The phenomenon of charge-stripe ordering in hole-doped antiferromagnets has received much attention since its discovery in \( \text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4 \) by elastic neutron scattering.\(^1\) Much of this interest has been motivated by the proximity between stripe order and high temperature superconductivity and the potential relationship between these two states.\(^2\)\(^3\)\(^4\) It is now accepted that competing electronic interactions can stabilize charge-stripe order, but the question of whether the order observed in \( \text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4 \) is a genuine electronic phenomenon or specific to a particular distortion of the \( \text{Cu}_2\text{O}_2 \) plane remains controversial.\(^5\)

Evidence for stripe ordering have been reported so far in the lanthanum cuprates \( \text{La}_{2−x−y}\text{Nd}_x\text{Sr}_y\text{CuO}_4 \) and more recently in \( \text{La}_{2−x}\text{Ba}_x\text{CuO}_4 \).\(^6\) These compounds undergo a first order transition from an orthorhombic (LTO) to a tetragonal (LTT) phase which affects superconductivity dramatically at optimal hole doping.\(^6\) In both phases, the \( \text{CuO}_6 \) octahedra tilt collectively toward the \( c \)-axis of the perovskite structure.\(^6\) This distortion produces a staggered buckling of the \( \text{Cu}_2\text{O}_2 \) plane with a symmetry different for LTO and LTT phases.\(^7\)\(^8\) Stripe order emerges in lieu of superconductivity when the tilt exceeds \( \approx 3.6 \)° in the LTT phase.\(^7\)\(^8\)

Despite those observations, the reason for the disappearance of superconductivity is not understood. Neutron-scattering experiments in \( \text{La}_{2−x−y}\text{Nd}_x\text{Sr}_y\text{CuO}_4 \) have shown that the stripe arrangement mimics, to some extent, the symmetry of the tilt pattern of the LTT phase, and the detection of the stripe order in this compound is coincident with the first order structural transition.\(^6\) This suggests strong pinning of the charge-stripe order by the underlying lattice, which tends to localize charge carriers. Yet, this picture appears incomplete for \( \text{La}_{1.65}\text{Eu}_{0.2}\text{Sr}_{0.15}\text{CuO}_4 \) where signs of ordering of the \( \text{Cu}3\text{d} \) moments are observed only below 30K, while the LTT phase occurs at \( T_{LTT}=135\text{K} \).\(^8\)\(^9\)\(^10\) Neutron scattering has failed so far to find evidence of charge-stripe order in \( \text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4 \) but the slow dynamics of the \( \text{Cu}3\text{d} \) moments, probed by NMR at low temperature, has been shown to be consistent with the picture of a glass-forming charge-stripe liquid state.\(^11\) This is indicative of strong frustration, which could also be detrimental to superconductivity.

To clarify the relation between freezing, superconductivity and structural distortion, we use pressure to change the buckling of the \( \text{Cu}_2\text{O}_2 \) plane without modifying doping or substitutional disorder. We have investigated a \( \text{La}_{1.65}\text{Eu}_{0.2}\text{Sr}_{0.15}\text{CuO}_4 \) single crystal under hydrostatic pressure up to 2.9 GPa by means of the magnetization relaxation rate \( 139\text{T}_1^{-1} \) of the \( 139\text{La} \) nuclear spins, the magnetic ac susceptibility \( \chi_{ac} \) and the in-plane resistivity \( \rho_{ab} \). The pressure-temperature phase diagram of \( \text{La}_{1.65}\text{Eu}_{0.2}\text{Sr}_{0.15}\text{CuO}_4 \) is obtained from the pressure dependence of four distinct quantities. First, the freezing temperature, \( T_{f0} \), is defined from the maximum of \( 139\text{T}_1^{-1} \) where the frequency scale \( \Omega \) of the magnetic hyperfine field fluctuations at the \( \text{La} \) site equals the Larmor frequency \( (\omega_0 = 50\text{MHz}) \) of the \( 139\text{La} \) nuclear spins. Second, the temperature \( T_{LT} \) also is determined from \( 139\text{T}_1^{-1} \) through its response to fluctuations of the surrounding electric field gradient near the first order structural transition.\(^12\) Third, the superconducting transition temperature \( T_c \) is determined from the temperature dependence of \( \chi_{ac} \). Fourth, the amplitude of the upturn in \( \rho_{ab} \) observed below 100K measures the tendency for charge carriers to localize on lowering temperature. This study shows as a whole that the disappearance of superconductivity in \( \text{La}_{1.65}\text{Eu}_{0.2}\text{Sr}_{0.15}\text{CuO}_4 \) originates from long-time dynamical properties of the charge inhomogeneous phase. This anomalous long-time behavior appears to be controlled by the amplitude of the buckling of the \( \text{Cu}_2\text{O}_2 \) layer which decreases under pressure.
The central (m1 = +1/2 ↔ −1/2) transition. $^{139}T_1^{-1}$ was measured up to 2.7 GPa by monitoring the recovery of the magnetization after an inversion pulse in a field of 83.5 kOe. After completing NMR experiments, the resistivity and magnetic susceptibility measurements were carried out simultaneously up to 2.9 GPa.

Fig.1 shows the temperature dependence of the relaxation rate $^{139}T_1^{-1}$ for different values of pressure. The features observed at ambient pressure ($P_0$) have been examined already and discussed in detail. They can be summarized as follows. The discontinuous drop of $^{139}T_1^{-1}$ around $T_{LT} \approx 135$ K indicates the occurrence of the first order structural transition from LTO to LTT. The broad peak in the relaxation rate $^{139}T_1^{-1}$ manifests a gradual freezing of the hyperfine field induced at the La site by the Cu 3d localized moments. We thus read from Fig.1 the pressure dependence of $T_{LT}$ and $T_{\omega_0}$ and we observe that both decrease continuously with increasing pressure. It is striking, however, that $T_{\omega_0}$ saturates near 3K for $P \gtrsim 1.8$ GPa while $T_{LT}$ continues to decrease at higher pressure. Fig.1 makes it obvious that $^{139}T_1^{-1}(T)$ below 30 K is unchanged between 2.3 and 2.7 GPa, whereas $T_{LT}$ is reduced by a factor of two. These differences establish the remarkable fact that the properties of the freezing of the Cu 3d moments no longer depend on the underlying lattice at high pressure.

When looking at Fig.1, a question arises as to whether the temperature of the glass transition, $T_g$, remains finite or drops to zero under pressure. It should be emphasized that $T_g$ is conceptually different from $T_{\omega_0}$. Insofar as $T_{\omega_0}$ indicates only the temperature at which $\Omega \approx \omega_0$, it can relate to dynamical properties at thermal equilibrium whereas $T_g$ marks the onset of a fully static nonequilibrium state, the system being frozen out into a glass.

The relation between $T_{\omega_0}$ and $T_g$ is a priori unknown but the two temperatures clearly differ at $P_0$ where $T_g \lesssim 5$K and $T_{\omega_0} \approx 25$K. From $^{139}T_1^{-1}$ alone, we can not determine the value of $T_g$ since $^{139}T_1^{-1}$ measures only the spectral weight of the fluctuations at frequencies close to $\omega_0$. Nevertheless, it can be seen in Fig.1 that the broad maximum of $^{139}T_1^{-1}$ occurs around 3K at high pressure. This means that $\Omega \approx \omega_0$ in this temperature range while the system is frozen out at $P_0$. Therefore, $T_g$ has dropped significantly and, hence disappearance of the glass phase under pressure is conceivable but remains to be proven. This said, one should keep in mind that despite the pressure dependence of $^{139}T_1^{-1}$ revealing a considerable enhancement of the Cu 3d moments fluctuations with increasing pressure, dynamics still remains extremely slow ($\approx \tau_{\text{e-f}} \sim 10^{-4}$eV) compared to typical electron time scales. In particular, at low temperature, dynamics is certainly
The resistivity $\rho_{ab}$ measured in the CuO$_2$ plane, is shown in Fig.3. We analyze the data as follows. For each value of pressure, we fit $\rho_{ab}$ in the temperature interval 150-300K to the linear form $\rho_0 + \gamma T$ and extract the quantity $\rho_{ip}(T) = \rho_{ab}(T) - \rho_0 - \gamma T$. We find that the residual term $\rho_0$ varies smoothly with pressure. At $P_0$, $\rho_0 = 2.5 \pm 0.001$ m$\Omega$.cm and decreases at the rate of $-0.13$ m$\Omega$.cm.GPa$^{-1}$. The slope of the linear term, $\gamma = 5.08 \pm 0.02$ $\mu\Omega$.cm at $P_0$ and drops to 4.03 $\pm$ 0.02 at 0.67 GPa, which is the first pressure point in our experiment. $\gamma$ remains unchanged at higher pressure, the variation being less than 0.4%.

This linear term in the resistivity is typical of the metallic phase of optimally doped cuprates. It is considered to be an evidence for a non-Fermi liquid behavior, which might be related to a quantum-phase transition at $T = 0$. In La$_{1.65}$Eu$_{0.3}$Sr$_{0.15}$CuO$_4$ it can be seen in Fig.3 that this feature is unaffected by pressure.

Most of the effect of increasing pressure on $\rho_{ab}$ is reflected in the amplitude of the upturn. This upturn is characteristic of the LTT phase around optimal Sr doping and its amplitude increases with rare-earth substitution. Because superconductivity is suppressed also with increasing rare-earth content, the upturn might be related to a competing order, but the mechanism by which localization occurs is still unknown. Nevertheless, we can estimate the amplitude of the upturn from Fig.3 as the maximum of the term $\rho_{ip}$. We find that it decays as $e^{-P/P_s}$ with $P_s = 1.5 \pm 0.1$ GPa, as shown in the lower panel of Fig.4.

The relevance of $P_s$ becomes clear when comparing $T_{LT}$, $T_c$, $T_{\omega}$ and the maximum of $\rho_{ip}$ as a function of pressure in Fig.4. We discern two distinct regimes on either side of $P_s$, which differ in the way variations of $T_{LT}$ alter the electronic properties of the CuO$_2$ layer. To better appreciate the role of the lattice, we compare $T_c$ and $T_{LT}$ as a function of Eu content in La$_{2-x}$Sr$_x$CuO$_4$ with that obtained in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$ under pressure, in the inset of Fig.4. The correspondence between the two sets of data is clear: increasing pressure is equivalent to reducing Eu content and, by the same token, to the buckling of the CuO$_2$ layer. It is, therefore, the amplitude of the structural distortion that controls the interplay between freezing and superconductivity in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$. However, the two compete with each other only when $P \leq P_s$, where $T_{LT}$ varies slowly with pressure. Above $P_s$, the two phenomena no longer interfere and, both freezing and superconductivity depend only weakly on pressure. Since the temperature $T_{LT}$ is connected to the amplitude of the staggered buckling of the CuO$_2$ layer, the sharp contrast above $P_s$ between the rapid drop of $T_{LT}$ and the saturation of $T_c$ and $T_{\omega}$ reveals the important conclusion that the coexistence between slow dynamics of the Cu 3d moments and superconductivity at high pressure is electronic in origin. Also, the slow dynamics and the presence of buckling of the CuO$_2$ layer do not limit $T_c$, which reaches its optimal value above $P_s$. It is then clear that the key insight provided by our work is that the mechanism of the dramatic suppression of $T_c$ in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$ is to be found in the long time ($t \geq \omega_0^{-1}$) dynamical properties of the inhomogeneous phase at low pressure or equivalently, at
FIG. 4: Overall phase diagram of La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$. Upper panel: pressure dependence of $T_{LT}$ (full squares), $T_c$ (onset) (empty squares) and $T_{c0}$ (full triangles). For $P < P_s$, $dT_{LT}/dP = -11.5$ K GPa$^{-1}$ and for $P > P_s$, $dT_{LT}/dP = -66$ K GPa$^{-1}$. Lower panel: maximum of $\rho_{cu}$ (see text) as a function of pressure. $\rho_{cu}$ has been normalized to its value at $P_0$ and the continuous line is a fit to $e^{P/P_0}$ with $P_0 = 1.5 \pm 0.1$ GPa. Inset: $T_c$ versus $T_{LT}$ measured in La$_{1.65-y}$Eu$_y$Sr$_{0.15}$CuO$_4$ for different values of $y$ ranging between 0.03 and 0.3 (full circles) and versus pressure in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$ (open circles) obtained in the present work.

high buckling amplitude.

At $P_0$, we have shown that the onset of slow dynamics of the Cu 3d moments below 30K can be understood in terms of a glass-forming stripe-liquid phase. Following this idea, a possible interpretation of the decrease of $T_{cu}$ under pressure is that frustration causing charge stripes to freeze out into a glass is gradually released under pressure. The reduction of the structural distortion is more likely to increase the mobility of charge carriers in the CuO$_2$ layer, thus enhancing the fluidity of the electronic matrix. This idea is also well supported by the fact that most of the reduction of the resistivity upturn is found where $T_{cu}$ decreases, which implies a connection between freezing and localization of the charge carriers. Insofar as the slow dynamics is driven by slowly moving charge stripes in the CuO$_2$ plane, we can infer from the present data that glassiness, rather than stripes, is what dominantly competes with superconductivity in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$. This leaves open the question of what makes charge stripes glassy. The pressure dependence of the glass transition temperature $T_g$ particularly in relation to the qualitative changes occurring around $P_s$, remains to be investigated to test these ideas.

To conclude, we report a detailed investigation of the structural and electronic properties of a La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$ single crystal under pressure by means of $^{139}$La-NMR, resistivity and magnetic ac susceptibility measurements. Our primary result is clear evidence that the sharp suppression of superconductivity in La$_{1.65}$Eu$_{0.2}$Sr$_{0.15}$CuO$_4$ originates from anomalous long-time dynamics of the charge inhomogeneous phase. This reveals the key role of frustration in the interplay between static inhomogeneities and superconductivity in cuprates. The work at Los Alamos National Laboratory and Brookhaven was performed under the auspices of the US Department of Energy (Contract No. DE-AC02-98CH10886).

* Present address: Laboratorium für Festkörperphysik HPF, ETH Hönggerberg CH-8093 Zürich
† Present address: Max Planck Institute for Chemical Physics of Solids, Noethnitzer Str. 40, 01187 Dresden, Germany.
[1] J. M. Tranquada, B. J. Sternlieb, J. D. Axe, Y. Nakamura, and S. Uchida, Nature 375, 561 (1995).
[2] E. Dagotto, J. Burgy, and A. Moreo, Solid State Communications 126, 9 (2003).
[3] S. A. Kivelson, I. P. Bindloss, E. Fradkin, V. Oganesyan, J. M. Tranquada, A. Kapitulnik, and C. Howald, eprint cond-mat/0210683 (2003).
[4] A. H. Castro Neto and C. Morais Smith, eprint cond-mat/0304094 (2003).
[5] J. M. Tranquada, J. D. Axe, N. Ichikawa, A. Moodenbaugh, Y. Nakamura, and S. Uchida, Physical Review Letter 78, 338 (1997).
[6] M. Fujita, H. Goka, K. Yamada, and M. Matsuda, Physical Review Letter 88, 167008 (2002).
[7] J. D. Axe and M. K. Crawford, Journal of Low Temperature Physics 95, 271 (1994).
[8] B. Simović, M. Hücke, P. Hammel, B. Büchner, and A. Revcolevschi, Physical Review B 67, 224503 (2003).
[9] B. Büchner, M. Breuer, A. Freimuth, and A. P. Kampf, Physical Review Letters 73, 1841 (1994).
[10] H.-H. Klaus, W. Wagener, M. Hillberg, W. Kopmann, H. Walf, F. J. Litterst, M. Hücke, and B. Büchner, Physical Review Letters 85, 4590 (2000).
[11] B. Simović, P. C. Hammel, M. Hücke, B. Büchner, and A. Revcolevschi, Physical Review B 68, 012415 (2003).
[12] B. J. Suh, P. C. Hammel, M. Hücke, and B. Büchner, Physical Review B 59, R3952 (1999).
[13] J. Thompson, Review of Scientific Instruments 55, 231 (1984).
[14] T. Valla, A. V. Fedorov, P. Johnson, B. O. Wells, S. L. Hulbert, Q. Li, G. D. Gu, and N. Koshizuka, Science 285, 2110 (1999).
[15] M. Hücker, *Thesis* (University of Cologne, 1994).
[16] Y. Dimashko, C. Morais Smith, N. Hasselmann, and A. Caldeira, Physical Review B 60, 88 (1999).