Anomalous Metals and Failed Superconductors

With

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Context – Two Pillars of Our Understanding of Quantum Mater

"Anderson localization" implies no metals in 2D

Small Ginzburg parameter implies there are no important superconducting fluctuations in "conventional" superconductors

Both are seemingly wrong.

“Anderson localization” implies no metals in 2D?

$$\sigma = \frac{e^2}{h}\,(k_F \ell)\left\{1 - \left(\frac{1}{2\pi k_F \ell}\right)\log\left|\frac{L_T}{\ell}\right| \; + \ldots\right\}$$

Extended using perturbative RG analysis

Verified numerically for non-interacting particles

No theoretical control in the presence of strong interactions or when $k_F\ l \sim 1$.

$$T^\star \sim E_F \exp[-\pi k_F \ell]$$

Even for weak interactions, there could be new effects at scales $E_F >>> E >>> T^*$.

“Anderson localization” implies no metals in 2D??

Apparent Metal Insulator Transition in Clean 2DEGs with large r_s

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Quantum Hall Metal in 2DEG in large H

Quantum Superconductor to Insulator transitions in 2D

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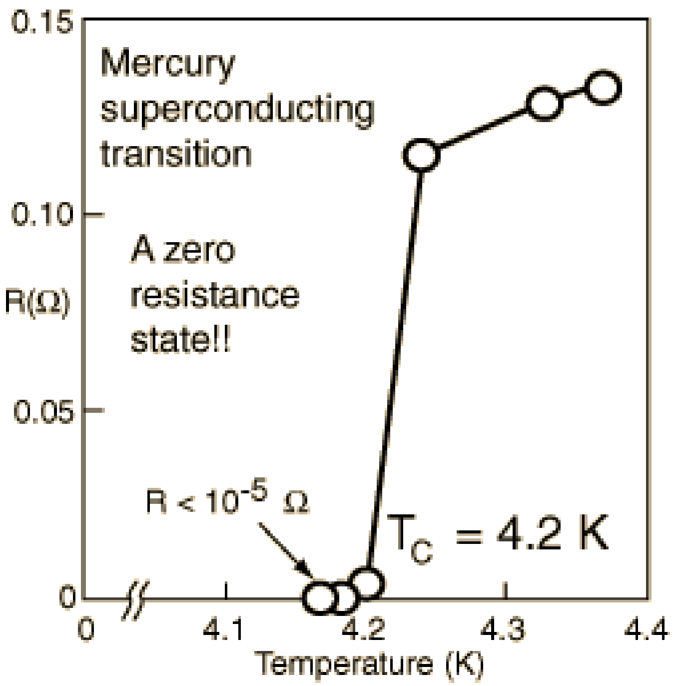
Quantum Superconductor to Metal transitions in 2D

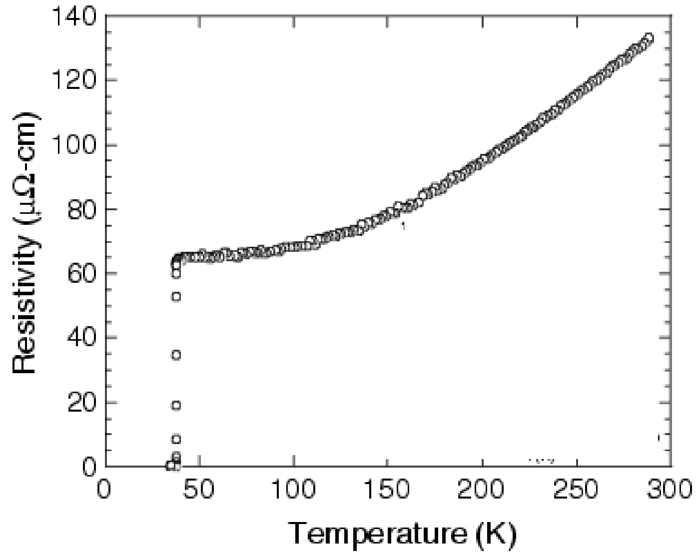
Small Ginzburg parameter implies there are no important superconducting fluctuations in “conventional” superconductors

$$\mathcal{N} = \rho(E_F)(\xi_0)^d \Delta_0 \qquad \mathcal{G} = 1/\mathcal{N}$$

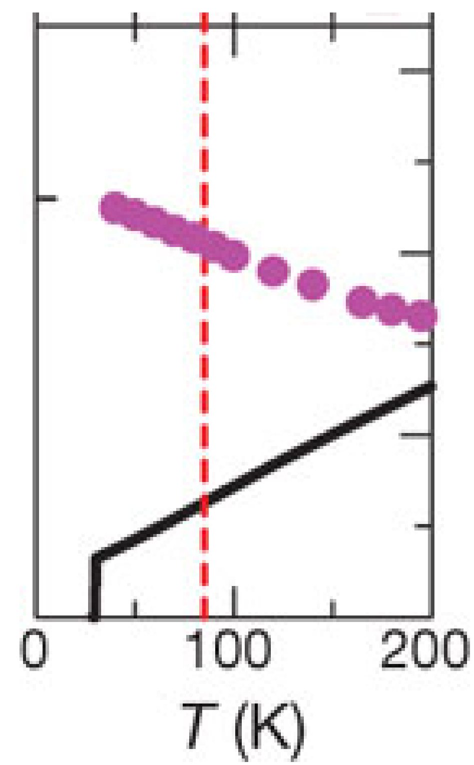
Small Ginzburg parameter implies there are no important superconducting fluctuations in “conventional” superconductors



Onnes data on Hg



MgB_2



Matsuda data on Fe 122

Small Ginzburg parameter implies there are no important superconducting fluctuations in "conventional" superconductors

$$\mathcal{N} = \rho(E_F)(\xi_0)^d \Delta_0 \qquad\qquad \mathcal{G} = 1/\mathcal{N}$$

"Fluctuation Superconductivity" of Aslamazov-Larkin and Maki-Thomson are small (Gaussian) corrections to mean-field theory except in parametrically narrow region around T_c.

Small Ginzburg parameter implies there are no important superconducting fluctuations in “conventional” superconductors

The case of the quantum transition is even worse:

$$\Delta_0 \sim \omega_0 \ \exp[-1/\lambda^{eff}(x)]$$

$$\lambda^{eff} > 0 \text{ for } x < x_c$$

$$\lambda^{eff} < 0 \text{ and } \Delta_0 = 0 \text{ for } x < x_c$$

$$\lambda^{eff} = 0 \text{ for } x = x_c$$

Interactions in other channels are “irrelevant.”

There are no quantum critical fluctuations at all!

Quantum phase transitions from SC state to non-superconducting state

Varying gate voltage, magnetic field, film thickness …

As T tend to zero,

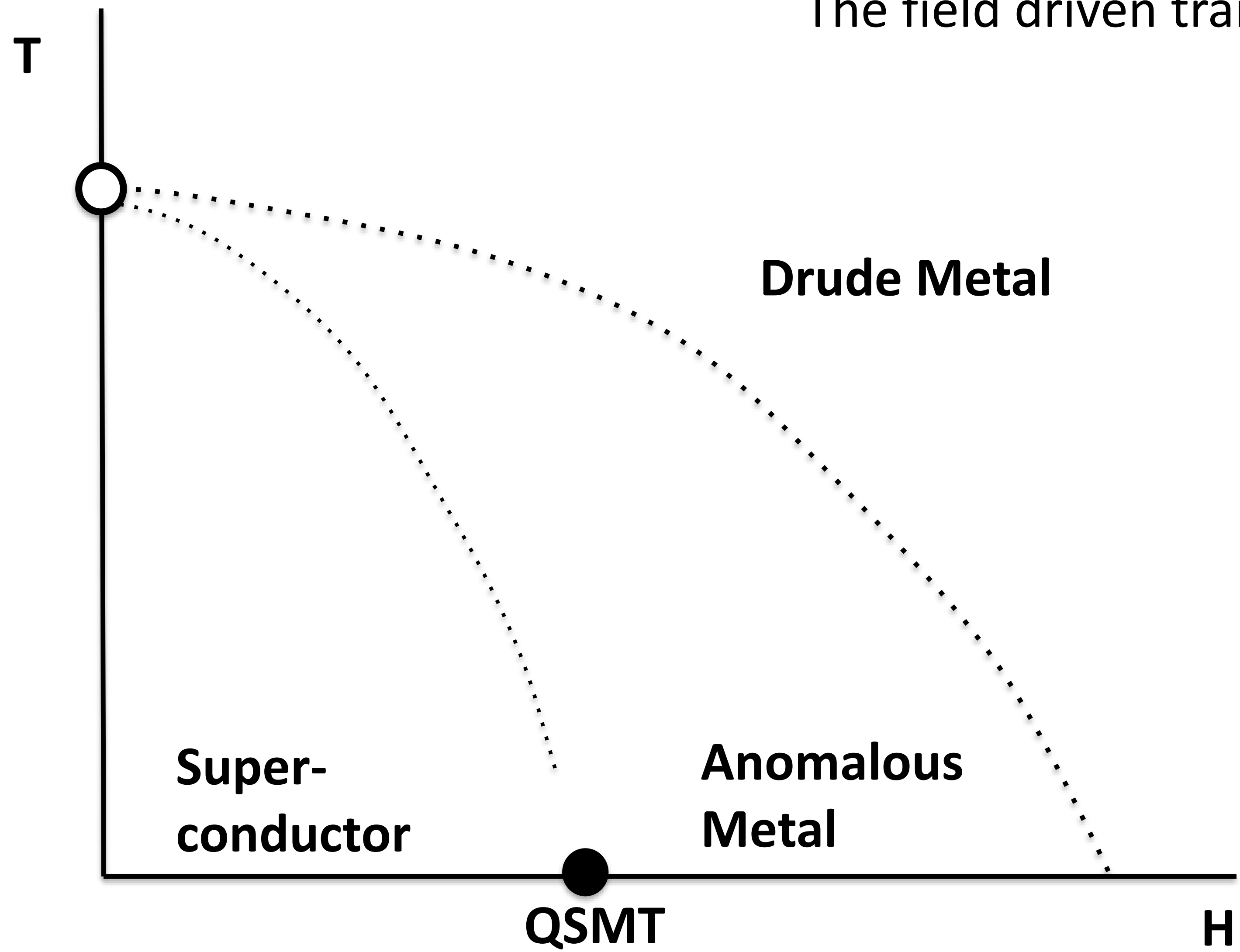
Superconducting for $x < x_c$

Non superconducting for $x > x_c$

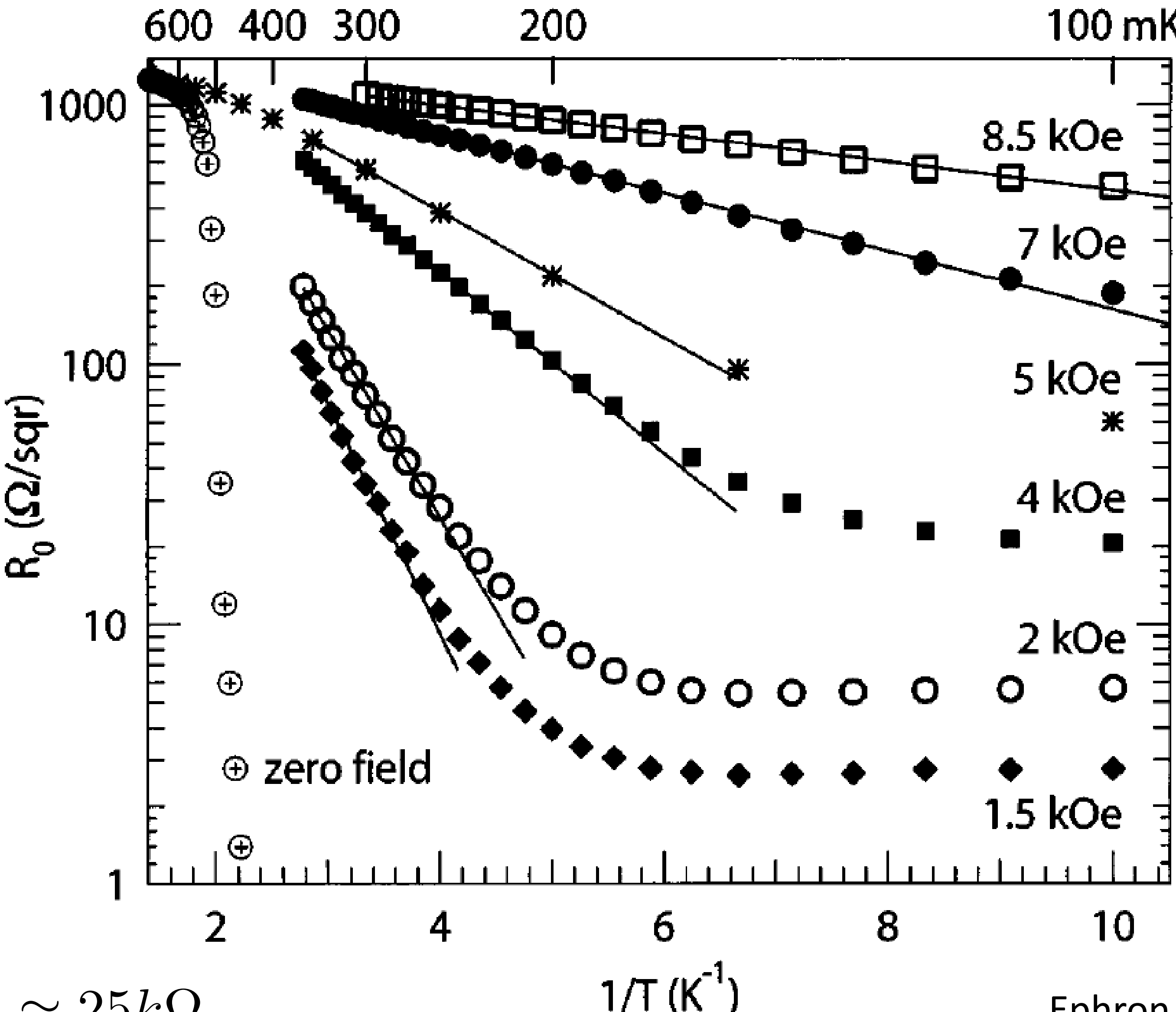
Normal state characterized by Drude conductivity:

$$\rho = h/e^2 \ (k_F \ell)^{-1} \qquad h/e^2 \approx 25 k\Omega$$

The field driven transition



Magnetic Field Driven QSMT in aMoGe films



$h/e^2 \approx 25k\Omega$

Ephron *et al*, PRL (1996)

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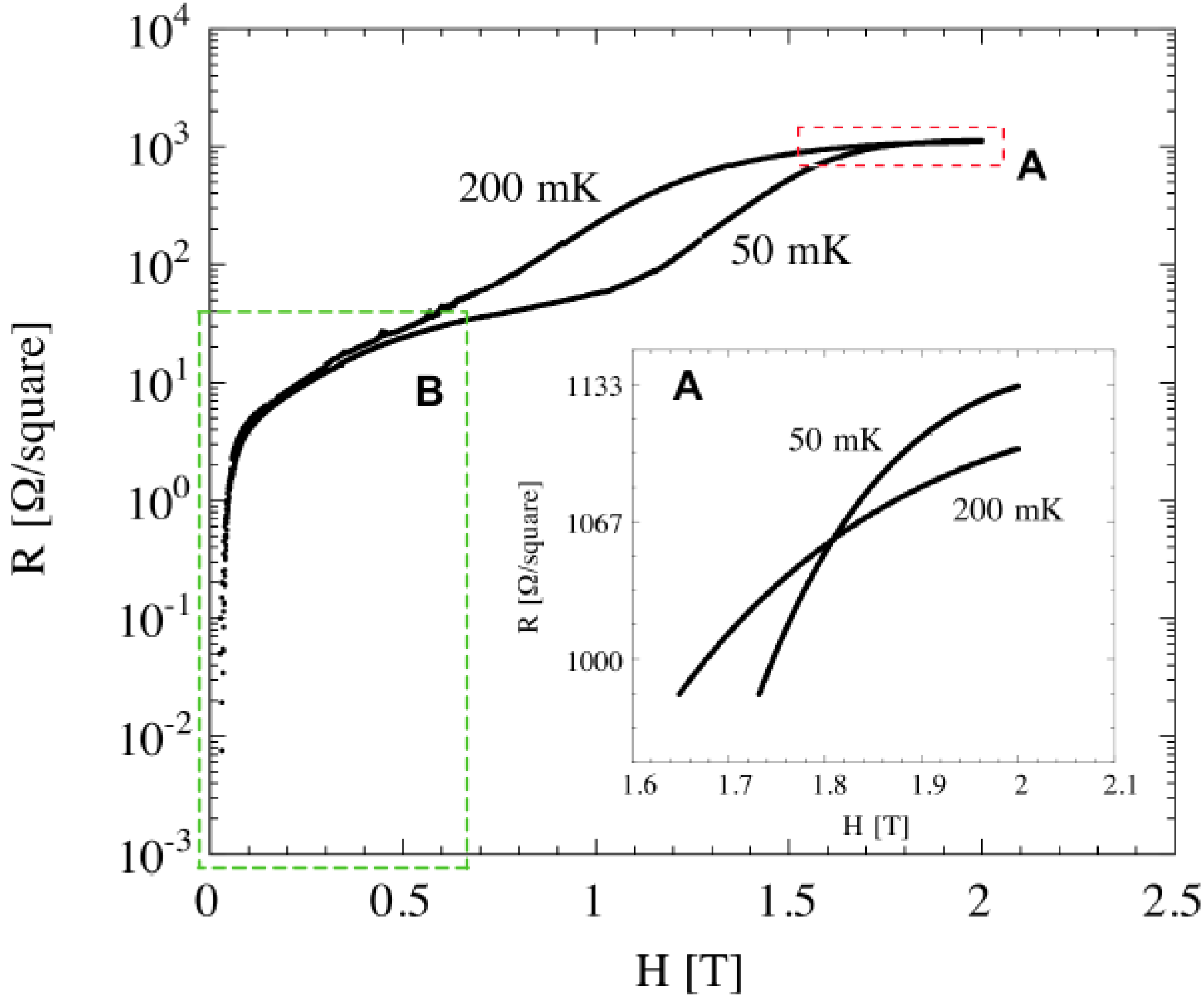
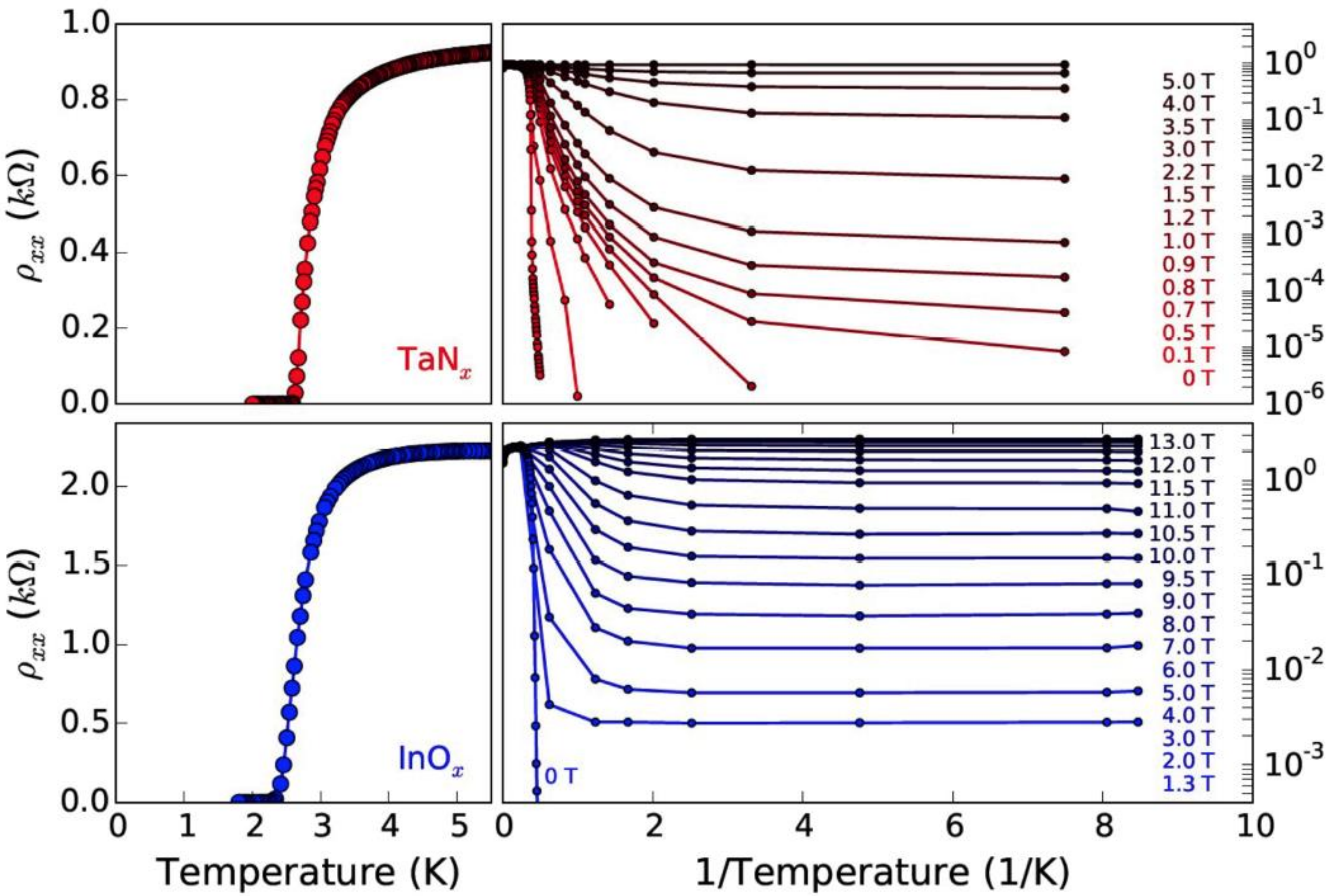


$h/e^2 \approx 25k\Omega$

Mason and Kapitulnik, PRL (1999)

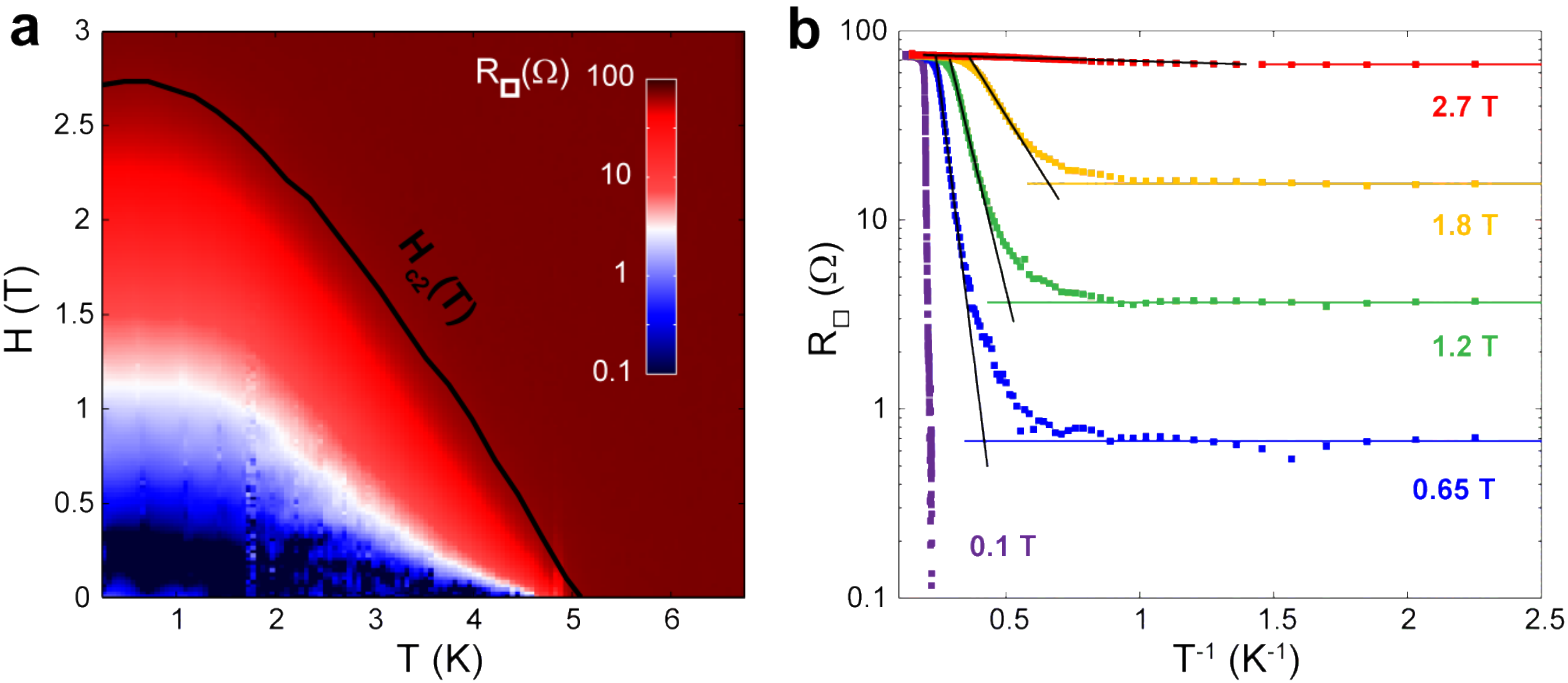
Magnetic Field Driven QSMT a-TaN_x and a-InO_x films



$$e^2/h \approx 25k\Omega$$

Breznay and Kapitulnik, Science Advances (2017)

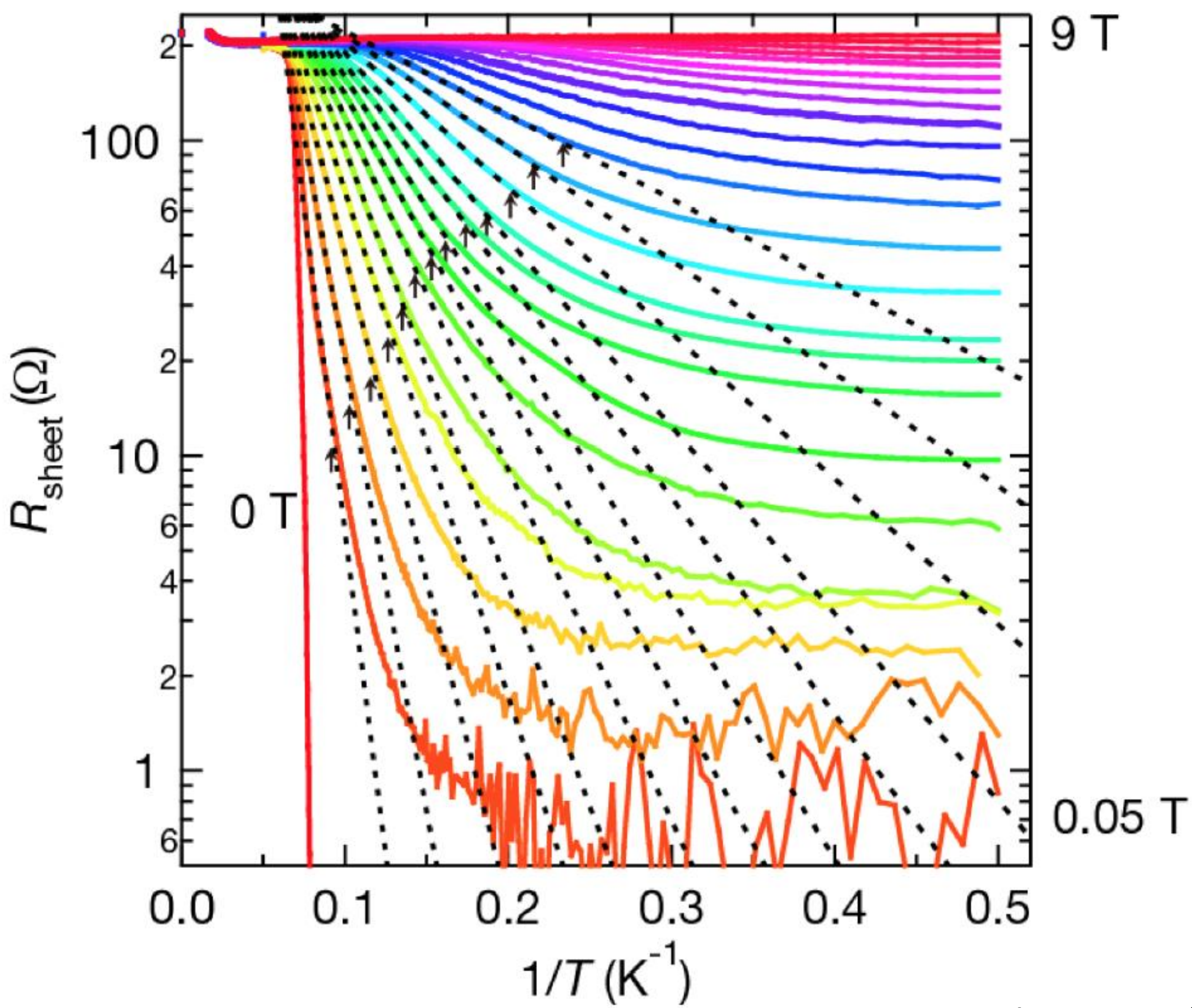
Magnetic Field Driven QSMT in crystalline films of $NbSe_2$



$$h/e^2 \approx 25k\Omega$$

Tsen *et al*, Nature Physics (2016)

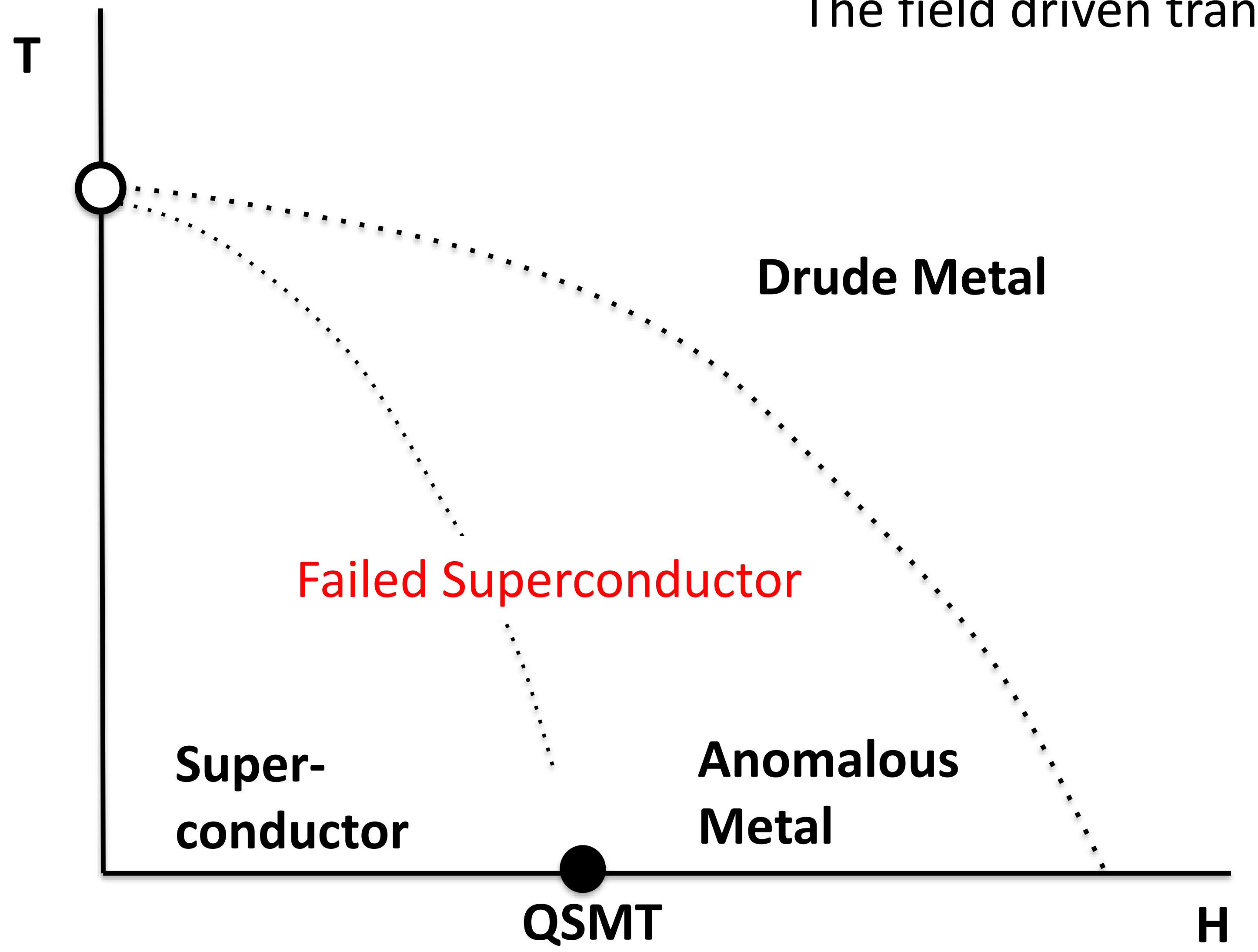
Magnetic Field Driven QSMT in a highly crystalline ZrNCl electric double layer transistor (Ion gated)

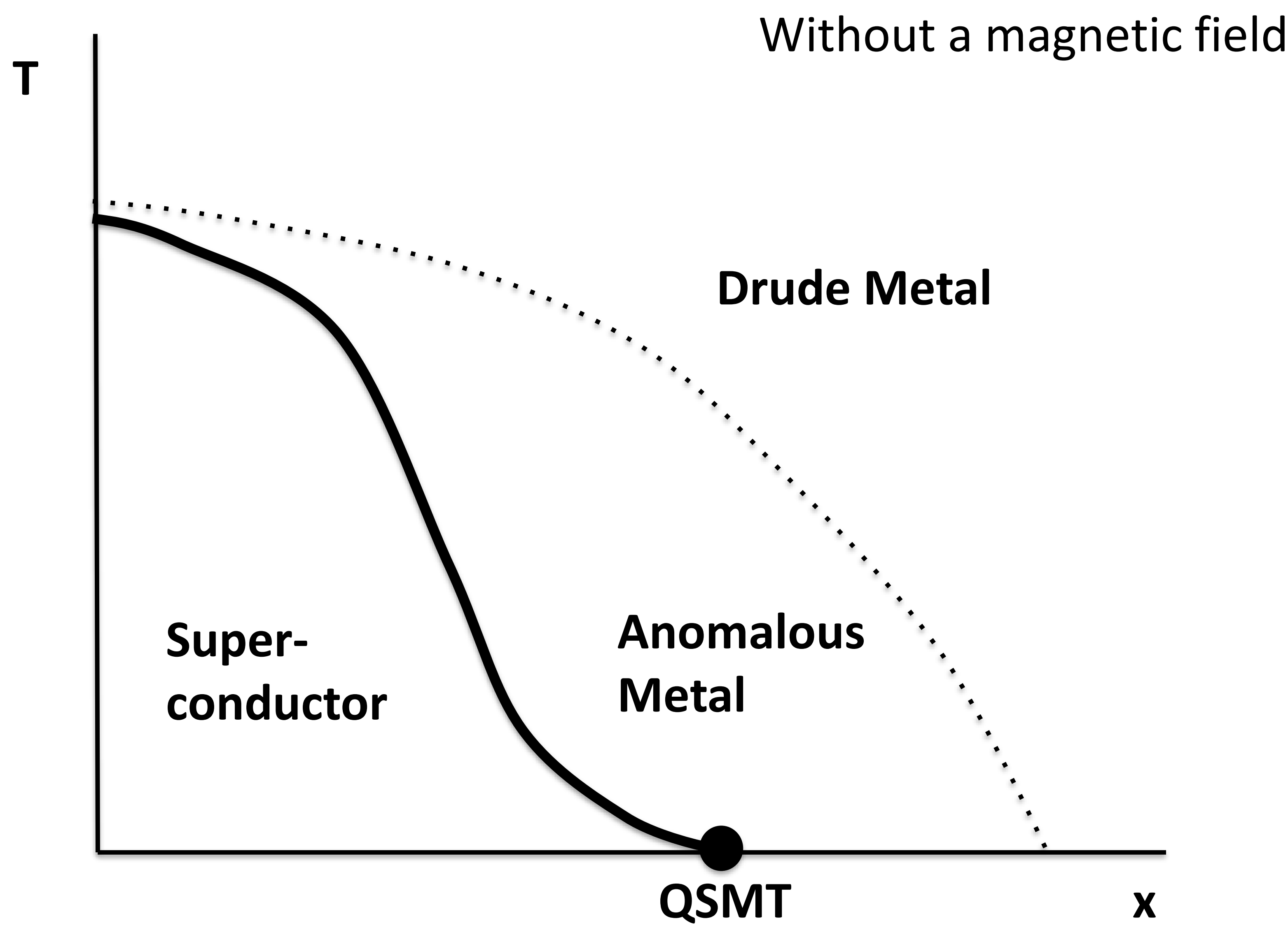


$$h/e^2 \approx 25k\Omega$$

Saito *et al*, Science (2015)

The field driven transition




Without a magnetic field
T
Drude Metal
Super-
conductor
Anomalous
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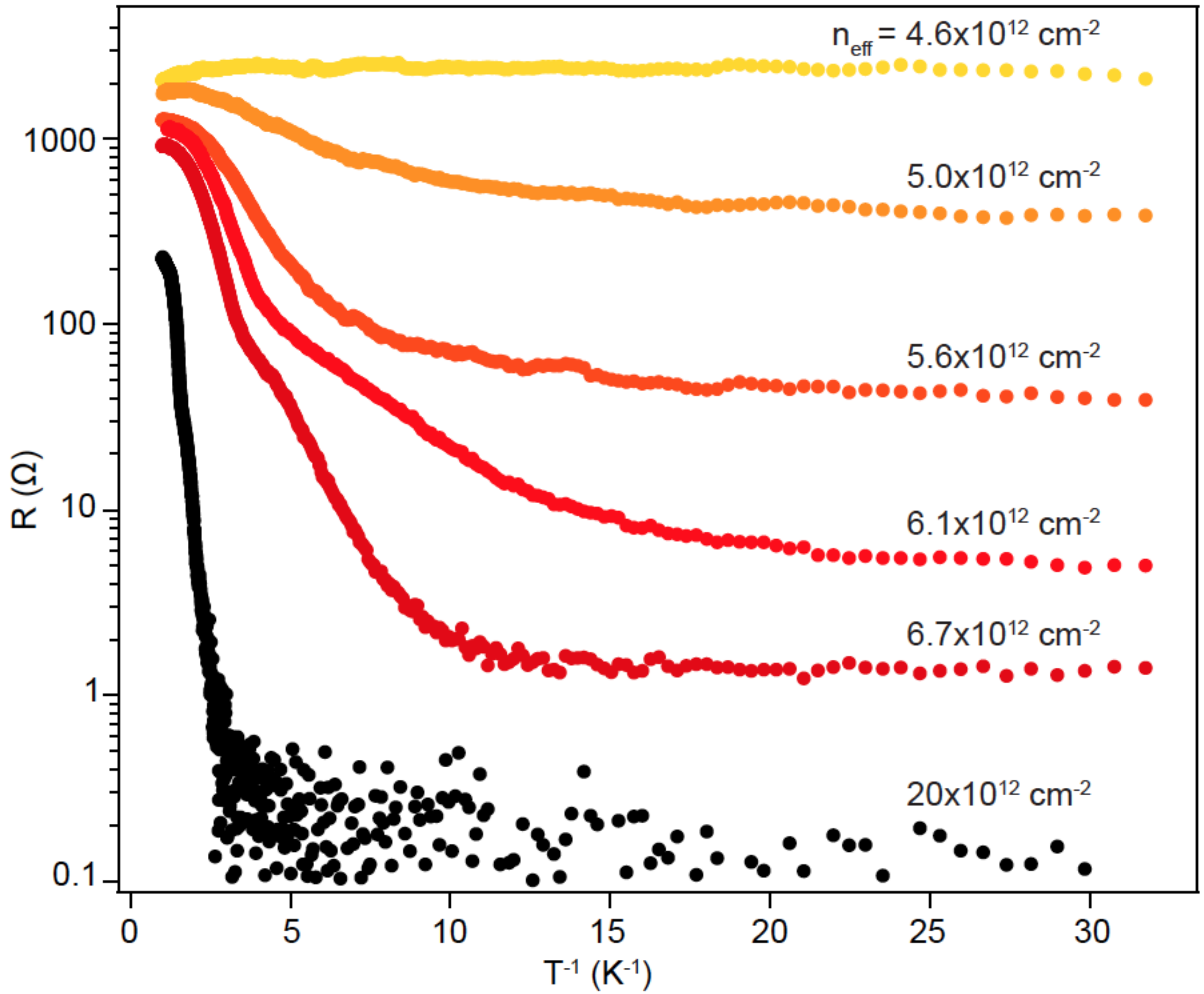
QSMT
x

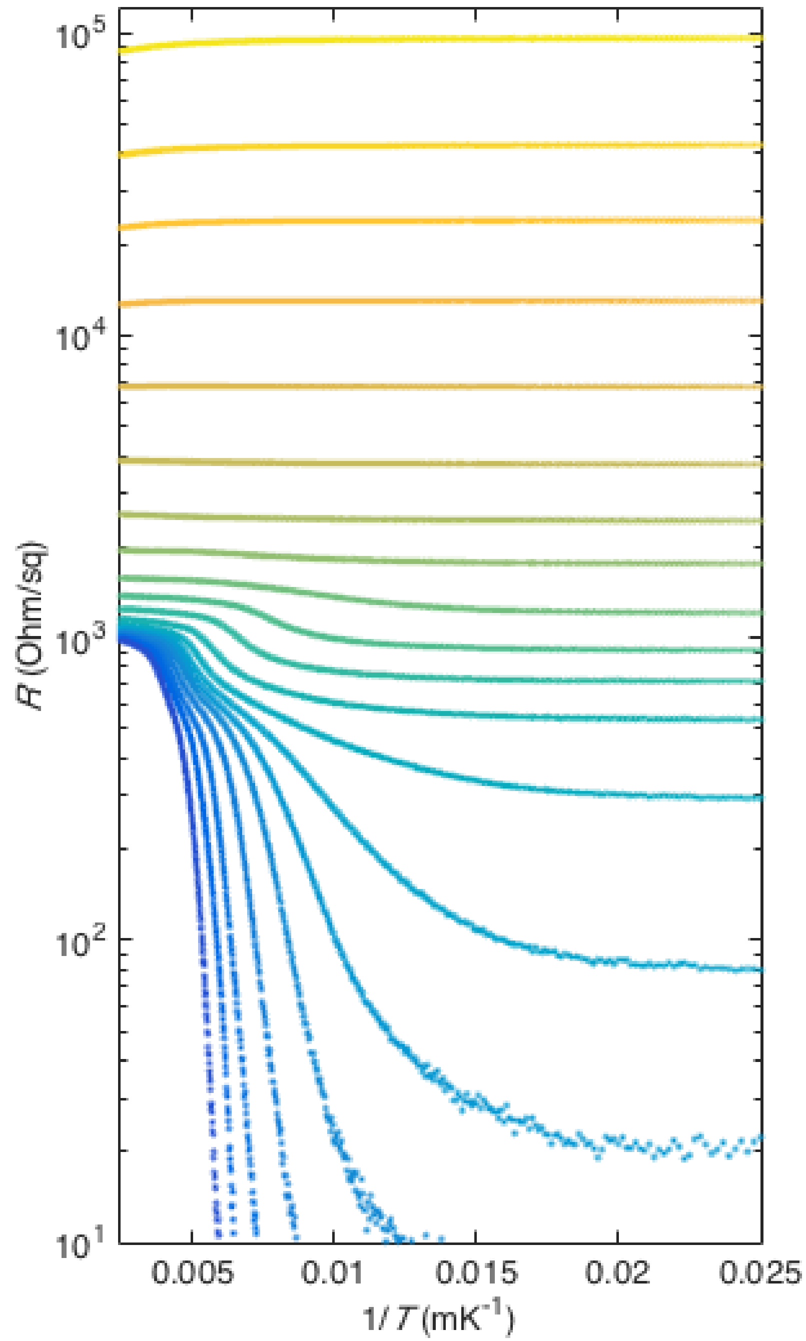
Gate voltage driven QSMT in a WTe_2 flake



Sajidi *et al* (D. Cobden group from U. Washington) unpublished

$$h/e^2 \approx 25k\Omega$$

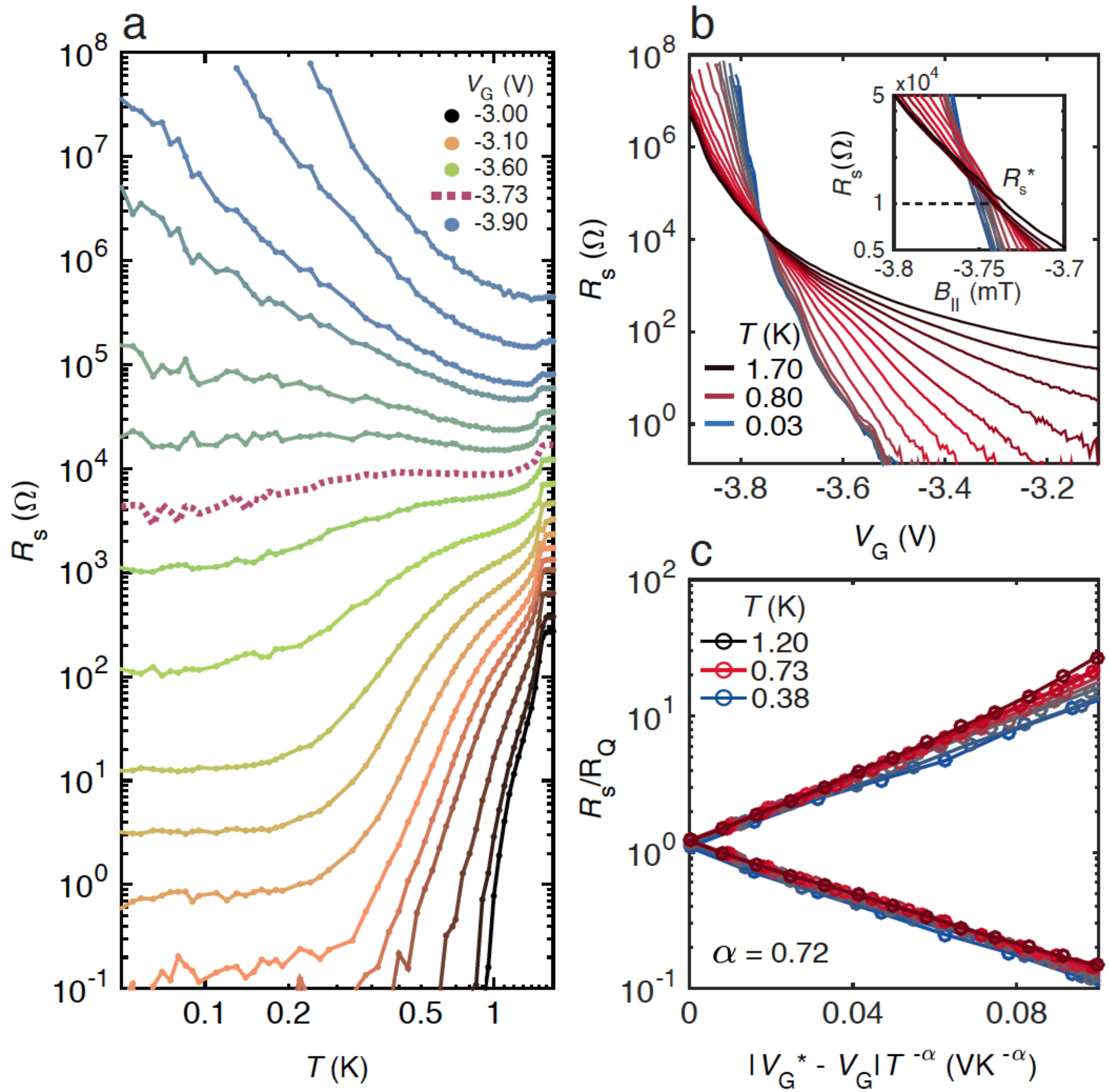
Gate voltage Driven QSMT in a $SrTiO_3$-$SrAlO_3$ heterostructure



Chen *et al* (H. Hwang's group at Stanford) submitted for publication)

$$h/e^2 \approx 25k\Omega$$

Gate voltage Driven QSMT in a gated two-dimensional semiconductor-superconductor array



Bottcher et al (C. Marcus's group at Niels Bohr Institute, submitted for publication)

$$h/e^2 \approx 25k\Omega$$

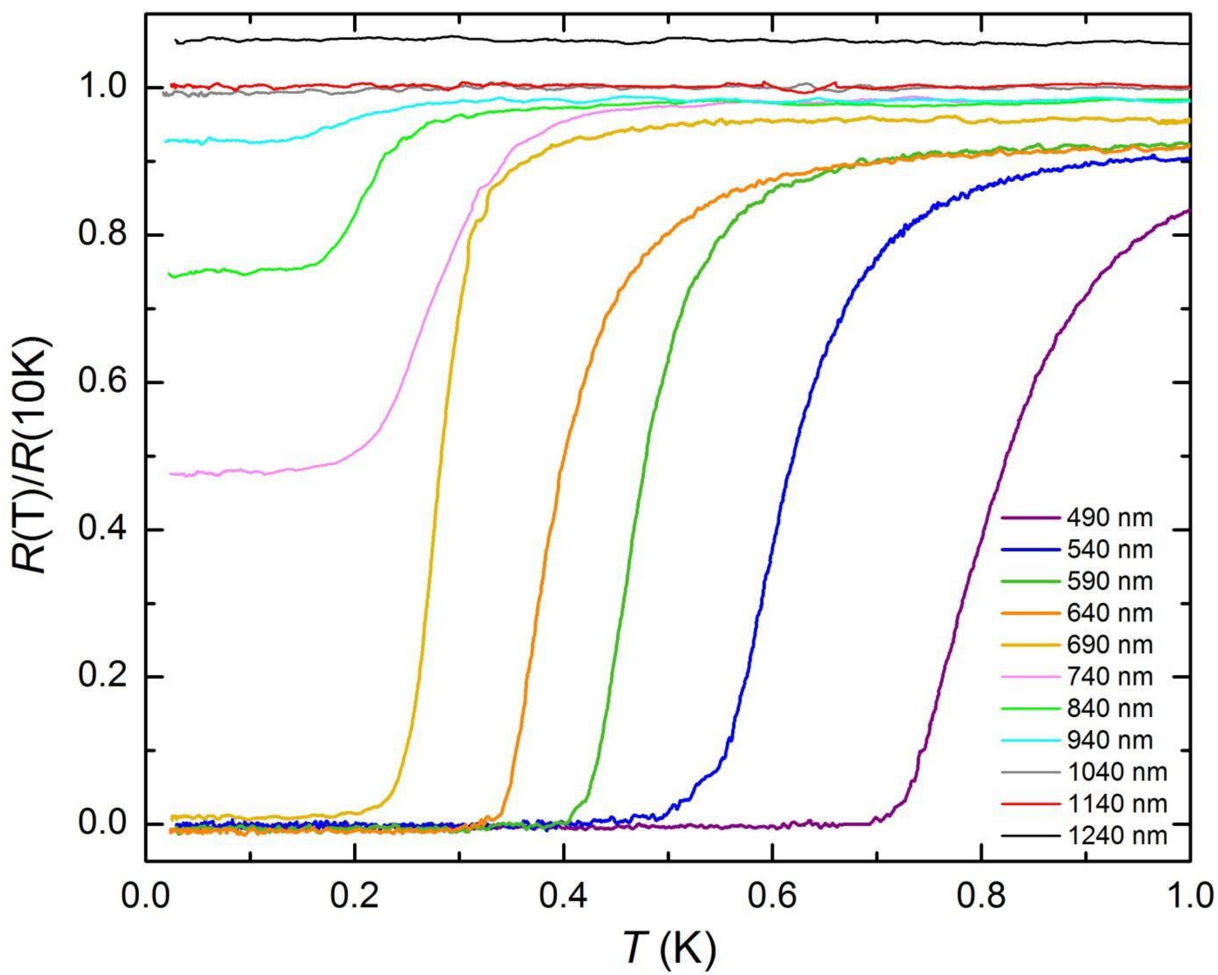
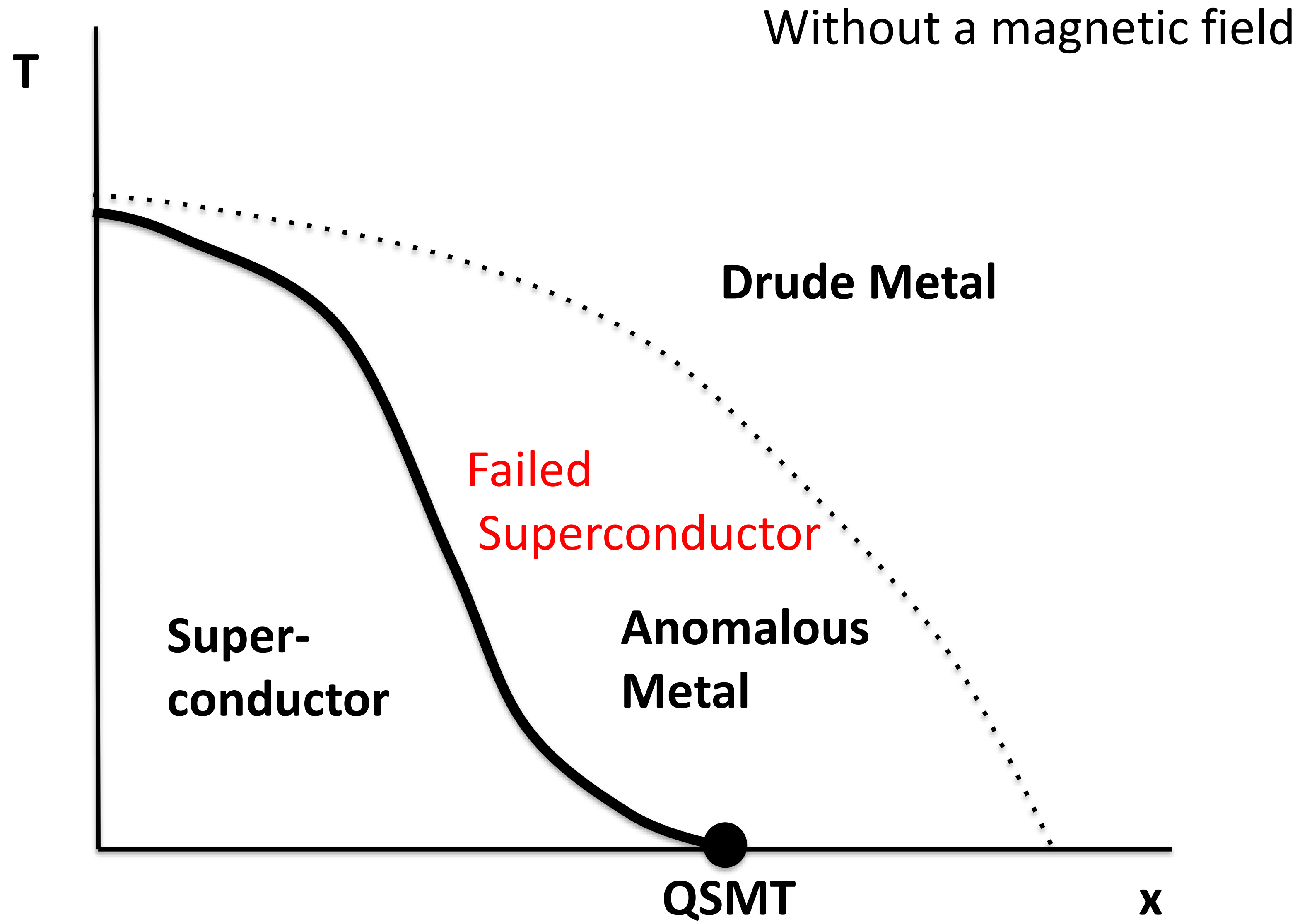


FIG. 4. Normalized resistance as a function of temperature for SNS arrays of widely spaced islands. For spacings exceeding 700 nm, the BKT transition is interrupted by a low-temperature metallic state. The data for $d \leq 690$ nm and for $d \geq 740$ nm come from different substrates, having Nb island heights of 125 nm and 145 nm, respectively.

Eley *et al*, arxiv 1206.5999



Without a magnetic field
T
Drude Metal
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x

Some aspects of the theory

Consider problem of superconducting grains embedded in a metal and tune QSMT as function of concentration

$$\chi_j(T) = \text{SC susceptibility of grain } j$$

$$J_{ij}(T) = \text{Josephson coupling between grain } i \text{ and } j$$

$$X_{ij}(T) \equiv \sqrt{\chi_i(T)\ |J_{ij}(T)|^2\ \chi_j(T)}$$

Mean field estimate of T_c

$$\overline{\sum_j X_{ij}(T_c)} = A_c$$

B. Spivak, P. Oreto, and S. A. Kivelson, “Theory of quantum metal to superconductor transitions in highly conducting systems, Phys. Rev. B **77**, 214523 (2008).

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Mean field estimate of T_c

$$\overline{\sum_j X_{ij}(T_c)} = A_c$$

$$\chi_j(T) < \chi_j(0) < \infty$$

$$J_{ij}(T) \sim |\vec{R}_{ij}|^{-d} \text{ for } |\vec{R}_{ij}| < L_T$$

$$J_{ij}(T) \sim \exp[-|\vec{R}_{ij}|/L_T] \text{ for } |\vec{R}_{ij}| > L_T$$

$$\sum_j X_{ij}(T) \sim \log[L_T]$$

The ground state is always superconducting!

$$\chi_j(T) = \text{SC susceptibility of grain } j$$

$$J_{ij}(T) = \text{Josephson coupling between grain } i \text{ and } j$$

$$X_{ij}(T) \equiv \sqrt{\chi_i(T)\ |J_{ij}(T)|^2\ \chi_j(T)}$$

Mean field estimate of T_c

$$\overline{\sum_j X_{ij}(T_c)} = A_c$$

$$\chi_j(T) < \chi_j(0) < \infty$$

$$J_{ij}(T) \sim |\vec{R}_{ij}|^{-d}\left[1 + \mu \log^2 |\vec{R}_{ij}|\right]^{-1} \quad \text{for } |\vec{R}_{ij}| < L_T$$

$$\sum_j X_{ij}(T) \sim \chi(0)\ J_{nn}(0)$$

Presence of (weak) repulsive interactions in metals result in a failed superconductor and an anomalous metal near QSMT

While this is a good theory “in principle” it has problems with the broad stability of the anomalous metal

Mean field estimate of T_c

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Presence of (weak) repulsive interactions in metals result in a failed superconductor and an anomalous metal near QSMT

$$\text{Quantum critical regime :}\ \ A_c > \chi(0) J_{nn}(0) > \text{small}$$

$$L_T > R_{nn} \qquad\qquad T < J_{nn}(0) \sim 1/\chi(0)$$

$$\chi(0) \sim \rho(E_F)V\ \ \exp[+\sigma^{eff}/\sigma_q]\ \ \text{for}\ \ \text{large grain}$$

$$\chi(0) \sim \rho(E_F)V \quad \text{for}\ \ \text{small grain}$$

For the most part, these are not “strongly correlated materials”

What is needed is theory beyond ADG

There are missing “small” effects which are larger than T*
and larger than T_c as T_c tends to 0.

Fermi liquid “theory”   Localization “theory”   BCS theory

Thank you.

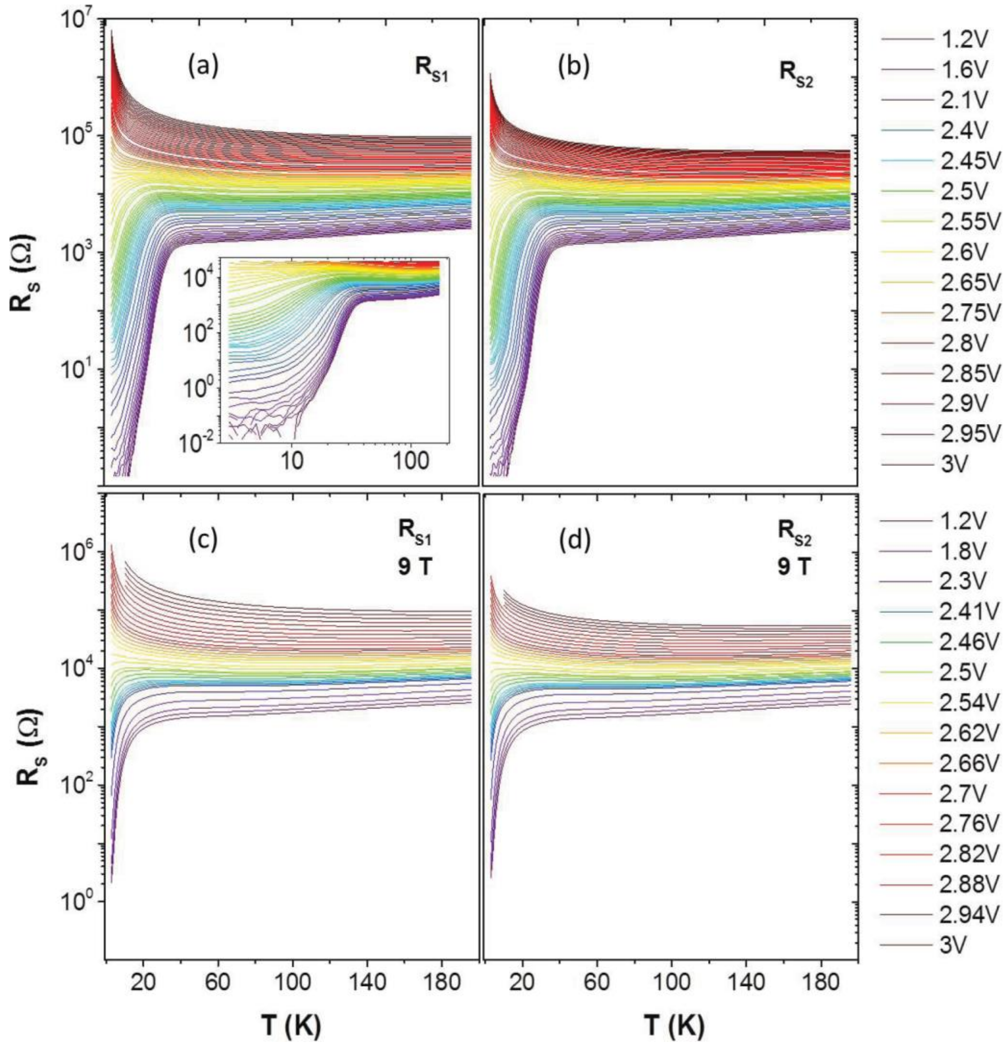

FIG. 7. (Color online) Sheet resistance as a function of temperature for different values of V_G and in two different magnetic fields. Panels (a) and (c) show the data taken in the R_{s1} direction with 0 T and 9 T magnetic fields, respectively, and panels (b) and (d) show the measurements obtained for the R_{s2} direction under 0 T and 9 T magnetic fields, as well. The inset of panel (a) shows a magnification of the superconducting part in a log-log scale.