Universal relationship between the energy scales of the pseudogap phase, the superconducting state and the charge density wave order in copper oxide superconductors

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We report the hole doping dependencies of the pseudogap phase energy scale, $2\Delta_{PG}$, the antinodal (nodal) superconducting energy scales $2\Delta^N_{SC}$ ($2\Delta^N_{ANSC}$) and the charge density wave energy scale, $2\Delta_{CDW}$. They have been extracted from the electronic Raman responses of distinct copper oxide families. For all the cuprates studied, we reveal universal doping dependencies which suggest that $2\Delta_{PG}$, $2\Delta^N_{ANSC}$ and $2\Delta_{CDW}$ are governed by common microscopic interactions and that these interactions become relevant well above the superconducting transition at $T_c$. In sharp contrast, $2\Delta^N_{SC}$ tracks the doping dependence of $T_c$, appearing to be controlled by a different kind of interactions than the energy scales above.

I. INTRODUCTION

The overriding question that remains unanswered since the discovery of superconductivity in cuprates by Bednorz and Muller in 1986 [1] is what are the underlying quantum electronic orders that control the temperature-doping ($T-p$) cuprate phase diagram? This question leads to other recurring questions: What are the origins of the dome-like shapes that draw the superconducting transition temperature $T_{SC}(p)$ and the charge density wave transition temperature $T_{CDW}(p)$? Why the pseudogap temperature $T_{PG}(p)$ decreases linearly as $p$ increases? In order to address these key questions, we have explored the doping dependencies of the underlying energy scales associated with the transition temperatures which constitute the cuprate phase diagram. The electronic Raman spectroscopy (ERS) appeared as a very effective probe to track the energy scales of the cuprates phase diagram whether for the detection of the superconducting gap, the pseudogap [2–10] or more recently the charge density wave gap [11]. Indeed, the ERS is an energy-resolved and momentum averaged probe, it is therefore quite sensitive to any kind of gap opening without being blurred by the momentum variations [12]. In this article, we report ERS measurements performed on four distinct cuprates: HgBa$_2$CuO$_{4+\delta}$ (Hg-1201), YBa$_2$Cu$_3$O$_{6+\delta}$ (Y-123), Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) and HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ (Hg-1223). The details of the ERS experimental procedure is given in Appendix A. In the first section, we show how to detect and define the energy scales of the anti-nodal part of the superconducting (SC) gap and the pseudogap (PG) in cuprates. The second section is dedicated to the determination of the charge density wave (CDW) gap and the nodal part of the SC gap and finally in the third section, we show how the energy scales are universally linked in a similar manner in several cuprates families and how they are connected to the ($T-p$) cuprate phase diagram.

II. ANTI-NODAL SUPERCONDUCTING AND PSEUDOGAP ENERGY SCALES

We focus first on the $B_{1g}$ (Anti-Nodal) superconducting Raman responses of two under-doped (UD) cuprates belong to two distinct families: the (UD 117) Hg-1223 and Bi-2212 (UD 75) single crystals. In bracket the number corresponds to the $T_c$ value. Details on the crystals growth, the $T_c$ values and doping are given in Appendix B. In Figure 1 (a) and (b), the SC Raman responses of Hg-1223 and Bi-2212 at 12 K exhibit a well defined pair breaking peak, $2\Delta^N_{SC}$, at two times the energy of the SC gap measured by tunneling and angular resolved photo-emission spectroscopy. It corresponds to the maximum amplitude of the $d$-wave SC gap probed at the antinodes. It is located around 1500 cm$^{-1}$ and 570 cm$^{-1}$ for Hg-1223 and Bi-2212 respectively and marked by a red arrow. The $2\Delta^N_{AN}$ peak is associated on its high energy side with a dip in the electronic continuum. The dip is revealed by comparing the SC (at 12 K) and the normal
Raman responses just above $T_c$ (122K for Hg-1223) and (90 K for Bi-2212). In previous works, we showed that this peak-dip structure detected in the superconducting $B_{1g}$ Raman response results from the interplay between the PG and the SC gap [9, 10, 13]. These experimental findings are supported by cluster dynamical mean field results on the Hubbard Model [14, 15]. The peak-dip structure is emphasized by the subtracted Raman responses $\Delta \chi''_{B_{1g}}(12, 122K) = \chi''_{B_{1g}}(12) - \chi''_{B_{1g}}(122K)$ and $\Delta \chi''_{B_{1g}}(12, 90K)$ for Hg-1223 and Bi-2212 respectively (see insets of panels (a) and (b)). We established (i) that the peak-dip structure is only detected when the pseudogap exists [9, 10, 13] and (ii) it can be smoothly connected to the loss of spectral weight related to the PG above $T_c$ (see Appendix C). Above $T_c$, as the temperature is lowered from $T \geq 280$ K, see Fig.1 (c) and (d), we observe simultaneously a loss and a slight increase of spectral weight of the electronic background below and above 2000 cm$^{-1}$ and 1000 cm$^{-1}$ for respectively Hg-1223 and Bi-2212. This is due to a quasi-particles spectral weight transfer from low to high frequency which characterizes the pseudogap phase. This is underlined by the subtracted Raman responses $\Delta \chi''_{B_{1g}}(122, 280 K)$ (for Hg-1223) and $\Delta \chi''_{B_{1g}}(90, 285 K)$ (for Bi-2212) which signal the loss and the increase of the spectral weight in the negative and positive part of the spectra respectively, as shown in the insets of the (c) and (d) panels. In the positive part of the spectra, it is hard to accurately define an energy scale for the PG in the normal state, because the hump is almost flat on a large frequency range (2500-4500 cm$^{-1}$) and (800-2000 cm$^{-1}$) for Hg-1223 and Bi-2212 respectively. On the other hand, the energy of the dip end of the SC $B_{1g}$ response is more easily detectable and since it corresponds to the Raman signature of the PG in the SC state [9–11, 13], we defined it as the PG energy scale, $2\Delta_{PG}$, marked by a blue arrow.

### III. NODAL SUPERCONDUCTING AND CHARGE DENSITY WAVE ENERGY SCALES

Let’s focus now on the $B_{2g}$ Raman responses obtained from the under-doped Hg-1223, Hg-1201 and Y-123 cuprates. The details of the crystal growths and characterizations of Hg-1201 and Y-123 can be found in Refs. [16, 17]. Below $T_c$ (red curves on the (a) and (b) panels of Fig.2), we detect two distinct features arrowed $2\Delta_{SC}$ and $2\Delta_{CDW}$ in the Raman spectra of Hg-1223 and Hg-1201: a peak and a hump. These features are revealed by subtracting the Raman responses measured at 12 K and $T \geq 280$ K. The shaded area allows a better visualization of the CDW signal. In the case of Hg-1223 and Y-123 the fits allows us to eliminate the SC nodal gap. Details of the fitting procedure is reported in Appendix D. (d)-(f) Subtracted Raman responses between selected temperature above $T_c$ and $T \geq 280$ and (g)-(i) Temperature dependence of the CDW hump area. The black arrow indicates the temperature onset $T_{CDW}$ for each compound. The error bars represent standard deviations of the integrated hump area. The vertical dotted line indicates the superconducting transition temperature, $T_c$. of the SC $B_{1g}$ response is more easily detectable and since it corresponds to the Raman signature of the PG in the SC state [9–11, 13], we defined it as the PG energy scale, $2\Delta_{PG}$, marked by a blue arrow.
V. CONCLUSION

We determine the universal energy scales behaviour associated with the the $T - P$ cuprate phase diagram by extracting from electronic Raman scattering measurements the energy scales of the PG phase, of the anti-nodal and nodal superconducting state and of the charge density wave order for several cuprates families (Hg-1223, Hg-1201, Y-123 and Bi-2212). In all these cuprates, we find that $\Delta_{PG}(p)$, $2\Delta_{AN}^{SC}(p)$ and $2\Delta_{CDW}$ related to Hg-1223 compounds for several doping levels. The doping dependence of these four energy scales are shown in panels (a) and (e) for Hg-1223, (b) and (f) for Y-123, (c), (g) for Hg-1201 and (d), (f) for Bi-2212. Remarkably, the PG, the anti-nodal (AN) SC and the CDW energy scales for all these cuprate families, decrease linearly as $p$ increases on a substantial doping range (panels (a)-(d)). The $2\Delta_{PG}$ scale, is about twice as great as that of the $2\Delta_{AN}^{SC}$ and $2\Delta_{CDW}$ scales which are found to be very close to each other. On the contrary, the $2\Delta_{NSC}$ scale is non monotonic, it increases with doping up to the optimal doping level ($p = 0.16$)(see panels (e)-(h)) and then it decreases in the over-doped regime ($p \geq 0.16$).

As a result, the $2\Delta_{NSC}(p)$ has a dome like shape fully observed in panel (g) and (h) for Hg-1201 and Bi-2212. If we now venture into a comparison between the doping dependence of these energy scales and the $T - p$ cuprate phase diagram (see panels (i)-(l)), the salient experimental facts are that $2\Delta_{PG}(p)$ and the $2\Delta_{NSC}(p)$ follow the same behavior as $T_{PG}(p)$ and $T_{c}(p)$ respectively, while $2\Delta_{CDW}(p)$ and $2\Delta_{AN}^{SC}(p)$ do not follow $T_{CDW}(p)$ and $T_{c}(p)$ respectively. At this stage, we are not in a position to propose a theory that would allow us to fully understand the doping dependencies of the energy scales and their correspondences with the characteristic temperatures of the cuprate phase diagram. What we can however hypothesize is that the three energy scales (PG, AN-SC and CDW) which have the same doping dependence, probably have a common microscopic origin. This could be e.g. short range anti-ferromagnetic fluctuations [63] which decrease as one moves away by doping from Mott insulating anti-ferromagnetic phase [64–72]. Another point worth mentioning is the same doping dependence of the N-SC and $T_{c}$ as opposed to the AN-SC gap that does not follow $T_{c}$. This suggests that nodal quasi-particles are likely not subject to the same electronic interactions governing quasi-particles at the anti-nodes. On the other hand, the close values of the AN-SC and CDW energy scales, which we report here in several cuprates (panels (a)-(d)), is a surprising fact that deserves to be explored in the light of recent theoretical models[73–80].
2\Delta_{CDW}(p) have the same doping dependence as \(T^*(p)\) : they decrease monotonically as doping increases. This suggests that they are all driven by the same microscopic interactions. On the contrary, the nodal component of the SC gap \(2\Delta_{SC}(p)\), which follows the same doping dependence as \(T_c(p)\), does not appear to be affected by any of the above interactions.

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Appendix A: Details of the electronic Raman experiments

Raman experiments have been carried out using a JY-T64000 spectrometer in single grating configuration using a 600 grooves/mm grating and a Thorlabs NF533-17 notch filter to block the stray light. The spectrometer is equipped with a nitrogen cooled back illuminated 2048x512 CCD detector. We use the 532 nm excitation line from a diode pump solid state with laser power maintained at 4 mW. Measurements between 10 and 290 K have been performed using an ARS closed-cycle He cryostat. This configuration allows us to cover a wide spectral range (90 cm$^{-1}$ to 2500 cm$^{-1}$) with a resolution set at 5 cm$^{-1}$. Spectra have been obtained from a single frame. Each frame is repeated twice to eliminate cosmic spikes and acquisition time is about 20 minutes. For comparison, in our initial study [81–83] we took almost a day to acquire a spectrum in a short range of 1000 cm$^{-1}$ with a single channel detection. All the spectra have been corrected for the Bose factor and the instrumental spectral response. They are thus proportional to the imaginary part of the Raman response function $\chi''(\omega,T)$. The $B_{1g}$ symmetry is obtained from crossed polarizations along the Cu-O bond directions. Then, the crystal is rotated by 45° using an Attocube piezo-rotator ANR 101 to obtain the $B_{2g}$ symmetry always using crossed polarizations. The $B_{1g}$ symmetry probes mostly the principal axes of the BZ, (anti-nodal region) and it corresponds to the maximum amplitude of the SC gap while the $B_{2g}$ symmetry probes mainly the diagonal of the BZ, (nodal region) and it corresponds to the region where the amplitude of the d-wave SC gap is vanished.

Appendix B: Details on the crystal growth, doping and critical temperature of Hg-1223 and Bi-2212 single crystals

1. Hg-1223

The Hg-1223 single crystals were grown by a single step synthesis [26, 84]. The as-grown single crystal has a critical temperature, $T_c \approx 110$ K. $T_c$ has been changed by annealing the single crystal under vacuum or oxygen. A thorough X-ray diffraction analysis reveals that oxygen atoms are removed (for under-doping) or added (for doping) inside the Hg layer [85]. The doping levels were estimated from the empirical Presland-Tallon’s law [86]. The single crystals are parallelepiped with a typical cross section of $0.7 \times 0.7$ mm$^2$ and a thickness of 0.2 mm. The c-axis is normal to the surface with the a-b plane directions 45° from the edges. In order to have high optical quality surface, the crystals have been polished using diamond paste at 1/10 μm. DC magnetization measurements under zero field cooling (ZFC) have been performed after polishing and displayed in Fig. 4 (a). The transition temperature $T_c$ and its width, $\Delta T_c$, was estimated by taking the maximum and the full width at half maximum of the peak of the first derivative of each Dc magnetization curve shown in Fig. 4 (b). The $T_c$ and $\Delta T_c$ values for each doping are the following: p=0.16 ($T_c = 133$ K, $\Delta T_c = 1$ K), p=0.14 ($T_c = 127$ K, $\Delta T_c = 1.5$ K), p=0.12 ($T_c = 117$ K, $\Delta T_c = 5$ K), p=0.11 ($T_c = 105$ K, $\Delta T_c = 4$ K), p=0.04 ($T_c = 92$ K, $\Delta T_c = 7$ K). $\Delta T_c$ broadens when we move away from the optimal doping level. This reflects slightly doping inhomogeneity in the single crystal with under-doping.

![FIG. 4.](image)

FIG. 4. (a) Zero field cooling magnetization curves of Hg-1223 single crystals for several doping levels. The applied magnetic field is perpendicular to the (ab) plane and its magnitude is of $\approx 10$ Oe. (b) First derivative of the magnetization curves displayed in (a). The location of the peak maximum indicates the value of $T_c$ and its full width at half maximum the transition width.

2. Bi-2212

The Bi-2212 single crystals were grown by using a floating zone method. The optimal doped sample with $T_c = 90$ K was grown at a velocity of 0.2 mm per hour in air [87]. In order to get over-doped samples down to $T_c = 65$ K, the as-grown single crystal was put into a high oxygen pressured cell between 1000 and 2000 bars and then was annealed from 350°C to 500°C during 3 days [88]. The over-doped samples below $T_c = 60$ K was obtained from as-grown Bi-2212 single crystals put into a pressure cell (Autoclave France) with 100 bars oxygen pressure and annealed from 9 to 12 days at 350 °C. Then the samples were rapidly cooled down to room temperature by maintaining a pressure of 100 bars. The critical temperature $T_c$ for each crystal has been determined from magnetization susceptibility measurements at a 10 Gauss field parallel to the c-axis of the crystal. In the over-doped regime, $T_c$ increases linearly with $2\Delta_{SC}^{AN}$. From a linear fit of the $T_c$ values between $T_c = 50$ K and $T_c = 90$ K, we find the reliable relationship: $T_c = (2\Delta_{SC}^{AN})/8.2 + 28.6$ [8]. In the
under-doped regime $T_c$ falls down abruptly as a function of $\Delta_{SC}^N$ (see Fig. 5). The level of doping $p$ was defined from $T_c$ using Presland and Tallon’s equation [86]: $1 - T_c/T_c^{\text{max}} = 82.6(p-0.16)^2$. In the over-doped regime, estimate of $p$ can be determined from $2\Delta_{SC}^N$ using the above two equations.

![Graph showing critical Temperature $T_c$ vs $2\Delta_{AN}^N$ with a linear fit](image)

**Fig. 5.** Evolution of the critical temperature $T_c$ versus pair breaking peak $2\Delta_{AN}^N$: $T_c$ and $2\Delta_{AN}^N$ are respectively deduced from magnetic susceptibility and Raman measurements of Bi-2212 crystals with distinct oxygen annealing treatments (see text). The black solid line corresponds to the linear fit of $T_c$ just above $T_c$ under-doped regime. The maximum value of $T_c$ is reached for 90 K.

Appendix C: Connection between the dip structure in the superconducting state and the normal state pseudogap

In order to show that there is a direct link between the dip-structure detected in the SC state Raman response and the spectral weight loss detected in the normal state Raman response when the pseudogap phase settles down, we have simultaneously plotted (see Fig. 6 (a)) the doping evolution of the dip and the loss of spectral weight of an UD 75 Bi-2212. The characteristic elements of the peak-dip structure measured on an UD Bi-2212 ($p=0.12$) are defined in Fig. 6 (b). We quantified the dip depth from the subtracted Raman response measured at low temperature ($\approx 12$ K) in the superconducting state and just above $T_c$. The loss of spectral weight is defined in ref. [7, 8]. From Fig. 6 (a), it clearly appears that the dip depth and the loss of spectral weight associated to the pseudogap phase have the same doping trend and disappear together at $p = 0.22$ where the PG collapses and the Anti-bonding band of the Fermi surface changes of topology from hole like to electron like as shown in ref.[8, 10]. These results are supported by cellular dynamical mean field theory calculations (see appendix in [26]).

Appendix D: Procedure for the extraction of the CDW signal below the critical temperature

As shown in Fig 2, the $2\Delta_N$ peak and the $2\Delta_{CDW}$ hump can be overlapped in the Raman spectra. In order to isolate the $2\Delta_{CDW}$ contribution from the $2\Delta_N$ one. We proceeded as follows: we first fitted the $2\Delta_N$ peak by a standard asymmetric Gaussian (AsG) function given by $A/(1+(1+\exp(-\omega - \omega_c + \omega_1/2)/\omega_2))) \times (1 - 1/(1+\exp(-\omega - \omega_c - \omega_1/2)/\omega_3)))$ and then subtracted the area of the AsG function from the Raman spectra. The set of the fitting parameters used for the UD 117 Hg-1223 (0.12) are ($A=13, \omega_c=456$ cm$^{-1}$, $\omega_1=80$ cm$^{-1}$, $\omega_2=90$ cm$^{-1}$, $\omega_3=85$ cm$^{-1}$) and for Y-123: $A=14, \omega_c=145$ cm$^{-1}$, $\omega_1=16$ cm$^{-1}$, $\omega_2=21$ cm$^{-1}$, $\omega_3=128$ cm$^{-1}$.

Appendix E: Extraction of the energy scales from the Raman response of Hg-1223 systems

1. Superconducting Anti-Nodal and Pseudogap energy scales versus doping

The $\Delta_{SC}^N$ scale is the maximum energy of the d-wave SC gap which takes place in the anti-nodal region of the BZ. Experimentally, the $2\Delta_{SC}(p)$ scale corresponds to the location of the pair breaking peak indicated by a red arrow in the first panels (a)-(d) of Fig. 7. We see that $2\Delta_{SC}(p)$ extracted from the Hg-1223 Raman spectra decreases in intensity and increases in frequency as $p$ is lowering. These doping behaviors is a common feature to all the cuprates studied (see Fig. 3). Note that the rapid intensity decreasing of $2\Delta_{SC}(p)$ as $p$ decreases is likely
due the loss of the spectral weight in the anti-nodal region generated by the pseudogap phase. The PG energy scale, $2\Delta_{PG}$, is defined as the frequency for which the dip ends in the electronic continuum of the SC $B_{1g}$ Raman response of Hg-1223. Remarkably, it is approximately at the same frequency than the one for which the PG depletion ends in the normal state (see panels (e)-(h)). This is pointed out by the dashed line in the pairs of panels (a,e), (b,f) and (c,g) (d,h) of Fig. 7. Note that this is not always the case.

2. Nodal Superconducting and charge density wave energy scales

The temperature dependence of the $B_{2g}$ Raman responses of Hg-1223 for several doping levels are shown in Fig. 8. In first row we detect both $2\Delta_{CDW}$ case. The pair breaking peak indicated by a red arrow determine the $2\Delta_{SC}$ value and the pseudogap energy $2\Delta_{PG}$ is defined from the energy for which the dip ends. The inset in panel (d) corresponds to a zoom of the $B_{1g}$ Raman response in order to point out the $2\Delta_{SC}$.

tively ($A=5, \omega_c=441 \text{ cm}^{-1}, \omega_1=292 \text{ cm}^{-1}, \omega_2=47 \text{ cm}^{-1}, \omega_3=116 \text{ cm}^{-1}$), ($A=13, \omega_c=456 \text{ cm}^{-1}, \omega_1=80 \text{ cm}^{-1}, \omega_2=90 \text{ cm}^{-1}, \omega_3=85 \text{ cm}^{-1}$), ($A=8, \omega_c=540 \text{ cm}^{-1}, \omega_1=200 \text{ cm}^{-1}, \omega_2=80 \text{ cm}^{-1}, \omega_3=110 \text{ cm}^{-1}$) and ($A=7, \omega_c=770 \text{ cm}^{-1}, \omega_1=80 \text{ cm}^{-1}, \omega_2=50 \text{ cm}^{-1}, \omega_3=40 \text{ cm}^{-1}$). Above $T_c$, the nodal SC gap, $2\Delta_{SC}$, is gone and only remains the CDW gap: a dip-hump structure (see $\Delta_{B_{2g}}(\omega, T)$ in the third row of Fig. 8). Note that the CDW dip-hump structure is observable in the Raman spectra for $p=0.11, 0.12$ and 0.14 while for $p=0.16$ is hardly detectable, likely because the CDW signal collapse below or close to $T_c = 133 \text{ K}$. Note that the best determination of the CDW energy scale, $\Delta_{CDW}(p)$ is obtained by analyzing the nodal Raman responses at low temperature. However, the extraction of $\Delta_{CDW}(p)$ is complicated by the existence of SC signal. See the subtracted Raman response $\Delta_{B_{2g}}(\omega, T)$ in $12 \text{ K}$ of Hg-1223 (left panel of Fig. 9). The situation is even more complex for $p=0.16$ where the Raman CDW signal coincides with the nodal SC one. Yet, if we increase $T$ just below $T_c$ which allows us to weaken the SC signal and bring out the CDW signal, we get reliable $\Delta_{CDW}(p)$ values. This is achieved by measuring $\Delta_{B_{2g}}(\omega, T)$ at $T \approx 25 \text{ K}$ below $T_c$ for each doping level (see right panel of Fig. 9). We then find that $\Delta_{CDW} = 1150, 1030, 930$ and $730 \text{ cm}^{-1}$ for respectively $p=0.11, 0.12; 0.14$ and $p=0.16$. Note that this procedure is available because as this has been seen before, the location of CDW hump is almost temperature independent.
FIG. 9. (Color online). Left and right panels are respectively the subtracted Raman responses of Hg-1223, $\Delta \chi''_{B2g}(T_0, T \approx 12 \text{ K})$ and $\Delta \chi''_{B2g}(T_0, T_c - 25 \text{ K})$ for various doping levels. The $T_0$ values for each doping are listed in the text. The black arrows indicate the location of $\Delta_{\text{CDW}}(p)$ and $\Delta_{\text{NSC}}(p)$. The red dotted line is just a guide for the eyes.
B. Loret, Y. Gallais, M. Cazayous, R. D. Zhong, H. Alloul, F. Rullier-Albenque, B. Vignolle, D. Colson, S. Sakai, M. Civelli, and M. Imada, Phys. Rev. Lett. 118, 047001 (2017).

B. Loret, Y. Gallais, M. Cazayous, R. D. Zhong, J. Schneeloch, G. D. Gu, A. Forget, D. Colson, and A. Sacuto, Phys. Rev. B 96, 094525 (2017).

B. Loret, Y. Gallais, M. Cazayous, R. D. Zhong, J. Schneeloch, G. D. Gu, A. Forget, D. Colson, and A. Sacuto, Nature Physics Letters (EPL) 116, 197001 (2016).

B. Loret, A. Forget, J.-B. Moussy, S. Poissonnet, P. Bonnaille, G. Collin, P. Thury, A. Sacuto, and D. Colson, Inorganic Chemistry, Inorg. Chem. 56, 9396 (2017).

Y. Gallais, A. Sacuto, P. Bourges, Y. Sidis, A. Forget, and D. Colson, Phys. Rev. Lett. 88, 177401 (2002).

T. Masui, M. Limonov, H. Uchiyama, S. Lee, S. Tajima, and A. Yamanaka, Phys. Rev. B 68, 060506(R) (2003).

W. Guyard, M. Le Tacon, M. Cazayous, A. Sacuto, A. Georges, D. Colson, and A. Forget, Phys. Rev. B 77, 024524 (2008).

Y. Li, M. Le Tacon, Y. Matiks, A. V. Boris, T. Loew, C. T. Lin, L. Chen, M. K. Chan, C. Dorow, L. Ji, N. Barisić, X. Zhao, M. Greven, and B. Keimer, Phys. Rev. Lett. 111, 187001 (2013).

K. McElroy, D.-H. Lee, J. E. Hoffman, K. M. Lang, J. E. Lee, E. W. Hudson, H. Eisaki, S. Uchida, and J. C. Davis, Phys. Rev. Lett. 94, 197005 (2005).

O. Fischer, M. Kugler, I. Maggio-Aripi, C. Berthod, and C. Renner, Rev. Mod. Phys. 79, 353 (2007).

K. K. Gomes, A. N. Pasupathy, A. Pushp, S. Ono, Y. Ando, and A. Yazdani, Nature 447, 569 (2007).

A. Pushp, C. V. Parker, A. N. Pasupathy, K. K. Gomes, S. Ono, J. Wen, Z. Xu, G. Gu, and A. Yazdani, Science 324, 1689 (2009).

F. Venturini, M. Opel, R. Hackl, H. Berger, L. Forr, and B. Revaz, Proc. of the Conf. on Spectros. in Novel Supercond., Journal of Physics and Chemistry of Solids 63, 2345 (2002).

S. Sugai, H. Suzuki, Y. Takayanagi, T. Hosokawa, and N. Hayamizu, Phys. Rev. B 68, 184504 (2003).

Y. Gallais, M. L. Tacon, A. Sacuto, and D. Colson, Europhysics Letters (EPL) 73, 594 (2006).

F. Venturini, M. Opel, R. Hackl, H. Berger, L. Forró, and B. Revaz, J. Phys. Chem. Solids 63, 2345 (2002).
[39] A. Carrington, D. Colson, Y. Dumont, C. Ayache, A. Bertinotti, and J. Marucco, Physica C: Superconductivity **234**, 1 (1994).

[40] M.-H. Julien, P. Carretta, M. Horvatic, C. Berthier, Y. Berthier, P. Ségransan, A. Carrington, and D. Colson, Phys. Rev. Lett. **76**, 4238 (1996).

[41] J. J. McGuire, M. Windt, T. Startseva, T. Timusk, D. Colson, and V. Viallet-Guillen, Phys. Rev. B **62**, 8711 (2000).

[42] R. Daou, J. Chang, D. LeBoeuf, O. Cyr-Choinire, F. Lal-S. Blanco-Canosa, A. Frano, E. Schierle, J. Por-Y. Sidis and P. Bourges, Journal of Physics: Conference

[43] Y. Li, V. Balédent, N. Barisic, T. Loew, M. Minola, M. Bluschke, E. Weschke, B. Keimer, L. Zambelli, Nature **463**, 519 (2010).

[44] Y. Sidis and P. Bourges, Journal of Physics: Conference Series **449**, 012012 (2013).

[45] S. Blanco-Canosa, A. Frano, E. Schierle, J. Porras, T. Loew, M. Minola, M. Bluschke, E. Weschke, B. Keimer, and L. Taillere, Nature **463**, 519 (2010).

[46] R. Comin and A. Damascelli, Annual Review of Condensed Matter Physics **7**, 369 (2016), https://doi.org/10.1146/annurev-conmatphys-031115-011401.

[47] R. Arpaia, S. Caprara, R. Fumagalli, G. De Vecchi, Y. Y. Peng, E. Andersson, D. Betto, G. M. De Luca, N. B. Brookes, F. Lombardi, M. Saluzzo, L. Braicovich, C. Di Castro, M. Grilli, and G. Ghiringhelli, Science **365**, 906 (2019), https://science.sciencemag.org/content/365/6456/906.full.pdf.

[48] T. Wu, H. Mayaffre, S. Krmer, M. Horvatic, C. Berthier, W. Hardy, R. Liang, D. Bonn, and M.-H. Julien, Nat. Commun. **6**:6438 doi: 10.1038/ncomms7438 6 (2015).

[49] Y. Li, V. Balédent, N. Barisic, Y. Cho, B. Fauche, Y. Sidis, G. Yu, X. Zhao, P. Bourges, and M. Greven, Nature **455**, 372 (2008).

[50] V. Balédent, D. Haug, Y. Sidis, V. Hinkov, C. T. Lin, and P. Bourges, Phys. Rev. B **83**, 104504 (2011).

[51] Y. Li, V. Balédent, N. Barisic, Y. C. Cho, Y. Sidis, G. Yu, X. Zhao, P. Bourges, and M. Greven, Phys. Rev. B **84**, 224508 (2011).

[52] N. Barisic, M. K. Chan, Y. Li, G. Yu, X. Zhao, M. Dressel, A. Smontara, and M. Greven, Proc Natl Acad Sci USA **110**, 12235 (2013).

[53] W. Tabis, B. Yu, I. Bialo, M. Bluschke, T. Kolodziej, A. Kozlowski, E. Blackburn, K. Sen, E. M. Forgan, M. v. Zimmermann, Y. Tang, E. Weschke, B. Vignolle, M. Hep-ting, H. Gretarsson, R. Sutarto, F. He, M. Le Tacon, N. Barisic, G. Yu, and M. Greven, Phys. Rev. B **96**, 134510 (2017).

[54] T. Watanabe, T. Fujii, and A. Matsuda, Phys. Rev. Lett. **79**, 2113 (1997).

[55] T. Usui, D. Fujiwara, S. Adachi, H. Kudo, K. Murata, H. Kushibiki, T. Watanabe, K. Kudo, T. Nishizaki, N. Kobayashi, S. Kimura, K. Yamada, T. Naito, T. Noji, and Y. Koike, Journal of the Physical Society of Japan **83**, 064713 (2014), https://doi.org/10.7566/JPSJ.83.064713.

[56] J. Hwang, T. Timusk, and G. D. Gu, Nature **427**, 714 (2004).

[57] R. Dipasupil, M. Oda, N. Momono, and M. Ido, Journal of the Physical Society of Japan **71**, 1535 (2002), https://doi.org/10.1143/JPSJ.71.1535.

[58] L. Őzyuzer, J. F. Zasadzinski, K. E. Gray, C. Kendziora, and N. Miyakawa, Europhysics Letters (EPL) **58**, 589 (2002).

[59] I. M. Vishik, M. Hashimoto, R.-H. He, W.-S. Lee, F. Schmitt, D. Lu, R. G. Moore, C. Zhang, W. Meevasana, T. Sasagawa, S. Uchida, K. Fujita, S. Ishida, M. Ishikado, Y. Yoshida, H. Eisaki, Z. Hussain, T. P. Devereaux, and Z.-X. Shen, PNAS **109**, 18332 (2012).

[60] A. Kaminski, T. Kondo, T. Takeuchi, and G. Gu, Philosophical Magazine **95**, 453 (2015).

[61] L. Mangin-Tho, Y. Sidis, P. Bourges, S. De Almeida-Didry, F. Giovannelli, and I. Laffez-Monot, Phys. Rev. B **89**, 094523 (2014).

[62] E. H. da Silva Neto, P. Aynajian, A. Frano, R. Comin, E. Schierle, E. Weschke, A. Gyenis, J. Wen, J. Schneeloch, Z. Xu, S. Ono, G. Gu, M. Le Tacon, and A. Yazdani, Science **343**, 393 (2014).

[63] D. Scalapino, Physics Reports **250**, 329 (1995).

[64] G. Kotliar, Phys. Rev. B **37**, 3664 (1988).

[65] N. Bulut, D. J. Scalapino, and S. R. White, Phys. Rev. Lett. **72**, 705 (1994).

[66] B. Kyung, V. Hankevych, A.-M. Daré, and A.-M. S. Tremblay, Phys. Rev. Lett. **93**, 147004 (2004).

[67] B. Kyung, S. S. Kanchala, D. Sénéchal, A.-M. S. Tremblay, M. Civiello, and G. Kotliar, Phys. Rev. B **73**, 165114 (2006).

[68] B. Kyung, D. Sénéchal, and A.-M. S. Tremblay, Phys. Rev. B **80**, 205109 (2009).

[69] E. Gull, O. Parcollet, and A. J. Millis, Phys. Rev. Lett. **110**, 216405 (2013).

[70] W. Wu, M. Ferrero, A. Georges, and E. Kozik, Phys. Rev. B **96**, 041105(R) (2017).

[71] L. Fratino, P. Sénon, M. Charlebois, G. Sordi, and A.-M. S. Tremblay, Phys. Rev. B **95**, 235109 (2017).

[72] W. Wu, M. S. Scheurer, S. Chatterjee, S. Sachdev, A. Georges, and M. Ferrero, Phys. Rev. X **8**, 021048 (2018).

[73] Y. Wang, D. F. Agterberg, and A. Chubukov, Phys. Rev. Lett. **114**, 197001 (2015).

[74] X. Wang, Y. Wang, Y. Schattner, E. Berg, and R. M. Fernandes, Phys. Rev. Lett. **120**, 247002 (2018).

[75] K. B. Efetov, H. Meier, and C. Pépin, Nat. Phys. **9**, 442 (2013).

[76] S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013).

[77] J. C. S. Davis and D.-H. Lee, Proceedings of the National Academy of Sciences **110**, 17623 (2013), http://www.pnas.org/content/110/44/17623.full.pdf.

[78] A. Allais, D. Chowdhury, and S. Sachdev, Nat. Commun. **5**:5771 doi: 10.1038/ncomms6771 (2014).

[79] E. Fradkin, S. A. Kivelson, and J. M. Tranquada, Rev. Mod. Phys. **87**, 457 (2015).

[80] D. Chakraborty, M. Grandadam, M. H. Hamidian, J. C. S. Davis, M. H. Hamidian, and P. Devereaux, and Z.-X. Shen, PNAS **109**, 18332 (2012).

[81] A. Sacuto, R. Combescot, N. Bontemps, P. Monod, V. Viallet, and D. Colson, EPL (Europhysics Letters) **39**, 207 (1997).
[82] A. Sacuto, R. Combescot, N. Bontemps, C. A. Müller, V. Viallet, and D. Colson, Phys. Rev. B 58, 11721 (1998).
[83] A. Sacuto, J. Cayssol, P. Monod, and D. Colson, Phys. Rev. B 61, 7122 (2000).
[84] D. Colson, A. Bertinotti, J. Hammann, J. Marucco, and A. Pinatel, Physica C: Superconductivity 233, 231 (1994).
[85] A. Bertinotti, J.-F. M. D. Colson, G. L. B. V. Viallet, L. Fruchter, C. Marcenat, and J. H. A. Carrington, Hg-Based High Tc Superconductors, edited by E. Narlikar (Nova Science Publisher (NY), 1997).
[86] M. R. Presland, J. L. Tallon, R. G. Buckley, R. S. Liu, and N. E. Flower, Physica C 176, 95 (1991).
[87] J. Wen, Z. Xu, G. Xu, M. Hcker, J. Tranquada, and G. Gu, Journal of Crystal Growth 310, 1401 (2008), the Proceedings of the 15th International Conference on Crystal Growth (ICCG-15) in conjunction with the International Conference on Vapor Growth and Epitaxy and the US Biennial Workshop on Organometallic Vapor Phase Epitaxy.
[88] L. Mihaly, C. Kendziora, J. Hartge, D. Mandrus, and L. Forro, Review of Scientific Instruments 64, 2397 (1993), https://doi.org/10.1063/1.1144459.