

Dynamical Scaling Reveals Topological Defects and Anomalous Evolution of a Photoinduced Phase Transition

Gal Orenstein^{1,2,*}, Ryan A. Duncan^{1,2}, Gilberto A. de la Peña Muñoz^{1,2}, Yijing Huang^{1,2}, Viktor Krapivin^{1,2}, Quynh Le Nguyen³, Samuel Teitelbaum⁴, Anisha G. Singh⁵, Roman Mankowsky⁶, Henrik Lemke⁶, Mathias Sander⁶, Yunpei Deng⁶, Christopher Arrell⁶, Ian R. Fisher⁵, David A. Reis^{1,2} and Mariano Trigo^{1,2,†}

¹Stanford PULSE Institute, *SLAC National Accelerator Laboratory*, Menlo Park, California 94025, USA

²Stanford Institute for Materials and Energy Sciences, *SLAC National Accelerator Laboratory*, Menlo Park, California 94025, USA

³Linac Coherent Light Source, *SLAC National Accelerator Laboratory*, Menlo Park, California 94025, USA

⁴Department of Physics, *Arizona State University*, Tempe, Arizona 85281, USA

⁵Department of Applied Physics, *Stanford University*, Stanford, California 94305, USA

⁶*Paul Scherrer Institut*, Villigen, Switzerland



(Received 24 June 2024; revised 23 May 2025; accepted 28 July 2025; published 28 August 2025)

Nonequilibrium states of quantum materials can exhibit exotic properties and enable unprecedented functionality and applications. These transient states are inherently inhomogeneous, characterized by the formation of topologically protected structures, requiring nanometer spatial resolution on femtosecond timescales to resolve their evolution. Using ultrafast total x-ray scattering at a free electron laser and a sophisticated scaling analysis, we gain unique access to the dynamics on the relevant mesoscopic length scales. Our results provide direct evidence that ultrafast excitation of LaTe_3 leads to formation of topological vortex strings of the charge density wave. These dislocations of the charge density wave exhibit anomalous, subdiffusive dynamics, slowing the equilibration process, providing rare insight into the nonequilibrium mesoscopic response in a quantum material. Our findings establish a general framework to investigate properties of topological defects, which are expected to be ubiquitous in nonequilibrium phase transitions and may arrest equilibration and enhance competing orders.

DOI: [10.1103/w9v5-rwjf](https://doi.org/10.1103/w9v5-rwjf)

Subject Areas: Condensed Matter Physics,
Materials Science,
Strongly Correlated Materials

I. INTRODUCTION

One of the defining features of complex matter is the competition between several active degrees of freedom, which leads to highly heterogeneous, often modulated ground states in quantum materials [1]. The relationship between these spatial fluctuations, topological defects and competing phases remains a fundamental problem in condensed matter physics [2–9]. Ultrafast light pulses could provide insight into this relation by driving nonequilibrium phase transitions [10–22]; however, visualizing the transient structures at the relevant mesoscopic length scales is challenging. Novel x-ray free electron laser (XFEL) sources offer the sensitivity to all

length scales and can probe the spatial complexity of these transient states on ultrafast timescales [23]. Here, we use an XFEL to unveil the mesoscopic dynamics of topological defects of charge order following a nonequilibrium symmetry-breaking phase transition.

In a material undergoing a symmetry-breaking phase transition under nonequilibrium conditions, the low-symmetry phase develops independently in separate regions of space, leaving behind disconnected domains. This leads to the formation of topological defects (TDs) by the Kibble-Zurek mechanism [24,25]. Despite a long history of theoretical studies [25–27] and more recent experimental implementations in artificial quantum circuits [28,29], understanding the impact of TDs on transient states of materials remains notoriously challenging due to the lack of suitable quantitative probes at the intrinsic nanometer length scales and picosecond timescales of the defects. As a result, photoinduced states of materials are often interpreted in terms of time-dependent average order parameters, even though many nonequilibrium states are expected to evolve as transient glasses of topological defects.

*Contact author: galore@slac.stanford.edu

†Contact author: mtrigo@slac.stanford.edu

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

Previous works have presented indirect evidence of the central role of TDs in the evolution of quantum materials far from equilibrium [21,30–34]. In particular, several ultrafast structural dynamics measurements have attributed variations in the momentum integrated Bragg diffraction and Bragg peak width to formation and dynamics of TDs. However, other prevalent forms of spatial inhomogeneity, such as strain, can result in similar effects [35]. Therefore, measurements with fine wave-vector resolution, which can resolve the subtle variations of scattering around the Bragg peak, are required for a sophisticated and quantitative analysis of momentum features that are directly associated with TD dynamics.

Here, we use the unprecedented temporal and momentum resolution provided by an x-ray free electron laser to reveal the existence of photoinduced topological defects and capture their dynamics. We study the photoinduced coarsening process of the charge order in the prototypical charge density wave (CDW) material LaTe_3 , which is a member of the rare-earth tritellurides. These materials possess a layered, quasi-two-dimensional crystal structure and undergo a second-order phase transition with temperature into a CDW state directed along the in-plane c axis [36–38]. Recently, the rare-earth tritellurides have attracted attention as a model system to investigate the dynamics of symmetry-breaking phase transitions [11,19,30,32,39,40]. The high-quality data from the XFEL enables a sophisticated scaling analysis of the structure factor. This incisive analysis reveals unequivocal signatures of vortex strings, which govern the return to equilibrium with a growth exponent of $\beta = 0.29$. The subdiffusive coarsening process is likely due to restricted microscopic mobility of the CDW dislocations corresponding to the vortex strings.

II. EXPERIMENTAL SIGNATURES OF COARSENING

We probed the dynamics of the lattice component of the CDW in LaTe_3 using 50-fs, 10-keV hard x-ray pulses at the Bernina instrument [41] of the SwissFEL facility [42]. The dynamics were initiated by a 35-fs optical pump pulse as illustrated in Fig. 1(a) (see Appendix A). The following results were taken with a pump fluence of 8 mJ/cm^2 . Figure 1(b) shows the detector image of the $\mathbf{G} = (2/a, 2/b, (1 - q_{\text{CDW}})/c)$ CDW Bragg peak, where a , b , and c are the respective standardized cell parameters and $q_{\text{CDW}} \approx 2/7$. The intensity is shown with logarithmic scale and integrated over pump-probe delays between -2 and 22 ps . The peak elongates in the b^* direction due to shorter correlations along the out-of-plane b axis compared to the in-plane a - c axes.

Figure 1(c) shows the intensity normalized by the equilibrium value as a function of pump-probe delay, t , at the representative regions along the b^* direction marked in Fig. 1(b). The intensity near the peak (blue line), which represents the long-range order of the CDW, decreases

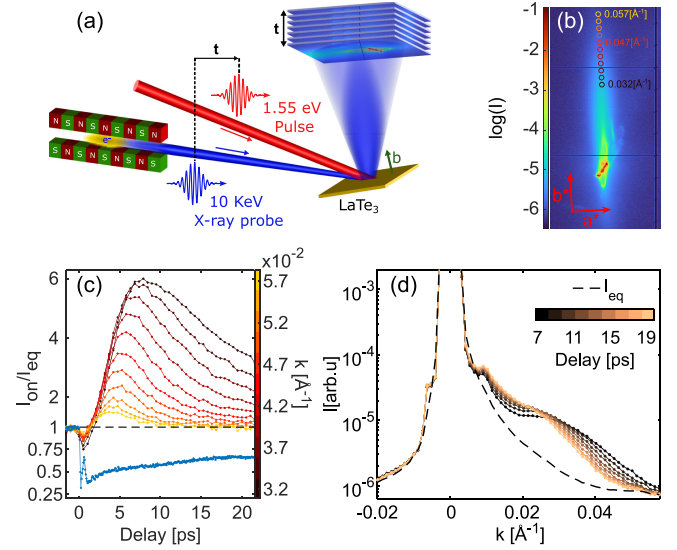


FIG. 1. X-ray scattering signatures of coarsening dynamics. (a) Experimental setup. The dynamics were initiated by an intense 800-nm pulse. The temporal evolution of the CDW's lattice component was probed by 10-keV hard x-ray pulses delayed by t with respect to the 800-nm pulses. (b) Detector image of the $(2, 2, 1 - q_{\text{CDW}})$ superlattice peak, integrated over all pump-probe delays. The red arrows indicate directions on the detector which are predominantly oriented along the b^* and a^* axes. The circles correspond to the black to yellow lines in (c). (c) X-ray intensity versus t , normalized by the equilibrium intensity. The blue line shows the normalized intensity near the peak. The black to yellow lines correspond to the same colored circles in (b). (d) X-ray intensity on a logarithmic scale versus wave vector along $\mathbf{G} + \mathbf{k}$, for $\mathbf{k} \approx (0, k, 0)$, at different pump-probe delays starting from 6.5 ps. The dashed black line is the equilibrium intensity. The intensity in (c) and (d) is averaged over a time window and regions of the detector as described in Appendix B 1.

sharply after $t = 0$ and remains depressed below the equilibrium level throughout our measurement. Generally, photoexcitation above the CDW band gap induces a fast suppression of the long-range order, which subsequently recovers with an extremely long timescale depending on the strength of the excitation [14,21,31,39]. In contrast, on the tail of the peak (black to yellow lines), the initial decrease in normalized intensity due to the suppression of the CDW modulation is followed by an increase well above equilibrium values over several picoseconds. This increase starts after $t \approx 1 \text{ ps}$, which is roughly the time it takes for the CDW electronic gap to restore according to time- and angle-resolved photoelectron spectroscopy measurements [11,32]. The increase of diffuse intensity away from the CDW wave vector is a signature of growing inhomogeneity and spatial fluctuations of the CDW induced by photoexcitation. Its observation is enabled by the high brightness of the XFEL together with its exceptional temporal and wave-vector resolution, which allow subtle details of the dynamics of the diffuse intensity on the tails of the peak to be captured.

In Fig. 1(d), we show the scattering intensity $I(k, t)$ as a function of wave vector along $\mathbf{G} + \mathbf{k}$, for $\mathbf{k} \approx (0, k, 0)$, at representative delays after approximately 6.5 ps. Comparing these plots with the equilibrium intensity shown by the black dashed line, it is clear that the tails of the peak grow initially (black dots) and gradually narrow back at later times (copper dots). The narrowing is the hallmark of coarsening of spatially inhomogeneous regions as the system recovers toward equilibrium. The asymmetry in the peak shape is likely from the grazing geometry. The outgoing photons at the left side of the peak have a shallower exit angle with respect to the sample surface and suffer stronger absorption.

III. OBSERVATION OF SUBDIFFUSIVE DYNAMICS

To study the wave-vector dependence of the coarsening process, it is convenient to define $h(k, t) = k^2 S(k, t)$, where $S(\mathbf{k}, t)$ is the structure factor as measured by x-ray scattering. In Fig. 2(a), we show the measured $h(k, t)$ by plotting $k^2 I(k, t)$ at several representative delays, normalizing each trace by its maximal value. The traces exhibit a distinct maximum whose horizontal position $k_m(t)$ shifts visibly to lower k values with increasing t . To robustly resolve the horizontal shift of the maximum shown in Fig. 2(a), we fit the maximum region for each delay to a Gaussian and identify $k_m(t)$ with the Gaussian's center. In Fig. 2(b), we plot $\log[k_m(t)]$ versus $\log(t)$. The plot fits a straight line very well with a slope of $\beta = 0.29$. In Supplemental Material Fig. S1 [43], we plot similar traces to Fig. 2 for fluences of 4, 6, and 9 mJ/cm², showing no

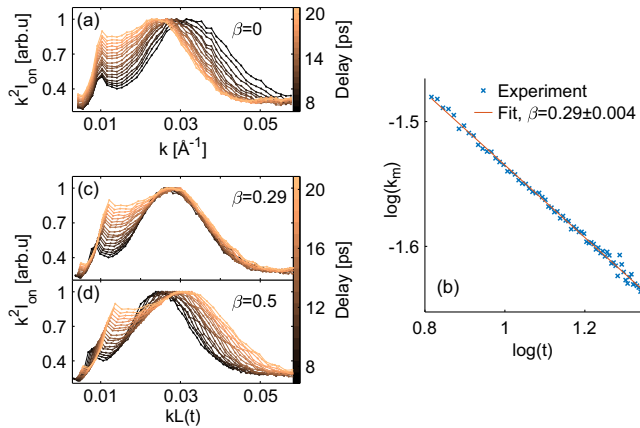


FIG. 2. Dynamic scaling exhibiting a subdiffusive growth exponent. (a) $k^2 I(k, t)$ [the measured $h(k, t)$] plotted at different delays. The vertical axis was normalized by the maximum value for each delay. (b) $\log[k_m(t)]$ versus $\log(t)$. The red solid straight line is the fit to the data with $\beta = 0.29$. (c), (d) The traces plotted in (a) plotted with the horizontal axis scaled by $L(t) = (At)^\beta$ per delay for $\beta = 0.29$ and 0.5 , respectively. In both (c) and (d), A was chosen to be $1/12 \text{ \AA}^{1/\beta}/\text{ps}$ for better visualization. Note that the traces in (a) correspond to $\beta = 0$.

notable change to β . This demonstrates that the power law is an intrinsic property of the system, which does not depend on the excitation strength.

As the system evolves toward equilibrium, topological defects annihilate and the independently ordered domains coalesce. Generally, this coarsening process is expected to obey self-similar dynamic scaling [21,26,34,44,45], where the fluctuations are characterized by a single length scale $L(t)$. Here, $L(t)$ corresponds to a mean domain size or an average distance between TDs. Under such conditions, $S(\mathbf{k}, t)$ has the scaling form

$$S(\mathbf{k}, t) = g(t)F(\mathbf{k}L(t)),$$

$$L(t) = (At)^\beta, \quad (1)$$

where $g(t)$ is an amplitude which depends only on time and scales the intensity equally for all wave vectors, $F(\mathbf{x})$ is a universal function, A^β is a proportionality constant, and β determines whether the coarsening is superdiffusive ($\beta > 1/2$), diffusive ($\beta = 1/2$), or subdiffusive ($\beta < 1/2$). Since $h(k, t)$ has the same scaling form as $S(k, t)$, the k position of the maximum as a function of time, $k_m(t)$, satisfies $k_m(t) \propto L^{-1}(t) \propto t^{-\beta}$, because $L(t)$ is the only relevant length scale, completely governing the system's evolution. Furthermore, $k_m(t)$ is independent of $g(t)$, because $g(t)$ scales the intensity equally for all wave vectors (see Appendix B 2).

In Fig. 2(c), we plot the same traces as in Fig. 2(a), with the horizontal axis rescaled for each delay by $L(t) \propto t^\beta$ with $\beta = 0.29$. The maxima as well as the entire region with $kL(t) > 0.02$ collapse quite well for all presented delays. The deviation from scaling at low k is expected, since scaling applies only at length scales smaller than the system size. In the photoexcited system, the system size is effectively the pumped volume, which is limited by the laser penetration depth. Here, the stationary local maximum around $k = 0.01 \text{ \AA}^{-1}$ in Fig. 2(a), which can be seen in Fig. 1(d) as well, is associated with the 100–200 $\text{\AA}$ penetration depth of the laser [39], so a robust data collapse is observed up to length scales of approximately 50 $\text{\AA}$. This data collapse clearly shows that the system exhibits a coarsening length scale $L(t) \propto t^{0.29}$. To further confirm this result, in Fig. 2(d) we rescale the horizontal axis of each trace in Fig. 2(a) by $L(t) \propto t^\beta$ for $\beta = 0.5$. The data collapse is visibly better for $\beta = 0.29$ [Fig. 2(c)] than for $\beta = 0.5$ [Fig. 2(d)], confirming that the system indeed behaves subdiffusively. Subdiffusive behavior suggests that the dynamics are constrained by additional conserved quantities. It has been established that for a system with a conserved order parameter $\beta = 0.25$ [27]. While the appropriate order parameter, which theoretically describes the CDW here, is quite different from a conserved order parameter, the anomalous subdiffusive dynamics is a manifestation of restricted microscopic motion of the system.

The scaling of $F(\mathbf{x})$, as well as the value of the growth exponent β , are powerful indicators of the symmetry of the order parameter and reveal microscopic properties and conserved quantities [44,46–48]. A growth exponent of $\beta = 0.29$ is an intriguing result. Extensive theoretical studies [27,44] concluded that, in systems with a non-conserved order parameter, the recovery of long-range order at long times follows a diffusive process with $\beta = 0.5$. Experimentally, recent ultrafast works on CDWs attempted to relate the time-resolved intensity and width of the Bragg peak with topological defects [21,32–34], reporting exponents that range from $\beta = 0.5$ [21] to $\beta = 0.03$ [34]. However, these measurements alone are not a unique signature of TDs, because many sources of heterogeneity such as strain [35] and disorder [23,49] can induce peak broadening and suppress the peak intensity. Additionally, variations in Bragg peak intensity cannot directly distinguish between spatially inhomogeneous dynamics and spatially coherent processes described by an average order parameter.

In Sec. IV, we show that the *momentum-resolved* x-ray scattering around the CDW peak exhibits specific *power laws* that are robust signatures of the TDs. This analysis on our high-wave-vector-resolution data enables a quantitative measurement of the topological defect properties and order parameter symmetry. It shows scaling evidence that the coarsening process is dominated by photoinduced vortex strings or dislocations of the CDW. The subdiffusive behavior is likely a signature of the restricted mobility of these dislocations.

IV. SCATTERING SIGNATURES OF VORTEX STRINGS

The unique properties of the XFEL enable us to measure the subtle intensity changes around the CDW peaks with high sensitivity and wave-vector resolution and search for these power-law signatures of the TDs [Eq. (2)]. The black to yellow dotted lines in Fig. 3(a) show the scattering intensity for $k > 0.02 \text{ \AA}^{-1}$ at different times in a log-log plot, and the blue line is a k^{-5} power law. Clearly, at large k , the traces for different times, as represented by the solid lines with markers, exhibit a similar k^{-5} behavior. To extract the scaling, we take the 174 data points with markers in Fig. 3(a) and fit them to $Ct^\alpha k^\eta$, extracting $\alpha = -0.96$ and $\eta = -4.96$. The red and blue symbols in the log-log plot in Fig. 3(b) show $I(k, t)t^{-\alpha}$ and $I(k, t)k^{-\eta}$, which are the data points collapsed in t and k , respectively, using the extracted exponents α and η . This remarkable data collapse indicates that the asymptotic scattering is governed by Eq. (2) with $\eta = 4.96$. In Supplemental Material Fig. S2 [43], we show the data collapse in t for fluences of 4, 6, and 9 mJ/cm², resulting in similar values for η .

At large wave vectors, where interference between multiple TDs is negligible, the structure factor for a network of TDs has the asymptotic form of an isolated

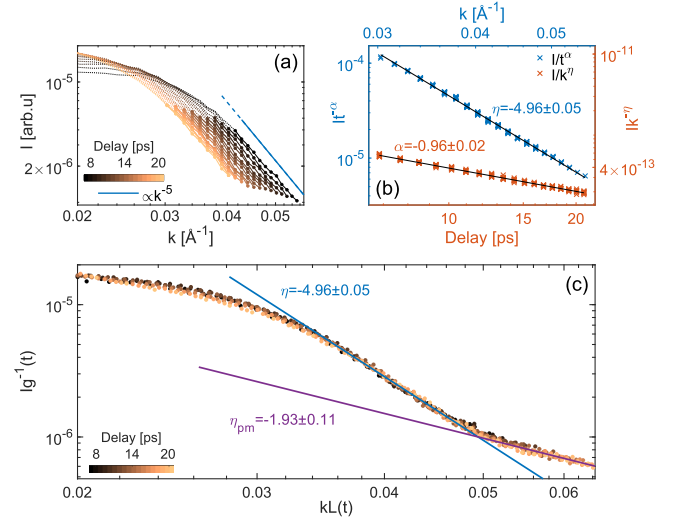


FIG. 3. Data collapse and vortex string power law in momentum space. (a) Scattering intensity versus k for $k > 0.02 \text{ \AA}^{-1}$ on logarithmic scales for different delays. The solid lines with markers highlight the power-law region at high k . (b) Data collapse of the 174 points marked in (a). The blue and red symbols show $I(k, t)t^{-\alpha}$ ($\alpha = -0.96$, left axis) and $I(k, t)k^{-\eta}$ ($\eta = -4.96$, right axis) versus k (top) and t (bottom) axes, respectively; all axes are logarithmic. The black solid straight lines are the fit to data with $\eta = -4.96$ and $\alpha = -0.96$. (c) $I(k, t)g^{-1}(t)$ versus $kL(t)$, for $kL(t) > 0.02$, using only α , β , and η ; both axes are logarithmic. The different colors represent different delays, and the solid straight lines show power laws associated with different regions.

defect. This asymptotic form is universal and depends only on n , the number of components of the vector order parameter, and d , the spatial dimension of the system [50,51]:

$$S_{\text{TD}}(k, t) \propto \rho(t)k^{-(n+d)}, \quad (2)$$

where $\rho(t)$ is the density of TDs, which under reasonable conditions also exhibits power-law behavior, $\rho(t) \propto t^\alpha$ [26,50,51]. For the incommensurate CDW considered here, the expectation is that $n = 2$ and $d = 3$; thus, the stable TDs are vortex strings [26] with the asymptotic structure factor $S(k, t) \sim \rho(t)k^{-5}$. The fact that our measurements show that $\eta = -(n + d) \approx 5$, independently of the pump fluence, provides decisive evidence that vortex strings dominate the scattering in the high- k tail following the ultrafast quench. The analysis presented here has been carried out along the out-of-plane direction; however, the exponent η and the coarsening dynamics are independent of the anisotropy in this system (see Supplemental Material [43]).

Having found a clear signature of vortex strings in the scattering, we now combine the scaling expression in Eq. (1) with the asymptotic scattering in Eq. (2) to scale the data. We find that, for the vortex string power-law

region, $g(t) \propto t^{\alpha-\eta\beta}$ (see Appendix B 3). We use the β , α , and η extracted from our data to determine $g(t) \propto t^{0.48}$ and, together with $L(t)$, scale $I(k, t)$ according to Eq. (1), as shown in Fig. 3(c). This plot shows remarkable self-similarity for $kL(t) > 0.02$. The data scaling relies on the vortex string parameters α and η , which were extracted independently of β , yet these parameters collapse the data at lower k as well, beyond the power-law region where $I(k, t) \propto t^\alpha k^\eta$. This relation between the TD scaling in k and the global self-similar behavior in time reveals the strong connection between the vortex strings and the subdiffusive coarsening process.

Figure 3(c) provides additional insight into the evolution of the nonequilibrium state. Our high-resolution measurements clearly identify a crossover from $\eta = -4.96$ (solid blue line) to $\eta_{pm} = -1.93$ (solid purple line) at large $kL(t)$. This crossover means that at later times, as the TD density decreases, the scattering at high k is no longer dominated by the TDs; instead, scattering comes primarily from phase modes, which have the asymptotic form $S(k, t) \sim k^{-2}$ [27].

V. PHENOMENOLOGICAL GINZBURG-LANDAU MODEL

To visualize the vortex string dynamics, we simulated the Ginzburg-Landau model [26,52] for a complex order

parameter ($n = 2$), $\psi(\mathbf{r}, t)$, in three spatial dimensions ($d = 3$) (see Appendix C and Supplemental Material Movie 1 [43]). Figures 4(a)–4(c) show the surface $|\psi(\mathbf{r}, t)|^2 = 0.5$ following a sudden quench to the low-symmetry potential energy, at representative delays of 4, 8, and 22 ps, respectively. The initial random configuration of the disordered state around $\psi(\mathbf{r}, t) = 0$ quickly breaks down into strings whose density decreases with time [26]. Figure 4(d) shows the phase of $\psi(\mathbf{r}, t)$ winding by 2π around the string center on the plane $z = 20$ indicated in Fig. 4(c); this winding of the phase occurs along the entire string length and is a topological invariant. Therefore, vortex strings can vanish only by annihilating with other vortex strings with an opposite winding number or by shrinking of closed loops [26]. The solid symbols in Fig. 4(e) show the simulated $S(k, t)$ versus k on a log-log plot, and the solid lines are power-law fits. The blue symbols exhibit an asymptotic power law with an exponent of $\eta = -5.2$, which agrees well with our experimental observations (Fig. 3). In contrast, the green symbols in Fig. 4(e) correspond to a thermal equilibrium starting from the ordered state, $\psi(\mathbf{r}, t) = 1$. In this case, the system does not produce vortex strings, and it exhibits a power law with $\eta = -1.8$, close to the theoretical $\eta = -2$ expected for phase modes. Furthermore, the blue symbols in Fig. 4(e) show a crossover between scattering dominated by vortex

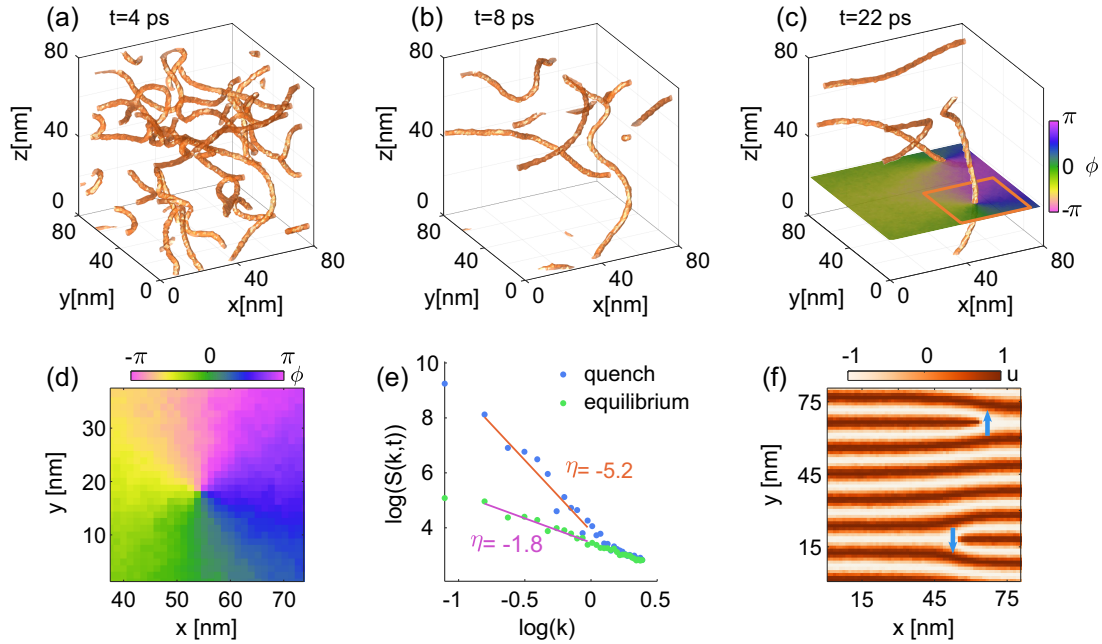


FIG. 4. Ginzburg-Landau simulations of vortex strings. (a)–(c) Isosurface plots of $|\psi(\mathbf{r}, t)|^2 = 0.5$ at representative times after a sudden quench to the low-symmetry Ginzburg-Landau potential. These plots are snapshots of the evolution shown in Supplemental Material Movie 1 [43]. (d) An enlarged view of the order parameter phase, $\phi(\mathbf{r}, t) = \arg\{\psi(\mathbf{r}, t)\}$, on the plane indicated in (c), which winds by 2π around the vortex string. (e) Simulated structure factor $S(k, t)$ on a log-log plot (solid symbols), averaged between approximately 2 and 8 ps. Blue dots represent $S(k, t)$ when the system is quenched suddenly from the high-symmetry phase. Green symbols represent $S(k, t)$ without vortex strings (only phase modes) and were computed from thermal equilibrium starting in the ordered phase. (f) Illustration of the CDW lattice distortion given by $u(x, t) \propto \cos[\mathbf{q} \cdot \mathbf{r} + \phi(\mathbf{r}, t)]$ at $t = 22$ ps with the $\phi(\mathbf{r}, t)$ from the plane indicated in (c). For better visibility, we use $\mathbf{q} \approx \mathbf{q}_{\text{CDW}}/6$.

strings, $S \sim k^{-5}$, to scattering dominated by phase modes, $S \sim k^{-2}$. We observe a similar crossover experimentally in Fig. 3(c).

In the present context, vortex strings correspond to dislocations of the CDW. Figure 4(f) illustrates a CDW lattice distortion in the $z = 20$ nm plane, taking the phase from Fig. 4(c). The vortices with opposite winding numbers correspond to two dislocations with opposite Burgers vectors [53], indicated by blue arrows in Fig. 4(f). While the simple Ginzburg-Landau theory correctly predicts the formation of vortex strings with $n + d = 5$ [26,44], it incorrectly predicts purely diffusive coarsening with $\beta = 0.5$ [26,44]. The observed subdiffusive dynamics requires a description beyond this phenomenological model, as it does not account for the anisotropic motion of the dislocations along and perpendicular to the Burgers vectors. More fundamentally, the model describes a generalized order parameter and does not include the microscopic spatial modulation of the CDW, which may constrain the motion of topological defects. Dislocations with restricted mobility are analogous to other systems with restricted motion, which exhibit subdiffusive thermalization and broken ergodicity due to additional conserved microscopic quantities [47,48]. Theoretical work incorporating such microscopic effects has shown that they can indeed give rise to subdiffusive behavior consistent with our observations [54]. Clearly, our measurements and incisive analysis reveal subtle microscopic details that challenge the canonical framework used in the interpretation of many ultrafast condensed-matter experiments [14,19,30,32].

VI. CONCLUSIONS

Our x-ray diffuse scattering measurements reveal explicit hallmarks of photoinduced topological defects of the prototypical CDW in LaTe_3 on ultrafast timescales. We show that shortly after photoexcitation the evolution of the highly nonequilibrium state is subdiffusive, indicating that the dynamics is dominated by the restricted motion of the topological vortex strings, which crucially impacts the system's thermalization and broken ergodicity. Our methods, as well as the implications of our findings, extend well beyond LaTe_3 , as formation of topological defects is expected to be ubiquitous in symmetry-breaking phase transitions under nonequilibrium conditions [24,25] even in quantum systems [28,29]. Thus, the high-resolution XFEL measurements, combined with scaling and data collapse analysis, establish an incisive approach to probe the mesoscopic, out-of-equilibrium behavior of intertwined orders in quantum materials [20].

ACKNOWLEDGMENTS

We acknowledge the Paul Scherrer Institute, Villigen, Switzerland for provision of free-electron laser beam time at the Bernina instrument of the SwissFEL ARAMIS

branch. G. O., R. A. D., G. A. P. M., Y. H., V. K., D. A. R., and M. T. were supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences through the Division of Materials Sciences and Engineering under Contract No. DE-AC02-76SF00515. For crystal growth and characterization, A. G. S. and I. R. F. were supported by the Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF00515. G. O. acknowledges support from the Koret Foundation. R. A. D. acknowledges support through the Bloch Postdoctoral Fellowship in Quantum Science and Engineering from the Stanford University Quantum Fundamentals, Architectures, and Machines initiative (Q-FARM), and the Marvin Chodorow Postdoctoral Fellowship from the Stanford University Department of Applied Physics. Q. L. N. acknowledges support by the Q-FARM Bloch Fellowship and U.S. DOE (DE-AC02-76SF00515).

APPENDIX A: EXPERIMENTAL DETAILS

Single crystals of LaTe_3 were grown from a self-flux [36,55]. Below the transition temperature, which is estimated at approximately 670 K [56], LaTe_3 develops an incommensurate CDW with wave vector along the in-plane c axis. The in-plane a and c axes of the samples were determined with x-ray diffraction by comparing the intensity of the (0, 6, 1) peak with its forbidden counterpart (1, 6, 0). The crystal was cleaved before the experiment and kept under nitrogen gas flow to avoid oxidation. The sample normal was along the b axis.

Measurements were performed at the Bernina instrument [41] of the SwissFEL facility [42]. We probed the dynamics of the lattice component of the CDW using 50-fs monochromatized hard x-ray pulses, tuned to 10 keV. The dynamics were initiated by a 35-fs optical pump pulse with a wavelength of 800 nm. Measurements were conducted in a grazing incidence geometry to achieve similar x-ray (150 nm) and optical (20 nm) penetration depths. The x-ray beam was incident at 1° with respect to the sample surface, focused to a $0.01 \text{ mm} \times 0.2 \text{ mm}$ spot, while the laser was impinging on the sample at an angle of 5° , focused to $0.3 \text{ mm} \times 0.4 \text{ mm}$. The scattered photons were recorded by a Jungfrau area detector positioned 482 mm from the sample. We present results for a fluence of 8 mJ/cm^2 ; however, measurements were taken with 4, 6, and 9.7 mJ/cm^2 as well, showing no notable change to the exponents β and $n + d$.

APPENDIX B: DATA ANALYSIS DETAILS

1. Averaging for Figs. 1(c) and 1(d)

- (i) *Figure 1(c), black to yellow lines*—A 20 pixel $\times$ 20 pixel average and a 525 fs time average, corresponding to approximately 2400 x-ray pulses per time point.

- (ii) *Figure 1(c), blue line*—A 10 pixel vertical $\times$ 6 pixel horizontal average [directions are relative to Fig. 1(b)] and a 75 fs time average, corresponding to approximately 350 x-ray pulses per time point.
- (iii) *Figure 1(d)*—A 10 pixel vertical $\times$ 20 pixel horizontal average [directions are relative to Fig. 1(b)] and a 828-fs time average, corresponding to approximately 3800 x-ray pulses per time point.

2. Relation between $k_m(t)$, $L(t)$, and $g(t)$

In the main text, we defined $h(k, t) = k^2 S(k, t)$, which has the same scaling form as $S(k, t)$ [Eq. (1)] with $\tilde{g}(t) = g(t)L^{-2}(t)$ and $\tilde{F}[kL(t)] = [kL(t)]^2 F[kL(t)]$. We want to show that the position of the maximum of $h(k, t)$ as a function of time satisfies the relation $k_m(t) = x_m L^{-1}(t)$, where x_m does not depend on time or $g(t)$. The maximum of $h(k, t)$ obeys

$$\frac{\partial h(k_m(t), t)}{\partial k} = g(t) \{ 2k_m(t) F(k_m(t)L(t)) + k_m^2(t) L(t) F'(k_m(t)L(t)) \} = 0, \quad (\text{B1})$$

where $F'(x) = dF(x)/dx$. Clearly, $g(t)$ drops out of this equation, which yields

$$2F(k_m(t)L(t)) + k_m(t)L(t)F'(k_m(t)L(t)) = 0. \quad (\text{B2})$$

Equation (B3) depends on time only through the function $k_m(t)L(t)$; therefore, it can be solved by the time-independent variable x_m defined as

$$k_m(t) = x_m L^{-1}(t). \quad (\text{B3})$$

Thus, $k_m(t)$ has the same scaling as $L^{-1}(t)$. When $L(t)$ is a power law, the exponent can be extracted directly from the position of the maximum, $k_m(t)$, as shown in the logarithmic plot in Fig. 2(b).

3. Scaling of the data, using α , β , and η

To scale the measured intensity $I(k, t)$, we assume both scaling forms [Eqs. (1) and (2)] and find $g(t)$:

$$\begin{aligned} S(k, t) &= C t^{\alpha-\eta\beta} [kL(t)]^\eta, \\ g(t) &= C t^{\alpha-\eta\beta}. \end{aligned} \quad (\text{B4})$$

APPENDIX C: GINZBURG-LANDAU SIMULATION DETAILS

We performed Ginzburg-Landau simulations in three spatial dimensions for a complex order parameter including a random Langevin force. The temporal evolution was simulated using the Euler-Maruyama method, and the spatial derivatives were calculated with a Fourier spectral method. The order parameter $\psi(\mathbf{r}, t)$ in the low-symmetry free energy evolves according to [26]

$$\Gamma \frac{\partial \psi}{\partial t} = \{1 - |\psi|^2\} \psi + \frac{1}{2} \xi^2 \nabla^2 \psi + \zeta, \quad (\text{C1})$$

where $\Gamma = 4.8$ ps is a phenomenological damping, $\xi = 1.2$ nm is the coherence length of the order parameter, and ζ is the random Langevin force. For simplicity, we have assumed the terms to be isotropic, which should not affect the general conclusion extracted from the simulations. The simulations were carried out on a $64 \times 64 \times 64$ grid representing a volume of $80 \text{ nm} \times 80 \text{ nm} \times 80 \text{ nm}$, with a time step of 20.8 fs over a range of 25 ps.

For the vortex string results [Figs. 4(a)–4(d) and blue symbols in 4(e)], we started with a random initial condition with zero spatial mean, $\int d^3 r \psi(\mathbf{r}, 0) = 0$. This corresponds to the system suddenly being quenched to the low-symmetry free energy at $t > 0$, forming TDs. The thermal equilibrium simulation [green symbols in Fig. 4(e)] started from an ordered state of $\psi(\mathbf{r}, 0) = 1$ and develops only low-energy excitations, i.e., phase modes.

The structure factor is given by $S(k, t) = |\tilde{\psi}(\mathbf{k}, t)|^2$, where $\tilde{\psi}(\mathbf{k}, t)$ is the Fourier transform of $\psi(\mathbf{r}, t)$. The graphs in Fig. 4(e) were obtained by averaging $S(k, t)$ between 2 and 8 ps.

We performed a finite size analysis to verify that the values of the exponents do not depend on the volume of the cubic simulation box, defined as $V = (N\xi)^3$. The values converge to the results shown in Fig. 4(e) for $N > 60$.

-
- [1] E. Dagotto, *Complexity in strongly correlated electronic systems*, *Science* **309**, 257 (2005).
 - [2] V. F. Mitrović, E. E. Sigmund, M. Eschrig, H. N. Bachman, W. P. Halperin, A. P. Reyes, P. Kuhns, and W. G. Moulton, *Spatially resolved electronic structure inside and outside the vortex cores of a high-temperature superconductor*, *Nature (London)* **413**, 501 (2001).
 - [3] B. Kalisky, J. R. Kirtley, J. G. Analytis, J.-H. Chu, A. Vailionis, I. R. Fisher, and K. A. Moler, *Stripes of increased diamagnetic susceptibility in underdoped superconducting $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ single crystals: Evidence for an enhanced superfluid density at twin boundaries*, *Phys. Rev. B* **81**, 184513 (2010).
 - [4] A. Mesaros, K. Fujita, H. Eisaki, S. Uchida, J. C. Davis, S. Sachdev, J. Zaanen, M. J. Lawler, and E.-A. Kim, *Topological defects coupling smectic modulations to intra-unit-cell nematicity in cuprates*, *Science* **333**, 426 (2011).
 - [5] Y. I. Joe, X. M. Chen, P. Ghaemi, K. D. Finkelstein, G. A. de la Peña, Y. Gan, J. C. T. Lee, S. Yuan, J. Geck, G. J. MacDougall, T. C. Chiang, S. L. Cooper, E. Fradkin, and P. Abbamonte, *Emergence of charge density wave domain walls above the superconducting dome in 1T-TiSe₂*, *Nat. Phys.* **10**, 421 (2014).
 - [6] S. Yan, D. Iaia, E. Morosan, E. Fradkin, P. Abbamonte, and V. Madhavan, *Influence of domain walls in the incommensurate charge density wave state of Cu intercalated 1T-TiSe₂*, *Phys. Rev. Lett.* **118**, 106405 (2017).

- [7] J. A. W. Straquadine, F. Weber, S. Rosenkranz, A. H. Said, and I. R. Fisher, *Suppression of charge density wave order by disorder in Pd-intercalated ErTe₃*, *Phys. Rev. B* **99**, 235138 (2019).
- [8] Y. Yu and S. A. Kivelson, *Fragile superconductivity in the presence of weakly disordered charge density waves*, *Phys. Rev. B* **99**, 144513 (2019).
- [9] A. Fang, J. A. W. Straquadine, I. R. Fisher, S. A. Kivelson, and A. Kapitulnik, *Disorder-induced suppression of charge density wave order: STM study of Pd-intercalated ErTe₃*, *Phys. Rev. B* **100**, 235446 (2019).
- [10] D. N. Basov, R. D. Averitt, and D. Hsieh, *Towards properties on demand in quantum materials*, *Nat. Mater.* **16**, 1077 (2017).
- [11] F. Schmitt, P. S. Kirchmann, U. Bovensiepen, R. G. Moore, L. Rettig, M. Krenz, J.-H. Chu, N. Ru, L. Perfetti, D. H. Lu, M. Wolf, I. R. Fisher, and Z.-X. Shen, *Transient electronic structure and melting of a charge density wave in TbTe₃*, *Science* **321**, 1649 (2008).
- [12] D. Fausti, R. I. Tobey, N. Dean, S. Kaiser, A. Dienst, M. C. Hoffmann, S. Pyon, T. Takayama, H. Takagi, and A. Cavalleri, *Light-induced superconductivity in a stripe-ordered cuprate*, *Science* **331**, 189 (2011).
- [13] H. Ichikawa, S. Nozawa, T. Sato, A. Tomita, K. Ichiyonagi, M. Chollet, L. Guerin, N. Dean, A. Cavalleri, S.-i. Adachi, T.-h. Arima, H. Sawa, Y. Ogimoto, M. Nakamura, R. Tamaki, K. Miyano, and S.-y. Koshihara, *Transient photo-induced ‘hidden’ phase in a manganite*, *Nat. Mater.* **10**, 101 (2011).
- [14] T. Huber, S. O. Mariager, A. Ferrer, H. Schäfer, J. A. Johnson, S. Grübel, A. Lübcke, L. Huber, T. Kubacka, C. Dornes, C. Laulhe, S. Ravy, G. Ingold, P. Beaud, J. Demsar, and S. L. Johnson, *Coherent structural dynamics of a prototypical charge-density-wave-to-metal transition*, *Phys. Rev. Lett.* **113**, 026401 (2014).
- [15] L. Stojchevska, I. Vaskivskiy, T. Mertelj, P. Kusar, D. Svetin, S. Brazovskii, and D. Mihailovic, *Ultrafast switching to a stable hidden quantum state in an electronic crystal*, *Science* **344**, 177 (2014).
- [16] T. F. Nova, A. S. Disa, M. Fechner, and A. Cavalleri, *Metastable ferroelectricity in optically strained SrTiO₃*, *Science* **364**, 1075 (2019).
- [17] X. Li, T. Qiu, J. Zhang, E. Baldini, J. Lu, A. M. Rappe, and K. A. Nelson, *Terahertz field-induced ferroelectricity in quantum paraelectric SrTiO₃*, *Science* **364**, 1079 (2019).
- [18] Z. Sun and A. J. Millis, *Transient trapping into metastable states in systems with competing orders*, *Phys. Rev. X* **10**, 021028 (2020).
- [19] A. Kogar, A. Zong, P. E. Dolgirev, X. Shen, J. Straquadine, Y.-Q. Bie, X. Wang, T. Rohwer, I.-C. Tung, Y. Yang, R. Li, J. Yang, S. Weathersby, S. Park, M. E. Kozina, E. J. Sie, H. Wen, P. Jarillo-Herrero, I. R. Fisher, X. Wang, and N. Gedik, *Light-induced charge density wave in LaTe₃*, *Nat. Phys.* **16**, 159 (2020).
- [20] J. Ravník, M. Diego, Y. Gerasimenko, Y. Vaskivskiy, I. Vaskivskiy, T. Mertelj, J. Vodeb, and D. Mihailovic, *A time-domain phase diagram of metastable states in a charge ordered quantum material*, *Nat. Commun.* **12**, 2323 (2021).
- [21] S. Vogelgesang, G. Storeck, J. G. Horstmann, T. Diekmann, M. Sivilis, S. Schramm, K. Rossnagel, S. Schäfer, and C. Ropers, *Phase ordering of charge density waves traced by ultrafast low-energy electron diffraction*, *Nat. Phys.* **14**, 184 (2018).
- [22] S. Wandel *et al.*, *Enhanced charge density wave coherence in a light-quenched, high-temperature superconductor*, *Science* **376**, 860 (2022).
- [23] S. Wall, S. Yang, L. Vidas, M. Chollet, J. M. Glowacki, M. Kozina, T. Katayama, T. Henighan, M. Jiang, T. A. Miller, D. A. Reis, L. A. Boatner, O. Delaire, and M. Trigo, *Ultrafast disordering of vanadium dimers in photoexcited VO₂*, *Science* **362**, 572 (2018).
- [24] T. W. B. Kibble, *Topology of cosmic domains and strings*, *J. Phys. A* **9**, 1387 (1976).
- [25] W. H. Zurek, *Cosmological experiments in superfluid helium?*, *Nature (London)* **317**, 505 (1985).
- [26] M. Mondello and N. Goldenfeld, *Scaling and vortex-string dynamics in a three-dimensional system with a continuous symmetry*, *Phys. Rev. A* **45**, 657 (1992).
- [27] G. F. Mazenko and M. Zannetti, *Instability, spinodal decomposition, and nucleation in a system with continuous symmetry*, *Phys. Rev. B* **32**, 4565 (1985).
- [28] T. Manovitz, S. H. Li, S. Ebadi, R. Samajdar, A. A. Geim, S. J. Evered, D. Bluvstein, H. Zhou, N. U. Koyluoglu, J. Feldmeier, P. E. Dolgirev, N. Maskara, M. Kalinowski, S. Sachdev, D. A. Huse, M. Greiner, V. Vuletić, and M. D. Lukin, *Quantum coarsening and collective dynamics on a programmable simulator*, *Nature (London)* **638**, 86 (2025).
- [29] T. I. Andersen *et al.*, *Thermalization and criticality on an analogue–digital quantum simulator*, *Nature (London)* **638**, 79 (2025).
- [30] R. Yusupov, T. Mertelj, V. V. Kabanov, S. Brazovskii, P. Kusar, J.-H. Chu, I. R. Fisher, and D. Mihailovic, *Coherent dynamics of macroscopic electronic order through a symmetry breaking transition*, *Nat. Phys.* **6**, 681 (2010).
- [31] T. Mertelj, P. Kusar, V. V. Kabanov, P. Giraldo-Gallo, I. R. Fisher, and D. Mihailovic, *Incoherent topological defect recombination dynamics in TbTe₃*, *Phys. Rev. Lett.* **110**, 156401 (2013).
- [32] A. Zong, A. Kogar, Y.-Q. Bie, T. Rohwer, C. Lee, E. Baldini, E. Ergeçen, M. B. Yilmaz, B. Freelon, E. J. Sie, H. Zhou, J. Straquadine, P. Walmsley, P. E. Dolgirev, A. V. Rozhkov, I. R. Fisher, P. Jarillo-Herrero, B. V. Fine, and N. Gedik, *Evidence for topological defects in a photoinduced phase transition*, *Nat. Phys.* **15**, 27 (2019).
- [33] Y. Cheng, A. Zong, L. Wu, Q. Meng, W. Xia, F. Qi, P. Zhu, X. Zou, T. Jiang, Y. Guo, J. van Wezel, A. Kogar, M. W. Zuerch, J. Zhang, Y. Zhu, and D. Xiang, *Ultrafast formation of topological defects in a two-dimensional charge density wave*, *Nat. Phys.* **20**, 54 (2024).
- [34] M. Mitrano, S. Lee, A. A. Husain, L. Delacretaz, M. Zhu, G. de la Peña Muñoz, S. X.-L. Sun, Y. I. Joe, A. H. Reid, S. F. Wandel, G. Coslovich, W. Schlotter, T. van Driel, J. Schneeloch, G. D. Gu, S. Hartnoll, N. Goldenfeld, and P. Abbamonte, *Ultrafast time-resolved x-ray scattering reveals diffusive charge order dynamics in La_{2-x}Ba_xCuO₄*, *Sci. Adv.* **5**, eaax3346 (2019).
- [35] D. A. Reis, M. F. DeCamp, P. H. Bucksbaum, R. Clarke, E. Dufresne, M. Hertlein, R. Merlin, R. Falcone, H. Kapteyn,

- M. M. Murnane, J. Larsson, T. Missalla, and J. S. Wark, *Probing impulsive strain propagation with x-ray pulses*, *Phys. Rev. Lett.* **86**, 3072 (2001).
- [36] N. Ru, C. L. Condon, G. Y. Margulis, K. Y. Shin, J. Laverock, S. B. Dugdale, M. F. Toney, and I. R. Fisher, *Effect of chemical pressure on the charge density wave transition in rare-earth tritellurides RTe_3* , *Phys. Rev. B* **77**, 035114 (2008).
- [37] H. Yao, J. A. Robertson, E.-A. Kim, and S. A. Kivelson, *Theory of stripes in quasi-two-dimensional rare-earth tellurides*, *Phys. Rev. B* **74**, 245126 (2006).
- [38] N. Ru, *Charge density wave formation in rare-earth tritellurides*, Ph.D. thesis, Stanford University, 2008.
- [39] M. Trigo, P. Giraldo-Gallo, J. N. Clark, M. E. Kozina, T. Henighan, M. P. Jiang, M. Chollet, I. R. Fisher, J. M. Glowia, T. Katayama, P. S. Kirchmann, D. Leuenberger, H. Liu, D. A. Reis, Z. X. Shen, and D. Zhu, *Ultrafast formation of domain walls of a charge density wave in SmTe_3* , *Phys. Rev. B* **103**, 054109 (2021).
- [40] Y. Wang, I. Petrides, G. McNamara, M. M. Hosen, S. Lei, Y.-C. Wu, J. L. Hart, H. Lv, J. Yan, D. Xiao, J. J. Cha, P. Narang, L. M. Schoop, and K. S. Burch, *Axial Higgs mode detected by quantum pathway interference in RTe_3* , *Nature (London)* **606**, 896 (2022).
- [41] G. Ingold *et al.*, *Experimental station Bernina at SwissFEL: Condensed matter physics on femtosecond time scales investigated by x-ray diffraction and spectroscopic methods*, *J. Synchrotron Radiat.* **26**, 874 (2019).
- [42] E. Prat *et al.*, *A compact and cost-effective hard x-ray free-electron laser driven by a high-brightness and low-energy electron beam*, *Nat. Photonics* **14**, 748 (2020).
- [43] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/w9v5-rwjr> for details on fluence dependence, effects of anisotropy and supplemental movie 1.
- [44] A. J. Bray and A. D. Rutenberg, *Growth laws for phase ordering*, *Phys. Rev. E* **49**, R27 (1994).
- [45] A. P. Y. Wong, P. Wiltzius, R. G. Larson, and B. Yurke, *Power-law scattering in fluids with a nonscalar order parameter*, *Phys. Rev. E* **47**, 2683 (1993).
- [46] P. C. Hohenberg and B. I. Halperin, *Theory of dynamic critical phenomena*, *Rev. Mod. Phys.* **49**, 435 (1977).
- [47] M. Pretko and L. Radzihovsky, *Fracton-elasticity duality*, *Phys. Rev. Lett.* **120**, 195301 (2018).
- [48] A. Gromov, A. Lucas, and R. M. Nandkishore, *Fracton hydrodynamics*, *Phys. Rev. Res.* **2**, 033124 (2020).
- [49] X. Wang, J. C. Ekström, A. U. J. Bengtsson, A. Jarnac, A. Jurgilaitis, V.-T. Pham, D. Kroon, H. Enquist, and J. Larsson, *Role of thermal equilibrium dynamics in atomic motion during nonthermal laser-induced melting*, *Phys. Rev. Lett.* **124**, 105701 (2020).
- [50] A. J. Bray and S. Puri, *Asymptotic structure factor and power-law tails for phase ordering in systems with continuous symmetry*, *Phys. Rev. Lett.* **67**, 2670 (1991).
- [51] A. J. Bray and K. Humayun, *Universal amplitudes of power-law tails in the asymptotic structure factor of systems with topological defects*, *Phys. Rev. E* **47**, R9 (1993).
- [52] A. E. Tarkhov, A. V. Rozhkov, and B. V. Fine, *Dynamics of topological defects after photoinduced melting of a charge density wave*, *Phys. Rev. B* **106**, L121109 (2022).
- [53] F. Nabarro, *Theory of Crystal Dislocations* (Oxford University Press, New York, 1967).
- [54] M. Qi and A. Lucas, *Kinematically constrained vortex dynamics in charge density waves*, [arXiv:2310.00051](https://arxiv.org/abs/2310.00051).
- [55] N. Ru and I. R. Fisher, *Thermodynamic and transport properties of YTe_3 , LaTe_3 , and CeTe_3* , *Phys. Rev. B* **73**, 033101 (2006).
- [56] B. F. Hu, B. Cheng, R. H. Yuan, T. Dong, and N. L. Wang, *Coexistence and competition of multiple charge-density-wave orders in rare-earth tritellurides*, *Phys. Rev. B* **90**, 085105 (2014).