Tutorial
Superconductor-Insulator transition

Christoph Strunk

University of Regensburg

Outline

- Localization: suppression of diffusion by disorder

  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity

- Suppression of zero-resistance state by phase fluctuations

- Suppression of Cooper-pairing by disorder

- Direct superconductor-insulator transition

- ‚Failed‘ superconductors and insulators:

  Kravchenko et al. 1994: „There are ~~no~~ metals in two dimensions!“

Localization

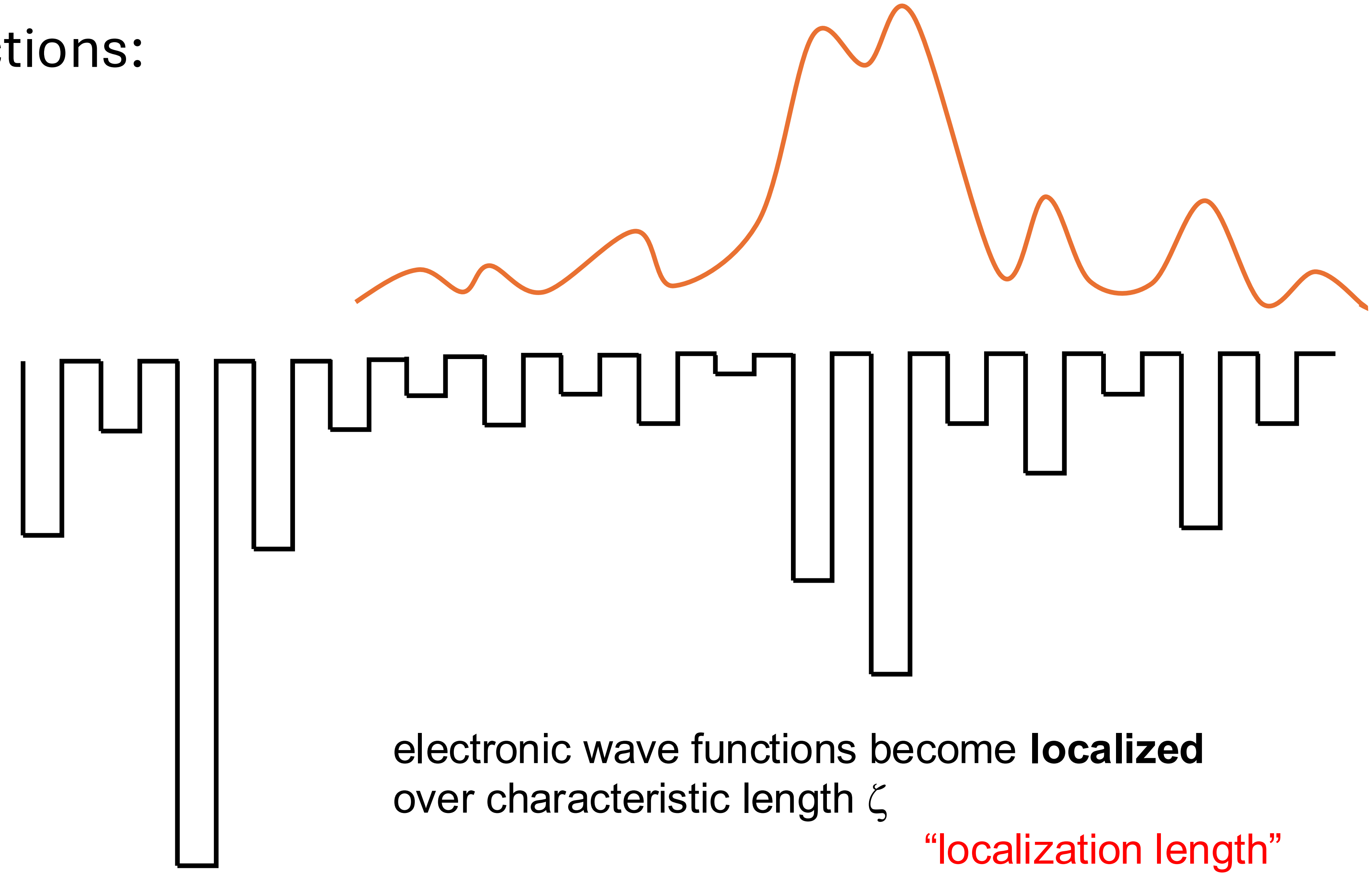
Numerical simulations show that diffusion is suppressed in presence of sufficently strong on-site disorder

- Two seminal predictions:

P. W. Anderson,

On the absence of localization in certain random lattices

Phys. Rev. **109**, 1492 (1958).



electronic wave functions become **localized** over characteristic length ζ

“localization length”

Localization

Experimental realization:
doped semicoductors, e.g., Si:P

- Two seminal predictions:

P. W. Anderson,

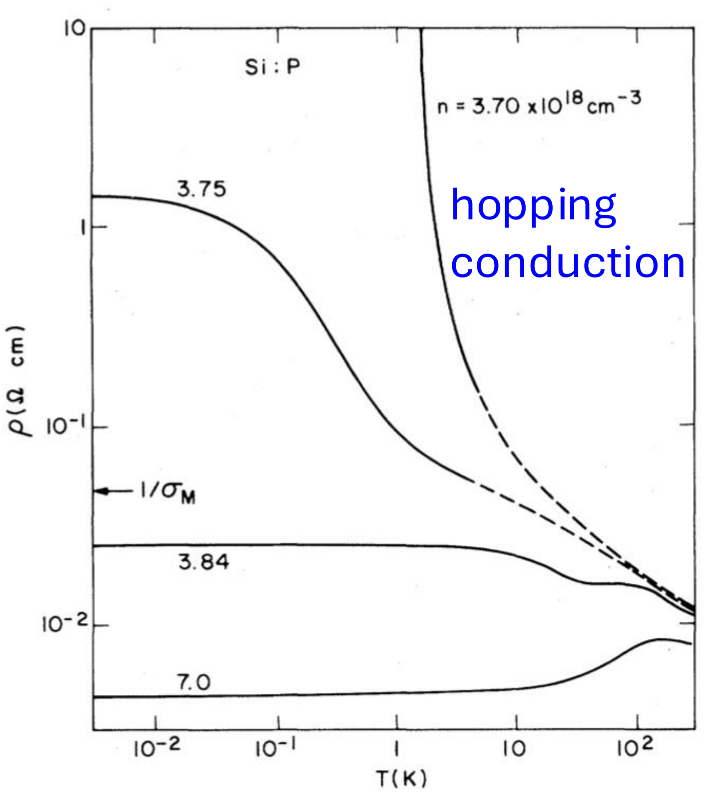
On the absence of localization in certain random lattices

Phys. Rev. **109**, 1492 (1958).

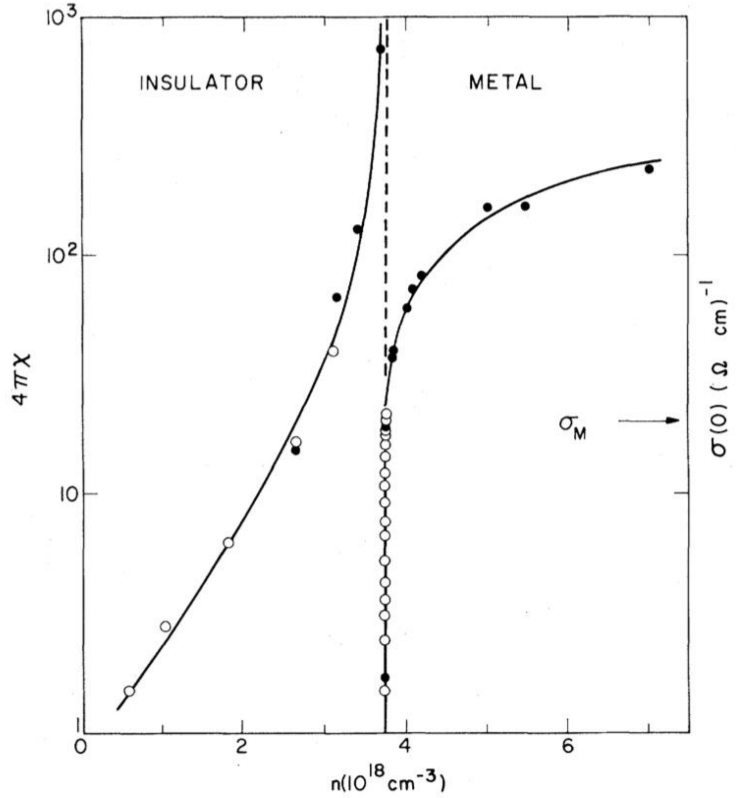
T. F. Rosenbaum, R. F. Milligan, M. A. Paalanen, G. A. Thomas, R. N. Bhatt, W. Lin

Metal-insulator transition (MIT) in a doped semiconductor

Phys. Rev. B **27**, 7509 (1983)



resistivity $\rho(0)$ diverges below and saturates above MIT in the limit $T \to 0$



both, $\rho(0)$ and $\chi(0)$ diverge at MIT

Localization

- Two seminal predictions:

E. Abrahams, P. W. Anderson,
D. C. Licciardello, T. V. Ramakrishnan,

Scaling Theory of Localization:
Absence of Quantum Diffusion in Two Dimensions

Phys. Rev. Lett. **42**, 673 (1979)

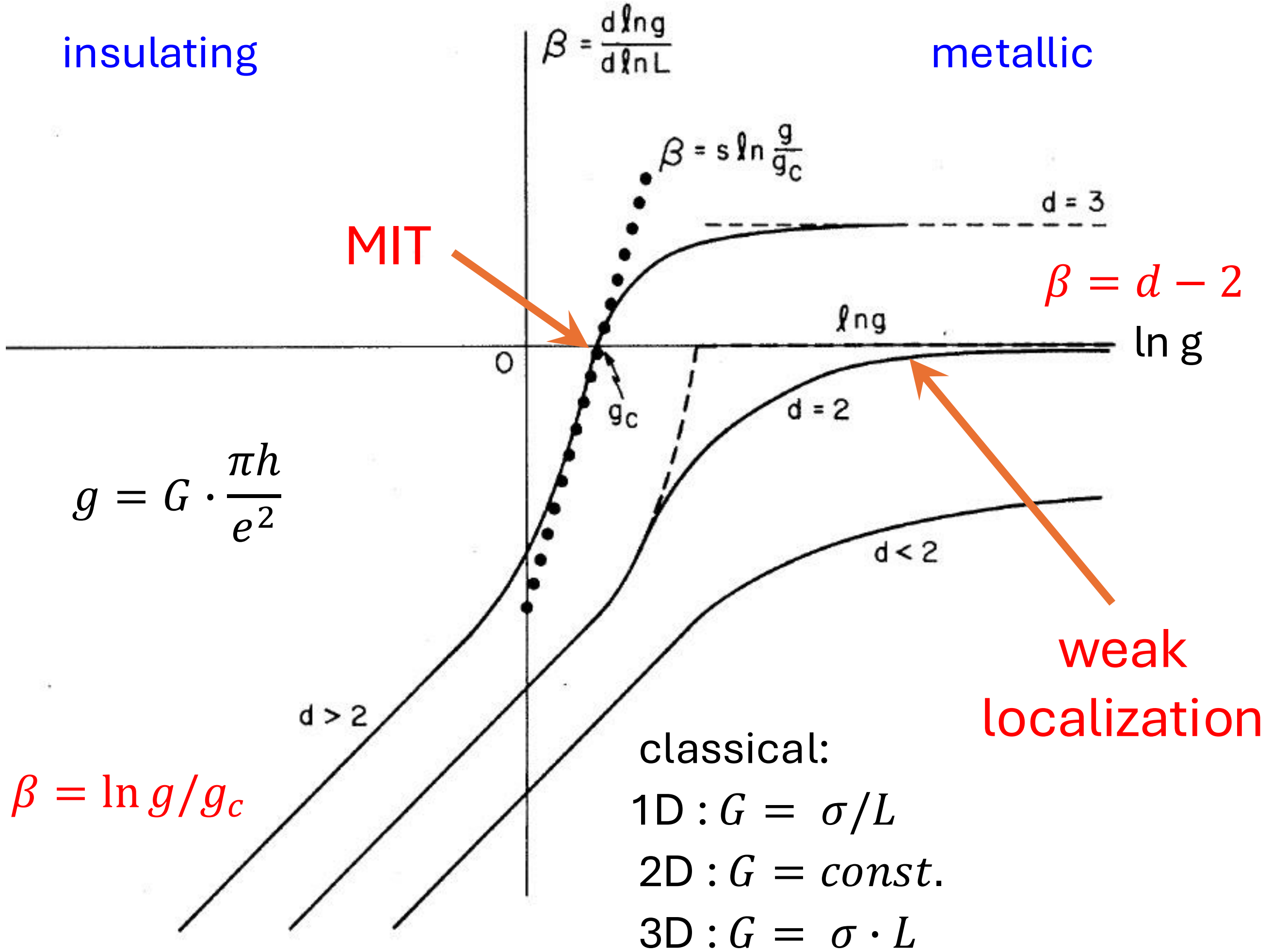
Conductance G of a hypercube becomes a function of size L (in units of ζ):

classical regime: $G(L) = \sigma \cdot L^{d-2}$

localized regime: $G(L) \propto \exp(-L)$

strong localization

Scaling arguments show that in 2D and in absence of interactions this occurs at arbitrarily weak disorder



Weak Localization

If the film is larger than the phase-coherence length L_φ, then L has to be replaced by $L_\varphi(T)$.
Hence, $R(T)$ was predicted to show T-dependent *quantum corrections*:

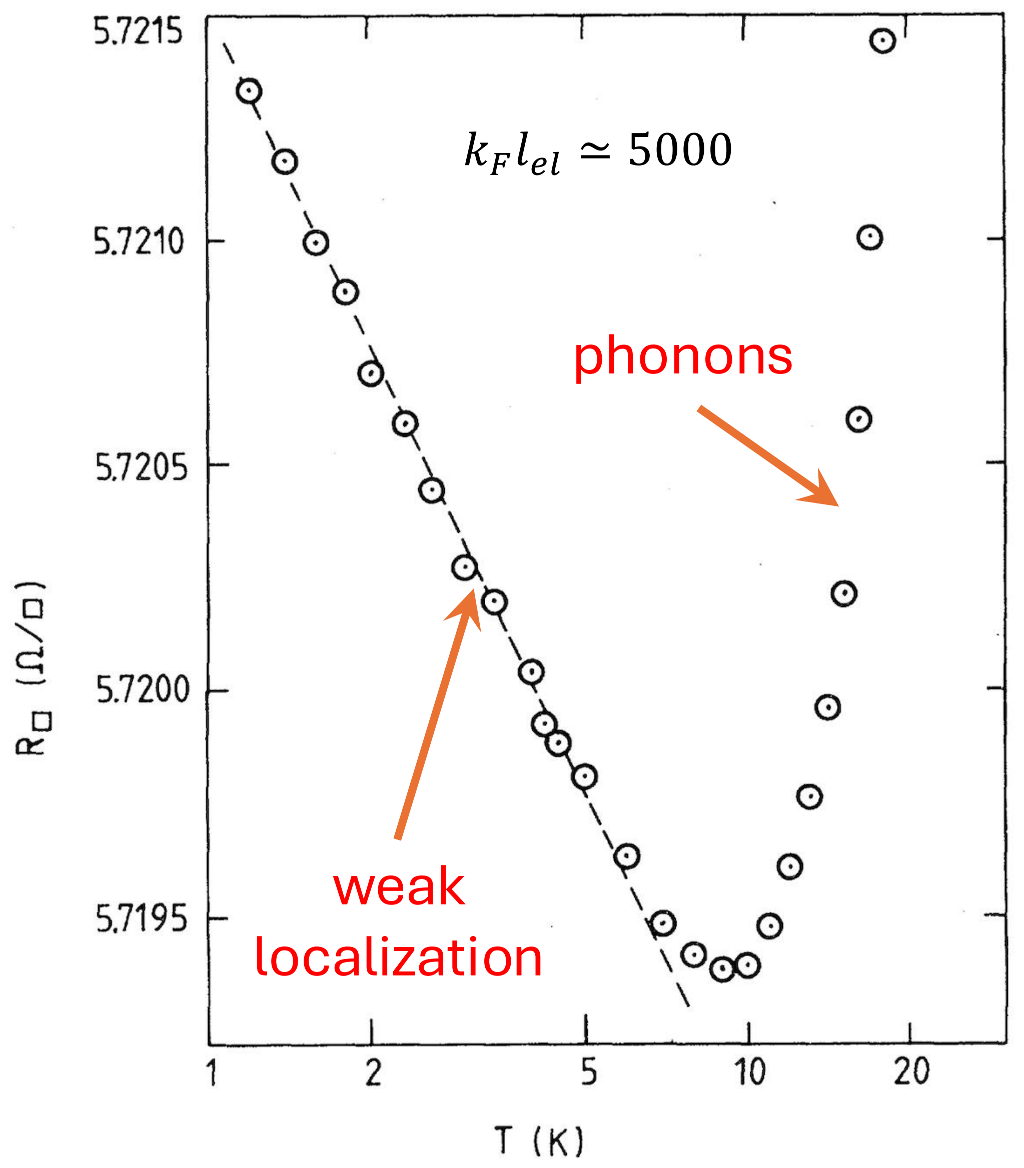
Altshuler, B. L., and A. G. Aronov, JETP Lett. **30**, 514 (1979).
Altshuler, B. L., and A. G. Aronov, JETP **50**, 968 (1979).
Altshuler, B.L., and A. G. Aronov, JETP Lett. **33**, 499 (1981).

SPOILER ALERT

In order to see the predicted crossover to insulating behavior for systems with $k_F\ell \gg 1$, one would have to measure the conductance at exponentially low temperatures,

$$T < T^\star \sim E_F \exp[-\pi k_F \ell]. \qquad (1)$$

A. Kapitulnik, S. V. Kivelson, B. Spivak
Colloquium: Anomalous metals: Failed superconductors
Rev. Mod. Phys. **91**, 011002 (2019)



L. Van den Dries, C. Van Haesendonck, Y. Bruynseraede, G. Deutscher
Two-Dimensional Localization in Thin Copper Films
Phys. Rev. Lett. **46**, 565 (1981)

Localization

For a comprehensive review:

Disordered electronic systems

Patrick A. Lee

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

T. V. Ramakrishnan

Department of Physics, Banaras Hindu University, Varanasi-221005 (U.P.), India

Rev. Mod. Phys. **57**, 287 (1985)

Localization

Experimental difficulty:

Q: How to make homogenuously disordered thin films?

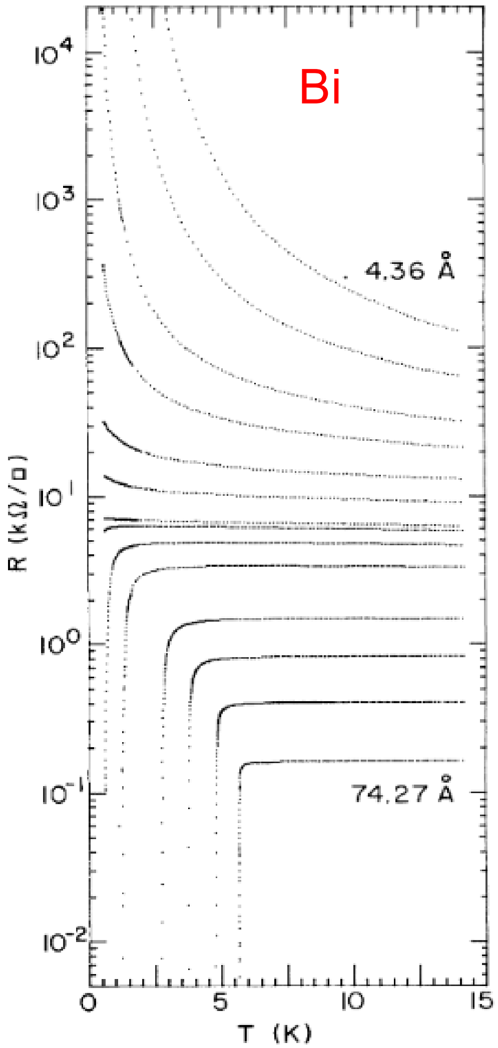
A: Use quench-condensed amorphous films (e.g.: Bi)

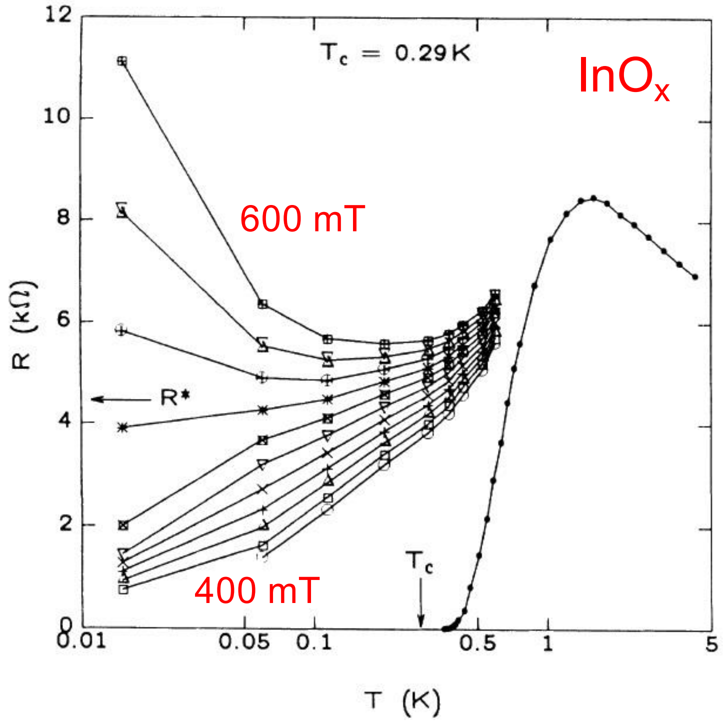
- Two seminal predictions:

E. Abrahams, P. W. Anderson,
D. C. Licciardello, T. V. Ramakrishnan,

Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions

Phys. Rev. Lett. **42**, 673 (1979)





D. Haviland, Y. Liu, A. Goldman,

Onset of superconductivity in the two-dimensional limit

Phys. Rev. Lett. **62**, 2180 (1989)

A. F. Hebard, M. A. Paalanen

Magnetic-Field-Tuned Superconductor-Insulator Transition in Two-Dimensional Films

Phys. Rev. Lett. **65**, 927 (1990)

Outline

- Localization: suppression of diffusion by disorder

  Abrahams et al. 1979: „There are no metals in two dimensions!“

- **Superconductivity**

Superconductivity

- Repulsive (Coulomb) part of electron-electron is strongly screened
- Arbitrarily small attractive interactions can lead to Cooper-instability
- Electrons condense pairwise into new ground state: **superfluid condensate**
- Excitation spectrum of quasiparticles displays energy gap Δ

In presence of disorder, superflow is significantly suppressed: $\vec{j}_s \propto 1/R_N$

P.W. Anderson:

- Nonmagnetic impurities should not affect Cooper pairing.

This is valid only for relatively weak disorder:

- Slowing down of electron diffusion reduces screening and T_c

Supercurrent

Normal electric currents are driven by electric potential (ϕ_{el}) differences :

$\vec{j}_{\mathrm{N}} = -\sigma_{\mathrm{N}}\,\mathrm{grad}\,\phi_{\mathrm{el}}$ but, in superconductors: $\mathrm{grad}\,\phi_{\mathrm{el}} \equiv 0$ (in the stationary case)

So - what's drives a supercurrent?

$$\boxed{\vec{j}_{\mathrm{S}} = -2e\,|\psi|^2\,\frac{\hbar}{m^*}\left(\boxed{\mathrm{grad}\,\varphi} + \frac{2e}{\hbar}\vec{A}\right)}\,, \quad \text{where} \quad \psi(\vec{r}) = |\psi(\vec{r})|^2 \exp i\varphi(\vec{r})$$

complex order parameter

current-phase-relation (2nd Ginzburg-Landau equation/ 1st Josephson equation)

Ginzburg & Landau: supercurrents are driven by (gauge-invariant) phase differences!

electric potential differences generate a time evolution of the phase :

$$\boxed{\frac{\partial}{\partial t}\varphi(\vec{r},t) = \frac{2e}{\hbar}\phi_{\mathrm{el}}(\vec{r},t)}$$

2nd Josephson equation → acceleration of superfluid condensate, if $\mathrm{grad}\,\phi_{\mathrm{el}} \neq 0$

London equations

A) Take curl of current-phase-relation:

$$\mathrm{rot}\ \vec{j}_\mathrm{S} = -2e\,|\psi|^2\,\frac{\hbar}{m^*}\left(\cancel{\mathrm{rot\ grad}}\ \varphi + \frac{2e}{\hbar}\mathrm{rot}\ \vec{A}\right) = -\underbrace{\frac{4e^2|\psi|^2}{m^*}}_{\Lambda_\mathrm{L}^{-1}}\ \vec{B}$$

2nd London equation

Meissner – Effect !

$$\Lambda_\mathrm{L}^{-1} = \frac{4e^2|\psi(T)|^2}{m^*} = \frac{1}{\mu_0\lambda^2(T)}$$

$$J_s(T) = \frac{\hbar^2}{4e^2k_\mathrm{B}}\cdot\frac{d}{\Lambda_\mathrm{L}}$$

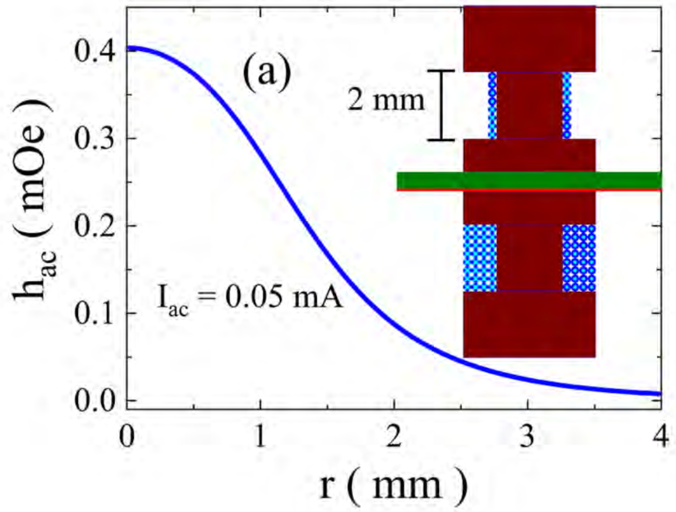
London parameter, equivalent to

superfluid density

penetration depth

superfluid weight

superfluid phase stiffness



see, e.g., S. Mandal et al., Supercond. Sci. Tech. **36**, 014004 (2023)

Two-coil method allows to measure Λ_L^{-1} in thin films with thickness $d \lesssim \lambda(T)$

London equations

B) Take time derivative of current-phase-relation:

$$\frac{\partial \vec{j}_\mathrm{S}}{\partial t} = -2e\,|\psi|^2\,\frac{\hbar}{m^*}\left(\mathrm{grad}\,\frac{\partial \varphi}{\partial t} + \frac{2e}{\hbar}\frac{\partial \vec{A}}{\partial t}\right) = \Lambda_\mathrm{L}^{-1}\,\vec{E}$$

1st London equation

ideal conductor : $\sigma = \infty$

$$\frac{\partial I_\mathrm{S}}{\partial t} = \underbrace{\frac{wd}{\ell}\,\Lambda_\mathrm{L}^{-1}}_{L_\mathrm{kin}^{-1}} \cdot V$$

the 1st London equation is an induction law !

total inductance : $L = L_\mathrm{geo} + L_\mathrm{kin}$

$$= \mu_0 \frac{w}{\ell}\left(d + \frac{\lambda^2}{d}\right)$$

L_kin important, if film thickness: $d \lesssim \lambda(T)$

Why "superfluid density" is a seductive, but sometimes misleading concept

- it suggest a link to electron density $n_S = n_e/2$ and that at low temperature all electrons are paired up into Cooper pairs
- wrong: only electrons within Δ around Fermi surface pair up, the others are invisible because of Pauli principle
- in experiments, $\Lambda_{\mathrm{L}}^{-1}$ *strongly depends on mean free path*, while a carrier density should not: Cooper pairs propagate dissipationless, but still need diffusion times $L^2/D_{\mathrm{electron}}$ to travel a distance L in the superconductor
- Only the ratio $\Lambda_{\mathrm{L}}^{-1} = \dfrac{4e^2 n_S}{m^*} = \dfrac{1}{\mu_0 \lambda^2(T)}$ is generally relevant, but not n_S and m^* separately
- supercurrent is simply given by: $\vec{j}_s = \dfrac{\hbar}{2e\Lambda_L}\left(\mathrm{grad}\,\varphi + \dfrac{2e}{\hbar}\vec{A}\right)$
- dirty limit BCS-theory results in $\Lambda_{\mathrm{L}}^{-1} = \dfrac{\Delta(0)}{\hbar R_N d} = \dfrac{\Delta(0)}{\hbar \rho_N} \neq \dfrac{1}{\rho_N \tau}$ with $\tau = \infty$

Outline

- Localization: suppression of diffusion by disorder

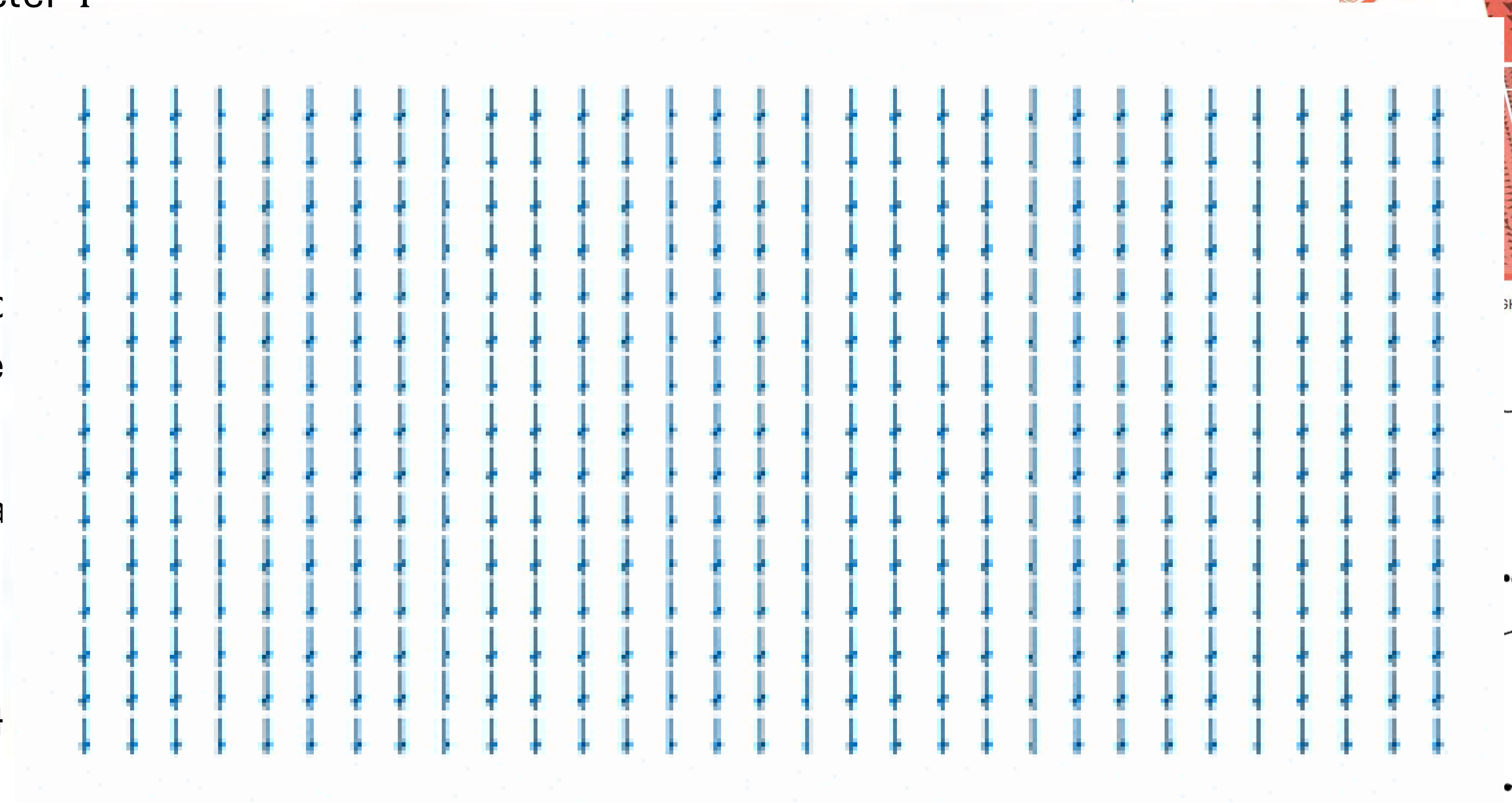
  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity

- **Suppression of zero-resistance state by phase fluctuations**

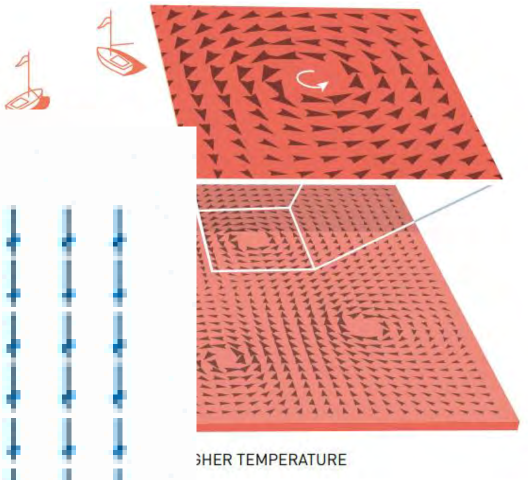
Berezinski-Kosterlitz-Thouless transition

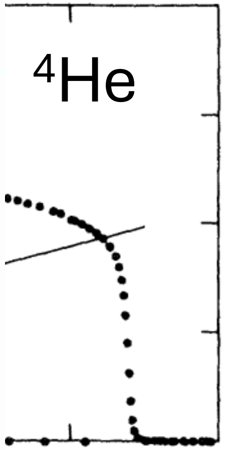
Superfluid stiffness J_s: energy scale for twisting the phase of the order parameter Ψ



Topological phase

- Unbinding c
  at critical te
- Sudden dro
  universal va
  $J_s(T_{\mathrm{BKT}}) =$
- Clear experi
  superfluid ^{4}H





Kosterlitz, Thouless, J. Phys. C (1973), Kosterlitz, J. Phys. C (1974)
Ambegaokar et al., PRL (1978), PRB (1980)

McQueeney et al., PRL (1984)

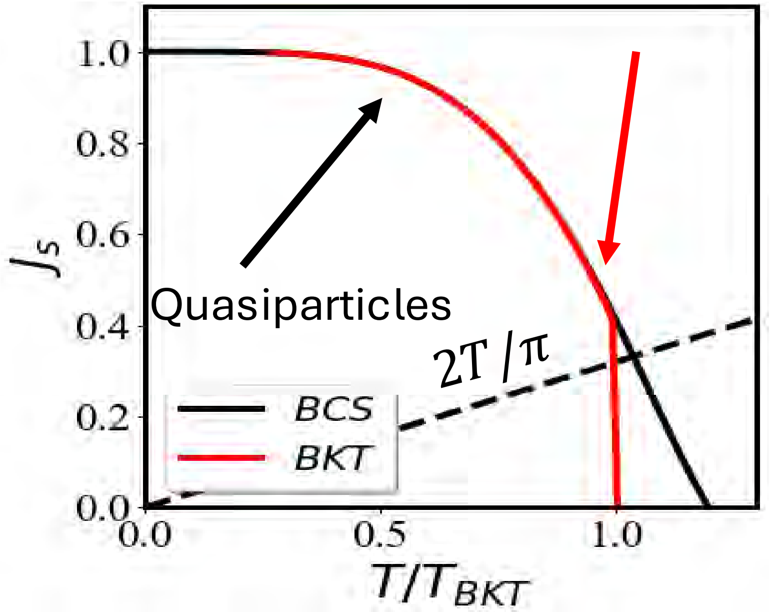
BKT transition in superconductors

In 2D superconductors situation much less clear:

- Few comparisons of superfluid stiffness signatures and transport signatures on the same device

- BKT transition in superconducting films often displays strong broadening:

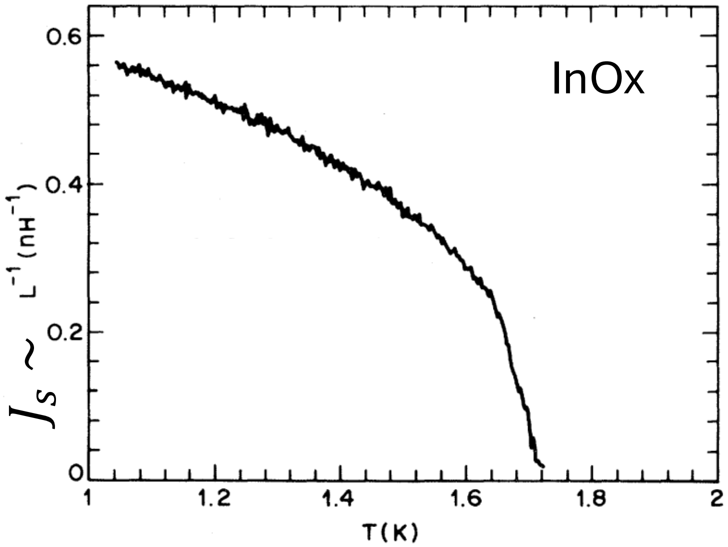
Cartoon:



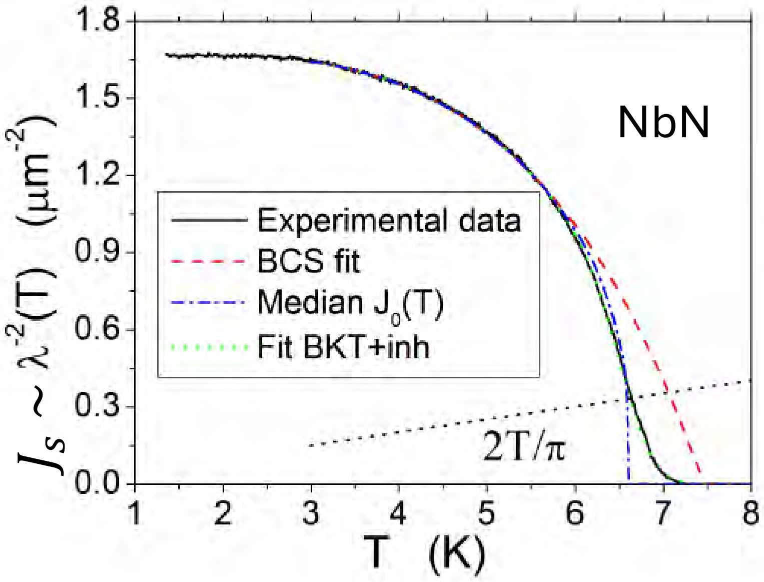
- Cannot be explained by finite size effects
  (see poster L. Pfaffinger)

- Most probably due to material inhomogeneity

more recent experiments:



Fiory et al., Phys. Rev. B **28**, 5075 (1983)

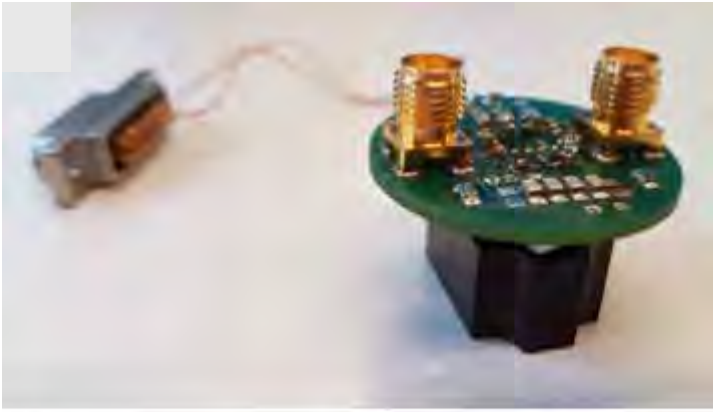


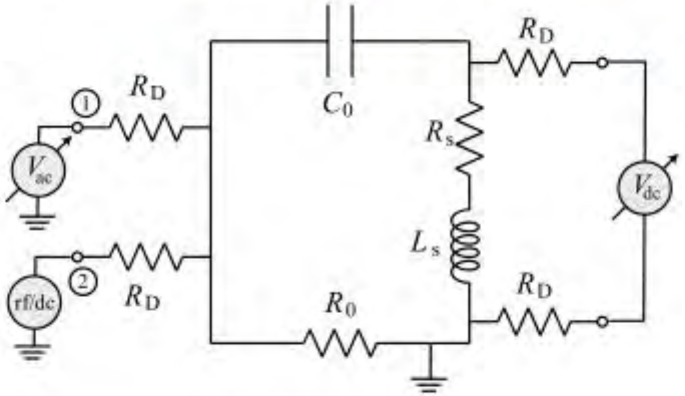
Yong et al., PRB **87**, 184505 (2013)

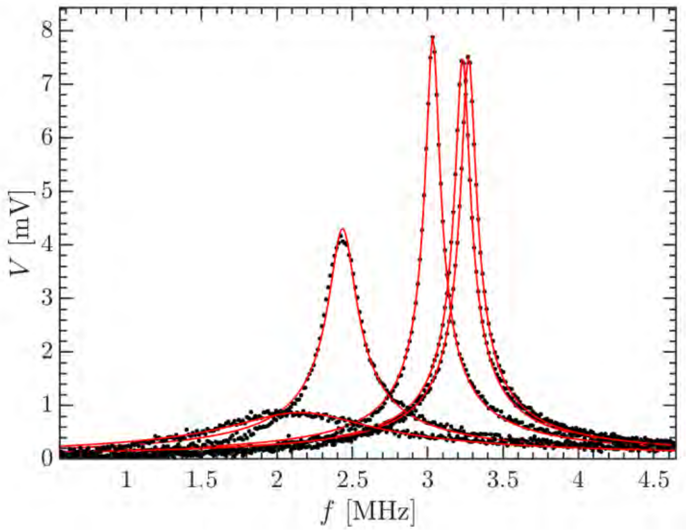
J_s from kinetic inductance measurements

Resonator method: put superconducting strip of sample in series with Cu-coil

- decrease in resonance frequency f_0 corresponds to increase in kinetic inductance of sample
- decrease in internal Q-factor Q_i corresponds to increase in sample resistance
- J_s is very sensitive to magnetic field







measure superfluid stiffness via kinetic inductance $L_\blacksquare$:

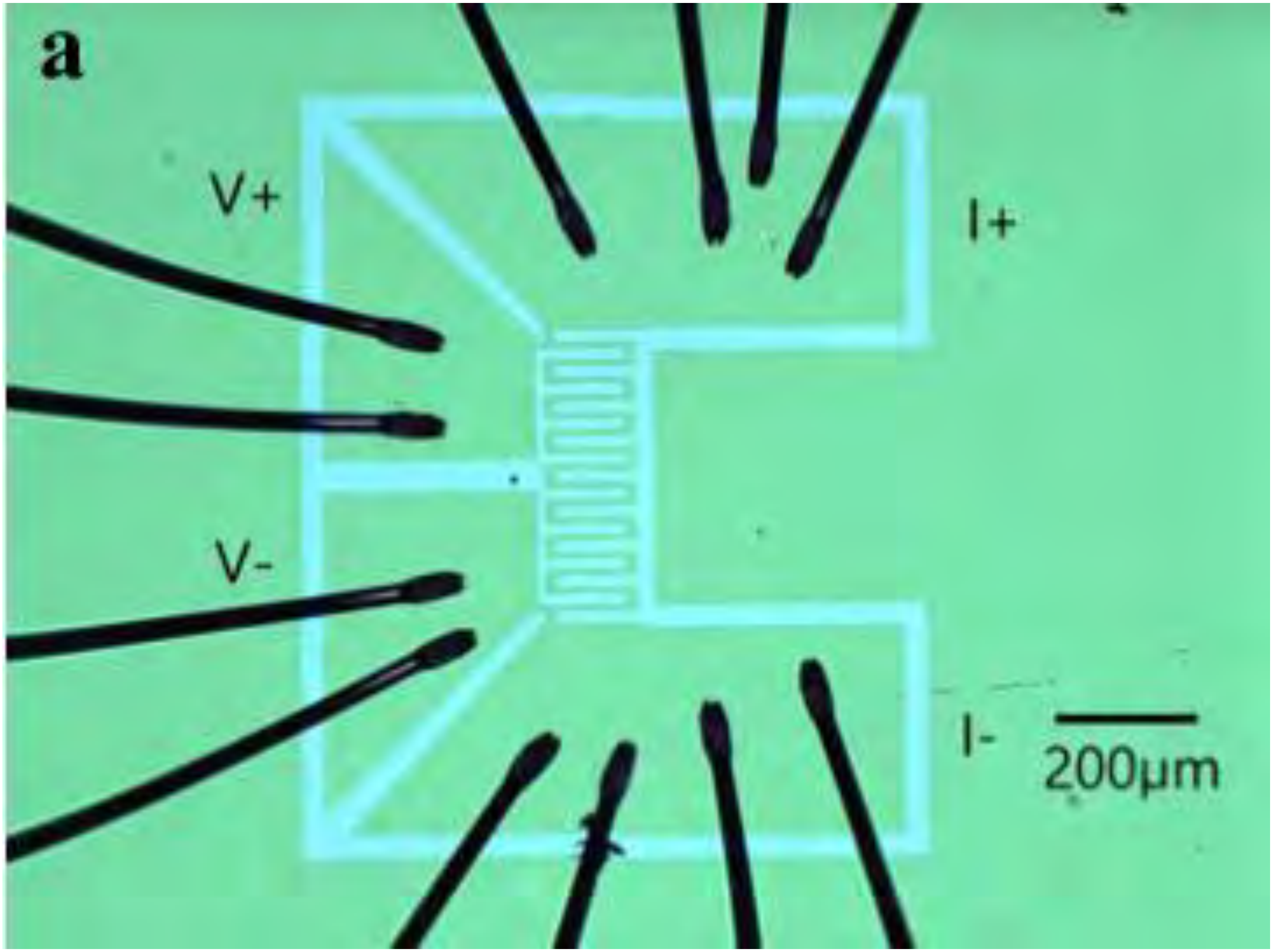
$$J_s = \frac{\Phi_0^2}{16\pi^2 k_B L_\blacksquare} = \frac{\hbar^2}{4e^2 k_B} \cdot \frac{d}{\mu_0 \lambda^2(T)}$$

Dirty limit BCS: $J_s(T=0) = \dfrac{\Phi_0^2 \Delta(0)}{4\pi k_B \hbar R_N}$

Meservey & Tedrow, J. Appl. Phys. 1969, Baumgartner et al. PRL 2021

Our samples

- 3 nm thin films NbN films on Si/SiO2 substrate
- Preparation by atomic layer deposition
  at IPHT Jena
- Patterned into long meanders (40 – 200 squares) for high resolution in resistance and inductance
- Vary widths ($10, 50, 200 \ldots\ \mu\mathrm{m}$) and disorder levels ($R_{\blacksquare}(300\ \mathrm{K}) = 1.5 - 3.3\ \mathrm{k}\Omega$, controlled by N2 during deposition or aging)



Our samples: linear resistance

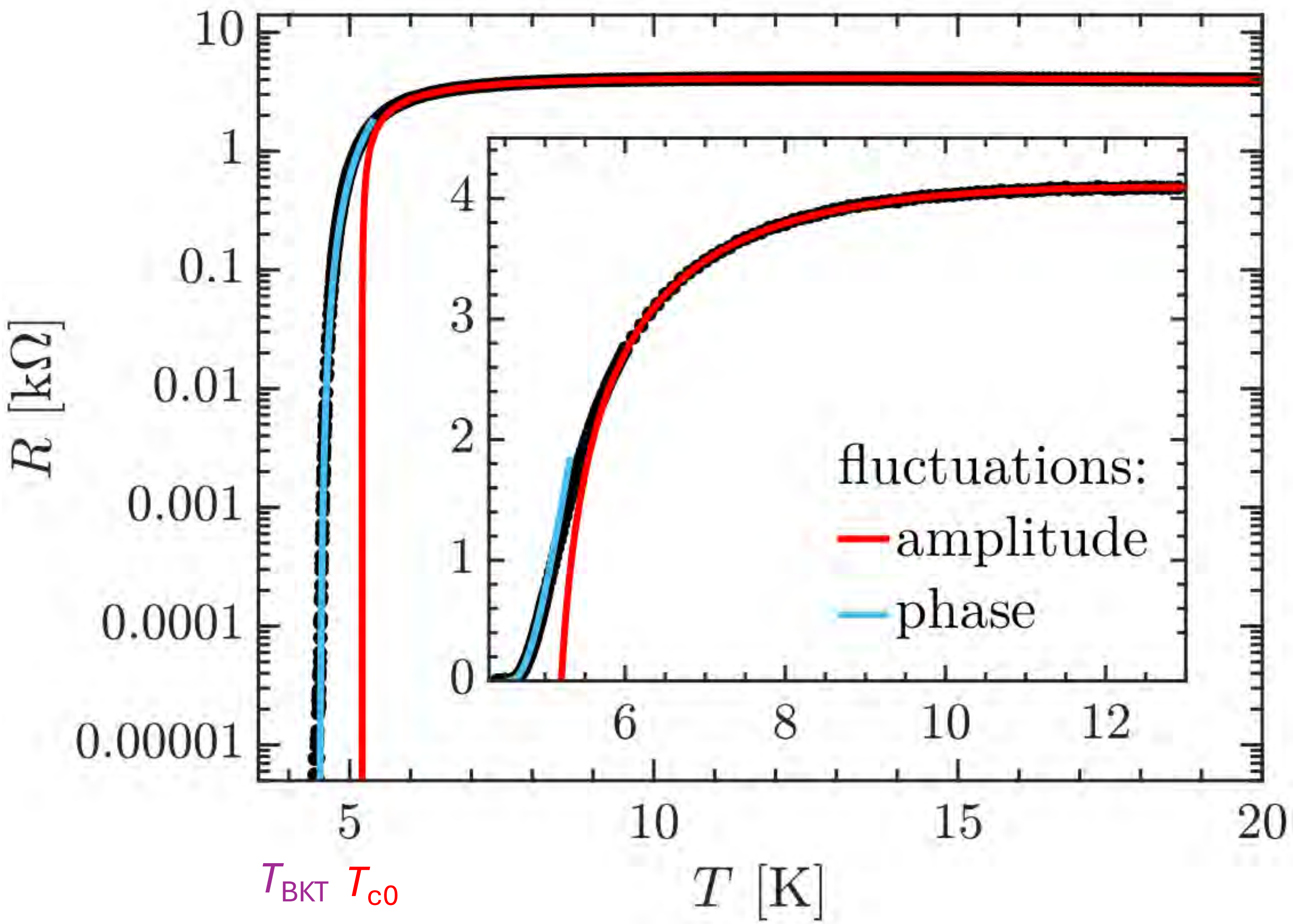
Resistance curves well described by fluctuation conductivity:

above T_{c0} :
amplitude fluctuations of the order parameter

Between T_{BKT} and T_{c0}:
phase fluctuations of the order parameter

Onset of resistance following a „square root cusp“ in temperature:

$$R \sim \exp\left(\frac{-b}{\sqrt{\frac{T}{T_{BKT}} - 1}}\right)$$



Ambegaokar et al., PRL **40**, 783 (1978), PRB **21**, 1806 (1980)

A. Weitzel, PRL **131**, 186002 (2023)

Expectations for DC IV-characteristics

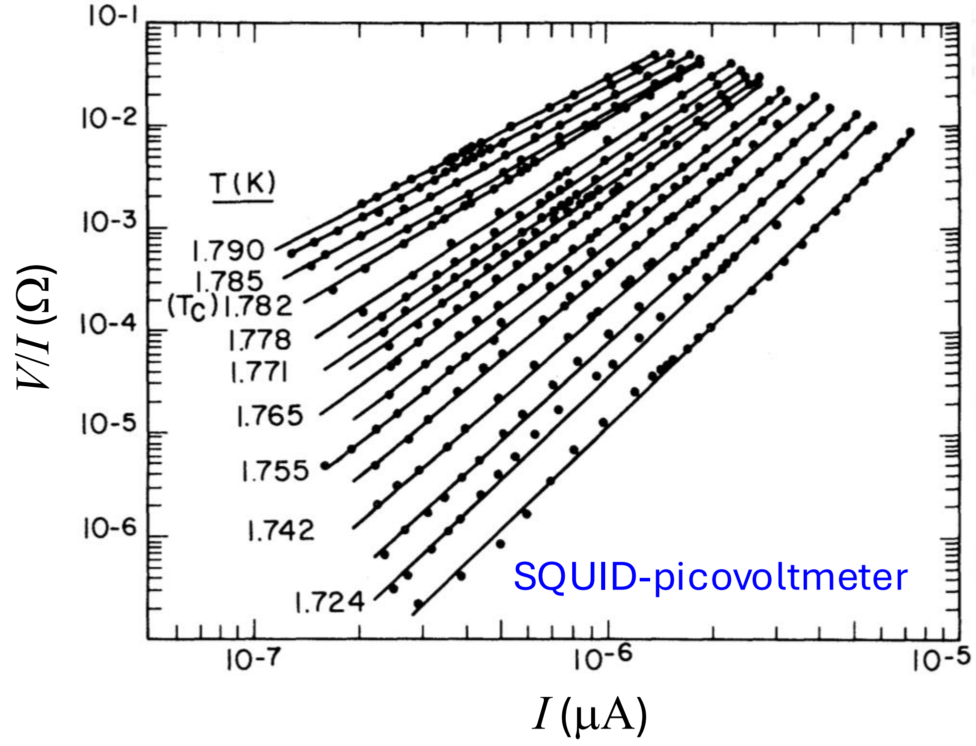
non-linear transport characteristics :

- onset of linear resistance at $T = T_{BKT} < T_{c0}$
- power law behavior of IVs: $V \sim I^{\alpha}$
- power law exponent jumps from α = 1 to 3 at $T = T_{\mathrm{BKT}}$
- Direct relation to superfluid stiffness:

$$\alpha(T) = 1 + \frac{\pi J_s(T)}{T}$$

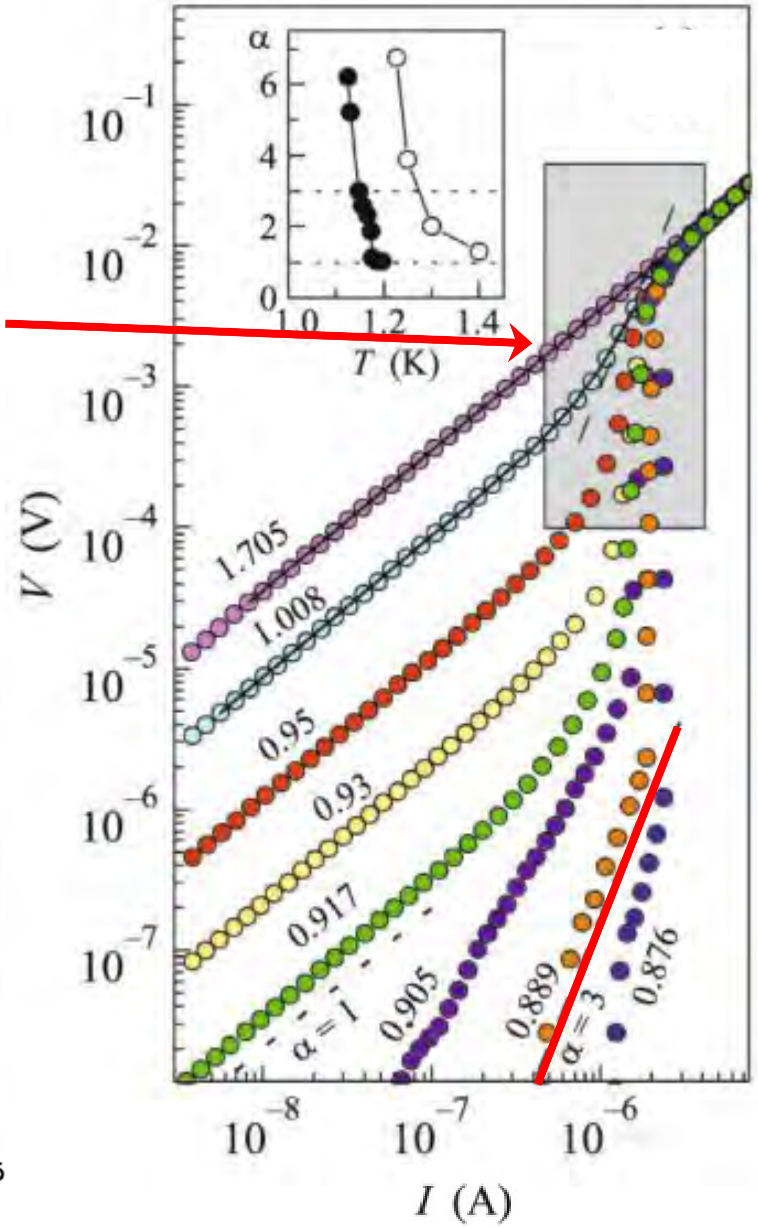
so far very few direct comparisons between $V(I)$ and L_K

Theory:
Ambegaokar, Halperin, Siggia, Nelson
PRL **40**, 783 (1978), PRB **21**, 1806 (1980)



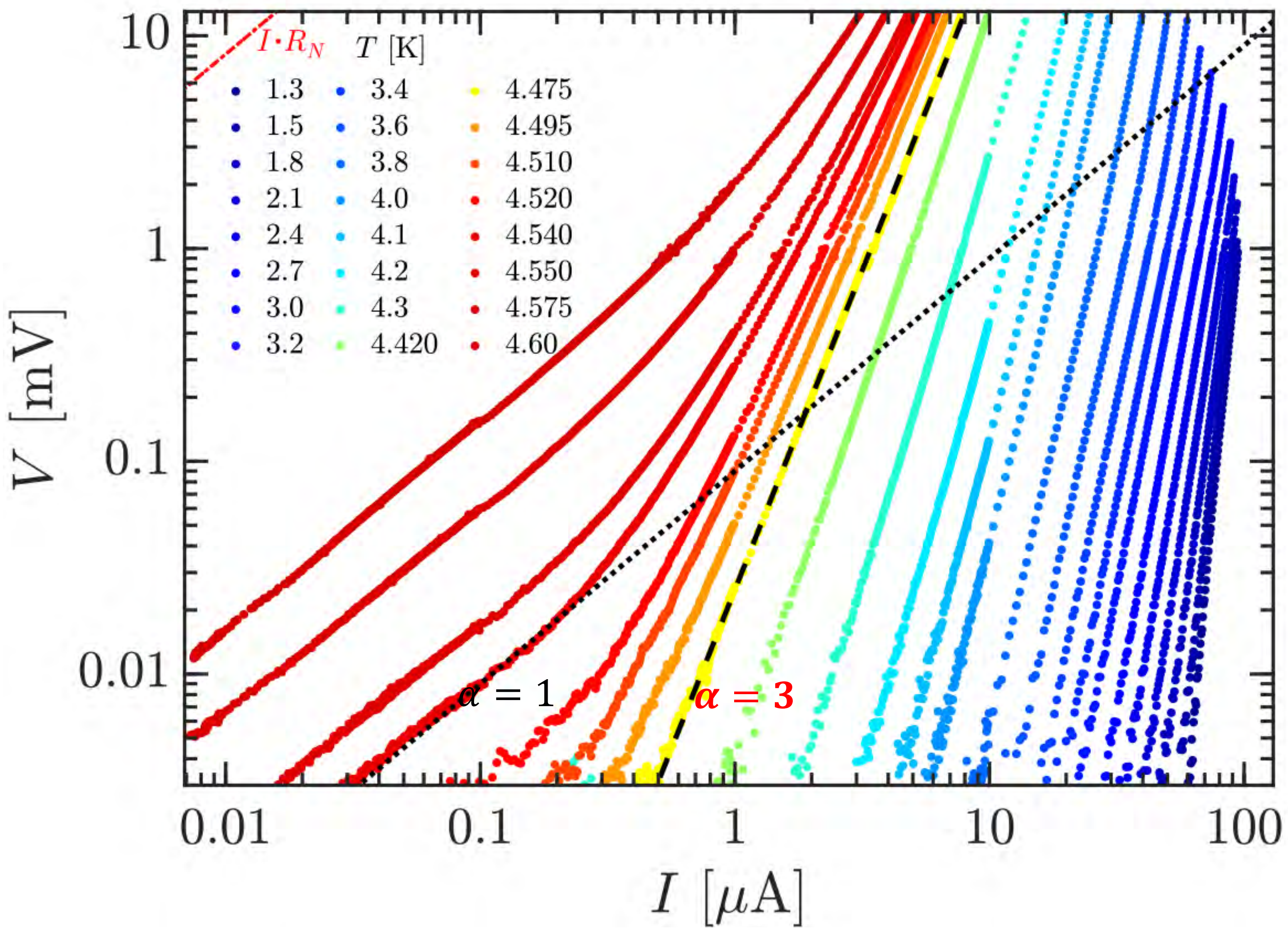
Fiory et al., Phys. Rev. B **28**, 5075 (1983)

electron heating regime!



Postolova et. al, JETP Lett., **100** (2014)

J_s and T_{BKT} from DC IV-characteristics



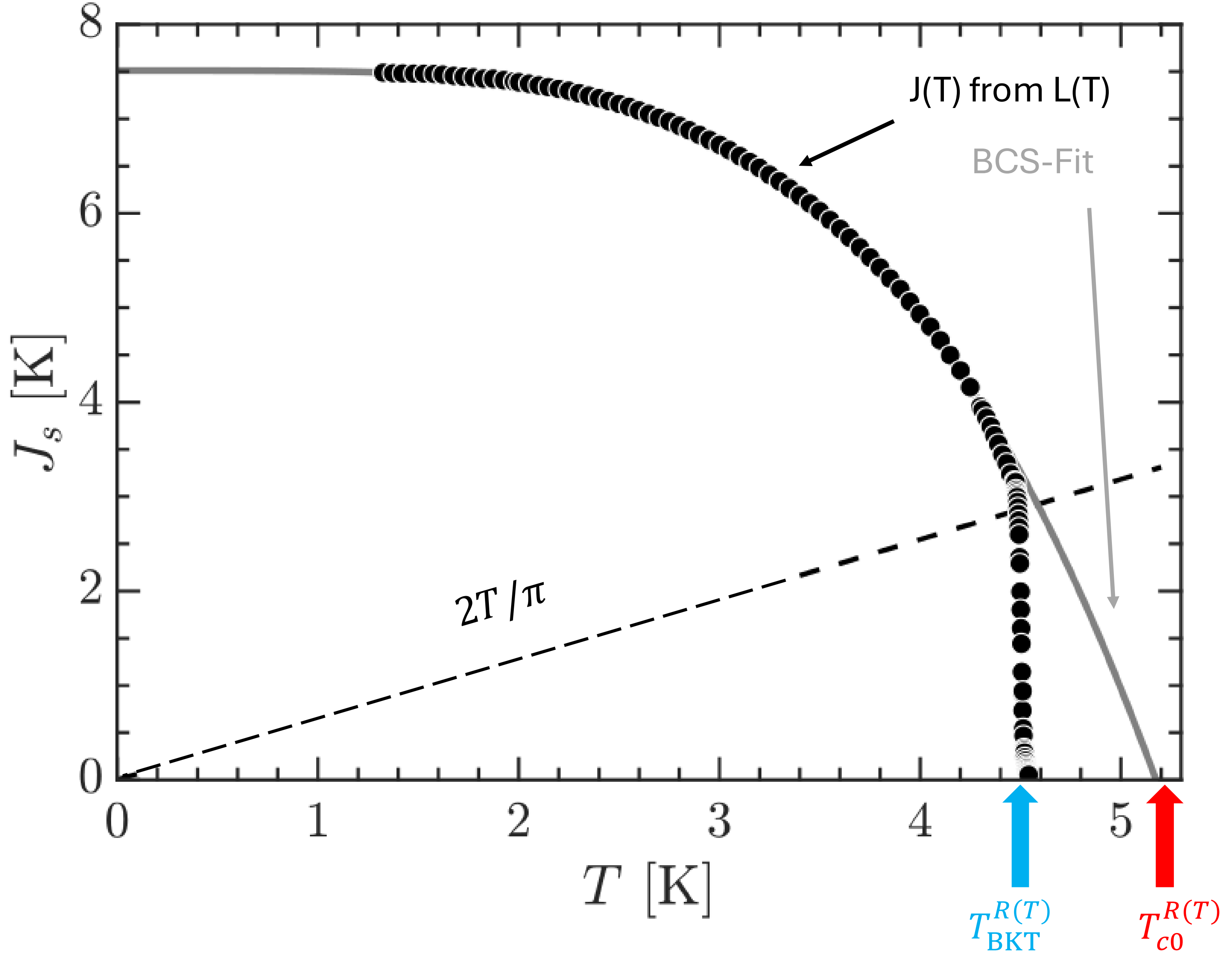
- Fast measurements (~ 2 s) of IV-characteristics to minimize heating
- Power-law behavor over 2-3 orders of magnitude in V
- J_s from power law exponent $\alpha(T)$:

$$\alpha(T) = 1 + \frac{\pi J_s(T)}{T}$$

- Comparison between $R(T)$ and $I(V)$:
  - $T_{\mathrm{BKT}}^{R(T)} = 4.471$ K,
  - $T(\alpha = 3) = 4.475$ K

A. Weitzel, PRL **131**, 186002 (2023)

Temperature dependence of J_s



$$BKT: \quad J_s(T_{BKT}) = \frac{2}{\pi} T_{BKT}$$

$$BCS: \quad J_s(T) = J_0 \frac{\Delta(T)}{\Delta(0)} \tanh\left(\frac{\Delta(T)}{2k_B T}\right)$$

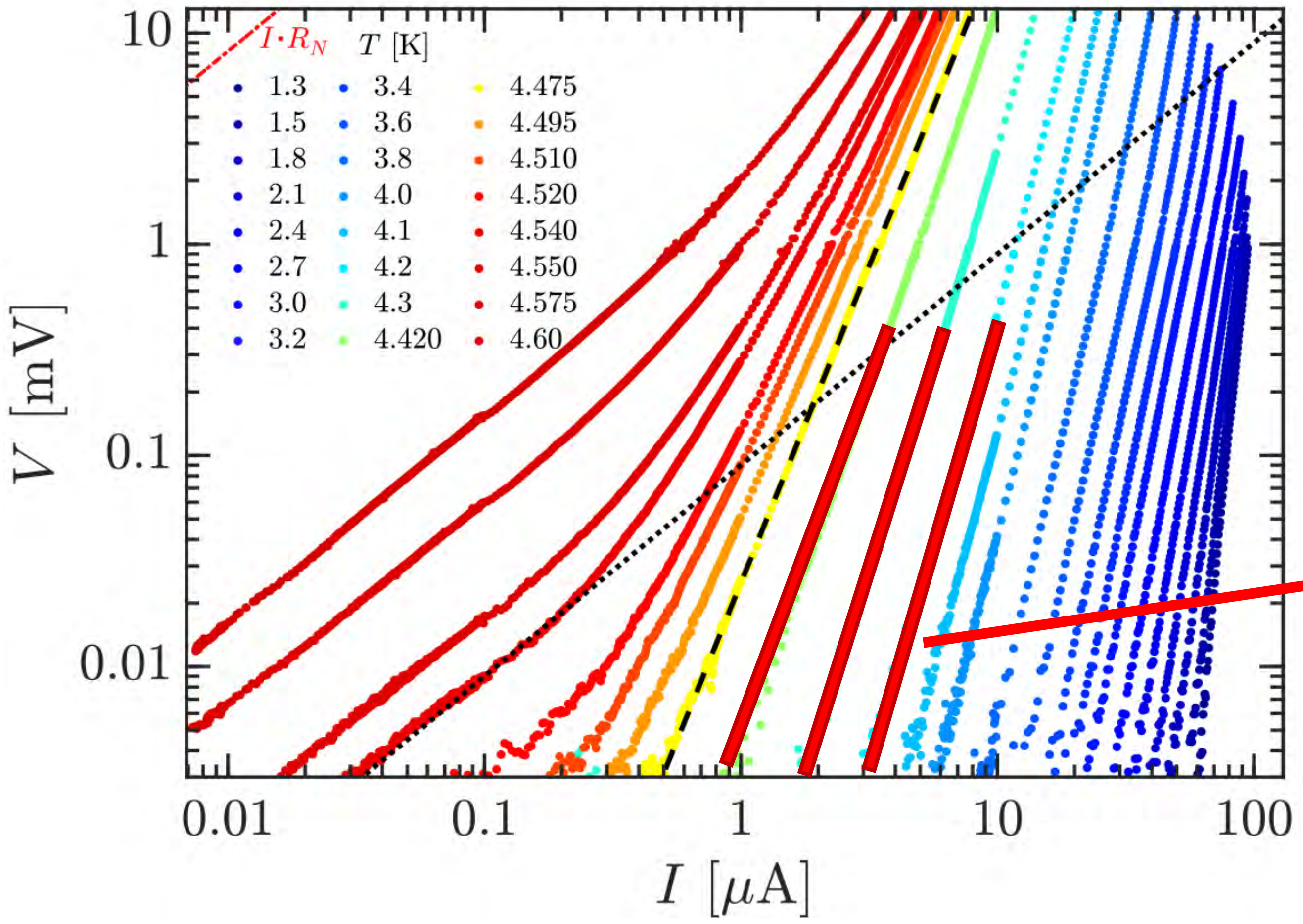
- sharp transition in $J_s(T)$
- excellent agreement between resistive and inductive transition temperatures

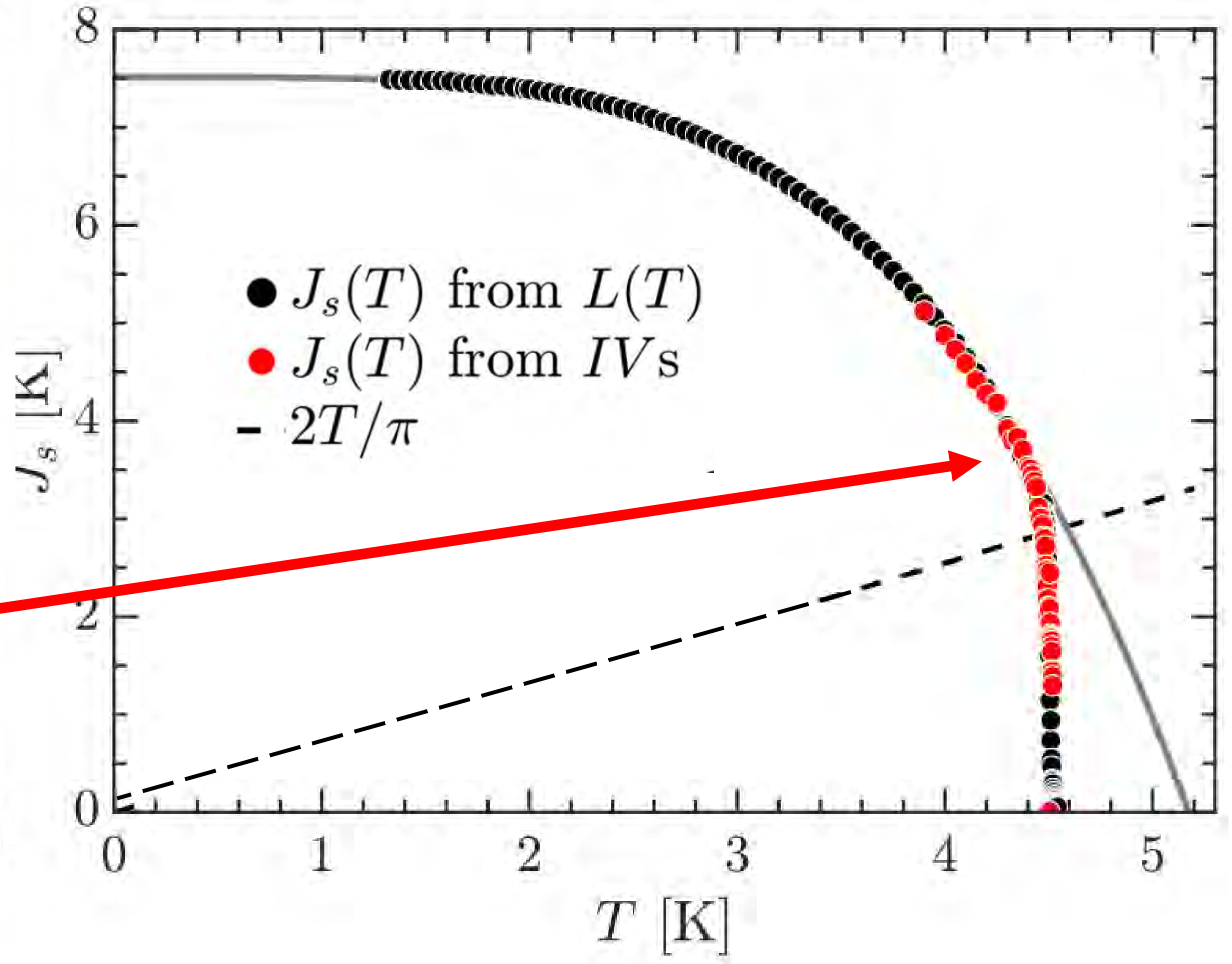
A. Weitzel, PRL **131**, 186002 (2023)

Comparison between $L(T)$ and $I(V)$

$$V(I) = A \cdot I^{\alpha(T)}$$

$$\alpha(T) = 1 + \frac{\pi J_s(T)}{T}$$





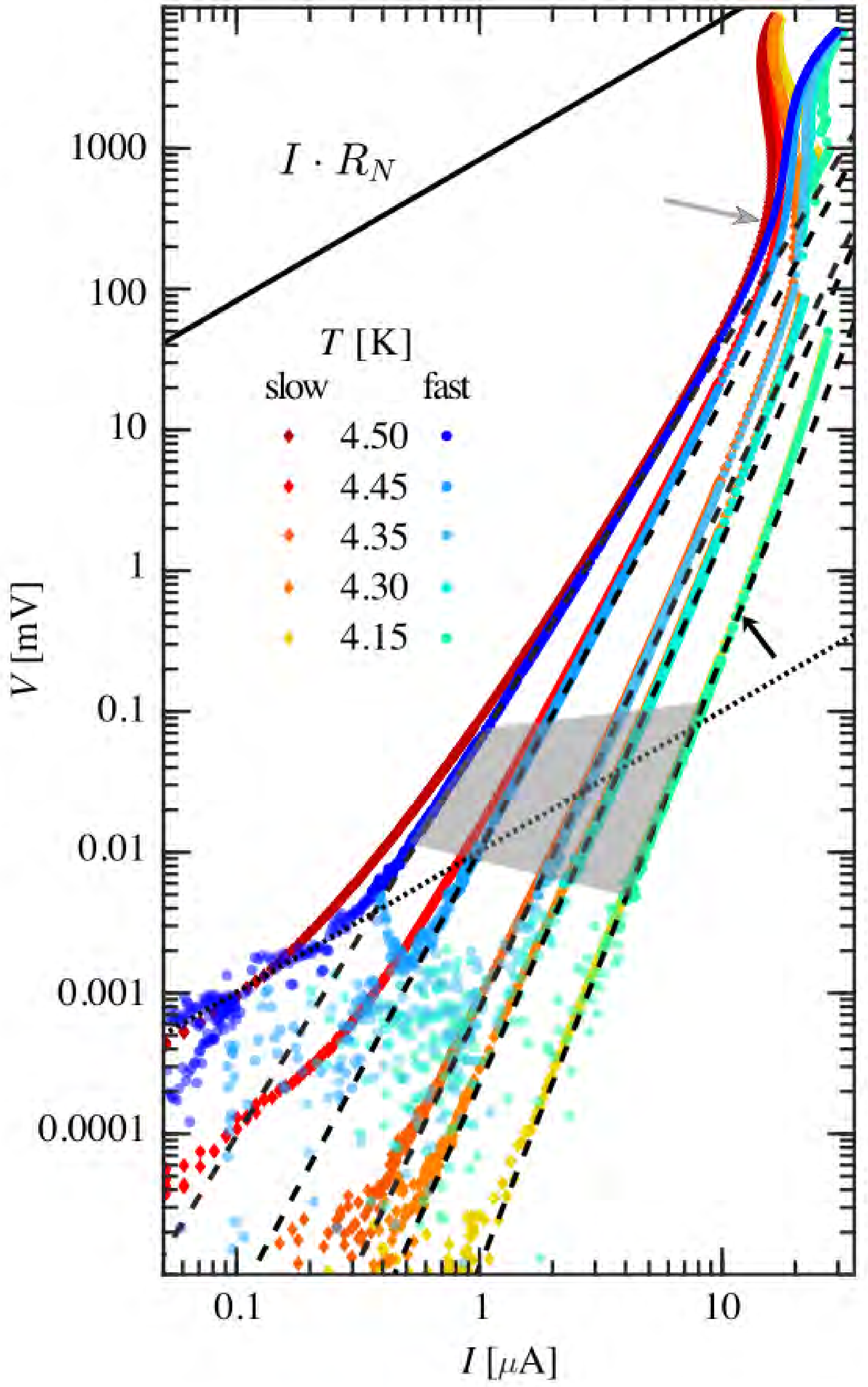
Excellent agreement between $J_s(T)$ from $L(T)$ and $I(V)$

A. Weitzel, PRL **131**, 186002 (2023)

Subtleties of IV characteristics

Comparison between fast (~ 2 s) and slow (~ 10 min):

- „Large“ area of agreement
- At few picowatts:
  electron overheating (black arrow)
- At microwatts: stage heating (grey arrow)
- At low voltage: Ohmic tails



Questions?

Outline

- Localization: suppression of diffusion by disorder

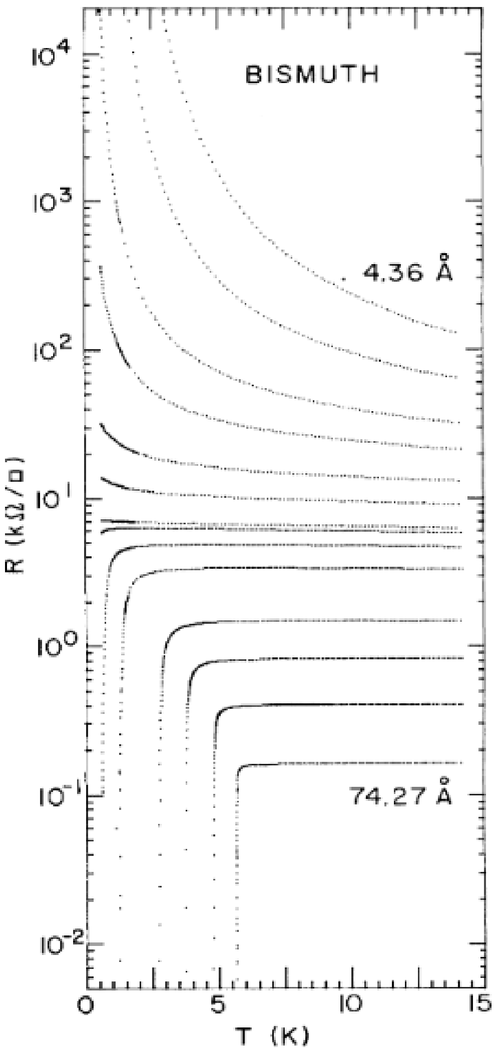
  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity

- Suppression of zero-resistance state by phase fluctuations

- **Suppression of Cooper-pairing by disorder**

From superconductor to insulator, a continuous quantum phase transition ?



Haviland et al., PRL **62** 2180, 1989

Effect of *strong* disorder on the superconducting order parameter

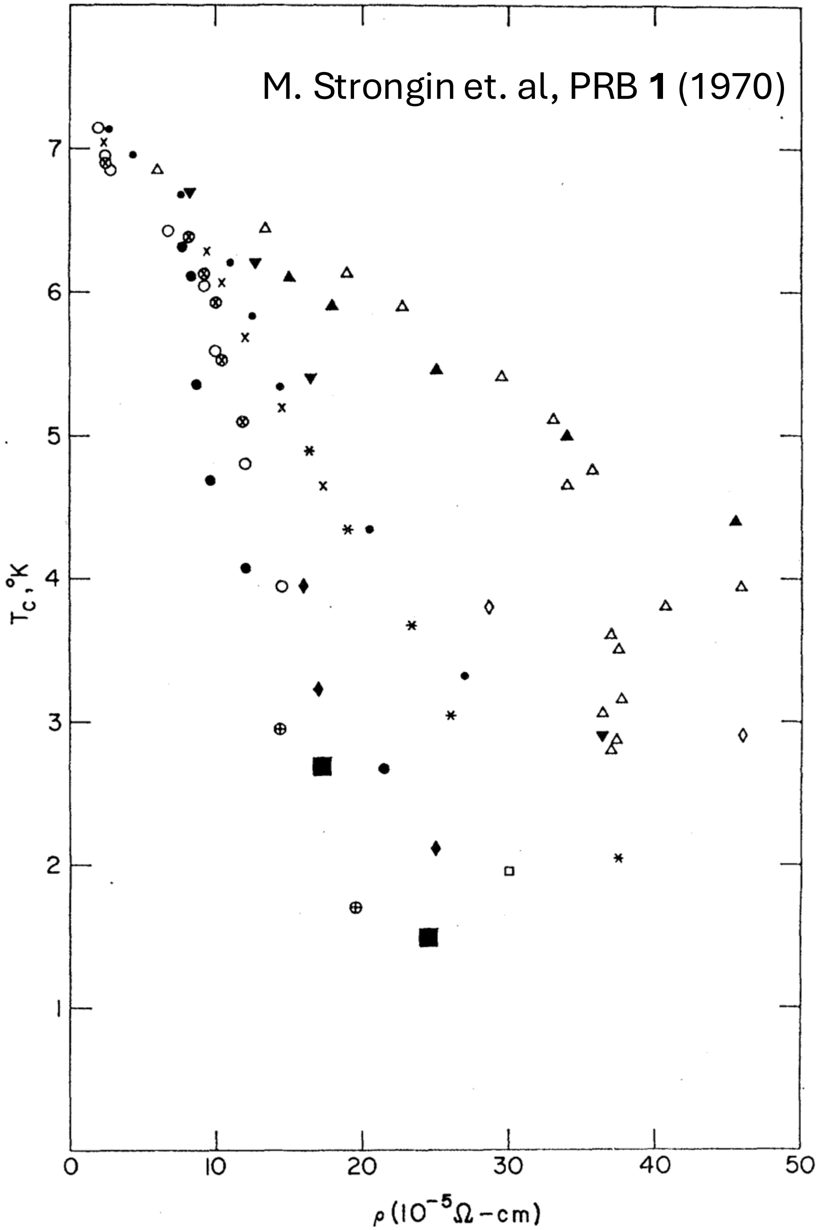
$$\Psi(\boldsymbol{r}) = \Delta(\boldsymbol{r})e^{i\varphi(\boldsymbol{r})}$$

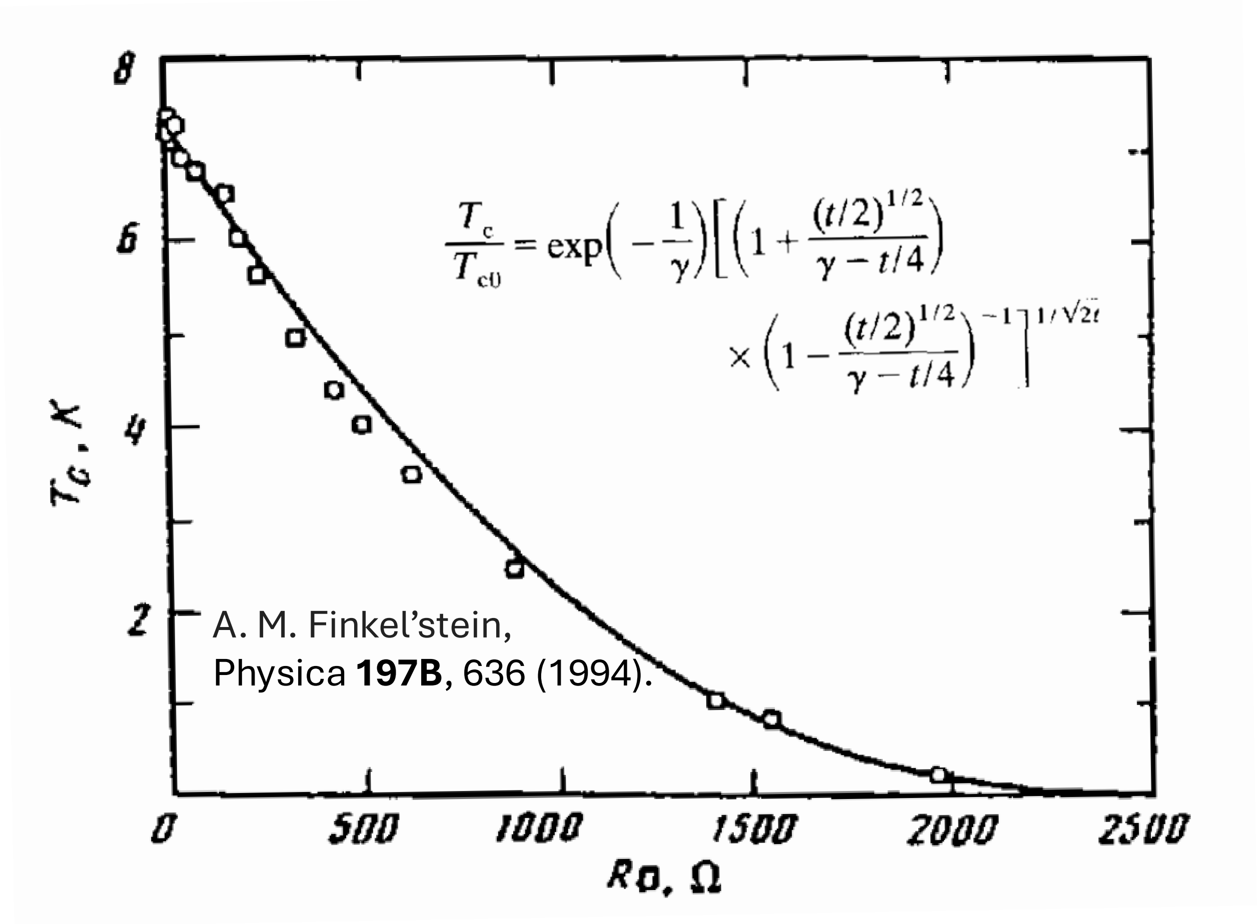
Fermionic route:
suppression of *amplitude* of superconducting order parameter

Bosonic route:
amplitude of order parameter remains finite,
but phase fluctuations destroy superfluid *phase stiffness*

Fermionic approach

Enhancement of Coulomb interaction suppresses electron screening and thus pairing amplitude $\Delta(T)$ and mean field T_c





A. M. Finkel'stein, Physica **197B**, 636 (1994)

parameters t and γ are related to Drude scattering time and electron density

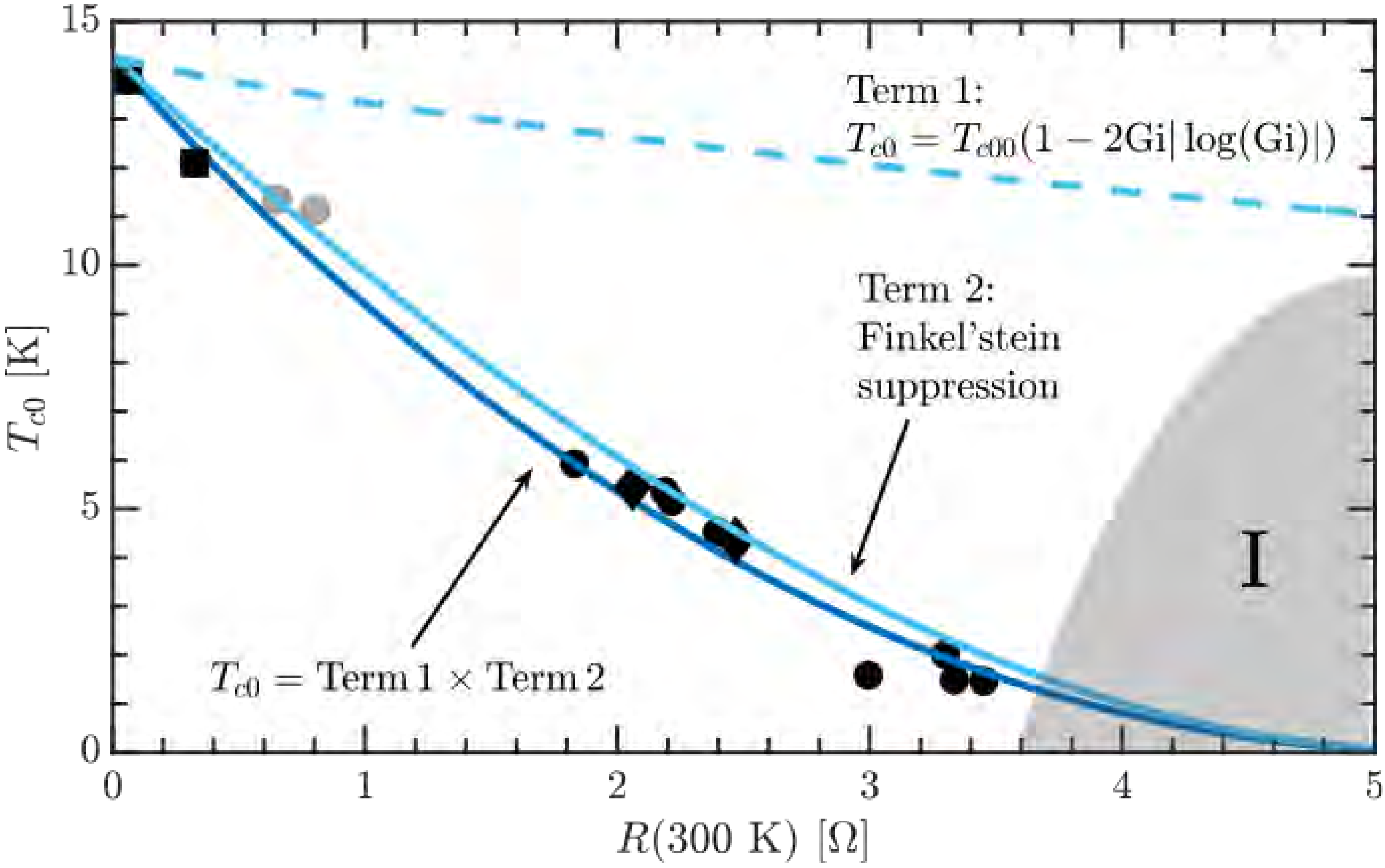
Fermionic approach

Enhancement of Coulomb interaction suppresses pairing amplitude $\Delta(T)$ and T_{c0}

Monotonic suppression of T_{c0} , but no SIT expected from this theory

Data NbN:

(A. Weitzel, UR)



A. M. Finkel'stein, Physica **197B**, 636 (1994)

Outline

- Localization: suppression of diffusion by disorder

  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity
- Suppression of zero-resistance state by phase fluctuations
- Suppression of Cooper-pairing by disorder
- **Direct superconductor-insulator transition**

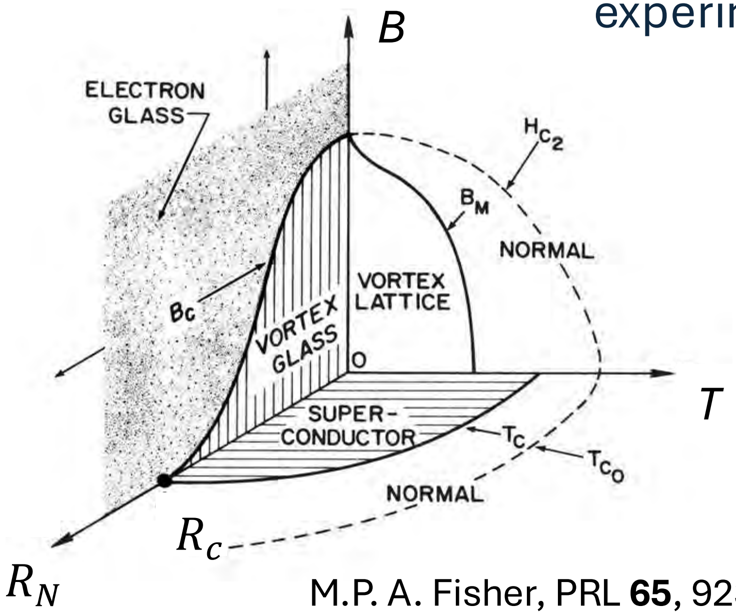
Bosonic approach

Continous quantum phase transition between a **vortex glass phase** (superconducting) and a **Cooper-pair glass phase** (insulating), characterized by:

- diverging coherence length: $\xi \propto |R_c - R_N|^{-\nu}$
- vanishing characteristic energy: $T_{\mathrm{BKT}} \propto \xi^{-z} \propto |R_c - R|^{z\nu}$
- phase transition at $T = 0$ in magnetic field: $B_c \propto |R_c - R|^{2\nu}$

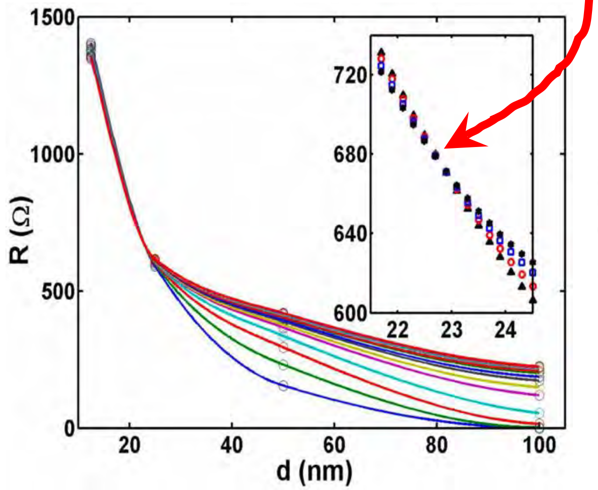
$$\left.\begin{matrix} T_{\mathrm{BKT}} \propto \xi^{-z} \propto |R_c - R|^{z\nu} \\ B_c \propto |R_c - R|^{2\nu} \end{matrix}\right\} \quad B_c \propto T_{\mathrm{BKT}}^{2/z}$$

- universal scaling behavior in magnetic feld: $R_\square = \frac{h}{4e^2} f\left(|B - B_c|/T^{1/z_B\nu_B}\right)$

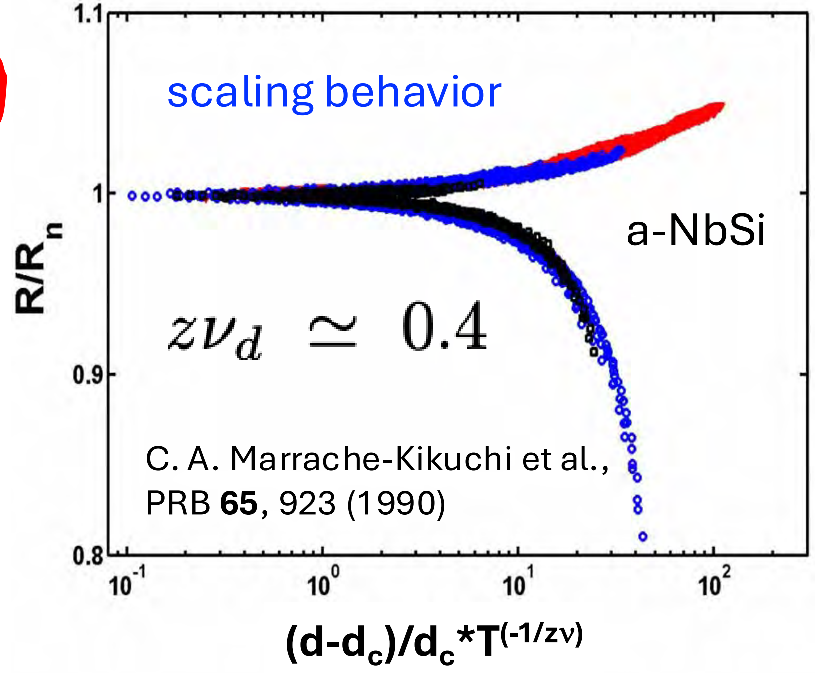


M.P. A. Fisher, PRL **65**, 923 (1990)

experimental signature: crossing points



in resistance isotherms

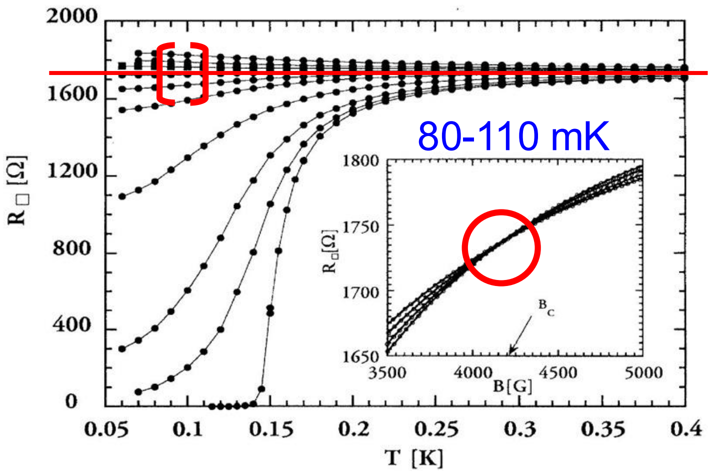


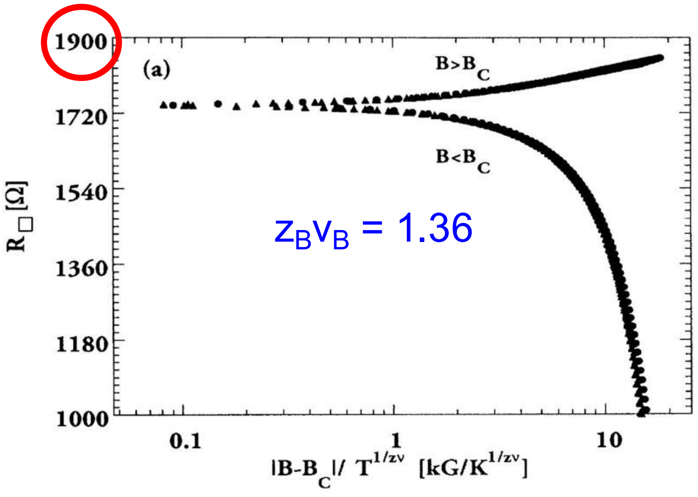
C. A. Marrache-Kikuchi et al., PRB **65**, 923 (1990)

Bosonic approach

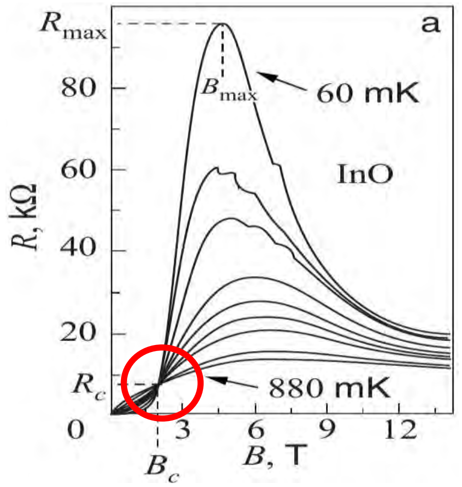
scaling behavior in magnetic field

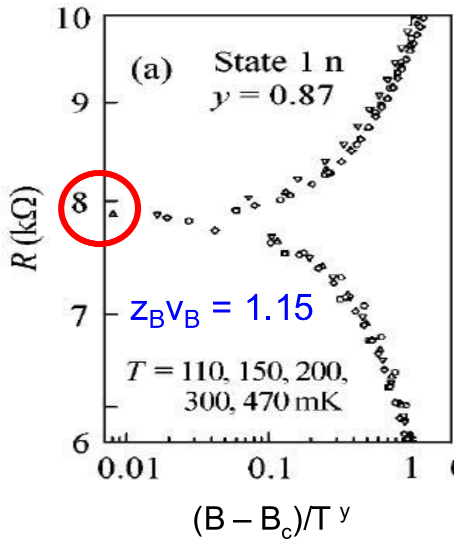
Amorphous MoGe
A. Yazdani and A. Kapitulnik
Phys. Rev. Lett. **74**, 3037 (1995)





Amorphous InO_x
V.F. Gantmakher et al.,
JETP **71**, 473 (2000)





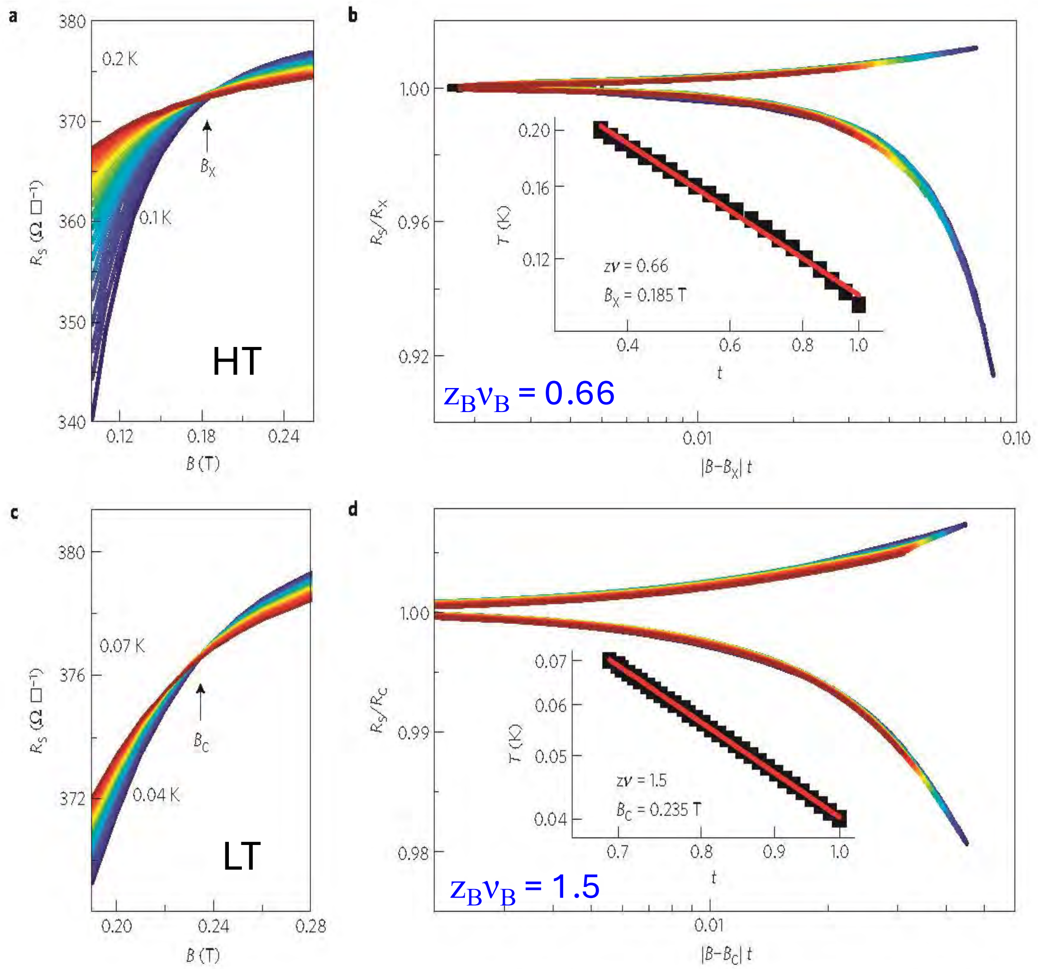
Questions:

- what is an insulator?
- what about about highly insulating states?
- how universal is the scaling?
- how significant is it?

ARTICLES
PUBLISHED ONLINE: 14 APRIL 2013 | DOI: 10.1038/NMAT3624
nature materials

Multiple quantum criticality in a two-dimensional superconductor

J. Biscaras[1], N. Bergeal[1], S. Hurand[1], C. Feuillet-Palma[1], A. Rastogi[2], R. C. Budhani[2,3], M. Grilli[4], S. Caprara[4] and J. Lesueur[1]*

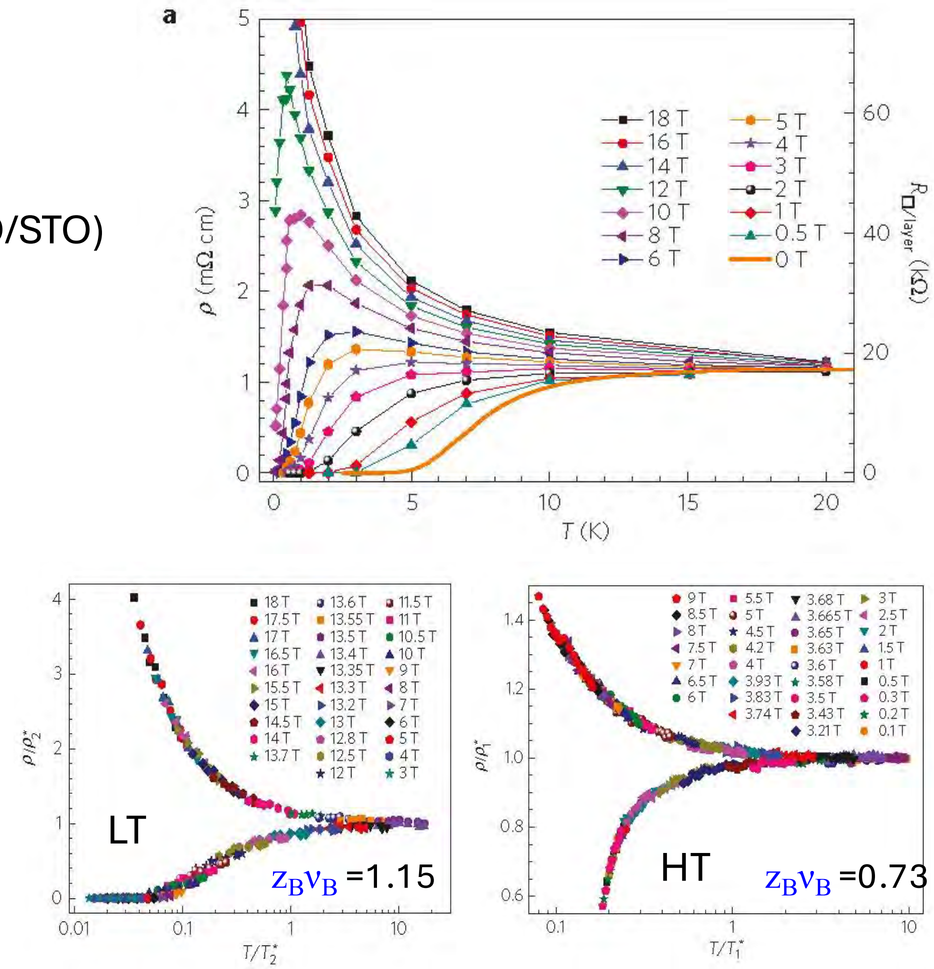


nature physics
ARTICLES
PUBLISHED ONLINE: 4 MAY 2014 | DOI: 10.1038/NPHYS2961

Two-stage magnetic-field-tuned superconductor–insulator transition in underdoped $La_{2-x}Sr_xCuO_4$

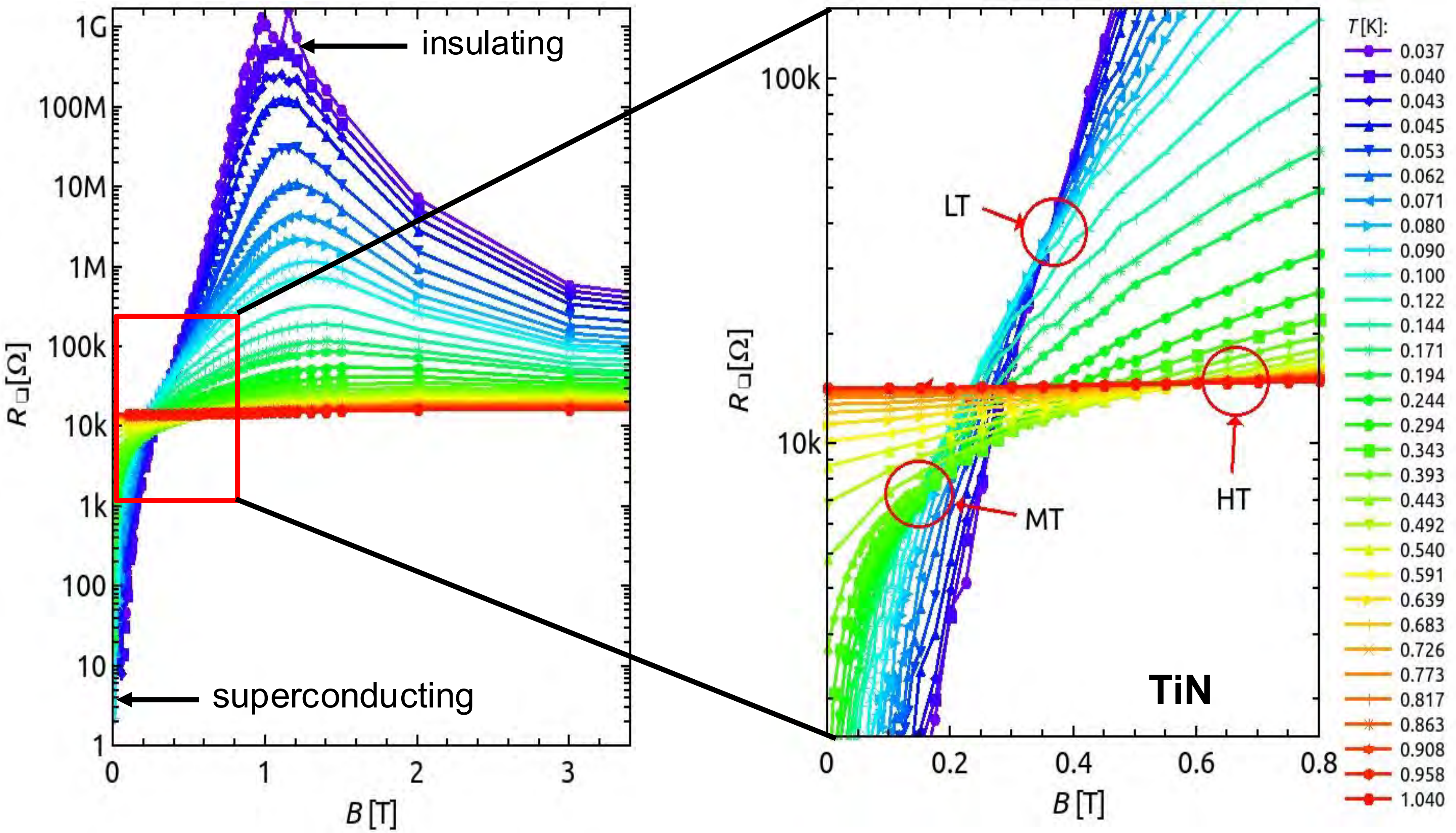
Xiaoyan Shi[1†], Ping V. Lin[1], T. Sasagawa[2], V. Dobrosavljević[1] and Dragana Popović[1]*

(LTO/STO)



Bosonic route

scaling behavior in magnetic field



three crossing points, where R(B)s intersect!

Questions:

- what is an insulator?
- what about about highly insulating states?
- how universal is the scaling?
- how significant is it?

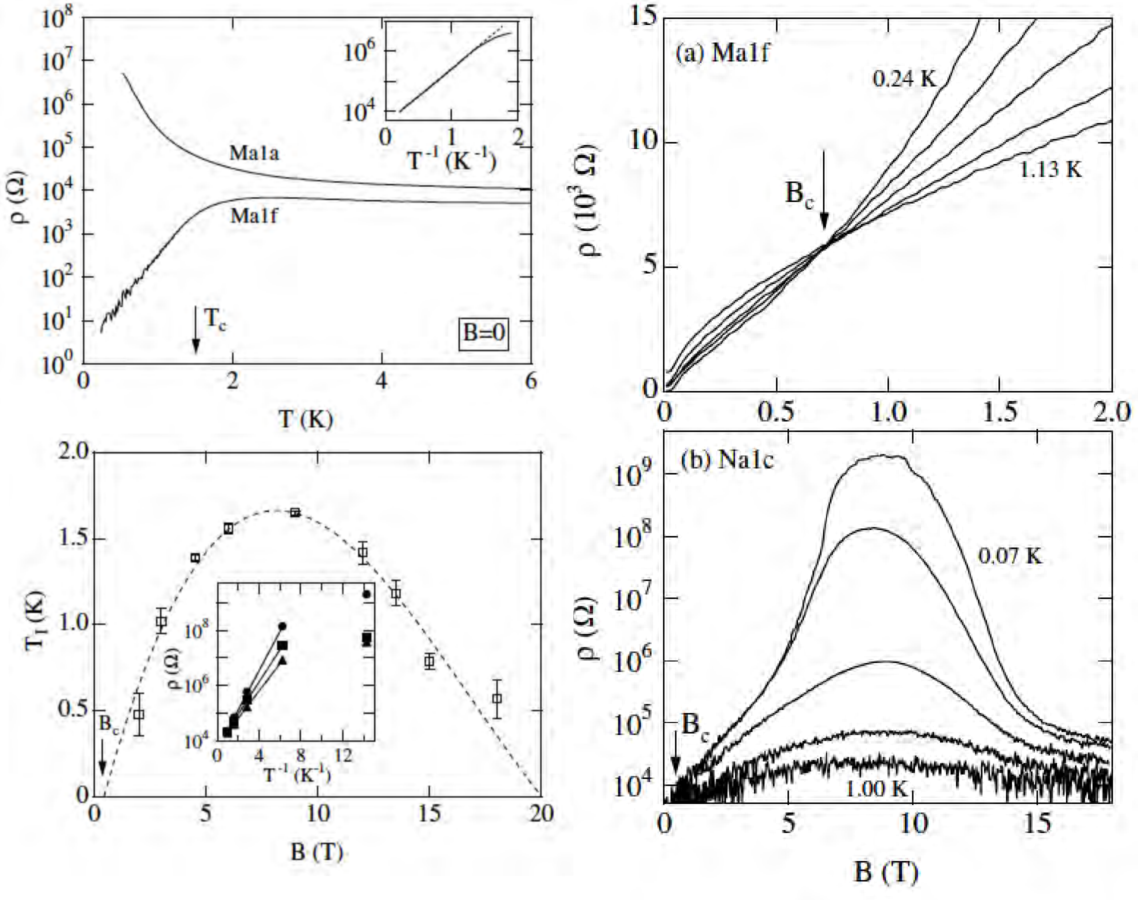
K. Kronfeldner, T. I. Baturina, and C. S., Phys. Rev. B **103**, 184512 (2021)

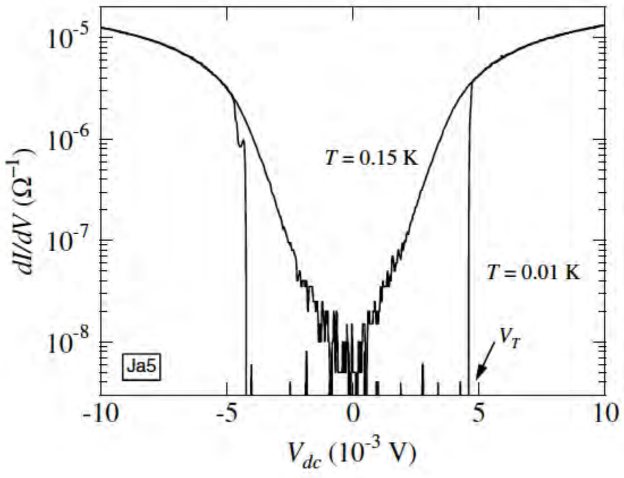
Direct superconductor/insulator transition
with Arrhenius-like conductance on the insulating side

G. Sambandamurthy, D. Shahar, et al.,
Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors
Phys. Rev. Lett. **94**, 017003 (2005)

G. Sambandamurthy, D. Shahar, et al.
Superconductivity-Related Insulating Behavior
Phys. Rev. Lett. **92**, 107005 (2004)

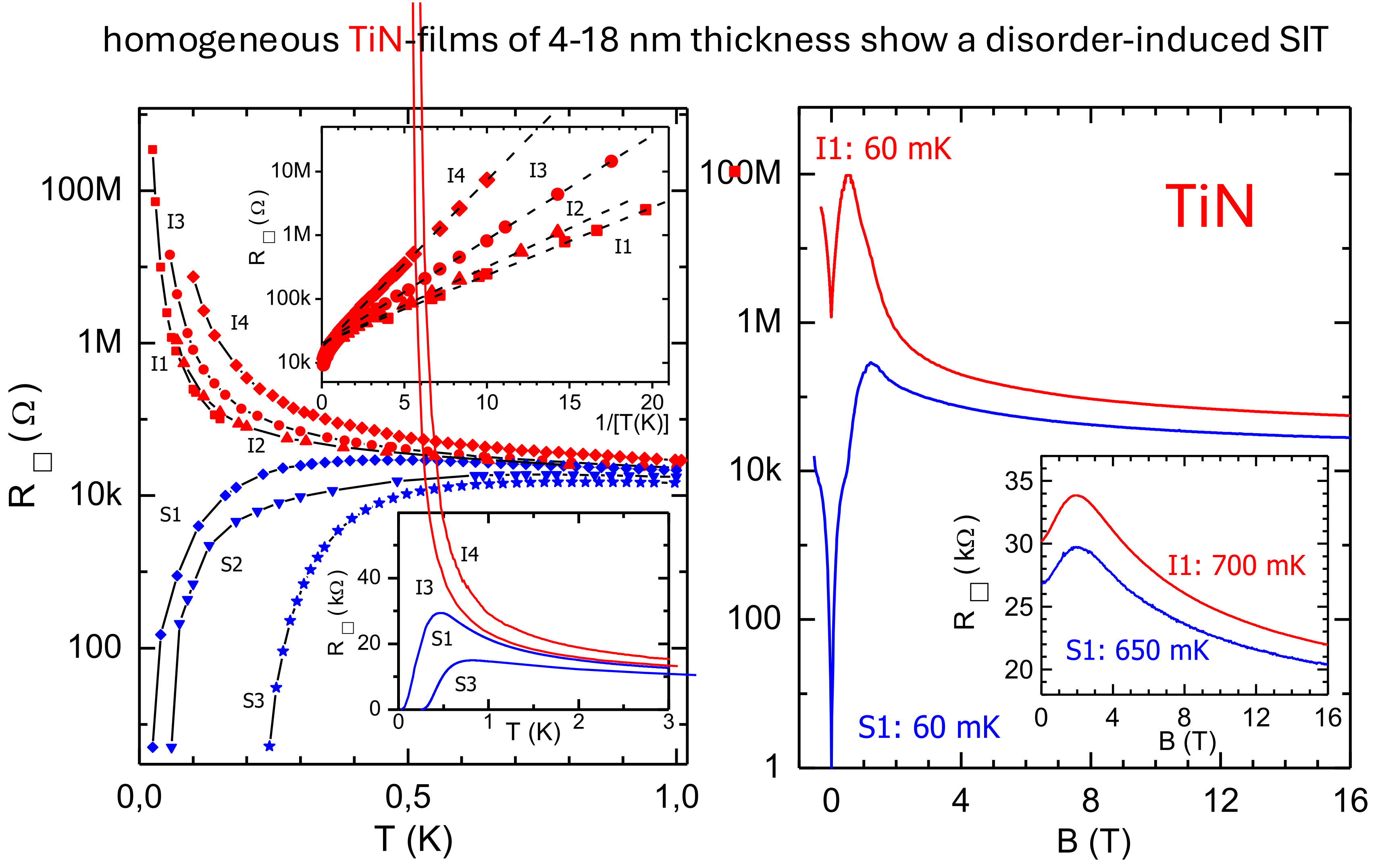
InO_x





Direct superconductor/insulator transition
with Arrhenius-like conductance on the insulating side

homogeneous TiN-films of 4-18 nm thickness show a disorder-induced SIT



T. Baturina, C.S. et al., PRL **99**, 257003 (2007)

Qualitatively similar behavior for insulating and superconducting films

Exponential decay of magneto-resistance at high fields:
gradual suppression of superconducting OP

Very similar behavior of insulating and superconducting films for T > 600 mK

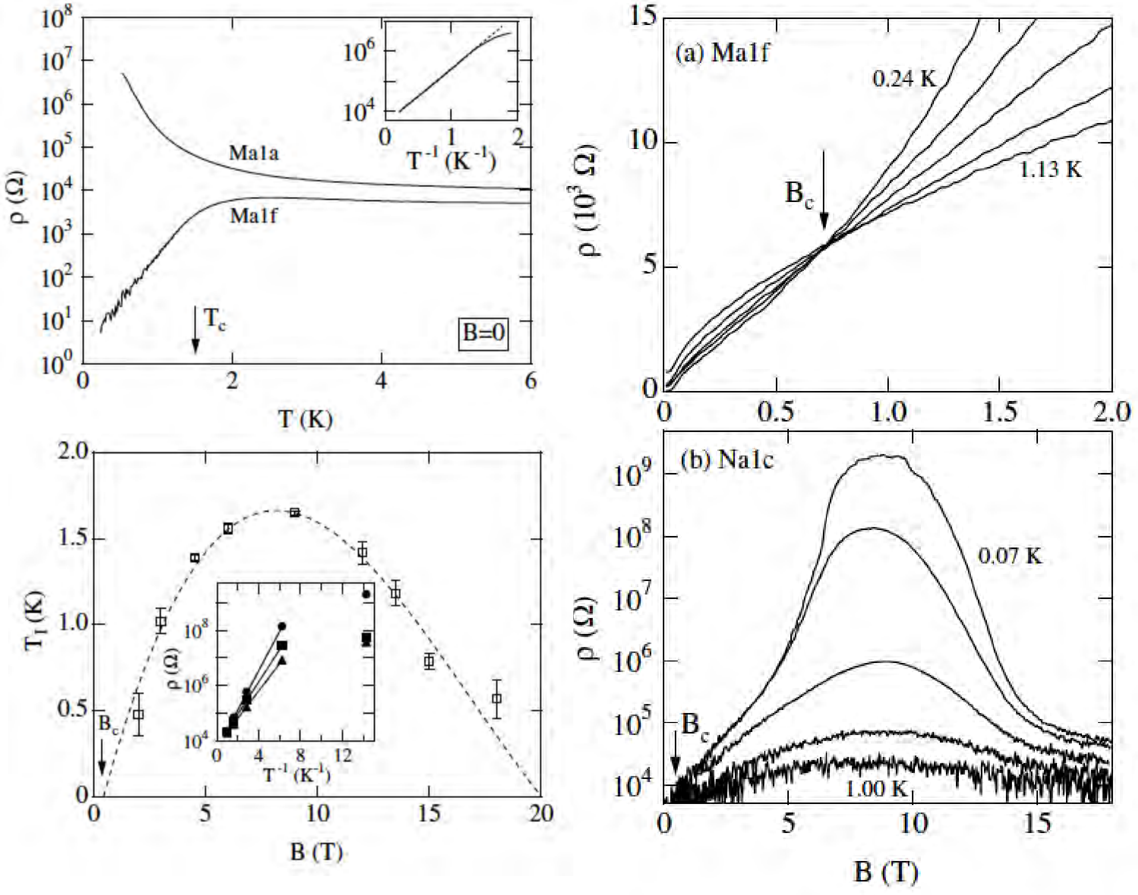
Superconductivity important for insulating behavior ?!

quasi-metallic phase at high B

low B:
‚Cooper-pair' - insulator !

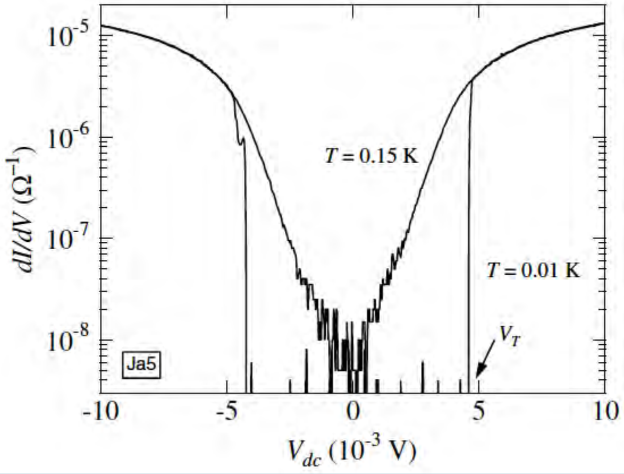
Direct superconductor/insulator transition
with Arrhenius-like conductance on the insulating side

G. Sambandamurthy, D. Shahar, et al.
Superconductivity-Related Insulating Behavior
Phys. Rev. Lett. **92**, 107005 (2004)



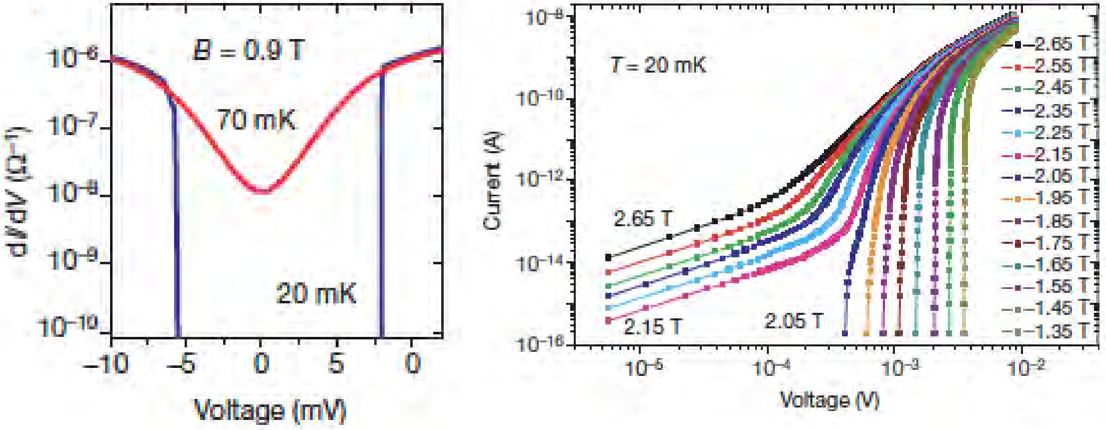
G. Sambandamurthy, D. Shahar, et al.,
Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors
Phys. Rev. Lett. **94**, 017003 (2005)

InO_x

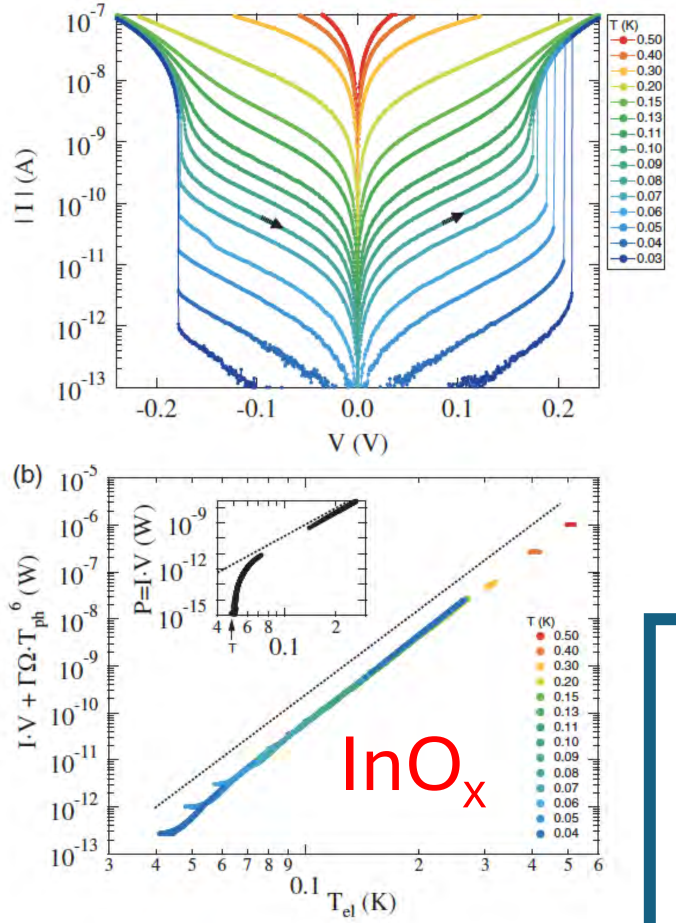


V. M. Vinokur, T. I. Baturina, C. Strunk, et al.
Superinsulator and quantum synchronization
Nature **452**, 613 (2008)

TiN



Alternative theory for jumps in $I(V)$ and the nature of the insulating state

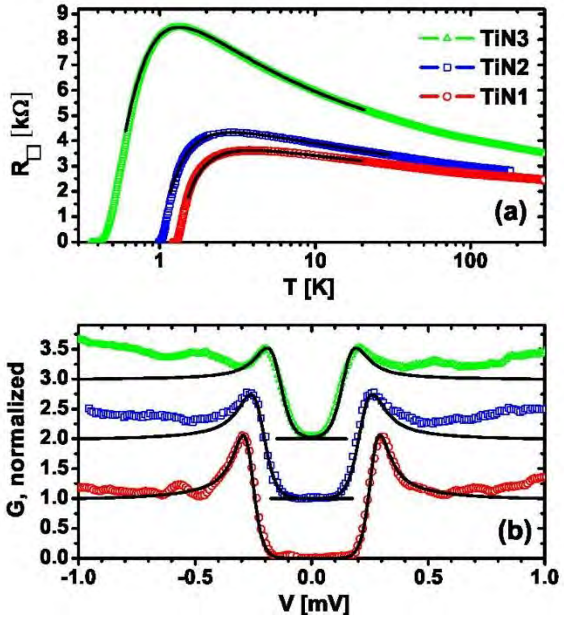


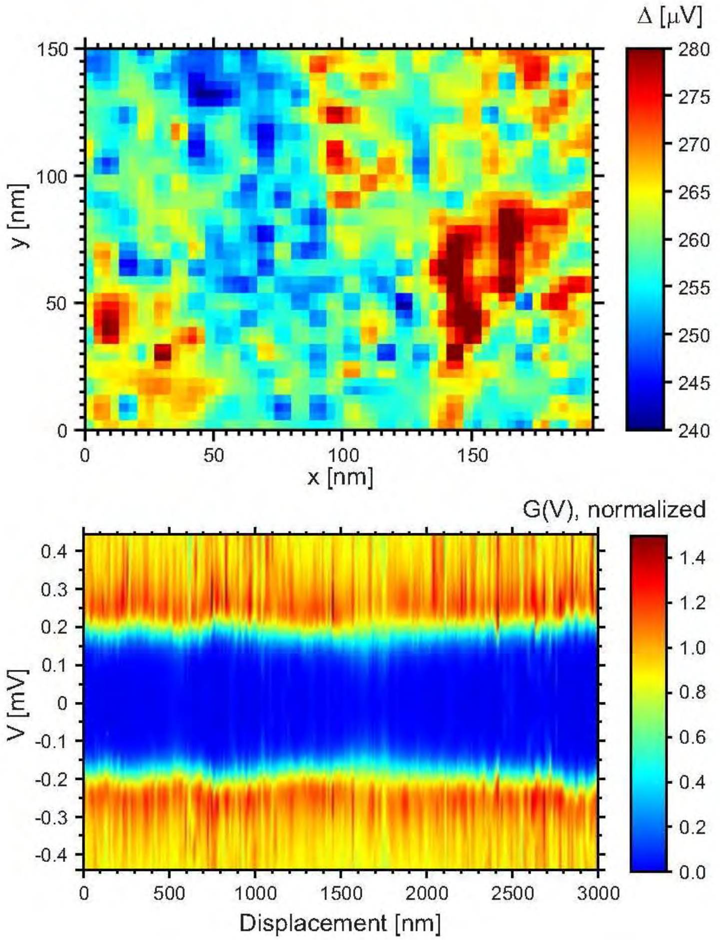
Assumptions:

- $I(V)$ is intrisically linear
- T_{el} decouples from T_{ph} and is determined from heat balance equation:

$$\frac{V^2}{R(T_{el})} = \Gamma\Omega(T_{el}^{\beta} - T_{ph}^{\beta})$$

- $R(T)$ varies fast enough





M. Ovadia, B. Sacépé, D. Shahar
Electron-Phonon Decoupling in Disordered Insulators
Phys. Rev. Lett. **102**, 176802 (2009)

B. Altshuler, V. Kravtsov, I. Lerner, I. Aleiner,
Jumps in Current-Voltage Characteristics in Disordered Films
Phys. Rev. Lett. **102**, 176803 (2009).

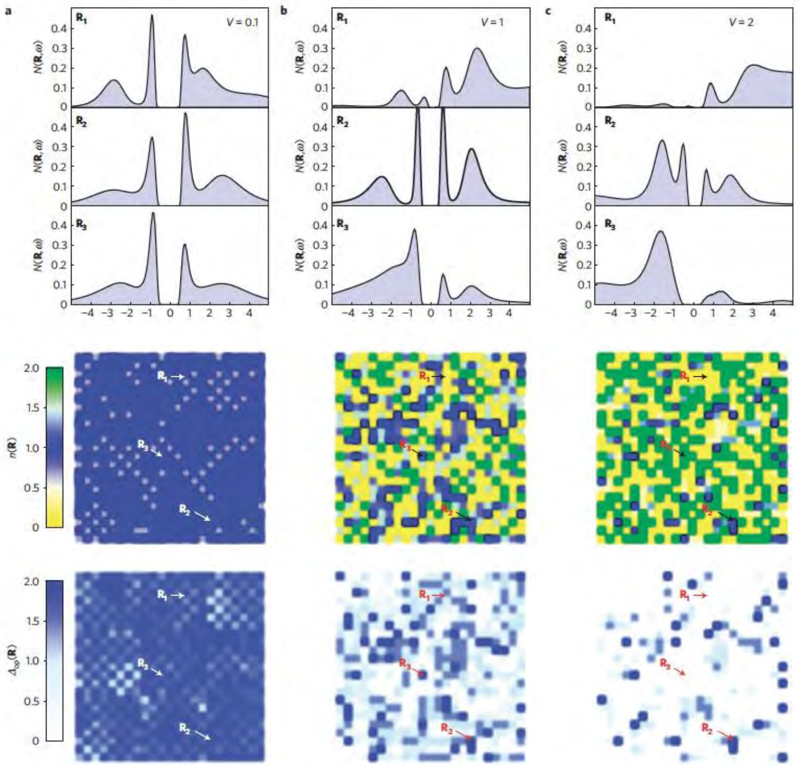
B. Sacepe, C. Chapelier, T. I. Baturina, V.M. Vinokur, M.R. Baklanov, M. Sanquer
Disorder-Induced Inhomogeneities of the Superconducting State Close to the Superconductor-Insulator Transition
Phys. Rev. Lett. **101**, 157006 (2008)

Emergent granularity of the SC order parameter

local DoS

electron density

local pairing amplitude

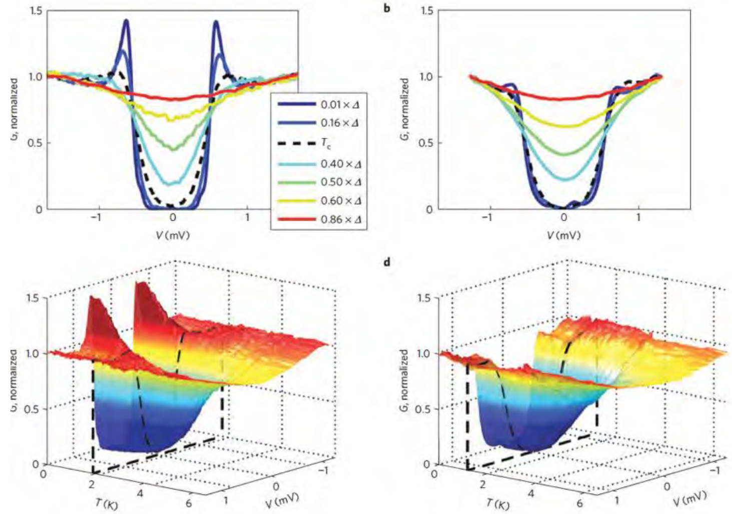


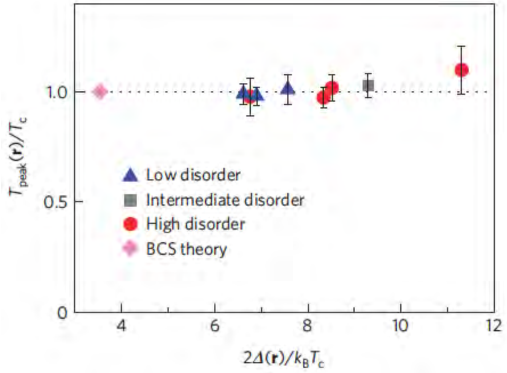
- Theory predicts correlation between onset of coherence peaks in spectra and zero resistance state:
- SIT is driven by the increase of incoherent pairs at the expense of the condensate.
- Close to the transition, on the superconducting side, Δ strongly fluctuates, indicating a spontaneously formed inhomogeneity.
- On the insulating side, the transport is dominated by incoherent Cooper pair hopping.

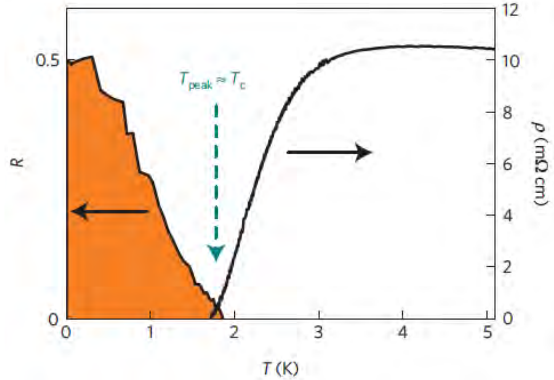
See: A. Ghosal, M. Randeria, N. Trivedi,
Inhomogeneous pairing in highly disordered s-wave superconductors
PRL **81**, 3940 (1998), PRB **65**, 014501 (2001).

K. Bouadim, Y. L. Loh, M. Randeria, N. Trivedi,
Single- and two-particle energy gaps across the disorder-driven superconductor–insulator transition
Nat. Phys. **7**, 884 (2011)

Experiment:

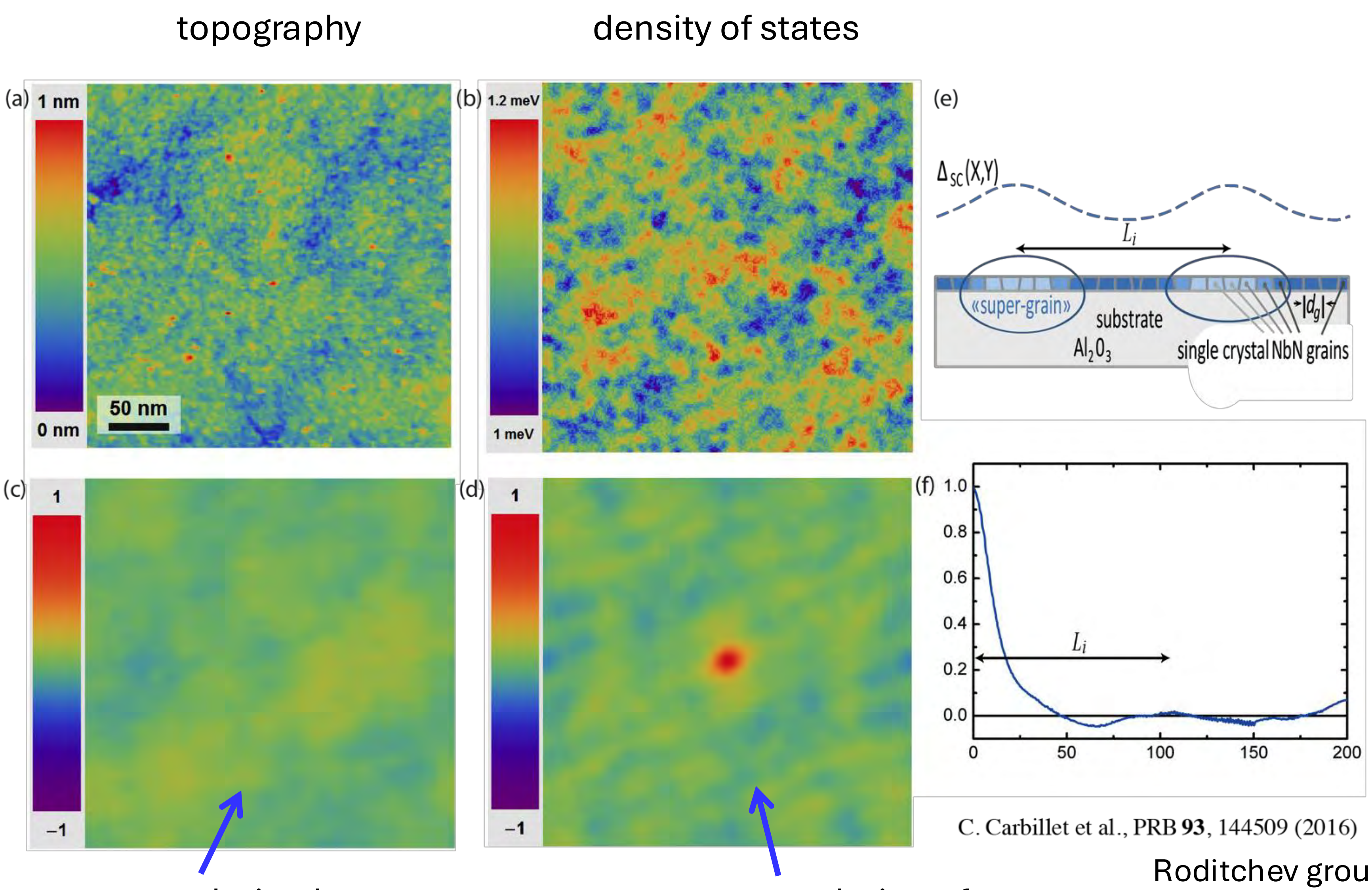






B. Sacépé, T. Dubouchet, Chapelier, M. Sanquer, M. Ovadia, D. Shahar, M. Feigel'man, L. Ioffe
Localization of preformed Cooper pairs in disordered superconductors
Nat. Phys. **7**, 239 (2011)

Emergent granularity in NbN thin films



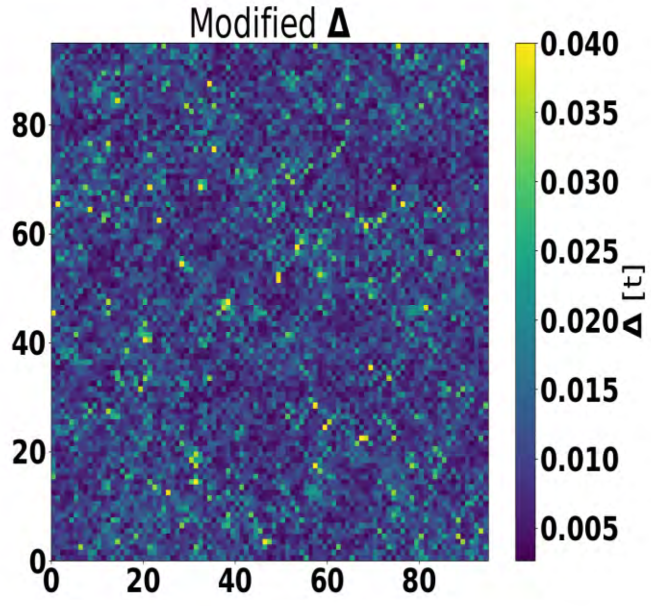
no cross-correlation between topography and electronic granularity

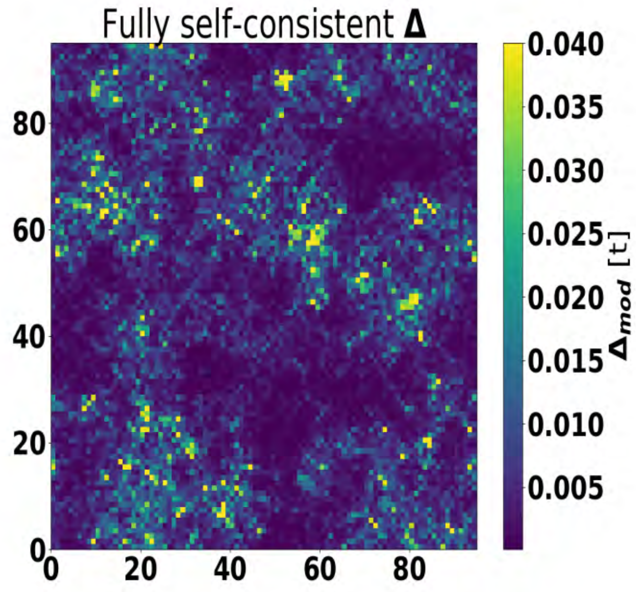
auto-correlation of electronic granularity

C. Carbillet et al., PRB **93**, 144509 (2016)

Roditchev group, INSP Paris

Numerical calculation of Δ(r) in presence of strong disorder





Pairing amplitude in real space the for a specific disorder configuration on a 96x96 lattice:

simplified self-consistency scheme

following Feigel'man, Ioffe, Kravtsov, Cuevas, Ann. Phys. 325, 1368 (2010)

fully self-consistent scheme

(see also Bouadim et al., Nat. Phys. 2011)

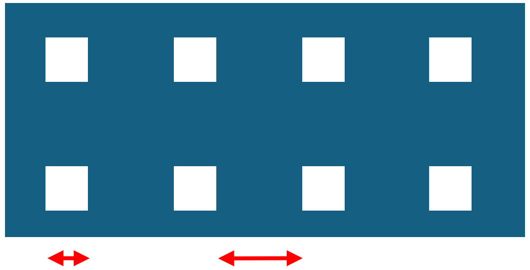
(same disorder and parameter configuration, phase fluctuations neglected)

calculations by M. Stosiek, F. Evers

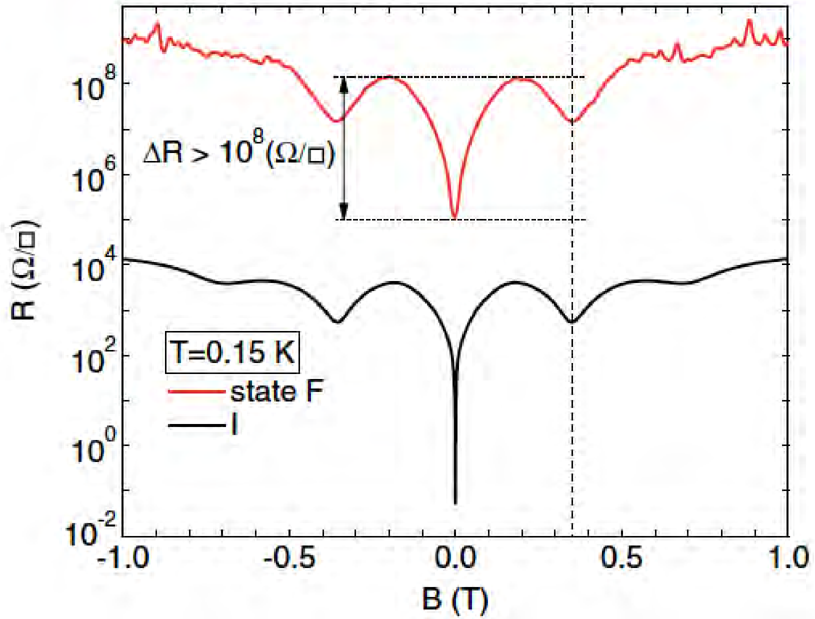
Direct superconductor/insulator transition
with Arrhenius-like conductance on the insulating side

G. Kopnov, O. Cohen, M. Ovadia, K. H. Lee, C. C. Wong, D. Shahar
Little-Parks Oscillations in an Insulator
Phys. Rev. Lett. **109,** 167002 (2012)

nano-perforated InO_x - film

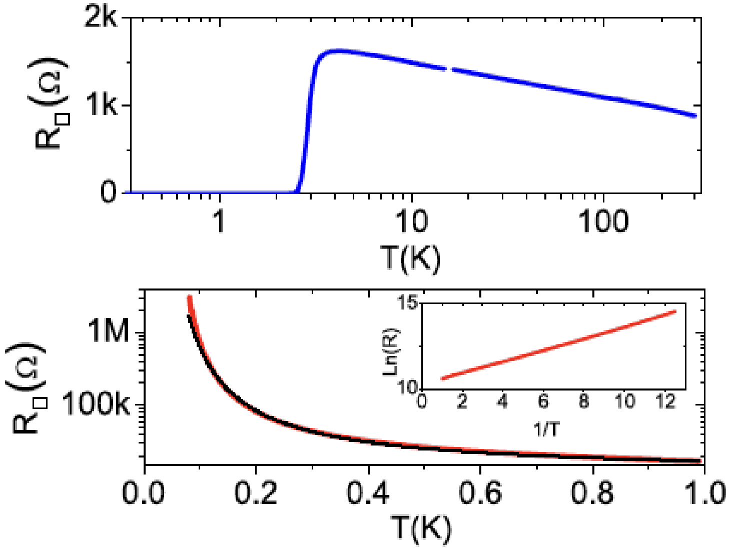


Evidence for
fluxoid quantization
in the insulating state



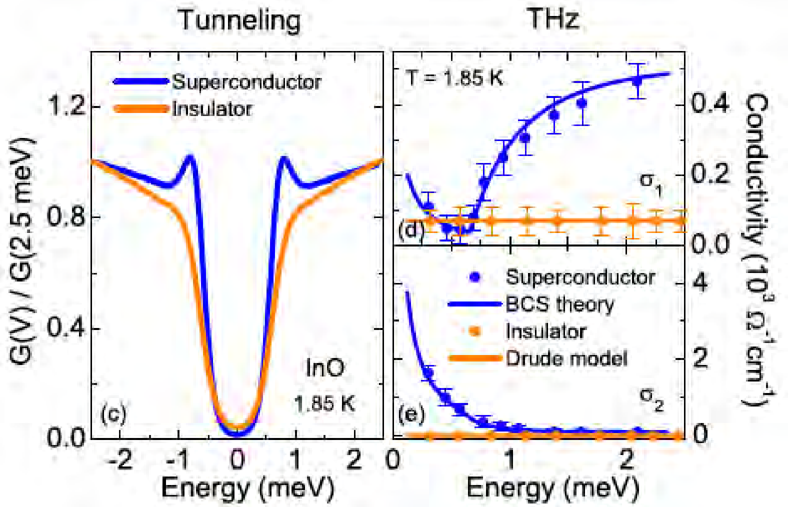
D. Sherman, G. Kopnov, D. Shahar, A. Frydman
Measurement of a Superconducting Energy Gap in a Homogeneously Amorphous Insulator
Phys. Rev. Lett. **108**, 177006 (2012)

compare planar
tunnel junctions to
superconducting
and insulating
InO_x - films



Superconducting
gap persists on
insulating side, also
in THz-spectroscopy

D. Sherman, B. Gorshunov, S. Poran, N. Trivedi, E. Farber, M. Dressel, A. Frydman
Effect of Coulomb interactions on the disorder-driven superconductor-insulator transition
Phys. Rev. B **89,** 035149 (2014)



How to model the Cooper-pair insulator:

- thermally activated conductance

  expt.: Palaanen & Hebard, Ovadyahu, and many others

  theory: Fistul, Baturina, Vinokur, PRL **100** (2008)

  Feigel'man, Ioffe, Kravtsov, Cuevas, Ann. Physics 325, 1368 (2010);

  Feigelman, Ioffe, Mezard, PRB **82**, 184534 (2010)

- strongly non-monotonic magnetoresistance

  expt.:Gantmakher et al., Shahar et al., Baturina et al. and others

  Theory: Dubi, Meir, Avishai, Nature **449** 876 (2007)

- non-linearities in IV-characteristics

  expt. Baturina et al.; Ovadia et al.,

  theory: Vinokur et al., Altshuler et al.

Motivated by emergent inhomogeneity in superconducting condensate –

→ exploit knowledge about Josephson junction array (JJAs) and assume that superfluid condensate fractionalizes into small droplets with a random Josephson coupling

Josephson arrays in the charging regime

J. Mooij, B.J. van Wees, L.J. Geerlings, M. Peters, R. Fazio and G. Schön,
Unbinding of Charge-Anti-Charge Pairs in Two-Dimensional arrays of small Tunnel Junctions
Phys. Rev. Lett. **65**, 645 (1990)

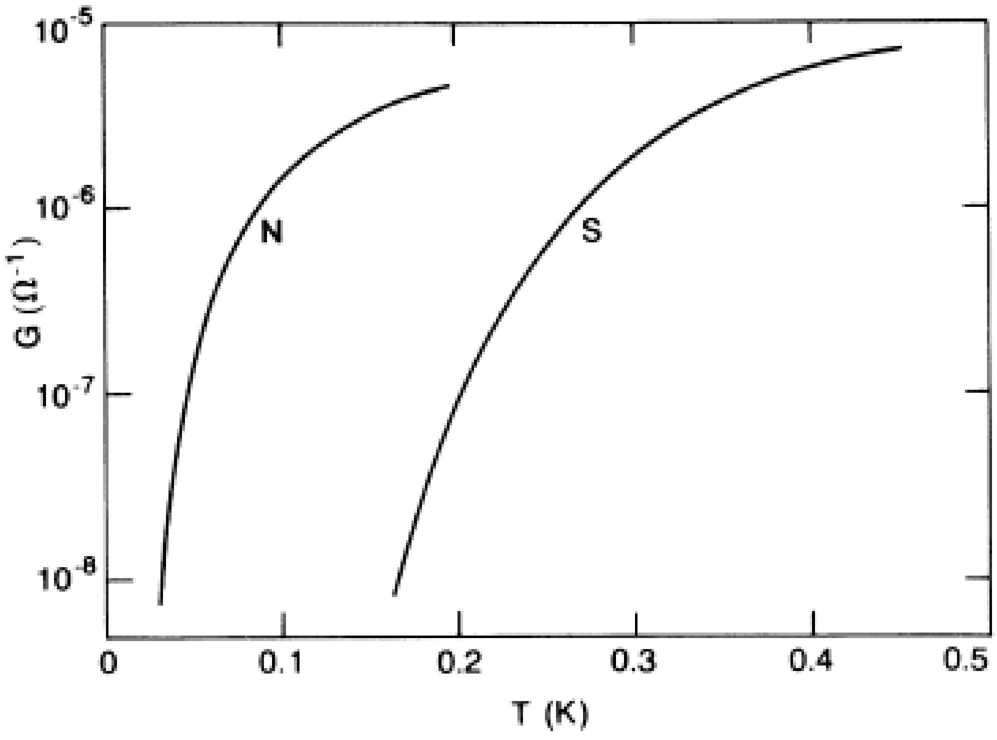


FIG. 3. Measured conductance of an array of (100 nm)² aluminum tunnel junctions, 190 cells long and 60 cells wide. *N* is in the normal state (magnetic field of 3T applied); *S* in the superconducting state.

consider JJ-arrays in the limit $E_J < E_C$

superconducting array turns insulating at much higher temperatures !

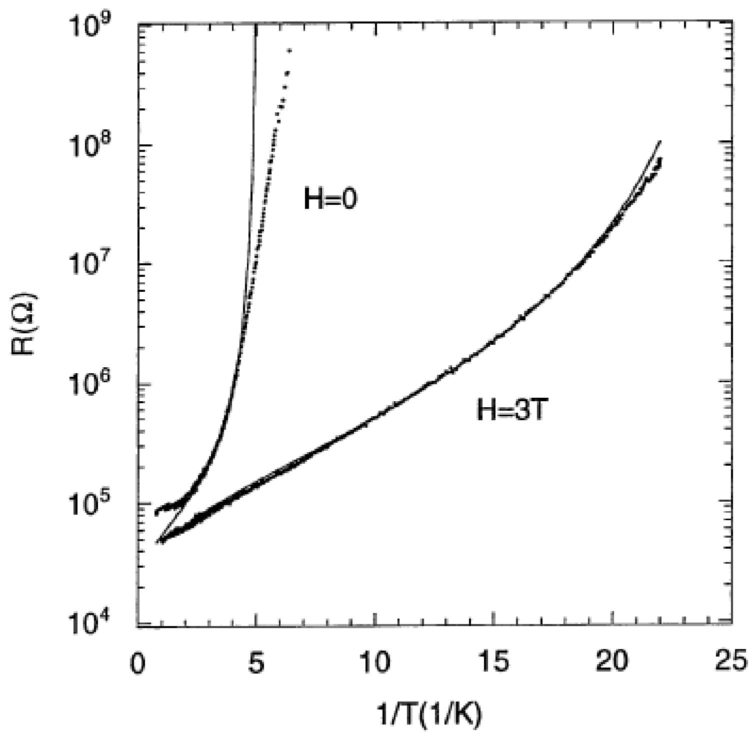
H. v.d.Zant, R. Fazio
Phys. Repts. **355**, 235 (2001)

Super-exponential behavior in JJ-arrays

Journal of the Physical Society of Japan
Vol. 64, No. 1, January, 1995, pp. 19–21

Precursor of Charge KTB Transition in Normal and Superconducting Tunnel Junction Array

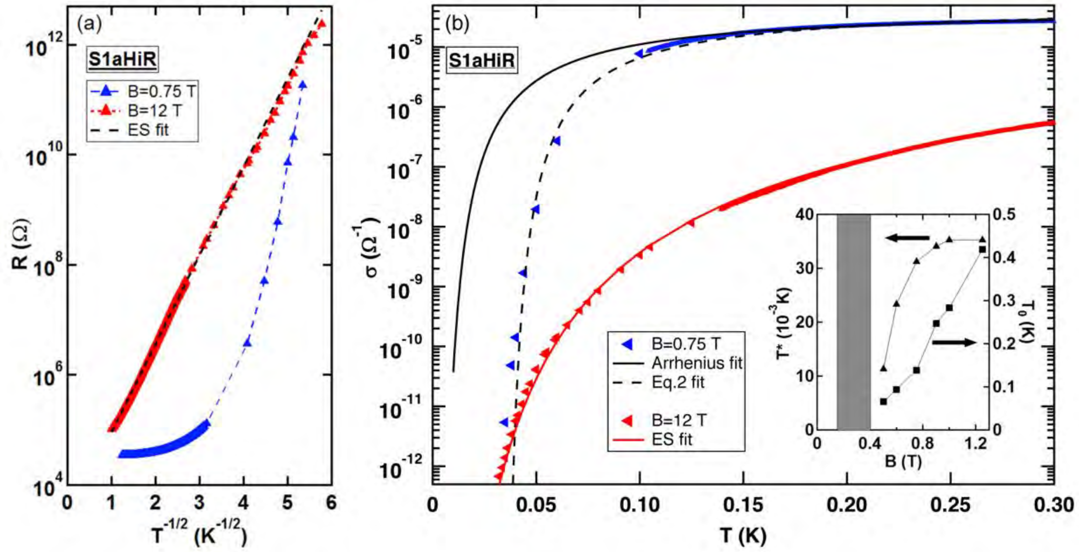
Akinobu KANDA and Shun-ichi KOBAYASHI



The array was 380 junctions in length and 331 junctions in width. Each junction had an area of 0.0072 $(\mu m)^2$, normal-state tunneling resistance $R_N = 32$ kΩ and the capacitance $C = 1.1 \times 10^{-15}$ F. The self-capacitance of the island electrode was 5.1×10^{-17} F. The method to estimate these values is described in ref. 7. Consequently, the charging energy $E_C = e^2/2C = 0.81$ K, the Josephson coupling energy $E_J = 0.31$ K and $\Lambda = 5.7$ junctions.

Resistance at low T grows faster than expected from an Arrhenius law!

Super-exponential resistance in homogenously disordered films



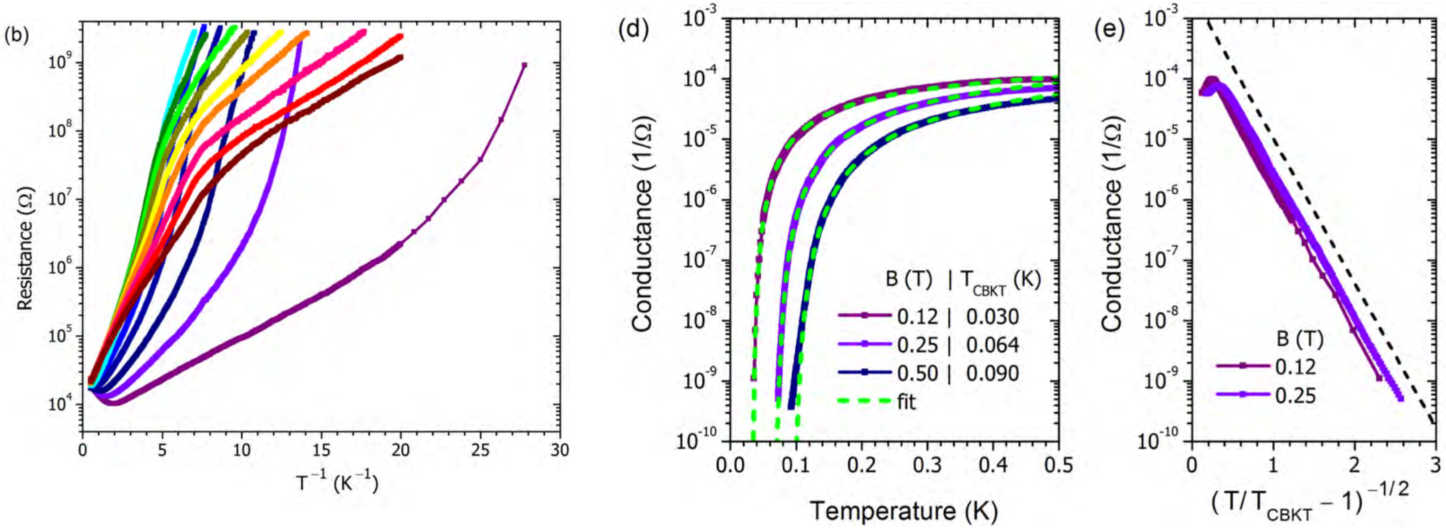
InO$_x$

Evidence for a Finite-Temperature Insulator

M. Ovadia[1,†], D. Kalok[1], I. Tamir[1], S. Mitra[1], B. Sacépé[1,2,3] & D. Shahar[1]

$$R(T) \propto \exp\left(\frac{a}{1 - T/T^*}\right)$$

Sci. Rept. **5**, 13503 (2015)



Charge Berezinskii-Kosterlitz-Thouless transition in superconducting NbTiN films

A. Yu. Mironov, T. F. Rosenbaum, V. V. Vinokur, T. I. Baturina, et. al.

NbTiN$_x$

$$R(T) \propto \exp\left(\frac{b}{(1 - T/T^*)^{1/2}}\right)$$

Sci. Rept. **8**, 4082 (2018)

Questions:

- What is the mechanism of destruction of superconductivity – fermionic of bosonic or both?

- Do Josephson coupled droplets with a fully developed order parameter exist at the SIT that can be Josphson coupled

- What is the role of Coulomb interactions within the bosonic approach?

- What is the transport mechanism of preformed pairs?

- When does hopping of Cooper pairs transitions to the hopping of single electrons?

Outline

- Localization: suppression of diffusion by disorder

  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity

- Suppression of zero-resistance state by phase fluctuations

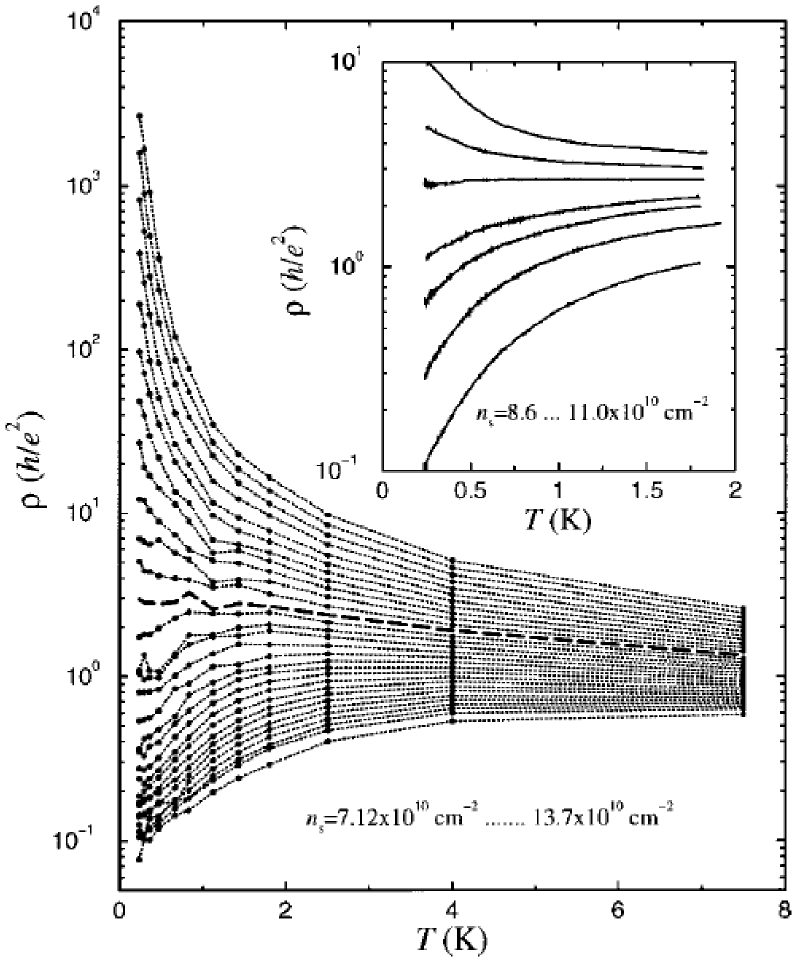
- Suppression of Cooper-pairing by disorder

- Direct superconductor-insulator transition

- **‚Failed‘ superconductors and insulators:**

  Kravchenko et al. 1994: „There are ~~no~~ metals in two dimensions!“

Normal metals in two dimensions?



S. V. Kravchenko, D. Simonian, M. P. Sarachik
W. Mason, J. E. Furneaux
Electric Field Scaling at a B = 0 Metal-Insulator Transition in Two Dimensions
Phys. Rev. Lett. **77**, 4938 (1996).

- Electron-electron interactions matter!
- Already early theory suggested that MIT may occur in clean systems [Finkelstein (1984), Castellani, et al. (1984)]
- Clear metal insulator transition observed in the 2D electron systems in high mobility MOSFETs at very low density!
- Critical resistance $R_c \simeq \frac{h}{e^2} \simeq 25.8\ \mathrm{k}\Omega$

REVIEWS OF MODERN PHYSICS, VOLUME 73, APRIL 2001

***Colloquium*: Metallic behavior and related phenomena in two dimensions**

Elihu Abrahams

Center for Materials Theory, Physics Department, Rutgers University, Piscataway, New Jersey 08854

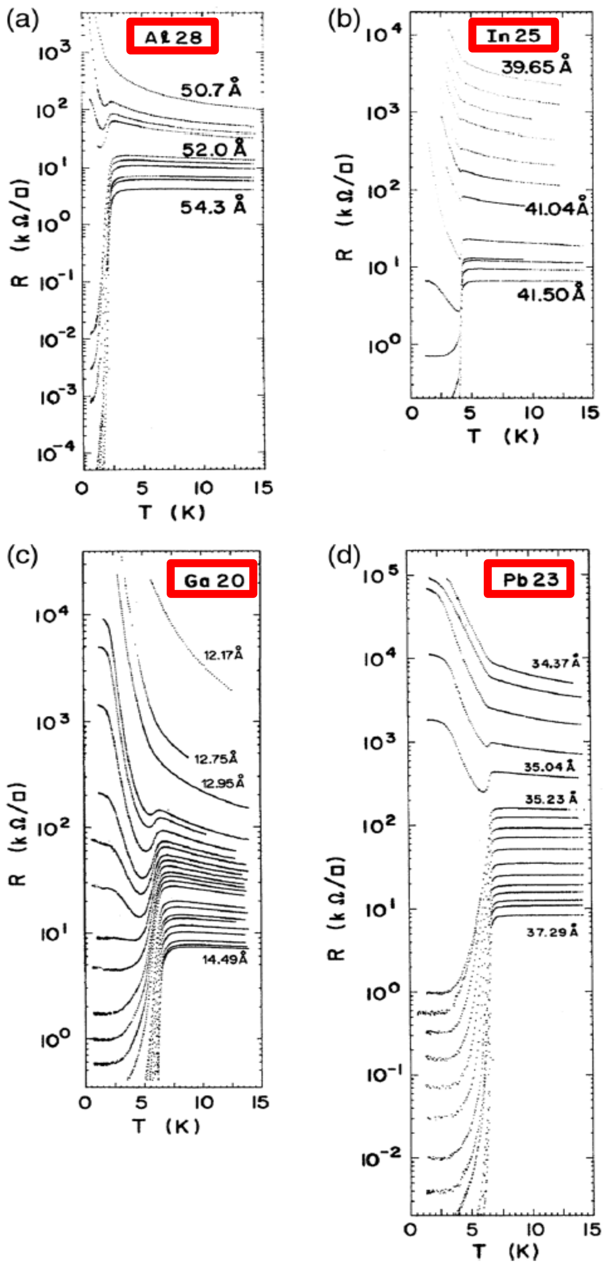
Sergey V. Kravchenko

Physics Department, Northeastern University, Boston, Massachusetts 02115

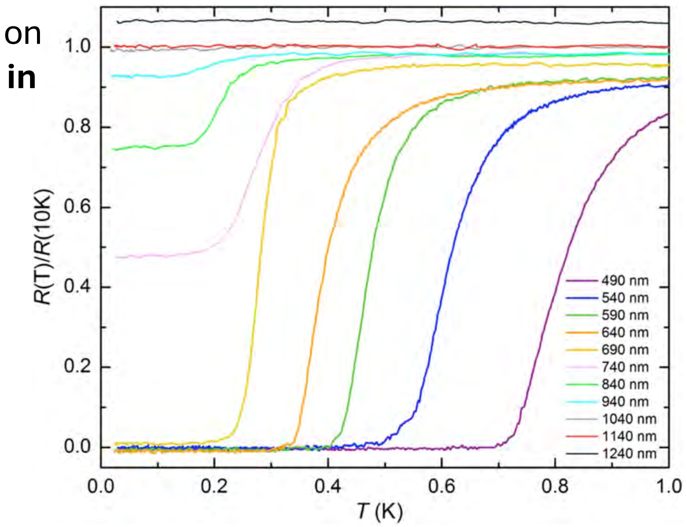
Myriam P. Sarachik

Physics Department, City College of the City University of New York, New York, New York 10031

Granular superconductors and Josephson junction arrays



S. Eley, S.Gopalakrishnan, P. M. Goldbart, N. Mason
Approaching zero-temperature metallic states in mesoscopic superconductor–normal–superconductor arrays
Nat. Phys. 8, 59 (2012).

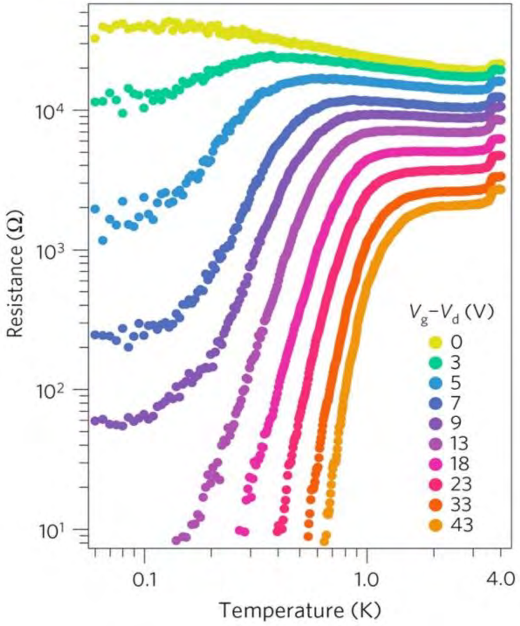


Low-T saturation observed for:

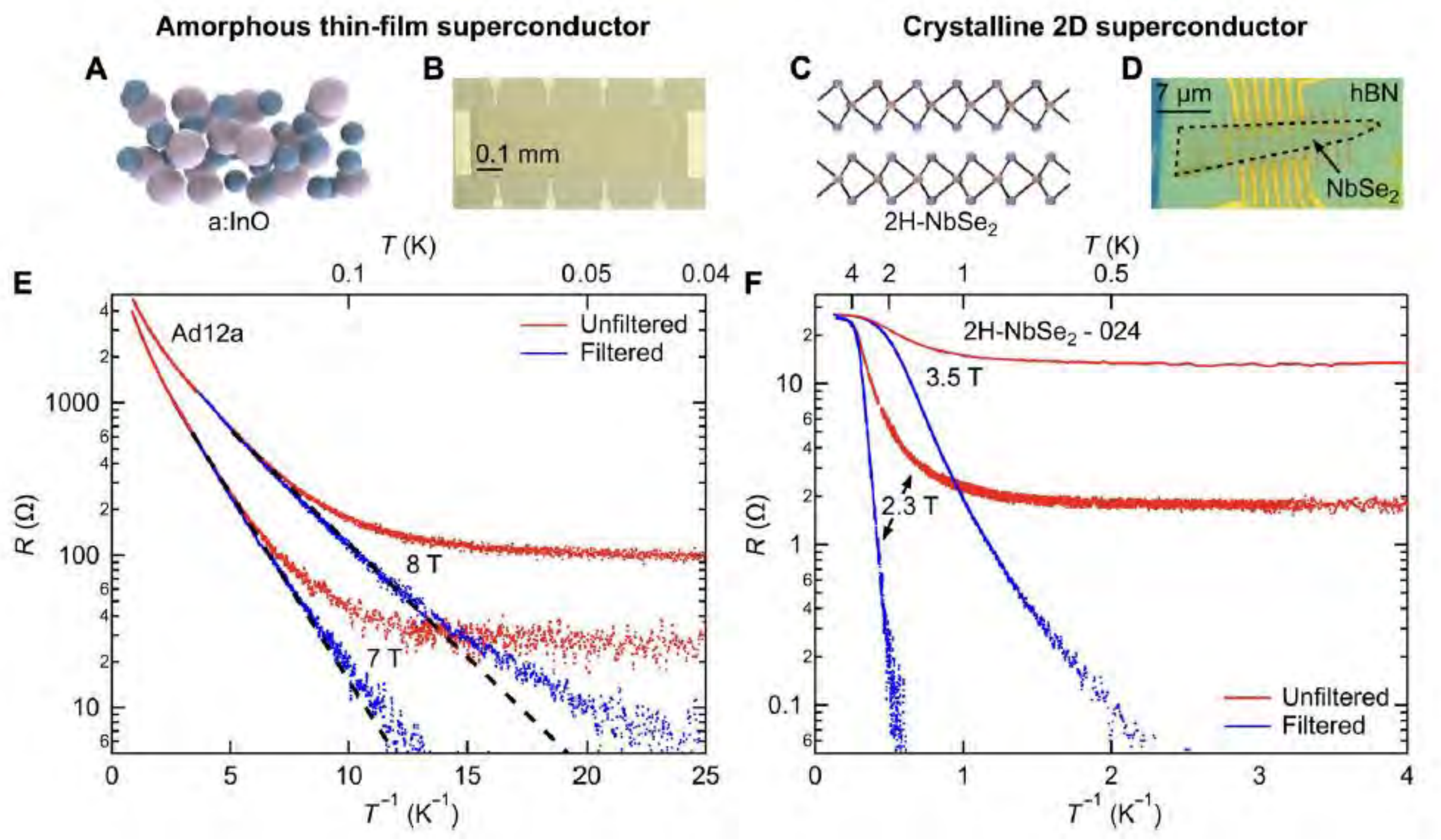
- granular films (random JJ-arrays)
- arrays of metallic SNS-junctions
- Sn droplets on graphene

H. M. Jaeger, D. B. Haviland, B. G. Orr, A. M. Goldman
Onset of superconductivity in ultrathin granular metal films
Phys. Rev. B **40**, 182 (1989).

Z. Han, et al., B. Sacepe, and V. Bouchiat,
Collapse of superconductivity in a hybrid tin–graphene Josephson junction array
Nat. Phys. **10**, 380 (2014).



Possible artifacts from insufficient rf-filtering of cryogenic wiring?



I. Tamir et al., C. Dean, D. Shahar

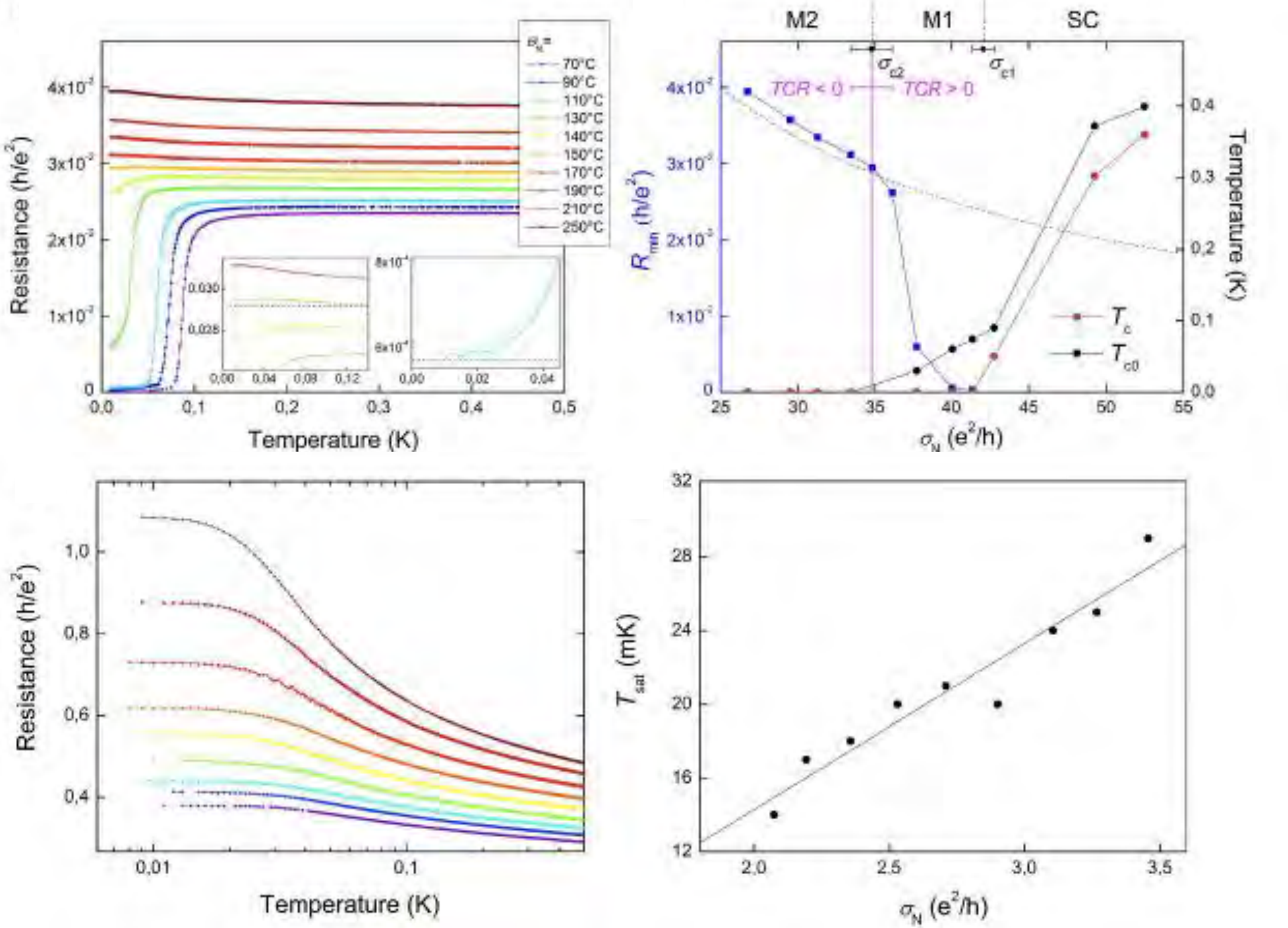
Sensitivity of the superconducting state in thin films

Sci. Adv. **5** eaau3826 (2019).

„Failed“ superconductors and insulators appear also with state-of-the-art filtering...

Tune sheet resistance of $Nb_{13.5}Si_{86.5}$ films by annealing:

- saturation for both, *superconducting* and *insulating* films
- the **Bose-metal** remains an enigma...



F. Couëdo, O. Crauste, A. A. Drillien, V. Humbert
L. Bergé, C. A. Marrache-Kikuchi, L. Dumoulin
Dissipative phases across the superconductor-to-insulator transition
Sci. Rept. **6**:35834 (2016).

Overview

- Localization: suppression of diffusion by disorder

  Abrahams et al. 1979: „There are no metals in two dimensions!“

- Superconductivity
- Suppression of zero-resistance state by phase fluctuations
- Suppression of Cooper-pairing by disorder
- Direct superconductor-insulator transition
- ‚Failed‘ superconductors and insulators:

  Kravchenko et al. 1994: „There are ~~no~~ metals in two dimensions!“