



Universiteit
Leiden
The Netherlands

Visualizing strongly-correlated electrons with a novel scanning tunneling microscope

Battisti, I.

Citation

Battisti, I. (2019, May 8). *Visualizing strongly-correlated electrons with a novel scanning tunneling microscope*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/72410>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/72410>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/72410> holds various files of this Leiden University dissertation.

Author: Battisti, I.

Title: Visualizing strongly-correlated electrons with a novel scanning tunneling microscope

Issue Date: 2019-05-08

Bibliography

- [1] N. W. Ashcroft, N. Mermin. *Solid State Physics*. Holt, Rinehart and Winston, New York (1976).
- [2] J. Schrieffer. What is a quasi-particle? *J. Res. Natl. Bur. Stand. Sect. A Phys. Chem.* **74A**, 537 (1970).
- [3] P. W. Anderson. More Is Different. *Science* **177**, 393–396 (1972).
- [4] K. Fujita, M. Hamidian, I. Firmo, S. Mukhopadhyay, C. K. Kim, H. Eisaki, S.-I. Uchida, J. C. Davis. Spectroscopic Imaging STM: Atomic-Scale Visualization of Electronic Structure and Symmetry in Underdoped Cuprates. In *Theor. Methods Strongly Correl. Syst.*, chap. 3, 73–109. Springer Berlin Heidelberg (2015).
- [5] N. F. Mott. *Metal-Insulator Transitions*. Taylor & Francis, London (1990).
- [6] M. Imada, A. Fujimori, Y. Tokura. Metal-insulator transitions. *Rev. Mod. Phys.* **70**, 1039–1263 (1998).
- [7] D. I. Khomskii. *Transition metal compounds*. Cambridge University Press(2014).
- [8] G. Kotliar, D. Vollhardt. Strongly Correlated Materials: Insights From Dynamical Mean-Field Theory. *Phys. Today* **57**, 53–59 (2004).
- [9] P. A. Lee, N. Nagaosa, X.-G. Wen. Doping a Mott insulator: Physics of high-temperature superconductivity. *Rev. Mod. Phys.* **78**, 17–85 (2006).
- [10] J. Bednorz, K. Müller. Possible High- T_c Superconductivity in the BaLaCu0 System. *Z.Phys.B-Condensed Matter* **64**, 189–193 (1986).
- [11] B. Keimer, S. A. Kivelson, M. R. Norman, S. Uchida, J. Zaanen. From quantum matter to high-temperature superconductivity in copper oxides. *Nature* **518**, 179–186 (2015).
- [12] N. P. Armitage, P. Fournier, R. L. Greene. Progress and perspectives on electron-doped cuprates. *Rev. Mod. Phys.* **82**, 2421–2487 (2010).
- [13] E. Fradkin, S. A. Kivelson, J. M. Tranquada. Colloquium: Theory of intertwined orders in high temperature superconductors. *Rev. Mod. Phys.* **87**, 457–482 (2015).

- [14] N. E. Hussey, K. Takenaka, H. Takagi. Universality of the Mott–Ioffe–Regel limit in metals. *Philos. Mag.* **84**, 2847–2864 (2004).
- [15] C. Howald, P. Fournier, A. Kapitulnik. Inherent inhomogeneities in tunneling spectra of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8-x}$ crystals in the superconducting state. *Phys. Rev. B* **64**, 100504 (2001).
- [16] K. M. Lang, V. Madhavan, J. E. Hoffman, E. W. Hudson, H. Eisaki, S. Uchida, J. C. Davis. Imaging the granular structure of high- T_c superconductivity in underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Nature* **415**, 412–416 (2002).
- [17] K. McElroy. Atomic-Scale Sources and Mechanism of Nanoscale Electronic Disorder in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Science* **309**, 1048–1052 (2005).
- [18] J. E. Hoffman. Imaging Quasiparticle Interference in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Science* **297**, 1148–1151 (2002).
- [19] Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, J. C. Davis. An Intrinsic Bond-Centered Electronic Glass with Unidirectional Domains in Underdoped Cuprates. *Science* **315**, 1380–1385 (2007).
- [20] M. J. Lawler, K. Fujita, J. Lee, A. R. Schmidt, Y. Kohsaka, C. K. Kim, H. Eisaki, S. Uchida, J. C. Davis, J. P. Sethna, E.-A. Kim. Intra-unit-cell electronic nematicity of the high- T_c copper-oxide pseudogap states. *Nature* **466**, 347–351 (2010).
- [21] D. Griffiths. *Introduction to quantum mechanics*. Cambridge University Press, second ed. (2016).
- [22] G. Binnig, H. Rohrer. Scanning Tunneling Microscopy - from Birth to Adolescence (Nobel Lecture). *Angew. Chemie Int. Ed. English* **26**, 606–614 (1987).
- [23] R. M. Feenstra, J. Stroscio, A. Fein. Tunneling spectroscopy of the $\text{Si}(111)2\times 1$ surface. *J. Vac. Sci. Technol. B* **5**, 295–306 (1987).
- [24] M. Crommie, C. Lutz, D. Eigler. Imaging standing waves in a 2D electron gas. *Nature* **363**, 524–527 (1993).
- [25] L. Petersen, P. T. Sprunger, P. Hofmann, E. Lægsgaard, B. G. Briner, M. Döering, H.-P. Rust, A. M. Bradshaw, F. Besenbacher, E. W. Plummer. Direct imaging of the two-dimensional Fermi contour: Fourier-transform STM. *Phys. Rev. B* **57**, R6858–R6861 (1998).
- [26] S. H. Pan, E. W. Hudson, J. C. Davis. Vacuum tunneling of superconducting quasiparticles from atomically sharp scanning tunneling microscope tips. *Appl. Phys. Lett.* **73**, 2992–2994 (1998).
- [27] S. H. Pan, E. W. Hudson, K. M. Lang, H. Eisaki, S. Uchida, J. C. Davis. Imaging the effects of individual zinc impurity atoms on superconductivity in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$. *Nature* **403**, 746–750 (2000).
- [28] E. W. Hudson, K. M. Lang, V. Madhavan, S. H. Pan, H. Eisaki, S. Uchida, J. C. Davis. Interplay of magnetism and high- T_c superconductivity at individual Ni impurity atoms in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Nature* **411**, 920–924 (2001).

-
- [29] C. J. Chen. *Introduction to Scanning Tunneling Microscopy*. Oxford University Press, first ed. (2000).
 - [30] J. E. Hoffman. Spectroscopic scanning tunneling microscopy insights into Fe-based superconductors. *Reports Prog. Phys.* **74**, 124513 (2011).
 - [31] H. Bruus, K. Flensberg. *Many-body quantum theory in condensed matter physics*. Oxford University Press, New York (2004).
 - [32] P. Coleman. *Introduction to many-body physics*. Cambridge University Press (2015).
 - [33] P. Abbamonte, E. Demler, J. Séamus Davis, J.-C. Campuzano. Resonant soft X-ray scattering, stripe order, and the electron spectral function in cuprates. *Phys. C Supercond.* **481**, 15–22 (2012).
 - [34] K. McElroy, R. W. Simmonds, J. E. Hoffman, D.-H. Lee, J. Orenstein, H. Eisaki, S. Uchida, J. C. Davis. Relating atomic-scale electronic phenomena to wave-like quasiparticle states in superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Nature* **422**, 592–596 (2003).
 - [35] K. Fujita, C. K. Kim, I. Lee, J. Lee, M. H. Hamidian, I. A. Firmo, S. Mukhopadhyay, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, J. C. Davis. Simultaneous Transitions in Cuprate Momentum-Space Topology and Electronic Symmetry Breaking. *Science* **344**, 612–616 (2014).
 - [36] M. P. Allan, K. Lee, A. W. Rost, M. H. Fischer, F. Massee, K. Kihou, C.-H. Lee, A. Iyo, H. Eisaki, T.-M. Chuang, J. C. Davis, E.-A. Kim. Identifying the ‘fingerprint’ of antiferromagnetic spin fluctuations in iron pnictide superconductors. *Nat. Phys.* **11**, 177–182 (2015).
 - [37] B. B. Zhou, S. Misra, E. H. Da Silva Neto, P. Aynajian, R. E. Baumbach, J. D. Thompson, E. D. Bauer, A. Yazdani. Visualizing nodal heavy fermion superconductivity in CeCoIn_5 . *Nat. Phys.* **9**, 474–479 (2013).
 - [38] M. P. Allan, F. Massee, D. K. Morr, J. Van Dyke, A. W. Rost, A. P. Mackenzie, C. Petrovic, J. C. Davis. Imaging Cooper pairing of heavy fermions in CeCoIn_5 . *Nat. Phys.* **9**, 468–473 (2013).
 - [39] P. Roushan, J. Seo, C. V. Parker, Y. S. Hor, D. Hsieh, D. Qian, A. Richardella, M. Z. Hasan, R. J. Cava, A. Yazdani. Topological surface states protected from backscattering by chiral spin texture. *Nature* **460**, 1106–1109 (2009).
 - [40] H. Inoue, A. Gyenis, Z. Wang, J. Li, S. W. Oh, S. Jiang, N. Ni, B. A. Bernevig, A. Yazdani. Quasiparticle interference of the Fermi arcs and surface-bulk connectivity of a Weyl semimetal. *Science* **351**, 1184–1187 (2016).
 - [41] A. Gyenis, H. Inoue, S. Jeon, B. B. Zhou, B. E. Feldman, Z. Wang, J. Li, S. Jiang, Q. D. Gibson, S. K. Kushwaha, J. W. Krizan, N. Ni, R. J. Cava, B. A. Bernevig, A. Yazdani. Imaging electronic states on topological semimetals using scanning tunneling microscopy. *New J. Phys.* **18**, 105003 (2016).
 - [42] P. Sessi, V. M. Silkin, I. A. Nechaev, T. Bathon, L. El-Kareh, E. V. Chulkov, P. M. Echenique, M. Bode. Direct observation of many-body charge density

- oscillations in a two-dimensional electron gas. *Nat. Commun.* **6**, 8691 (2015).
- [43] Z. Wang, D. Walkup, P. Derry, T. Scaffidi, M. Rak, S. Vig, A. Kogar, I. Zeljkovic, A. Husain, L. H. Santos, Y. Wang, A. Damascelli, Y. Maeno, P. Abbamonte, E. Fradkin, V. Madhavan. Quasiparticle interference and strong electron–mode coupling in the quasi-one-dimensional bands of Sr_2RuO_4 . *Nat. Phys.* **13**, 799–805 (2017).
- [44] A. Damascelli, Z. Hussain, Z.-X. Shen. Angle-resolved photoemission studies of the cuprate superconductors. *Rev. Mod. Phys.* **75**, 473–541 (2003).
- [45] R. S. Markiewicz. Bridging k and q space in the cuprates: Comparing angle-resolved photoemission and STM results. *Phys. Rev. B* **69**, 214517 (2004).
- [46] U. Chatterjee, M. Shi, A. Kaminski, A. Kanigel, H. M. Fretwell, K. Terashima, T. Takahashi, S. Rosenkranz, Z. Z. Li, H. Raffy, A. Santander-Syro, K. Kadowaki, M. R. Norman, M. Randeria, J. C. Campuzano. Nondispersive Fermi Arcs and the Absence of Charge Ordering in the Pseudogap Phase of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Phys. Rev. Lett.* **96**, 107006 (2006).
- [47] K. McElroy, G.-H. Gweon, S. Y. Zhou, J. Graf, S. Uchida, H. Eisaki, H. Takagi, T. Sasagawa, D.-H. Lee, A. Lanzara. Elastic Scattering Susceptibility of the High Temperature Superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$: A Comparison between Real and Momentum Space Photoemission Spectroscopies. *Phys. Rev. Lett.* **96**, 067005 (2006).
- [48] R. M. Feenstra, J. Y. Lee, M. H. Kang, G. Meyer, K. H. Rieder. Band gap of the $\text{Ge}(111)c(2\times 8)$ surface by scanning tunneling spectroscopy. *Phys. Rev. B* **73**, 035310 (2006).
- [49] R. M. Feenstra, Y. Dong, M. P. Semtsiv, W. T. Masselink. Influence of tip-induced band bending on tunneling spectra of semiconductor surfaces. *Nanotechnology* **18**, 044015 (2007).
- [50] M. Weimer, J. Kramar, J. Baldeschwieler. Band bending and the apparent barrier height in scanning tunneling microscopy. *Phys. Rev. B* **39**, 5572 (1989).
- [51] R. Feenstra. SEMITIP v6 (2011).
- [52] S. C. White, U. R. Singh, P. Wahl. A stiff scanning tunneling microscopy head for measurement at low temperatures and in high magnetic fields. *Rev. Sci. Instrum.* **82**, 113708 (2011).
- [53] S. H. Pan, E. W. Hudson, J. C. Davis. ^3He refrigerator based very low temperature scanning tunneling microscope. *Rev. Sci. Instrum.* **70**, 1459–1463 (1999).
- [54] F. Pobell. *Matter and Methods at Low Temperatures*. Springer Berlin Heidelberg, 3rd ed. (2007).
- [55] R. J. Hussey, J. Wilson. *Advanced Technical Ceramics Directory and Databook*. Springer (2012).
- [56] A. L. Woodcraft, A. Gray. A low temperature thermal conductivity database. In *Low Temp. Detect. LTD 13*, 681–684 (2009).

-
- [57] NIST. NIST online cryogenic database. Tech. rep., National Institute of Standards and Technology (2018).
 - [58] K. M. Bastiaans, T. Benschop, D. Chatzopoulos, D. Cho, Q. Dong, Y. Jin, M. P. Allan. Amplifier for scanning tunneling microscopy at MHz frequencies. *Rev. Sci. Instrum.* **89**, 093709 (2018).
 - [59] K. M. Bastiaans, D. Cho, T. Benschop, I. Battisti, Y. Huang, M. S. Golden, Q. Dong, Y. Jin, J. Zaanen, M. P. Allan. Charge trapping and super-Poissonian noise centres in a cuprate superconductor. *Nat. Phys.* **14**, 1183–1187 (2018).
 - [60] COMSOL AB. COMSOL Multiphysics 5.2 (2015).
 - [61] J. H. Kindt, G. E. Fantner, J. A. Cutroni, P. K. Hansma. Rigid design of fast scanning probe microscopes using finite element analysis. *Ultramicroscopy* **100**, 259–265 (2004).
 - [62] C. R. Ast, M. Assig, A. Ast, K. Kern. Design criteria for scanning tunneling microscopes to reduce the response to external mechanical disturbances. *Rev. Sci. Instrum.* **79**, 093704 (2008).
 - [63] J. Maess, A. J. Fleming, F. Allgöwer. Simulation of dynamics-coupling in piezoelectric tube scanners by reduced order finite element analysis. *Rev. Sci. Instrum.* **79**, 015105 (2008).
 - [64] C. Braunsman, T. E. Schäffer. High-speed atomic force microscopy for large scan sizes using small cantilevers. *Nanotechnology* **21**, 225705 (2010).
 - [65] M. J. Rost, L. Crama, P. Schakel, E. van Tol, G. B. E. M. van Velzen-Williams, C. F. Overgaw, H. ter Horst, H. Dekker, B. Okhuijsen, M. Seynen, A. Vijftigchild, P. Han, A. J. Katan, K. Schoots, R. Schumm, W. van Loo, T. H. Oosterkamp, J. W. M. Frenken. Scanning probe microscopes go video rate and beyond. *Rev. Sci. Instrum.* **76**, 053710 (2005).
 - [66] M. J. Rost, G. J. C. van Baarle, A. J. Katan, W. M. van Spengen, P. Schakel, W. A. van Loo, T. H. Oosterkamp, J. W. M. Frenken. Video-rate scanning probe control challenges: setting the stage for a microscopy revolution. *Asian J. Control* **11**, 110–129 (2009).
 - [67] Y. I. Yanson, F. Schenkel, M. J. Rost. Design of a high-speed electrochemical scanning tunneling microscope. *Rev. Sci. Instrum.* **84**, 023702 (2013).
 - [68] R. S. Perry, F. Baumberger, L. Balicas, N. Kikugawa, N. J. C. Ingle, A. Rost, J. F. Mercure, Y. Maeno, Z. X. Shen, A. P. Mackenzie. Sr_2RhO_4 : a new, clean correlated electron metal. *New J. Phys.* **8**, 175 (2006).
 - [69] F. Baumberger, N. J. C. Ingle, W. Meevasana, K. M. Shen, D. H. Lu, R. S. Perry, A. P. Mackenzie, Z. Hussain, D. J. Singh, Z.-X. Shen. Fermi Surface and Quasiparticle Excitations of Sr_2RhO_4 . *Phys. Rev. Lett.* **96**, 246402 (2006).
 - [70] T. Craig. *Imaging Interacting Electrons in Sr_2RhO_4* . Msc thesis, University of St. Andrews (2012).
 - [71] B. J. Kim, H. Jin, S. J. Moon, J.-Y. Kim, B.-G. Park, C. S. Leem, J. Yu, T. W. Noh, C. Kim, S.-J. Oh, J.-H. Park, V. Durairaj, G. Cao, E. Rotenberg. Novel

- $J_{\text{eff}}=1/2$ Mott State Induced by Relativistic Spin-Orbit Coupling in Sr_2IrO_4 . *Phys. Rev. Lett.* **101**, 076402 (2008).
- [72] J. G. Rau, E. K.-H. Lee, H.-Y. Kee. Spin-Orbit Physics Giving Rise to Novel Phases in Correlated Systems: Iridates and Related Materials. *Annu. Rev. Condens. Matter Phys.* **7**, 195–221 (2016).
- [73] S. J. Moon, H. Jin, K. W. Kim, W. S. Choi, Y. S. Lee, J. Yu, G. Cao, A. Sumi, H. Funakubo, C. Bernhard, T. W. Noh. Dimensionality-Controlled Insulator-Metal Transition and Correlated Metallic State in $\text{Sr}_{n+1}\text{Ir}_n\text{O}_{3n+1}$. *Phys. Rev. Lett.* **101**, 226402 (2008).
- [74] H. Watanabe, T. Shirakawa, S. Yunoki. Microscopic Study of a Spin-Orbit-Induced Mott Insulator in Ir Oxides. *Phys. Rev. Lett.* **105**, 216410 (2010).
- [75] C. Martins, M. Aichhorn, L. Vaugier, S. Biermann. Reduced Effective Spin-Orbital Degeneracy and Spin-Orbital Ordering in Paramagnetic Transition-Metal Oxides: Sr_2IrO_4 vs Sr_2RhO_4 . *Phys. Rev. Lett.* **107**, 266404 (2011).
- [76] J. H. Seo, G. H. Ahn, S. J. Song, X. Chen, S. D. Wilson, S. J. Moon. Infrared probe of pseudogap in electron-doped Sr_2IrO_4 . *Sci. Rep.* **7**, 10494 (2017).
- [77] B. H. Kim, G. Khaliullin, B. I. Min. Magnetic Couplings, Optical Spectra, and Spin-Orbit Exciton in 5d Electron Mott Insulator Sr_2IrO_4 . *Phys. Rev. Lett.* **109**, 167205 (2012).
- [78] Q. Wang, Y. Cao, J. A. Waugh, S. R. Park, T. F. Qi, O. B. Korneta, G. Cao, D. S. Dessau. Dimensionality-controlled Mott transition and correlation effects in single-layer and bilayer perovskite iridates. *Phys. Rev. B* **87**, 245109 (2013).
- [79] A. de la Torre, S. McKeown Walker, F. Y. Bruno, S. Ricc , Z. Wang, I. Gutierrez Lezama, G. Scheerer, G. Girit, D. Jaccard, C. Berthod, T. K. Kim, M. Hoesch, E. C. Hunter, R. S. Perry, A. Tamai, F. Baumberger. Collapse of the Mott Gap and Emergence of a Nodal Liquid in Lightly Doped Sr_2IrO_4 . *Phys. Rev. Lett.* **115**, 176402 (2015).
- [80] V. Brouet, J. Mansart, L. Perfetti, C. Piovera, I. Vobornik, P. Le F vre, F. Bertran, S. C. Riggs, M. C. Shapiro, P. Giraldo-Gallo, I. R. Fisher. Transfer of spectral weight across the gap of Sr_2IrO_4 induced by La doping. *Phys. Rev. B* **92**, 081117 (2015).
- [81] B. J. Kim, H. Ohsumi, T. Komesu, S. Sakai, T. Morita, H. Takagi, T. Arima. Phase-Sensitive Observation of a Spin-Orbital Mott State in Sr_2IrO_4 . *Science* **323**, 1329–1332 (2009).
- [82] J. Kim, D. Casa, M. H. Upton, T. Gog, Y.-J. Kim, J. F. Mitchell, M. van Veenendaal, M. Daghofer, J. van den Brink, G. Khaliullin, B. J. Kim. Magnetic Excitation Spectra of Sr_2IrO_4 Probed by Resonant Inelastic X-Ray Scattering: Establishing Links to Cuprate Superconductors. *Phys. Rev. Lett.* **108**, 177003 (2012).
- [83] X. Chen, J. L. Schmehl, Z. Islam, Z. Porter, E. Zoghlin, K. Finkelstein, J. P. C. Ruff, S. D. Wilson. Unidirectional spin density wave state in metallic

- ($\text{Sr}_{1-x}\text{La}_x$) $_2\text{IrO}_4$. *Nat. Commun.* **9**, 103 (2018).
- [84] J. Dai, E. Calleja, G. Cao, K. McElroy. Local density of states study of a spin-orbit-coupling induced Mott insulator Sr_2IrO_4 . *Phys. Rev. B* **90**, 041102 (2014).
 - [85] J. Nichols, N. Bray-Ali, A. Ansary, G. Cao, K.-W. Ng. Tunneling into the Mott insulator Sr_2IrO_4 . *Phys. Rev. B* **89**, 085125 (2014).
 - [86] Q. Li, G. Cao, S. Okamoto, J. Yi, W. Lin, B. C. Sales, J. Yan, R. Arita, J. Kuneš, A. V. Kozhevnikov, A. G. Eguiluz, M. Imada, Z. Gai, M. Pan, D. G. Mandrus. Atomically resolved spectroscopic study of Sr_2IrO_4 : Experiment and theory. *Sci. Rep.* **3**, 3073 (2013).
 - [87] F. Wang, T. Senthil. Twisted Hubbard Model for Sr_2IrO_4 : Magnetism and Possible High Temperature Superconductivity. *Phys. Rev. Lett.* **106**, 136402 (2011).
 - [88] H. Watanabe, T. Shirakawa, S. Yunoki. Monte Carlo Study of an Unconventional Superconducting Phase in Iridium Oxide $J_{\text{eff}}=1/2$ Mott Insulators Induced by Carrier Doping. *Phys. Rev. Lett.* **110**, 027002 (2013).
 - [89] O. B. Korneta, T. Qi, S. Chikara, S. Parkin, L. E. De Long, P. Schlottmann, G. Cao. Electron-doped $\text{Sr}_2\text{IrO}_{4-\delta}$: Evolution of a disordered $J_{\text{eff}}=1/2$ Mott insulator into an exotic metallic state. *Phys. Rev. B* **82**, 115117 (2010).
 - [90] Y. Klein, I. Terasaki. Insight on the electronic state of Sr_2IrO_4 revealed by cationic substitutions. *J. Phys. Condens. Matter* **20**, 295201 (2008).
 - [91] M. Ge, T. F. Qi, O. B. Korneta, D. E. De Long, P. Schlottmann, W. P. Crummett, G. Cao. Lattice-driven magnetoresistivity and metal-insulator transition in single-layered iridates. *Phys. Rev. B* **84**, 100402 (2011).
 - [92] X. Chen, T. Hogan, D. Walkup, W. Zhou, M. Pokharel, M. Yao, W. Tian, T. Z. Ward, Y. Zhao, D. Parshall, C. Opeil, J. W. Lynn, V. Madhavan, S. D. Wilson. Influence of electron doping on the ground state of ($\text{Sr}_{1-x}\text{La}_x$) $_2\text{IrO}_4$. *Phys. Rev. B* **92**, 075125 (2015).
 - [93] Y. K. Kim, O. Krupin, J. D. Denlinger, A. Bostwick, E. Rotenberg, Q. Zhao, J. F. Mitchell, J. W. Allen, B. J. Kim. Fermi arcs in a doped pseudospin- $1/2$ Heisenberg antiferromagnet. *Science* **345**, 187–190 (2014).
 - [94] Y. J. Yan, M. Q. Ren, H. C. Xu, B. P. Xie, R. Tao, H. Y. Choi, N. Lee, Y. J. Choi, T. Zhang, D. L. Feng. Electron-Doped Sr_2IrO_4 : An Analogue of Hole-Doped Cuprate Superconductors Demonstrated by scanning tunneling microscopy. *Phys. Rev. X* **5**, 041018 (2015).
 - [95] Y. K. Kim, N. H. Sung, J. D. Denlinger, B. J. Kim. Observation of a d-wave gap in electron-doped Sr_2IrO_4 . *Nat. Phys.* **12**, 37–41 (2016).
 - [96] K. Wang, N. Bachar, J. Teyssier, W. Luo, C. W. Rischau, G. Scheerer, A. de la Torre, R. S. Perry, F. Baumberger, D. van der Marel. Mott transition and collective charge pinning in electron doped Sr_2IrO_4 . *Phys. Rev. B* **98**, 045107 (2018).

- [97] Y. Ando, A. N. Lavrov, S. Komiya, K. Segawa, X. F. Sun. Mobility of the Doped Holes and the Antiferromagnetic Correlations in Underdoped High- T_c Cuprates. *Phys. Rev. Lett.* **87**, 017001 (2001).
- [98] Y. Okada, D. Walkup, H. Lin, C. Dhital, T.-R. Chang, S. Khadka, W. Zhou, H.-T. Jeng, M. Paranjape, A. Bansil, Z. Wang, S. D. Wilson, V. Madhavan. Imaging the evolution of metallic states in a correlated iridate. *Nat. Mater.* **12**, 707–713 (2013).
- [99] I. Zeljkovic, Z. Xu, J. Wen, G. Gu, R. S. Markiewicz, J. E. Hoffman. Imaging the Impact of Single Oxygen Atoms on Superconducting $\text{Bi}_{2+y}\text{Sr}_{2-y}\text{CaCu}_2\text{O}_{8+x}$. *Science* **337**, 320–323 (2012).
- [100] C. Ye, P. Cai, R. Yu, X. Zhou, W. Ruan, Q. Liu, C. Jin, Y. Wang. Visualizing the atomic-scale electronic structure of the $\text{Ca}_2\text{CuO}_2\text{Cl}_2$ Mott insulator. *Nat. Commun.* **4**, 1365 (2013).
- [101] P. Cai, W. Ruan, Y. Peng, C. Ye, X. Li, Z. Hao, X. Zhou, D.-H. Lee, Y. Wang. Visualizing the evolution from the Mott insulator to a charge-ordered insulator in lightly doped cuprates. *Nat. Phys.* **12**, 1047–1051 (2016).
- [102] Y. Kohsaka, K. Iwaya, S. Satow, T. Hanaguri, M. Azuma, M. Takano, H. Takagi. Imaging Nanoscale Electronic Inhomogeneity in the Lightly Doped Mott Insulator $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$. *Phys. Rev. Lett.* **93**, 097004 (2004).
- [103] Y. Kohsaka, T. Hanaguri, M. Azuma, M. Takano, J. C. Davis, H. Takagi. Visualization of the emergence of the pseudogap state and the evolution to superconductivity in a lightly hole-doped Mott insulator. *Nat. Phys.* **8**, 534–538 (2012).
- [104] J. W. Alldredge, J. Lee, K. McElroy, M. Wang, K. Fujita, Y. Kohsaka, C. Taylor, H. Eisaki, S. Uchida, P. J. Hirschfeld, J. C. Davis. Evolution of the electronic excitation spectrum with strongly diminishing hole density in superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$. *Nat. Phys.* **4**, 319–326 (2008).
- [105] H. Wang, S.-L. Yu, J.-X. Li. Fermi arcs, pseudogap, and collective excitations in doped Sr_2IrO_4 : A generalized fluctuation exchange study. *Phys. Rev. B* **91**, 165138 (2015).
- [106] A. Moutenet, A. Georges, M. Ferrero. Pseudogap and electronic structure of electron-doped Sr_2IrO_4 . *Phys. Rev. B* **97**, 155109 (2018).
- [107] C. V. Parker, P. Aynajian, E. H. da Silva Neto, A. Pushp, S. Ono, J. Wen, Z. Xu, G. Gu, A. Yazdani. Fluctuating stripes at the onset of the pseudogap in the high- T_c superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$. *Nature* **468**, 677–680 (2010).
- [108] R. Comin, A. Damascelli. Resonant X-Ray Scattering Studies of Charge Order in Cuprates. *Annu. Rev. Condens. Matter Phys.* **7**, 369–405 (2016).
- [109] S. H. Simon. *The Oxford Solid State Basics*. Oxford University Press (2013).
- [110] X. Blase, E. Bustarret, C. Chapelier, T. Klein, C. Marcenat. Superconducting group-IV semiconductors. *Nat. Mater.* **8**, 375–382 (2009).

-
- [111] N. F. Mott. The metal-insulator transition in an impurity band. *Le J. Phys. Colloq.* **37**, C4–301–C4–306 (1976).
 - [112] M. A. Kastner, R. J. Birgeneau, G. Shirane, Y. Endoh. Magnetic, transport, and optical properties of monolayer copper oxides. *Rev. Mod. Phys.* **70**, 897–928 (1998).
 - [113] V. I. Anisimov, M. A. Korotin, J. Zaanen, O. K. Andersen. Spin bags, polarons, and impurity potentials in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. *Phys. Rev. Lett.* **68**, 345–348 (1992).
 - [114] C. Martins, B. Lenz, L. Perfetti, V. Brouet, F. Bertran, S. Biermann. Nonlocal Coulomb correlations in pure and electron-doped Sr_2IrO_4 : Spectral functions, Fermi surface, and pseudo-gap-like spectral weight distributions from oriented cluster dynamical mean-field theory. *Phys. Rev. Mater.* **2**, 032001 (2018).
 - [115] C.-L. Song, Y.-P. Jiang, Y.-L. Wang, Z. Li, L. Wang, K. He, X. Chen, X.-C. Ma, Q.-K. Xue. Gating the charge state of single Fe dopants in the topological insulator Bi_2Se_3 with a scanning tunneling microscope. *Phys. Rev. B* **86**, 045441 (2012).
 - [116] V. W. Brar, R. Decker, H.-M. Solowan, Y. Wang, L. Maserati, K. T. Chan, H. Lee, Ç. O. Girit, A. Zettl, S. G. Louie, M. L. Cohen, M. F. Crommie. Gate-controlled ionization and screening of cobalt adatoms on a graphene surface. *Nat. Phys.* **7**, 43–47 (2011).
 - [117] D. T. Walkup. *Doping and strain effects in strongly spin-orbit coupled systems*. Ph.D. thesis, Boston College (2016).
 - [118] M. M. Ugeda, A. J. Bradley, S.-F. Shi, F. H. da Jornada, Y. Zhang, D. Y. Qiu, W. Ruan, S.-K. Mo, Z. Hussain, Z.-X. Shen, F. Wang, S. G. Louie, M. F. Crommie. Giant bandgap renormalization and excitonic effects in a monolayer transition metal dichalcogenide semiconductor. *Nat. Mater.* **13**, 1091–1095 (2014).
 - [119] D. Wong, Y. Wang, J. Jung, S. Pezzini, A. M. DaSilva, H.-z. Tsai, H. S. Jung, R. Khajeh, Y. Kim, J. Lee, S. Kahn, S. Tollabimazraehno, H. Rasool, K. Watanabe, T. Taniguchi, A. Zettl, S. Adam, A. H. MacDonald, M. F. Crommie. Local spectroscopy of moiré-induced electronic structure in gate-tunable twisted bilayer graphene. *Phys. Rev. B* **92**, 155409 (2015).
 - [120] M. Morgenstern, V. Gudmundsson, R. Dombrowski, C. Wittneven, R. Wiesendanger. Nonlocality of the exchange interaction probed by scanning tunneling spectroscopy. *Phys. Rev. B* **63**, 201301 (2001).
 - [121] F. Marczinowski, J. Wiebe, F. Meier, K. Hashimoto, R. Wiesendanger. Effect of charge manipulation on scanning tunneling spectra of single Mn acceptors in InAs. *Phys. Rev. B* **77**, 115318 (2008).
 - [122] F. Herbert, A. Krishnamoorthy, K. Van Vliet, B. Yildiz. Quantification of electronic band gap and surface states on $\text{FeS}_2(100)$. *Surf. Sci.* **618**, 53–61 (2013).
 - [123] A. Sabitova, P. Ebert, A. Lenz, S. Schaafhausen, L. Ivanova, M. Dähne, A. Hoffmann, R. E. Dunin-Borkowski, A. Förster, B. Grandidier, H. Eisele. Intrinsic

- bandgap of cleaved ZnO(110) surfaces. *Appl. Phys. Lett.* **102**, 021608 (2013).
- [124] K. Teichmann, M. Wenderoth, S. Loth, R. G. Ulbrich, J. K. Garleff, A. P. Wijnheijmer, P. M. Koenraad. Controlled Charge Switching on a Single Donor with a Scanning Tunneling Microscope. *Phys. Rev. Lett.* **101**, 076103 (2008).
- [125] A. P. Wijnheijmer, J. K. Garleff, K. Teichmann, M. Wenderoth, S. Loth, P. M. Koenraad. Single Si dopants in GaAs studied by scanning tunneling microscopy and spectroscopy. *Phys. Rev. B* **84**, 125310 (2011).
- [126] S. Loth, M. Wenderoth, L. Winking, R. G. Ulbrich, S. Malzer, G. H. Döhler. Probing Semiconductor Gap States with Resonant Tunneling. *Phys. Rev. Lett.* **96**, 066403 (2006).
- [127] J. D. Jackson. Boundary-value problems with dielectrics. In *Class. Electrodyn.* John Wiley & Sons, third ed. (1999).
- [128] S. Varyukhin, A. Zkharov. Anisotropic dielectric constant of La_2CuO_4 . *Phys. C Supercond.* **185-189**, 975–976 (1991).
- [129] S. Chikara, O. Korneta, W. P. Crummett, L. E. DeLong, P. Schlottmann, G. Cao. Giant magnetoelectric effect in the $J_{\text{eff}}=1/2$ Mott insulator Sr_2IrO_4 . *Phys. Rev. B* **80**, 140407 (2009).
- [130] A. P. Wijnheijmer, J. K. Garleff, K. Teichmann, M. Wenderoth, S. Loth, R. G. Ulbrich, P. A. Maksym, M. Roy, P. M. Koenraad. Enhanced Donor Binding Energy Close to a Semiconductor Surface. *Phys. Rev. Lett.* **102**, 166101 (2009).
- [131] D.-H. Lee, J. A. Gupta. Tunable Control over the Ionization State of Single Mn Acceptors in GaAs with Defect-Induced Band Bending. *Nano Lett.* **11**, 2004–2007 (2011).
- [132] H. Zheng, J. Kröger, R. Berndt. Spectroscopy of Single Donors at ZnO(0001) Surfaces. *Phys. Rev. Lett.* **108**, 076801 (2012).
- [133] H. Zheng, A. Weismann, R. Berndt. Manipulation of Subsurface Donors in ZnO. *Phys. Rev. Lett.* **110**, 226101 (2013).
- [134] G. A. Steele, R. C. Ashoori, L. N. Pfeiffer, K. W. West. Imaging Transport Resonances in the Quantum Hall Effect. *Phys. Rev. Lett.* **95**, 136804 (2005).
- [135] Z. Wang, Y. Okada, J. O’Neal, W. Zhou, D. Walkup, C. Dhital, T. Hogan, P. Clancy, Y.-J. Kim, Y. F. Hu, L. H. Santos, S. D. Wilson, N. Trivedi, V. Madhavan. Disorder induced power-law gaps in an insulator–metal Mott transition. *Proc. Natl. Acad. Sci.* **115**, 11198–11202 (2018).
- [136] J. L. Collins, A. Tadich, W. Wu, L. C. Gomes, J. N. B. Rodrigues, C. Liu, J. Hellerstedt, H. Ryu, S. Tang, S.-K. Mo, S. Adam, S. A. Yang, M. S. Fuhrer, M. T. Edmonds. Electric-field-tuned topological phase transition in ultrathin Na_3Bi . *Nature* **564**, 390–394 (2018).
- [137] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, P. Jarillo-Herrero. Unconventional superconductivity in magic-angle graphene superlattices. *Nature* **556**, 43–50 (2018).

-
- [138] M. P. Allan, A. W. Rost, A. P. Mackenzie, Y. Xie, J. C. Davis, K. Kihou, C. H. Lee, A. Iyo, H. Eisaki, T.-M. Chuang. Anisotropic Energy Gaps of Iron-Based Superconductivity from Intraband Quasiparticle Interference in LiFeAs. *Science* **336**, 563–567 (2012).
 - [139] M. P. Allan, A. W. Rost, A. P. Mackenzie, Y. Xie, J. C. Davis, K. Kihou, C. H. Lee, A. Iyo, H. Eisaki, T.-M. Chuang. Anisotropic Energy Gaps of Iron-Based Superconductivity from Intraband Quasiparticle Interference in LiFeAs. *Science* **336**, 563–567 (2012).
 - [140] M. A. Sulangi, M. P. Allan, J. Zaanen. Revisiting quasiparticle scattering interference in high-temperature superconductors: The problem of narrow peaks. *Phys. Rev. B* **96**, 134507 (2017).
 - [141] M. A. Sulangi, J. Zaanen. Quasiparticle density of states, localization, and distributed disorder in the cuprate superconductors. *Phys. Rev. B* **97**, 144512 (2018).
 - [142] M. Itoh, T. Shimura, Y. Inaguma, Y. Morii. Structure of 2D conductor Sr_2RhO_4 . *J. Solid State Chem.* **118**, 206 (1995).
 - [143] B. J. Kim, J. Yu, H. Koh, I. Nagai, S. I. Ikeda, S.-J. Oh, C. Kim. Missing xy-Band Fermi Surface in 4d Transition-Metal Oxide Sr_2RhO_4 : Effect of the octahedra rotation on the electronic structure. *Phys. Rev. Lett.* **97**, 106401 (2006).
 - [144] G.-q. Liu, V. N. Antonov, O. Jepsen, O. K. Andersen. Coulomb-Enhanced Spin-Orbit Splitting: The Missing Piece in the Sr_2RhO_4 Puzzle. *Phys. Rev. Lett.* **101**, 026408 (2008).
 - [145] A. P. Mackenzie, Y. Maeno. The superconductivity of Sr_2RuO_4 and the physics of spin-triplet pairing. *Rev. Mod. Phys.* **75**, 657–712 (2003).
 - [146] G. Zhang, E. Gorelov, E. Sarvestani, E. Pavarini. Fermi Surface of Sr_2RuO_4 : Spin-Orbit and Anisotropic Coulomb Interaction Effects. *Phys. Rev. Lett.* **116**, 106402 (2016).
 - [147] B. Stöger, M. Hieckel, F. Mittendorfer, Z. Wang, D. Fobes, J. Peng, Z. Mao, M. Schmid, J. Redinger, U. Diebold. High Chemical Activity of a Perovskite Surface: Reaction of CO with $\text{Sr}_3\text{Ru}_2\text{O}_7$. *Phys. Rev. Lett.* **113**, 116101 (2014).
 - [148] L. J. Sandilands, W. Kyung, S. Y. Kim, J. Son, J. Kwon, T. D. Kang, Y. Yoshida, S. J. Moon, C. Kim, T. W. Noh. Spin-Orbit Coupling and Interband Transitions in the Optical Conductivity of Sr_2RhO_4 . *Phys. Rev. Lett.* **119**, 267402 (2017).
 - [149] T. Dahm, D. J. Scalapino. Quasi-particle interference probe of the self-energy. *New J. Phys.* **16**, 023003 (2014).
 - [150] A. J. Macdonald, Y.-S. Tremblay-Johnston, S. Grothe, S. Chi, P. Dosanjh, S. Johnston, S. A. Burke. Dispersing artifacts in FT-STs: a comparison of set point effects across acquisition modes. *Nanotechnology* **27**, 414004 (2016).

- [151] Y. He, Y. Yin, M. Zech, A. Soumyanarayanan, M. M. Yee, T. Williams, M. C. Boyer, K. Chatterjee, W. D. Wise, I. Zeljkovic, T. Kondo, T. Takeuchi, H. Ikuta, P. Mistark, R. S. Markiewicz, A. Bansil, S. Sachdev, E. W. Hudson, J. E. Hoffman. Fermi Surface and Pseudogap Evolution in a Cuprate Superconductor. *Science* **344**, 608–611 (2014).
- [152] C. M. Varma, P. B. Littlewood, S. Schmitt-Rink, E. Abrahams, A. E. Ruckenstein. Phenomenology of the normal state of Cu-O high-temperature superconductors. *Phys. Rev. Lett.* **63**, 1996–1999 (1989).
- [153] J. Zaanen, Y.-W. Sun, Y. Liu, K. Schalm. *Holographic duality in condensed matter physics*. Cambridge University Press (2016).
- [154] R. A. Davison, K. Schalm, J. Zaanen. Holographic duality and the resistivity of strange metals. *Phys. Rev. B* **89**, 245116 (2014).
- [155] M. A. Sulangi, J. Zaanen. Self-energies and quasiparticle scattering interference. *Phys. Rev. B* **98**, 094518 (2018).
- [156] A. V. Semenov, I. A. Devyatov, P. J. de Visser, T. M. Klapwijk. Coherent Excited States in Superconductors due to a Microwave Field. *Phys. Rev. Lett.* **117**, 047002 (2016).