Discovery of Charge Density Waves in Cuprate Superconductors
up to the Critical Doping and Beyond

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The unconventional normal-state properties of the cuprates are often discussed in terms of emergent electronic order that onsets below a putative critical doping, \( x_c \approx 0.19 \). Charge density wave (CDW) correlations represent one such order; however, experimental evidence for such order generally spans a limited range of doping that falls short of the critical value \( x_c \), leading to questions regarding its
essential relevance. Here, we use x-ray diffraction to demonstrate that CDW correlations in La$_{2-x}$Sr$_x$CuO$_4$ persist up to a doping of at least $x = 0.21$. The correlations show strong changes through the superconducting transition, but no obvious discontinuity through $x_c \approx 0.19$, despite changes in Fermi surface topology and electronic transport at this doping. These results prompt a reconsideration of the role of CDW correlations in the high-$T_c$ cuprate phase diagram.

The cuprate high-$T_c$ superconductors are often conceptualized as doped Mott insulators, in which the electronic ground state spontaneously breaks rotational and/or translational symmetry$^{1,2}$. While cuprate CDW correlations were discovered over two decades ago$^3$, their possible contribution to the cuprates’ anomalous electronic properties remains a matter of vigorous debate$^{1,4-8}$ with increasing attention in light of the ubiquity of CDW order in different cuprate families$^{3,9-17}$. The cuprate phase diagram, shown in Fig. 1A, shows that pseudogap, strange metal, and superconducting phases exist over an extensive doping range below a critical doping level of $x_c \approx 0.19$, above which the cuprate electronic properties become gradually more Fermi-liquid-like$^{18-25}$. If CDW correlations are confined only to the underdoped cuprates, as previous studies suggested$^{9-16}$, that would preclude the possibility of CDW correlations having an important role in the anomalous electronic properties. It has, for example, been argued that since CDW correlations disappear at $x \ll x_c$, the nominal quantum critical point (QCP) associated with the termination of pseudogap must be magnetic in nature$^6$. Alternatively, recent
tunneling spectroscopy studies have suggested a vestigial nematic QCP\textsuperscript{26,27}. The presence or absence of CDW correlations is also crucial for the relevance of intertwined order, as some theoretical models for pair density wave superconductors require the presence of CDW correlations\textsuperscript{1,28}. Recent x-ray measurements have observed CDW correlations in underdoped and optimally doped cuprates up to temperatures well above the nominal CDW transition temperature\textsuperscript{29,30}. This motivates proposals for phase diagrams in which CDW correlations extend up to higher dopings than previously thought\textsuperscript{30}. Herein, we address this issue by focusing on La\textsubscript{2-x}Sr\textsubscript{x}CuO\textsubscript{4} (LSCO\textsubscript{x}) in view of its particularly well characterized transport properties and the feasibility of synthesizing high-quality samples across the whole phase diagram\textsuperscript{19,22-25}.

We start by illustrating the cuprate electronic structure evolution with doping as shown in Fig. 1B. At low doping, to the extent that a Fermi surface (FS) exists, it is hole-like and centered at the Brillouin zone (BZ) corner. Increasing the hole concentration decreases the chemical potential, which eventually passes through a saddle point of the Fermi surface at a doping close to $x_c$, resulting in a Lifshitz transition to an electron-like FS at the BZ center. Figure 1C-E shows angle-resolved photoemission spectroscopy (ARPES) measurements for LSCO\textsubscript{12}, LSCO\textsubscript{17}, and LSCO\textsubscript{21}. The Lifshitz transition is seen between LSCO\textsubscript{17} and LSCO\textsubscript{21}, consistent with $x_c = 0.19$ and with previous ARPES studies\textsuperscript{31,32}.
Having confirmed the electronic structure, we now show our main experimental finding of CDW correlations beyond $x_c$. Figure 2 plots x-ray reciprocal space scans for LSCO21 at $T = 16$ K, where reciprocal space is defined in terms of scattering vector $Q = (H, K, L)$ using lattice constants $a = b \approx 3.8$ Å and $c \approx 13.2$ Å. High sensitivity is achieved by exploiting the high brightness of the National Synchrotron Light Source II and by careful configuration of the detection system to suppress background signal\footnote{33}. Superlattice peaks are observed at $(0.235, 0, 12.5)$, and equivalent locations, along both the $H$ and $K$ directions (Fig. 2 A and B). The observed $H = 0.235$ is essentially the same as the CDW wavevector in underdoped LSCO\textsuperscript{14-16,34} and is consistent with the charge stripe picture\textsuperscript{2,3}. The peaks are symmetric with respect to $\pm H$ and $K$ and are observed in multiple Brillouin zones including $(\pm 0.235, 0, L)$ for $L = 8.5$ & $12.5$. An $L$-scan along $Q = (-0.235, 0, L)$ (Fig. 2D) shows that the intensity is broadly peaked at half-integer $L$ similar to underdoped LSCO\textsuperscript{14-16}. These results demonstrate the presence of CDW correlations beyond $x_c$ in LSCO.

Figure 3 summarizes the doping and temperature dependence of the CDW correlations. In Fig. 3A, Lorentzian-squared fits to the data are shown, which are parameterized in terms of amplitude, $l_{CDW}(T)$, and in-plane correlation length, $\xi_{\parallel}(T) = 1/HWHM$ (where HWHM is half-width at half-maximum). Since domain formation can lead to transverse peak splitting in LSCO (Refs. 14,34 and Fig. 3A), we scan through peaks in all three reciprocal space directions and use two Lorentzian-squared functions displaced in the $K$ (transverse) direction where necessary to account for the full intensity distribution. Peak
widths are determined by the $H$ (longitudinal) cut. $l_{CDW}(T)$ is found to be largest near $T_{SC}$ for all dopings (Fig. 3B). Above $T_{SC}$, both $l_{CDW}$ and $\xi_{\parallel}(T)$ decrease with increasing temperature but remain finite at least to $T = 90$ K (Fig. 3A). Interestingly, the correlation length can be separated into a nearly $T$-independent region where $\xi_{\parallel}(T)$ is approximately 4-unit-cells (about one period of the CDW order), and a strongly $T$-dependent region where $\xi_{\parallel}(T)$ continues to expand until SC intervenes. We refer to the CDW in the $T$-independent region as “precursor” CDW correlations in that they come before the emergence of a stronger, better-correlated CDW at low temperatures. (Note that for these measurements we do not have the energy resolution to directly distinguish between dynamic and static correlations.) This phenomenology is consistent with recent resonant inelastic x-ray scattering studies of $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ (LBCOx) and $\text{YBa}_2\text{Cu}_3\text{O}_6$+, which show a similar two-stage CDW formation$^{29,30,35,36}$. While the CDW evolves smoothly from LSCO12 to LSCO21, both $\xi_{\parallel}$ and the onset temperature of the longer-range CDW, $T_{\xi}$, are suppressed in the overdoped regime around $x_c$ (Fig.3C and Fig.4). No CDW correlations are observed in our high-sensitivity x-ray measurements at $x = 0.25$.

Previous measurements of the same $x = 0.12$ sample allow us to compare the CDW order parameter, taken to be captured by the total $Q$-integrated scattering intensity, to other cuprate systems$^{14}$. The CDW order parameter of LSCO12 is only four times weaker than $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$ (which has the strongest zero-field CDW order). With increasing doping, the LSCO CDW becomes somewhat stronger for $x = 0.17$ and drops appreciably
for $x = 0.21^{33}$. Consequently, CDW correlations can have an appreciable effect on the physics of LSCO$_x$ for dopings through $x_c$.

Figure 4 summarizes our main observations -- that CDW correlations exist across almost the whole doping phase diagram. It immediately yields two important consequences for the cuprates. Firstly, the very similar CDW properties that are observed either side of the Lifshitz transition, provide a vivid demonstration of the fact that they cannot be explained with a weak coupling Fermi surface nesting picture. Instead, the nearly constant $Q_{\text{CDW}}$ for doping $x > 0.125$ support strong coupling mechanisms, where the CDW is driven by a subtle balance between Coulomb interactions and kinetic energy$^2$. Secondly, the continuous evolution of the CDW correlations appear to be inconsistent with a QCP associated with CDW or coupled CDW/SDW order$^4,8$.

Our observations also urge a re-examination of the potential role of the CDW in the anomalous electronic properties of the cuprates. CDW correlations are a prerequisite (but not a proof) of several prominent theories of cuprate properties, which would be expected to apply across the phase diagram and not just in the underdoped cuprates where CDW correlations have been studied extensively in the past. These include the possibility that CDW correlations play a key role in the electronic transport properties$^4,8$. Theories of pair density wave order$^1,28,37,38$, which predict the type of competition between the CDW and uniform d-wave superconductivity, also fall in this category. As shown in Fig.3, both the CDW peak intensity and the CDW correlation length grow on cooling before saturating
below $T_{\text{SC}}$, without any clear evidence for a phase transition. This behavior would be consistent with a possible fluctuating CDW component that competes with superconductivity and could consequently affect cuprate transport properties\textsuperscript{22-25,30}.

Finally, we note that a charge Bragg peak has recently been observed in overdoped (Bi,Pb)$_{2.12}$Sr$_{1.88}$CuO$_6$ (Bi2201), with a maximum doping comparable to that observed here\textsuperscript{17}. This state, termed re-entrant charge order, has several properties that are different to CDW states in LSCO and other cuprates. Re-entrant charge order appears to exist in an isolated region of the overdoped phase diagram, disconnected from the underdoped CDW order. The correlation length and temperature scale of the state are also far higher than other cuprates. Intriguingly, no interaction between the CDW and superconductivity is observed. All other similarly well-correlated CDW states are associated with strong suppression of superconducting order. All these behaviors are in strong contrast with the CDW in overdoped LSCO, where the CDW wavevectors, correlation length and temperature dependence evolve smoothly from the underdoped LSCO properties and strongly intertwine with low-temperature transport properties. Based on the electronic structure of Bi2201 and the wavevector of re-entrant charge order around 0.1 r.l.u., which extrapolates roughly linearly from the underdoped CDW wavevector, re-entrant charge order was proposed to arise due to a van Hove singularity\textsuperscript{17}. The overdoped CDW in LSCO appears to have no connection to this mechanism. Instead, our observations support the strong coupling mechanisms, where the CDW is driven by a subtle balance between Coulomb interactions and kinetic energy\textsuperscript{2}. 


In summary, high-sensitivity x-ray measurements have revealed that cuprate CDW correlations persist across almost the whole cuprate doping phase diagram, despite dramatic changes in the cuprate transport properties and Fermi surface topology, before disappearing when fermi-liquid-like properties are restored. We have shown that these correlations impact superconductivity even in overdoped cuprates, suggesting that CDW correlations can have a far more extensive role in the cuprate phase diagram than was previously envisaged, and prompting investigations of CDW correlations in other overdoped cuprates.

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**Author contribution:** H.M., T.Y., K.K., E.V., and P.D.J. performed the ARPES measurement. H.M., G.F. T.A.A., I.K.R., R. A.-E, C.N., and M.P.M.D performed the x-ray measurements. Y.L., G.D.G., M.O., K.K., and N.M. grew the LSCO samples and characterized their transport properties. H.M., P.D.J., and M.P.M.D. analyzed the data. H.M., J.M.T., and M.P.M.D. wrote the paper. **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.

**Figure 1:** Doping dependent electronic structure of LSCO. (A) Phase diagram of the hole doped cuprates, constructed from magnetization, Nernst effect and resistivity data.
for LSCO\textsuperscript{6,18}. (B) Schematic band structure of LSCO. The Fermi energy, $E_F$, crosses the anti-nodal saddle point (SP) near $x_c \approx 0.19$ driving a Lifshitz transition. (C)-(E) Fermi surface topology of LSCO12, LSCO17 and LSCO21. The intensity plots are obtained by integrating the spectra within $\pm 10$ meV of $E_F$. Orange dashes outline the antiferromagnetic Brillouin zone. Red dashed contours represent a tight-binding fit of the FS. The data shown in (C)-(E) were collected at 11 K.

\textbf{Figure 2: Discovery of a CDW beyond $x_c$ in LSCO.} (A) and (B) x-ray diffraction measurements of LSCO21 at $T = 16$ K along (0, $K$, 12.5) and ($H$, 0, 12.5). Peaks are observed at (0, 0.235, 12.5) and (0.235, 0, 12.5). The H-scans in (C) reveal further CDW peaks at $(\pm 0.235, 0, L)$ for $L = 8.5$ and 12.5. The data at $L = 8.5$ are offset by -10 counts/second for visibility. (D) The $L$-dependence of the intensity along ($-0.235, 0, L$) demonstrates poorly correlated out-of-phase CDW stacking along the c-axis. Solid curves in (A)-(D) are fits to the experimental data.
Figure 3: CDW temperature dependence. (A) Doping dependence of the CDW intensity for temperatures $T < T_{SC}$, $T \approx T_{SC}$, and $T > T_{SC}$. The inset of each panel represents the respective cut in reciprocal space. The intensity comparison of different samples was achieved via sequential measurements under similar conditions. (B) The temperature dependence of the CDW intensity in LSCO. The shaded area corresponds to $T_{\xi}$ where the in-plane CDW correlation length, $\xi_||$, starts to increase, as determined in (C). The colored shaded curves in (C) track the temperature dependent $\xi_||$ for different dopings. The $\xi_||$ increases with decreasing temperature for $T_{SC} < T < T_{\xi}$. Two independent measurements of LSCO17 samples at different beamlines show consistent suppression of $\xi_||$ and $T_{\xi}$, indicating that systematic errors are minimal.
**Figure 4: Illustration of the extent of CDW correlations in the cuprate phase diagram suggested by this work.** Very short-range CDW correlations appear at high temperature for $0.12 < x < 0.21$, which we refer to as a precursor CDW\textsuperscript{29,35,36} and which have a correlation length of approximately one CDW period. At lower temperature, the correlations start to grow into larger CDW domains, as evidenced by the increased correlation length. Below this, bulk $d$-wave superconductivity intervenes at $T_{SC}$ whereupon both the CDW amplitude and the correlation length saturate or start to decrease. The doping dependence reveals an anticorrelation between $T_{\xi}$ of and $T_{SC}$ providing evidence for a non-trivial interaction between the CDW and superconductivity. The CDW intensity disappears in heavily overdoped LSCO\textsuperscript{25}, where the Fermi liquid (FL) normal state is
recovered$^{33}$. The red diamonds come from the present study. Pink squares and green circles are data extracted from previous work$^{14,15,34,39}$. 
Discovery of Charge Stripes Beyond the Critical Doping in La$_{2-x}$Sr$_x$CuO$_4$

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Materials and Methods

Sample

Single crystals of La$_{2-x}$Sr$_x$CuO$_4$ (x=0.12, 0.17, 0.21 and 0.25) were grown by the traveling-solvent floating-zone method. For each composition, a single feed rod with a length of 20–25 cm was used; after growth, the first few centimeters of the crystal rod were removed and discarded, while the remainder was annealed in flowing O$_2$ at 980 °C for 1 week. The superconducting transition temperatures, 28, 37, 30 and 10 K, were determined by dc magnetization measurements in a field of 1 mT applied (after cooling in zero field).

ARPES

ARPES measurements were performed at the 21-ID-1 beamline of the National Synchrotron Light Source II (NSLS2) using a Scienta-DA30 analyzer. Due to the small incident beam spot-size (less than 10×10 μm$^2$), both the sample position and the incident light angle are fixed during the measurement. The ARPES intensity maps are obtained using the mapping-mode of the DA30-analyzer, which can cover 30 degrees of cone acceptance without sample rotation. All samples were cleaved in situ and measured at 11 K with a vacuum better than 5×10$^{-11}$ Torr. The photon energy was set to 60 eV for LSCO12 and LSCO17 with 18 meV energy resolution. To confirm the FS of LSCO21 is a closed loop at the Γ point, we set the photon energy to 195 eV for LSCO21 with 90 meV
energy resolution. At this energy, we were able to cover the second Brillouin zone without sample rotation.

**Non-resonant hard x-ray scattering**

High-precision x-ray scattering measurements were performed at the In-situ and Resonant (ISR) 4-ID beamline of NSLS2 and 4-ID-D beamline of Advanced Photon Source (APS). The incident photon energy was set to 8.98 keV slightly below the Cu K-edge to minimize the fluorescence background (Fig. S1). The measurements at NSLS2 used an avalanche photodiode (APD) detector. A LiF(004) crystal analyzer was used to further reduce the background scattering (Fig. S2). The measurements at APS used a Vortex Si drift detector without crystal analyzer.

**Supporting Text**

**ARPES tight binding model**

The band-dispersion shown in the main text has the form\(^1,2\):

\[
\varepsilon_k = \mu - 2t[\cos(k_x a) + \cos(k_y a)] - 4t_1 \cos(k_x a) \cos(k_y a) - 2t_2[\cos(2k_x a) + \cos(2k_y a)] \\
- 4t_3[\cos(2k_x a) \cos(k_y a) + \cos(k_x a) \cos(2k_y a)] - 4t_4 \cos(2k_x a) \cos(2k_y a)
\]

(Eq. S1)

Here \(t\) and \(t_i\) (i=1,2,3,4) are hopping parameters. Their relative ratios are \(t_1/t=-0.136\), \(t_2/t=0.068\), \(t_3/t=0\), \(t_4/t=-0.02\), and \(t=1720\) meV. The change of Fermi-surface is achieved by tuning the chemical potential, \(\mu\), while keep the hopping parameters unchanged.
**Band dispersion of LSCO21 near the (-\(\pi\), 0) point**

To further prove the FS forms a closed loop in LSCO21, we show the band dispersion along (-\(\pi\), 0)\(\rightarrow\)(0,0) direction. Consistent with the intensity map, we observed a hole-like band at the (-\(\pi\), 0) point (Fig. S3). A parabolic fitting of the dispersion below 0.3 eV indicates the van Hove singularity is above \(E_F\).

**Recovery of Fermi liquid in LSCO25**

The ARPES intensity map of LSCO25 at \(E_F\) is shown in Figure S4a. In agreement with previous studies\(^2,3\), well-defined quasi-particles (QPs) are recovered in this heavily overdoped sample as shown in Fig. S4b and S4c. Near \(E_F\), the QP scattering rate, \(\Gamma(\omega) = \text{Im}\Sigma(k, \omega) = \frac{1}{2} \hbar v_F \Delta k(\omega)\). Here \(\text{Im}\Sigma(k, \omega)\) is the imaginary part of the self-energy, \(v_F\) and \(\omega\) are the Fermi velocity and the binding energy, respectively\(^4\). \(\Delta k(\omega)\) can be extracted by fitting the momentum distribution curve (MDC) with a Lorentzian function:

\[
I^{MDC}(k, \omega) = I_{BG}(\omega) + \frac{I_0(\omega)}{(k - k_0)^2 + (\Delta k)^2}
\]

(Eq. S2)

Here \(I_{BG}(\omega)\) and \(I_0(\omega)\) are constants at fixed \(\omega\). Figure S4c shows the extracted \(\Delta k(\omega)\), which can be fitted by \(a + b\omega^2\), as expected for a Fermi liquid. The recovery of QP coherence is also evident by directly comparing energy distribution curves (EDCs) of LSCO12 and LSCO25 at nearby \(k_F\). The significantly enhanced coherent spectral weight is consistent with the FL behavior in LSCO25.
Absence of CDW superlattice in LSCO25

Figure S5 shows the K and H scans near possible CDW wavevectors. Within experimental uncertainty, we do not observe any CDW superlattice peaks at $T=10\, K\sim T_{SC}$ in LSCO25. The same result is consistently observed on different samples and different beamlines. The absence of CDW is consistent with the Fermi-liquid behavior shown in previous section.

Absence of CDW superlattice along the $(\pi, \pi)$ direction

We also checked the CDW superlattice peak along the $(\pi, \pi)$ direction. Figure S6 shows the data in LSOC12 and LSCO21 at 16 K. Within the experimental uncertainty, no CDW intensity is observed along the $(\pi, \pi)$ direction in LSOC12 and LSCO21. This observation together with the extensive characterizations shown in the main text demonstrate that CDW in LSOC12 and LSCO21 are the same kind of CDW and thus exclude stripe-checkerboard CDW QCP at zero field$^{5-8}$.

Fitting of the CDW peak

Following previous studies$^{9-12}$, the CDW peaks are fitted by a Lorenzian-squared function

$$I_{CDW}(T) = I_{BG}(T) + \frac{I_0(T)}{\left(1 + \left[\frac{Q - Q_0(T)}{\Gamma^2}\right]^2\right)^2}$$

(Eq. S3)

where $I_{BG}(T)$ is a polynomial background. The relation between, $\Gamma$, half-width-at-half-maximum (HWHM) and in-plane correlation length, $\xi_\parallel$, is given by $\text{HWHM}=\sqrt{\sqrt{2} - 1} \Gamma = 1/\xi_\parallel$. 
In Fig. 2 of the main text, we show representative fittings for scans along \( \mathbf{Q}_{CDW} \) (longitudinal scans). We have used a polynomial function up to \( x^3 \) to account for the background. Representative fittings for scan perpendicular to \( \mathbf{Q}_{CDW} \) (transverse scan) are shown in Fig. S7. We note we used two peaks to fit transverse scans in LSCO12 due to the known splitting of CDW peaks in these samples \(^{12,13}\). The range of HWHMs that are extracted from different transverse and longitudinal scans is smaller than 5\% of the averaged value.

**The integrated CDW intensity**

Assuming a weak interplanar CDW correlation, the integrated x-ray scattering intensity,

\[
I_{int} = I_0 \cdot HWHM^2 = I_{peak} \cdot (\sqrt{2} - 1) \Gamma^2,
\]

is used to estimate the magnitude of the CDW order parameter\(^{14}\). Former x-ray studies found that the CDW magnitude in LSCO12 is about four times smaller than \( \text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4 \) and \( \text{YBa}_2\text{Cu}_3\text{O}_{6.6} \). This is based on a direct comparison of 9 keV x-ray scattering intensity in reflection. We note that LSCO has shorter penetration depth of between 6.7-6.9 \( \mu m \) (dependent of doping) compared to 8.2 \( \mu m \) in YBCO. LSCO also has fewer CuO\(_2\) planes per unit volume, such that approximately three times fewer CuO\(_2\) planes are illuminated in LSCO compared to YBCO. In this study, we use the same LSCO12 sample as of the previous work\(^{12}\). The comparable CDW peak intensity and correlation length proves that CDW order parameter is of a substantial size throughout the phase diagram (Fig.4 of the main text) and expected to have an appreciable effect of the transport properties.
As we discussed in the main text, $I^{int}$ also varies with doping. Based on the fitted result shown in Fig. 3 of the main text, we find that $I^{int}_{12}:I^{int}_{17}:I^{int}_{21} = 4:7:1$. The appreciable reduction of $I^{int}$ in LSCO21 is consistent with the crossover from strange metal to Fermi liquid phase at low temperature.

**Figure S1: Experimental conditions.** (a) and (b) show energy scans near the Cu K-edge and $\theta$ scan on (008) Bragg peak, respectively.
Figure S2: X-ray scattering. The schematic experimental geometry at the 4-ID beamline of NSLS2.
Figure S3: The band dispersion of LSCO21 near the \((\pi,0)\) point. (a) Fermi surface mapping of LSCO21. Photon energy was set to be 195 eV with 90 meV energy resolution. A horizontal cut of the data (the white line in (a)) is showed in (b). The blue dashed curve is a parabolic fitting of the band dispersion.

Figure S4: The electronic structure of LSCO25. (a) ARPES intensity map at \(E_F\). The intensity is obtained by integrating the spectra in a ±10 meV energy window with respect to \(E_F\). (b) Band dispersion along the red-line shown in (a). MDC (blue circles) and a Lorentzian-function (Eq. S2) fitting (red dashed curve) on \(E_F\) is shown in the upper-right panel of (c). The extracted MDC-width, \(\Delta k\), as function of energy shows a \(\omega^2\)-dependence,
consistent with Fermi liquid behavior. The red-dashed curve shown in the main panel of (c) is a quadratic function, $a+b\omega^2$, fitting of the extracted $\Delta k$. The bottom-left panel compares EDCs of LSCO12 (red) and LSCO25 (blue) at representative $k_F$, which are close in momentum space.

Figure S5: Absence of a CDW peak in LSCO25. (a) and (b) shows scans along the K and H directions, respectively. The scans are taken at L=12.5, the in-plane scan-trajectories are shown as insets to each panel.
Figure S6: Absence of CDW peaks along the Brillouin diagonal zone direction. (a) scan trajectories of the data shown in (b) for LSCO12, and in (c) for LSCO21. Note data in (b) and (c) are taken at different Brillouin zones.

Figure S7: Fitting of the CDW superlattice peak. Representative Lorentzian-squared fitting (Eq. S3) of the CDW peak perpendicular to $Q_{\text{CDW}}$ near $T_{\text{SC}}$ are shown in (a)-(c). Note that the data in LSCO12 is composed of two peaks, as previously demonstrated$^{12,13}$.

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