Quantum criticality in twisted transition metal dichalcogenides

Near the boundary between ordered and disordered quantum phases, several experiments have demonstrated metallic behaviour that defies the Landau Fermi liquid paradigm. In moiré heterostructures, gate-tuneable insulating phases driven by electronic correlations have been recently discovered. Here, we use transport measurements to characterize metal–insulator transitions (MITs) in twisted WSe₂ near half filling of the first moiré subband. We find that the MIT as a function of both density and displacement field is continuous. At the metal–insulator boundary, the resistivity displays strange metal behaviour at low temperatures, with dissipation comparable to that at the Planckian limit. Further into the metallic phase, Fermi liquid behaviour is recovered at low temperature, and this evolves into a quantum critical fan at intermediate temperatures, before eventually reaching an anomalous saturated regime near room temperature. An analysis of the residual resistivity indicates the presence of strong quantum fluctuations in the insulating phase. These results establish twisted WSe₂ as a new platform to study doping and bandwidth-controlled metal–insulator quantum phase transitions on the triangular lattice.

In materials with strong Coulomb interactions, many interaction-driven quantum phases have been observed, including Mott insulators, superconductors and density waves. The most intriguing electronic properties of these materials are not found in these ordered phases, but instead in the adjacent metallic phases, which exhibit anomalous transport properties that defy description by the Landau Fermi liquid paradigm. One striking manifestation of this is the temperature and magnetic field dependence of the resistance of the metallic phase, which deviates strongly from the expected $T^2$ or $B^2$ dependence predicted by Fermi liquid theory. Other transport coefficients, including the Hall coefficient, Nernst effect and thermal conductivity, display anomalous properties as well. These ‘strange metal’ properties are often associated with a quantum critical point, a second order quantum phase transition driven by a control parameter such as doping, applied field or pressure. Understanding the nature of quantum fluctuations and how they give rise to anomalous metallic properties is among the most important open problems in condensed matter physics.

Recently, moiré heterostructures have emerged as a new class of materials that exhibit interesting quantum electronic phases. The importance of strong electron correlations to the insulating phases found at integer filling of the moiré lattice has been unambiguously established, but much less is known either experimentally or theoretically about the nature of the metallic states that exist nearby or the transitions that connect metallic and insulating states. MITs can generally be driven by either carrier doping or by tuning electronic bandwidth. In most materials, these transitions are first order due to electron–lattice coupling, with additional complications introduced by chemical disorder. In this work, we present twisted homobilayer WSe₂ (tWSe₂) as an ideal platform to realize continuous MITs. In this system, both the electron density and the electronic structure can be tuned in a facile manner using electrostatic gates without introducing additional disorder (Fig. 1a). Owing to large spin-orbit coupling and layer hybridization, tWSe₂ is effectively a one-orbital correlated triangular model simulator (Fig. 1b), for which a correlated insulating phase has been previously observed at half filling. This insulating state can be turned metallic by both electrostatic doping and vertical displacement field, enabling sensitive control over a large phase space where the transport properties can be systematically measured.

Continuous Mott transition

The resistance of the sample with a twist angle of 4.2° measured at low temperature (1.6 K) is shown as a function of density and displacement field in Fig. 1c (see Extended Data Fig. 1 for data from another sample). In our homobilayer tWSe₂, the displacement field changes the bandwidth of the lowest moiré band as well as influencing the on-site Coulomb energy by changing the spatial structure of the Wannier functions. We perform temperature-dependent resistivity measurements to determine which of the regions in Fig. 1c corresponds to insulating behaviour. We determine gaps from the measured activation energy of the resistivity (Extended Data Fig. 2) and find that the insulating gaps as a function of both doping (fig. 1d) and displacement field (fig. 1e) smoothly approach zero at the metal–insulator boundary, indicating...
We first focus on the doping-driven MITs. The temperature-dependent resistivity $\rho(T)$ and its first derivative $\partial\rho/\partial T$ are shown in Fig. 2a,b. From Fig. 2b, the MIT boundary is clearly visualized as a dome around $v = -1$, extending to a maximum temperature of approximately 10 K. Two doping-driven MITs are seen near $v = -1.1$ and $v = -0.9$. At the MIT boundary itself, the temperature dependence of the resistivity is $T$-linear down to the lowest temperature and $\partial\rho/\partial T$ is maximized (1.5 K for this data set, but down to 200 mK in other data sets and across several samples) as shown in Fig. 2c,d.

We now describe the transport over a wider range of doping than that shown in Fig 2. Technically, we cannot access all dopings for all displacement fields owing to constraints associated with the maximum gate voltages that we can apply before breakdown. Therefore, in Fig. 3a, we fix a top gate value of $-8V$ for the same sample as shown in Fig. 2. At this top gate voltage, the insulating state near half filling is weak, with a maximum gap of less than 0.2 meV. At high doping (well beyond half filling), the resistivity is fit well by a $T^2$ temperature dependence at low temperature. As we approach the MIT from high doping, the maximum temperature to which the $T^2$ fit holds decreases, and a region of $T$-linear resistance appears above this temperature. Near the MIT, the resistance obeys $T$-linear behaviour down to the lowest temperatures of our measurement. At temperatures just above the insulating phase, the resistivity is also $T$-linear. Upon reducing the doping further, a second MIT is seen, near which the resistivity is again $T$-linear down to the lowest temperature. Finally, at an even smaller doping of $v = -0.84$, $T^2$ resistivity is recovered at low temperature. The overall temperature dependence of the resistivity is summarized in Fig. 3b, with exemplary curves with fits shown in Fig. 3c. Two quantum critical fans of $T$-linear behaviour project to near the MITs on either side of the insulating region, with Fermi liquid $T^2$ behaviour recovered away from the quantum critical region.

In strongly correlated materials like the cuprate superconductors, the $T$-linear behaviour continues to be observed to anomalously high temperatures, leading to resistances that are well above the Lofe–Regel limit. We observe instead a saturation of the resistivity at temperatures of order 200 K (Fig. 3c), and this displays a weak doping dependence in the range of 3–6 kΩ. In tWSe2, at the twist angles of our samples (4–5°), theory indicates that the bandwidth is of the order of 50 meV. Furthermore, both theory and experiment indicate that there is no true gap between the lowest moiré subband and higher bands. Thus, thermal excitation of carriers to higher bands would seem to be an unlikely explanation for this phenomenon.

**Doping-driven metal–insulator transition**

Fig. 1 | Continuous metal–insulator transition in twisted WSe$_2$. a, Illustration of a dual-gated twisted-bilayer WSe$_2$ device. Biasing the top gate ($V_{BG}$) and bottom gate ($V_{BG}$) allows independent control of the transverse displacement field and carrier density. b, Representation of bilayer WSe$_2$, twisted to angle $\theta$. The resulting moiré pattern acts like a superlattice potential with triangular symmetry. c, Low temperature resistance ($T = 1.6 K$) plotted versus displacement field, $D$, and band filling, $v$, for a sample with twist angle $\theta = 4.2^\circ$. The band filling is defined in units of electrons per unit cell of the moiré superlattice. Varying the displacement field allows in situ bandwidth tuning at a second order transition. The phase diagram that emerges from these measurements is an insulating phase that is shaped roughly like an ellipse in density and displacement field, bounded by a ring of quantum critical points that separate it from metallic states.

b

**Fig. 2 | Doping-driven metal–insulator transition in twisted WSe$_2$.** a, Colour plot of resistivity versus temperature and doping for a 4.2° device at a fixed top gate value of $-6.75 V$. b, First derivative in temperature of the resistivity from Fig. 1. c, Change in temperature with respect to doping for $-6.75 V$. d, Line plots of the resistivity for doping ranges near the zero temperature MITs. The green highlighted curves display insulating behaviour, with a MIT defined by the blue dashed lines. At the metal–insulator boundary, the low temperature transport is $T$-linear (black curves). Further into the metal, the resistance starts to develop $T^2$ behaviour at low temperature (red curve in e).
In Fermi liquid theory, the quadratic parameter $a_\alpha$ in $\rho(T) = a_\alpha T^2 + \rho_0$ is associated with the square of the effective Fermi temperature $a_\alpha \sim T_F^{-1}$. Systems with a quantum critical point exhibit a $1/(\nu - \nu_{\text{critical}})$ divergence of $a_\alpha$, indicating the collapse of the Fermi temperature. Our data show that $a_\alpha$ increases by over an order of magnitude near the quantum critical points $\nu = -1.24$ and $\nu = -0.94$, as seen in Fig. 3b. By contrast, we find very little dependence of $a_\alpha$ in the metallic region beyond $\nu = -2$. Along with $a_\alpha$, we plot in Fig. 3a the parameter $\alpha_{\text{LT}}$ from linear fits to resistivity of the form $\rho(T) = \alpha_{\text{LT}} T + \rho_0$. This parameter shows maxima at the quantum critical points, where $T$-linear behaviour is observed to lowest temperature. From Drude model considerations, we can obtain an estimate of the scattering time $\tau$ of the quasiparticles in the system. Similarly to ref. 26, we can assign a dimensionless parameter $C$ such that $\tau = \frac{1}{Ck TB}$ for which, if $C \rightarrow 1$, the system nears the Planckian dissipation regime. For $\text{tWSe}_2$, the effective mass is $\sim 0.4m_e$ (ref. 23) and $\sim 5 \times 10^2$ cm$^{-2}$, then $C = \frac{\hbar e^2}{me_0 a_\alpha} \sim 0.027a_\alpha$. In our case, $C$ changes from 1 to 10 (Extended Data Fig. 3) and is maximized at the quantum critical point itself, as expected from the critical divergence of the scattering rate.

**Fig. 4** | Anomalous magnetotransport. a. Doping dependence of the longitudinal magnetoresistance for a sample at a twist angle of 4.5°, in the metallic region in the vicinity of the quantum critical point. At low fields (0–1 T) the resistivity smoothly evolves in doping from a $B^2$ form deep in the metallic phase (bottom curve) to $B$-linear behaviour in the vicinity of the quantum critical point (top curves). b. Doping dependence of the Hall resistance over the same range shown in a. The Hall resistivity shows dramatic changes associated with the collapse of the Fermi surface upon approaching the quantum critical point. c. Fit results of longitudinal resistivity in a from 0 to 1 T to $\rho = \beta B^2$ with a confidence interval greater than 95%. We observe a critical increase in the parameter $\beta$ as it nears half filling, corresponding to a transition from $B^2$ to $B$-linear behaviour. Sample fits are displayed in the inset.
Unconventional magnetoresistance behaviour

Along with the $T$-linear behaviour generically observed at quantum critical points, unconventional superconductors such as the cuprates and pnictides exhibit $B$-linear magnetoresistance above the putative quantum critical point. In these materials, superconductivity obscures the low field, low temperature limit. An exemplary set of curves of the longitudinal and Hall magnetoresistance is shown for a sample with a twist angle of $4.5^\circ$ at a top gate voltage of $-19$ V, for which the maximum insulating gap at half filling is $-0.7$ fmeV (Fig. 4a,b; see Extended Data Fig. 4 for another sample). The low field (below 1T) longitudinal magnetoresistance shows an evolution from a weak $B^2$ dependence at $v = -1.2$ to a strong $B$-linear dependence near the MIT. The entire set of data at low field is well described by an ansatz previously proposed for the cuprates and pnictides $\rho(B) = \sqrt{v + \beta B^2}$ (ref. 39) as shown in Fig. 4c. The extracted values of $\beta$ as a function of $v$ are shown in Fig. 4c, displaying a large increase upon approaching the insulating phase, corresponding to a crossover from $B^2$ to $B$-linear behaviour. Such a crossover does not occur near full filling; $B^2$-behaviour is retained near full filling (see Extended Data Fig. 5). In the cuprates and pnictides, it has been phenomenologically observed that the slope of the $B$-linear magnetoresistance and the linear-in-$T$ resistance at zero field are comparable by converting magnetic field to temperature via the relationship $\mu_B B = k_B T$. Such a conversion in our case would imply that $\sqrt{\beta} = g' \mu_B B / k_B T$. Indeed, assuming $g' \sim 25$ near half filling and converting the values of $\sqrt{\beta} = 600$–$800 \Omega K$ using this relationship gives $\alpha_L$ = 36–48, close to the experimentally observed values of 46 $\Omega K$ at zero field for this particular dataset. Analogous to the case for cuprates and pnictides, the implication is that magnetic field and temperature both play important roles in determining the scattering rate in the quantum critical region.

Displacement field-driven metal–insulator transition

So far, we have discussed the phase diagram at a fixed top gate voltage and described transport near the doping-driven quantum critical points. Increasing the displacement field also results in a MIT at $D_{\text{critical}} = 0.33$ V nm$^{-1}$. At this field-driven MIT, the resistivity is again found to be $T$-linear to the lowest temperature (Fig. 5a, inset). At even higher values of displacement field, $T^*$ behaviour is recovered in the low temperature resistivity (Fig. 5a, inset) and $\alpha_L$ rises by an order in magnitude as it approaches $D_{\text{critical}}$ (Extended Data Fig. 6), again indicating the collapse of the Fermi temperature in the field-driven transition.

Hartee–Fock calculations (see Extended Data Fig. 7) show that for band dispersions believed to be relevant to tWSe$_2$, and for interaction strengths in a physically reasonable intermediate coupling range, a metal–insulator–metal sequence of transitions occurs as the displacement field is varied. Theory suggests that at zero displacement field the insulating phase is non-magnetic, does not break spatial symmetry, and is most probably a spin liquid of some type. Experimentally, we observe that the insulating gaps decrease at high magnetic field, consistent with a non-magnetic state (Extended Data Fig. 8). Very recent results indicate that the transition is second order. The quantum critical scaling that we observe in the vicinity of the transitions suggests that the insulating phase is characterized by an order parameter whose fluctuations go soft at the transition and can scatter electrons. Thus, both the doping and displacement field MITs host quantum critical points, and we next investigate the metallic phase in the entire $v$–$D$ phase diagram through temperature-dependent resistance measurements. We find that both the magnitude of the insulating gap (Fig. 5b) and the slope of the $T$-linear behaviour (Fig. 5c) show a similar evolution with displacement field. This strong correlation between the $T$-linear behaviour and the magnitude of the correlated gap, as well as...
the presence of $T$ resistivity far from the quantum critical points, indicate that in this temperature regime the resistance is well described by contributions from strong electronic correlations. Electron–phonon scattering may have a role in the observed temperature dependence, but a crossover from $T$-linear to $T^2$ behaviour would not be expected solely from electron–phonon scattering. In this regard, the situation is different from twisted bilayer graphene$^{39-41}$, where a debate exists about the role of electron-phonon scattering in the observed $T$-linear resistivity$^{39-41}$.

Residual resistivity

In the metallic regions of the phase diagram, the resistivity can be extrapolated down to zero temperature to define a residual resistivity $\rho_0$. In pure conventional metals, $\rho_0$ arises from impurity scattering. In other studies of quantum critical systems, the analysis of $\rho_0$ near a quantum critical point has been complicated by the need to fabricate different samples, with potentially different impurity concentrations. Here, from a single sample, it is evident that the residual resistivity is small and weakly doping-dependent in the metallic phase. On the insulating side of the quantum critical point, the resistivity just above the MIT is also $T$-linear. We can extrapolate this $T$-linear dependence to zero temperature to extract a $\rho_0$ at these doping values as well (Fig. 5d). The overall behaviour of $\rho_0$ across the phase diagram (Fig. 5e) demonstrates a marked resemblance to the magnitude of the insulating gap itself (Fig. 5b). The implication is that the $\rho_0$ seen above the insulating phase reflects the physics of fluctuations of the order parameter of the insulating state itself. A second observation is that with $\nu$ fixed at $\sim 1$, we find that the gap fully opens when $\rho_0$ is between 2 and 3 $\Omega$ (Fig. 5f), and that there is a rapid rise of $\rho_0$ on entering the insulator from the metal. Indeed, theories that predict spin liquid behaviour in continuous, quantum critical transition from a metallic to an insulating side of the quantum critical point$^{38}$.

Conclusion

The transport data presented here provide compelling evidence of a continuous, quantum critical transition from a metallic to an insulating state, as doping and bandwidth are varied in a system of interacting fermions on a triangular lattice with a band filling near one hole per lattice site. The experimental platform provides access to the temperature, doping and bandwidth-controlled transition within one sample, removing the ambiguities associated with the need to fabricate a range of samples that have plagued previous work. The re-entrant nature of the transition with displacement field establishes that the interaction strength is moderate, of the order of the bandwidth, and prior theoretical work strongly suggests that the moderate correlation insulating phase is exotic, potentially a spin liquid. Furthermore, theoretical predictions on the doping-tuned MIT indicate a wealth of interaction-driven metallic phases in this particular system$^{26}$. Our results strongly imply that, whatever its origin, the insulating phase is characterized by fluctuations that can scatter electrons, become soft at the transition, and have a nontrivial effect at higher temperatures above the scale at which the insulating gap opens. Our work opens new avenues in the study both of spin liquids and of correlation-driven insulators more generally.

Online content

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Methods

Sample preparation

Sample preparation is discussed in detail in ref. 13. Twisted WSe₂ samples were prepared using the dry stamp and ‘tear-and-stack’ techniques40,41. WSe₂ is first picked up using the top hBN (hexagonal boron nitride) flake and then placed on top of pre-patterned Cr/Pt (2 nm/20 nm) contacts42 on the bottom hBN. A combination of metal and/or graphite is used for the top and bottom gates, as shown in Fig. 1a (see Extended Data Fig. 9 for device image). From atomic force microscopy measurements, we determine the thicknesses of the hBN: 4.2 ˚ sample (top, 38 nm; bottom, 32 nm) and 4.5 ˚ sample (top, 52.1 nm; bottom, 31.3 nm).

Doping, displacement field and twist angle determination

As described in ref. 13, the geometric capacitance of the top and bottom gates can be extracted via Landau levels from \( n = \frac{\phi_0}{\pi e} \). We measure two Landau fans in the samples listed, one projecting to the band edge, from which we determine the intrinsic doping \( n_0 \), and the other projecting to full filling of the moiré unit cell, from which we determine the full filling density \( n_s \). By assuming a linear gate response of the system, doping and displacement field can be obtained using \( n = \frac{C_{BG} \rho + C_{TG} \rho_0}{\rho_0} + n_0 \) and \( D = \frac{C_{BG} \rho + C_{TG} \rho_0}{2 \rho_0} \).

As the contact doping is solely controlled by the top gate voltage, only displacement field in the \( +z \) direction is accessible.

DFT (density functional theory) calculations predict a twofold degeneracy of the top moiré valence band, for which we find experimental evidence in the Landau fans from the band edge at low magnetic fields13. The twist angle is determined from \( n_s = \frac{2}{\pi} a + \frac{\pi}{4(1 - \cos \theta)} \) where \( a = 0.328 \) nm (ref. 27) is the WSe₂ lattice constant.

Fitting procedures

Our fitting procedure first attempts to fit the low temperature resistivity to the form \( \rho(T) = a_0 T^2 + p_0 \) from base temperature to a maximum temperature that yields the highest \( r^2 \) value. A fit is considered acceptable if the \( r^2 \) value is higher than 0.95. With the exception of the quantum critical point itself and the insulating region, it is always found that a \( T^2 \) fit is appropriate at low temperature according to this criterion. The region of \( T^2 \)-linear behaviour is found above the region of \( T^3 \)-linear behaviour, except for at the quantum critical point itself, where the \( T^3 \)-linear behaviour extends down to the lowest temperatures. A similar criterion \( (r^2 > 0.95) \) is used to mark the upper boundary of \( T^2 \)-linear behaviour at each doping (see Extended Data Fig. 10 for an example of a crossover of \( T^2 \) to \( T^1 \)-linear with fits).

Data availability

The data that support the findings of this study are available from the corresponding authors upon request.

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Author contributions

A.G., L.W., E.-M.S. and D.A.R. fabricated the samples. A.G., L.W. and E.-M.S. performed the transport measurements. A.G. and G.S.G.P. analysed the data. D.A.R., B.K. and J.H. grew the WSe₂ crystals. K.W. and T.T. grew the hBN crystals. J.Z. and A.J.M. supervised the theoretical aspects of this work. A.G., A.N.P., C.R.D. and A.J.M. wrote the manuscript with input from all the authors.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Quantum critical transport at a twist angle of 4.5°. a, color plot of resistivity as a function of temperature and doping. b, line cuts showing the regimes of $T^2$, $T$-linear and insulating behaviour as a function of doping.
Extended Data Fig. 2 | Arrhenius fits to resistance. When our samples show insulating behaviour, they display metal-insulator transition region that is 1-5 K wide. Below the metal-insulator transition, the temperature-dependent resistance displays activated behaviour over 1-2 decades in resistance. Arrhenius fits to extract gap magnitudes are made in this range of temperature. At the lowest temperature, the temperature dependence is often not exponential, likely due to disorder. Shown here is an example of a typical curve that has the insulating temperature dependence described above. The linear fit is defined over a region chosen such that $r^2$ is maximized (always greater than 0.9).
Planckian parameter $C$ defined from fits to T-linear resistivity on a device with twist angle $4.2^\circ$ and top gate voltage $T_G = -6.75V$ and plotted against nominal density $\nu$ as defined in the text. The insulating regime extends from $\nu = -1.15$ to $\nu = -0.95$. 

Extended Data Fig. 3 | Planckian parameter $C$. Planckian parameter $C$ defined from fits to T-linear resistivity on a device with twist angle $4.2^\circ$ and top gate voltage $T_G = -6.75V$ and plotted against nominal density $\nu$ as defined in the text. The insulating regime extends from $\nu = -1.15$ to $\nu = -0.95$. 

Extended Data Fig. 4 | Anomalous magnetotransport for 4.2° twist sample.

**a.** Longitudinal and **c.** Hall magnetoresistance as a function of doping density in the metallic regime, approaching the quantum critical point. **b.** Temperature dependence for the same doping range. **d.** Fit coefficient $\beta$ from $\rho(B) = \sqrt{|\nu| \beta B^2}$ shows a marked increase on approaching the quantum critical point near $\nu = -1$. 
Extended Data Fig. 5 | Magnetotransport beyond full filling. B-quadratic behaviour of a, longitudinal resistivity near full-filling. b, The Hall effect shows a sign change as is expected when going across bands.
Extended Data Fig. 6 | Collapse of the Fermi temperature in the D-driven transition. Quadratic coefficient versus displacement field at half-filling for the 4.2˚ sample. The rise of $\alpha_Q$ as one approaches the displacement field-driven metal-insulator transition indicates the collapse of the Fermi temperature similarly to what is observed in the doping-driven transition.
Extended Data Fig. 7 | Hartree-Fock calculations at half-filling. Our Hartree-Fock calculations are based on an effective single-band Hubbard model with on-site interactions with a bandwidth chosen to match DFT calculations of the electronic structure. At zero displacement field, the system goes from paramagnetic metal to 120°-antiferromagnetic metal with a first order transition at non-zero $U_c$, then quickly becomes an insulator at a slightly larger $U_c$. As the displacement field is applied, the critical $U_c$ to turn on magnetism decreases first and then increases continuously. The $U_c$ of the metal-insulator transition and the size of the energy gap change in the same manner. Shown here are the energy gap sizes versus displacement field at a twist angle of 5.09°.
Extended Data Fig. 8 | Non-magnetism in the insulating gap. Correlated gap versus B field for different displacement fields for the 4.2˚ sample. The correlated gap is non-magnetic and eventually closes at higher magnetic fields. When a perpendicular magnetic field is applied, we would expect the insulating gap to increase if the insulator is a ferromagnet, while we would expect it to decrease if it is an antiferromagnetic state or a spin liquid.
Extended Data Fig. 9 | Ohmic contacts and twist angle homogeneity. 

**a**, Optical microscope image of the 4.2˚ sample. **b**, Representative I-V at 200mK for the 4.2˚ sample indicating good contact quality. Curves are offset for clarity. Dashed lines indicate $V_{xx} = 0$. We find our contact resistances to be between 2 to 10kΩ for all contacts for the data shown in main figures and that value is fairly temperature independent. We perform a four-probe measurement to minimize the effects of contact resistance. We also monitor the lock-in phase of our low frequency ($\sim 17.7$Hz) AC measurements to ensure that it is close to zero at all times. **c**, Resistivity curves at 1.6K from two different pairs of leads, they correspond to slightly different twist angles for the two pairs of contacts (4.1˚ and 4.2˚). Crossed out leads indicated high contact resistance. Hall bar channel is 3µm wide and 7µm long.
Extended Data Fig. 10 | Crossover from T-quadratic to T-linear at ν = −0.84 for 4.2˚ sample. An example of our fitting procedures described in our method section is shown here for the doping of ν = −0.84 (also in the main text figure 3c). We find that the resistivity is fit well ($r^2 = 0.997$) by a $T^2$ form up to a temperature of 16.5K, and is fit well ($r^2 = 0.993$) by $T$ linear form between 16.5 and 47 K. We note that a linear fit between 1.6 and 6 K yields a $r^2$ of 0.92, clearly worse than the quadratic fit.