Colloquium: Nonthermal pathways to ultrafast control in quantum materials

Alberto de la Torre*
Department of Physics, Brown University, Providence, Rhode Island 02912, USA

Dante M. Kennes†
Institut für Theorie der Statischen Physik, RWTH Aachen University and JARA-Fundamentals of Future Information Technology, 52056 Aachen, Germany
Max Planck Institute for the Structure and Dynamics of Matter, Center for Free-Electron Laser Science (CFEL), Luruper Chaussee 149, 22761 Hamburg, Germany

Martin Claassen‡
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA

Simon Gerber§
Laboratory for Micro and Nanotechnology, Paul Scherrer Institut, Forschungsstrasse 111, CH-5232 Villigen PSI, Switzerland

James W. McIver¶ and Michael A. Sentef∗∗
Max Planck Institute for the Structure and Dynamics of Matter, Center for Free-Electron Laser Science (CFEL), Luruper Chaussee 149, 22761 Hamburg, Germany

(Dated: September 27, 2021)

We review recent progress in utilizing ultrafast light-matter interaction to control the macroscopic properties of quantum materials. Particular emphasis is placed on photoinduced phenomena that do not result from ultrafast heating effects but rather emerge from microscopic processes that are inherently nonthermal in nature. Many of these processes can be described as transient modifications to the free energy landscape resulting from the redistribution of quasiparticle populations, the dynamical modification of coupling strengths and the resonant driving of the crystal lattice. Other pathways result from the coherent dressing of a material’s quantum states by the light field. We discuss a selection of recently discovered effects leveraging these mechanisms, as well as the technological advances that led to their discovery. A road map for how the field can harness these nonthermal pathways to create new functionalities is presented.

CONTENTS

I. Introduction 1
II. Emergent phenomena after pulsed laser excitation 3
A. Weak-excitation regime: Collective modes and disentangling degrees of freedom 3
B. Optical switching 4
C. Out-of-equilibrium critical behavior 6
D. Nonlinearities and dynamical couplings 7
1. Dynamical Hubbard $U$ 7
2. Nonlinear phononics 9
III. Dressed states of nonequilibrium matter 9
A. Theory introduction 10
1. Dynamical localization in a driven atomic chain 11
2. Floquet primer 12
B. Dressed band structures: Floquet topological insulators 13
C. Towards Floquet many-body physics: Heating and interactions 15
D. Engineering correlated systems 16
IV. Outlook 18
Acknowledgments 19
A. Technical advances shaping ultrafast quantum materials science 19
1. Experimental tools 19
2. Theoretical tools 21
References 22

I. INTRODUCTION

Quantum materials host a wide range of many-body and topological phenomena that both challenge our physical understanding of solids and offer possibilities for next-generation technologies. From unconventional superconductivity to topologically protected edge modes, the remarkable physics in quantum materials emerges...
from complex interactions between spin, charge, lattice, and orbital degrees of freedom (Keimer and Moore, 2017) and the geometric and topological aspects of their wavefunctions (Narang et al., 2021; Wang and Zhang, 2017). Many materials host multiple quantum phases that can be independently accessed by application of external perturbations such as electromagnetic fields, pressure, strain, or chemical doping, making these systems ideal platforms for future technological applications (Tokura et al., 2017). Moreover, the search for new ways to create and control their macroscopic properties continues to improve our fundamental understanding of the interactions between the underlying degrees of freedom, which in turn may lead to new functionalities (Alexandradinata et al., 2020; Basov et al., 2017; Giustino et al., 2021).

One promising route to controlling and understanding quantum materials is ultrafast light-matter interaction. This can induce long-lived nonequilibrium states with functionally-relevant properties that cannot be realized in thermal equilibrium. Since the pioneering work of Koshihara et al. 1990 on photoinduced phase transitions, ultrafast optical experiments have been used to investigate a variety of nonequilibrium effects in quantum materials. Breakthrough results in the past decade include the surgical decoupling of microscopic degrees of freedom in iron-based superconductors (Gerber et al., 2017), ultrafast switching into hidden phases in transition metal dichalcogenides (Stojchevska et al., 2014), dynamically controlled microscopic interactions in correlated transition metal oxides (Först et al., 2011), possible light-induced superconductivity in organic compounds (Mitrano et al., 2016), and photon dressed topological states in topological insulators (Wang et al., 2013) and graphene (McIver et al., 2019).

The mechanisms behind many of the most intriguing nonequilibrium phenomena go beyond the simple melting of thermal states by laser-induced heating. Instead, they rely on distinct nonthermal pathways, such as transient modifications to the free energy landscape or photon dressing effects, where quasi-thermal descriptions based
Here, we survey recent efforts in applying nonthermality as a resource to exert control over quantum materials on ultrashort timescales in a flexible and reversible manner. We highlight a selection of phenomena that emerge after pulsed laser excitation, including nonthermal switching mechanisms, out-of-equilibrium critical behavior, and the nonlinear control of microscopic couplings and phononics (Sec. II). Another class of nonthermal phenomena are those that occur during the duration of the laser pulse, where the microscopic degrees of freedom are strongly coupled to the amplitude, frequency and polarization of the light field, in some cases forming dressed states that can be described by Floquet theory. We review recent realizations of Floquet engineering protocols in quantum materials and discuss new theoretical directions for future experiments (Sec. III).

Recent progress in the field is due in part to the development of improved time-resolved experimental techniques. State-of-the-art light sources can now reliably generate intense optical pulses at wavelengths spanning from the THz to the extreme ultraviolet with a wide range of available pulse durations and repetition rates (Bartels et al., 2002; Cerullo and De Silvestri, 2003; Liu et al., 2017; Reimann, 2007; Steinmeyer et al., 1999). These advances have enabled a surgical approach to photoexciting (‘pumping’) quantum materials in pump-probe experiments, for example by selectively accessing electronic transitions, directly coupling to collective modes, or intentionally avoiding such resonances entirely. This enhanced pump tunability, combined with a fleet of experimental probes targeting complementary macroscopic observables (Fig. 1 and App. A.1), has led to an improved understanding of nonequilibrium phenomena in solids and the nonthermal pathways leading to their creation. Moreover, these results have triggered complementary theoretical efforts towards modeling microscopic dynamics in photoexcited quantum materials (App. A.2).

A full-fledged review of the rapidly growing field of ultrafast quantum materials science is beyond the scope of this Colloquium. To account for the important early works, we refer to other reviews, including Averitt and Taylor 2002, Basov et al. 2011, Orenstein 2012, Zhang and Averitt 2014 and Giannetti et al. 2016, which provide extensive reports of ultrafast spectroscopy of strongly correlated electron systems. Kirilyuk et al. 2010 wrote an in-depth review on ultrafast magneto-optical effects. Buzzi et al. 2018 reviewed ultrafast structural dynamics in solids probed by time-resolved X-ray scattering. Overviews of time-resolved inelastic X-ray scattering have been provided by Cao et al. 2019 and Mitrano and Wang 2020. Further reviews on Floquet engineering can be found in (Bukov et al., 2015; Oka and Kitamura, 2019; Rudner and Lindner, 2020).

II. EMERGENT PHENOMENA AFTER PULSED LASER EXCITATION

We discuss here emergent phenomena in quantum materials occurring after photoexcitation by an ultrafast laser pulse. In particular, we focus on processes dominated by dynamics that cannot be described by a hot electronic subsystem which thermalizes back to equilibrium through heat exchange with the cold crystalline lattice (phonons), the so-called two-temperature models (Allen, 1987; Anisimov et al., 1974) or n-temperature generalizations (Koopmans et al., 2010). These descriptions rest on the assumption that the mutual couplings between degrees of freedom are not modified by the excitation (Allen, 1987; Bauer et al., 2015; Petek and Ogawa, 1997). In quantum materials, this is not necessarily the case, and the optical excitation can result in modified or suppressed coupling constants (Ishioka et al., 2008; Murakami et al., 2015). More importantly, these simplified models neglect nonthermal effects resulting from ultrafast light-matter coupling. For example, in many correlated systems the notion of thermality, in the sense of a unique thermal density matrix and temperature, breaks down on ultrashort (femtosecond) to intermediate (subpicosecond) timescales (Kemper et al., 2018). This departure from the thermal response makes the pulsed excitation of quantum materials a unique strategy for creating and controlling quantum phenomena.

We depict in Fig. 2 different scenarios of transient phenomena in terms of a simplified free energy landscape as a function of growing excitation strength. In the weak-excitation regime, the optical drive can excite collective oscillations of the underlying order parameters (Fig. 2(a), Sec. II.A). By tracking these modes in the time domain one can disentangle microscopic degrees of freedom and their mutual couplings. In some materials, photoexcitation can drive the system into a different low-energy state or hidden states not accessible in thermal equilibrium (Fig. 2(b), Sec. II.B). Under the right excitation conditions, ultrafast transient modifications of the free energy landscape can also induce nonequilibrium phase transitions and enable the study of nonthermal critical behavior (Fig. 2(c), Sec. II.C). Finally, strong excitations can drive a system into nonlinear regimes, dynamically modifying the effective microscopic couplings governing its quantum many-body wavefunction, thus providing another strategy to investigate emergent phenomena with no equilibrium counterpart (Fig. 2(d), Sec. II.D).

A. Weak-excitation regime: Collective modes and disentangling degrees of freedom

We consider a situation where the system under investigation is only weakly driven, i.e., it remains in a linear regime [Fig. 2(a)]. The recovery towards equilibrium is
sensitive to collective modes and reflects the characteristic timescales of the different degrees of freedom. Prominent examples of coherent modes in ordered states that have been probed using time-domain techniques are amplitude modes of charge-density wave materials (Demsar et al., 1999a, 2002; Lee et al., 2012; Mihailovic, 2019; Schmitt et al., 2008; Zong et al., 2019a), potential excitonic insulators (Werdehausen et al., 2018), and the Higgs amplitude (Chu et al., 2020; Matsunaga et al., 2013, 2014) and Leggett modes (Giorgianni et al., 2019), as well as Josephson plasmons (Laplace and Cavalleri, 2016) in superconductors.

In the weak-excitation regime, charge, lattice, spin or orbital degrees of freedom of correlated electron systems can be disentangled in the time domain by appropriate choice of the experimental probe [Fig. 3(a)]. Under particular circumstances these techniques can be brought together in a unified fashion, as demonstrated by Gerber et al. 2017 where time- and angle-resolved photoemission spectroscopy (tr-ARPES) and X-ray scattering were used to study the significance of a cooperative interplay among electron-electron and electron-phonon interactions in the iron-based superconductor parent compound FeSe. Figure 3(b) depicts how both the lattice displacement and the electronic band structure lock into a coherent $A_{1g}$ phonon mode that is driven by an ultrafast infrared (IR) laser pulse. In turn, this THz frequency locking of the two degrees of freedom allows for a purely experimental, highly precise quantification of fundamental physical properties. For example, for FeSe it was used to quantify the orbitally-resolved electron-phonon deformation potential, which reveals the critical importance of electron correlations for the material’s properties.

This example shows that such multi-messenger approaches not only allow inferring nonequilibrium characteristics, but also to extract equilibrium properties via the time domain (Gerber et al., 2017; Mitrano et al., 2019). A caveat concerns the difficulty in bringing together more than one ultrafast experiment in a unified fashion. Ideally, a multi-messenger experiment is conducted in one single setup, e.g. as used for simultaneous detection of electronic and structural (Porers et al., 2014) or multiple structural orders (Kogar et al., 2020; Morrison et al., 2014; Zhou et al., 2021). This ensures that the pumping conditions, such as pump fluence, pump and probe beam profile, time resolution, penetration depth (effectively absorbed energy densities) and, notably, also the definition of time zero (the instant when the pump pulse excites the sample) are guaranteed to be consistent. Such unified experimental setups will not only allow comparing the amplitude signals of the disentangled degrees of freedom, but also their phase relation and decay rates (dephasing times), paving the way towards coherent quantum control of (dis-)entangled degrees of freedom.

### B. Optical switching

Going one step further away from equilibrium, a natural question to ask is whether nonthermal pathways can be found to photoinduce a phase transition, that is, optically switch the system into parts of the free energy landscape that are not accessible in thermal equilibrium. Indeed, the key idea behind optically driven switching is similar to basic concepts of chemical reaction pathways, in which catalysts help the system overcome an activation energy barrier in order to trigger the intended reaction.

We start with a pedagogical description within a free energy landscape framework, as sketched in Fig. 2(b) (Nasu et al., 2001). We consider a long-range ordered symmetry-broken ground state given by one of the global minima of the free energy landscape, indicated by $A$. In order to reach any of the local minima in its vicinity ($C$) the system has to overcome an associated energy cost that might be insurmountable in thermal equilibrium. However, excitation with an ultrashort laser pulse can lift the system over this energy barrier by nondiabatic energy transfer into the electronic degrees of free-
FIG. 3 Multi-messenger probing of disentangled microscopic degrees of freedom. (a) A portfolio of ultrafast techniques has been used to investigate photoinduced melting of charge-density wave order in the materials (La/Tb)Te$_3$, including time-resolved X-ray diffraction (tr-XRD), time- and angle-resolved photoemission spectroscopy (tr-ARPES), transient optical spectroscopy (TOS) and ultrafast electron diffraction (UED). The signals obtained can be qualitatively and quantitatively different since distinct degrees of freedom are probed. Taken from Zong et al., 2019a. (b) Se atoms in FeSe are coherently displaced following photoexcitation by an ultrafast IR pulse, which can be directly measured by tr-XRD (blue, top). At the same time, corresponding energy-shifts of electron bands are revealed by tr-ARPES (orange, middle; green, bottom). The schematic on the right depicts the $A_{1g}$ phonon mode which induces the periodic modulation of the lattice and electronic bands. Taken from Gerber et al., 2017.

FIG. 4 Ultrafast switching. (a) At equilibrium 1T-TaS$_2$ goes through successive CDW transitions as a function of temperature, resulting in an insulating low-temperature state that is characterized by strong correlations (blue, circles; red, triangle up). Upon photoexcitation with a single 35-fs optical pulse, a long-lived metallic state emerges (green, triangle down). Adapted from Vaskivskyi et al., 2015 © The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). (b) Photoexcitation of electrons in bismuth changes the local nuclear potential energy. For excitation densities above 2% the amplitude of the initiated $A_{1g}$ mode drives a transition to a higher-symmetry phase. The $A_{1g}$ phonon mode, characteristic of the low symmetry phase, gets damped as the new phase is reached. Adapted from Teitelbaum et al., 2018.
of a Ginzburg-Landau (GL) theory we point the reader to a the recent work by Sun and Millis 2020.

Nonthermal metastable phases open new opportunities for controllable and reversible switching and thus promises potential for technological applications. This has motivated work in a variety of quantum material families. To exemplify the universality of optical switching, and to acknowledge their relevance within the ultrafast condensed matter field, we highlight here three research directions: (i) light-induced insulator-to-metal transitions in nanofabricated (Liu et al., 2012) and pristine samples of the correlated insulator VO$_2$ (Baum et al., 2007; Becker et al., 1994; Cavalleri et al., 2004, 2001; Morrison et al., 2014; Otto et al., 2019; Wall et al., 2018; Wegkamp et al., 2014), (ii) the control of the spin-orbit-lattice coupled ground state in manganites (Tokura and Nagaosa, 2000) by either laser (Beaud et al., 2014; Ichikawa et al., 2011; Li et al., 2018, 2013; Takubo et al., 2005; Teitelbaum et al., 2019; Zhang et al., 2016) or electric field (Asamitsu et al., 1997) pulses, and (iii) the emergence of a long-lived state with superconducting-like properties at higher temperatures than at equilibrium upon light-induced suppression of the charge (stripe) order in the 1/8-doped cuprates (Cremin et al., 2019; Fausti et al., 2011; Nicoletti et al., 2014) and in K$_3$C$_{60}$(Budden et al., 2021; Cantaluppi et al., 2018; Mitrano et al., 2016).

These works have paved the way for moving the field towards developing new flexible, fast and reversible switching strategies, for example unimpeded by the healing of topological defects (Mihailovic, 2019; Mraz et al., 2021). Here the field of multiferroic materials—in which magnetism is controlled by DC electric fields—has served as inspiration (Spaldin, 2020) for ultrafast experiments that reported the engineering of ferroelectric states (Kubacka et al., 2014; Stoica et al., 2019). Ultrafast switching into a metastable ferroelectric phase has been observed after coherently driving the quantum paraelectric phase of SrTiO$_3$ with strong THz fields (Li et al., 2019; Nova et al., 2019). This approach has also been used to demonstrate the ultrafast reversibility of the ferroelectric polarization in both directions, essential for future technological applications (Mankowsky et al., 2017; Qi et al., 2009). Additionally, the exciting prospect of utilizing laser pulses to switch the topological state of a material has recently been demonstrated in THz-driven WTe$_2$ (Sie et al., 2019).

Finally, we discuss the key ideas behind symmetry-guided switching (Chou et al., 2017; Dasari and Eckstein, 2019; Dehghani et al., 2021; Dehghani and Mitra, 2017; Kennes et al., 2019a; Ono and Ishihara, 2019; Sentaef et al., 2017; Tsuji and Aoki, 2015) on the specific example of chiral superconductors (Claassen et al., 2019), which constitutes a theoretically proposed but not yet experimentally verified ultrafast switching paradigm. Going back to Fig. 2(b), this example corresponds to a free energy landscape with two minima A and B which represent the left- and right-handed chiral ground states of a topological superconductor. It was shown that a combination of linearly polarized followed by circularly polarized laser pulses can nudge the system from the right-to the left-handed chiral ground state. Importantly, the system can immediately be switched back equally fast by applying another sequence of pulses and simply changing the chirality of the circularly polarized laser pulse. The key ingredient besides laser polarization is the duration of the two pulses: the circular pulse has to be applied while the system has not yet recovered from the linear pulse and remains in a superposition of the two chiral states. Recently, it was shown theoretically how the same mechanism, but with spatially localized laser spots, could be used to write, move, or erase chiral domains in real space (Yu et al., 2021).

C. Out-of-equilibrium critical behavior

Ultrafast photoexcitation can induce an instantaneous change of the free energy landscape by suppressing the relevant order parameter [Fig. 2(c)]. This phenomenology challenges our understanding of symmetry-breaking phase transitions. In equilibrium, the macroscopic time-dependent GL theory assumes an order parameter which varies ‘sufficiently’ slowly in time. However, when the order parameter is suppressed on system-intrinsic timescales, it is unclear whether equilibrium concepts (universality classes, scaling) remain applicable, and how the order parameter fluctuations evolve after light excitation. Here we discuss out-of-equilibrium symmetry-breaking phase transitions both as a pathway towards accessing nonthermal effects but also as a platform to study fundamental questions about macroscopic properties associated with order parameter dynamics. The seminal works by Hohenberg and Halperin 1977, Polkovnikov et al. 2011 and Täuber 2017 offer comprehensive reviews.

An example of universal critical behavior in out-of-equilibrium phase transitions is the slowing down of the recovery dynamics. Similarly to what occurs in thermal equilibrium, in the vicinity of a second-order transition, spatial fluctuations of the order parameter diverge, and the exponential rate with which the ordered phase is reinstated vanishes following a power law. This has been seen, for example, in the electronic recovery of charge order in perovskite manganites (Beaud et al., 2014) and La$_{1-x}$Sr$_x$/3FeO$_3$ (Zhu et al., 2018), in the suppression dynamics of the charge density wave in LaTe$_3$ (Zong et al., 2019a), as well as in the spin and orbital dynamics in YVO$_3$ and GdVO$_3$(Yusupov et al., 2010b), and LaVO$_3$ (Lovinger et al., 2020). Divergent slow dynamics also characterize the ultrafast suppression of the nematic electronic order in FeSe (Shimojima et al., 2019) and in iron pnictides (Patz et al., 2014). This seemingly universal behavior in out-of-equilibrium second-order phase
FIG. 5 Nonthermal critical behavior. (a) Nonequilibrium phase diagram as a function of $U_i$ and size of the quench $U_i - U_c$. A splitting of the critical point into thermal and nonthermal antiferromagnetic (AFM) critical points is observed. (b) Time evolution of the magnetization for a quench of the electron-electron interaction $U_i \rightarrow U_i$ in the antiferromagnetic phase of the Hubbard model. Each color represents a different value of $U_i$ (left: $U_i = 1.0, 1.1, \ldots, 1.9$ and right: $U_i = 1.5, 1.6, \ldots, 2.4$ from bottom to top). Adapted from Tsuji et al. 2013.

transitions has been discussed in the time-dependent GL framework (Dolgirev et al., 2020), by stochastic Langevin equations describing the relevant subsystems (Sieberer et al., 2016), and by non-equilibrium Green’s functions (Schüler et al., 2018).

Additionally, ultrafast phase transitions open the possibility to study the effects of nonadiabatic suppression. Near the phase transition the ordered and disordered phases are quasi-degenerate in energy. This allows the fluctuations of the order parameter to be arbitrarily slow. Within the Kibble-Zurek mechanism (Kibble, 1976; Zurek, 1996), when the order parameter suppression happens on timescales faster than that of the fluctuations, coherence between order-parameter domains is lost and the critical behavior is replaced by recovery dynamics dominated by the healing of topological defects. This behavior is universal (Bray, 1994) and has been observed in the long-time recovery dynamics after suppression of the striped phase in cuprates (Mitrano et al., 2019) and of the charge order in LaTe$_3$ (Zong et al., 2019b), TbTe$_3$ (Mertelj et al., 2013; Yusupov et al., 2010a), and 1T-TaS$_2$ (Vogelgesang et al., 2018). A different nonthermal scenario has been shown to emerge when two strongly coupled order parameters are quenched by a laser: In the striped nickelate La$_{1.75}$Sr$_{0.25}$NiO$_4$ an absence of topological defects was reported in conjunction with slow phase fluctuation recovery (Chuang et al., 2013; Lee et al., 2012) and explained by a time-dependent GL theory (Kung et al., 2013).

We finally discuss predictions of nonthermal behavior in strongly correlated systems when driven through a phase transition (Chiocchetta et al., 2017). For example, quenching of the electron-electron repulsion $U$ in the antiferromagnetic phase of the Hubbard model results in a suppression of the magnetization. Depending on the size of the quench it was shown that a nonzero order parameter and coherent amplitude mode oscillations survive even for quenched values of $U$ at which the system would be in the disordered phase in thermal equilibrium (Balzer et al., 2015; Sandri and Fabrizio, 2013; Tsuji et al., 2013; Werner and Murakami, 2020; Werner et al., 2012). This gives rise to a prototypical out-of-equilibrium phase diagram shown in Fig. 5, where the suppression of the amplitude mode is associated with a secondary nonthermal critical point at $U_i = U^{nth}_c$. It is worth noting that such a transition is not expected within the GL picture, where at the critical point the amplitude mode oscillations vanish as the curvature of the free energy potential is suppressed and, consequently, the restoring force disappears (Hohenberg and Halperin, 1977).

D. Nonlinearities and dynamical couplings

We now discuss cases where nonlinear regimes are reached through intense excitation and showcase two examples: (i) dynamical effective interactions due to modified electronic screening, in which the nonlinearity stems from electron-electron interactions, and (ii) strongly driven crystal lattices, in which the nonlinearity is due phonon-phonon interactions or other phonon-related nonlinearities. We note that this classification is mainly for pedagogical reasons. In reality, in both cases the effective Hamiltonian is transiently modified, and it is not always straightforward to reveal the microscopic origin for this modification. The first direct experimental evidence of transiently changed electron-electron interactions was interpreted in the context of (ii) (Kaiser et al., 2014a; Singla et al., 2015).

1. Dynamical Hubbard $U$

The dynamical regime after ultrafast photoexcitation opens a pathway for changing the effective interactions in correlated materials. The paradigmatic example for such an effective interaction is the Hubbard $U$, which
parametrizes the screened local part of the Coulomb integrals of strongly localized (typically $d$ or $f$) orbitals. Examples for applications of the Hubbard model are transition-metal oxides (Imada et al., 1998). There, localized transition-metal ions are embedded between more delocalized ligand orbitals, which often are energetically separated from the $d$ orbitals. In such cases a down-folding procedure can be applied (Miyake et al., 2009), in which the low-energy effective model contains a Hubbard $U$ that depends on the screening from electrons in delocalized environmental orbitals. The key idea of dynamical Hubbard $U$ is that the electronic excitations created after interaction with an ultrafast laser pulse can modify the screening environment, effectively changing $U$ within femtosecond timescales [Fig. 6(a)].

To explain the underlying mechanism, we discuss here the transient reduction of $U$ upon photoexcitation in the correlated antiferromagnetic charge-transfer insulator NiO predicted within time-dependent density functional theory plus $U$ (TDDFT+$U$) (Tancogne-Dejean et al., 2018). The underlying physics can be understood as follows: The electronic structure of NiO is such that the localized correlated subspace of mainly $d$-orbital character and the rest of the system of mainly $p$-orbital character can be considered independently. Photoexcitation of electrons from the localized subspace into delocalized states results in additional screening. This naturally leads to a decrease of the effective $U$. It is instructive to think of the excitation as an induced time-dependent polarization of the localized electrons, affecting the dielectric properties of the delocalized electrons, which is expected for strong driving fields even for frequencies away from optical transitions. Similar results were obtained by Gillmeister et al., 2020 and Golež et al., 2019 using different methods.

Experimental evidence for a dynamically modified Hubbard $U$ by photoexcitation of electron-hole pairs was reported in the transition-metal dichalcogenide MoTe$_2$ (Beaulieu et al., 2021). In this material, the uncorrelated band structure has two electron-like bands crossing the Fermi level $E_F$ at the edge of the Brillouin zone. However, this is not observed in photoemission. Instead, as explained by DFT+$U$, the Hubbard $U$ pushes the respective states above $E_F$. This effect can be partially undone on ultrafast timescales, as demonstrated by tr-ARPES, ~200 fs after photoexcitation, an ultrafast Lifshitz transition was observed, at which the Fermi surface topology changed because the electron-like bands were pushed below $E_F$ triggered by dynamical reduction of $U$.

A different route towards dynamical modulation of Hubbard $U$ is the coherent driving of the crystal lattice. Dynamical $U$ through phonon driving was first demonstrated in a prototypical one-dimensional Mott-insulating charge transfer salt (Kaiser et al., 2014a; Singla et al., 2015) and more recently reported as a microscopic mechanism for possible photomolecular superconductivity far above equilibrium $T_c$ in two-dimensional molecular crystals (Buzzi et al., 2020; Tindall et al., 2020). The phononic route towards dynamical interactions is particularly suited for molecular crystals, where the effective local sites of the Hubbard model are comprised of entire molecules or parts thereof, which can be vibrationally excited and the on-site effective interaction thus changed [Fig. 6(b)] through the deformation of the intra-molecular wavefunction during the vibration. The key advantage of resonant phonon excitation in the mid-IR frequency

---

**Fig. 8**

- (a) Screening is typically enhanced when a material is excited by an optical laser pulse, which creates electronic excitations, resulting in a dynamically reduced time-dependent $U$ (Tancogne-Dejean et al., 2018; Golež et al., 2019). In charge-transfer insulators this results in a narrowing of both the Mott-Hubbard gap between the upper and lower Hubbard bands (UHB and LHB, respectively), as well as the charge-transfer gap $\Delta$ (Tancogne-Dejean et al., 2020).
- (b) For a mid-IR laser excitation, resonant with an IR-active phonon mode, the dynamical $U$ can parametrically depend on the phonon mode coordinate $Q_{IR}$ via a nonlinear electron-phonon interaction ($Q_{IR}^2 U$). Whether $U$ increases or decreases on average depends on the sign of this nonlinearity.
range, compared to photodoping by optical pulses, lies in the spectral selectivity of the excitation pathway. This leads us to the discussion of vibrational control of emergent quantum phenomena in the following subsection.

2. Nonlinear phononics

We now focus on resonant excitation of the crystal lattice with THz and mid-IR laser pulses. The notion of mode-selective control of the crystal lattice in quantum materials was coined ‘nonlinear phononics’ and relies on the symmetries of the crystal and the phonon modes (Fürst et al., 2011; Subedi et al., 2014). There are three main differences from experiments where a pump interacts directly with the electronic degrees of freedom. (i) The energy from the pump is transferred into an initially coherent motion of an IR-active phonon mode, which then further interacts with other phonon modes, as well as, electrons and other collective degrees of freedom in the system. (ii) The targeted excitation of a particular phonon mode opens additional pathways for mode-selective control not accessible in traditional driving schemes. (iii) Salient effects can already happen during the pulse pulse and can often be understood as parametric excitation of degrees of freedom that are coupled to the driven mode.

We consider a crystal with an inversion center in which parity is a good quantum number and phonon modes can be grouped into even (Raman-active) and odd (IR-active). Lowest-order anharmonicity leads to a nonlinear coupling of the form \( g_{cubic}Q_{IR}^2Q_R \) between an IR and a Raman (R) mode, with a coupling strength \( g_{cubic} \) that is determined by the anharmonic potential. Coherent driving of the IR mode to large amplitudes [Fig. 7(a)], using strong mid-IR laser pulses, couples to the Raman modes such that a unidirectional displacive force occurs that is proportional to the square of the IR-mode displacement [Fig. 7(b)]. The consequences of the respective transient crystal structures [Fig. 7(c)] on the electronic subsystem have been shown to bear potential for changing the phases of quantum materials on ultrafast timescales (Mankowsky et al., 2016). As an example for fingerprints of a transiently modified lattice structure in pump-probe experiments, we show transient Bragg peak intensities [Fig. 7(d)] from femtosecond X-ray diffraction, supported by ab initio density functional theory calculations of the Cu-O distance [Fig. 7(e)], in the YBa\(_2\)Cu\(_3\)O\(_6,5\) high-temperature superconductor (Mankowsky et al., 2014).

Among others, coherent control of the crystal lattice by driving to anharmonic regimes has been suggested as a mechanism to induce ultrafast phase transitions, such as a lattice-controlled metal-insulator transition (Rini et al., 2007), and lead to states of matter without equilibrium counterparts, including possible light-induced superconductivity (Fausti et al., 2011; Hu et al., 2014; Kaiser et al., 2014b; Mankowsky et al., 2014). In turn, these groundbreaking experiments have stimulated considerable theoretical activity on nonequilibrium superconductivity (Babadi et al., 2017; Coulthard et al., 2017; Dasari and Eckstein, 2018; Denny et al., 2015; Kennes et al., 2017; Kim et al., 2016; Knap et al., 2016; Komnik and Thorwart, 2016; Mazza and Georges, 2017; Murakami et al., 2017; Nava et al., 2018; Okamoto et al., 2016; Raines et al., 2015; Sentef, 2017; Sentef et al., 2016, 2017; Wang et al., 2018a), as well as a lively debate on how we should understand and interpret optical superconducting-like signatures on transient timescales (Densar, 2020; Zhang et al., 2020). Furthermore, coherent optical driving of the lattice has been suggested as a path towards switching applications (see Sec. II.B) as well as a means of mapping of interatomic forces and potentials (von Hoegen et al., 2018; Kozi et al., 2019). Another developing subfield is phono-magnetism (Afanasiev et al., 2021; Disa et al., 2020; Giorgianni et al., 2021; Juraschek et al., 2020; Nova et al., 2017; Stupakiewicz et al., 2021), in which magnetic properties of materials are modified via coherent phonon dressing.

To summarize, phononic control of quantum materials is a rapidly growing research field, conceptually located at the boundary between ultrafast dynamics after short laser excitation and dressed states of nonequilibrium matter, which will be discussed in the following.

III. DRESSED STATES OF NONEQUILIBRIUM MATTER

Another class of nonequilibrium phenomena encompasses the effects that occur in solids during optical illumination. Examples include high-harmonic generation (Ghimire et al., 2011; Schubert et al., 2014; von Hoegen et al., 2018), sub-cycle electron and spin dynamics (Kampfrath et al., 2011; Lucchini et al., 2016; Reimann et al., 2018; Schultze et al., 2013), light-field driven currents (Higuchi et al., 2017; Schifferin et al., 2013) and the parametric amplification of plasma waves (Rajasekaran et al., 2016). Comprehensive reviews of many of these topics can be found in Ghimire and Reis 2018 and Kampfrath et al. 2013. Here, we focus on observables described by the coherent dressing of a material’s quantum states by the rapidly oscillating light-field. The manner and degree to which the states are dressed are determined by the amplitude, frequency and polarization of the electromagnetic drive. Such coherent light-matter interaction thereby provides an external control knob for transiently tuning the electronic and magnetic interactions in solids, which can be used to engineer quantum states with no equilibrium counterpart.

The consequences of photon dressing have long been investigated in the context of atomic systems and have led to applications in atomic clocks, precision spectroscopy, and quantum information processing (Scully...
FIG. 7 Transient crystal structure from nonlinear phononics. (a) Oscillatory dynamics of an IR-active phonon mode coordinate \( Q_{\text{IR}} \) is induced under resonant driving by a mid-IR laser pulse. (b) Due to nonlinear phonon-phonon coupling to a Raman mode (coordinate \( Q_{\text{R}} \)) of the form \( Q_{\text{IR}}^2 Q_{\text{R}} \), the potential energy of the Raman mode is transiently shifted to a new minimum, following the squared amplitude \( Q_{\text{IR}}^2 \). Accordingly, the Raman mode is displaced towards its transient potential minimum, which remains as long as the dynamics of the IR-active mode is coherent. (c) For \( \text{YBa}_2\text{Cu}_3\text{O}_6.5 \), the motion of the optically excited coherent \( B_{1u} \) mode leads to a transiently modified crystal structure, which was measured using time-resolved X-ray diffraction (Mankowsky et al., 2014) and is compatible with light-induced superconducting behavior. (d) Time-resolved relative change of intensity, \( \Delta I/I \), of two representative Bragg peaks. Solid curves show the ab initio calculated structure based on nonlinear phonon-mode coupling. (e) Transient change in the Cu–O distance \( d \) obtained from the calculation. Adapted from Mankowsky et al., 2015 (a,b) and Buzzi et al., 2018 (c-e).

and Zubairy, 1997). At the root of many of these phenomena is the alternating current (AC) Stark effect, a process whereby the oscillating electromagnetic field effectively shifts or splits electronic energy levels via the electric dipole interaction (Autler and Townes, 1955). This fundamental dressing effect has also been observed in solid state systems using the strong AC fields in ultrafast laser pulses (Bonitz, 2016; Fröhlich et al., 1985; Haug and Jauho, 2008; Mücke et al., 2001; Reutzel et al., 2020; Rossi and Kuhn, 2002; Schäfer and Wegener, 2002; Sie et al., 2015).

Quantum materials can be dressed by light in more complex ways than isolated atomic systems by exploiting the additional degrees of freedom that interact with the light field. While this enhanced complexity is an opportunity for realizing novel material responses, it comes at the cost of increased dissipation, which leads to decoherence due to electron-electron, electron-phonon and other scattering mechanisms. Far stronger optical fields are thereby required to overcome these sources of decoherence in driven solid-state electronic systems (Aeschlimann et al., 2021; Nuske et al., 2020; Sato et al., 2019), which have historically made dressed states difficult to experimentally access.

Advances in the generation of strong-field laser pulses now make it possible to routinely access regimes where dressing effects dominate the response of optically driven quantum materials, which are being investigated with the aid of a new generation of ultrafast experimental probes (McIver et al., 2019; Wang et al., 2013). Theoretical breakthroughs utilizing Floquet theory (Lindner et al., 2011; Oka and Kitamura, 2019; Rudner and Lindner, 2020) are simultaneously offering unprecedented guidance for experiments. This combined effort has led to remarkable discoveries and predictions (Fig. 8). We review some of these developments in the following sections.

A. Theory introduction

To introduce the concept of dressed states in solids, we begin with the intuitive example of a periodically driven atomic chain in the high-frequency limit. We then generalize to the case of arbitrary frequency, for which Floquet theory provides a flexible and powerful framework to describe dressing effects.
1. Dynamical localization in a driven atomic chain

Consider a one-dimensional tight-binding model of noninteracting spinless fermions in second quantization

\[ H = -\sum_n t_0 c_n^\dagger c_{n+1} + \text{H.c.} = \sum_k \epsilon(k) c_k^\dagger c_k, \]  

(1)

where \( t_0 \) is the hopping amplitude and \( c_n^\dagger \) annihilates (creates) a fermion on site \( n \). In momentum space, one obtains a dispersion relation \( \epsilon(k) = -2t_0 \cos(ka) \), where \( a \) is the lattice constant.

Next consider a coupling to a time-periodic longitudinal electric field \( E(t) = E_0 \sin(\omega t) \) with a field strength \( E_0 \) and frequency \( \omega \), which can be included by the Peierls substitution \( t_0 \rightarrow t_h(t) = t_0 e^{ieA(t)/\hbar} \) where \( A(t) = E_0/\omega \cos(\omega t) \) is the vector potential, such that \( E(t) = -\partial_t A(t) \). When the driving frequency is larger than the intrinsic energy and timescales in the system, the high-frequency oscillations cancel each other. Time averaging \( t_h(t) \), denoted by \( \langle \ldots \rangle \), yields \( t_{\text{eff}} = \langle t_h(t) \rangle = t_0 J_0(F) \), where \( J_0 \) is the 0th-order Bessel function. We introduced the dimensionless Floquet parameter

\[ F = \frac{aeE_0}{\hbar \omega}, \]  

(2)

to parameterize the strength of the electromagnetic drive, with \( e \) the elementary charge. Since \( |J_0(x)| < 1 \), the resulting effective hopping amplitude \( t_{\text{eff}} \) is always smaller than the equilibrium value \( t_0 \), meaning that on average (i.e., in the effective or dressed picture) the electrons in the driven chain are more localized than in the undriven chain. This real-space description of dynamical localization is depicted in Fig. 9(a).

Equivalently, in momentum space, the effect of dynamical localization is captured by the minimal coupling \( k \rightarrow k - eA(t)/\hbar \) in the band dispersion. The effect of the electric field is to periodically shake the dispersion to the left and right [bottom row of Fig. 9(a)]. When considering the minimum of the equilibrium dispersion

FIG. 8 Versatile functionalities enabled by Floquet engineering. (a) Periodic driving using optical fields can steer the macroscopic properties of quantum materials by dressing their microscopic degrees of freedom, such as electronic hopping parameters. (b) Examples include proposals and experimental realizations of new electronic band structures (Mahmood et al., 2016; Wang et al., 2013), the manipulation of band topologies (Kitagawa et al., 2011; Lindner et al., 2011; McIver et al., 2019; Oka and Aoki, 2009), and the observation of excitonic Stark shifts caused by the creation of strong synthetic magnetic fields (Kim et al., 2014; Sie et al., 2015). Additional proposals include the optical control of magnetic correlations (Claassen et al., 2017; Kennes et al., 2018; Mentink et al., 2015), experimentally observed in quantum simulation settings (Görg et al., 2018), the creation of fractionized quasiparticles obeying nonabelian statistics (Lee et al., 2018), and forms of photon-dressed superconductivity (Kennes et al., 2019a; Knap et al., 2016; Murakami et al., 2017; Tindall et al., 2020).
relation at \( k = 0 \), one finds that this shaking on average shifts the bottom of the band dispersion to higher energy in the effective picture. Analogously, the dispersion maxima at the zone boundaries are lowered in energy upon averaging. The net effect in the effective, or dressed, picture is a reduction in bandwidth compared to the equilibrium dispersion relation. This example demonstrates how periodic driving provides a tuning knob for materials properties via the renormalization of electronic hopping (Bucksbaum et al., 1990; Claassen et al., 2017; Dunlap and Kenkre, 1986; Kennes et al., 2019a, 2018; Mentink et al., 2015).

2. Floquet primer

Floquet theory provides a powerful basis to treat a periodically driven quantum system beyond high- or low-frequency expansions. Such a system is governed by the time-dependent Schrödinger equation:

\[
\frac{i\hbar}{\partial t} |\Psi(t)\rangle = H(t) |\Psi(t)\rangle ,
\]

with a time-periodic Hamiltonian \( H(t + T) = H(t) \) with period \( T \). Floquet 1883 showed that the solution to Eq. (3) can be written as:

\[
|\Psi_1(t)\rangle = e^{-it\epsilon_1/\hbar} |\Psi(t)\rangle ,
\]

where the \( T \)-periodic wavefunction \( |\Phi_1(t)\rangle = |\Phi_1(t + T)\rangle \) and the quasi-energies \( \epsilon_1 \) are determined by the algebraic equation

\[
(\epsilon_1 + n\hbar \omega) |\Phi_1^n\rangle = \sum_{n'} H^{n-n'} |\Phi_1^{n'}\rangle ,
\]

with frequency \( \omega = 2\pi/T \) and Fourier decompositions \( H^n = \frac{1}{T} \int_0^T dt e^{int \omega} H(t) \) and \( \langle \Phi_1^n | \Phi_1^{n'} \rangle = \frac{1}{T} \int_0^T dt e^{int \omega} |\Psi(t)\rangle \). This maps a periodic differential equation to an algebraic (quasi-equilibrium) problem. The time-dependent problem is transformed into an effective static Hamiltonian by considering \( \hat{\mathcal{H}}_\Phi = \sum \Phi_1^n |\Phi_1^n\rangle \langle \Phi_1^n| \) and

\[
\hat{\mathcal{H}}_\Phi = \epsilon_1 |\Phi_1\rangle \langle \Phi_1| ,
\]

such that

\[
\hat{\mathcal{H}} = \begin{pmatrix}
\epsilon_1 & H^{-1} & H^{-2} & H^{-3} & H^{-4} \\
H^1 & H^0 - (\epsilon_1/\hbar \omega) & H^{-1} & H^{-2} & H^{-3} \\
H^2 & H^1 & H^0 - \hbar \omega & H^{-1} & H^{-2} \\
H^3 & H^2 & H^1 & H^0 - \hbar \omega & H^{-1} \\
H^4 & H^3 & H^2 & H^1 & \ddots
\end{pmatrix} .
\]
The physics can be summarized as follows: Floquet-Bloch bands form and hybridize at their crossing points, opening band gaps $|\Delta_1, \Delta_2|$ in Fig. 10(b)]. A second-order process also causes a gap to open at the Dirac point $(\Delta_0)$ because the interaction breaks time-reversal symmetry. The resulting fully-gapped Floquet-Bloch bands have a nonzero Berry curvature distribution that causes charges to undergo an anomalous Hall effect. By reversing the helicity of the light, the polarity of the induced Berry curvature distribution, and hence the direction of the net anomalous Hall current, can be controlled.

In the high-frequency limit, where the Floquet sidebands do not overlap and thus there are no gaps due to band crossings, the Hamiltonian for the driven system is

$$H_{\text{ef}} \approx H_0 + \frac{[H_1, H_2]}{\hbar \omega},$$

where the first term is the equilibrium Dirac Hamiltonian and the second term is responsible for the gap opening at the Dirac point. Specifically for a two-dimensional Dirac cone with energy-momentum relation $\epsilon(k) = \hbar v_F |k|$, with Fermi velocity $v_F$, one obtains $\Delta_0 = 2\hbar^{-1}e^2\nu_F^3E_0^2/\omega^3 = 2\hbar^{-1}e^2\nu_F^3A_{1/0}^2/\omega$, which scales quadratically with the peak electric field $E_0$ and is enhanced for small frequencies.

Kitagawa et al. 2011 interpreted Eq. (7) as the energy difference (\Delta_0) between two processes, where an electron in the $n=0$ Dirac cone first absorbs (emits) a circularly polarized photon to enter the $n=1$ ($n=-1$) sector, then emits (absorbs) a photon of the same helicity to return to the $n=0$ sector [Fig. 10(b)]. In real space, this corresponds to a double hopping in the unit cell that has the net effect of introducing chiral intra-sublattice tunneling elements to the effective Hamiltonian [Fig. 10(c)]. The effective Hamiltonian is identical to that proposed by Haldane for a topological Chern insulator in graphene (Haldane, 1988), which was previously believed to be inaccessible via any realistic experimental setting. When only the lower Chern band is populated, a topological phase is expected to develop hosting a quantized anomalous Hall effect carried by chiral edge states, which would be photon-dressed in this case.

Floquet topological insulators have been studied in the high-frequency limit using a variety of quantum simulation platforms, most notably in photonic waveguides (Rechtsman et al., 2013), where the propagating edge mode was directly observed, and in driven optical lattices of ultracold fermions (Jotzu et al., 2014). Later theoretical works confirmed that topological states could also be created in the low-frequency limit [Fig. 10(b)], with the difference being that the multitude of Floquet-Bloch bands that form due to the additional gap openings can have Chern numbers $|C| > 1$, i.e., multiple edge modes (Claassen et al., 2016; Dehghani et al., 2015; Mikami et al., 2016; Sentef et al., 2015; Usaj et al., 2014). An additional topological invariant, dubbed winding number, can also arise in the low-frequency limit (Kitagawa et al., 2011).
FIG. 10 Topological Floquet engineering in Dirac systems. (a) A coherent interaction with circularly polarized light was predicted to induce a photon-dressed topological band structure in graphene, characterized by protected chiral edge states (Kitagawa et al., 2011; Oka and Aoki, 2009). (b) When the Floquet sidebands form they hybridize at their crossing points, opening band gaps ($\Delta_1$, $\Delta_2$). A gap also opens at the Dirac point ($\Delta_0$) due to a two-photon absorption/emission process that breaks time-reversal symmetry. The resulting Floquet-Bloch bands are fully gapped and possess a nonzero total Berry curvature and Chern number. (c) Real space schematic of the two-photon absorption/emission hopping process that induces a gap at the Dirac point in graphene. (d) tr-ARPES data of Bi$_2$Se$_3$ detecting the formation of Floquet-Bloch bands from the Dirac surface states. Taken from Mahmood et al. 2016. (e) Nonequilibrium anomalous Hall conductance of graphene driven by circularly polarized light as a function of the equilibrium Fermi level ($E_F$). Red and blue shading corresponds to $E_F$ being gated to the regions where the gaps $\Delta_0$ and $\Delta_1$ were predicted to appear. Taken from McIver et al. 2019.

et al., 2010; Rudner et al., 2013), which is defined over time rather than momentum space and, thus, only realizable in periodically driven systems. Observations of such ‘anomalous Floquet topological insulators’ have also been reported in the quantum simulation community (Kitagawa et al., 2012; Maczewsky et al., 2017).

In a landmark paper, Wang et al. 2013 reported the first spectroscopic evidence of topological Floquet-Bloch bands in a solid within the Dirac surface states of the topological insulator Bi$_2$Se$_3$ using tr-ARPES [Fig. 10(d)]. The data reveal multiple dressed sidebands and the opening of band gaps, similar to those illustrated in [Fig. 10(b)].

McIver et al. 2019 reported the first electrical transport results from topological Floquet-Bloch bands. Using an ultrafast transport device (bottom center panel of Fig. 1), an anomalous Hall effect was detected in graphene illuminated by a circularly polarized mid-IR pulse. Remarkably, at high laser pulse fluences they observed that the anomalous Hall conductance saturated on the order of two conductance quanta—the same value predicted in the high-frequency limit (Kitagawa et al., 2011). When the graphene Fermi level was tuned away from charge neutrality using an electrostatic gate [Fig. 10(e)], features were observed in the conductance spectrum closely aligned with the opening of the band gaps $\Delta_0$ and $\Delta_1$, as predicted by Floquet theory for their laser pulse parameters. Subsequent numerical studies confirmed that the observed photocurrents originated from the formation of topological Floquet-Bloch bands (Nuske et al., 2020; Sato...
et al., 2019). These results are an encouraging sign that Floquet-engineered topological edge states are a distinct possibility in optically driven Dirac materials.

C. Towards Floquet many-body physics: Heating and interactions

The experiments by Wang et al. 2013 and McIver et al. 2019 demonstrate that Floquet engineering in quantum materials is realistic despite the presence of strong dissipation, which leads to decoherence. However, the tr-ARPES data also reveals significant pump-induced carrier excitation, leading to a nonequilibrium dressed electron distribution in the Floquet-Bloch bands. Here, distributional and dissipative effects play an important role already even in the absence of electronic interactions (Dehghani et al., 2014; Iadecola et al., 2015; Seetharam et al., 2015), and contribute for instance to substantial deviations from quantization of the Hall conductivity and edge state transport in Floquet band topological insulators (Farrell and Pereg-Barnea, 2016; Kundu and Seradjeh, 2013). The roles of heating and thermalization hence can be expected to take on an outsized role as ‘Floquet engineering’ is extended towards the control of interacting many-body states of matter. Therefore, materials and driving protocols need to be chosen carefully in order to minimize heating and carrier redistribution such that a nonequilibrium state proximal to the ground state of the effective Hamiltonian is realized.

Theoretically, there have been multiple proposals to address the challenge of heating. In general, closed periodically driven interacting systems continuously absorb energy and heat to a featureless infinite-temperature steady state by virtue of the eigenstate thermalization hypothesis for nonintegrable systems (D’Alessio and Rigol, 2014). However, tailored drive protocols can be chosen to suppress heating at short times and realize a potentially long-lived ‘prethermal’ regime. Here, a central ingredient is a separation of energy scales, and, thus, a separation of timescales in the driven system, which entail an ergodic obstruction to fast energy absorption. After an initial ramp-on period, governed by fast switch-on processes, the intermediate time (period-averaged) dynamics can saturate to a prethermal plateau, governed by an effective Hamiltonian that captures a controlled Floquet modification, leading to observable consequences for instance in correlation functions or spectroscopic probes of the system. This regime is bounded by a timescale that signifies the onset of heating towards a featureless high-temperature state [Fig. 11], which can in principle nevertheless retain certain correlations when constrained by exact nonabelian symmetries (Tindall et al., 2019).

Most of our current understanding regards the limit of high-frequency driving (Claassen et al., 2017; Gulden et al., 2020; Haldar et al., 2018; Machado et al., 2020, UHB). 

![FIG. 11 Routes to avoid runaway heating. (a) Generic interacting systems heat up upon applying a continuous drive, detrimental to coherent control. However, by tuning the drive frequency to a spectral gap in the system, this heating can in principle be pushed to (exponentially) large times. Control of prethermal states can then be achieved on intermediate to long timescales until thermalization sets in. (b) Examples of condensed matter systems for which such a strategy could be applied. The upper two and bottom left subpanels show Mott and charge transfer insulators (LHB and UHB denote the lower and upper Hubbard band, respectively). Another example are quantum Hall insulators (lower right subpanel). Between the different Landau-Levels (LL) energy gaps proportional to the externally applied magnetic field emerge. Frequency detuning to the sharp resonances between LLs could, in principle, allow for prethermal state Floquet control of the system.](image-url)
2019; Mentink et al., 2015; Peronaci et al., 2018; Vajna et al., 2018; Weidinger and Knap, 2017), where the pump frequency exceeds local energy scales. In this limit rigorous results for slow heating were recently established (Abanin et al., 2017a,b, 2015; Ho et al., 2018; Kuwahara et al., 2016; Mori et al., 2018, 2016). Notably, these works provide only mathematical bounds for the onset of heating to featureless states at infinite temperature, which can be exceeded in specific settings. Many-body localized (MBL) systems constitute an important exception (DAlessio and Polkovnikov, 2013; Lazarides et al., 2014, 2015; Ponte et al., 2015). Here, heating can be averted via a lack of ergodicity, stabilizing a tantalizing array of bona fide nonequilibrium phases, such as time-crystalline orders or Floquet topological phases (Decker et al., 2020; Rovny et al., 2018; Zeug and Sheng, 2017).

In practice, a high-frequency driving limit is absent in most real materials, since higher-lying bands and collective excitations provide a multitude of possibilities for resonant absorption at higher frequencies. Similarly, while MBL is realizable in cold atomic systems (Singh et al., 2019), it is typically destabilized in solids due to energy dissipation to the lattice or other degrees of freedom. Nonetheless, sufficiently slow energy absorption, for instance due to off-resonant driving or other ergodic obstructions to heating, can realize ‘prethermal’ dynamical regimes at short times (Fig. 11), which can harbor intriguing emergent phenomena (Claassen, 2021; Gulden et al., 2020; Haldar et al., 2018; Luitz et al., 2020; Rovny et al., 2018). Therefore, a central problem is to identify materials and driving regimes for which comparatively long-lived prethermal regimes persist in a realistic setting. Notably, these arguments imply that Floquet control of quantum phases in solids entails a two-fold challenge: engineering (i) a prethermal Hamiltonian that captures the desired dynamics on sufficiently long timescales, and (ii) an electronic distribution with respect to this prethermal Hamiltonian on the same timescales.

A complementary route to Floquet engineering aims to exploit dissipation in open systems to stabilize a driven steady state at long times, for which the energy influx absorbed from the pump is compensated by energy dissipation into the environment (Esin et al., 2018; Seetharam et al., 2019). In a solid-state setting, the crystal lattice can act as a ‘thermostat’ for the electronic system due to the large timescale separation between electronic and lattice dynamics, with early works suggesting routes towards the controlled dissipative population of single-particle Floquet states (Deighani et al., 2014; Iadecola et al., 2015; Seetharam et al., 2015). The phase diagrams of infinite-time steady states of clean systems have been established to exhibit rich phase transitions (Kalthoff et al., 2021; Klöckner et al., 2020; Mendoza-Arenas et al., 2017; Mitra et al., 2006; Peronaci et al., 2018; Walldorf et al., 2019), which are, however, expected to be first order at finite driving frequency (Mathey and Diehl, 2019).

D. Engineering correlated systems

A tantalizing prospect concerns utilizing tailored light pulses to engineer novel phases of matter in correlated electron systems. The use of light to modulate interactions or selectively break symmetries to tune the interplay of competing phases promises a rich playground to stabilize new phases of matter but remains a largely unexplored and methodologically challenging regime. We discuss in the following different examples.

**Magnetic Mott insulators** have recently emerged as a promising class of candidate materials for Floquet engineering in correlated systems (Bukov et al., 2016; Claassen et al., 2017; Kennes et al., 2018; Mentink et al., 2015; Walldorf et al., 2019). In a Mott insulator, strong local Coulomb repulsion—typically in localized transition-metal d orbitals—freezes low charge degrees of freedom at commensurate filling to open an insulting gap and form local magnetic moments. If the pump frequency is sufficiently red-detuned from the charge gap, energy cannot be absorbed resonantly as photons couple to charge [Fig. 12(a,b)]. Remarkably, while the charge sector remains inert on short timescales, a prethermal regime can emerge which is characterized by transiently modified effective magnetic interactions between the local moments (Claassen et al., 2017; Mentink et al., 2015).

A minimal model to describe these effects is the driven half-filled single-band Hubbard model

$$H(t) = -t_h \sum_{\langle ij \rangle \sigma} e^{i \mathbf{A}(t) \cdot \mathbf{r}_{ij} / \hbar} \, \hat{c}_{i \sigma} \hat{c}_{j \sigma} + U \sum_i \hat{n}_{i \uparrow} \hat{n}_{i \downarrow},$$

where $t_h$ and $U$ denote hopping of electrons between neighboring sites and local Coulomb repulsion, respectively. The optical pump enters via minimal coupling to a gauge field $\mathbf{A}(t)$.

In equilibrium, the half-filled Hubbard model at low energies and large $U$ canonically maps onto effective nearest-neighbor Heisenberg interactions $J \approx \frac{4t_h^2}{U}$ which arise from virtual exchange. Suppose that the pump frequency $\omega$ is sufficiently red-detuned from the Mott gap $\sim U - 4t_h$. If the charge sector remains inert out of equilibrium, then a perturbative calculation, which simultaneously integrates out charge degrees of freedom and photons, leads to a transient photoinduced renormalization of spin-exchange interactions, proportional to

$$J \approx \sum_m \frac{4t_h^2 \langle F_m \rangle^2}{U - m \hbar \omega},$$

(Chaudhary et al., 2019; Itin and Katsnelson, 2015; Mentink et al., 2015).

A physical picture readily emerges by noting that the electronic participating in the exchange process can now lower the Coulomb repulsion energy $U$ of the virtual intermediate state by absorbing a photon from the pump field, thereby enhancing the effective spin exchange. A schematic depiction of this process is shown in Fig. 12(c). Conversely, for strong pump fields, higher-order multiphoton processes can dominate and even permit flip-
FIG. 12 Floquet engineering of magnetic interactions. (a) Schematic of manipulating magnetic degrees of freedom via irradiation of quantum magnets with light. (b) In Mott insulators, pumping below the charge gap suppresses charge excitations on short timescales while renormalizing the magnetic interactions at low energies. (c) Irradiation with light can alter conventional spin-exchange interactions via reducing the energy cost of intermediate virtual states of electronic tunnelling. (d) Circularly polarized light can induce new types of magnetic interactions, such as SU(2)-symmetric chiral three-spin exchange interactions due to dynamical time-reversal symmetry breaking, which are absent in equilibrium.

ping the sign of Heisenberg exchange if \( m \)-photon processes with \( m \hbar \omega > U \) dominate (Mentink et al., 2015). For a typical Mott antiferromagnet with \( U \sim 2 \) eV, \( t_h \sim 0.1 \) eV, \( a \sim 3 \) Å (corresponding to \( J \sim 20 \) meV in equilibrium), and pumping at 700 nm, one finds an enhancement of the exchange coupling in the range \( \Delta J \sim 0.2 \) to 20 meV for a peak field strength of 0.05 to 0.5 V Å\(^{-1}\) (Batignani et al., 2015).

Frustrated quantum magnets, encompassing materials in which competing magnetic interactions render minimizing the free energy landscape nontrivial, are another interesting class to study. In these compounds, transient modifications of the magnetic interactions are expected to have a sizeable effect. While the role of overall renormalization of Heisenberg interactions discussed above is reflected solely in shifts of the excitation spectrum without affecting the ground state, strongly frustrated systems typically host rich phase diagrams of competing magnetic orders such that a small photoinduced transient change of competing subdominant interactions can ‘nudge’ the system into a proximal phase (Kennes et al., 2019a). Moreover, such materials are highly sensitive to the breaking of symmetries, which grants a powerful handle to steer the nonequilibrium phase on prethermal timescales, which can be kept sufficiently long via detuning from the Mott gap.

From these considerations, one avenue of utilizing Floquet engineering to transiently stabilize a novel correlated state of matter builds upon the observation that pumping a frustrated Mott insulator with circularly polarized light permits the selective breaking of time-reversal symmetry (TRS) and inversion without breaking the SU(2) spin-rotational symmetry of the magnetic moments (Claassen et al., 2017; Kitamura et al., 2017). Notably, while TRS can be readily broken in equilibrium via external magnetic fields, the dominant contribution to low-energy spin dynamics comes from a Zeeman splitting that breaks SU(2), quickly magnetizing the system. Instead, the role of the pump is to generate a transient photoduced scalar spin chirality \( S_i \cdot (S_j \times S_k) \), whose form can be inferred from symmetry considerations alone, and microscopically arises from fourth-order virtual processes involving elementary triangles of the underlying lattice [Fig. 12(d)]. For example, it was shown that in Kagome antiferromagnets, such as herbertsmithite, a weak optical pump tuned between one- and two-photon resonances of the parent Mott insulator can induce a transition to a proximal chiral spin liquid phase (Claassen et al., 2017),
suggesting a novel nonequilibrium pathway to one of the earliest and most elusive candidates of a gapped quantum spin liquid with topological order.

*Strong spin-orbit coupled multi-orbital compounds* constitute a natural generalization of such a nonequilibrium separation of charge and spin degrees of freedom (Arakawa and Yonemitsu, 2021; Hejazi *et al.*, 2019; Liu *et al.*, 2018; Sriram and Claassen, 2021), which could allow for Floquet engineering while mitigating heating. In the orthorhombic titanates, the partially-filled $t_{2g}$ manifold has been proposed as a prime target for optical manipulation of effective Kugel-Khomskii spin-orbital interactions. In Kitaev materials such as α-RuCl$_3$, Floquet engineering can modify the interplay between Kitaev and competing exchange interactions to manipulate the magnetic state and induce a quantum spin liquid. In charge transfer insulators such as the cuprates, photoinduced rotational symmetry breaking was proposed to engineer magnetic interactions and ultimately destabilize the Mott antiferromagnetic phase in favor of a $d$-wave superconductor (Kennes *et al.*, 2019a). Conversely, theoretical predictions of spectroscopic signatures suggest that the controlled manipulation of magnetic exchange interactions could be observed in time-resolved Raman or resonant inelastic X-ray scattering (Wang *et al.*, 2018b), for instance via tracking the softening of bimagnon excitations (Wang *et al.*, 2018c).

*Fractional quantum Hall systems* are another intriguing direction to engineer prethermal correlated phases using external driving. While a vast series of Abelian filling fractions have been experimentally realized (Stormer *et al.*, 1999), more elusive fractional quantum Hall states (Moore and Read, 1991; Read and Rezayi, 1999) with non-Abelian quasiparticles are well-known to prefer fine-tuned or multi-body interactions for stabilization (Greiter *et al.*, 1991), while simultaneously incurring tremendous interest for potential applications in topological quantum computing and beyond (Nayak *et al.*, 2008). In principle, Landau levels in ultraclean electron gases provide a natural separation of energy scales for Floquet engineering. If the pump frequency is sufficiently detuned from a cyclotron resonance, the regularity in Landau level spacing guarantees the absence of multi-photon resonances at low photon numbers. If heating can be suppressed, such a setting has been predicted to give rise to photoinduced three-body interactions that arise from virtual inter-Landau-level scattering (Lee *et al.*, 2018), suggesting a nonequilibrium route to stabilize a Moore-Read state. Conversely, resonant excitation between Landau levels has been proposed to engineer effective multi-layer fractional quantum Hall models (Ghazaryan *et al.*, 2017).

**IV. OUTLOOK**

In this Colloquium, we discussed a set of results that provide insights into ultrafast phenomena in photoexcited quantum materials. These advances rely on an unprecedented range of optical excitations and a growing set of tools to probe and simulate nonthermal pathways towards control and functionality on ultrafast timescales. In particular, photoinduced phase transitions to thermally inaccessible states via short optical excitation or photon dressing constitute promising routes towards achieving nonequilibrium functionality.

Recent studies of photoinduced phase transitions have provided a more detailed understanding of the relevant microscopic degrees of freedom and their nonthermal behavior, and have revealed the interplay between these degrees of freedom in the time domain. The realization of new applications based on optical switching into metastable phases is already being explored. For instance, the photoinduced charge configuration change of $1T$-TaS$_2$ emerges as a new avenue for memory devices in low-temperature circuitry (Mraz *et al.*, 2021). Similarly, advances in optical switching of superconductors (Budden *et al.*, 2021) could be integrated in future microelectronics. In order to expand the range of applications, mandates identifying further materials whose nonthermal energy landscape allows for efficient switching mechanisms into metastable states.

Creation and control of properties through light-matter coupling via Floquet engineering is another promising approach. In order to realize robust functionality and devices, it is necessary to understand the role of dissipation and identify strategies to mitigate heating and decoherence. As such, a firm understanding of the coupling to environmental degrees of freedom is necessary. Moreover, suitable candidate materials need to be identified which host appropriate electronic structures and interactions to minimize energy absorption at selected frequencies while still permitting a controlled modification of the salient electronic features.

In order to reach the final goal of *new functionalities* based on quantum dynamics far from equilibrium, it will be of increasing importance to (i) design materials tailored towards enabling precise nonequilibrium control by integrating materials synthesis and nonequilibrium experimentation synergistically, and to (ii) establish further bridges between the existing ultrafast material science community and adjacent research fields. For example, the young field of polaritonic chemistry is bridging nonequilibrium quantum chemistry, quantum optics, and nanoplasmonics (Ebbesen, 2016; Feist *et al.*, 2018; Flick *et al.*, 2018; Ruggenthaler *et al.*, 2018). Inspired in part by these efforts, *cavity material science* is an emergent topic at the boundary between quantum optics and nonequilibrium material science (Hübener *et al.*, 2020; Juraschek *et al.*, 2019). The key idea is the re-
placement of a strong laser by a few-photon state in a strongly light-matter-coupled cavity that enables control of the material properties. One possible route towards cavity control could employ the quantum nature of photons for effective Floquet engineering without the need for intense laser fields (Sentef et al., 2020).

Controlled synthesis of van der Waals heterostructures has recently emerged as a versatile tool to establish electronic and structural properties with unprecedented control and variety. In this context, twistronics—Moiré potential engineering by twisting adjacent layers—is set to play a crucial role. The twist angle provides a critical handle on designing electronic and structural properties which can be geared with great flexibility (Kennes et al., 2021). Crucially, the relevant kinetic energy scales of the Moiré superlattice can be orders of magnitude smaller than in the bulk material, suggesting that external nonequilibrium perturbations can have an outsized effect in determining electronic phases. Combining ultrafast light-matter interaction with twist control of such band structures hence suggests a particularly promising route towards nonequilibrium functionalization, with first explorations already under way (Kennes et al., 2021; Rodriguez-Vega et al., 2020; Topp et al., 2019). These efforts should of course be complemented by more traditional avenues of materials science, such as material synthesis tailored specifically to questions relevant to nonequilibrium control. For example a systematic exploration of engineerable free energy landscapes, particularly suitable for control via photoexcitation, in complex oxides is highly desirable.

These approaches expose the need for new paradigms of materials synthesis and predictions that address the requirements for ultrafast control of nonthermal states of matter. Theory needs to turn from toy models to realistic materials, to guide not only the process of directed materials synthesis, but also to provide principles for how nonthermal pathways of ultrafast control can be obtained. To achieve this leap, inspiration can be drawn from other fields, where such an integrated approach has already been established. Namely, an increased feedback between experimental characterization, theoretical understanding, and materials synthesis is a strategy that is successful employed in many branches of quantum materials research, for instance in the field of oxides (Coll et al., 2019), or in the study of quantum materials with angle-resolved photoemission spectroscopy (Sobota et al., 2021). This interdisciplinary approach requires additional effort, as a common language and concepts need to be developed for thinking about the underlying physics. Parts of such a program have been laid out in this Colloquium. This is but one step along the long path of unifying themes and languages with the goal of fostering the relatively young field of ultrafast quantum materials science.

ACKNOWLEDGMENTS

We are grateful to H. Aoki, R. Averitt, M. Bonitz, A. Cavalleri, M. Dean, P. Hofmann, D. Juraschek, P. Kirchmann, A. Kogar, W.-S. Lee, D. Mazzone, M. Mitrano, P. Narang, D. Nicoletti, B. Normand, H. Petek, J. Ravnik, G. Refael, R. Tuovinen and A. Zong for stimulating discussions and critical feedback. DMK, JWM and MAS acknowledge support from the Max Planck-New York City Center for Non-Equilibrium Quantum Phenomena. DMK acknowledges the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) for support through RTG 1995 and under Germany’s Excellence Strategy - Cluster of Excellence Matter and Light for Quantum Computing (ML4Q) EXC 2004/1 - 390534769. MC acknowledges support from a startup grant from the University of Pennsylvania, and from the Flatiron Institute, a division of the Simons Foundation. JWM acknowledges support from the Cluster of Excellence ‘CUI: Advanced Imaging of Matter’ of the Deutsche Forschungsgemeinschaft (DFG), EXC 2056, project ID 390715994 and is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB-925 – project 170620586. MAS acknowledges financial support through the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via the Emmy Noether program (SE 2558/2).

All authors contributed equally to this work.

Appendix A: Technical advances shaping ultrafast quantum materials science

1. Experimental tools

Time-resolved optical spectroscopy remains the most commonly used approach to access the time-dependent optical properties of quantum materials after photoexcitation. In recent years, the field has seen an evolution from the early measurements of transient absorption and reflectivity (Chemla and Shah, 2000; Elsayed-Ali et al., 1987; Koshihara et al., 1990; Miyano et al., 1997; Schoenlein et al., 1987; Tsen, 2001) into a multifaceted set of techniques, where the particular details of experiments depend on the targeted subsystem and dynamics (Averitt and Taylor, 2002; Orenstein, 2012). Some of the most advantageous capabilities of these approaches are: (i) direct detection of transient changes in the electronic joint density of states via frequency-resolved measurements of the transient complex optical conductivity from the THz to the extreme ultraviolet range (Baldini et al., 2020; Jager et al., 2017; Sie et al., 2015; Siegrist et al., 2019), (ii) simultaneous measurements of the dynamics of different subsystems by combining multiple detection schemes (von Hoegen et al., 2018), including transient non-linear optical processes (Malmood et al.,...
Ultrafast electron diffraction (UED) is a complementary scattering technique that also directly measures ultrafast structural dynamics in solids (Baum and Zewail, 2007; Siwick et al., 2003; Zewail, 2006). The larger scattering cross section of electrons, compared to X-ray photons, makes UED particularly suited to studying thin samples. New MeV electron sources (Weathersby et al., 2015), THz streaking (Kealhofer et al., 2016; Zhao et al., 2018) and pulse compression schemes (Kim et al., 2020; Qi et al., 2020) can now achieve < 100 fs time resolution. Recent experiments have taken advantage of these capabilities, e.g., to investigate lattice dynamics (Konstantinova et al., 2018; Mannebach et al., 2015; Waldecker et al., 2017) and electronic orders (Haupt et al., 2016; Le Guyader et al., 2017; Sie et al., 2019; Vogelgesang et al., 2018; Zong et al., 2018), as well as to study electron-phonon couplings (René de Cotret et al., 2019; Harb et al., 2016; Horstmann et al., 2020; Stern et al., 2018; Waldecker et al., 2016).

Time- and angle-resolved photoemission spectroscopy (tr-ARPES) measures changes in the band structure and single-particle spectral function of solids with momentum resolution (Bovensiepen and Kirchmann, 2012; Gedik and Vishik, 2017; Haight et al., 1988; Lv et al., 2019; Nicholson et al., 2018; Petek and Ogawa, 1997; Smallwood et al., 2016; Wegkamp et al., 2014; Zhou et al., 2018). This technique has been used, for example, to study decoherence effects in the excitation process (Höfer et al., 1997; Ogawa et al., 1997; Reutzel et al., 2019), to shed light on the physics of high-temperature superconductors (Avigo et al., 2013; Parham et al., 2017; Smallwood et al., 2012; Yang et al., 2014, 2019), to track the melting and recovery of charge-density wave orders (Hellmann et al., 2010, 2012; Ligges et al., 2018; Perfetti et al., 2006; Retting et al., 2016; Rohwer et al., 2011; Schmitt et al., 2008; Zong et al., 2019b), to directly probe excitonic states (Cui et al., 2014; Madéo et al., 2020), to measure the relaxation dynamics of photocurrents (Güde and Höfer, 2021; Reimann et al., 2018) and the coupling between electronic and lattice degrees of freedom (Gerber et al., 2017; Kemper et al., 2017; Na et al., 2019).

tr-ARPES also permits the detection of transiently populated topological states (Belopolski et al., 2017; Sobota et al., 2012, 2013; Zhang et al., 2017), observation of
Floquet-Bloch states (Mahmood et al., 2016; Wang et al., 2013), and identification of nonthermal electronic regimes (Gierz et al., 2013; Johannsen et al., 2013; Na et al., 2020). An exciting prospect is the implementation of new detection schemes extending time- and momentum-resolved microscopy to FELs (Kutnyakhov et al., 2020).

Time-resolved scanning probes. Time-resolved scanning near-field optical microscopy (tr-SNOM) tracks photoinduced changes in the optical constants of materials on the 10 nm length scale with high temporal and spectral resolution (Eisele et al., 2014; Wagner et al., 2014). tr-SNOM has been used, for example, to investigate photoinduced insulator-to-metal transitions (Dönges et al., 2016; Huber et al., 2016) and image the propagation of plasmon-polaritons in a variety of systems (Huber et al., 2017; Ni et al., 2016; Wagner et al., 2014). Ultrafast scanning tunneling microscopy (STM) is also gaining traction and probes quantum tunneling at the atomic length scale with sub-femtosecond time resolution (Cocker et al., 2013; Garg and Kern, 2020; Nunes and Freeman, 1993). Ultrafast STM has been used to track carrier and spin dynamics in photoexcited semiconductors (Terada et al., 2010; Yoshida et al., 2014), the ultrafast vibrational motion of a single molecule (Cocker et al., 2016), and image surface plasmons in gold (Garg and Kern, 2020).

Time-resolved transport. Microstructured devices incorporating laser-triggered photoconductive switches (Auston, 1975) have been used to investigate a variety of ultrafast transport phenomena, such as ballistic electron flow in carbon nanotubes (Zhong et al., 2008), helicity-dependent photocurrents in topological insulators (Kastl et al., 2015), and the transport properties of Floquet-Bloch states in graphene (Kastl et al., 2015). Ultrafast transport dynamics have also been probed in carbon nanotubes (Gabor et al., 2012), graphene (Sun et al., 2012), and various van der Waals heterostructures (Arp et al., 2019; Ma et al., 2016; Massicotte et al., 2016) by measuring the photocurrent generated in response to two time-delayed laser pulses.

2. Theoretical tools

Time-dependent density functional theory (TDDFT) is an extension of ground-state density functional theory, with similar merits and challenges (Marques et al., 2012; Ullrich, 2012). The full time-dependent Schrödinger equation for the many-particle wavefunction is replaced by an auxiliary set of Schrödinger (Kohn-Sham) equations, which determine the exact time-dependent density of the system (Runge and Gross, 1984). Coulomb interactions are accounted for via exchange-correlation potentials, though their exact forms are unknown in practice. TDDFT has been successfully applied to a host of systems in weak and strong external driving fields, ranging from atoms and molecules to periodic solids (De Gio- vannini et al., 2013; Lian et al., 2020). The strength of TDDFT lies in the ability to describe full-fledged material-specific details. However, the faithful description of nontrivial correlation effects still poses a severe challenge for TDDFT-based methods, in particular in pump-probe settings.

Nonequilibrium Green's functions and diagrammatic techniques provide a framework for obtaining few-body correlation functions of time-dependent problems without computing the actual many-body wave functions (Stefanucci and van Leeuwen, 2013). Green's function techniques are based on single-particle propagators that describe the probability amplitude for particles (electrons, phonons, etc.) to travel between two space-time points while interacting with the rest of the system. These many-body interactions are described through the many-body self-energy. Notable approximations to calculate the self-energy include the so-called GW approximation for screened interactions (Aryasetiawan and Gunnarsson, 1998; Thygesen and Rubio, 2007), nonequilibrium dynamical mean-field theory (DMFT) for strongly correlated systems, including Mott insulators with mainly local self-energies (Aoki et al., 2014; Freericks et al., 2006; Tsuji et al., 2008), and the real-time functional renormalization group (FRG) approach (Kennes et al., 2012). In a nonequilibrium setup these approximation schemes are more difficult to handle than in equilibrium because time-translational invariance cannot be exploited and, in general, two time variables instead of one energy variable must be kept. Nonequilibrium Green’s functions are an ideal starting point when approximations for the self-energy can be physically motivated, e.g., perturbative weak- or strong-coupling expansions, or the local-self-energy approximation of DMFT.

Green’s function-based real-time diagrammatic quantum Monte Carlo techniques provide alternative and a priori controlled solutions via stochastic sampling of a perturbation series. While these approaches suffer from a notorious ‘dynamical sign problem’ (Werner et al., 2009), whereby the non-positivity of sampling weights results in a computational effort that increases exponentially in time, recent algorithmic advances with modest computational scaling including the ‘inchworm’ algorithm (Cohen et al., 2015) and conformal transformations (Bertrand et al., 2019) have been put forward. Real-time diagrammatic quantum Monte Carlo is the method of choice whenever the sign problem can be averted.

Tensor networks provide a faithful representation of many-body states and operators as a ‘contraction’ network of tensors that encode the local properties of the system (Schollwöck, 2011; Verstraete et al., 2008). In one dimension matrix product states are one particularly prominent example of a tensor network and provide the basis for elegant density matrix renormalization group implementations (Schollwöck, 2011). In general, the representation of generic quantum states requires contract-
ing tensor dimensions that scale with the exponential size of the full many-body Hilbert space. However, in many physically relevant situations the notion of locality introduced by the tensor network allows one to represent states with low entanglement via tensors of much reduced dimensionality. In this sense, tensor networks might be viewed as a low-entanglement method. The entanglement of ground states generally scales favorably in low-dimensional systems due to the area law (Eisert et al., 2010; Orúš, 2014). Conversely, dynamics far from equilibrium typically involve highly excited states with volume law scaling of the entanglement entropy. Therefore, in nonequilibrium studies only short timescales can be simulated. Numerous methods for time-evolution have been proposed and benchmarked, including the block decimation, matrix product operator techniques, Krylov methods, or the time-dependent variational principle (Paeckel et al., 2019). In a nutshell, tensor networks are useful whenever entanglement entropy can be kept at bay.

Other variational techniques. Beyond asymptotically exact representations of the many-body wavefunction, simpler variational starting points serve as theoretical tools to gain insight into specific physical systems, often based on some intuition of the relevant physics. Examples include the time-dependent Gutzwiller approximation (Schiró and Fabrizio, 2010; Seibold and Lorenzana, 2001), variational Monte Carlo (Carleo et al., 2011), Gaussian and non-Gaussian variational states (Hackl et al., 2020; Shi et al., 2018), or Gross-Pitaevskii equations (Gross, 1961; Pitaevskii, 1961). More recently, machine learning-inspired restricted Boltzmann machines have emerged, which provide a more flexible variational subspace for time evolution (Carleo and Troyer, 2016). To summarize, common to all these techniques are Ansätze for the many-body wavefunction with an economical number of free parameters, which are governed by equations of motion as determined via the time-dependent variational principle. Though, the general usefulness of these techniques for simulations related to pump-probe experiments is not quite clear yet, they can provide a good starting point whenever a suitable variational manifold can be identified.

REFERENCES

Abanin, D. A., W. De Roeck, W. W. Ho, and F. Hivueneers (2017a), “A rigorous theory of many-body prethermalization for periodically driven and closed quantum systems,” Comm. Math. Phys. 354, 809.

Abanin, D. A. W., D. Roeck, Wen W. Ho, and F. Hivueneerts (2017b), “Effective Hamiltonians, prethermalization, and slow energy absorption in periodically driven many-body systems,” Phys. Rev. B 95, 014112.

Abanin, D. A. W., D. Roeck, and F. Hivueneerts (2015), “Exponentially slow heating in periodically driven many-body systems,” Phys. Rev. Lett. 115, 256803.

Aeschlimann, S. S. A. Sato, R. Krause, M. Chávez-Cervantes, U. De Giovannini, H. Hubener, S. Forti, C. Coletti, K. Hanff, K. Rossnagel, A. Rubio, and I. Gierz (2021), “Survival of Floquet-Bloch states in the presence of scattering,” Nano Lett. 21, 5028.

Afanasiev, D. J. R. Hortensius, B. A. Ivanov, A. Sasani, E. Bousquet, Y. M. Blanter, R. V. Mikhailovskiy, A. V. Kimel, and A. D. Caviglia (2021), “Ultrafast control of magnetic interactions via light-driven phonons,” Nat. Mater. 20, 607.

Alexandradinata, A., N. P. Armitage, A. Baydin, W. Bi, Y. Cao, H. J. Changlani, E. Chertkov, E. H. da Silva Neto, L. Delacretaz, I. El Baghari, G. M. Ferguson, W. J. Gannon, S. A. A. Ghorashi, B. H. Goodge, O. Goulo, G. Grissonnanche, A. Hallas, I. M. Hayes, Y. He, E. W. Huang, A. Kogar, D. Kumah, Y. J. Lee, A. Legros, F. Mahmood, Y. Maximenko, N. Pellatz, H. Polshyn, T. Sarkar, A. Schei, K. L. Seyler, Z. Shi, B. Skinner, L. Steinke, K. Thirunavukkarasu, T. V. Trevisan, M. Vogl, P. A. Volkov, Yao Wang, Yishu Wang, D. Wei, K. Wei, S. Yang, X. Zhang, Y.-H. Zhang, L. Zhao, and A. Zong (2020), “The future of the correlated electron problem,” arXiv:2010.00584.

Allen, P. B. (1987), “Theory of thermal relaxation of electrons in metals,” Phys. Rev. Lett. 59, 1460.

Anisimov, S. I., B. L. Kapeliovich, and T. L. Perelman (1974), “Electron emission from metal surfaces exposed to ultrashort laser pulses,” Sov. Phys. JETP 39, 375.

Aoki, H., N. Tsubui, M. Eckstein, M. Kollmar, T. Oka, and P. Werner (2014), “Nonequilibrium dynamical mean-field theory and its applications,” Rev. Mod. Phys. 86, 779.

Arakawa, N., and K. Youemitsu (2021), “Floquet engineering of mott insulators with strong spin-orbit coupling,” Phys. Rev. B 103, L100408.

Arlt, T. B., D. Pleskov, V. Aji, and N. M. Gabor (2019), “Electron-hole liquid in a van der Waals heterostructure photocell at room temperature,” Nat. Photon. 13, 245.

Aryasetiawan, F., and O. Gunnarsson (1998), “The GW method,” Rep. Prog. Phys. 61, 237.

Asamitsu, A., Y. Tomioka, H. Kuwahara, and Y. Tokura (1997), “Current switching of resistive states in magnetoresistive manganites,” Nature 388, 50.

Auston, D. H. (1975), “Picosecond optoelectronic switching and gating in silicon,” Appl. Phys. Lett. 26, 101.

Ault, S. H., and C. H. Townes (1955), “Stark effect in rapidly varying fields,” Phys. Rev. 100, 703.

Averitt, R. D., and A. J. Taylor (2002), “Ultrafast optical and far-infrared quasiparticle dynamics in correlated electron materials,” J. Phys. Cond. Mat. 14, R1357.

Avigo, I., R. Cortés, L. Retig, S. Thirupathaiah, H. S. Jeevan, P. Gegenwart, T. Wolf, M. Liggges, M. Wolf, J. Fink, and U. Bovensiepen (2013), “Coherent excitations and electron-phonon coupling in Ba/Fe2As2 compounds investigated by femtosecond time- and angle-resolved photoemission spectroscopy,” J. Condens. Matter Phys. 25, 094003.

Babadi, M., M. Knap, I. Martin, G. Refael, and E. Demler (2017), “Theory of parametrically amplified electron-phonon superconductivity,” Phys. Rev. B 96, 014512.

Baldini, E., M. A. Sentef, S. Acharya, T. Brunme, E. Sheveleva, F. Lyzwa, E. Pomjakushina, C. Bernhard, M. van Schilfgaarde, F. Carbone, A. Rubio, and C. Weber (2020), “Electron–phonon-driven three-dimensional metallicity in an insulating cuprate,” Proc. Natl. Acad. Sci. USA 117, 6409.

Baizer, K., F. A. Wolf, I. P. McCulloch, P. Werner, and
M. Eckstein (2015), “Nonthermal melting of Néel order in the Hubbard model,” Phys. Rev. X 5, 031039.

Bartels, R A, A. Paul, H. Green, H. C. Kapteyn, M. M. Murnane, S. Backus, I. P. Christov, Y. Liu, D. Attwood, and C. Jacobsen (2002), “Generation of spatially coherent light at extreme ultraviolet wavelengths,” Science 297, 376.

Basov, D N, R. D. Averitt, and D. Hsieh (2017), “Towards properties on demand in quantum materials,” Nat. Mater. 16, 1077.

Basov, D N, R. D. Averitt, D. van der Marel, M. Dressel, and K. Haule (2015), “Hot energy in a Heisenberg antiferromagnet,” Nat. Photon. 9, 506.

Bauer, M, A. Marienfeld, and M. Aeschlimann (2015), “Hot electron lifetimes in metals probed by time-resolved two-photon photoemission,” Prog. Surf. Sci. 90, 319.

Baum, P, D.-S. Yang, and A. H. Zewail (2007), “4D visualization of transitional structures in phase transformations by electron diffraction,” Science 318, 788.

Baum, P., and A. H. Zewail (2007), “Attosecond electron pulses for 4D diffraction and microscopy,” Proc. Natl. Acad. Sci. USA 104, 18409.

Beaud, P, A. Caviezel, S. O. Mariager, L. Rettig, G. Ingeborg, C. Dornes, S-W. Huang, J. A. Johnson, M. Radovic, T. Huber, T. Kubačka, A. Ferrer, H. T. Lemke, M. Chollet, D. Zhu, J. M. Glownia, M. Sikorski, A. Robert, H. Wadati, M. Nakamura, M. Kawasaki, Y. Tokura, S. L. Johnson, and U. Staub (2014), “A time-dependent order parameter for ultrafast photoinduced phase transitions,” Nat. Mater. 13, 923.

Beaurepaire, E., J.-C. Merle, A. Daunois, and J.-Y. Bigot (1996), “Ultrafast spin dynamics in ferromagnetic nickel,” Phys. Rev. Lett. 76, 4250.

Becker, M F, A. B. Buckman, R. M. Walser, T. Lépine, P. Georges, and A. Bruun (1994), “Femtosecond laser excitation of the semiconductor-metal phase transition in VO2,” Appl. Phys. Lett. 65, 1507.

Belopolski, I, P. Yu, D. S. Sanchez, Y. Ishida, T.-R. Chang, S. S. Zhang, S.-Y. Xu, H. Zheng, G. Chang, G. Bian, H.-T. Jeng, T. Kondo, H. Lin, Z. Liu, S. Shin, and M. Z. Hasan (2017), “Signatures of a time-reversal symmetric Weyl semimetal with only four Weyl points,” Nat. Commun. 8, 942.

Bertrand, C. S. Flores, O. Parcollet, and X. Waintal (2019), “Reconstructing nonequilibrium regimes of quantum many-body systems from the analytical structure of perturbative expansions,” Phys. Rev. X 9, 041008.

Bonitz, M (2016), Quantum Kinetic Theory (Springer International Publishing).

Bovensiepen, U, and P. S. Kirchmann (2012), “Elementary relaxation processes investigated by femtosecond photoelectron spectroscopy of two-dimensional materials,” Laser Photonics Rev. 6, 589.

Bray, A J (1994), “Theory of phase-ordering kinetics,” Adv. in Phys. 43, 357.

Brorson, S D, A. Kazeroonian, J. S. Moodera, D. W. Face, T. K. Cheng, E. P. Ippen, M. S. Dresselhaus, and G. Dresselhaus (1990), “Femtosecond room-temperature measurement of the electron-phonon coupling constant γ in metallic superconductors,” Phys. Rev. Lett. 64, 2172.

Bucksbaum, P H, A. Zavriyev, H. G. Muller, and D. W. Schmacher (1990), “Softening of the H2 molecule bond in intense laser fields,” Phys. Rev. Lett. 64, 1883.

Budden, M. T. Gebert, M. Buzzi, G. Jotzu, E. Wang, T. Matsuyama, G. Meier, Y. Laplace, D. Pontiroli, M. Riccò, F. Schlawin, D. Jaksch, and A. Cavalleri (2021), “Evidence for metastable photo-induced superconductivity in K4GeO6,” Nat. Phys. 17, 611.

Bukov, M, L. D’ Alessio, and A. Polkovnikov (2015), “Universal high-frequency behavior of periodically driven systems: from dynamical stabilization to Floquet engineering,” Adv. Phys. 64, 139.

Bukov, M, M. Kolodrubetz, and A. Polkovnikov (2016), “Schrieffer-Wolff transformation for periodically driven systems: Strongly correlated systems with artificial gauge fields,” Phys. Rev. Lett. 116, 125301.

Buzzi, M. F. Först, R. Mankowsky, and A. Cavalleri (2018), “Probing dynamics in quantum materials with femtosecond X-rays,” Nat. Rev. Mater. 3, 299.

Buzzi, M, D. Nicoletti, M. Fechner, N. Tancogne-Dejean, M. A. Sentef, A. Georges, T. Biesner, E. Uykur, M. Dressel, A. Henderson, T. Siegrist, J. A. Schlueter, K. Miyawaga, K. Kanoda, M.-S. Nam, A. Ardavan, J. Coulthard, J. Tindall, F. Schlawin, D. Jaksch, and A. Cavalleri (2020), “Photomolecular high-temperature superconductivity,” Phys. Rev. X 10, 031028.

Cantaluppi, A, M. Buzzi, G. Jotzu, D. Nicoletti, M. Mitrano, D. Pontiroli, M. Riccò, A. Perucchi, P. Di Pietro, and A. Cavalleri (2018), “Pressure tuning of light-induced superconductivity in K4GeO6,” Nat. Phys. 14, 837.

Cao, Y. D. G. Mazzzone, D. Meyers, J. P. Hill, X. Liu, S. Wall, and M. P. M. Dean (2019), “Ultrafast dynamics of spin and orbital correlations in quantum materials: An energy- and momentum-resolved perspective,” Philos. Trans. R. Soc. A 377, 20170480.

Carleo, G, F. Becca, M. Schirò, and M. Fabrizio (2011), “Localization and glassy dynamics of many-body quantum systems,” Sci. Rep. 2, 243.

Carleo, G, and M. Troyer (2016), “Solving the quantum many-body problem with artificial neural networks,” Science 355, 602.

Cavalleri, A, Th. Dekorsy, H. H. W. Chong, J. C. Kieffer, and R. W. Schoenlein (2004), “Evidence for a structurally-driven insulator-to-metal transition in VO2: A view from the ultrafast timescale,” Phys. Rev. B 70, 161102.

Cavalleri, A. M., Rini, H. H. W., Chong, T. E., Glover, P. A., Heimann, J. C., Kieffer, and R. W. Schoenlein (2005), “Band-selective measurements of electron dynamics in VO2 using femtosecond near-edge X-ray absorption,” Phys. Rev. Lett. 95, 067405.

Cavalleri, A, C. Tóth, C. W. Siders, J. A. Squier, F. Ráksi, P. Forget, and J. C. Kieffer (2001), “Femtosecond structural dynamics in VO2 during an ultrafast solid-solid phase transition,” Phys. Rev. Lett. 87, 237401.

Cavalleri, A. S. Wall, C. Simpson, E. Statz, D. W. Ward, K. A. Nelson, M. Rini, and R. W. Schoenlein (2006), “Tracking the motion of charges in a terahertz light field by femtosecond X-ray diffraction,” Nature 442, 664.

Cerullo, G, and S. De Silvestri (2003), “Ultrafast optical parametric amplifiers,” Rev. Sci. Instrum. 74, 1.
Claassen, M., C. Jia, B. Moritz, and T. P. Devereaux (2021), “Flow renormalization and emergent phenomena in superconductors,” Phys. Rev. B 95, 104507.

Chu, H., M.-J. Kim, K. Katsumi, S. Kovalev, R. D. Dawson, L. Schwarz, N. Yoshikawa, G. Kim, D. Putzky, Z. Z. Li, H. Raffy, S. Ger manskiy, J.-C. Deinert, N. Awari, I. Ilyakov, B. Green, M. Chen, M. Bawatna, G. Cristiani, G. Logvenov, Y. Gallais, A. V. Boris, B. Keimer, A. P. Schnyder, D. Manske, G. Gensch, Z. Wang, R. Shimano, and S. Kaiser (2020), “Phase-resolved Higgs response in superconducting cuprates,” Nat. Commun. 11, 1793.

Chuang, Y. D., W.-S. Lee, Y. F. Kung, A. P. Sorini, B. Moritz, R. G. Moore, L. Patthey, M. Frigo, D. H. Lu, P. S. Kirchner, J.-H. Pöhl, M. J. Stern, M. R. Otto, M. Sutton, and B. J. Siwick (2019), “Time- and momentum-resolved phonon population dynamics with ultrafast electron diffuse scattering,” Phys. Rev. B 100, 214115.

Coulthard, J. R., S. R. Clark, S. Al-Assam, A. Cavalleri, and D. Jakusch (2017), “Enhancement of superexchange pairing in the periodically driven Hubbard model,” Phys. Rev. B 96, 085104.

Cremers, N., J. Zhang, C. C. Home, G. D. Gu, Z. Sun, M. M. Fogler, A. J. Millis, D. N. Basov, and R. D. Averitt (2013), “Photoenhanced metastable c-axis electrode kinematics in stripe-ordered cuprate La$_{1.85}$Ba$_{0.15}$CuO$_4$,” Proc. Natl. Acad. Sci. USA 116, 19875.

Cui, X., C. Wang, A. Argondizzo, S. Garrett-Roe, B. Giumalov, and H. Petek (2014), “Transient excitons at metal surfaces,” Nat. Phys. 10, 505.

D’Alessio, L., and A. Polkovnikov (2013), “Many-body energy localization transition in periodically driven systems,” Ann. Phys. 333, 19.

D’Alessio, L., and M. Rigol (2014), “Long-time behavior of isolated periodically driven interacting lattice systems,” Phys. Rev. X 4, 041048.

Danz, T., T. Domröse, and C. Ropers (2021), “Ultrafast nanoimaging of the order parameter in a structural phase transition,” Science 371, 371.

Dasari, N., and M. Eckstein (2018), “Transient Floquet engineering of superconductivity,” Phys. Rev. B 98, 235149.

Dasari, N., and M. Eckstein (2019), “Ultrafast electric field controlled spin correlations in the hubbard model,” Phys. Rev. B 100, 121114.

De Giovannini, U., G. Brunetto, A. Castro, J. Walkenhorst, and A. Rubio (2013), “Simulating pump-probe photoelectron and absorption spectroscopy on the attosecond timescale with time-dependent density functional theory,” ChemPhysChem 14, 1363.

Dean, M. P. M., Y. Cao, X. Liu, S. Wall, D. Zhu, R. Mankowsky, V. Thampy, X. M. Chen, J. G. Vale, D. Casa, Jungho Kim, A. H. Said, P. Juhas, R. Alonso-Mori, M. J. Glownia, A. Robert, J. Robinson, M. Sikorski, S. Song, M. Kozhina, H. Lemke, L. Patthey, S. Owada, T. Katayama, M. Yabashi, Yoshikazu Tanaka, T. Togashi, J. Liu, C. Rayan Serrao, B. J. Kim, L. Huber, C. L. Chang, D. F. McMorrow, M. Forst, and J. P. Hill (2016), “Ultrafast energy- and momentum-resolved dynamics of magnetic correlations in the photo-doped Mott insulator Sr$_2$IrO$_4$,” Nat. Mater. 15, 601.

Decker, K. S. C., Karrasch, J. Eisert, and D. M. Kennes (2020), “Floquet engineering topological many-body localized systems,” Phys. Rev. Lett. 124, 190601.

Dehghani, H. M., Hafezi, and P. Ghaemi (2021), “Light-induced topological superconductivity via Floquet interaction engineering,” Phys. Rev. Res. 3, 023039.

Dehghani, H., and A. Mitra (2017), “Dynamical generation of
ulation of electrons in tunneling microscopy," Science **367**, 411.

Gedik, N, J. Orenstein, R. Liang, D. A. Bonn, and W. N. Hardy (2003), “Diffusion of nonequilibrium quasi-particles in a cuprate superconductor," Science **300**, 1410.

Gedik, N, and I. Vishik (2017), “Photoemission of quantum materials," Nat. Phys. **13**, 1029.

Gerasimenko, Y A, I. Vaskivskyi, M. Litskevich, J. Ravnik, J. Vodeb, M. Diego, V. Kabanov, and D. Mihailovic (2019), “Quantum jamming transition to a correlated electron glass in 1T-TaS$_2$," Nat. Mater. **18**, 1078.

Gerber, S, K. W. Kim, Y. Zhang, D. Zhu, N. Plonka, M. Yi, G. L. Dakovski, D. Leuenberger, P. S. Kirchmann, R. G. Moore, M. Chollet, J. M. Glownia, Y. Feng, J.-S. Lee, A. Mehta, A. F. Kemper, T. Wolf, Y.-D. Chuang, Z. Hussain, C.-C. Kao, B. Moritz, Z.-X. Shen, T. P. Devereaux, and W.-S. Lee (2015), “Direct characterization of photoinduced lattice dynamics in BaFe$_2$As$_2$," Nat. Commun. **6**, 7377.

Gerber, S, S.-L. Yang, D. Zhu, H. Soifer, J. A. Sobotka, S. Rebec, J. J. Lee, T. Jia, B. Moritz, C. Jia, A. Gauthier, Y. Li, D. Leuenberger, Y. Zhang, L. Chaix, W. Li, H. Jang, J.-S. Lee, M. Yi, G. L. Dakovski, S. Song, J. M. Glownia, S. Nelson, K. W. Kim, Y.-D. Chuang, Z. Hussain, R. G. Moore, T. P. Devereaux, W.-S. Lee, P. S. Kirchmann, and Z.-X. Shen (2017), “Femtosecond electron-phonon lock-in by photoemission and X-ray free-electron laser," Science **357**, 71.

Ghazaryan, A, T. Graß, M. J. Guillans, P. Ghaemi, and M. Hafezi (2017), “Light-induced fractional quantum Hall phases in graphene," Phys. Rev. Lett. **119**, 247403.

Ghimire, S, A. D. Dichiara, E. Sistrunk, P. Agostini, L. F. Dimaruo, and D. A. Reis (2011), “Observation of high-order harmonic generation in a bulk crystal," Nat. Phys. **7**, 138.

Ghimire, S, and D. A. Reis (2018), “High-harmonic generation from solids," Nat. Phys. **15**, 10.

Giannetti, C, M. Capone, D. Fausti, M. Fabrizio, F. Parmigiani, and D. Mihailovic (2016), “Ultrafast optical spectroscopy of strongly correlated materials and high-temperature superconductors: A non-equilibrium approach," Adv. Phys. **65**, 58.

Gierz, I, J. C. Petersen, M. Mitrano, C. Cacho, I. C. E. Turcu, E. Springate, A. Stöhr, A. Köhler, U. Starke, and A. Cavalleri (2013), “Snapshots of non-equilibrium Dirac carrier distributions in graphene," Nat. Mater. **12**, 1119.

Gillmeister, K Golež, D. C.-T. Chiang, N. Bittner, G. L. Dakovski, D. Leuenberger, P. S. Kirchmann, R. G. Moore, M. Chollet, J. M. Glownia, Y. Feng, J.-S. Lee, A. Mehta, A. F. Kemper, T. Wolf, Y.-D. Chuang, Z. Hussain, C.-C. Kao, B. Moritz, Z.-X. Shen, T. P. Devereaux, and W.-S. Lee (2015), “Direct characterization of photoinduced lattice dynamics in BaFe$_2$As$_2$," Nat. Commun. **6**, 7377.

Giorgianni, F, T. Cea, C. Vicario, C. P. Hauri, W. K. Withanage, X. Xi, and L. Benfatto (2019), “Leggett mode controlled by light pulses," Nat. Phys. **15**, 341.

Giorgianni, F, B. Wehinger, S. Allenspach, N. Colonna, C. Vicario, P. Puphal, E. Pomjakushina, B. Normand, and C. Rüegg (2022), “Nonlinear quantum magnetophononics in SrCu$_2$(BO$_3$)$_2$,” arXiv:2101.01189.

Giustino, F, M. Bibes, J. H. Lee, F. Trier, R. Valenti, S. M. Winter, Y.-W. Son, L. Taillefer, C. Hei, A. I. Figueroa, B. Plaçais, Q. S. Wu, O. V. Yazeyev, E. P. A. M. Bakkers, J. Nygård, P. Forn-Díaz, S. de Franceschi, L. E. F. Foa Torres, J. Mélver, A. Kumar, T. Low, R. Galceran, S. O. Valenzuela, M. V. Costache, A. Manchon, E.-A. Kim, G. R. Schleder, A. Fazzio, and S. Roche (2021), “The 2021 quantum materials roadmap," J. Phys. Mater. **3**, 042006.

Görg, F, M. Messer, K. Sandholzer, G. Jotzu, R. Desbuquois, and T. Esslinger (2018), “Enhancement and sign change of magnetic correlations in a driven quantum many-body system," Nature **553**, 481.

Greiter, M, X.-G. Wen, and F. Wilczek (1991), “Paired Hall state at half filling," Phys. Rev. Lett. **66**, 3205.

Gross, E P (1961), “Structure of a quantized vortex in boson systems," Il Nuovo Cimento **20**, 454.

Gulden, T, E. Berg, M. S. Rudner, and N. H. Lindner (2020), “Exponentially long lifetime of universal quasi-steady states in topological Floquet pumps," SciPost Phys. **9**, 15.

Güde, J, and U. Höfer (2021), “Ultrafast dynamics of photocurrents in surface states of three-dimensional topological insulators," Phys. Status Solidi B **258**, 200521.

Häckl, L, T. Guaita, T. Shi, J. Haegeman, E. Demler, and J. I. Cirac (2020), “Geometry of variational methods: Dynamics of closed quantum systems," SciPost Phys. **9**, 48.

Haught, R, J. A. Silberman, and M. I. Lüllie (1988), “Novel system for picosecond photoemission spectroscopy," Rev. Sci. Instrum. **59**, 1941.

Haldane, F D M (1988), “Model for a quantum Hall effect without Landau levels: Condensed-matter realization of the “parity anomaly”," Phys. Rev. Lett. **61**, 2015.

Haldar, A, R. Moessner, and A. Das (2018), “Onset of Floquet thermalization," Phys. Rev. B **97**, 245122.

Harb, M. H. Enquist, A. Jurgilaitis, F. T. Tuyakov, A. N. Obraztsov, and J. Larsson (2016), “Phonon-phonon interactions in photoexcited graphite studied by ultrafast electron diffraction," Phys. Rev. B **93**, 104104.

Haug, H, and A.-P. Jauho (2008), Quantum Kinetics in Transport and Optics of Semiconductors (Springer Berlin Heidelberg).

Haupt, K, M. Eichberger, N. Erasmus, A. Rohwer, J. Demurs, K. Rossnagel, and H. Schwoerer (2016), “Ultrafast metamorphosis of a complex charge-density wave," Phys. Rev. Lett. **116**, 016402.

Hejazi, K, J. Liu, and L. Balents (2019), “Floquet spin and spin-orbital Hamiltonians and doublon-holon generations in periodically driven insulators," Phys. Rev. B **99**, 205111.

Hellmann, S, M. Beye, C. Sohrt, T. Rohwer, F. Sorgenfrei, H. Redlin, M. Killäne, M. Marczyński-Bühhof, F. Hennies, M. Bauer, A. Föhlsch, L. Kipp, W. Wurth, and K. Rossnagel (2010), “Ultrafast melting of a charge-density wave in the Mott insulator 1T-TaS$_2$," Phys. Rev. Lett. **105**, 187401.

Hellmann, S, T. Rohwer, M. Killäne, K. Haniff, C. Sohrt, A. Stange, A. Carr, M. M. Murnane, H. C. Kapteyn, L. Kipp, M. Bauer, and K. Rossnagel (2012), “Time-domain classification of charge-density-wave insulators," Nat. Commun. **3**, 1009.

Higuchi, T, C. Heide, K. Ullmann, H. B. Weber, and P. Hommelhoff (2017), “Light-field-driven currents in graphene," Nature **540**, 224.

Ho, W W, I. Protopopov, and D. A. Abanin (2018), “Bounds on energy absorption and prethermalization in quantum systems with long-range interactions," Phys. Rev. Lett. **120**, 200601.

von Hoegen, A, R. Mankowsky, M. Fechner, M. Först, and A. Cavalleri (2018), “Probing the interatomic potential of solids with strong-field nonlinear phonics," Nature **555**, 79.

Höfer, U, I. L. Shumay, Ch. Reufl, U. Thomann, W. Wal-
Hohenberg, P C, and B. I. Halperin (1977), “Theory of dynamic critical phenomena,” Rev. Mod. Phys. 49, 435.
Horstmann, J G, H. Böckmann, B. Wit, F. Kurtz, G. Storeck, and C. Ropers (2020), “Coherent control of a surface structural phase transition,” Nature 583, 232.
Hu, W, S. Kaiser, M. Nicoletti, C. R. Hunt, I. Gierz, M. C. Hoffmann, M. Le Tacon, T. Loew, K. Beimer, and A. Cavalleri (2014), “Optically enhanced coherent transport in YBa₂Cu₃O₆.₅ by ultrafast redistribution of interpolar coupling structure,” Nat. Mater. 13, 705.
Hübener, H, U. De Giovannini, C. Schäfer, J. Andberger, M. Ruggenthaler, J. Faist, and A. Rubio (2020), “Engineering quantum materials with chiral optical cavities,” Nat. Mater. 19, 438.
Huber, M A, F. Mooshammer, M. Plankl, L. Viti, F. Sandner, L. Z. Kastner, T. Frank, J. Fabian, M. S. Vitiello, T. L. Cocker, and R. Huber (2017), “Femtosecond photonic switching of interface polaritons in black phosphorus heterostructures,” Nat. Nanotechnol. 12, 207.
Huber, M A, M. Plankl, M. Eisele, R. E. Marvel, F. Sandner, T. Korn, C. Schüller, R. F. Haglund Jr., R. Huber, and T. L. Cocker (2016), “Ultrafast mid-infrared nanoscopy of strained vanadium dioxide nanobeam,” Nano Lett. 16, 1421.
Huber, T. S. O, Mariager, A. Ferrer, H. Schäfer, J. A. Johnson, S. Grübel, A. Lübecke, L. Huber, T. Kubacka, C. Dornes, C. Laulhe, S. Ravy, G. Ingold, P. Beaud, J. Demsar, and S. L. Johnson (2014), “Coherent structural dynamics of a prototypical charge-density-wave-to-metal transition,” Phys. Rev. Lett. 113, 026401.
Iadecola, T. T, Neupert, and C. Chamon (2015), “Occupation of topological Floquet bands in open systems,” Phys. Rev. B 91, 235133.
Ichikawa, H, S. Nozawa, T. Sato, A. Tomita, K. Ichiyanagi, M. Chollet, L. Guerin, N. Dean, A. Cavalleri, S. Adachi, T. Arima, H. Sawa, Y. Ogimoto, M. Nakamura, R. Tamaki, K. Miyano, and S. Koshihara (2011), “Transient photoinduced ‘hidden’ phase in a manganese,” Nat. Mater. 10, 101.
Imada, M, A. Fujimori, and Y. Tokura (1998), “Metal-insulator transitions,” Rev. Mod. Phys. 70, 1039.
Ishioka, K, M. Hase, M. Kitajima, L. Wirtz, A. Rubio, and H. Petek (2008), “Ultrafast electron-phonon decoupling in graphene,” Phys. Rev. B 77, 121402(R).
Itin, A P, and M. I. Katsnelson (2015), “Effective hamiltonians for rapidly driven many-body lattice systems: Induced exchange interactions and density-dependent hopping,” Phys. Rev. Lett. 115, 075301.
Jager, M F, C. Ott, P. M. Kraus, C. J. Kaplan, W. Pouce, R. E. Marvel, R. F. Haglund, D. M. Neumark, and S. R. Leone (2017), “Tracking the insulator-to-metal phase transition in VO₂ with few-femtosecond extreme UV transient absorption spectroscopy,” Proc. Natl. Acad. Sci. USA 114, 9558.
Johannsen, J C S, Ulstrup, F. Cilingo, A. Crepaldi, M. Zacchigna, C. Cacho, I. C. E. Turcu, E. Springate, F. Fromm, C. Raidel, T. Seyller, F. Parmigiani, M. Grioni, and P. Hofmann (2013), “Direct view of hot carrier dynamics in graphene,” Phys. Rev. Lett. 111, 027403.
Johnson, S L, P. Beaud, C. J. Milne, F. S. Krasniqi, E. S. Zijlstra, M. E. Garcia, M. Kaiser, D. Grolimund, R. Abela, and G. Ingold (2008), “Nanoscale depth-resolved coherent femtosecond motion in laser-excited bismuth,” Phys. Rev. Lett. 100, 155501.
Johnson, S L, R. A. de Souza, U. Staub, P. Beaud, E. Möhr-Vorobeva, G. Ingold, A. Caviezel, V. Scagnoli, W. F. Schlotter, J. J. Turner, O. Krupin, W.-S. Lee, Y.-D. Chuang, L. Pattthey, R. G. Moore, D. Lu, M. Yi, P. S. Kirchmann, M. Trigo, P. Denes, D. Doering, Z. Hussain, Z.-X. Shen, D. Prabhakaran, and A. T. Boothroyd (2012), “Femtosecond dynamics of the collinear-to-spiral antiferromagnetic phase transition in CuO,” Phys. Rev. Lett. 108, 037203.
Jotzu, G, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, and T. Esslinger (2014), “Experimental realization of the topological Haldane model with ultracold fermions,” Nature 515, 237.
Juraschek, D M, P. Narang, and N. A. Spaldin (2020), “Phono-magnetic analogs to opto-magnetic effects,” Phys. Rev. Res. 2, 043035.
Juraschek, D M, T. Neuman, J. Flick, and P. Narang (2019), “Cavity control of nonlinear phononics,” arXiv:1912.00122.
Kaindl, R A, M. Woerner, T. Elsaesser, D. C. Smith, J. F. Ryan, G. A. Farman, M. P. McCurry, and D. G. Walmsley (2000), “Ultrafast mid-infrared response of YBa₂Cu₃O₇-δ,” Science 287, 470.
Kaiser, S S, R. R. Clark, D. Nicoletti, G. Cotugno, R. I. Tobey, N. Dean, S. Lupi, H. Okamoto, T. Hasegawa, D. Jaksh, and A. Cavalleri (2014a), “Optical properties of a vibrationally modulated solid state Mott insulator,” Sci. Rep. 4, 3823.
Kaiser, S. C R, Hunt, D. Nicoletti, W. Hu, I. Gierz, H. Y. Liu, M. Le Tacon, T. Loew, D. Haug, B. Keimer, and A. Cavalleri (2014b), “Optically induced coherent transport far above Tc in underdoped YBa₂Cu₃O₆+δ,” Phys. Rev. B 89, 184516.
Kalthoff, M H, D. M. Kennes, A. J. Millis, and M. A. Sentef (2021), “Nonequilibrium phase transition in a driven-dissipative quantum antiferromagnet,” arXiv:2107.03841.
Kamprath, T. A, S. Sell, G. Klatt, A. Pashkin, S. Mährlein, T. Dekorsy, M. Wolf, M. Fiebig, A. Leitenstorfer, and R. Huber (2011), “Coherent terahertz control of antiferromagnetic spin waves,” Nat. Photon. 5, 31.
Kamprath, T. K, Tanaka, and K. A. Nelson (2013), “Resonant and nonresonant control over matter and light by intense terahertz transients,” Nat. Photon. 7, 680.
Kastl, C. C, Karmetzky, H. Karl, and A. W. Holleitner (2015), “Ultrafast helicity control of surface currents in topological insulators with near-unity fidelity,” Nat. Commun. 6, 6617.
Kealhofer, C, W. Schneider, D. Ehberger, A. Ryabov, F. Krausz, and P. Baum (2016), “All-optical control and metrology of electron pulses,” Science 352, 429.
Keimer, B, and J. E. Moore (2017), “The physics of quantum materials,” Nat. Phys. 13, 1045.
Kemper, A F, O. Abdurazakov, and J. K. Freericks (2018), “General principles for the nonequilibrium relaxation of populations in quantum materials,” Phys. Rev. X 8, 041009.
Kemper, A F, M. A. Sentef, B. Moritz, T. P. Devereaux, and J. K. Freericks (2017), “Review of the theoretical description of time-resolved angle-resolved photoemission spectroscopy in electron-phonon mediated superconductors,” Ann. Phys. 529, 1600235.
Kennes, D M, M. Claassen, M. A. Sentef, and C. Karrasch (2019a), “Light-induced d-wave superconductivity through Floquet-engineered Fermi surfaces in cuprates,” Phys. Rev.
Kitagawa, T, T. Oka, A. Brataas, L. Fu, and E. Demler (2012), “Moiré heterostructures as a condensed-matter quantum simulator,” Nat. Phys. 17, 155.

Kennes, D M, S. G. Jakobs, C. Karrasch, and V. Meden (2012), “Renormalization group approach to time-dependent transport through correlated quantum dots,” Phys. Rev. B 85, 085113.

Kennes, D M, N. Müller, M. Pletyukhov, C. Weber, C. Bruder, F. Hasler, J. Klinovaja, D. Loss, and H. Schoeller (2019b), “Chiral one-dimensional Floquet topological insulators beyond the rotating wave approximation,” Phys. Rev. B 100, 041103.

Kennes, D M, A. de la Torre, A. Ron, D. Hsieh, and A. J. Millis (2018), “Floquet engineering in quantum chains,” Phys. Rev. Lett. 120, 127601.

Kennes, D M, E. Y. Wilner, D. R. Reichman, and A. J. Millis (2017), “Transient superconductivity from electronic squeezing of optically pumped phonons,” Nat. Phys. 13, 179.

Kibble, T W B (1976), “Topology of cosmic domains and strings,” J. Phys. A: Math. Gen. 9, 1387.

Kim, I H, N. A. Vinokurov, I. H. Baek, K. Y. Oang, M. H. Kim, Y. C. Kim, K.-H. Jang, K. Lee, S. H. Park, S. Park, J. Shin, J. Kim, F. Rotermund, S. Cho, T. Feurer, and Y. U. Jeong (2020), “Towards jitter-free ultrafast electron diffraction technology,” Nat. Photon. 14, 245.

Kim, J. J., Hong, C. J., Jin, S.-F., Shi, C.-Y., Chang, M.-H., Chiu, L.-J., Li, and F. Wang (2014), “Ultrafast generation of pseudo-magnetic field for valley excitons in WSe2 monolayers,” Science 346, 1205.

Kim, M. Y., Nomura, M., Ferrero, P., Seth, O., Parcollet, and A. Georges (2016), “Enhancing superconductivity in A3C60 fullerides,” Phys. Rev. B 94, 155152.

Kimmel, A V, A. M. Kaldashnikova, A. Pogrebna, and A. K. Zvezdin (2020), “Fundamentals and perspectives of ultrafast photoferroic recording,” Phys. Rep. 852, 1.

Kirilyuk, A. V. Kimel, and T. Rasing (2010), “Ultrafast optical manipulation of magnetic order,” Rev. Mod. Phys. 82, 2731.

Kiriyukhin, V, D. Casa, J. P. Hill, B. Keimer, A. Vigliante, Y. Tomoiaka, and Y. Tokura (1997), “An X-ray-induced insulator-metal transition in a magnetoresistive manganite,” Nature 386, 813.

Kitagawa, T, E. Berg, M. Rudner, and E. Demler (2010), “Topological characterization of periodically driven quantum systems,” Phys. Rev. B 82, 235114.

Kitagawa, T, M. A. Broome, A. Fedrizzi, M. S. Rudner, E. Berg, I. Kassal, A. Aspuru-Guzik, E. Demler, and A. G. White (2012), “Observation of topologically protected bound states in photonic quantum walks,” Nat. Commun. 3, 882.

Kitagawa, T, T. Oka, A. Brataas, L. Fu, and E. Demler (2011), “Transport properties of nonequilibrium systems under the application of light: Photoinduced quantum Hall insulators without Landau levels,” Phys. Rev. B 84, 235108.

Kitamura, S., T. Oka, and H. Aoki (2017), “Probing and controlling spin chirality in Mott insulators by circularly polarized laser,” Phys. Rev. B 96, 014406.

Klöckner, C, C. Karrasch, and D. M. Kennes (2020), “Nonequilibrium properties of Berezinski-Kosterlitz-Thouless phase transitions,” Phys. Rev. Lett. 125, 147601.

Knap, M, M. Babadi, G. Refael, I. Martin, and E. Demler (2016), “Dynamical Cooper pairing in nonequilibrium electron-phonon systems,” Phys. Rev. B 94, 214504.

Kogar, A, 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 (2020), “Light-induced charge density wave in LaTe3,” Nat. Phys. 16, 159.

Kommik, A, and M. Thorwart (2016), “BCS theory of driven superconductors,” Eur. Phys. J. B 89, 244.

Konstantinova, T, J. D. Rameau, A. H. Reid, O. Abdurazakov, L. Wu, R. Li, X. Shen, G. Gu, Y. Huang, L. Rettig, I. Avigo, M. Lligges, J. K. Freericks, A. F. Kemper, H. A. Dürr, Z. Bovensiepen, P. D. Johnson, X. Wang, and Y. Zhu (2018), “Nonequilibrium electron and lattice dynamics of strongly correlated Bi2Sr2CaCu2O8+δ single crystals,” Sci. Adv. 4, eaap7427.

Koopmans, B, G. Malinowski, F. Dalla Longa, D. Steiauf, M. Fähnle, T. Roth, M. Cinchetti, and M. Aeschlimann (2010), “Explaining the paradoxical diversity of ultrafast laser-induced demagnetization,” Nat. Mater. 9, 259.

Koshihara, S, Y. Tokura, T. Mitani, G. Saito, and T. Koda (1990), “Photoinduced valence instability in the organic molecular compound tetrathiafulvalene-p-chloranil (TTF-CA),” Phys. Rev. B 42, 6853.

Kozina, M., M. Fechner, P. Marsik, T. van Driel, J. M. Glownia, C. Bernhard, M. Radovic, D. Zhu, S. Bonetti, U. Staub, and M. C. Hoffmann (2019), “Terahertz-driven phonon upconversion in SrTiO3,” Nat. Phys. 15, 387.

Kubačka, T, J. A. Johnson, M. C. Hoffmann, C. Vicario, S. de Jong, P. Beaud, S. Grübel, S.-W. Huang, L. Huber, L. Pattley, Y.-D. Chuang, J. J. Turner, G. L. Dakovsky, W.-S. Lee, M. P. Minitti, W. Schlott, R. G. Moore, C. P. Hauri, S. M. Koopheyveh, V. Scagnoli, G. Ingold, S. L. Johnson, and U. Staub (2014), “Large-amplitude spin dynamics driven by a THz pulse in resonance with an electro-magnon,” Science 343, 1333.

Kundu, A., and B. Seradjeh (2013), “Transport signatures of Floquet Majorana fermions in driven topological superconductors,” Phys. Rev. Lett. 111, 136402.

Kung, Y, F. W.-S. Lee, C.-C. Chen, A. F. Kemper, A. P. Sorini, B. Moritz, and T. P. Devereaux (2013), “Time-dependent charge-order and spin-order recovery in striped systems,” Phys. Rev. B 88, 125114.

Kutnyakhov, D, R. P. Xian, M. Dadzik, M. Heber, F. Prescaccio, S. Y. Agustsson, L. Wenthaus, H. Meyer, S. Gieschen, G. Mercurio, A. Benz, K. Bühlm, S. Däster, R. Gort, D. Curcio, K. Volke, M. Bianchi, C. Sanders, J. A. Miwa, S. Ulstrup, A. Oelsner, C. Tasche, Y.-J. Chen, D. Vasilyev, K. Medjankis, G. Brenner, S. Dzijarzhytski, H. Redlin, B. Manschwetus, S. Dong, J. Hauer, L. Retig, F. Diekmann, K. Rossnagel, J. Demsar, H.-J. Elmers, G. Schnöhense, G. Brenner, S. Dziarjhytski, and U. Staub (2020), “Time- and momentum-resolved photoemission studies using time-of-flight momentum microscopy at a free-electron laser,” Rev. Sci. Instrum. 91, 013109.

Kuwahara, T, T. Mori, and K. Saito (2016), “Floquet-Magnus theory and generic transient dynamics in periodically driven many-body quantum systems,” Ann. Phys. 367, 96.

Laplace, Y, and A. Cavalleri (2016), “Josephson plasmonics
in layered superconductors,” Adv. Phys. 1, 387.

Laulhé, C. T. Huber, G. Lantz, A. Ferrer, S. O. Mariager, S. Grübel, J. Rittmann, J. A. Johnson, V. Esposito, A. Lübbeke, L. Huber, M. Kubli, M. Savoini, V. L. R. Jacques, L. Cario, B. Corraze, E. Janod, G. Ingold, P. Beaud, S. L. Johnson, and S. Ravy (2017), “Ultrafast formation of a charge density wave state in 1T-TaS2: Observation at nanometer scales using time-resolved X-ray diffraction,” Phys. Rev. Lett. 118, 247401.

Lazarides, A. A. Das, and R. Moessner (2014), “Equilibrium states of generic quantum systems subject to periodic driving,” Phys. Rev. E 90, 012110.

Lazarides, A. A. Das, and R. Moessner (2015), “Fate of many-body localization under periodic driving,” Phys. Rev. Lett. 115, 030402.

Le Guyader, L, T. Chase, A. H. Reid, R. K. Li, D. Svetin, M. Langner, N. Huse, J. S. Robinson, Y. Chen, S. Y. Zhou, G. Coslovich, B. Huber, D. A. Reis, R. A. Kaindl, R. W. Schoenlein, D. Doering, P. Denes, W. F. Schlottke, J. J. Turner, S. L. Johnson, M. Först, T. Sasagawa, Y. F. Kung, A. P. Sorini, A. F. Kemper, B. Moritz, T. P. Devereaux, D.-H. Lee, Z. X. Shen, and Z. Hussain (2012), “Phase fluctuations and the absence of topological defects in a photoexcited charge-ordered nickelate,” Nat. Commun. 3, 838.

Li, J., H. U. R. Strand, P. Werner, and M. Eckstein (2018), “Theory of photoinduced ultrafast switching to a spin-orbital ordered hidden phase,” Nat. Commun. 9, 4581.

Li, T. A. Patz, L. Mouchliadis, J. Yan, T. A. Lograsso, I. E. Perakis, and J. Wang (2013), “Femtosecond switching of magnetism via strongly correlated spin-charge quantum excitations,” Nature 496, 69.

Li, X., T. Qiu, J. Zhang, E. Baldini, J. Lu, A. M. Rappe, and K. A. Nelson (2019), “Ultrafast formation of a charge density wave state in 1T-TaS2 probed with MeV ultrafast electron diffraction,” Struct. Dyn. 4, 044020.

Lee, C. H., W. W. Ho, B. Yang, J. Gong, and Z. Papić (2018), “Floquet mechanism for non-Abelian fractional quantum Hall states,” Phys. Rev. Lett. 121, 237401.

Lee, W.S., Y. D. Chuang, R. G. Moore, Y. Zhu, L. Patthey, M. Trigo, D. H. Lu, P. S. Kirchmann, O. Krupin, M. Yi, M. Langner, N. Huse, J. S. Robinson, Y. Chen, S. Y. Zhou, G. Coslovich, B. Huber, D. A. Reis, R. A. Kaindl, R. W. Schoenlein, D. Doering, P. Denes, W. F. Schlottke, J. J. Turner, S. L. Johnson, M. Först, T. Sasagawa, Y. F. Kung, A. P. Sorini, A. F. Kemper, B. Moritz, T. P. Devereaux, D.-H. Lee, Z. X. Shen, and Z. Hussain (2012), “Phase fluctuations and the absence of topological defects in a photoexcited charge-ordered nickelate,” Nat. Commun. 3, 838.

Lv, B., T. Qian, and H. Ding (2019), “Angle-resolved photomission spectroscopy and its application to topological materials,” Nat. Rev. Phys. 1, 609.

Ma, Q., T. I. Andersen, N. L. Nair, N. M. Gabor, M. Mascotte, C. H. Lui, A. F. Young, W. Fang, K. Watanabe, T. Taniguchi, J. Kong, N. Gedik, F. H. L. Koppens, and P. Jarillo-Herrero (2016), “Tuning ultrafast electron thermalization pathways in a van der Waals heterostructure,” Nat. Phys. 12, 455.

Machado, F., D. V. Else, G. D. Kahanamoku-Meyer, C. Nayak, and N. Y. Yao (2020), “Long-range prethermal phases of nonequilibrium matter,” Phys. Rev. X 10, 011043.

Maczewsky, L. J., J. M. Zeuner, S. Nolte, and A. Szameit (2017), “Observation of photonic anomalous Floquet topological insulators,” Nat. Commun. 8, 13756.

Madéo, J., M. K. L. Man, C. Sahoo, M. Campbell, V. Pareek, E. L. Wong, A. Al-Mahboob, N. S. Chan, A. Karmakar, B. Murali K. Mariserla, X. Li, T. F. Heinz, T. Cao, and K. M. Dani (2020), “Directly visualizing the momentum-forbidden dark excitons and their dynamics in atomically thin semiconductors,” Science 370, 1199.

Mahmood, F., Z. Alpichshev, Y.-H. Lee, J. Kong, and N. Gedik (2018), “Observation of exciton–exciton interaction mediated valley depolarization in monolayer MoSe2,” Nano Lett. 18, 223.

Mahmood, F., C.-K. Chan, Z. Alpichshev, D. Gardner, Y. Lee, P. A. Lee, and N. Gedik (2016), “Selective scattering between Floquet-Bloch and Volkov states in a topological insulator,” Nat. Phys. 12, 306.

Mahmood, F., D. Chaudhuri, S. Gopalakrishnan, R. Nandkishore, and N. P. Armitage (2021), “Observation of a marginal Fermi glass using THz 2D coherent spectroscopy,” Nat. Phys. 17, 627.

Mankowsky, R., M. Först, and A. Cavalleri (2016), “Non-equilibrium control of complex solids by nonlinear phononics,” Rep. Prog. in Phys. 79, 064503.

Mankowsky, R., M. Först, T. Loew, J. Porras, B. Keimer, and A. Cavalleri (2015), “Coherent modulation of the YBa2Cu3O6+x atomic structure by displacive stimulated ionic Raman scattering,” Phys. Rev. B 91, 094308.

Mankowsky, R., A. von Hoegen, M. Först, and A. Cavalleri (2017), “Ultrafast reversal of the ferroelectric polarization,” Phys. Rev. Lett. 118, 197601.
“Nonequilibrium steady states and transient dynamics of conventional superconductors under phonon driving,” Phys. Rev. B 96, 045125.

Murakami, Y., P. Werner, N. Tsuji, and H. Aoki (2015), “Interaction quench in the Holstein model: Thermalization crossover from electron- to phonon-dominated relaxation,” Phys. Rev. B 91, 045128.

Na, M X, F. Boschini, A. K. Mills, M. Michiardi, R. P. Day, B. Zwartzenberg, G. Levy, S. Zhdanovich, A. F. Kemper, D. J. Jones, and A. Damascelli (2020), “Establishing non-thermal regimes in pump-probe electron relaxation dynamics,” Phys. Rev. B 102, 184307.

Na, M X, A. K. Mills, F. Boschini, M. Michiardi, B. Noszarzewski, R. P. Day, E. Razzoli, A. Sheyerman, M. Schneider, G. Levy, S. Zhdanovich, T. P. Devereaux, A. F. Kemper, D. J. Jones, and A. Damascelli (2019), “Direct determination of mode-projected electron-phonon coupling in the time domain,” Science 366, 1231.

Narang, P., C. A. C. Garcia, and C. Felser (2021), “The topology of electronic band structures,” Nat. Mater. 20, 293.

Naeska, M., P. Sutar, Y. Vaskivskyi, I. Vaskivskyi, D. Ven-na, M X, A. K. Mills, F. Boschini, M. Michiardi, R. P. Day, E. Razzoli, A. Sheyerman, M. Schneider, G. Levy, S. Zhdanovich, T. P. Devereaux, A. F. Kemper, D. J. Jones, and A. Damascelli (2019), “Direct determination of mode-projected electron-phonon coupling in the time domain,” Science 366, 1231.

Narang, P., C. A. C. Garcia, and C. Felser (2021), “The topology of electronic band structures,” Nat. Mater. 20, 293.

Naeska, M., P. Sutar, Y. Vaskivskyi, I. Vaskivskyi, D. Ven-gust, D. Svetin, V. V. Kabanov, D. Mihaiellovic, and T. Mertelj (2021), “First-order kinetics bottleneck during photoinduced ultrafast insulator–metal transition in 3D orbitally-driven Peierls insulator CuIr2S4,” New J. Phys. 23, 053023.

Nasu, K., H. Ping, and H. Mizouchi (2001), “Photoinduced structural phase transitions and their dynamics,” J. Phys. Condens. Matter 13, R693.

Nava, A. C., Giannetti, A., Georges, E., Tosatti, and M. Fabrizio (2018), “Cooling quasiparticles in $\alpha_3S_{20}$ fullerenes by excitonic mid-infrared absorption,” Nat. Phys. 14, 154.

Nayak, C. S., H. Simon, A. Stern, M. Freedman, and S. Das Sarma (2008), “Non-Abelian anyons and topological quantum computation,” Rev. Mod. Phys. 80, 1083.

Némes, P., M. Fiebig, T. Kumpfrath, and A. V. Kimel (2018), “Antiferromagnetic opto-spintronics,” Nat. Phys. 14, 229.

Ni, G. X., L. Wang, M. D. Goldflam, M. Wagner, Z. Fei, A. S. McLeod, M. K. Liu, F. Keilmann, B. Özvilmaz, A. H. Castro Neto, J. Hone, M. M. Fogler, and D. N. Basov (2016), “Ultrafast optical switching of infrared plasmon polaritons in high-mobility graphene,” Nat. Photon. 10, 244.

Nicholson, C. W., A. Lücke, W. G. Schmidt, M. Puppin, L. Rettig, R. Ernstorfer, and M. Wolf (2018), “Beyond the molecular movie: Dynamics of bands and bonds during a photoinduced phase transition,” Science 362, 821.

Nicoletti, D., E. Casandruc, Y. Laplace, V. Khanna, C. R. Hunt, S. Kaiser, S. S. Dhesi, G. D. Gu, J. P. Hill, and A. Cavalleri (2014), “Optically induced superconductivity in striped La$_{2-x}$Ba$_x$CuO$_y$ by polarization-selective excitation in the near infrared,” Phys. Rev. B 90, 100503.

Nicoletti, D. D., Fu, O. Mehol, S. Moore, A. S. Disa, G. D. Gu, and A. Cavalleri (2018), “Magnetic-field tuning of light-induced superconductivity in striped La$_{2-x}$Ba$_x$CuO$_y$,” Phys. Rev. Lett. 121, 267003.

Nova, T. F., A. Cartella, A. Cantaluppi, M. Först, D. Bossini, R. V. Mikhailovskiy, A. V. Kivel, R. Merlin, and A. Cavalleri (2017), “An effective magnetic field from optically driven phonons,” Nat. Phys. 13, 132.

Nova, T. F., A. S. Disa, M. Fechner, and A. Cavalleri (2019), “Metastable ferroelectricity in optically strained SrTiO$_3$,” Science 364, 1075.

Nunes, G. Jr, and M. R. Freeman (1993), “Picosecond resolution in scanning tunneling microscopy,” Science 262, 1029.

Nuske, M., L. Broers, B. Schulte, G. Jotzu, S. A. Sato, A. Cavalleri, A. Rubio, J. W. McIver, and L. Mathey (2020), “Floquet dynamics in light-driven solids,” Phys. Rev. Res. 2, 043408.

Ogawa, S. H., Nagano, H. Petek, and A. P. Heberle (1997), “Optical dephasing in Cu(111) measured by interferometric two-photon time-resolved photoemission,” Phys. Rev. Lett. 78, 1339.

Oka, T., and H. Aoki (2009), “Photovoltaic Hall effect in graphene,” Phys. Rev. B 79, 081406.

Oka, T., and S. Kitamura (2019), “Floquet engineering of quantum materials,” Annu. Rev. Condens. Matter Phys 10, 387.

Okamoto, J-i, A. Cavalleri, and L. Mathey (2016), “Theory of enhanced interlayer tunneling in optically driven high-$T_c$ superconductors,” Phys. Rev. Lett. 117, 227001.

Ono, A., and S. Ishihara (2019), “Nonequilibrium susceptibility in photoinduced Floquet states,” Phys. Rev. B 100, 075127.

Oostenrijk, J. (2012), “Ultrafast spectroscopy of quantum materials,” Phys. Today 65, 44.

Oriis, R. (2014), “A practical introduction to tensor networks: Matrix product states and projected entangled pair states,” Ann. Phys. 349, 117.

Otto, M. R. P., René de Cotret, D. A. Valverde-Chavez, K. L. Tiwari, N. Émond, M. Chaker, D. G. Cooke, and B. J. Swick (2019), “How optical excitation controls the structure and properties of vanadium dioxide,” Proc. Natl. Acad. Sci. USA 116, 450.

Paeckel, S. T., Köhler, A. Svoboda, S. R. Manmana, U. Schollwöck, and C. Hubig (2019), “Time-evolution methods for matrix-product states,” Ann. Phys. 411, 167998.

Parham, S. H. Li, T. J. Nummy, J. A. Waugh, X. Q. Zhou, J. Griffith, J. Schneeloch, R. D. Zhong, G. D. Gu, and D. S. Dessau (2017), “Ultrafast gap dynamics and electronic interactions in a photoexcited cuprate superconductor,” Phys. Rev. X 7, 041013.

Patz, A. T., Li, S. Ran, R. M. Fernandes, J. Schmalian, S. L. Bud’ko, P. C. Canfield, I. E. Perakis, and J. Wang (2014), “Ultrafast observation of critical nematic fluctuations and giant magnetoelastic coupling in iron pnictides,” Nat. Commun. 5, 3229.

Perfetti, L. P., A. Loukakos, M. Lisowski, U. Bovensiepen, H. Berger, S. Biermann, P. S. Cornaglia, A. Georges, and M. Wolf (2006), “Time evolution of the electronic structure of $\beta$-TaS$_2$ through the insulator-metal transition,” Phys. Rev. Lett. 97, 067402.

Peronaci, F., M. Schiro, and O. Parcollet (2018), “Resonant thermalization of periodically driven strongly correlated electrons,” Phys. Rev. Lett. 120, 197601.

Petek, H., and S. Ogawa (1997), “Femtosecond time-resolved two-photon photoemission studies of electron dynamics in metals,” Prog. Surf. Sci. 56, 239.

Pitaeviskii, L. P (1961), “Vortex lines in an imperfect Bose gas,” Sov. Phys. JETP. 13, 451.

Polkovnikov, A. K., Sengupta, A. Silva, and M. Vengalator (2011), “Nonequilibrium dynamics of closed interacting quantum systems,” Rev. Mod. Phys. 83, 863.

Ponte, P., Z. Papić, H. F. Huvemeers, and D. A. Abanin (2015), “Many-body localization in periodically driven systems,” Phys. Rev. Lett. 114, 140401.

Porer, M., M. Leierseder, J. M. Ménard, H. Dachraoui, L. Mouchliadis, I. E. Perakis, U. Heinzmann, J. Demsr,
K. Rossnagel, and R. Huber (2014), “Non-thermal separation of electronic and structural orders in a persisting charge density wave,” Nat. Mater. 9, 857.

Qi, F., Z. Ma, L. Zhao, Y. Cheng, W. Jiang, C. Lu, T. Jiang, D. Qian, Z. Wang, W. Zhang, P. Zhu, X. Zou, W. Wan, D. Xiang, and J. Zhang (2020), “Breaking 50 femtosecond resolution barrier in MeV ultrafast electron diffraction with a double bend achromatic compressor,” Phys. Rev. Lett. 124, 134803.

Qi, T., Y.-H. Shin, K.-L. Yeh, K. A. Nelson, and A. M. Rappe (2009), “Collective coherent control: Synchronization of polarization in ferroelectric PbTiO3 by shaped THz fields,” Phys. Rev. Lett. 102, 247603.

Raines, Z. M., V. Stanev, and V. M. Galitski (2015), “Enhancement of superconductivity via periodic modulation in a three-dimensional model of cuprates,” Phys. Rev. B 91, 184506.

Rajasekaran, S. E., Casandruc, Y. Laplace, D. Nicoletti, G. D. Gu, S. R. Clark, D. Jaksh, and A. Cavalleri (2016), “Parametric amplification of a superconducting plasma wave,” Nat. Phys. 12, 1012.

Read, N., and E. Rezayi (1999), “Beyond paired quantum Hall states: Parafemions and incompressible states in the first excited Landau level,” Phys. Rev. B 59, 8084.

Rechtsman, M. C., J. M. Zeuner, Y. Plotnik, Y. Lumer, D. Podoleky, F. Dreisow, S. Nolte, M. Segev, and A. Szameit (2013), “Photonic Floquet topological insulators,” Nature 496, 196.

Reimann, J. S., Schlauderer, C. P., Schmid, F. Langer, S. Baierl, K. A. Kohl, O. E. Tereshchenko, A. Kimura, C. Lange, J. Gudde, U. Höfer, and R. Huber (2018), “Subcycle observation of lightwave-driven Dirac currents in a topological surface band,” Nature 562, 396.

Reimann, K. (2007), “Table-top sources of ultrashort THz pulses,” Rep. Prog. Phys. 70, 1597.

Rettig, L., R. Cortés, J.-H. Chu, I. R. Fisher, F. Schmitt, R. G. Moore, Z.-X. Shen, P. S. Kirchmann, M. Wolf, and U. Bovensiepen (2016), “Persistent order due to transiently enhanced nesting in an electronically excited charge density wave,” Nat. Commun. 7, 10459.

Rettig, L. S. O. Mariager, A. Ferrer, S. Grübel, J. A. Johnson, J. Rittmann, T. Wolf, S. L. Johnson, G. Ingold, P. Beaud, and U. Staub (2015), “Ultrafast structural dynamics of the Fe-pnictide parent compound BaFe2As2,” Phys. Rev. Lett. 114, 067402.

Reutzel, M. A. Li, and H. Petek (2019), “Coherent two-dimensional multiphoton photoelectron spectroscopy of metal surfaces,” Phys. Rev. X 9, 011044.

Reutzel, M. A. Li, Z. Wang, and H. Petek (2020), “Coherent multidimensional photoelectron spectroscopy of ultrafast quasiparticle dressing by light,” Nat. Commun. 11, 2230.

Rini, M., R. Tobey, N. Dean, J. Itatani, Y. Tomioka, Y. Tokura, R. W. Schoenlein, and A. Cavalleri (2007), “Control of the electronic phase of a manganese by mode-selective vibrational excitation,” Nature 449, 72.

Rischel, C. A., Rousse, I., Uschmann, P.-A., Albourg, J.-P., Geindre, P., Audebert, J.-C., Gauthier, E., Fröster, J.-L., Martin, and A. Antonetti (1997), “Femtosecond time-resolved X-ray diffraction from laser-heated organic films,” Nature 390, 490.

Rodriguez-Vega, M. M., Vogl, and G. A. Fiete (2020), “Moiré-Floquet engineering of quantum materials: A review,” arXiv:2011.11079.

Rohwer, T. S., Hellmann, M. Wiesenmayer, C. Sohrt, A. Stange, B. Slomski, A. Carr, Y. Liu, L. M. Avila, M. Kalllänne, S. Mathias, L. Kipp, K. Rossnagel, and M. Bauer (2011), “Collapse of long-range charge order tracked by time-resolved photoemission at high momenta,” Nature 471, 490.

Rossi, F., and T. Kuhn (2002), “Theory of ultrafast phenomena in photoexcited semiconductors,” Rev. Mod. Phys. 74, 895.

Rovny, J. R. L., Blum, and S. E. Barrett (2018), “Observation of discrete-time-crystal signatures in an ordered dipolar many-body system,” Phys. Rev. Lett. 120, 180603.

Rudner, M. S., and N. H. Lindner (2020), “Band structure engineering and non-equilibrium dynamics in Floquet topological insulators,” Nat. Rev. Phys. 2, 229.

Rudner, M. S., N. H. Lindner, E. Berg, and M. Levin (2013), “Anomalous edge states and the bulk-edge correspondence for periodically driven two-dimensional systems,” Phys. Rev. X 3, 031005.

Ruggenthaler, M. N., Tancogne-Dejean, J., Flick, H., Appel, and A. Rubio (2018), “From a quantum-electrodynamic light–matter description to novel spectroscopies,” Nat. Rev. Chem. 2, 0118.

Runge, E., and E. K. U. Gross (1984), “Density-functional theory for time-dependent systems,” Phys. Rev. Lett. 52, 997.

Sahoo, S. I., Schneider, and S. Eggert (2019), “Periodically driven many-body systems: A Floquet density matrix renormalization group study,” arXiv:1906.00004.

Sala, V. G., S. Dal Conte, T. A. Miller, D. Viola, E. Luppi, V. Véniard, G. Cerullo, and S. Wall (2016), “Resonant optical control of the structural distortions that drive ultrafast demagnetization in Cr2O3,” Phys. Rev. B 94, 014340.

Sandri, M., and M. Fabrizio (2013), “Nonequilibrium dynamics in the antiferromagnetic Hubbard model,” Phys. Rev. B 88, 165113.

Sato, S. A., J. W. McIver, M. Nuske, P. Tang, G. Jotzu, B. Schulte, H. Höbener, U. De Giovannini, L. Mathey, M. A. Sentef, A. Cavalleri, and A. Rubio (2019), “Microscopic theory for the light-induced anomalous Hall effect in graphene,” Phys. Rev. B 99, 214302.

Schäfer, W., and M. Wegener (2002), Semiconductor Optics and Transport Phenomena (Springer Berlin Heidelberg).

Schiffer, A. T., Paasch-Colberg, N. Karpowicz, V. Apalkov, D. Gerster, S. Mühlbärdt, M. Korbman, J. Reichert, M. Schultze, S. Holzer, J. V. Barth, R. Kienberger, R. Ernstorfer, V. S. Yakovlev, M. I. Stockman, and F. Krausz (2013), “Optical-field-induced current in dielectrics,” Nature 493, 70.

Schiró, M., and M. Fabrizio (2010), “Time-dependent mean field theory for quench dynamics in correlated electron systems,” Phys. Rev. Lett. 105, 076401.

Schlauderer, S. C. Lange, S. Baierl, T. Ebnert, C. P. Schmid, D. C. Valovcin, A. K. Zvezdin, A. V. Kimel, R. V. Mikhailovskiy, and R. Huber (2019), “Temporal and spectral fingerprints of ultrafast all-coherent spin switching,” Nature 569, 383.

Schmitt, F. K., 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 (2008), “Transient electronic structure and melting of a charge density wave in TbTe3,” Science 321, 1649.

Schoenlein, R. W., S. Chattopadhyay, H. H. W. Chong, T. E. Glover, P. A. Heimann, C. V. Shank, A. A. Zholents, and

M. S. Zolotorev (2000), “Generation of femtosecond pulses of synchrotron radiation,” Science 287, 2373.

Schoenlein, R. W., W. P., Leemans, A. H. Chin, P. Volbeyn, T. E. Glover, P. Balling, M. Zolotorev, K.-J. Kim, S. Chat-topadhayay, and C. V. Shank (1996), “Femtosecond X-ray pulses at 0.4 Å generated by 90° Thomson scattering: A tool for probing the structural dynamics of materials,” Science 274, 236.

Schoenlein, R. W., W. Z. Lin, J. G. Fujimoto, and G. L. Eesley (1987), “Femtosecond studies of nonequilibrium electronic processes in metals,” Phys. Rev. Lett. 58, 1680.

Schollwöck, U (2011), “The density-matrix renormalization group in the age of matrix product states,” Ann. Phys. 326, 96.

Schubert, O., M. Hohenleutner, F. Langer, B. Urbanek, C. Lange, U. Huttner, D. Golde, T. Meier, M. Kira, S. W. Koch, and R. Huber (2014), “Sub-cycle control of terahertz high-harmonic generation by dynamical Bloch oscillations,” Nat. Photon. 8, 119.

Schüler, M., Y. Murakami, and P. Werner (2018), “Nonthermal switching of charge order: Dynamical slowing down and optimal control,” Phys. Rev. B 97, 155136.

Schultze, M. E., M. Rothschafter, A. Sommer, S. Holzner, W. Schweinberger, M. Fiess, M. Hofstetter, R. Kienberger, V. Apalkov, V. S. Yakovlev, M. I. Stockman, and F. Krausz (2013), “Controlling dielectrics with the electric field of light,” Nature 493, 75.

Scully, M. O., and M. S. Zubairy (1997), “Atom–field interaction – semiclassical theory,” in Quantum Optics (Cambridge University Press).

Seaberg, M. H., B. Holladay, J. C. T. Lee, M. Sikorski, A. H. Seddon, E. A., J. A. Clarke, D. J. Dunning, C. Masciovecchio, C. J. Milne, F. Parmigiani, D. Rugg, J. C. H. Spence, W. Wurth (2017), “Short-wavelength free-electron laser sources and science: A review,” Rep. Prog. Phys. 80, 096001.

Singh, K. C., J. Fujiwara, Z. A. Geiger, E. Q. Simmons, M. Lipatov, A. Cao, P. Dotti, S. V. Rajagopal, R. Senaratne, T. Shimasaki, M. Heyl, A. Eckardt, and D. M. Weld (2019), “Quantifying and controlling prethermal nonergodicity in interacting Floquet matter,” Phys. Rev. X 9, 041021.

Siegrist, F., J. A. Gessner, M. Osiander, C. Denker, Y.-P. Chang, M. C. Schröder, A. Guggenmos, Y. Cui, J. Walowski, U. Martens, J. K. Dewhurst, U. Kleineberg, M. Münnemann, S. Shamma, and M. Schultz (2019), “Light-wave dynamic control of magnetism,” Nature 571, 240.

Sibener, L. M., M. Buchhold, and S. Diehl (2016), “Keldysh field theory for driven open quantum systems,” Rev. Prog. Phys. 79, 096001.

Sawatzky, P. M., S. Kaiser, M. Forst, M. Mitrano, H. Y. Shirato, and C. V. Shank (1996), “Femtosecond X-ray Thomson scattering: A review,” Rep. Prog. Phys. 59, 2237.
the topological insulator Bi$_2$Se$_3$, ” Phys. Rev. Lett. 108, 117403.

Sobota, J A, S.-L. Yang, A. F. Kemper, J. J. Lee, F. T. Schmitt, W. Li, R. G. Moore, J. G. Analytis, I. R. Fisher, P. S. Kirchmann, T. P. Devereaux, and Z.-X. Shen (2013), “Direct optical coupling to an unoccupied Dirac surface state in the topological insulator Bi$_2$Se$_3$, ” Phys. Rev. Lett. 111, 136802.

Spaldin, N A (2020), “Multiferroics beyond electric-field control of magnetism,” Proc. R. Soc. A 476, 20190542.

Sriram, A, and M. Claassen (2021), “Light-induced control of magnetic phases in kitaev quantum magnets,” arXiv:2105.01062.

Stamm, C, T. Kachel, N. Pontius, R. Mitzner, T. Quast, K. Holldack, S. Khan, C. Lupulescu, E. F. Aziz, M. Wiestruck, H. A. Dürr, and W. Eberhardt (2007), “Femtosecond modification of electron localization and transfer of angular momentum in nickel,” Nat. Mater. 6, 740.

Stefanucci, G, and R. van Leeuwen (2013), Nonequilibrium Many-Body Theory of Quantum Systems: A Modern Introduction (Cambridge University Press).

Steinmeyer, G, D. H. Sutter, L. Gailmann, N. Matuschek, and U. Keller (1999), “Frontiers in ultrashort pulse generation: Pushing the limits in linear and nonlinear optics,” Science 286, 1507.

Stern, M, J. L. René de Cotret, M. R. Otto, R. P. Chatelain, J.-P. Boisvert, M. Sutton, and B. J. Siwick (2018), “Mapping momentum-dependent electron-phonon coupling and nonequilibrium phonon dynamics with ultrafast electron diffuse scattering,” Phys. Rev. B 97, 165416.

Stoica, V A, N. Laanait, C. Dai, Z. Hong, Y. Yuan, Z. Zhang, S. Lei, M. R. McCarter, A. Yadav, A. R. Damodaran, S. Das, G. A. Stone, J. Karapetrova, D. A. Walko, X. Zhang, L. W. Martin, R. Ramesh, L.-Q. Chen, H. Wen, V. Gopalakrishnan, and J. W. Freeland (2019), “Optical creation of a supercrystal with three-dimensional nanoscale periodicity,” Nat. Mater. 18, 377.

Stojchevska, L, I. Vaskivskyi, T. Mertelj, P. Kusar, D. Svetin, S. Brazovskii, and D. Mihailovic (2014), “Ultrafast switching to a stable hidden quantum state in an electronic crystal,” Science 344, 177.

Stormer, H L, D. C. Tsui, and A. C. Gossard (1999), “The fractional quantum Hall effect,” Rev. Mod. Phys. 71, S298.

Stupakiewicz, A, C. S. Davies, K. Szerenos, D. Afanasiev, K. S. Rabovich, A. V. Boris, A. Caviglia, A. V. Kimel, and A. Kirilyuk (2021), “Ultrafast phononic switching of magnetization,” Nat. Phys. 17, 489.

Subedi, A, A. Cavalleri, and A. Georges (2014), “Theory of nonlinear phononics for coherent light control of solids,” Phys. Rev. B 89, 220301.

Sun, D, G. Aivazian, A. M. Jones, J. S. Ross, W. Yao, D. Cobden, and X. Xu (2012), “Ultrafast hot-carrier-dominated photocurrent in graphene,” Nat. Nanotechnol. 7, 114.

Sun, Z, and A. J. Millis (2020), “Transient trapping into metastable states in systems with competing orders,” Phys. Rev. X 10, 021028.

Takubo, N, Y. Ogimoto, M. Nakamura, H. Tanamuro, M. Izumi, and K. Miyano (2005), “Persistent and reversible all-optical phase control in a manganite thin film,” Phys. Rev. Lett. 95, 017404.

Tancogne-Dejean, N, M. A. Sentef, and A. Rubio (2018), “Ultrafast modification of Hubbard $U$ in a strongly correlated material: Ab initio high-harmonic generation in NiO,” Phys. Rev. Lett. 121, 097402.

Tancogne-Dejean, N, M. A. Sentef, and A. Rubio (2020), “Ultrafast transient absorption spectroscopy of the charge-transfer insulator NiO: Beyond the dynamical Franz-Keldysh effect,” Phys. Rev. B 102, 115106.

Teitelbaum, S W, B. K. Ofori-Okai, Y. H. Cheng, J. Zhang, F. Jin, W. Wu, R. D. Averitt, and K. A. Nelson (2019), “Dynamics of a persistent insulator-to-metal transition in strained manganite films,” Phys. Rev. Lett. 123, 267201.

Teitelbaum, S W, T. Shim, J. W. Wolfson, Y. H. Cheng, I. J. Porter, M. Kandyla, and K. A. Nelson (2018), “Real-time observation of a coherent lattice transformation into a high-symmetry phase,” Phys. Rev. X 8, 31081.

Terada, Y, S. Yoshida, O. Takeuchi, and H. Shigekawa (2010), “Real-space imaging of transient carrier dynamics by nanoscale pump-probe microscopy,” Nat. Photon. 4, 869.

Thygesen, K S, and A. Rubio (2007), “Nonequilibrium GW approach to quantum transport in nano-scale contacts,” J. Chem. Phys. 126, 091101.

Tindall, J, F. Schlawin, M. Buzzi, D. Nicoletti, J. R. Coulthard, H. Gao, A. Cavalleri, M. A. Sentef, and D. Jaksch (2020), “Dynamical order and superconductivity in a frustrated many-body system,” Phys. Rev. Lett. 125, 137001.

Tindall, J. B, Buča, J. R. Coulthard, and D. Jaksch (2019), “Heating-induced long-range $\eta$ pairing in the Hubbard model,” Phys. Rev. Lett. 123, 030603.

Tokura, Y (2006), “Photoinduced phase transition: A tool for generating a hidden state of matter,” J. Phys. Soc. Japan 75, 011001.

Tokura, Y, M. Kawasaki, and N. Nagaosa (2017), “Emergent functions of quantum materials,” Nat. Phys. 13, 1056.

Tokura, Y, and N. Nagaosa (2000), “Orbital physics in transition-metal oxides,” Science 288, 462.

Topp, G E, G. Jotzu, J. W. McIver, L. Xian, A. Rubio, and M. A. Sentef (2019), “Topological Floquet engineering of twisted bilayer graphene,” Phys. Rev. Res. 1, 023031.

Torchinsky, D H F, Mahmood, A. T, Bollinger, I. Božović, and N. Gedik (2014), “Fluctuating charge-density waves in a cuprate superconductor,” Nat. Mater. 12, 387.

Trigo, M, J. Chen, M. P. Jiang, W. L. Mao, S. C. Riggs, M. C. Shapiro, I. R. Fisher, and D. A. Reis (2012), “Ultrafast pump-probe measurements of short small-polaron lifetimes in the mixed-valence perovskite Cs$_2$AuI$_6$ under high pressures,” Phys. Rev. B 85, 081102.

Trigo, M, M. Fuchs, J. Chen, M. P. Jiang, M. Cammarata, S. Fahy, D. M. Fritz, K. Gaffney, S. Ghimire, A. Higinbotham, S. L. Johnson, M. E. Kozina, J. Larsson, H. Lemke, A. M. Lindenberg, G. Ndashashimiyi, F. Quirin, K. Sokolowski-Tinten, C. Uher, G. Wang, J. S. Wark, D. Zhu, and D. A. Reis (2013), “Fourier-transform inelastic X-ray scattering from time- and momentum-dependent phonon–phonon correlations,” Nat. Phys. 9, 790.

Tsen, Kong-Thon (2001), Ultrafast Phenomena in Semiconductors (Springer New York).

Tsui, N, and H. Aoki (2015), “Theory of Anderson pseudospin resonance with Higgs mode in superconductors,” Phys. Rev. B 92, 064508.

Tsui, N, M. Eckstein, and P. Werner (2013), “Nonthermal antiferromagnetic order and nonequilibrium criticality in the Hubbard model,” Phys. Rev. Lett. 110, 136404.

Tsui, N, T. Oka, and H. Aoki (2008), “Correlated electron systems periodically driven out of equilibrium: Floquet + DMFT formalism,” Phys. Rev. B 78, 235124.
pump-probe scanning tunnelling microscopy,” Nat. Nanotechnol. 9, 588.
Yu, G, C. H. Lee, A. J. Heeger, N. Herron, and E. M. McCar- ron (1991), “Transient photoinduced conductivity in single
crystals of YBa2Cu3O6.3: “Photodoping” to the metallic
state,” Phys. Rev. Lett. 67, 2581.
Yu, T, M. Claassen, D. M. Kennes, and M. A. Sentef (2021),
“Optical manipulation of domains in chiral topological super- conductors,” Phys. Rev. Res. 3, 013253.
Yusupov, R V, D. Mihailovic, C. V. Colin, G. R. Blake, and
T. T. M. Palstra (2010b), “Critical phenomena and fem- tosecond ordering dynamics associated with electronic and
spin-ordered phases in YVO3 and GdVO3,” Phys. Rev. B 81, 075103.
Zeng, T-S, and D. N. Sheng (2017), “Prethermal time crystals
in a one-dimensional periodically driven Floquet system,”
Phys. Rev. B 96, 094302.
Zewail, A H (2006), “4D ultrafast electron diffraction, crys- tallography, and microscopy,” Ann. Rev. Phys. Chem. 57, 65.
Zhang, J, and R. D. Averitt (2014), “Dynamics and control in
complex transition metal oxides,” Annu. Rev. Mater. Res. 44, 19.
Zhang, J., X. Tan, M. Liu, S. W. Teitelbaum, K. W. Post, Feng Jin, K. A. Nelson, D. N. Basov, Wenbin Wu, and R. D. Averitt (2016), “Cooperative photoinduced
metastable phase control in strained manganite films,” Nat.
Mater. 15, 956.
Zhang, P, J. Z. Ma, Y. Ishida, L. X. Zhao, Q. N. Xu, B. Q. Lv, K. Yaji, G. F. Chen, H. M. Weng, X. Dai, Z. Fang, X. Q. Chen, L. Fu, T. Qian, H. Ding, and S. Shin (2017),
“Topologically entangled Rashba-split Shockley states on the surface of grey arsenic,” Phys. Rev. Lett. 118, 046802.
Zhang, S J, Z. X. Wang, H. Xiang, X. Yao, Q. M. Liu, L. Y. Shi, T. Lin, T. Dong, D. Wu, and N. L. Wang (2020), “Photoinduced nonequilibrium response in under- doped YBa2Cu3O6+x probed by time-resolved terahertz
spectroscopy,” Phys. Rev. X 10, 011056.
Zhao, L., Z. Wang, C. Lu, R. Wang, C. Hu, P. Wang, J. Qi, T. Jiang, S. Liu, Z. Ma, F. Qi, P. Zhu, Y. Cheng, Z. Shi, Y. Shi, W. Song, X. Zhu, J. Shi, Y. Wang, L. Yan, L. Zhu, D. Xiang, and J. Zhang (2018), “Terahertz streaking of few-femtosecond relativistic electron beams,” Phys. Rev. X 8, 021061.
Zhong, Z, N. M. Gabor, J. E. Sharpe, A. L. Gaeta, and P. L. McEuen (2008), “Terahertz time-domain measurement of ballistic electron resonance in a single-walled carbon nanotube,” Nat. Nanotechnol. 3, 201.
Zhou, F, J. Williams, S. Sun, C. D. Malliakas, M. G. Kanatzidis, A. F. Kemper, and C.-Y. Ruan (2021), “Nonequilibrium dynamics of spontaneous symmetry breaking into a hidden state of charge-density wave,” Nat. Commun. 12, 566.
Zhou, X, S. He, G. Liu, L. Zhao, L. Yu, and W. Zhang (2018), “New developments in laser-based photoemission spectroscopy and its scientific applications: A key issues review,” Rep. Prog. Phys. 81, 062101.
Zhu, D. A., Robert, T. Henighan, H. T. Lemke, M. Chollet, J. M. Glownia, D. A. Reis, and M. Trigo (2015), “Phonon spectroscopy with sub-meV resolution by femtosecond X-ray diffuse scattering,” Phys. Rev. B 92, 054303.
Zhu, Y, J. Hoffman, C. E. Rowland, H. Park, D. A. Walko, J. W. Freeland, P. J. Ryan, R. D. Schaller, A. Bhat- tacharya, and H. Wen (2018), “Unconventional slowing
down of electronic recovery in photoexcited charge-ordered
La1/3Sr2/3FeO3,” Nat. Commun. 9, 1799.
Zong, A, P. E. Dolgirev, A. Kogar, E. Ergeçen, M. B. Yilmaz, Y.-Q. Bie, T. Rohwer, I-C. Tung, J. Straquandine, X. Wang, Y. Yang, X. Shen, R. Li, J. Yang, S. Park, M. C. Hoffmann, B. K. Ofori-Okaik, M. E. Kozina, H. Wen, X. Wang, I. R. Fisher, P. Jarillo-Herrero, and N. Gedik (2019a), “Dy- namical slowing-down in an ultrafast photoinduced phase transition,” Phys. Rev. Lett. 123, 097601.
Zong, A, A. Kogar, Y. Q. Bie, T. Rohwer, C. Lee, E. Bal- dini, E. Ergeçen, M. B. Yilmaz, B. Freelon, E. J. Sie, H. Zhou, J. Straquandine, P. Walmsley, P. E. Dolgirev, A. V. Rozhkov, I. R. Fisher, P. Jarillo-Herrero, B. V. Fine, and N. Gedik (2019b), “Evidence for topological defects in a photoinduced phase transition.” Nat. Phys. 15, 27.
Zong, A., X. Shen, A. Kogar, L. Ye, C. Marks, D. Chowd- hury, T. Rohwer, B. Freelon, S. Weathersby, R. Li, J. Yang, J. Checkelsky, X. Wang, and N. Gedik (2018), “Ultrafast manipulation of mirror domain walls in a charge density wave,” Sci. Adv. 4, eaau5501.
Zurek, WH (1996), “Cosmological experiments in condensed matter systems,” Phys. Rep. 276, 177.