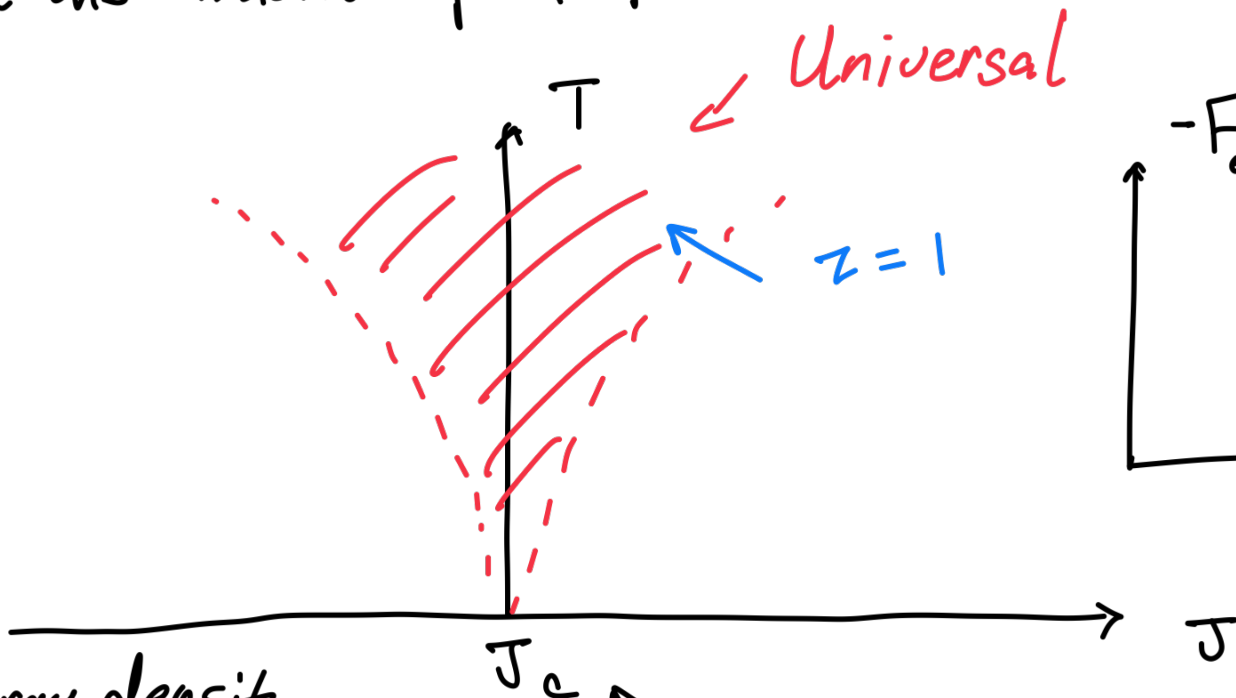
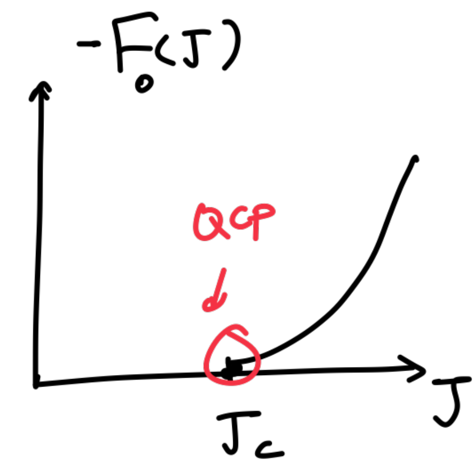
Phys525:
Quantum Condensed Matter Physics: Quantum Criticality
Basics, Dynamics and Topological criticality

Episode 18:
Application: General comments
(Wrap up)

General discussions of QCP



$\nwarrow$ QCP



free energy density

$$\frac{F}{V} = -\frac{T}{V} \ln Z(J, u \ldots ; T) \simeq T^{\frac{d}{z}+1} f_1\left(\frac{J-J_c}{T}\right) + \frac{F_0}{V}$$

be more precise, $\quad f_1 = \tilde{f}_1\left(\frac{J-J_c}{T} ; \left(\frac{T}{u}\right)^{\alpha}, \left(\frac{T}{u}\right)^{\beta}, \ldots\right)$

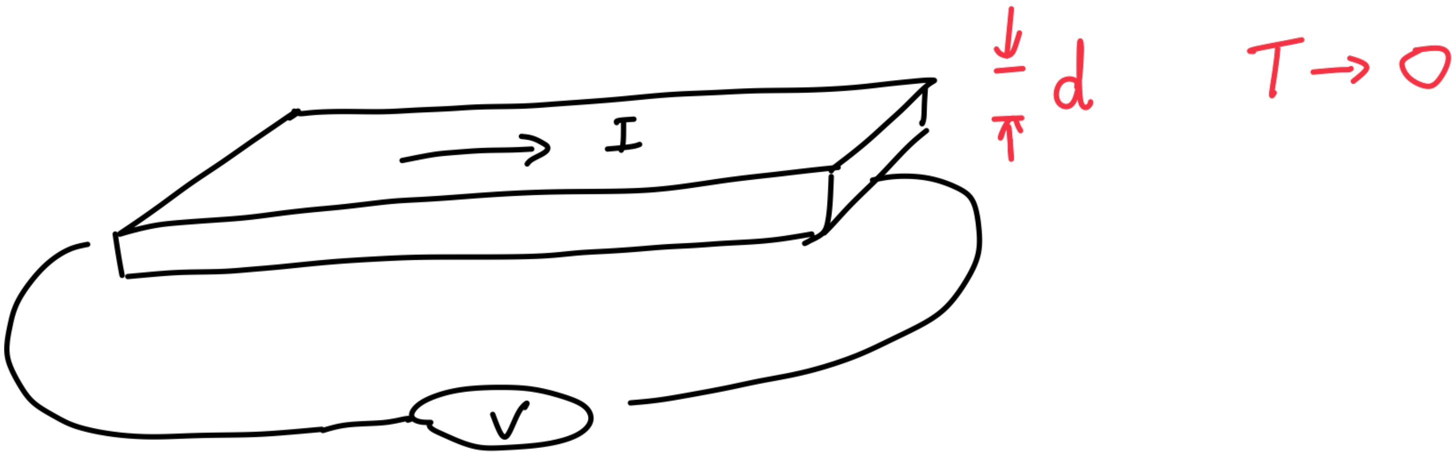
analytical

Renormalizability of QFT

$u \to \infty$

Onset of superconductivity in the two-dimensional limit

D. B. Haviland, Y. Liu, and A. M. Goldman, Phys. Rev. Lett. 62, 2180 (1989)

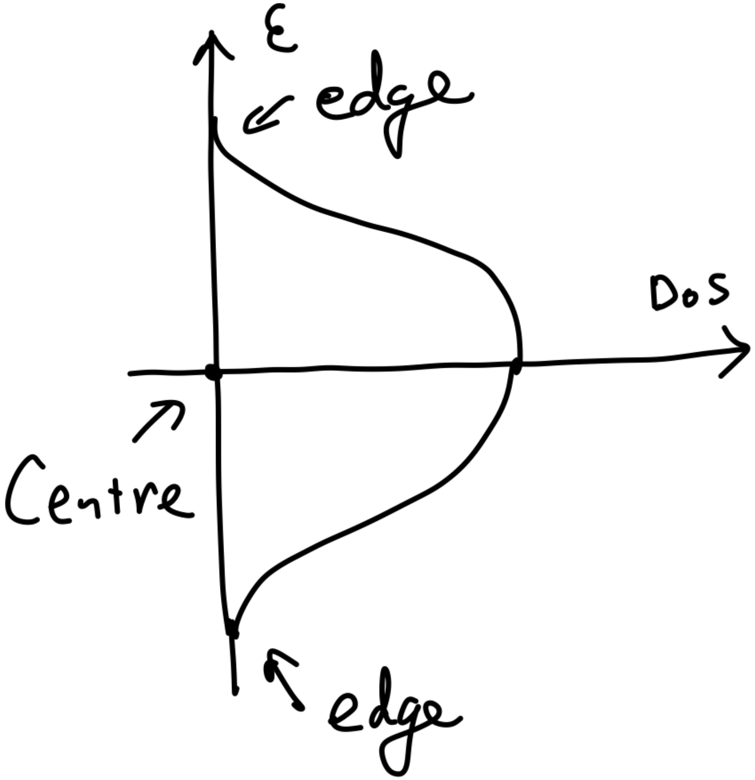


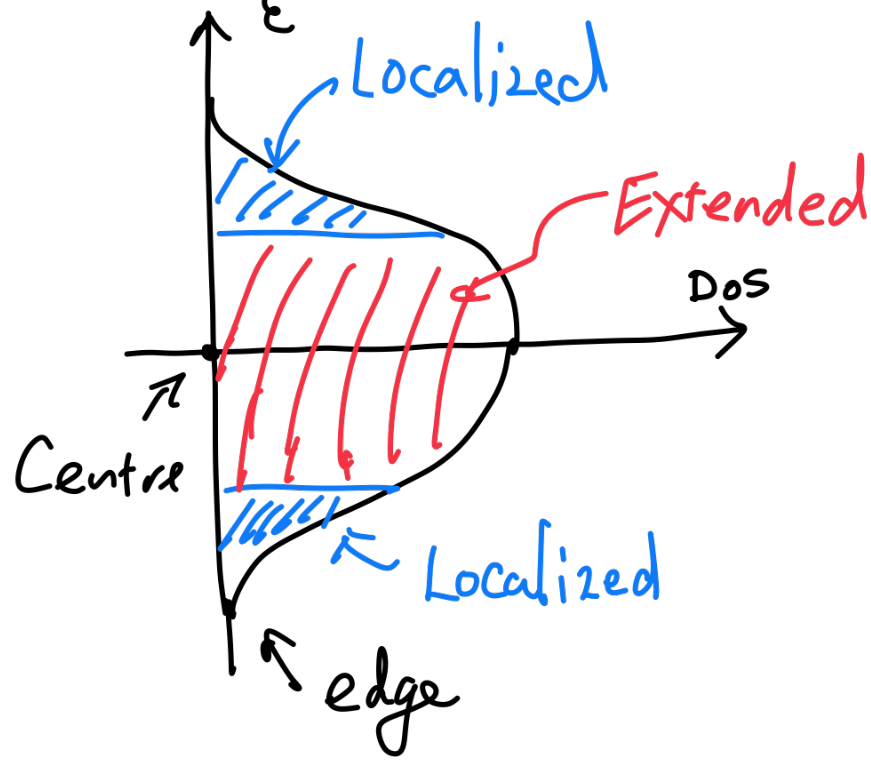
Background Stories on disorder electrons

2D Metals don't exist or absence of diffusion

(pointed out by Anderson et.al. 1979)

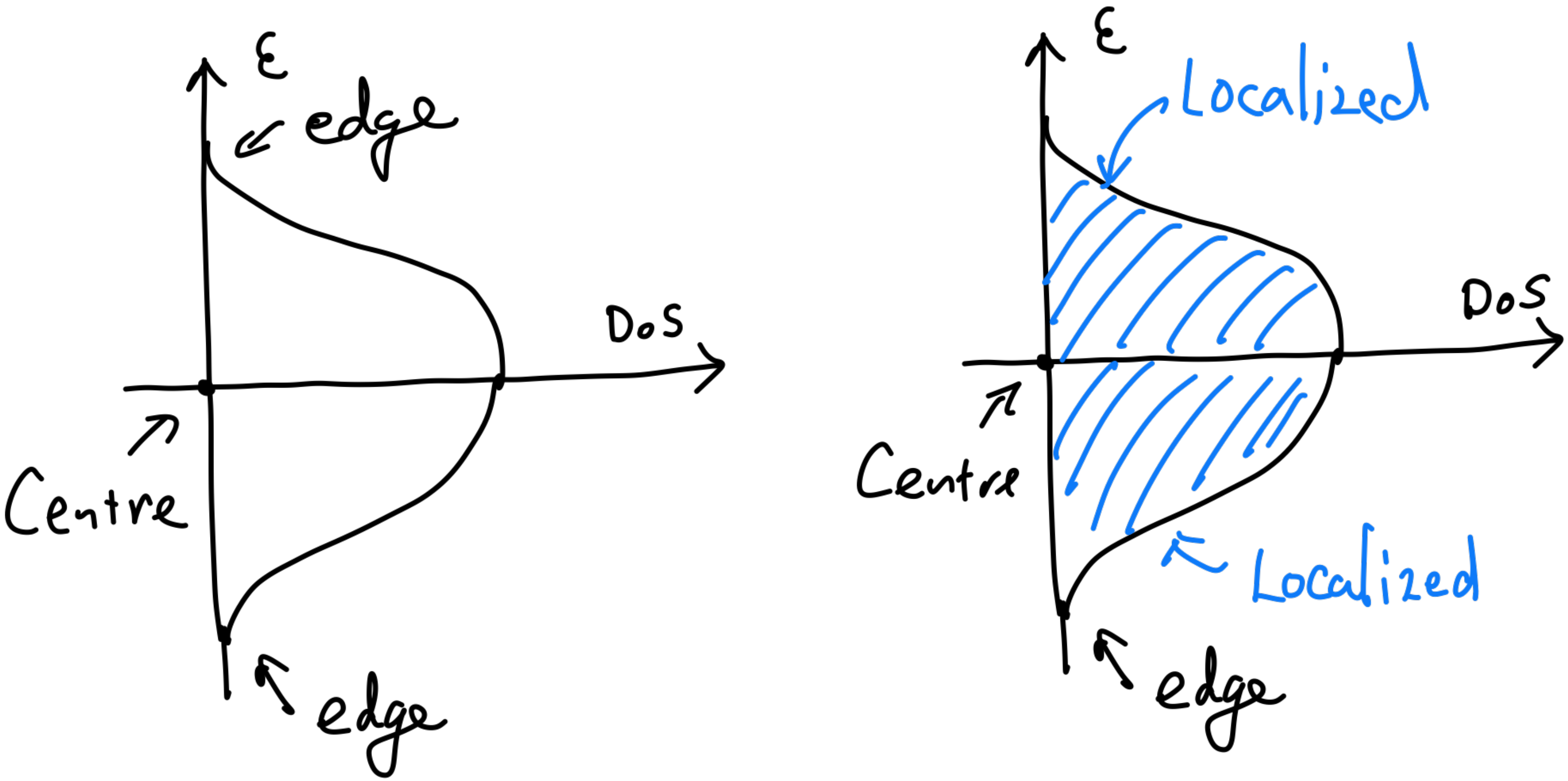
Background Stories on disorder electrons





Standard Paradigm 3D

Background Stories on disorder electrons



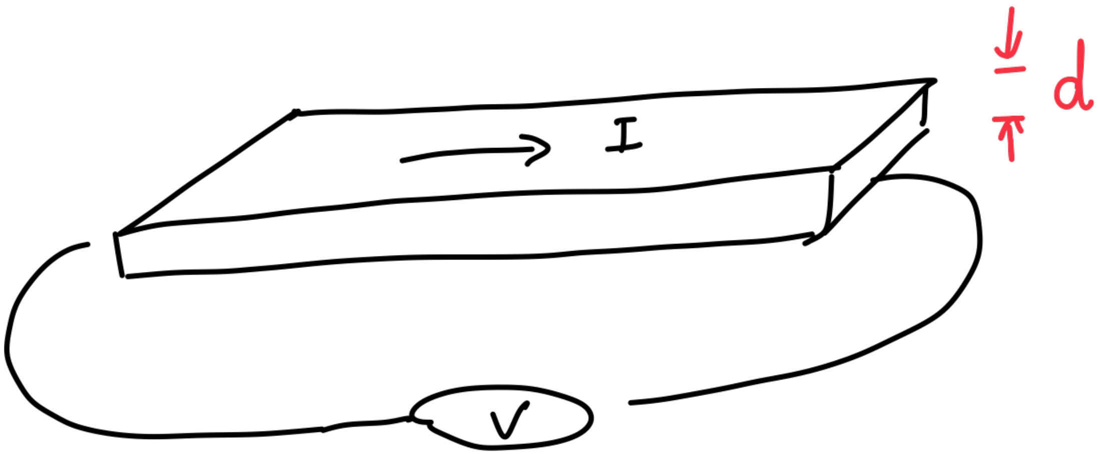
2D Absence of Diffusion

(No interacting Anderson Insulator)

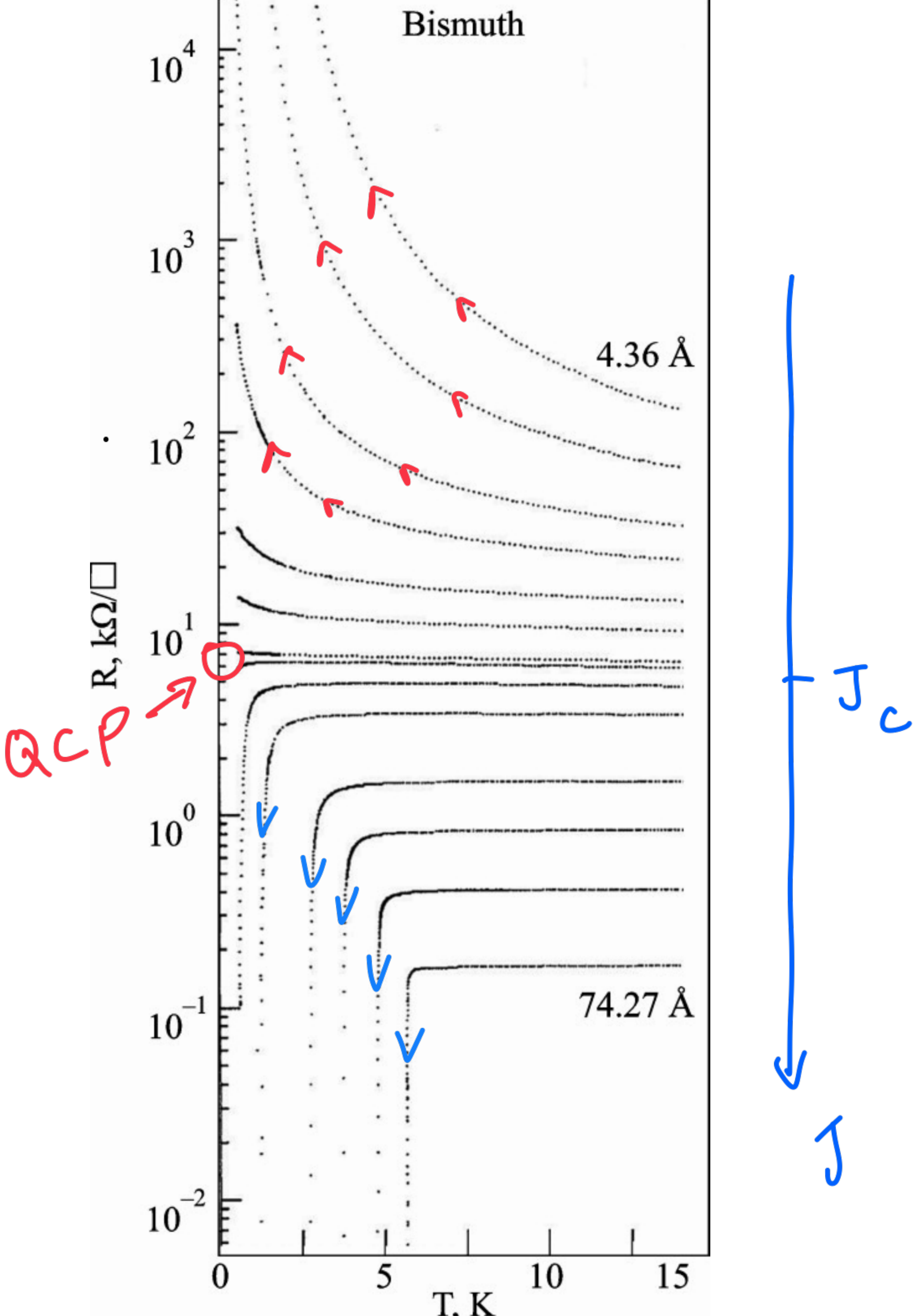
Adding interactions in !!

Onset of superconductivity in the two-dimensional limit

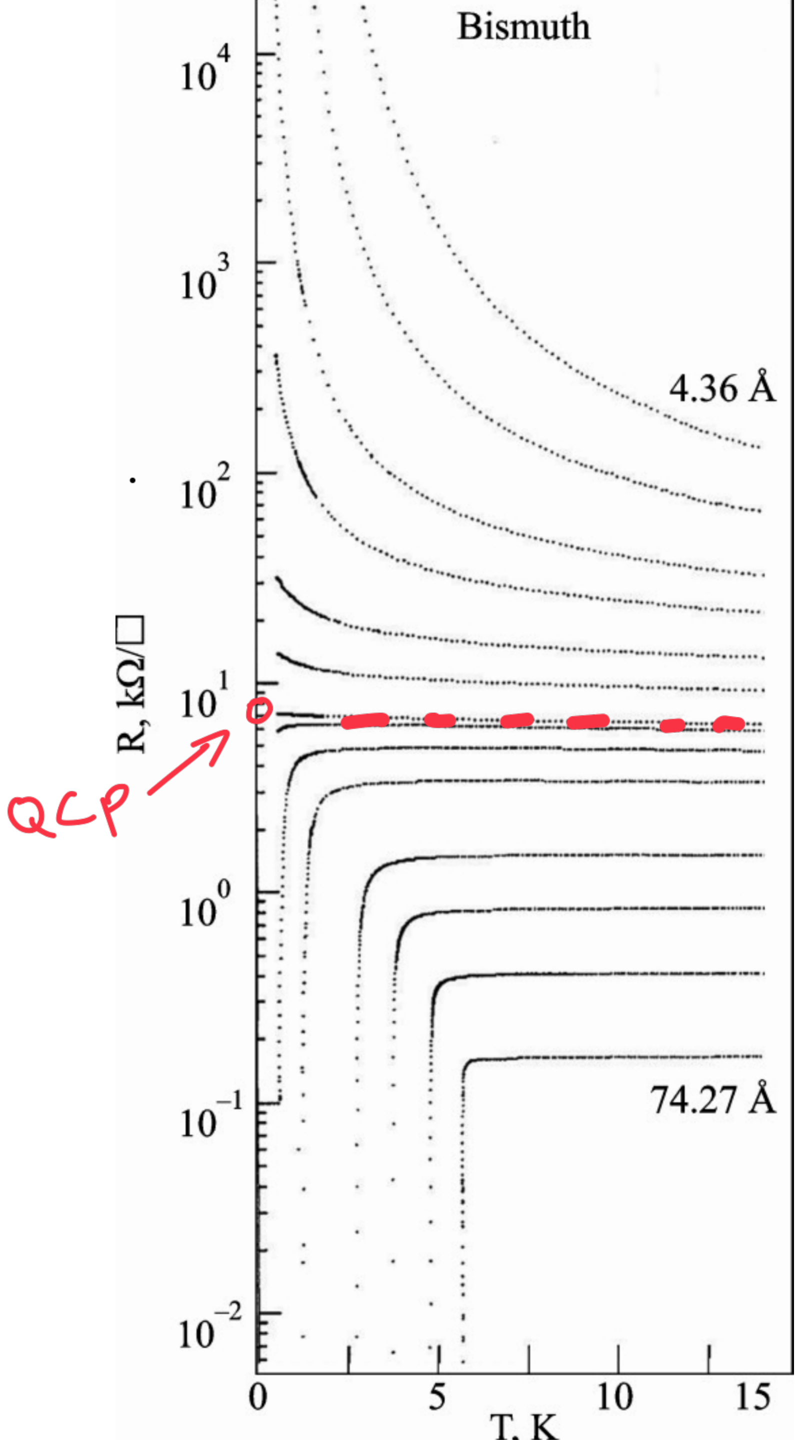
D. B. Haviland, Y. Liu, and A. M. Goldman, Phys. Rev. Lett. 62, 2180 (1989)

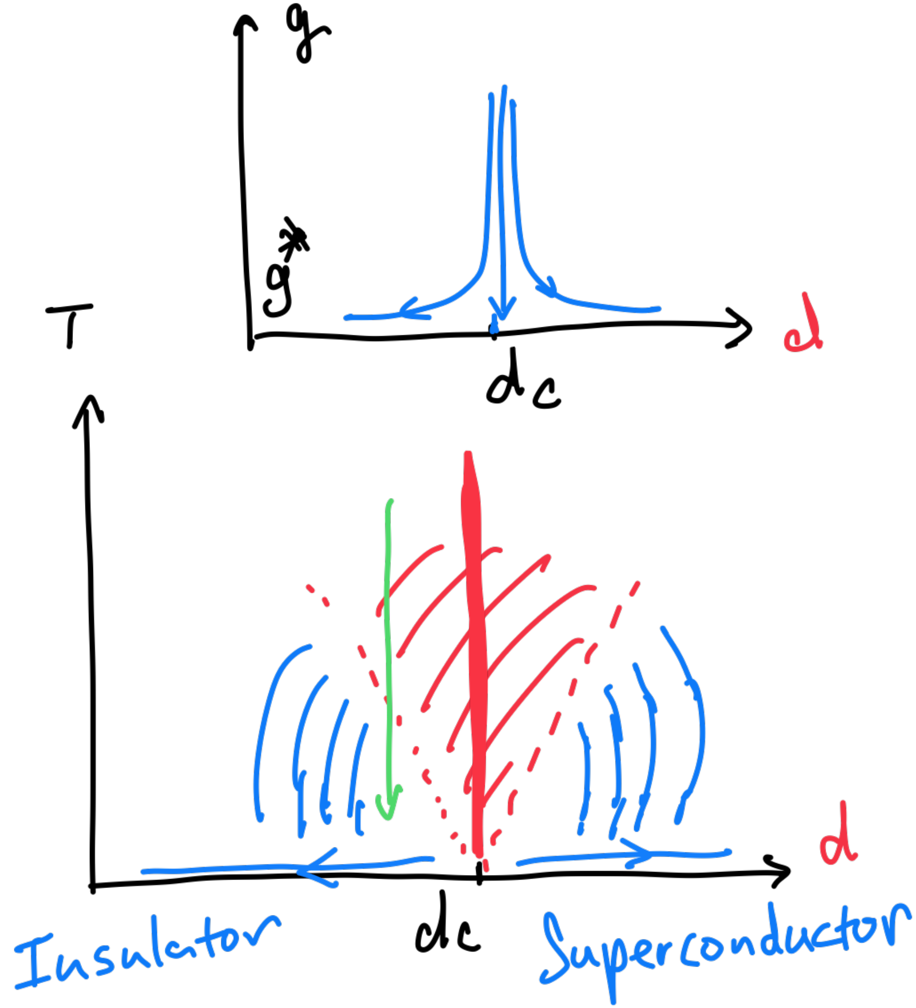


$T \to 0$



BHM with disorder


Bismuth
4.36 Å
74.27 Å
R, kΩ/□
T, K
0
5
10
15
QCP


g
g*
d
dc
T
d
dc
Insulator
Superconductor

nature physics

LETTERS

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Universal T-linear resistivity and Planckian dissipation in overdoped cuprates

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The perfectly linear temperature dependence of the electrical resistivity observed as $T \to 0$ in a variety of metals close to a quantum critical point[1–4] is a major puzzle of condensed-matter physics[5]. Here we show that T-linear resistivity as $T \to 0$ is a generic property of cuprates, associated with a universal scattering rate. We measured the low-temperature resistivity of the bilayer cuprate $Bi_2Sr_2CaCu_2O_{8+\delta}$ and found that it exhibits a T-linear dependence with the same slope as in the single-layer cuprates $Bi_2Sr_2CuO_{6+\delta}$ (ref. [6]), $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (ref. [7]) and $La_{2-x}Sr_xCuO_4$ (ref. [8]), despite their very different Fermi surfaces and structural, superconducting and magnetic properties. We then show that the T-linear coefficient (per CuO_2 plane), $A_1^{\square}$, is given by the universal relation $A_1^{\square} T_F = h/2e^2$, where e is the electron charge, h is the Planck constant and T_F is the Fermi temperature. This relation, obtained by assuming that the scattering rate $1/\tau$ of charge carriers reaches the Planckian limit[9,10], whereby $\hbar/\tau = k_B T$, works not only for hole-doped cuprates[6–8,11,12] but also for electron-doped cuprates[13,14], despite the different nature of their quantum critical point and strength of their electron correlations.

In conventional metals, the electrical resistivity $\rho(T)$ normally varies as T^2 in the limit $T \to 0$, where electron–electron scattering dominates, in accordance with Fermi-liquid theory. However, close to a quantum critical point (QCP) where a phase of antiferromagnetic order ends, $\rho(T) \sim T^n$, with $n < 2.0$. Most striking is the observation of a perfectly linear T dependence $\rho(T) = \rho_0 + A_1 T$ as $T \to 0$ in several very different materials, when tuned to their magnetic QCP; for example, the quasi-one-dimensional (1D) organic conductor $(TMTSF)_2PF_6$ (ref. [4]), the quasi-2D ruthenate $Sr_3Ru_2O_7$ (ref. [3]) and the 3D heavy-fermion metal $CeCu_6$ (ref. [1]). This T-linear resistivity as $T \to 0$ has emerged as one of the major puzzles in the physics of metals[5], and while several theoretical scenarios have been proposed[15], no compelling explanation has been found.

In cuprates, a perfect T-linear resistivity as $T \to 0$ has been observed (once superconductivity is suppressed by a magnetic field) in two closely related electron-doped materials, $Pr_{2-x}Ce_xCuO_{4\pm\delta}$ (PCCO)[2,16,17] and $La_{2-x}Ce_xCuO_4$ (LCCO)[13,14], and in three hole-

where $\rho(T) = \rho_0 + A_1 T$ as $T \to 0$ are very far from the QCP where long-range antiferromagnetic order ends ($p_N \sim 0.02$); for example, at $p = 0.24$ in Nd-LSCO (Fig. 1a) and in the range $p = 0.21$–0.26 in LSCO (Fig. 1b). Instead, these values are close to the critical doping where the pseudogap phase ends (that is, at $p^* = 0.23 \pm 0.01$ in Nd-LSCO (ref. [11]) and at $p^* \sim 0.18$–0.19 in LSCO (ref. [8])), where the role of antiferromagnetic spin fluctuations is not clear. In Bi2201, p^* is farther still (see Supplementary Section 10).

To make progress, several questions must be answered. Is T-linear resistivity as $T \to 0$ in hole-doped cuprates limited to single-layer materials with low T_c, or is it generic? Why is $\rho(T) = \rho_0 + A_1 T$ as $T \to 0$ seen in LSCO over an anomalously wide doping range[8]? Is there a common mechanism linking cuprates to the other metals where $\rho \sim T$ as $T \to 0$?

To establish the universal character of T-linear resistivity in cuprates, we have turned to $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). While Nd-LSCO and LSCO have essentially the same single electron-like diamond-shaped Fermi surface at $p > p^*$ (refs [19,20]), Bi2212 has a very different Fermi surface, consisting of two sheets, one of which is also diamond-like at $p > 0.22$, but the other is much more circular[21] (see Supplementary Section 1). Moreover, the structural, magnetic and superconducting properties of Bi2212 are very different to those of Nd-LSCO and LSCO: a stronger 2D character, a larger gap to spin excitations, no spin-density-wave order above $p \sim 0.1$ and a much higher superconducting T_c.

We measured the resistivity of Bi2212 at $p = 0.23$ by suppressing superconductivity with a magnetic field of up to 58 T. At $p = 0.23$, the system is just above its pseudogap critical point ($p^* = 0.22$ (ref. [22]); see Supplementary Section 2). Our data are shown in Fig. 2. The raw data at $H = 55$ T reveal a perfectly linear T dependence of $\rho(T)$ down to the lowest accessible temperature (Fig. 1a). Correcting for the magnetoresistance (see Methods and Supplementary Section 3), as was done for LSCO (ref. [8]), we find that the T-linear dependence of $\rho(T)$ seen in Bi2212 at $H = 0$ from $T \sim 120$ K down to T_c simply continues to low temperature, with the same slope $A_1 = 0.62 \pm 0.06\ \mu\Omega\,cm\,K^{-1}$ (Fig. 2b). Measured per CuO_2 plane, this gives $A_1^{\square} = A_1/d = 8.0 \pm 0.9\ \Omega\,K^{-1}$, where d is the (aver-

Planckian transport

$$\rho_{DC} = \rho_0 + A_1 T \quad (T^2 \text{ if fermi liquid})$$

$$A_1 \propto \alpha = \frac{\tau}{\frac{\hbar}{T}}$$