REPORT

SUPERCONDUCTIVITY

Scale-invariant magnetoresistance in a cuprate superconductor

P. Giraldo-Gallo[1,2]*, J. A. Galvis[1,3]*, Z. Stegen[1,4]†, K. A. Modic[5], F. F. Balakirev[6], J. B. Betts[6], X. Lian[1,4], C. Moir[1,4], S. C. Riggs[1], J. Wu[7], A. T. Bollinger[7], X. He[7,8], I. Božović[7,8], B. J. Ramshaw[6,9], R. D. McDonald[6], G. S. Boebinger[1,4], A. Shekhter[1]‡

The anomalous metallic state in the high-temperature superconducting cuprates is masked by superconductivity near a quantum critical point. Applying high magnetic fields to suppress superconductivity has enabled detailed studies of the normal state, yet the direct effect of strong magnetic fields on the metallic state is poorly understood. We report the high-field magnetoresistance of thin-film $La_{2-x}Sr_xCuO_4$ cuprate in the vicinity of the critical doping, $0.161 \leq p \leq 0.190$. We find that the metallic state exposed by suppressing superconductivity is characterized by magnetoresistance that is linear in magnetic fields up to 80 tesla. The magnitude of the linear-in-field resistivity mirrors the magnitude and doping evolution of the well-known linear-in-temperature resistivity that has been associated with quantum criticality in high-temperature superconductors.

High-temperature superconductivity in the cuprates is born directly out of a "strange" metallic state that is characterized by linear-in-temperature resistivity up to the highest measured temperatures (*1*–*4*). In conventional metals, current is carried by long-lived electronic quasiparticles, which requires the scattering length not to be significantly shorter than the de Broglie wavelength (*5*–*8*). In contrast, the resistivity in the strange metal state of the cuprates does not saturate or exhibit a crossover at the temperature where the inferred quasiparticle scattering length is comparable to the electronic wavelength. This behavior is sometimes referred to as "Planckian dissipation," which suggests that the transport relaxation rate $\hbar/\tau$ (where $\hbar$ is the reduced Planck constant and τ is the relaxation time) is limited directly by the thermal energy scale $k_B T$ (where k_B is the Boltzmann constant and T is absolute temperature) rather than by quasiparticle interactions and lattice disorder (*4*, *9*–*16*). This calls into question the very existence of quasiparticles in the strange metal state. More important, it indicates scale-invariant dynamics (i.e., the lack of an intrinsic energy scale). This behavior is observed in both classes of high-T_c superconductors—the cuprates and the pnictides (*17*, *18*)—but its microscopic origin and implications for superconductivity have yet to be fully understood.

Scale-invariant transport is commonly associated with metallic quantum criticality: A characteristic energy scale is continuously tuned by an external parameter and vanishes when the tuning parameter crosses a critical value (*4*). For hole dopings below the critical point, $p < 0.19$, the Hall effect in $La_{2-x}Sr_xCuO_4$ (*19*) and quantum oscillations in $YBa_2Cu_3O_{6+\delta}$ (*20*, *21*) provide evidence for a small carrier pocket, believed to be associated with a charge density wave (*22*–*24*). By contrast, when $p > 0.19$, quantum oscillations in $Tl_2Ba_2CuO_{6+\delta}$ (*25*) indicate a large hole-like Fermi surface, in agreement with band structure calculations (*26*). Measurements of Hall resistivity (*27*–*29*), the upper critical magnetic field (*30*), and the quasiparticle effective mass (*20*, *21*, *25*), as well as the zero-temperature collapse of a line of phase transitions (*31*–*35*), suggest a quantum critical point near $p = 0.19$. At this doping, the linear-in-temperature resistivity extends to the lowest temperatures (*4*, *16*, *36*), and therefore one might expect to access the anomalous behavior in the strange metal state in the broadest range of magnetic fields.

Magnetic fields have been instrumental in the study of both conventional and correlated metals because they couple directly to the charge carriers. Previous studies of the cuprates have made use of magnetic fields as a way of suppressing superconductivity to reveal the normal ground-state properties through the magnetoresistance and quantum oscillations (*16*, *17*, *19*–*21*, *25*, *27*–*29*, *36*–*39*). The linear-in-temperature resistivity, however, suggests a strong interaction between the metallic state and the critical fluctuations associated with the quantum critical point. What has been missing is a study of how the magnetic field affects these fluctuations and thus the metallic state. To this end, we studied the electrical transport of $La_{2-x}Sr_xCuO_4$ in high magnetic fields for a range of compositions near the critical doping, $x \approx 0.19$. We found a scale-invariant response to the magnetic field that is distinct from the well-understood response of charged quasiparticles to the Lorentz force in conventional metals (*40*, *41*). Strikingly, linear-in-field resistivity at high fields, together with linear-in-temperature resistivity at high temperatures, emerges as an intrinsic characteristic of the strange metal state in a cuprate superconductor.

Figure 1 shows the in-plane resistivity (ρ) of a thin-film $La_{2-x}Sr_xCuO_4$ cuprate sample at $p = 0.190$ (*42*–*47*) in magnetic fields aligned along the crystallographic c axis up to 80 T. Linear-in-temperature resistivity down to the superconducting transition temperature, $T_c = 38.6$ K (Fig. 1E), indicates close proximity to the critical doping. Figure 1A shows that the magnetoresistance below 40 K is linear in magnetic field over the entire normal-state field range. To quantify this observation, we define the field slope $\beta(B,T) = d\rho(B,T)/dB$. We observe that at 70 T, $\beta(B,T)$ saturates below 25 K (Fig. 1, B and C, and fig. S3), which suggests that linear-in-field resistivity is an intrinsic property of the strange metal state. The saturation value of β at low temperature and high fields in natural energy units is $\beta/\mu_B = 5.2$ μohm·cm/meV, where μ_B is the Bohr magneton. This is comparable in magnitude to the temperature slope, $\alpha(T) = d\rho(T)/dT$, which is 11.8 μohm·cm/meV in α/k_B energy units.

In conventional metals, magnetoresistance originates from the motion of electron quasiparticles around the Fermi surface under the action of the Lorentz force (*40*, *41*). For a given Fermi surface morphology, the strength of magnetoresistance is controlled by the product of the cyclotron frequency, $\omega_c = eB/m^*$ (where m^* is the quasiparticle mass), and the quasiparticle relaxation time τ. Magnetoresistance generally decreases in conventional metals as τ decreases with increasing temperature. This is in contrast to what we observe in $La_{2-x}Sr_xCuO_4$ at $p = 0.190$ (Fig. 1). At 80 T, and between 4 and 25 K, we observe nearly a factor of 2 increase in resistivity, suggesting a factor of 2 decrease in τ (Fig. 1, A and D) (*48*), and yet the strength of the magnetoresistance [$d\rho(T)/dB$] at 80 T between 4 and 25 K is independent of temperature (Fig. 1, B and C). This indicates that at very high magnetic fields, the transport relaxation rate is set directly by the magnetic field through $\hbar/\tau \propto \mu_B B$. A mechanism other than the traditional picture of orbiting quasiparticles must therefore underlie the high-field magnetoresistance in $La_{2-x}Sr_xCuO_4$. One conclusion is that the magnetic field directly affects the dynamics of critical fluctuations that are responsible for the relaxation time (*4*, *12*–*15*).

---

[1]National High Magnetic Field Laboratory (NHMFL), Florida State University, Tallahassee, FL 32310, USA. [2]Department of Physics, Universidad de Los Andes, Bogotá 111711, Colombia. [3]Departamento de Ciencias Naturales, Facultad de Ingeniería y Ciencias Básicas, Universidad Central, Bogotá 110311, Colombia. [4]Department of Physics, Florida State University, Tallahassee, FL 32310, USA. [5]Max Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany. [6]Los Alamos National Laboratory, Los Alamos, NM 87545, USA. [7]Brookhaven National Laboratory (BNL), Upton, NY 11973, USA. [8]Applied Physics Department, Yale University, New Haven, CT 06520, USA. [9]Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY 14853, USA.

*These authors contributed equally to this work.

†Present address: Northrop Grumman Corporation, Linthicum, MD 21090, USA.

‡Corresponding author. Email: arkady.shekhter@gmail.com

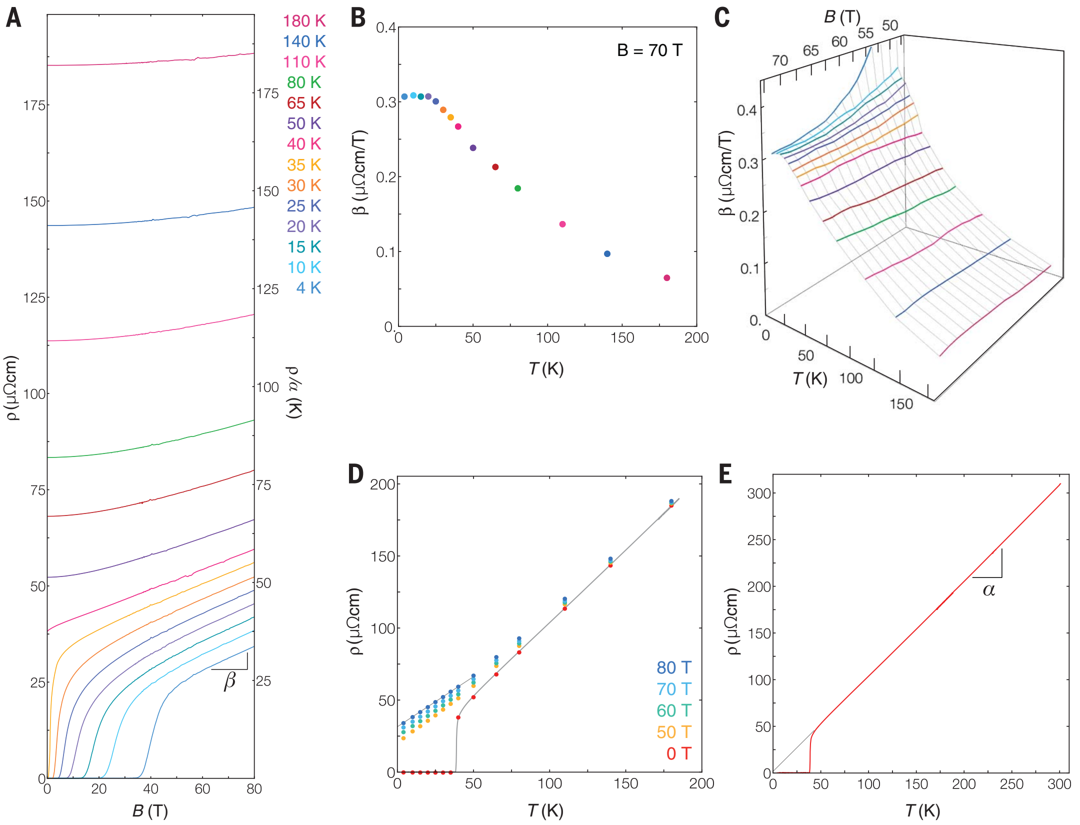

Fig. 1. *ab*-plane resistivity of thin-film $La_{2-x}Sr_xCuO_4$ at $p = 0.190$. The magnetic field is applied along the *c* axis. (**A**) Magnetoresistance up to 80 T for temperatures ranging from 4 K up to 180 K. The right axis indicates the resistivity in temperature units, ρ/α, where α is obtained from the linear fit in (E). The aspect ratio reflects natural energy units for the magnetic field, $\mu_B B$, and temperature, $k_B T$, where the energy of 80 T corresponds approximately to that of 53.7 K. (**B**) Temperature dependence of $\beta(B,T) = d\rho/dB$ at a fixed field of 70 T obtained as the slope of a linear fit to the magnetoresistance in (A) in the field range between 65 and 77 T. $\beta(B,T)$ saturates below about 25 K. Color coding for temperature values as indicated in (A) also applies to (B) and (C). (**C**) Magnetic field dependence of $\beta(B,T)$, showing that $\beta(B,T)$ saturates for $B > 50$ T in a broad temperature range, 10 K < T < 25 K. (**D**) Temperature dependence of the resistivity at fixed fields. The gray line indicates the zero-field resistivity from (E). (**E**) Zero-field resistivity up to room temperature. The gray line indicates a linear-fit extrapolation of the resistivity to temperatures below the superconducting transition, $\rho = \rho_0 + \alpha T$. The magnitude of the intercept, $\rho_0 \approx 1.5\ (\pm 2)$ μohm·cm, and the temperature slope, $\alpha \approx 1.02\ (\pm 0.01)$ μohm·cm/K, are found from a linear fit in a broad temperature range.

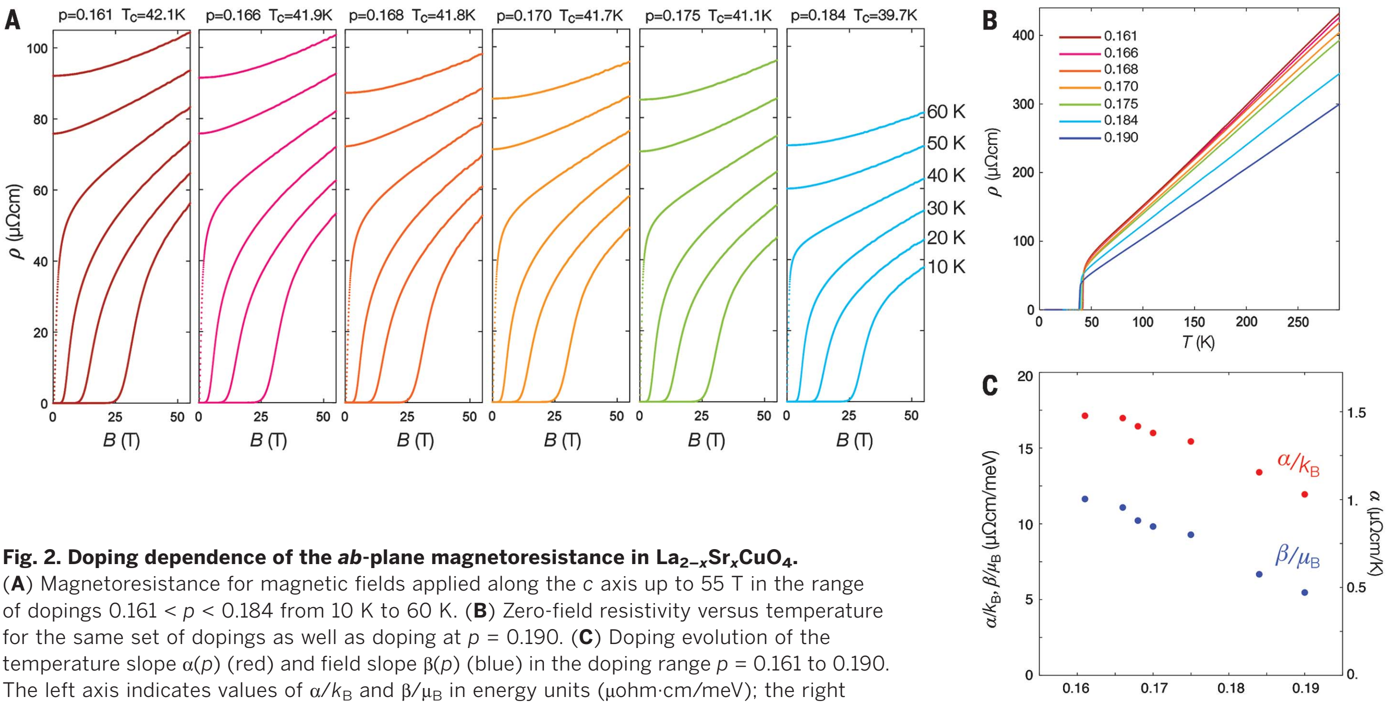

Fig. 2. Doping dependence of the *ab*-plane magnetoresistance in $La_{2-x}Sr_xCuO_4$. (**A**) Magnetoresistance for magnetic fields applied along the *c* axis up to 55 T in the range of dopings $0.161 < p < 0.184$ from 10 K to 60 K. (**B**) Zero-field resistivity versus temperature for the same set of dopings as well as doping at $p = 0.190$. (**C**) Doping evolution of the temperature slope $\alpha(p)$ (red) and field slope $\beta(p)$ (blue) in the doping range $p = 0.161$ to 0.190. The left axis indicates values of α/k_B and β/μ_B in energy units (μohm·cm/meV); the right axis indicates the value of α in μohm·cm/K.

The smooth evolution of the temperature slope $\alpha(p)$ across the critical doping (*16*, *49*) is another indication of a lack of well-defined quasiparticles in the strange metal phase at high temperatures, in contrast to the divergence of quasiparticle effective mass approaching the critical doping at low temperatures (*50*). The doping evolution of the magnitude of $\beta(p)$ may provide further insight into the character of transport in the strange metal state. We measured the *ab*-plane resistivity in magnetic fields along the *c* axis up to 55 T in $La_{2-x}Sr_xCuO_4$ over the range of dopings $p = 0.161$ to $p = 0.184$ (Fig. 2). All samples in this doping range exhibit linear-in-temperature resistivity at high temperatures (Fig. 2B). The saturation value of $\beta(p)$ is shown in Fig. 2C along with $\alpha(p)$ in natural energy units. Both $\alpha(p)/k_B$ and $\beta(p)/\mu_B$ decrease monotonically with doping in this doping range and evolve at a similar rate. The weak doping dependence of $\beta(p)$ and $\alpha(p)$ approaching critical doping is in apparent contrast to the rapid increase in the Hall coefficient (*27*–*29*) and the divergence of the effective mass (*21*) as the critical doping is approached at low temperature and high magnetic fields. This again indicates that despite the observation of quantum oscillations at low temperatures [in $YBa_2Cu_3O_{6+\delta}$ (*20*, *21*) and $Tl_2Ba_2CuO_{6+\delta}$ (*25*)], the high-field, high-temperature magnetoresistance in cuprates has a non-quasiparticle origin.

It is well known that the transport relaxation rate is linear-in-temperature, $\hbar/\tau \propto k_BT$, in the fan-shaped region of the temperature-doping plane (Fig. 3, magenta) emerging from the critical point (*49*). Our results (Fig. 2) suggest that an analogous fan-shaped region exists in the magnetic field–doping plane (Fig. 3, blue) where the relaxation rate is linear-in-field, $\hbar/\tau \propto \mu_B B$. This extends a quantum critical region in field, temperature, and doping where the transport relaxation rate is set by the dominant energy scale, $\hbar/\tau \propto \max\{k_BT, \mu_B B\}$, as illustrated in Fig. 3 (*51*).

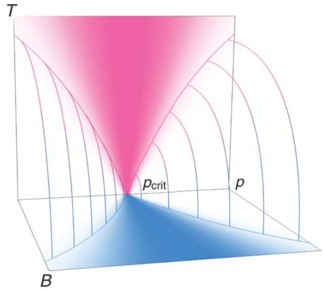

Fig. 3. Schematic doping-field-temperature (p-B-T) phase diagram in the vicinity of the critical doping p_{crit}. Note that the superconducting phase surrounding the critical point is not shown. The magenta lines indicate the extent of the fan-shaped region (shaded in magenta) in the p-T plane where linear-T resistivity exists. The fan-shaped region of linear-B resistivity in the p-B plane (shaded in blue) is bounded by the blue lines. The gradient-colored lines separate the region of the p-B-T space where scale-invariant transport behavior, $\hbar/\tau \propto \max\{k_BT, \mu_B B\}$, exists. In the region behind these lines, a large intrinsic energy scale suppresses the anomalous dependence of $\hbar/\tau$ on temperature and magnetic field. All lines in this drawing indicate a smooth crossover region, not a distinct phase boundary.

These measurements establish the linear magnetoresistance at very high fields as a fundamental property of the strange metal state in the cuprates. A linear dependence on an external energy scale is not the only possible outcome of scale invariance near quantum critical point; in principle, any power-law dependence is possible. It is therefore striking that the temperature and field dependence of the resistivity in $La_{2-x}Sr_xCuO_4$ assumes the simplest possible form. Both the cuprates and the pnictides (*18*) exhibit this simple form of scale invariance, revealing another universal characteristic of high-temperature superconductors.

REFERENCES AND NOTES

1. S. Martin, A. T. Fiory, R. M. Fleming, L. F. Schneemeyer, J. V. Waszczak, *Phys. Rev. B* **41**, 846(R) (1990).
2. P. W. Anderson, *Science* **256**, 1526–1531 (1992).
3. N. E. Hussey, *J. Phys. Condens. Matter* **20**, 123201 (2008).
4. B. Keimer, S. A. Kivelson, M. R. Norman, S. Uchida, J. Zaanen, *Nature* **518**, 179–186 (2015).
5. A. F. Ioffe, A. R. Regel, *Prog. Semicond.* **4**, 237–291 (1960).
6. N. F. Mott, *Philos. Mag.* **26**, 1015–1026 (1972).
7. V. J. Emery, S. A. Kivelson, *Phys. Rev. Lett.* **74**, 3253–3256 (1995).
8. N. E. Hussey, K. Takenaka, H. Takagi, *Philos. Mag.* **84**, 2847–2864 (2004).
9. C. M. Varma, P. B. Littlewood, S. Schmitt-Rink, E. Abrahams, A. E. Ruckenstein, *Phys. Rev. Lett.* **63**, 1996–1999 (1989).
10. P. Phillips, C. Chamon, *Phys. Rev. Lett.* **95**, 107002 (2005).
11. J. A. N. Bruin, H. Sakai, R. S. Perry, A. P. Mackenzie, *Science* **339**, 804–807 (2013).
12. J. Zaanen, *Nature* **430**, 512–513 (2004).
13. V. Aji, C. M. Varma, *Phys. Rev. Lett.* **99**, 067003 (2007).
14. J. Zaanen, Y. W. Sun, Y. Liu, K. Schalm, *Holographic Duality for Condensed Matter Physics* (Cambridge Univ. Press, 2015).
15. S. Lederer, Y. Schattner, E. Berg, S. A. Kivelson, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 4905–4910 (2017).
16. R. A. Cooper *et al.*, *Science* **323**, 603–607 (2009).
17. J. G. Analytis *et al.*, *Nat. Phys.* **10**, 194–197 (2014).
18. I. M. Hayes *et al.*, *Nat. Phys.* **12**, 916–919 (2016).
19. Y. Ando, Y. Kurita, S. Komiya, S. Ono, K. Segawa, *Phys. Rev. Lett.* **92**, 197001 (2004).
20. N. Doiron-Leyraud *et al.*, *Nature* **447**, 565–568 (2007).
21. B. J. Ramshaw *et al.*, *Science* **348**, 317–320 (2015).
22. J. Chang *et al.*, *Nat. Phys.* **8**, 871–876 (2012).
23. R. Comin *et al.*, *Science* **343**, 390–392 (2014).
24. T. P. Croft, C. Lester, M. S. Senn, A. Bombardi, S. M. Hayden, *Phys. Rev. B* **89**, 224513 (2014).
25. B. Vignolle *et al.*, *Nature* **455**, 952–955 (2008).
26. O. K. Andersen, A. I. Liechtenstein, O. Jepsen, F. Paulsen, *J. Phys. Chem. Solids* **56**, 1573–1591 (1995).
27. F. F. Balakirev *et al.*, *Nature* **424**, 912–915 (2003).
28. F. F. Balakirev *et al.*, *Phys. Rev. Lett.* **102**, 017004 (2009).
29. S. Badoux *et al.*, *Nature* **531**, 210–214 (2016).
30. G. Grissonnanche *et al.*, *Nat. Commun.* **5**, 3280 (2014).
31. B. Fauqué *et al.*, *Phys. Rev. Lett.* **96**, 197001 (2006).
32. J. Xia *et al.*, *Phys. Rev. Lett.* **100**, 127002 (2008).
33. A. Shekhter *et al.*, *Nature* **498**, 75–77 (2013).
34. Y. Lubashevsky, L. Pan, T. Kirzhner, G. Koren, N. P. Armitage, *Phys. Rev. Lett.* **112**, 147001 (2014).
35. L. Zhao *et al.*, *Nat. Phys.* **13**, 250–254 (2017).
36. G. S. Boebinger *et al.*, *Phys. Rev. Lett.* **77**, 5417–5420 (1996).
37. Y. Ando, G. S. Boebinger, A. Passner, T. Kimura, K. Kishio, *Phys. Rev. Lett.* **75**, 4662–4665 (1995).
38. F. Laliberté *et al.*, arXiv:1606.04491 [cond-mat.supr-con] (14 June 2016).
39. C. Proust, B. Vignolle, J. Levallois, S. Adachi, N. E. Hussey, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 13654–13659 (2016).
40. A. A. Abrikosov, *Fundamentals of the Theory of Metals* (North-Holland, 1988).
41. A. B. Pippard, *Magnetoresistance in Metals* (Cambridge Univ. Press, 1989).
42. G. Logvenov, A. Gozar, I. Božović, *Science* **326**, 699–702 (2009).
43. I. Božović, X. He, J. Wu, A. T. Bollinger, *Nature* **536**, 309–311 (2016).
44. J. Wu, I. Bozović, *APL Mater.* **3**, 062401 (2015).
45. H. Takagi *et al.*, *Phys. Rev. B* **40**, 2254–2261 (1989).
46. R. Liang, D. A. Bonn, W. N. Hardy, *Phys. Rev. B* **73**, 180505(R) (2006).
47. The value of p throughout this manuscript is determined from the superconducting transition temperature in a broad doping range (supplementary text and fig. S1).
48. Measurements of longitudinal and Hall resistivity in $YBa_2Cu_3O_{6+\delta}$ result in a similar estimate for the change in the inferred value of $\omega_c\tau$ in this temperature range (*29*).
49. Y. Ando, S. Komiya, K. Segawa, S. Ono, Y. Kurita, *Phys. Rev. Lett.* **93**, 267001 (2004).
50. The mass increases in $YBa_2Cu_3O_{6+\delta}$ cuprates by nearly a factor of 3 in the doping range of $p = 0.116$ to 0.152 and is expected to diverge around $p = 0.19$ (*21*).
51. Similar behavior in a pnictide superconductor has been phenomenologically captured by adding the thermal and magnetic field scales in quadrature (*18*). We note that in cuprates, the observed temperature-field competition is different. Unlike the saturation of the low-field magnetoresistance at high temperatures (Fig. 1A), the temperature dependence of resistivity at very high fields does not saturate at low temperatures (Fig. 1D).

ACKNOWLEDGMENTS

We thank J. Analytis, J.-H. Chu, N. Doiron-Leyraud, A. Finkel'stein, I. Fisher, S. Hartnoll, I. Hayes, S. Kivelson, J. Paglione, L. Taillefer, C. Varma, and J. Zaanen for discussions, and the entire 100 T operations team at the NHMFL Pulsed Field Facility for their support during the experiment. A.S. acknowledges the hospitality of the Aspen Center for Physics. **Funding:** The high-field resistivity measurements were performed in the 60 T long-pulse and 100 T magnet systems at the NHMFL Pulsed Field Facility, which is supported by NSF grant DMR-1157490 and the U.S. Department of Energy, Basic Energy Sciences (DOE/BES) "Science at 100 T" grant. Molecular beam epitaxy synthesis, lithography, and characterization of the samples were done at BNL, which is supported by DOE/BES, Materials Sciences and Engineering Division. X.H. was supported by the Gordon and Betty Moore Foundation's EPiQS Initiative through grant GBMF4410. Aspen Center for Physics is supported by NSF grant PHY-1066293. **Author contributions:** P.G.-G., J.A.G., Z.S., K.A.M., C.M., S.C.R., X.L., F.F.B., J.B.B., B.J.R., R.D.M., and A.S. performed the high-field resistivity measurements in the 60T long-pulse and 100T magnet systems at the NHMFL's Pulsed Field Facility. MBE synthesis, lithography, and characterization of the samples (by electron and x-ray diffraction, transport and magnetic measurements) were performed by X.H., J.W., A.T.B., and I.B. at BNL. P.G.-G., J.A.G., B.J.R., K.A.M., R.D.M., G.S.B., and A.S. analyzed the data and wrote the manuscript, with contributions from all other authors. **Competing interests:** Authors declare no competing interests. **Data availability:** Data needed to evaluate the conclusions of this manuscript are presented in the main text and supplementary materials.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/361/6401/479/suppl/DC1
Materials and Methods
Figs. S1 to S5
Data Files

27 March 2018; accepted 31 May 2018
10.1126/science.aan3178

Science

Scale-invariant magnetoresistance in a cuprate superconductor

P. Giraldo-Gallo, J. A. Galvis, Z. Stegen, K. A. Modic, F. F. Balakirev, J. B. Betts, X. Lian, C. Moir, S. C. Riggs, J. Wu, A. T. Bollinger, X. He, I. Bozovic, B. J. Ramshaw, R. D. McDonald, G. S. Boebinger and A. Shekhter

Science **361** (6401), 479-481.
DOI: 10.1126/science.aan3178

Cranking up the field

Cuprate superconductors have many unusual properties even in the ''normal'' (nonsuperconducting) regions of their phase diagram. In the so-called ''strange metal'' phase, these materials have resistivity that scales linearly with temperature, in contrast to the usual quadratic dependence of ordinary metals. Giraldo-Gallo *et al.* now find that at very high magnetic fields––up to 80 tesla––the resistivity of the thin films of a lanthanum-based cuprate scales linearly with magnetic field as well, again in contrast to the expected quadratic law. This dual linear dependence presents a challenge for theories of the normal state of the cuprates.

Science, this issue p. 479

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.