –heated to temperature $T_{\rm el}>T_{\rm bath}\,^{\circ}T_{\rm ph}$
- Linear (Ohmic) $R(T)$ has steep (Arrhenius-like) T -dependence which remains valid at a finite voltage with $T \to T_{\rm el}$
- $T_{\rm el}$ should be found from the balance of Joule heating (by electric field) and phonon cooling

Bi-stability in a nutshell

Heat balance: $$\frac{V^2}{R(T_{\rm el})} = \frac{\mathcal{E}(T_{\rm el})}{\tau_{\text{e-ph}}(T_{\rm el})} - \frac{\mathcal{E}(T_{\rm ph})}{\tau_{\text{e-ph}}(T_{\rm ph})} \propto T_{\rm el}^{\beta} - T_{\rm ph}^{\beta}$$



Bi-stable region

Two stable electron temperatures at the same voltage

Electron-phonon relaxation

Electron-phonon scattering rate in the clean metal:

$$\frac{\hbar}{\tau_{\text{e-ph}}} = \frac{T^3}{T_D^2}$$

T_{D} – Debye temperature;
assumed that p_F~Ñ/a (dense metal)

$$\frac{\hbar}{\tau_{\text{e-ph}}} = (k_F a)^3 \frac{T^3}{T_D^2}$$

in a semiconductor with p_F `Ñ/a

Energy relaxation (cooling) from the kinetic equation:

$$\frac{\dot{\mathcal{E}}}{\mathcal{V}} = \nu_0 \int \varepsilon \dot{f}(\varepsilon, T_{\text{el}}) \mathrm{d}\varepsilon \sim \frac{T_{\text{el}}^2}{\tau_{\text{e-ph}}(T_{\text{el}})} - \frac{T_{\text{ph}}^2}{\tau_{\text{e-ph}}(T_{\text{ph}})} \propto T_{\text{el}}^5 - T_{\text{ph}}^5$$

for a clean metal or semiconductor

Suppression of cooling by disorder

Dirty-metal (or low T) limit: $q_T \ell / \hbar \ll 1 \quad \Leftrightarrow \quad T\,\ell \ll \hbar v_{\mathrm{s}}$

{ – electron mean free path
u$_s$ – transverse sound velocity
q_T – thermal phonon momentum

(fulfilled with vengeance in all materials discussed)

The kinetic equation - within the Debye model, jelly approximation and taking into account phonon-induced impurity displacements,

$$\hat{H}^{\mathrm{imp}}_{\text{e-ph}} = -\frac{\mathrm{i}}{\mathcal{V}} \sum_{p,k,q} U(k) c^{\dagger}_{k+p+q} c_p \; (k \cdot u_q)$$

is solved exactly in the lowest order in disorder and results in

$$\frac{\hbar}{\tau_{\text{e-ph}}} \sim \underbrace{n^* \frac{q_T \ell}{\hbar}}_{\sim 10^{-4} \text{ in InO and TiN}} \frac{T^3}{T_D^2} \propto T^4$$

n^* – # of electrons per unit cell

Disorder-independent heat balance

Substituting the exact solution of the kinetic equation in the model results in the disorder-independent equation for heat balance in proper dimensionless variables:

$$\frac{V^2}{R}=\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \qquad \mapsto \qquad v^2\mathrm{e}^{-1/t_{\mathrm{el}}}=t_{\mathrm{el}}^6-t_{\mathrm{ph}}^6\,,$$

$$t\equiv\frac{T}{\Delta}\,,\quad v\equiv\frac{V}{V_0}\,,$$

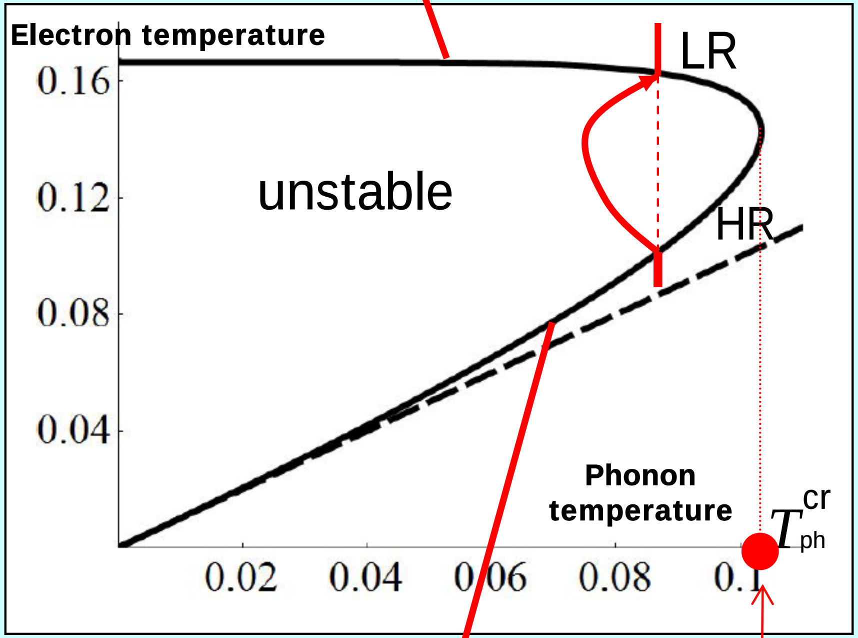
$$\frac{eV_0}{L}\equiv\frac{\alpha k_{\mathrm{F}}\Delta^3}{\Delta_0^2}\,,\quad \Delta_0\equiv\left(\rho v_{\mathrm{s}}^5\hbar^3\right)^{1/4}\,,\quad \alpha\equiv\frac{2\pi^2}{\sqrt{315}}\approx 1.1$$

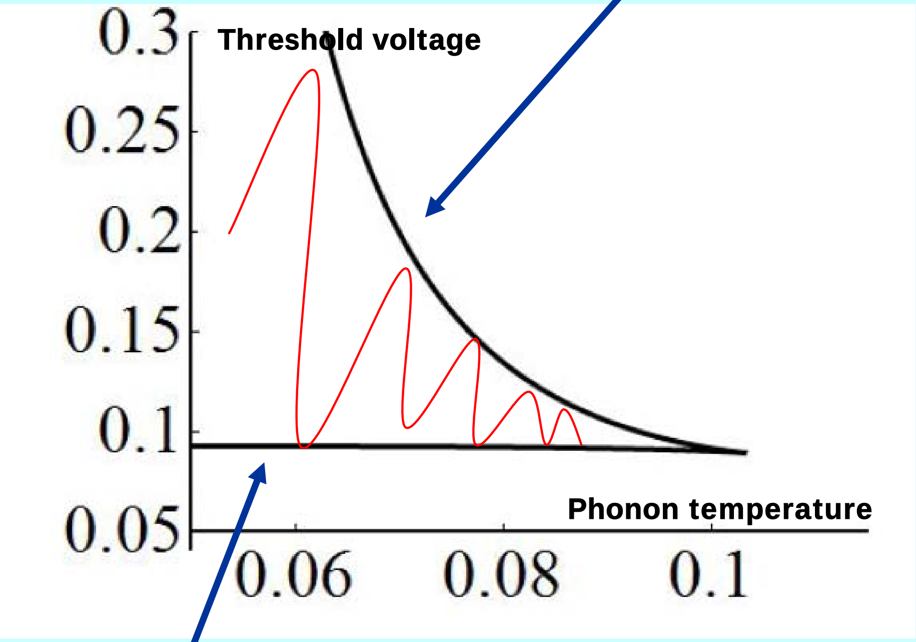
Heat balance depends ONLY on electron density (k_F), the Arrhenius pseudo-gap D and the `material' energy D_0

Critical temperature and voltage

Minimal temperature of the hot (LR) state is 0.14 D

Threshold voltage of the cold (HR) state is strongly T-dependent



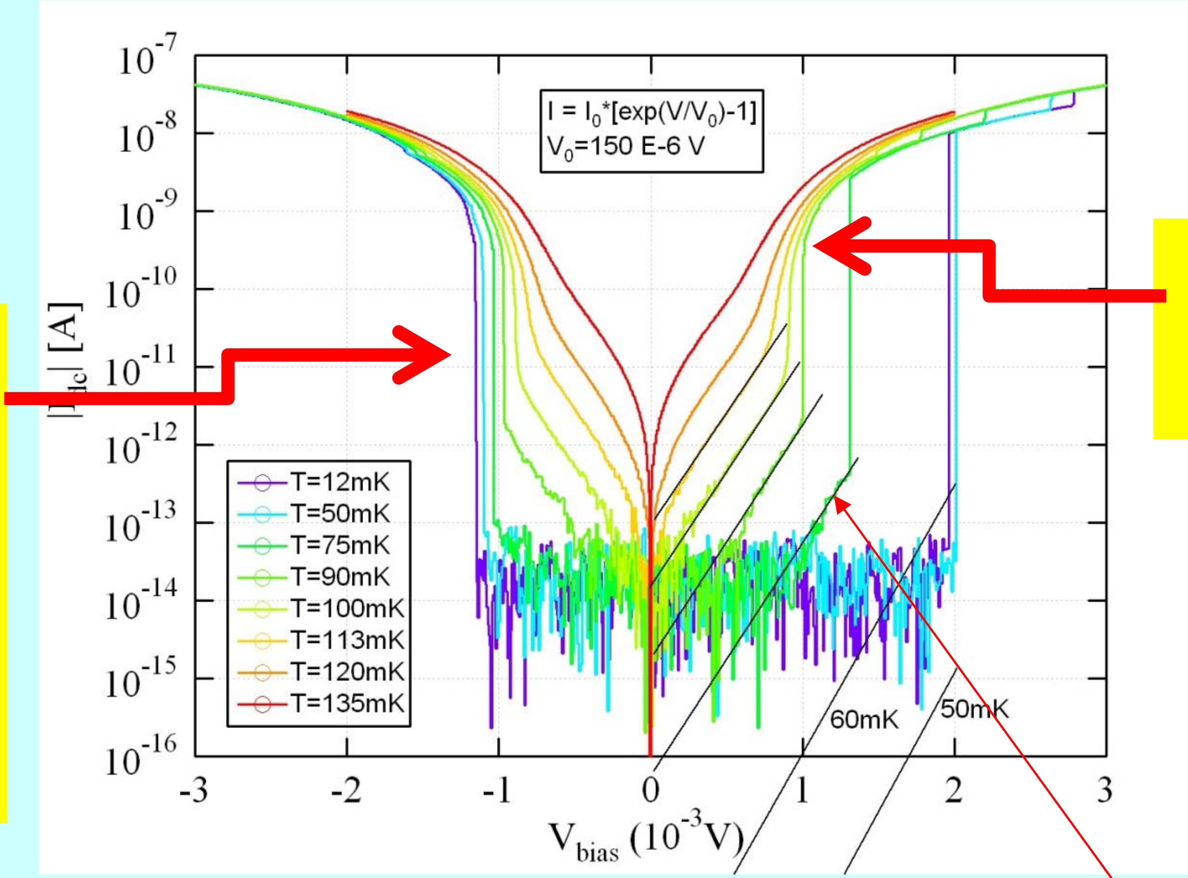


Maximal temperature of the cold (HR) state is close to the bath temperature

Threshold voltage for the hot (LR) state is almost independent of T_{bath}

Critical bath temperature T_{ph} depends only on D

Compare to the newest data



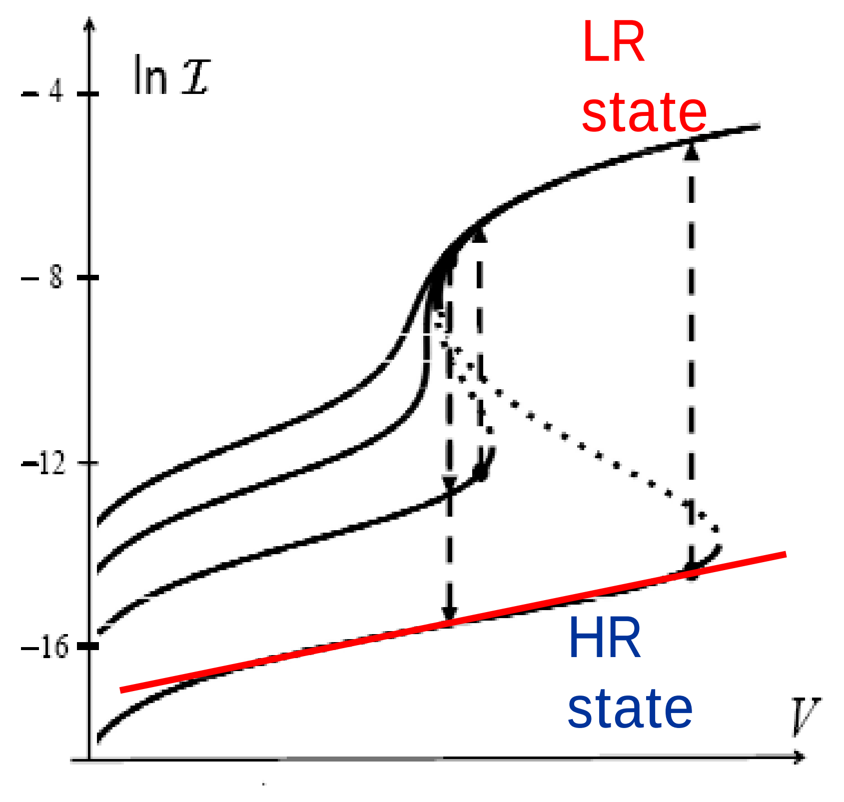
Threshold voltage for the hot (LR) state is almost independent of T_{bath}

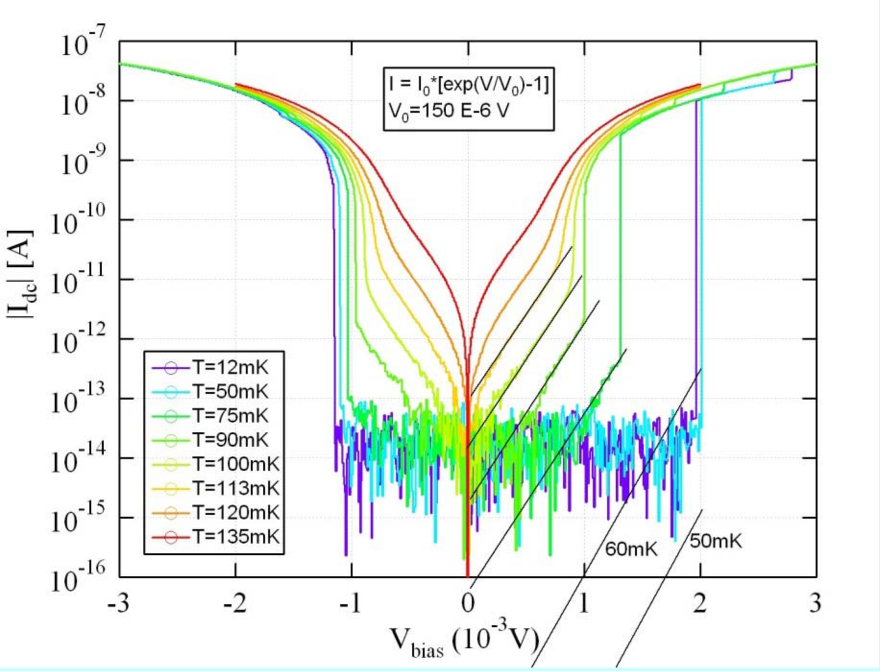
Threshold voltage of the cold (HR) state is strongly T-dependent

Non-zero log-linear conductance: the insulator is not ideal

M.Ovadia, B.Sacepe,
D.Shahar,
InO film (PRL,'09)

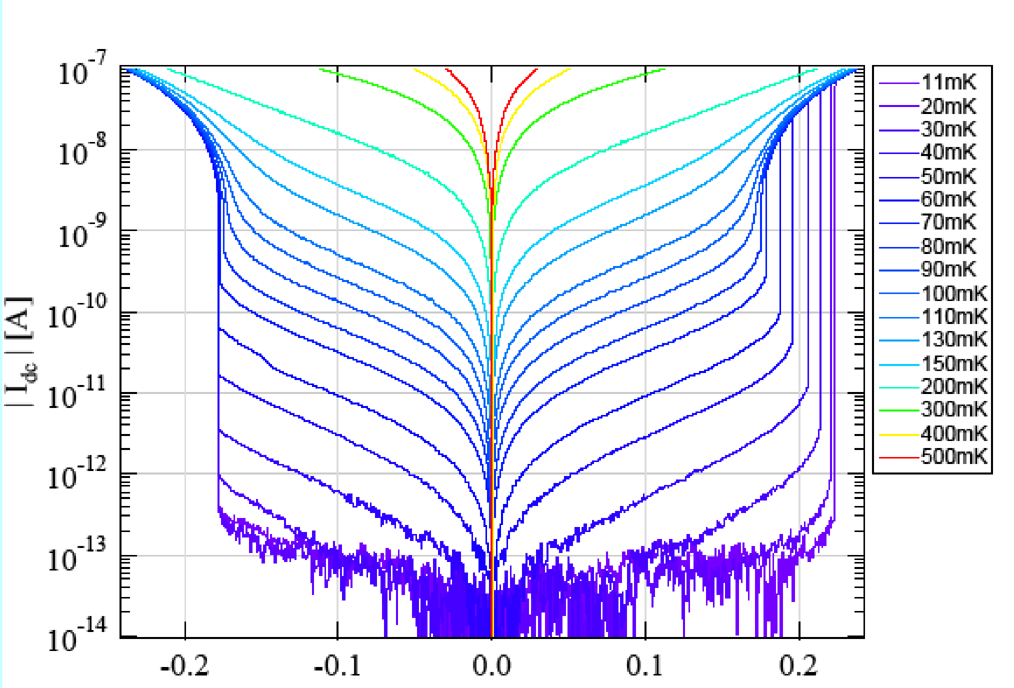
Nonlinear I-V characteristics





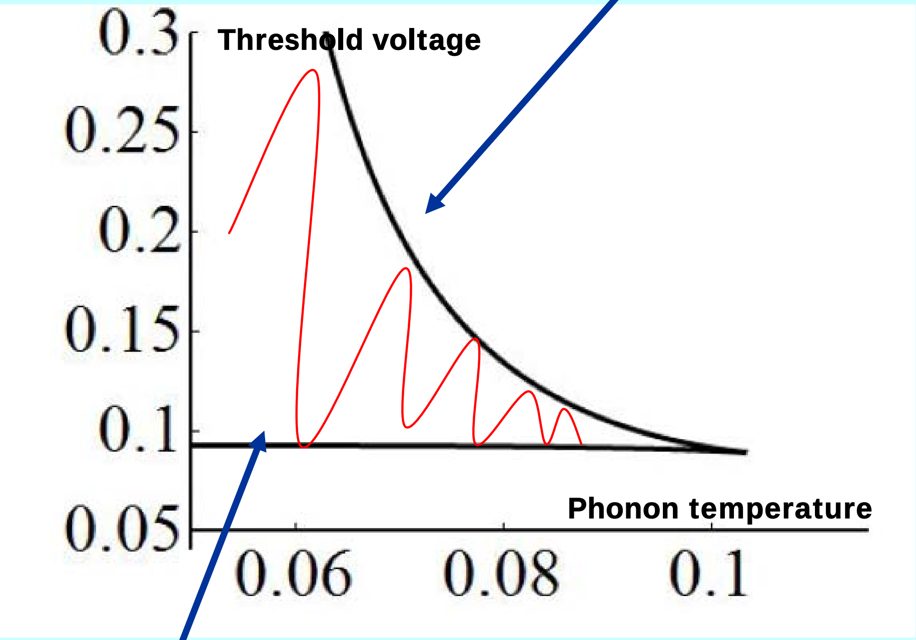
- Current jumps of several orders of magnitude
- Wide range of log-linear behavior in the HR state

T-dependence of jump voltage



The direction of voltage change

Limit of stability of the cold (HR) state is strongly *T*-dependent

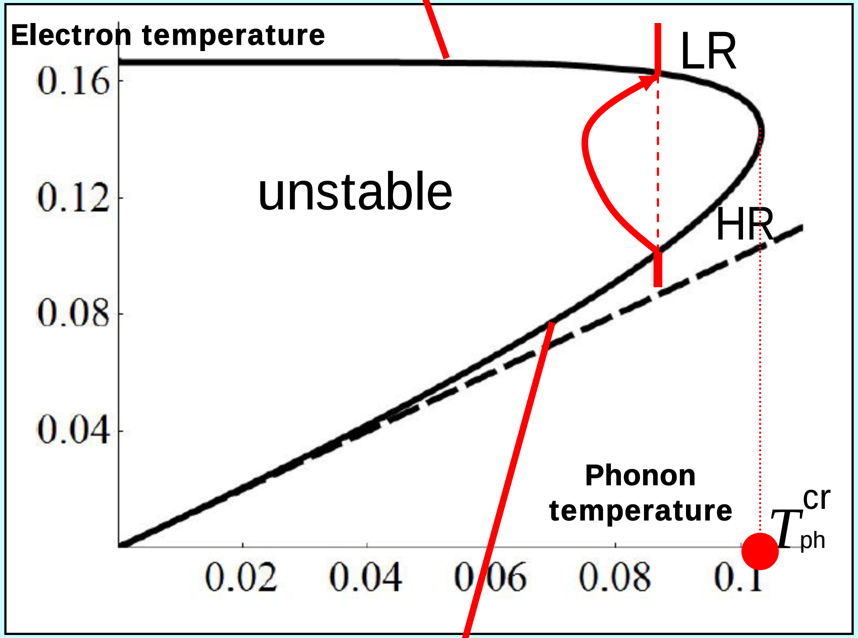


- ❖HR->LR voltage threshold strongly depends on *T*; LR->HR threshold has a weak *T*-dependence

Limit of stability for the hot (LR) state is almost independent of T_{bath}

Bistability temperature

Minimal temperature of the hot (LR) state is 0.14 D



Maximal temperature of the cold (HR) state is close to the bath temperature

Experimental bistability diagram (Ovadia, Sasepe, Shahar, 2009)

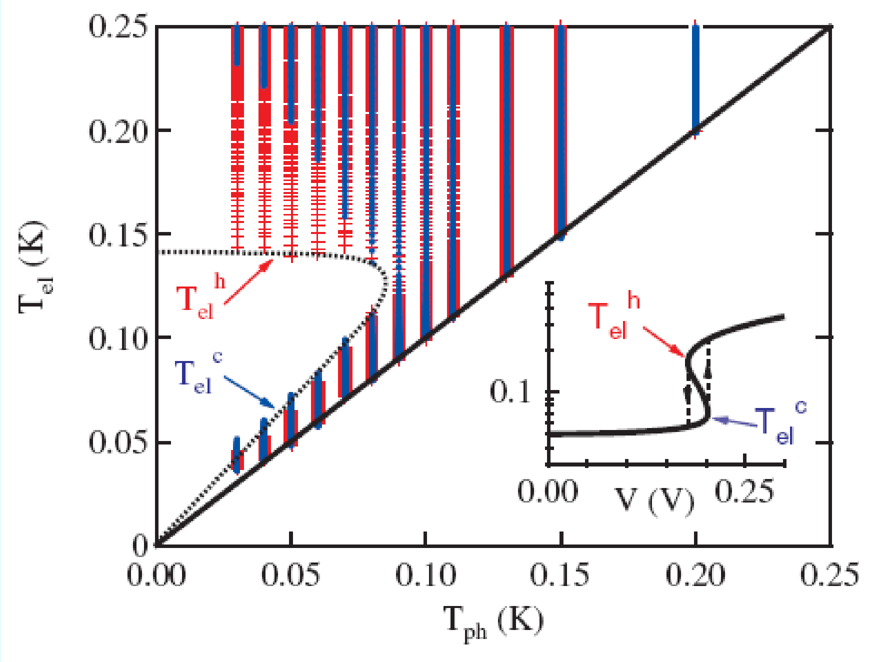


FIG. 3 (color online). T_{el} versus T_{ph}, showing the excluded region of temperatures which appears below $T_{ph} = 0.1$ K, and the accompanying hysteresis. Blue (dark gray) circles correspond to data measured while increasing $|V|$ and red (gray) crosses represent data taken while decreasing $|V|$. Inset:

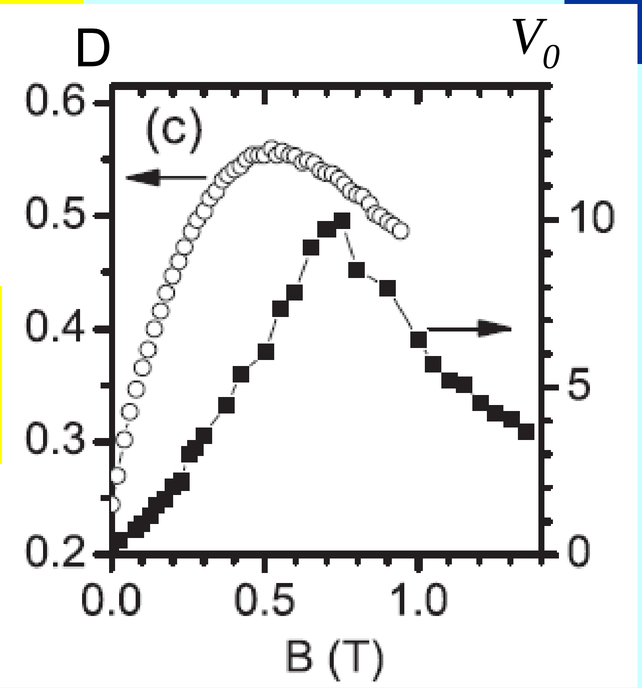
Quantitative comparison

$$\frac{eV_{\rm hot}^{\rm cr}}{L} \equiv \frac{0.1 k_{\rm F}\Delta^3}{\Delta_0^2}\,, \qquad T_{\rm ph}^{\rm cr} = 0.1\Delta\,, \qquad \Delta_0 \equiv (\rho v_{\rm s}^5 \hbar^3)^{1/4}$$

Theoretical estimates:
V=0.8 mV & T_{ph}^{cr}=190mK
for D=1.9K

Experimental data:
V=1.0 mV & T_{ph}^{cr}=120mK
for D=1.9K

Reasonable agreement in a wider range of D for TiN



Baturina et al, 2007

Beyond Arrhenius and $t_{\text{e-ph}}$

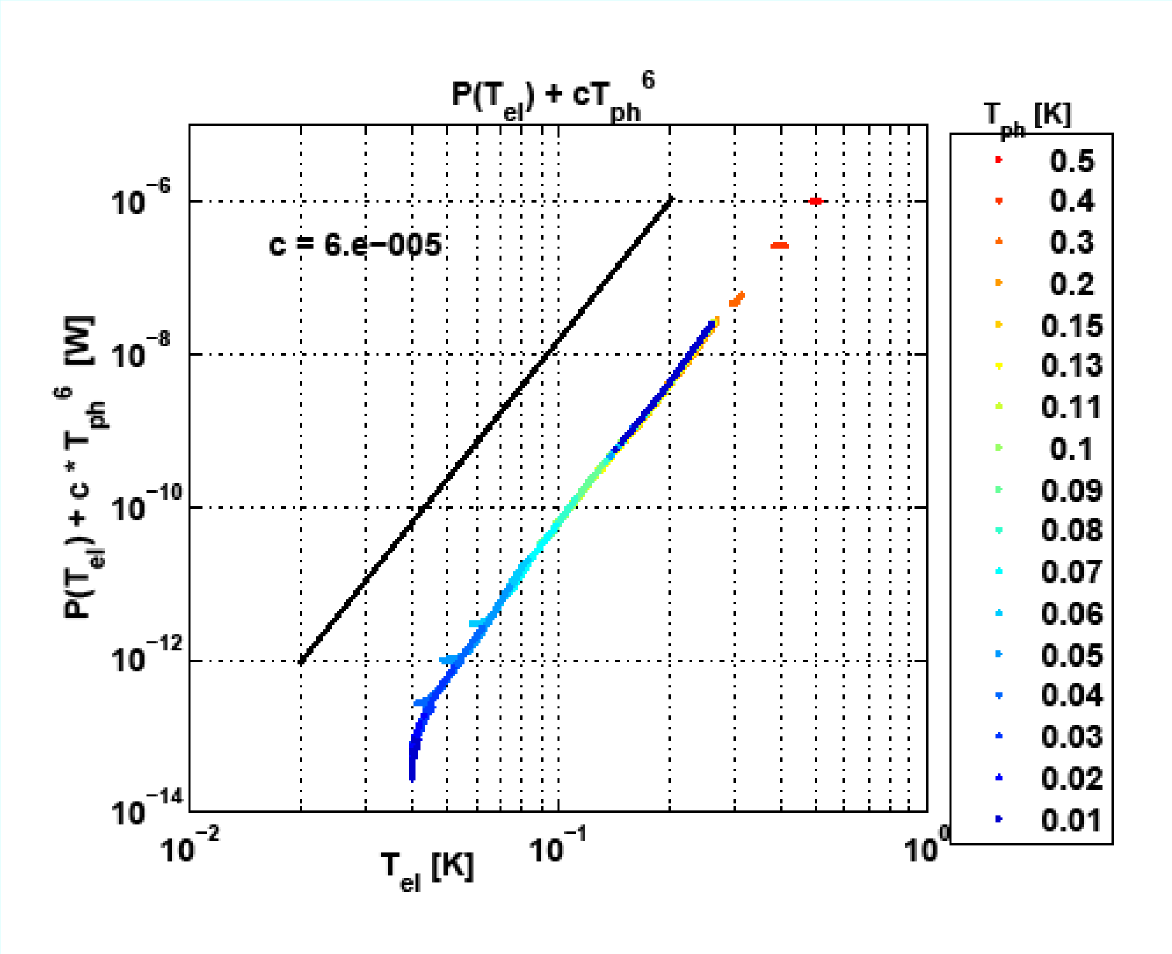
$$R(T) = R_0 \exp\left[(\Delta/T)^\gamma\right], \qquad \frac{V^2}{R(T_{\rm el})} \propto T_{\rm el}^\beta - T_{\rm ph}^\beta$$

Critical phonon temperature $t_{\text{ph}}^{\text{cr}} = T_{\text{ph}}^{\text{cr}}/\Delta$

$$t_{\rm ph}^{\rm cr} = (1+\beta/\gamma)^{-\frac{\beta+\gamma}{\gamma\beta}} = \begin{cases} 0.1 & \gamma = 1,\ \beta = 6 \\ 0.004 & \gamma = \frac{1}{2},\ \beta = 6 \\ 1.5 \cdot 10^{-6} & \gamma = \frac{1}{4},\ \beta = 6 \end{cases}$$

Scaling of the threshold voltage: $$V_{\rm LH}/\Delta^\beta = f(T_{\rm ph}/\Delta)\,.$$

Scaling

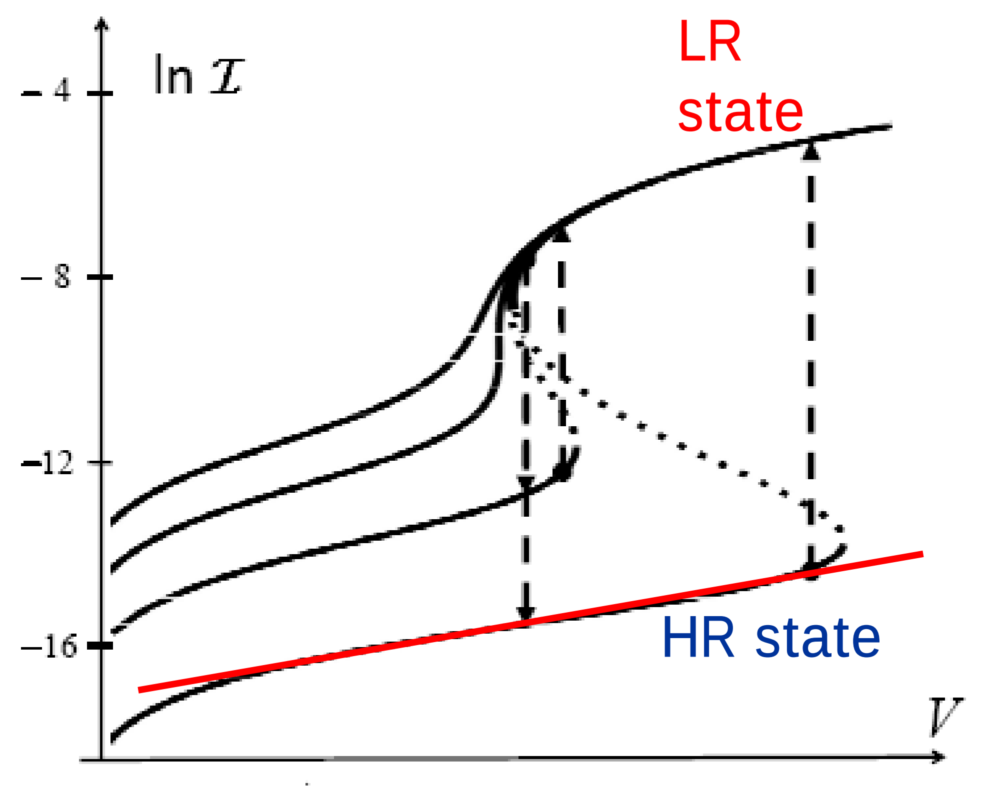


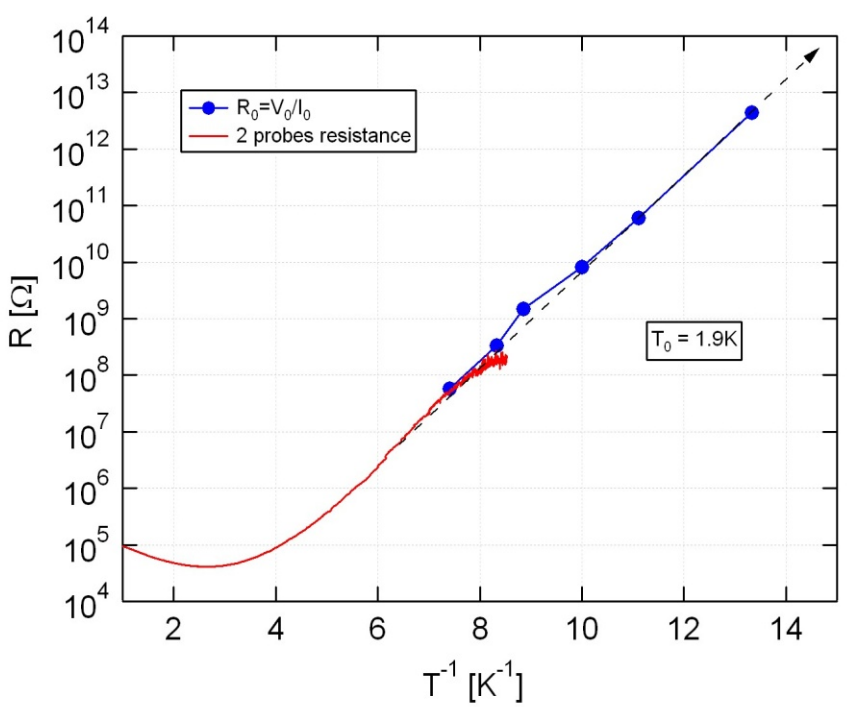
β=6 seems to be by far the best fit for the data

Not all experimental features captured

What is not quantitatively good: I_{max}/I_{min}<e in the HR state;

Experimentally this ratio is 10 ¸20; cannot be cured by any γ or β

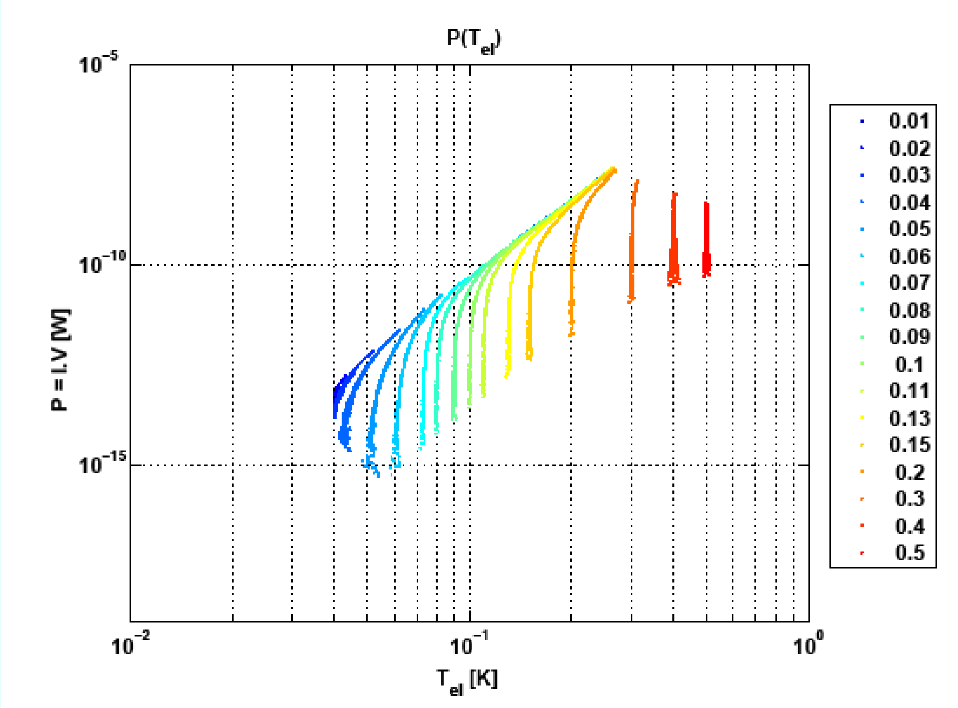




$$\ln\frac{I}{I_0}=\frac{V}{V_0}\,, \qquad \frac{V_0}{I_0}\approx 2R_0$$

Is overheating too mundane?

- Not known to happen on the insulating side, i.e. at R`h/e^2
- Never was looked after as it is in contradiction to the picture of phonon-assisted hopping
- "Checked for" and vigorously denied in YSi and magnetite
- Requires a new approach to electron hopping at low T



Summary

❿ Electrons overheating due to inefficient cooling and the resulting current bistability leads to giant current jumps

❿ Good qualitative agreement with experiment without fitting parameters

❿ A microscopic description of hopping electron transport in the absence of thermalization with phonons is wanted

❿ Direct measurement of the electron temperature in the hopping regime is a challenge