Signatures of quantum critical behavior in disordered TiN thin films (and wires)

arXiv:1806.01335


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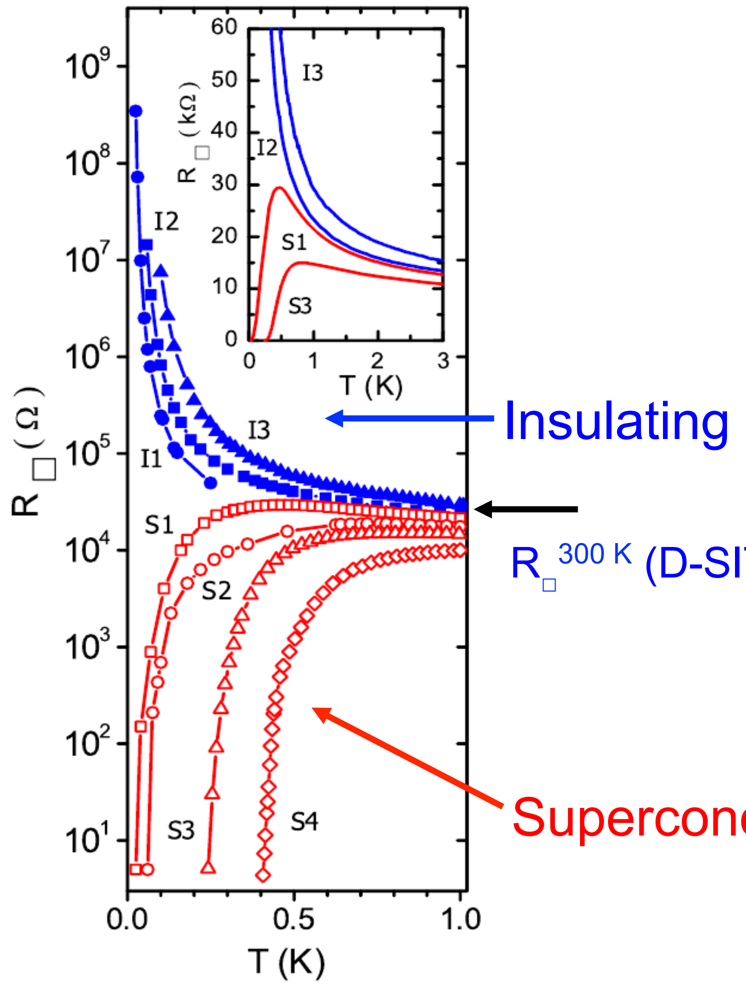
Superconductor-insulator transition (SIT) in TiN films

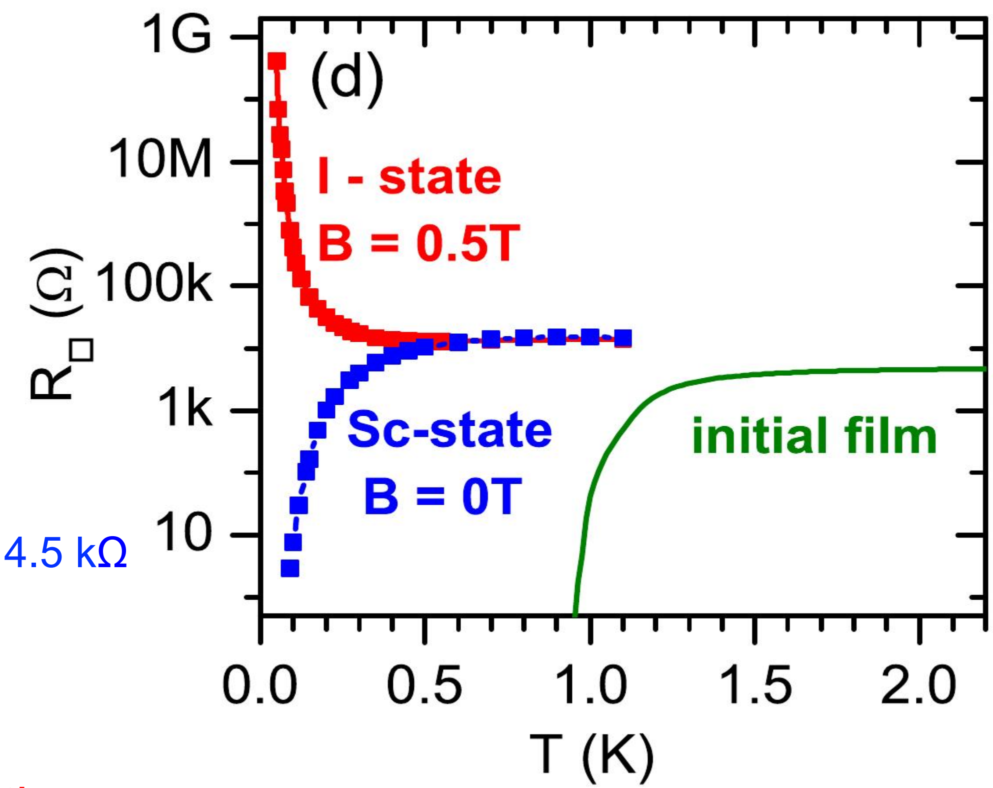
Disorder-driven SIT (D-SIT) (B = 0)



$R_\square^{300\,K}$ (D-SIT) ~ 4.5 kΩ

T. I. Baturina, C.S. et al., Phys. Rev. Lett. 2007

Field-driven SIT (B-SIT) (B > 0)



gentle increase of resistivity by ion milling or oxidation in air

T. I. Baturina et al., Appl. Phys. Lett. 2013

B-induced SIT as a quantum phase transition

- M. Fisher: apply dimensional analysis to B-SIT
- Duality between superconducting (S) and insulating (I) states:
  - → S: Cooper-pair condensate (localized vortices)
  - → I : Bose-fluid of unbound vortices (localized Cooper-pairs)
- Around B_c the resistance should satisfy the scaling form:

$$R = R_c \cdot f[(B - B_c)/T^{1/z\nu}]$$

with a dimensionless scaling function f, and the scaling exponent $z\nu$

(ν : correlation length exponent, z : dynamical exponent)

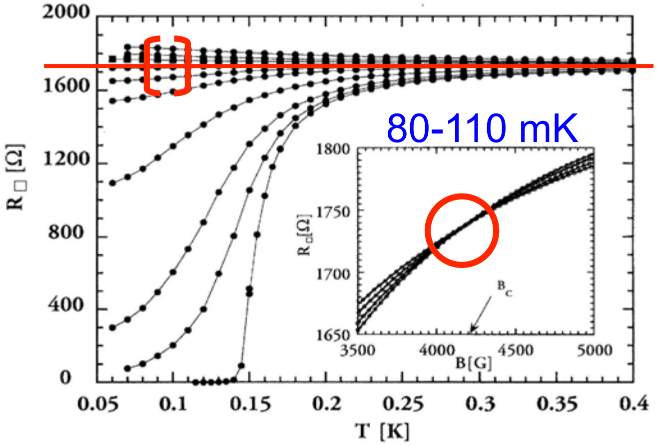
Search for crossing points in the magnetoresistance isotherms

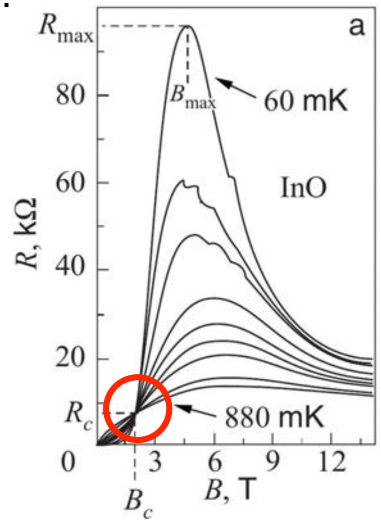
M. P. A. Fisher, PRL **64**, 587 and **65**, 7 (1990)

Crossing points in the magnetoresistance isotherms

Amorphous MoGe
A. Yazdani and A. Kapitulnik
Phys. Rev. Lett. **74**, 3037 (1994)

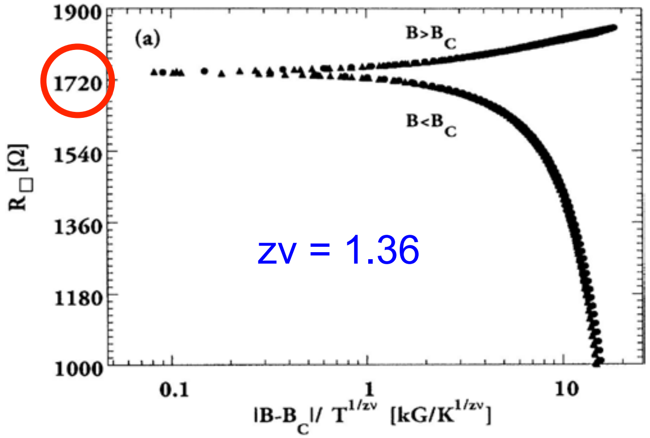
Amorphous indium oxide
V. F. Gantmakher et al.
JETP **71**, 473 (2000)

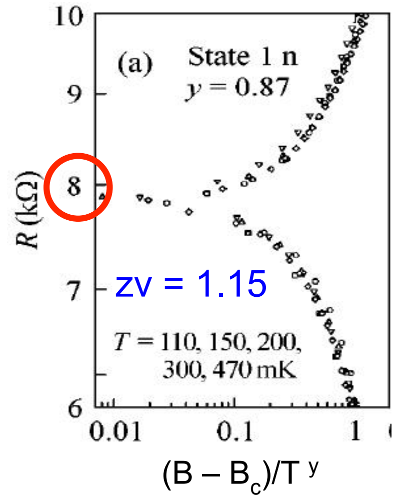




Plateau in the R(T) curve at the crossing field B_c

Crossing point in the magnetoresistance isotherms





Collapse of the R(B) isotherms in scaling plots with adjusted zν

very different strength of insulating behavior

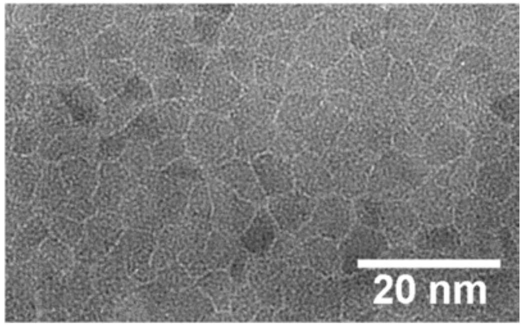
no universal critical resistance

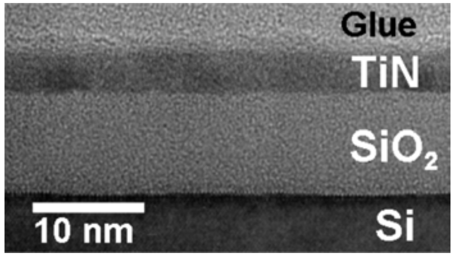
Outline:

- crossing points in the magnetoresistance of TiN thin films
- critical behavior of the B-induced SIT
  near the disorder-induced SIT
- self-induced granularity
- Josephson-like *superconducting* and Bloch-like *insulating* behavior in **narrow nanowires**

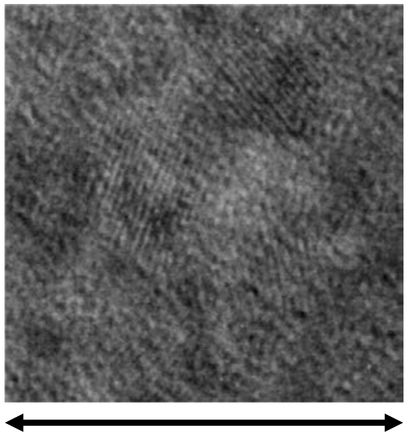
Film characteristics

T. I. Baturina, C.S. et al.,
Appl. Phys. Lett. **102** (2013)

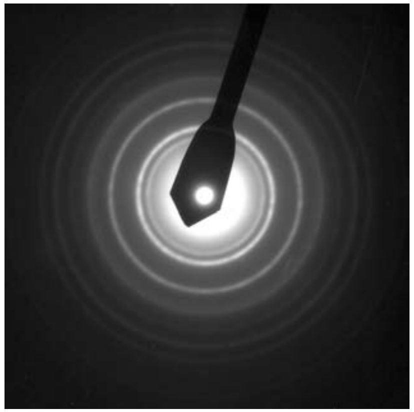




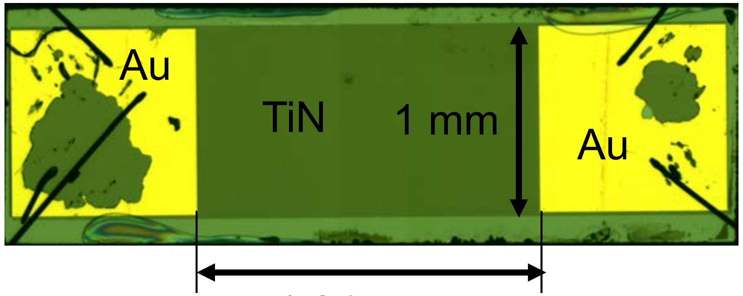
- ultrathin TiN films with thickness d = 3.6 nm
  atomic layer deposition at 400 °C
- polycrystalline structure



14 nm



Sample D03_S



1.84 mm

3.5 kΩ < $R_\square^{300\,K}$ < 4.5 kΩ

tuned by heating in air

properties of untreated film:

$R_\square^{300\,K}$ = 2.52 kΩ

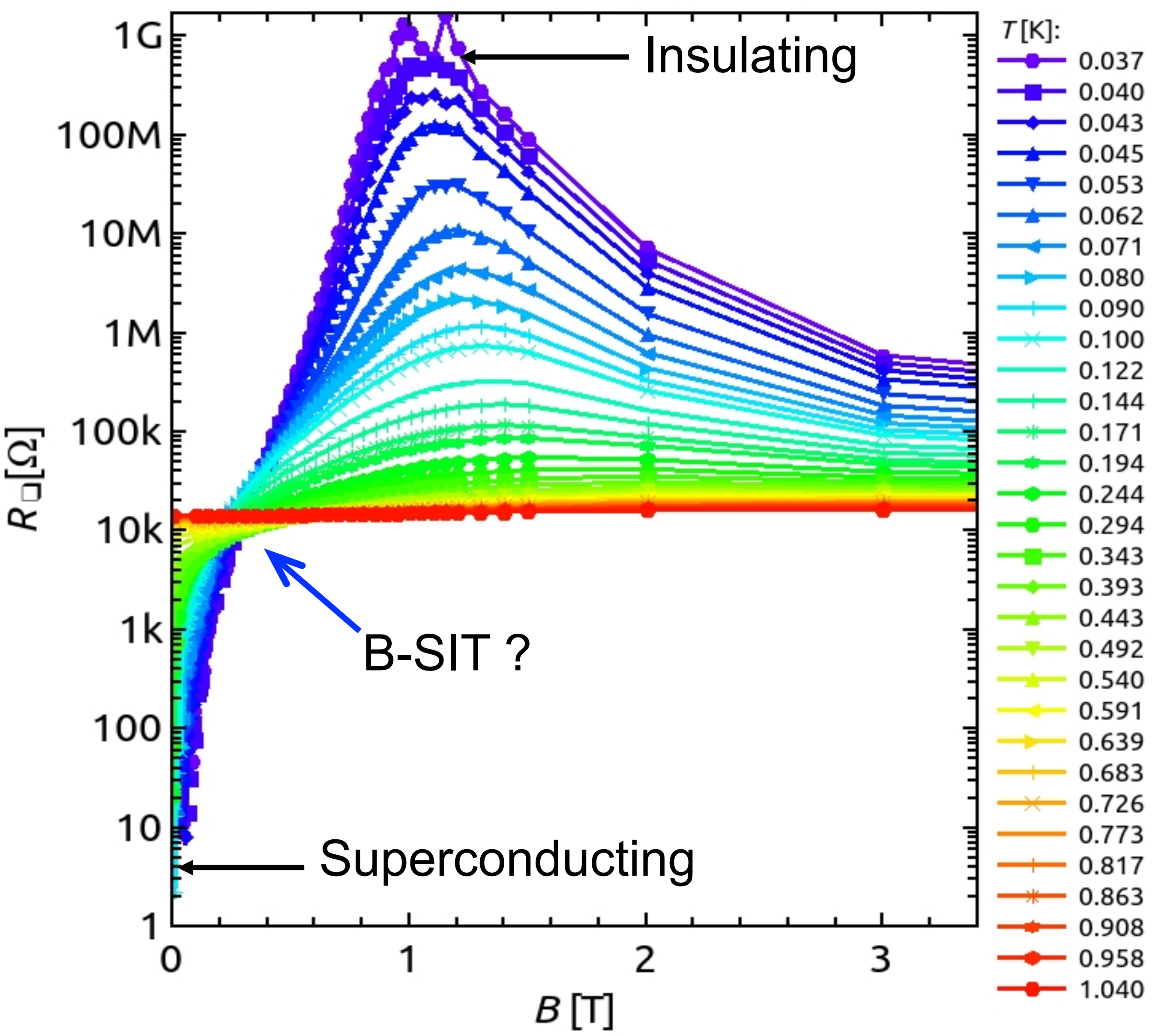
T_c = 1.29 K

$\xi_d(0)$ = 8.9 nm

D = 0.34 cm^2/s

n = 1.5 · 10^{22} cm^{-3}

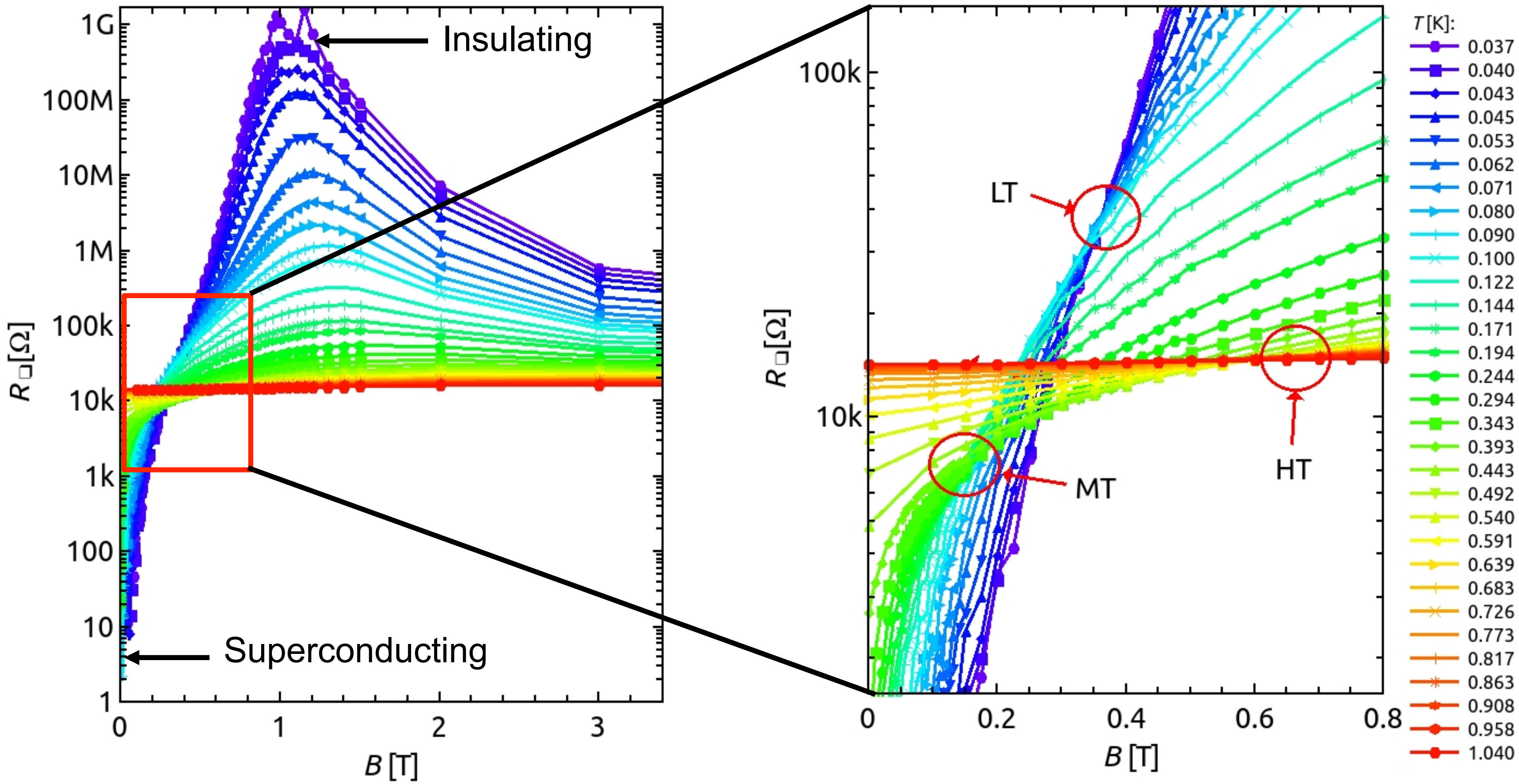
Magnetoresistance in critically disordered TiN films



similar to pheno-menology in InO

blurred crossing of magneto-resistance isotherms

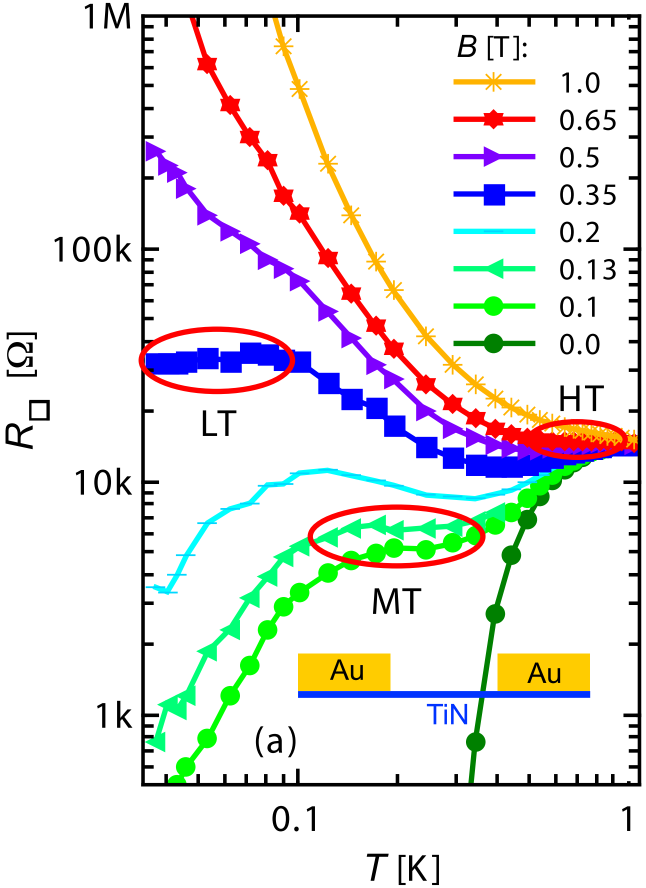
Magnetoresistance in critically disordered TiN films

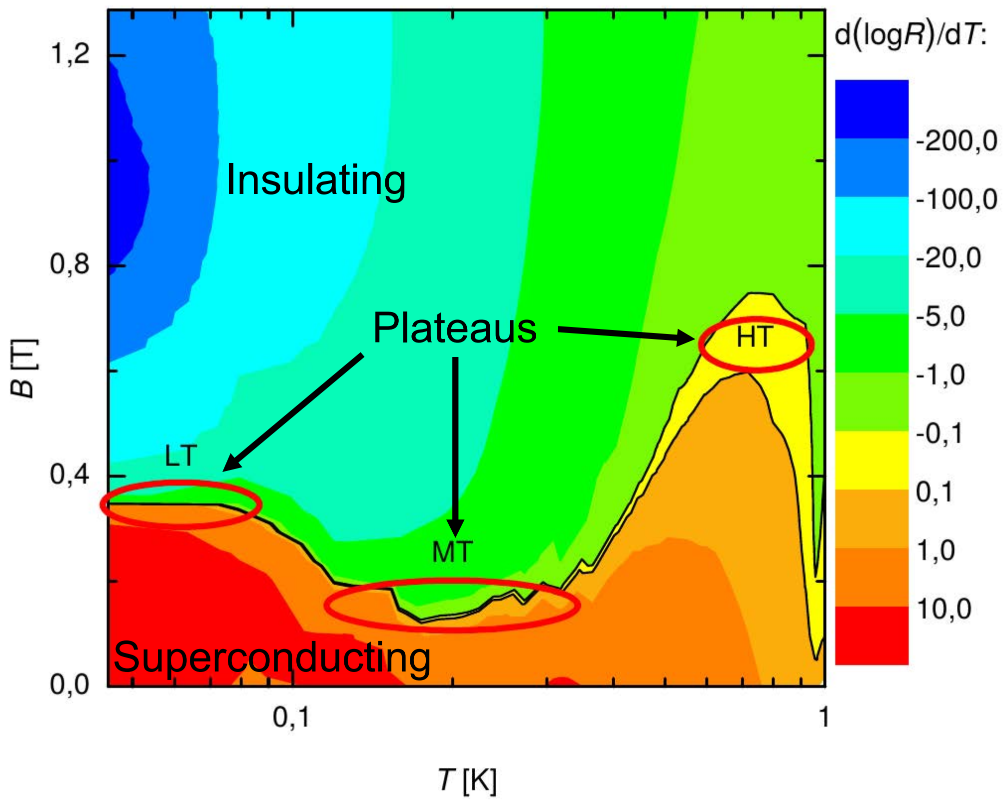


we find three crossing (*isosbestic)* points, where R(B)s intersect!

Greger, Kollar, Vollhardt, PRB **87** (2013)

Crossing points yield plateaus in the R(T) curves

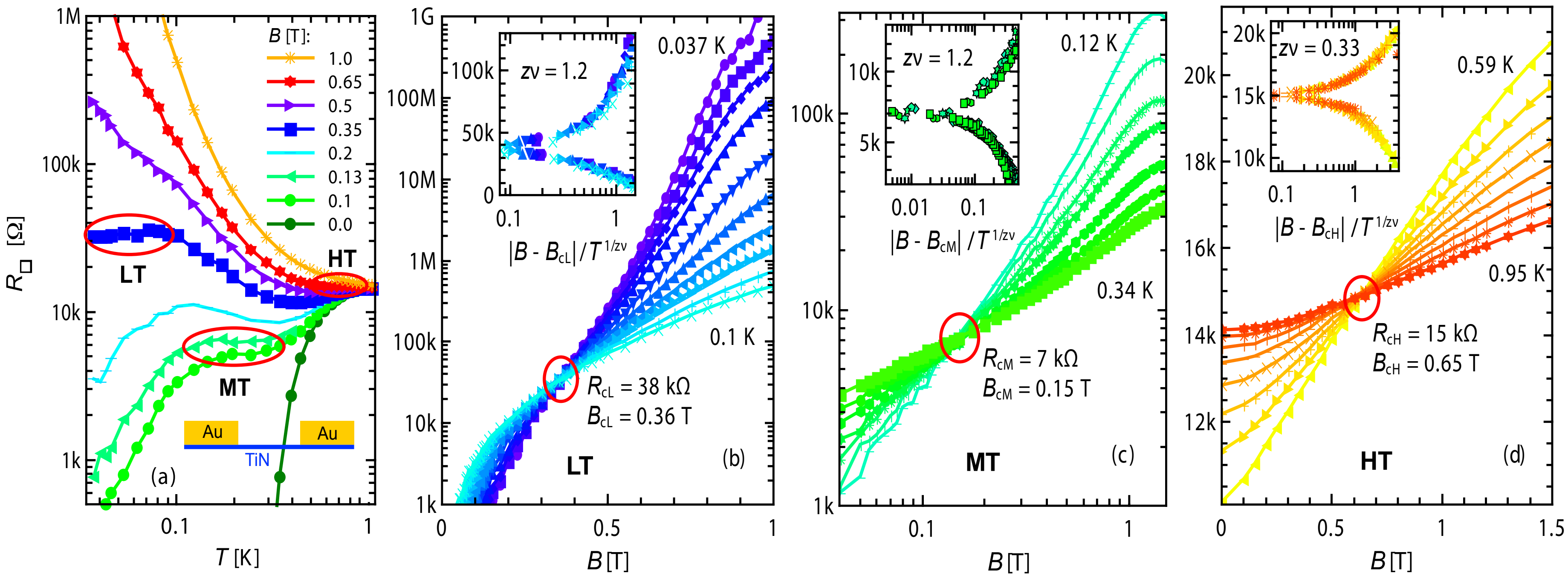




three distinct crossing point in R(B) isotherms -
what about quantum phase transitions?

→ **scaling analysis**

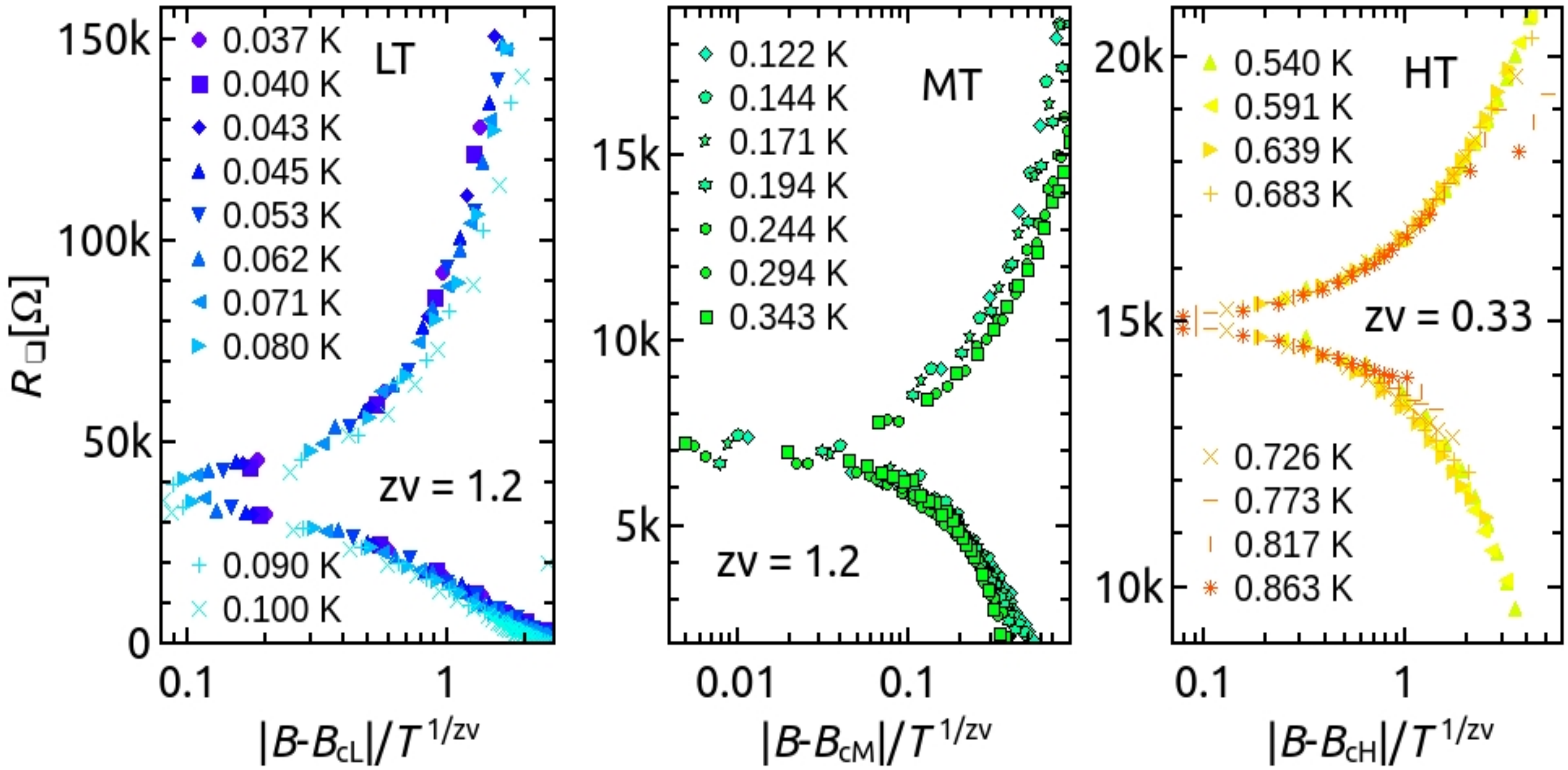
Crossing points yield plateaus in the R(T) curves



three distinct crossing point in R(B) isotherms -
what about quantum phase transitions?

scaling analysis

Scaling analysis



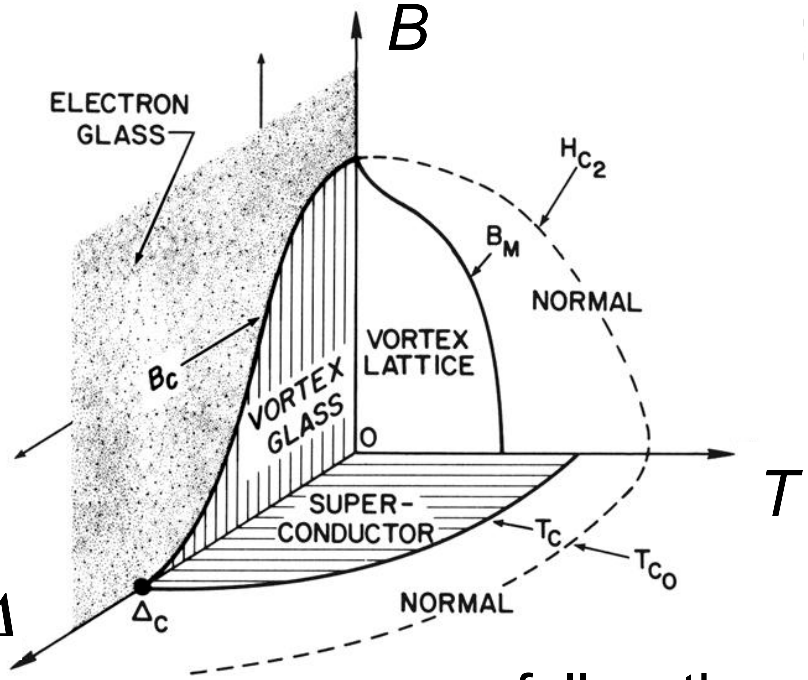
LT crossing point **MT crossing point** **HT crossing point:**

zν = 1.2 consistent with theoretical prediction of zν ≥ 1 for a SIT in a disordered system [M. P. A. Fisher, PRL **65**, 7 (1990)]

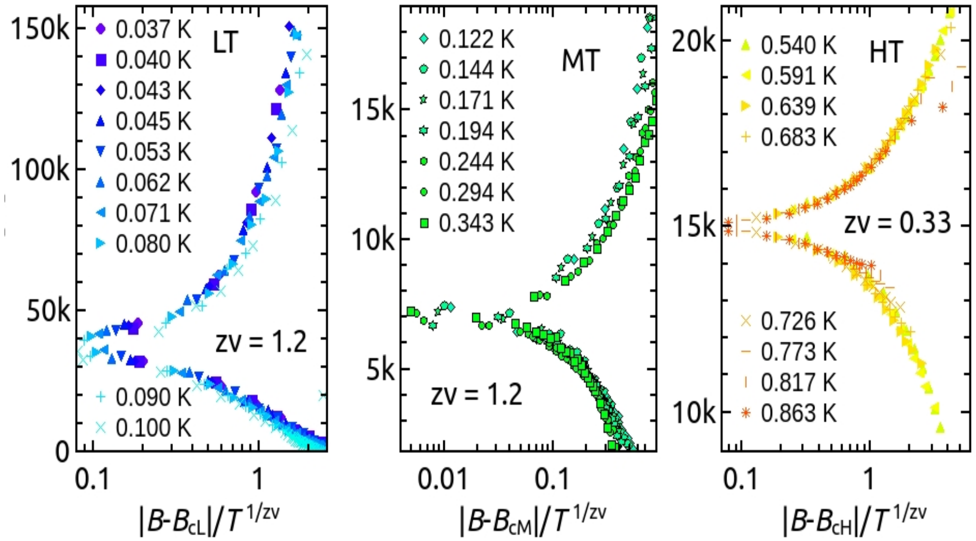
Where is the SIT?

how to identify universal behavior?

phase diagram Fisher:



disorder

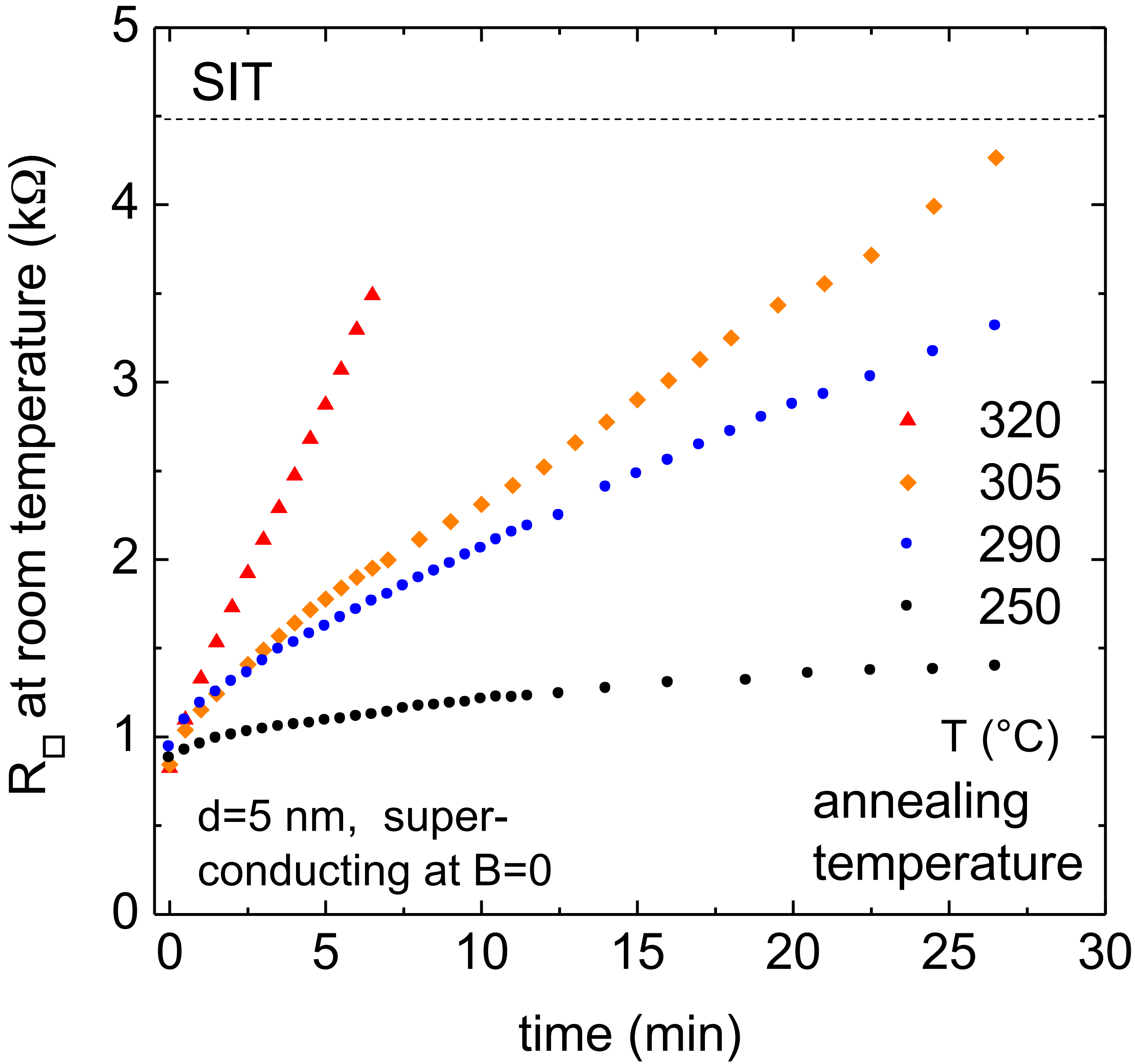


follow the evolution of the critical parameters
for the B-induced SIT,
when approaching the disorder-induced SIT

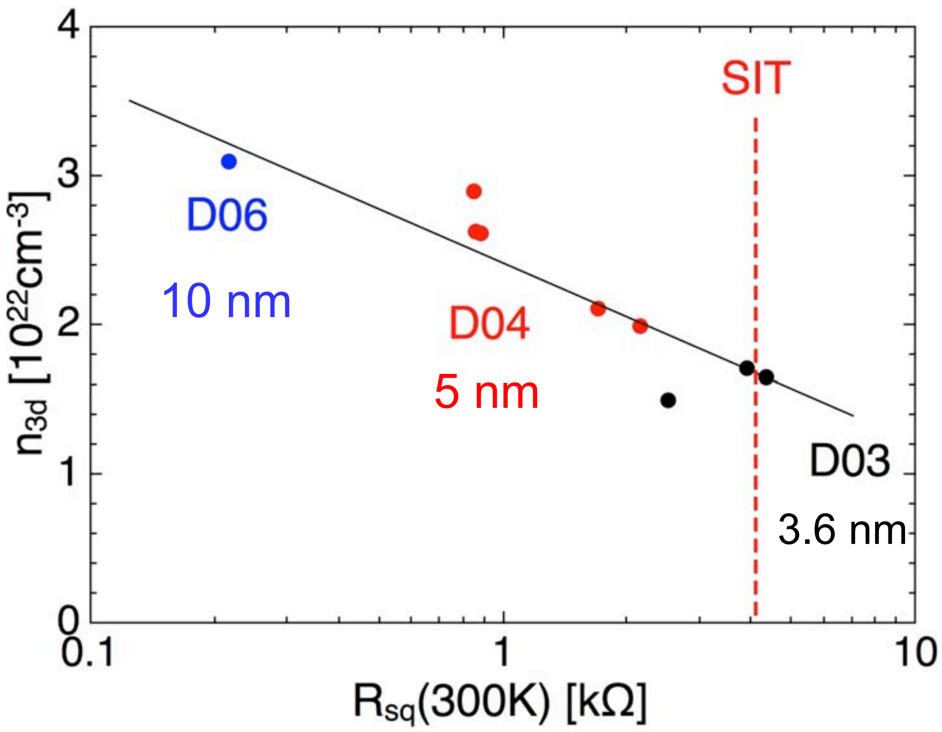
Fisher, PRL **65**, (1990)

see talk J. Lesueur

controlled oxidation of TiN films in air

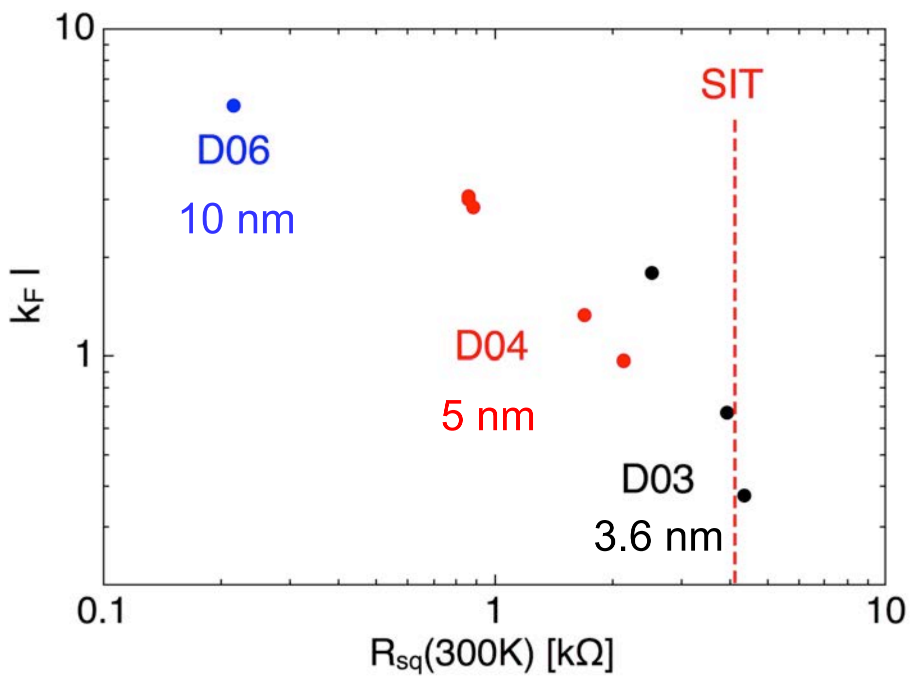


controlled oxidation of TiN films in air

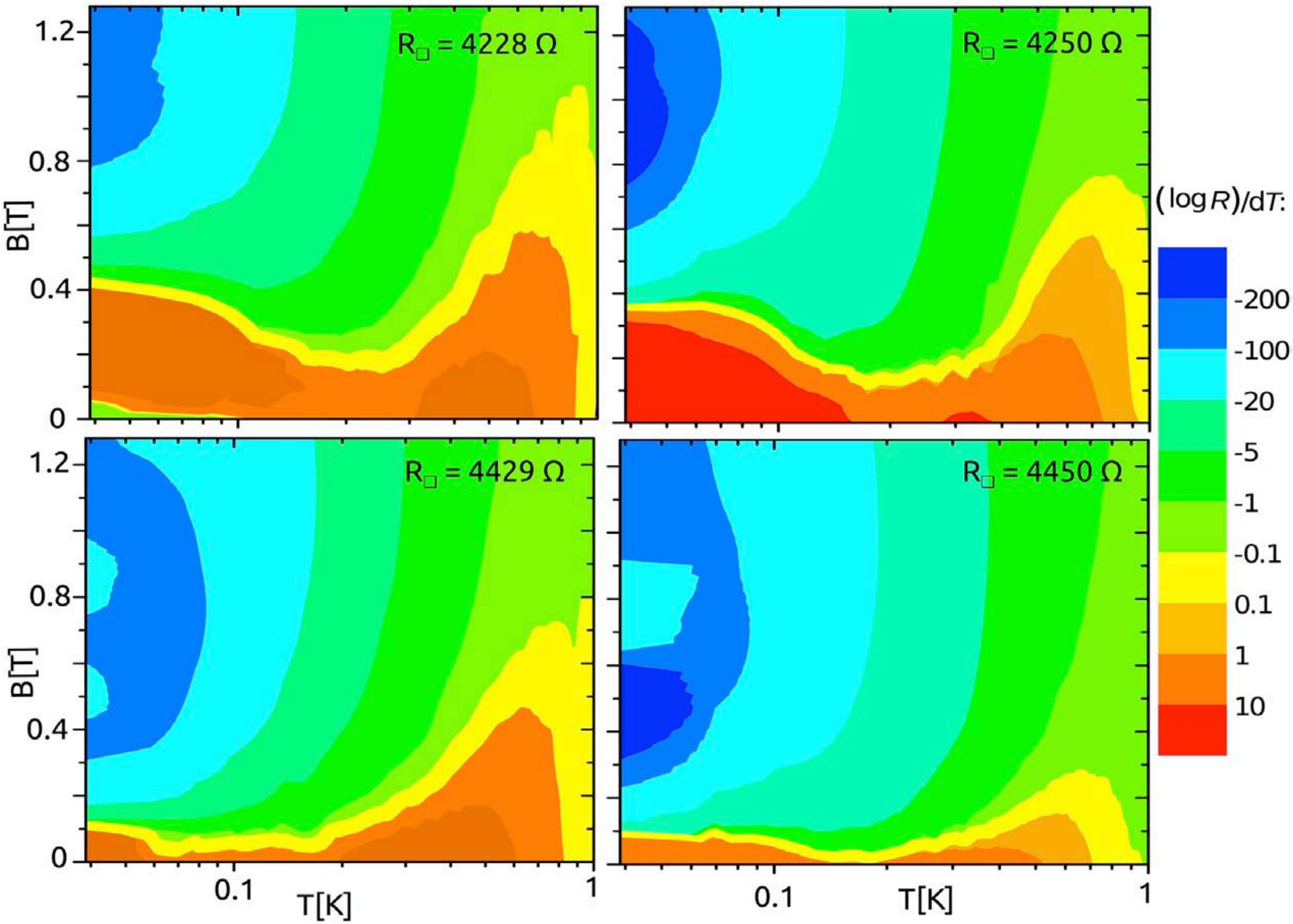


carrier density is metallic
and changes only by factor 2

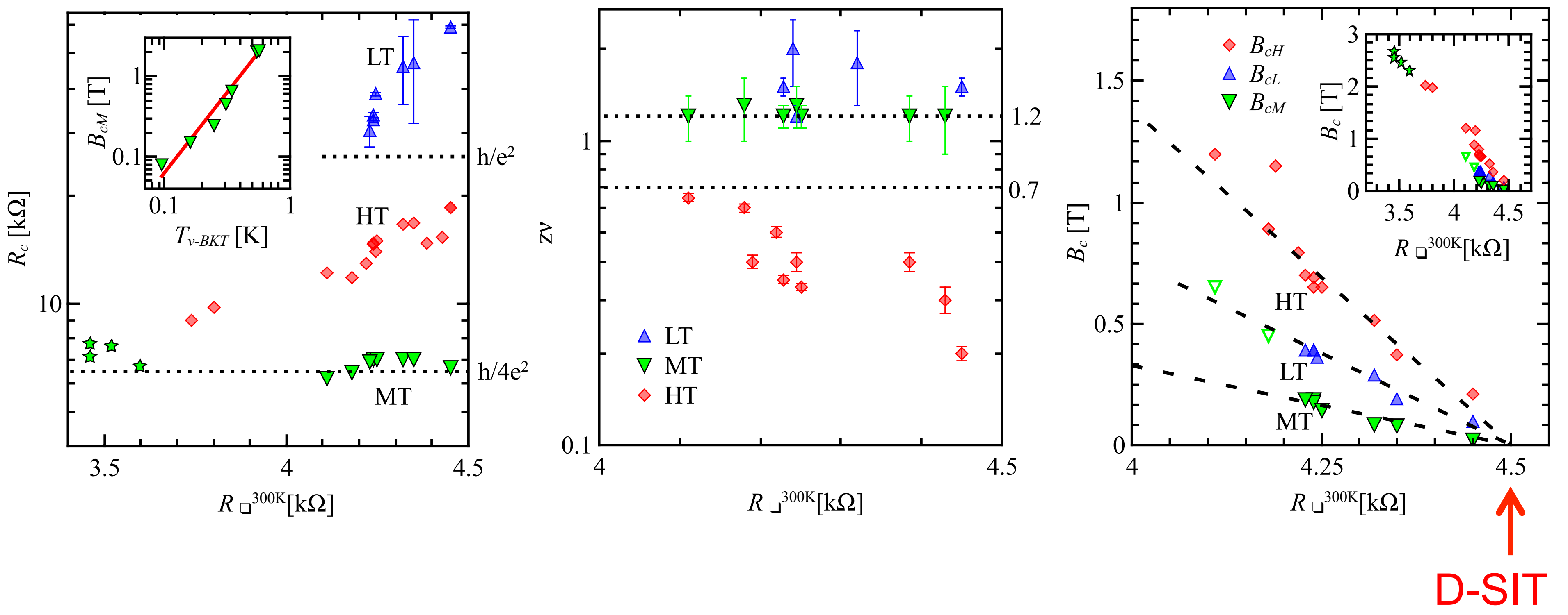
SIT occurs near $k_F l$ ~1



Evolution of SIT separatrix



Evolution of scaling parameters near SIT

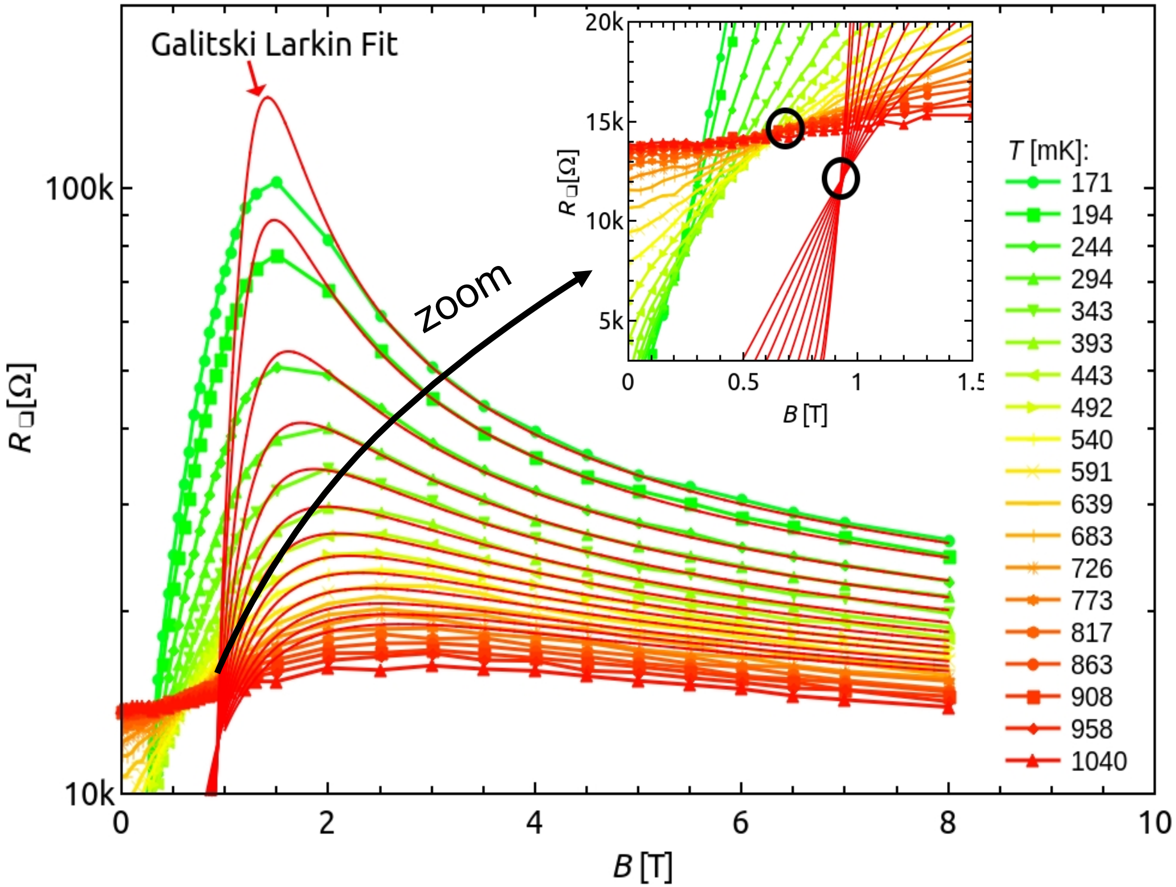


- only MT crossing point produces universal values of R_c and $z\nu$!
- B_c values converge towards zero at critical resistance for D-SIT

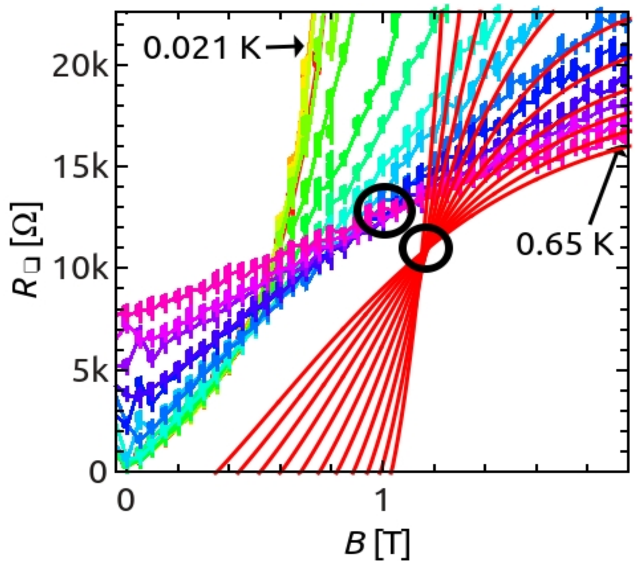
➡ intermediate plateau in R(T) may correspond to Fisher scenario

high T regime: superconducting fluctuations above B_{c2}

$R_{\square}^{300\ K} = 4.25\ k\Omega$



Less disordered sample:
$R_{\square}^{300\ K} = 4.18\ k\Omega$



theory by
Galitski & Larkin, PRB **63**, (2001)

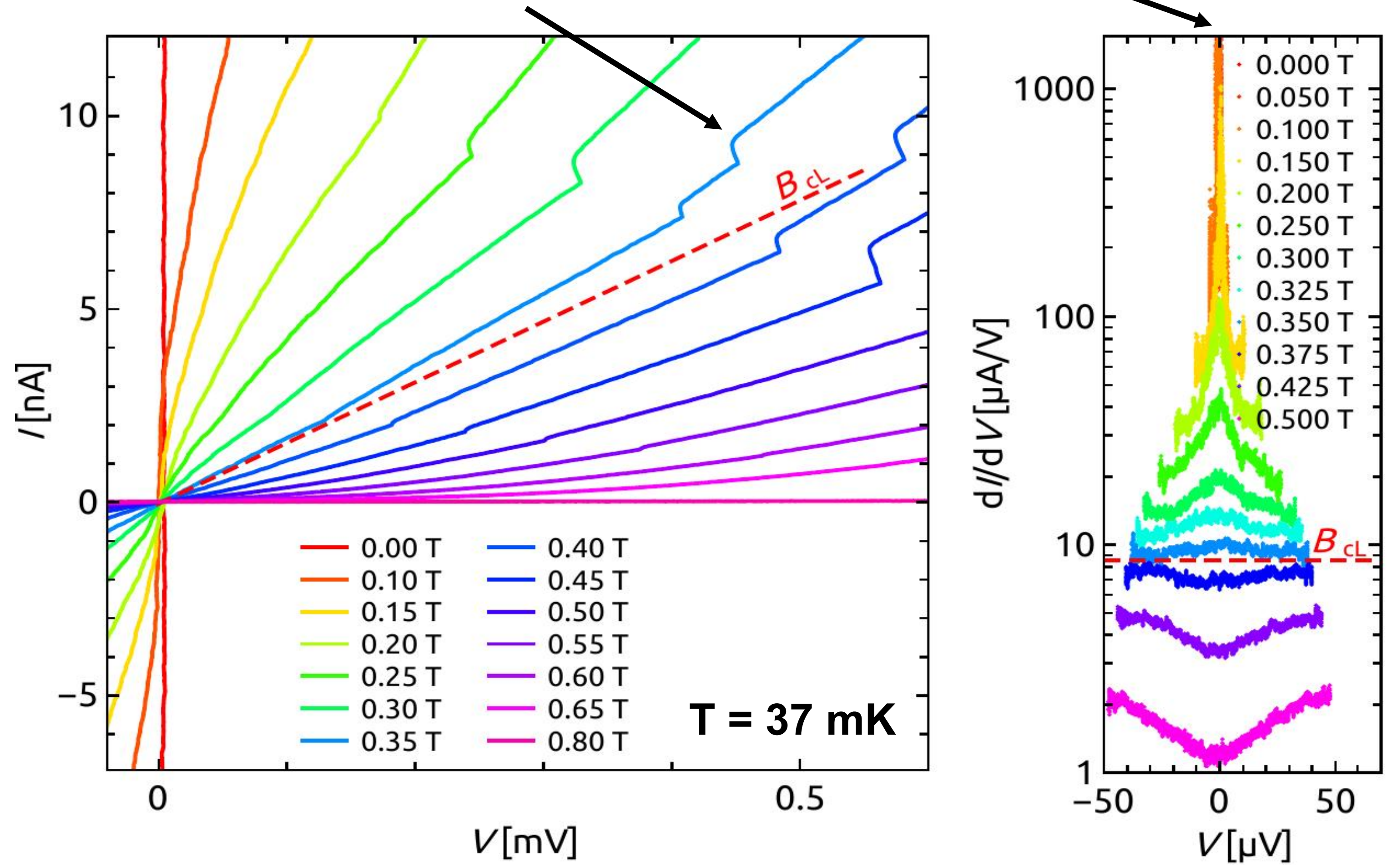
no quantum phase transition required to understand this particular isosbestic point

low T regime: signatures of mesoscopic inhomogeneities

Insulating and superconducting features **coexist** for 0.2 T ≤ B < B_{cL} = 0.36 T

current jumps at higher voltage for B ≥ 0.2 T found also in InO [O. Cohen et al., PRB **84,** (2011)]

diverging dI/dV around zero bias for B < B_{cL}

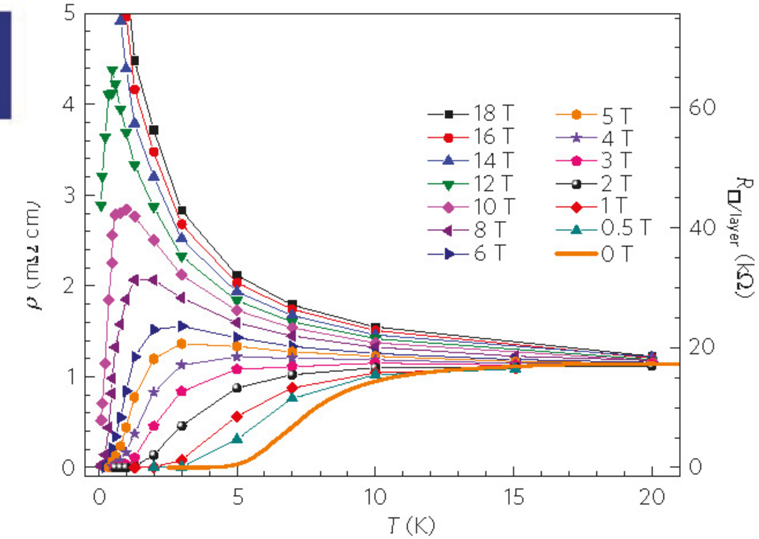


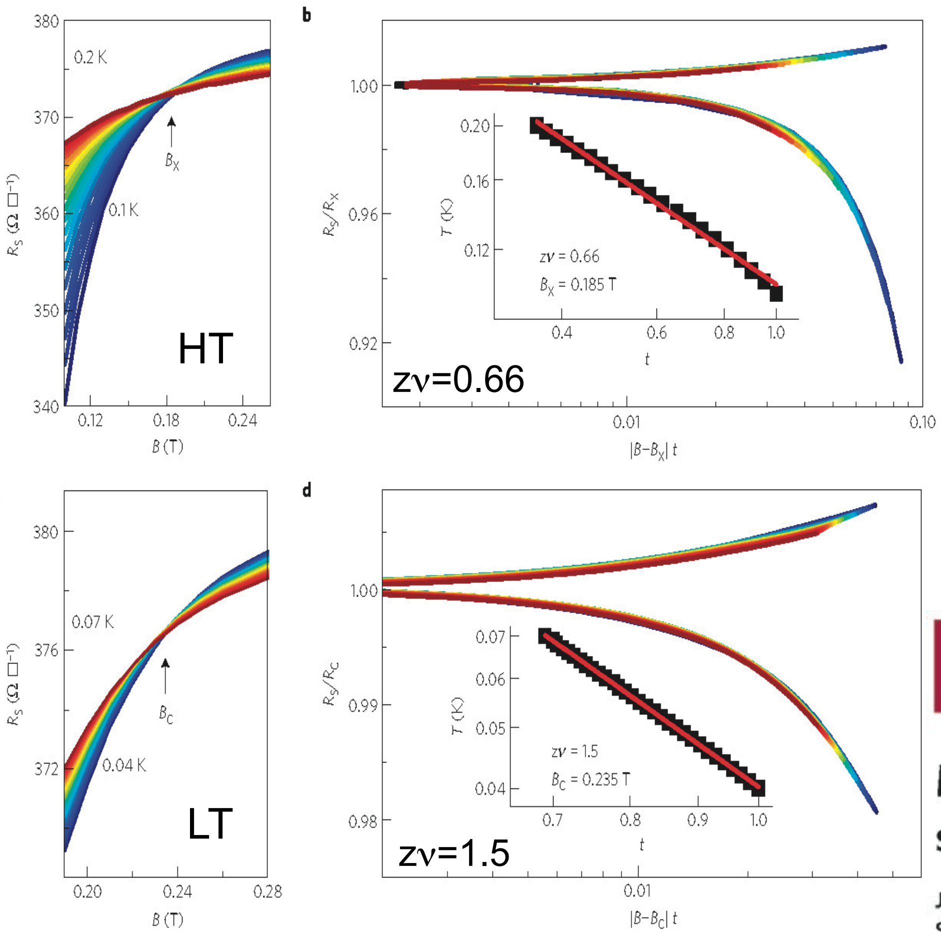
➡ formation of superconducting filaments on a mesoscopic scale

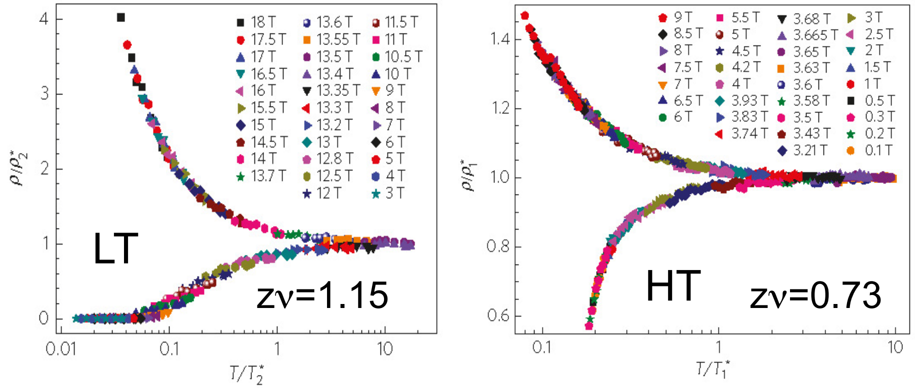
nature physics
ARTICLES
PUBLISHED ONLINE: 4 MAY 2014 | DOI: 10.1038/NPHYS2961

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*]







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

Multiple quantum criticality in a two-dimensional superconductor

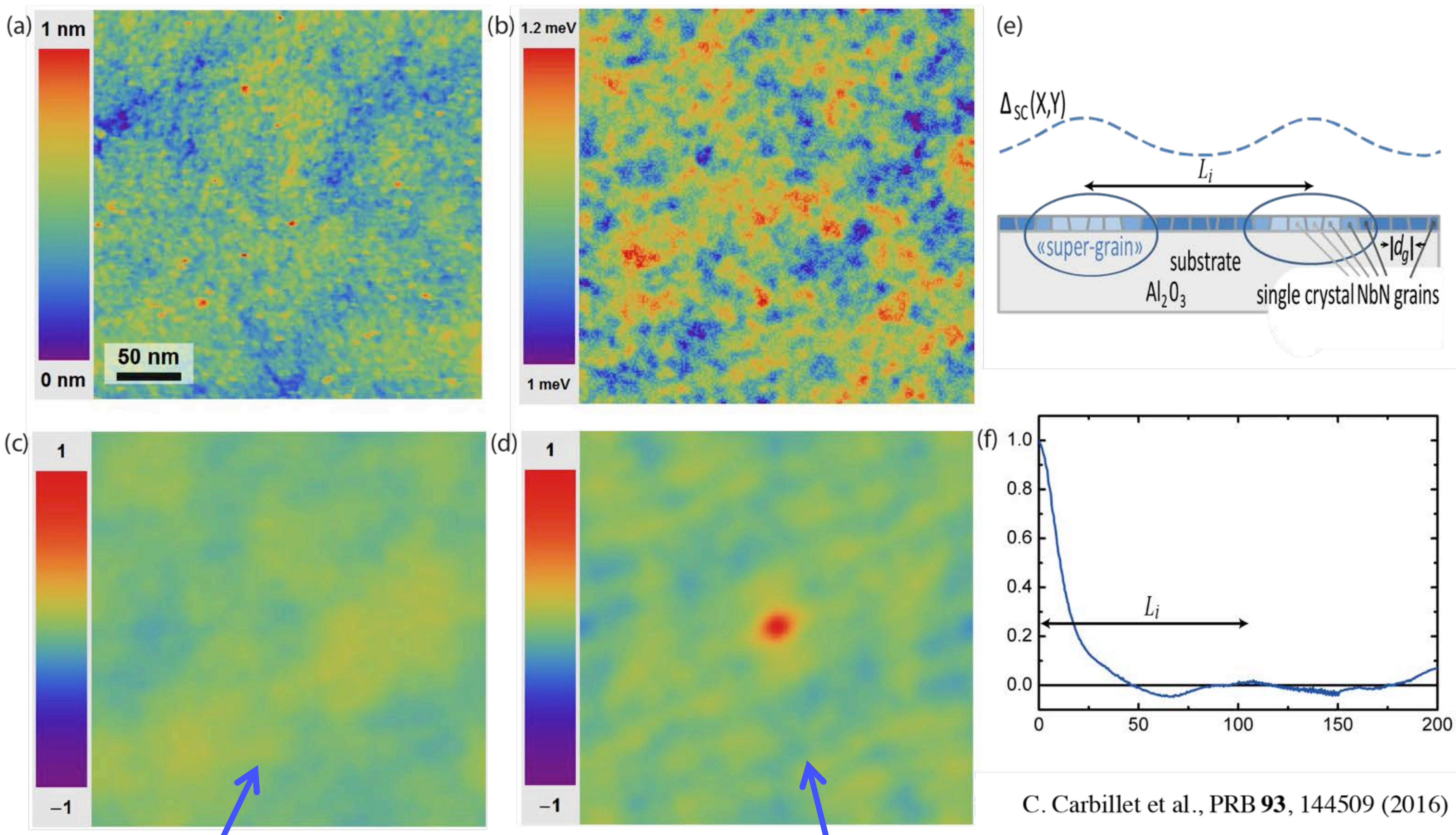
J. Biscaras[1], N. Bergeal[1], S. Hurand[1], C. Feuillet-Palma[1], A. Rastogi[2], R. C. Budhani[2,3], M. Grilli[4], S. Caprara[4] and J. Lesueur[1*]

Intermediate conclusion

- Several crossing points in magnetoresistance possible
- Despite very different origins, scaling often possible
- Strong similarities to phenomenology in InO_X
- More direct experimental information (besides $z\nu$) is desirable to understand specifics of the different phases:
  - mechanisms of conduction and insulation
  - is there a 'vortex Bose condensate' ?
  - use 2nd control parameter to check for universality!
  - features of the 'normal metal' at the critical point?

emergent electronic granularity in NbN

topography   density of states



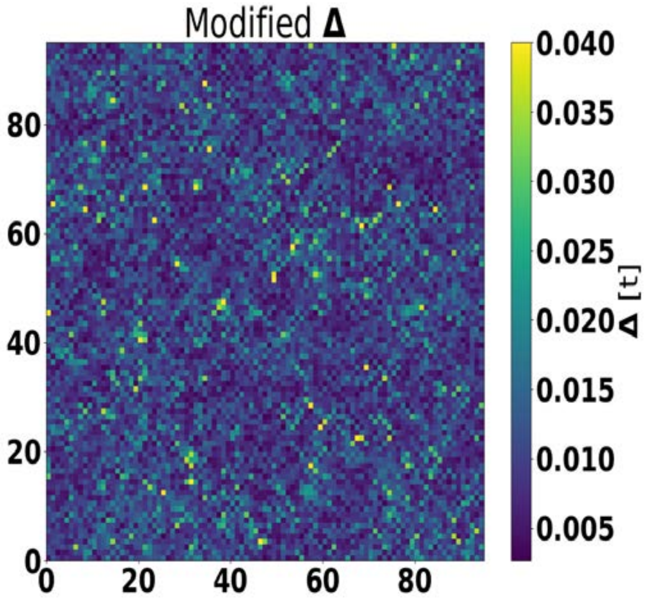
C. Carbillet et al., PRB **93**, 144509 (2016)

Roditchev group, INSP Paris

no cross-correlation between topography and electronic granularity

auto-correlation of electronic granularity

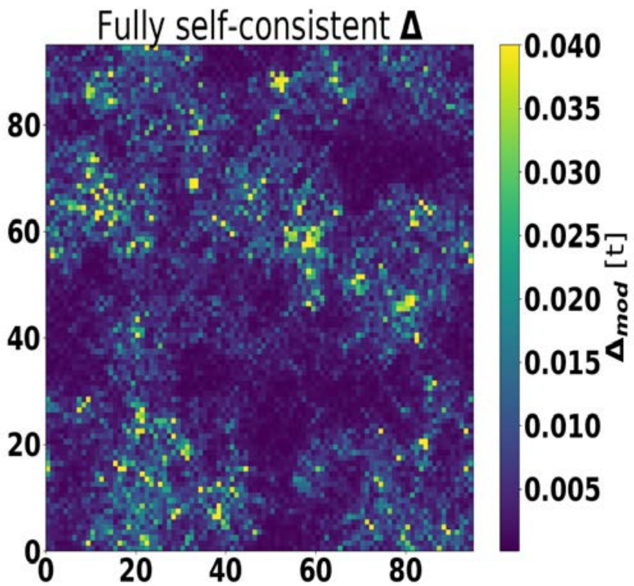
Numerical calculation of Δ(r) in presence of strong disorder



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)



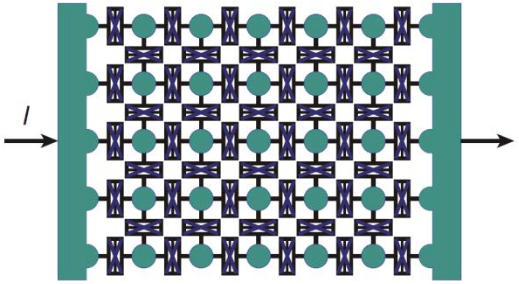
fully self-consistent scheme

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

(same disorder and parameter configuration, phase fluctuations neglected)

calculations by M. Stosiek, F. Evers

superconductor-insulator transition in TiN thin films



V. M. Vinokur et al., Nature **452**, 613-615 (2008)

model system: Josephson junction arrays

Quantum phase transitions and vortex dynamics in superconducting networks

Rosario Fazio[a,b,*], Herre van der Zant[c]

Phys. Rep. 355, 4 (2001) 235-334

two competing energy scales: **Josephson coupling energy E_J** vs. **charging energy E_C**

electronic fragmentation in TiN films → self organized superconducting islands

random Josephson junction array?

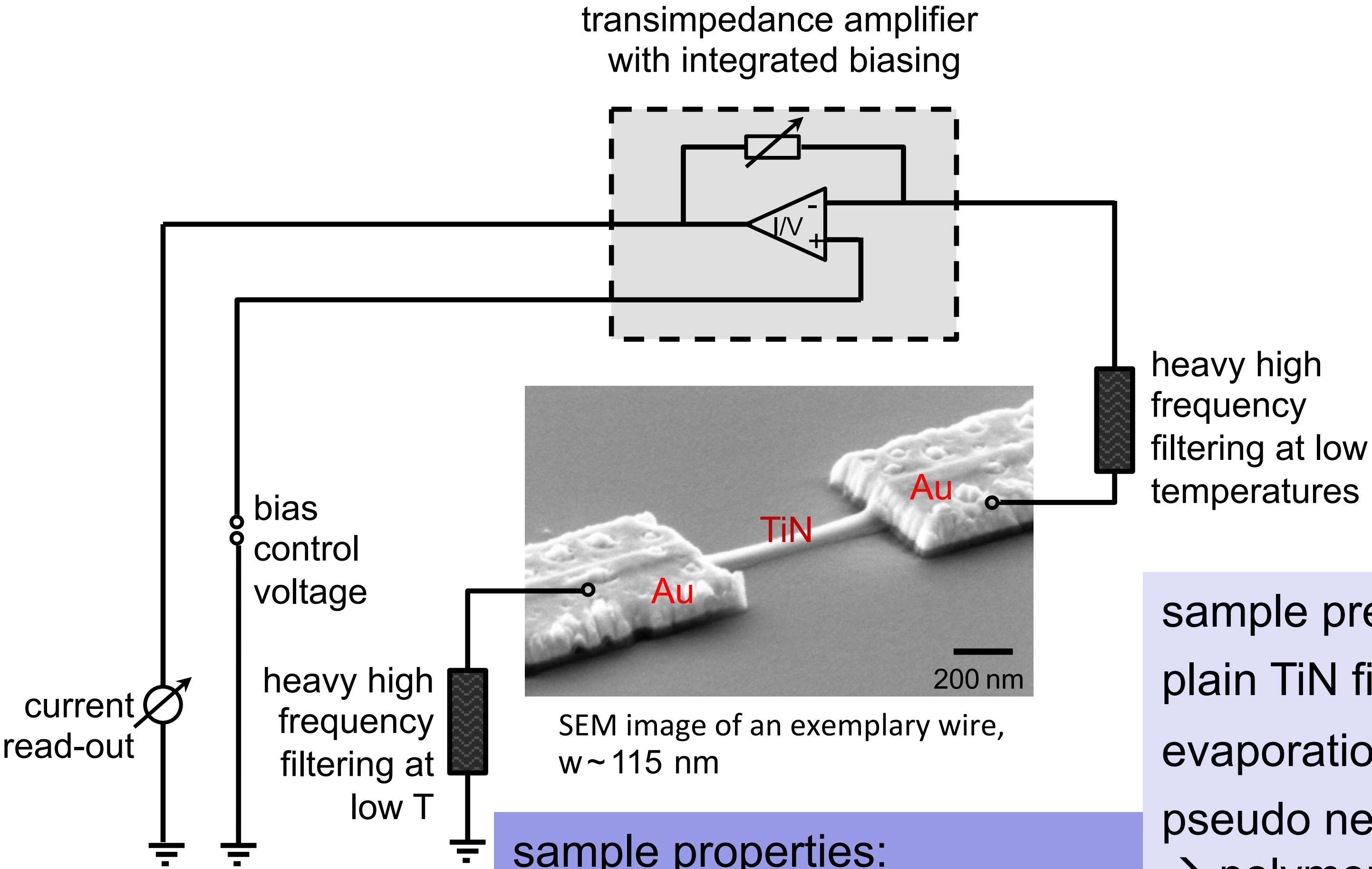
TiN: Sacépé et al., Phys. Rev. Lett. **101**, 157006 (2008)
NbN: Patel et al., Phys. Rev. B **80**, 012504 (2009), Carbillet et al., 93, 144509 (2016)
InO: Sacépé et al., Nat. Phys. **7**, 239 (2011)

Questions:

1. Is the superconductor-insulator transition in TiN thin films an effect of electronic fragmentation?

2. Can we find signatures of electronic fragmentation in submicron samples?

Sample layout and measurement setup



SEM image of an exemplary wire, w ~ 115 nm

sample properties:

fixed length *l* ~ 800 nm

varying widths w ~ 75-800 nm

1-10 squares

R_{300K} = 4.3 kΩ.. 44 kΩ

sample preparation:

plain TiN film deposited by ALD

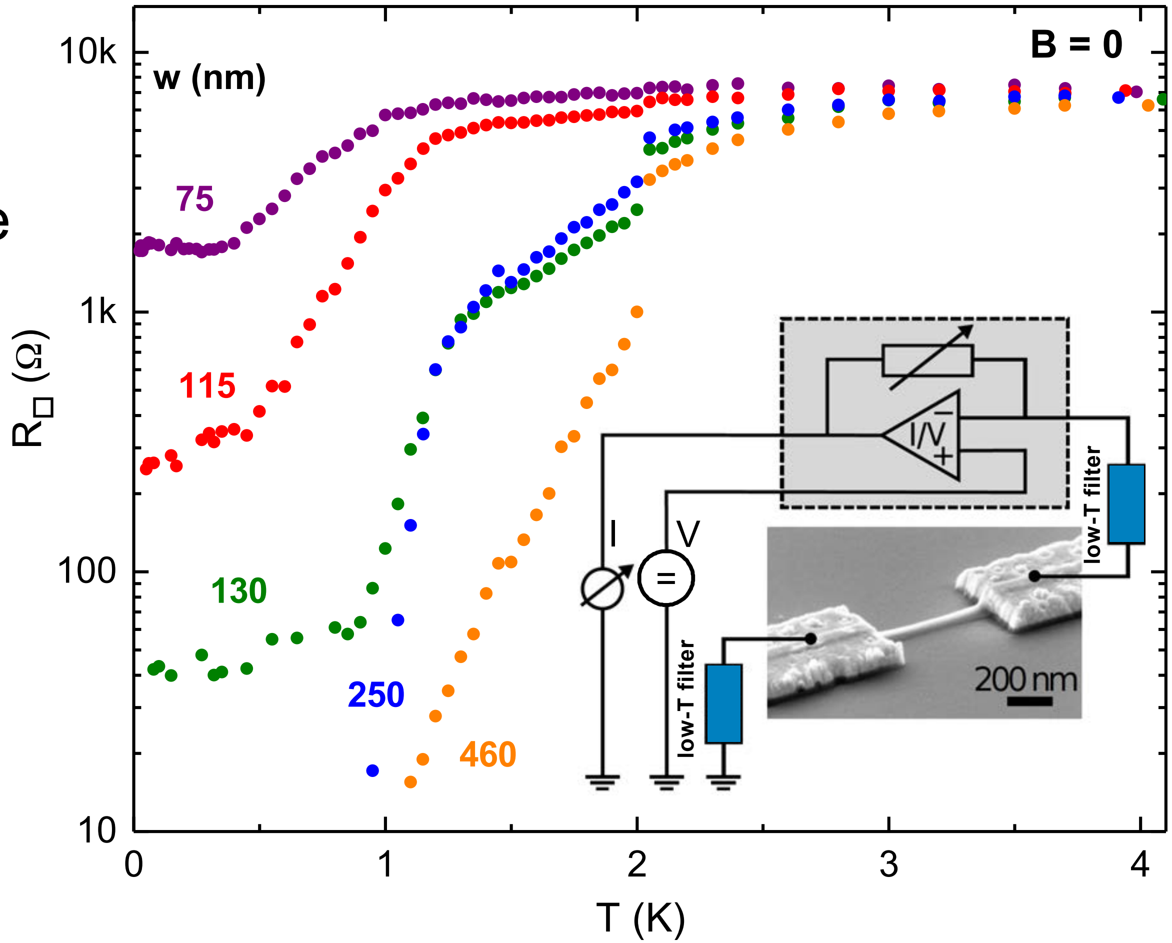
evaporation of Au contacts

pseudo negative EBL process
→ polymerized PMMA bridge between contacts

subtractive patterning by argon ion beam

width dependent saturation behavior in R(T)

- width dependent temperature behavior
- drop to zero resistance for wide wires
- saturation behavior for narrow wires
- suppression of global phase coherence
- evidence for quantum phase slips



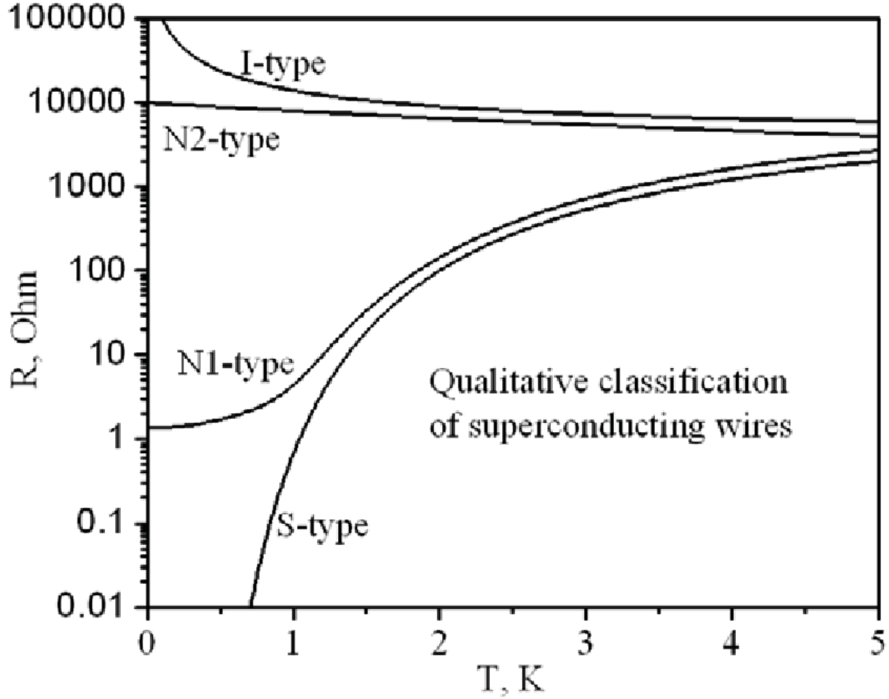
see also
Lau et al., PRL **87**, 217003 (2001)
Arutyunov et al., Phys. Rep. **464**, 1 (2008)
Bollinger et al., PRL **101**, 227003 (2008)

width dependent saturation behavior in R(T)

- width dependent temperature behavior
- drop to zero resistance for wide samples
- saturation behavior for small samples
- suppression of global phase coherence
- evidence for quantum phase slips

see also
Lau et al., PRL **87**, 217003 (2001)
Arutyunov et al., Phys. Rep. **464**, 1 (2008)
Bollinger et al., PRL **101**, 227003 (2008)

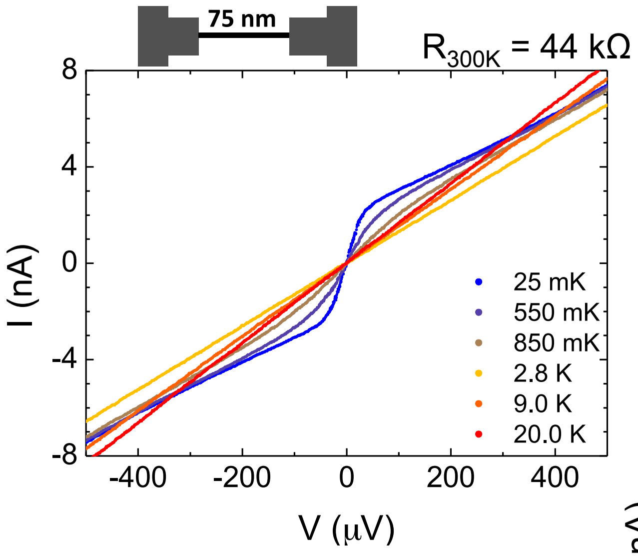
template fabricated α-MoGe nanowires



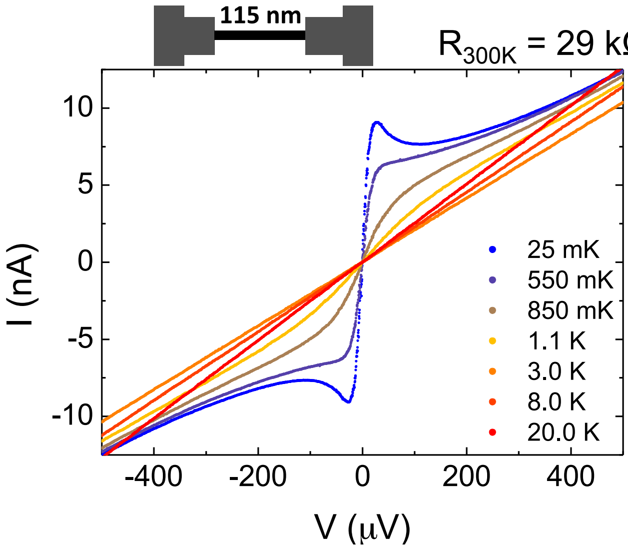
A. Bezryadin et al.,J. Phys.: Condens. Matter **20** (2008) 043202

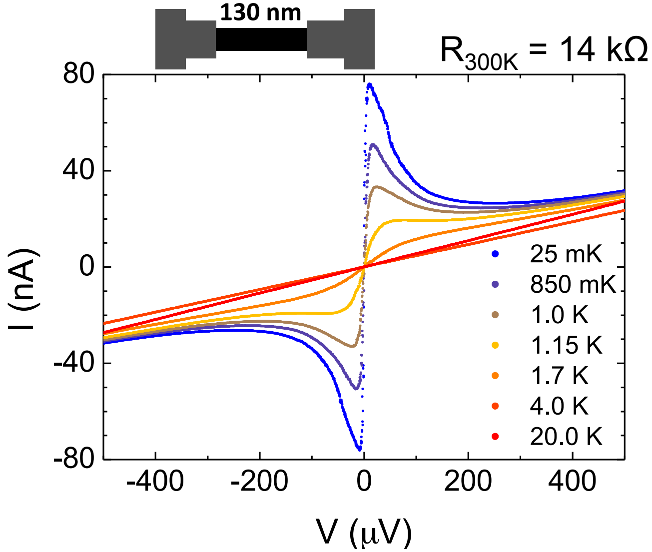
B = 0 T

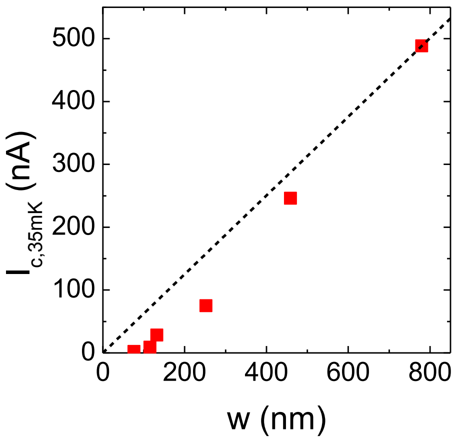
I(V) characteristics at B=0



- ❖ voltage bias
  → descending part of I(V)s accessible
- ❖ behavior different from superconducting films







critical current *density*
decreases with width

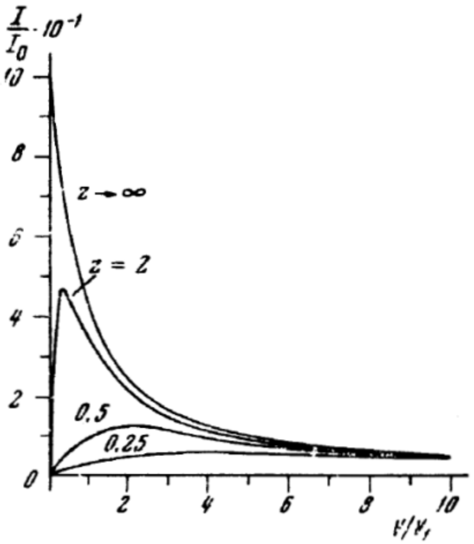
- ❖ **consistent with phase slip scenario**
- ❖ **I(V)s very similar to that of small Josephson junctions**

I(V) characteristics, behavior of small Josephson junctions

THE JOSEPHSON EFFECT IN SMALL TUNNEL CONTACTS

Yu. M. IVANCHENKO and L. A. ZIL'BERMAN

Sov. Phys. JETP **28**, 1272 (1969)



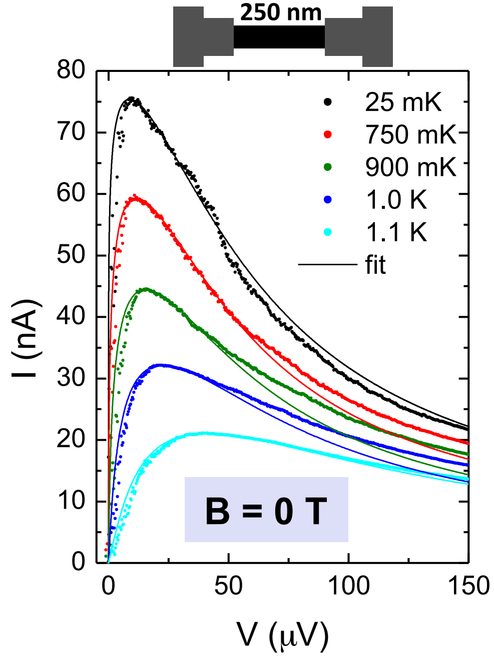
pure Ohmic damping,
phase fluctuations:

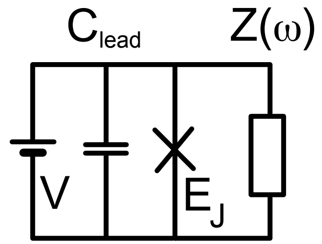
$$I(V_B) = I_0 \, \mathrm{Im}\left[\frac{I_{1-2i\beta eV_B/\hbar R_B}(\beta E_J)}{I_{-2i\beta eV_B/\hbar R_B}(\beta E_J)}\right]$$

$$V_B = V + R_B I, \; \beta = \frac{1}{k_B T}$$

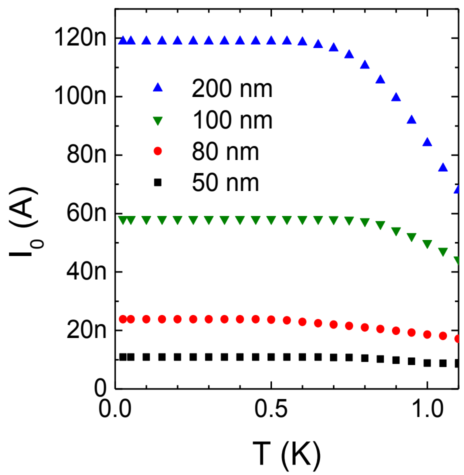
see also Steinbach et al., Phys. Rev. Lett. **87**, 13 (2001)

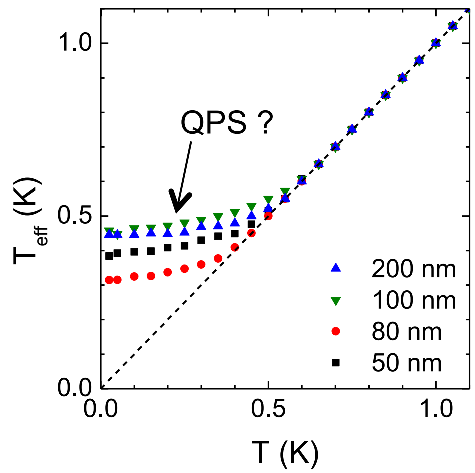
fit parameters: $I_0 = I_0(T),\, T = T_{eff}(T)$



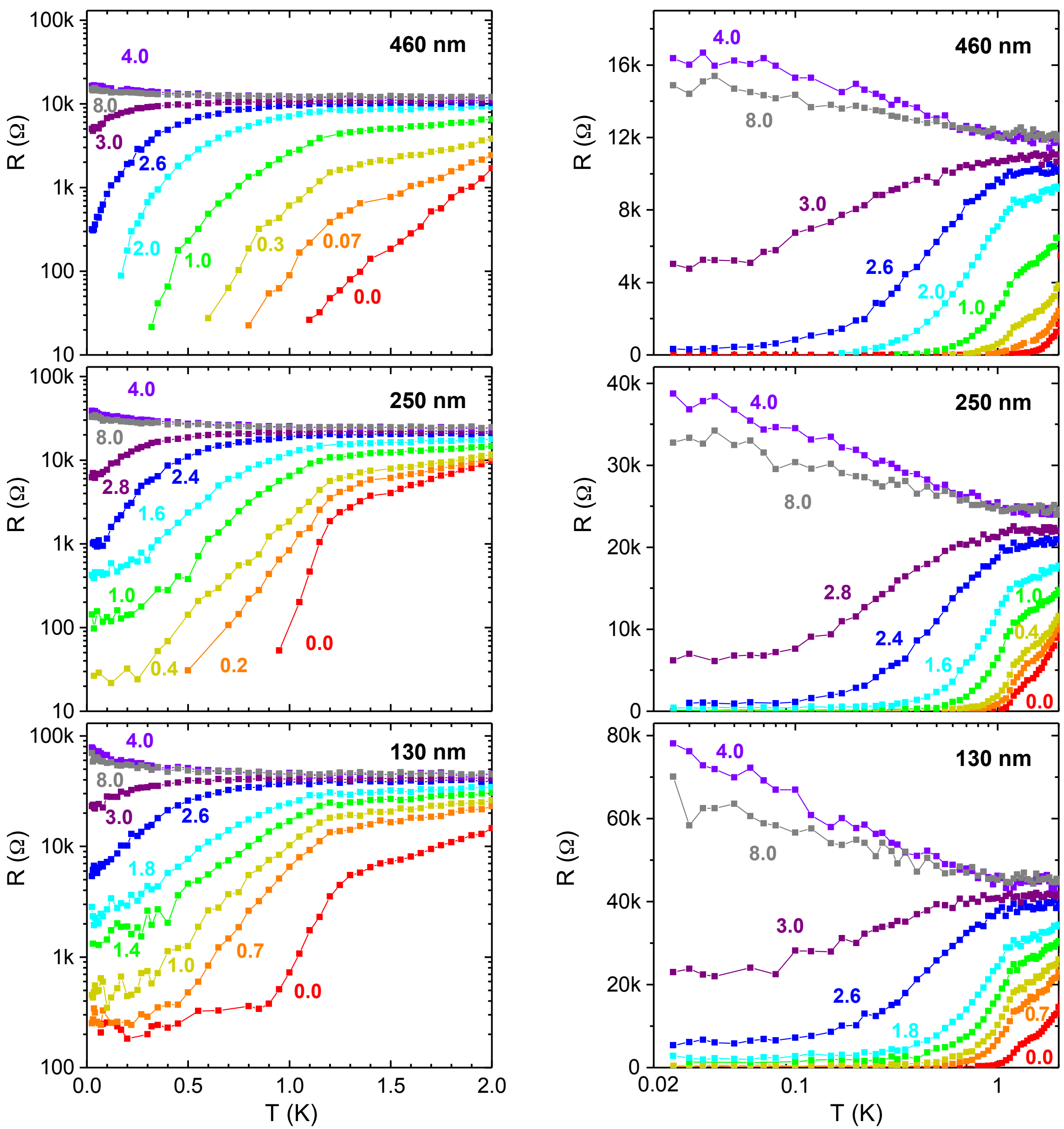


model describes diffusive motion resulting from thermal noise in the ohmic environ-ment of the junction





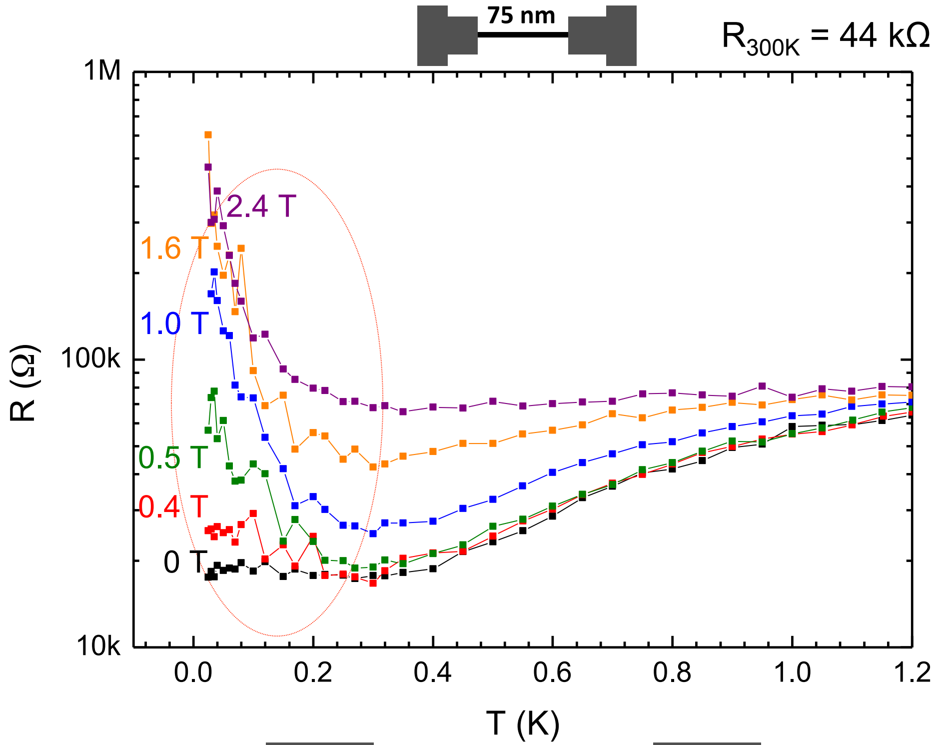
R(T) in perpendicular magnetic field for wider samples

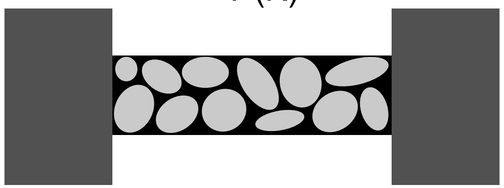


- saturating R at low T and B
- crossover to a weakly localized regime at high B
- no formation of highly insulating states

Cooper-pair insulator and superinsulator do not come from local conduction properties of the material, but require certain minimal size

evolution of R(T) in magnetic field

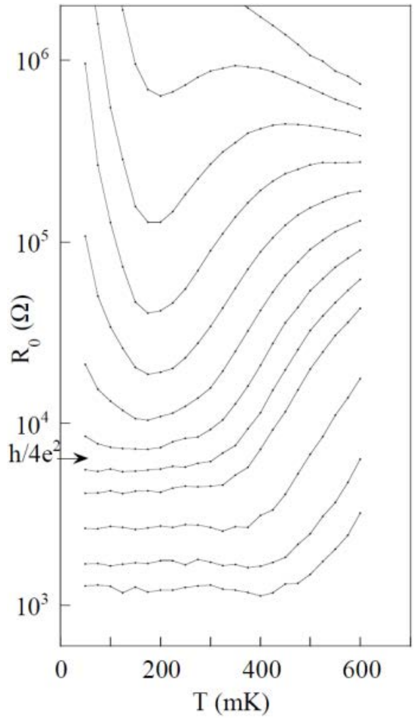


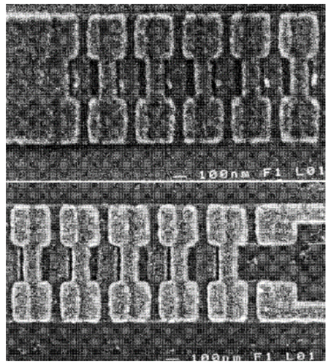


Superconducting and Insulating Behavior in One-Dimensional Josephson Junction Arrays

David B. Haviland, Karin Andersson, Peter Ågren

J. Low Temp. Phys. **118**, 5 (2000)





SEM image of two artificial SQUID arrays

- reentrant insulating behavior: understandable in terms of a magnetic field tuned E_J/E_C
- spontaneously formed random Josephson junction array? → compare to artificial JJ arrays

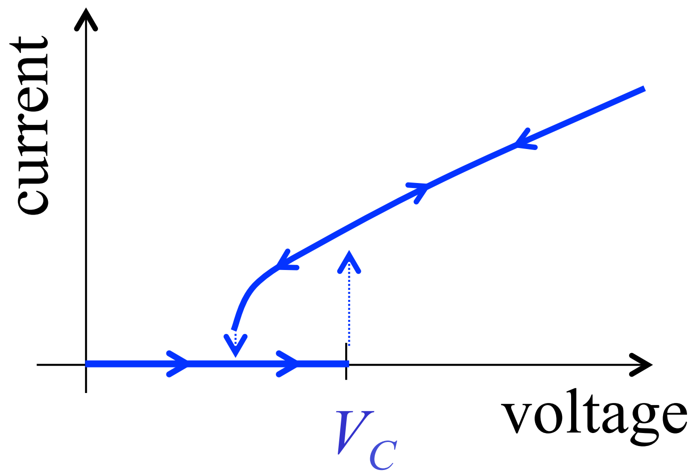
very similar behavior to that observed for one-dimensional Josephson junction arrays

charge-phase duality

$$\Delta Q \rightarrow 0$$

Coulomb Blockade of Cooper pair Tunneling

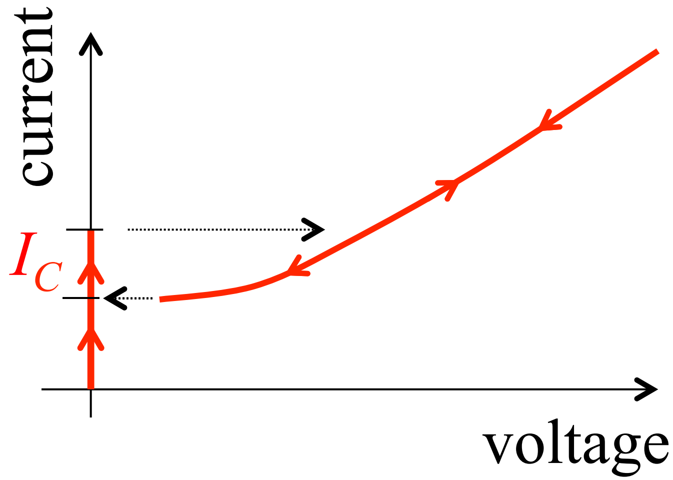
$$V = V_C \sin\chi \qquad I = \frac{2e}{2\pi}\frac{d\chi}{dt}$$



$$\Delta \Phi \rightarrow 0$$

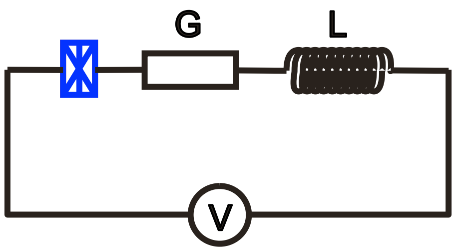
Josephson Effect

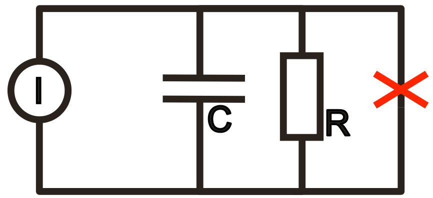
$$I = I_C \sin\phi \qquad V = \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$



Josephson junction acts as:

Non-linear capacitor



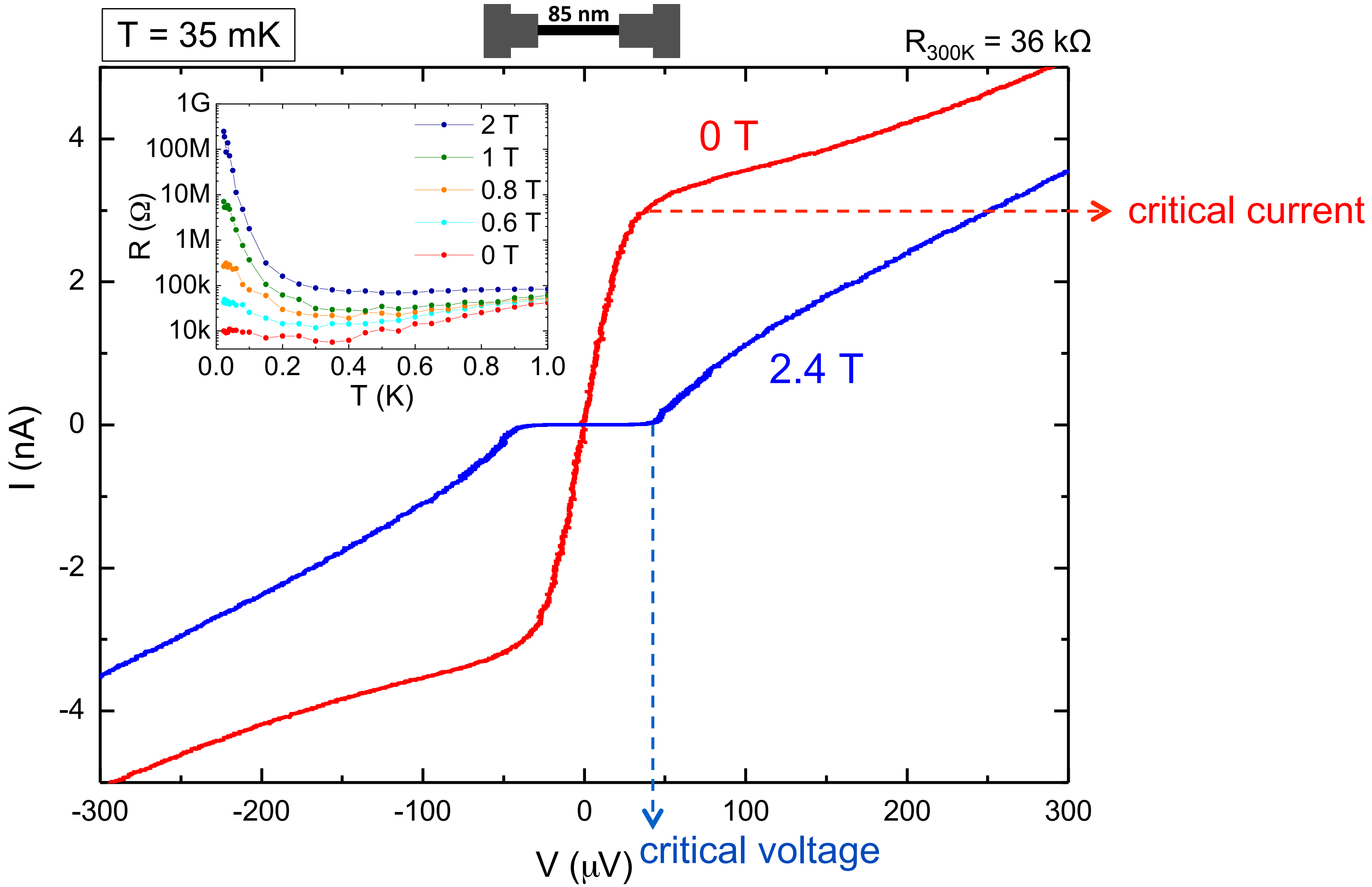


Non-linear inductor

evolution of R(T) in magnetic field

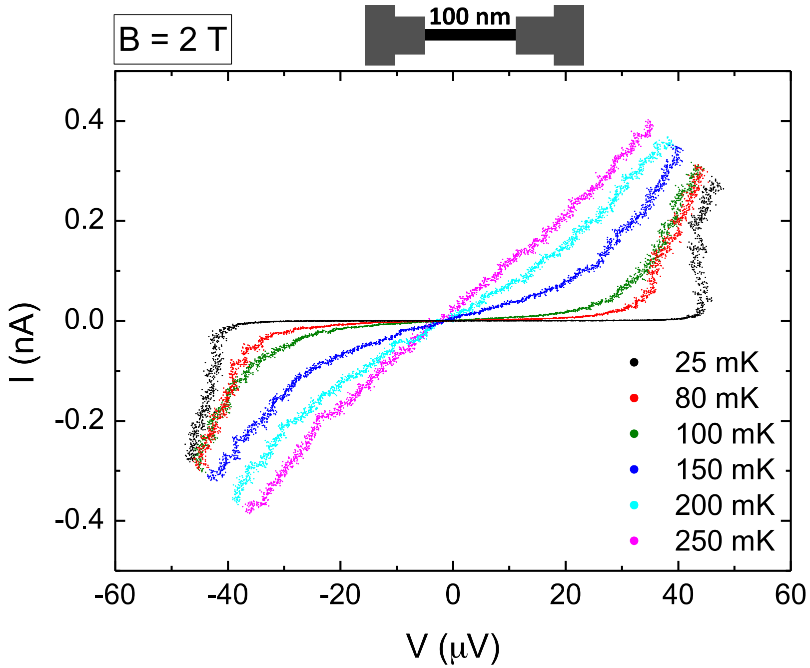
same film, different sample:

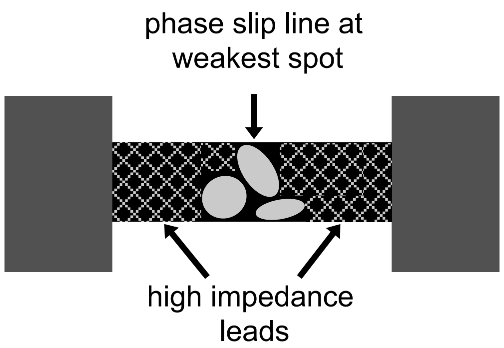
magnetic field induced superconductor-insulator transition



low T bias resistors 2 x 50 kΩ

characteristics of the insulating state

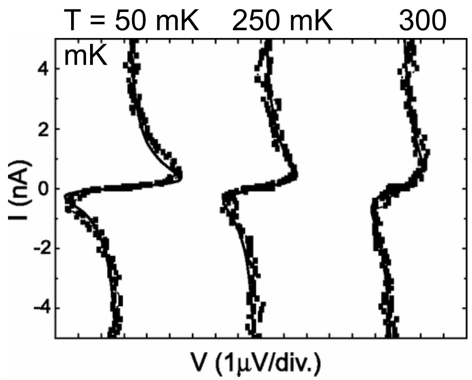


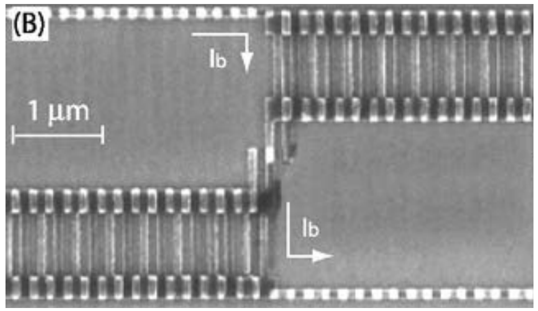


Phase-Charge Duality of a Josephson Junction in a Fluctuating Electromagnetic Environment

S. Corlevi,[1] W. Guichard,[1,2] F. W. J. Hekking,[2] and D. B. Haviland[1]

Phys. Rev. Lett. **97**, 096802 (2006)

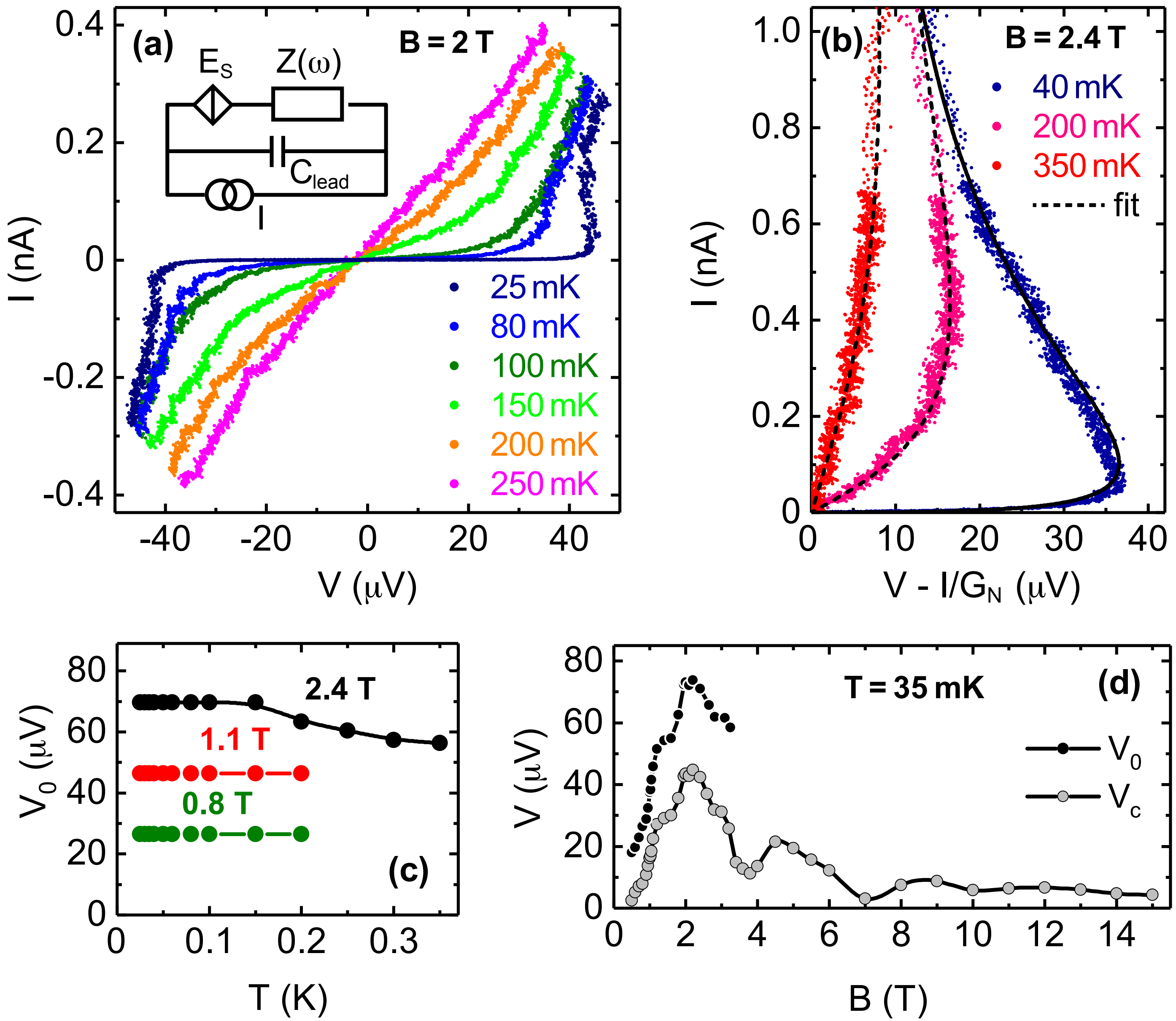




SEM image of a single junction configuration

very similar behavior to that observed for a single Josephson junction in a high impedance environment

characteristics of the insulating state



subtract voltage in 'normal' state:

IV-curves can be described by *dual* Ivanchenko-Zilberman-model