

Freezing and shielding under global quenches for long-range interacting many-body systems

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We investigate how local perturbations spread on long-range interacting spin chains and show how their nonequilibrium behavior exactly matches the one of a Fermi-Hubbard model with long-range hoppings. We then focus on the thermalization of the fermionic model following a sudden quench of local interactions between two distinct fermionic species. For both models, the quasiparticle spectrum consists of gapped low-energy levels, while the high-energy ones accumulate at a single point. When the low-energy gaps are large enough, turning on the local interactions does not effectively mix high- and low-energy modes, resulting in a freezing of the dynamical evolution. In general, the states within the excited subspace are shielded from the long-range signatures of the model, which are responsible for the low-energy extended states, and the dynamics effectively look as if long-range couplings were absent. This shielding mechanism becomes evident in the presence of disorder. It is shown that shielding and freezing are a universal feature of long-range interacting systems, and their relation to the existence of quasistationary states is conjectured.

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Introduction. Modern experimental quantum platforms allow us to address the out-of-equilibrium dynamics and to tailor the interaction shape of quantum many-body Hamiltonians [1]. Out of this exciting possibility, a great interest has spurred in the physics of long-range interacting quantum systems [2]. Conventionally, the term long range denotes couplings decaying as $1/r^\alpha$ (where r is the distance between two components of the many-body system under study). Depending on the dimension of the system d , one defines three regimes: (1) the local regime $\alpha > \alpha_*$, where α_* is a system- and phenomenon-dependent threshold beyond which nearest-neighbor or local physics is recovered; (2) the weak long-range regime ($d < \alpha < \alpha_*$), where long-range interactions are relevant, but thermodynamic functions remain extensive; and (3) finally, for $0 < \alpha < d$ the strong long-range regime appears where conventional thermodynamics becomes ill-defined [3]. Long-range quantum systems count several practical realizations, including Rydberg atom arrays [4], dipolar systems [5,6], trapped-ion setups [7], and cold atoms in cavity experiments [8–10], and are key candidates for the realization of efficient quantum computing devices [11].

In Refs. [12,13], it was observed that, even in the presence of strong long-range interactions, the dynamics were governed by an emergent short-range Hamiltonian, at least for initial states within specific subsets of the Hilbert space. In this case, the spreading of perturbation is confined to an effective light cone, as defined by the local *Lieb-Robinson* bound [14], and it deviates from the general expectations for

long-range interactions [15]. It is then said that such a portion of the Hilbert space is *shielded* from the effect of long-range interactions.

In the present work, we intend to provide solid evidence for the universality of the shielding phenomenon as well as to give further indications for the lack of thermalization produced by long-range interactions. Our approach is complementary to previous studies concerning two main aspects:

(1) The shielding phenomenon is shown to be universal as it occurs on equal footing for all values of α and it can be traced back to the overall properties of the weakly interacting quasiparticle spectrum.

(2) Our study also considers global quenches rather than only local ones [12,13], enlarging the applicability of the concept of “shielding.”

In order to provide solid arguments to the above statements, we study the dynamics of a spin model where the interactions are strongly long ranged as well as a Fermi-Hubbard model with long-ranged hopping amplitudes, both in $d = 1$ [16]. On the one hand, the choice of these two models serves the scope of proving universality of the shielding phenomenon, which will appear in both models. On the other hand, the existence of a wide range of established tools to study the dynamics of Fermi-Hubbard models such as dynamical mean-field theory (DMFT) [17–20] and unitary perturbation theory (UPT) [21,22] makes such a system an ideal playground for our study.

As we will demonstrate, both models admit a well-defined quasiparticle limit in the weak-interaction regime, which allows us to justify our conclusions based on the spectral properties of low-energy quasiparticles. As shown below, it is the discreteness of the quasiparticle spectrum that drives the phenomena of shielding and freezing. Since long-range couplings generate discrete spectra for any $d > \alpha$, our results can be readily generalized to dimensions $d > 1$. Furthermore, the detailed structure of the underlying lattice plays no significant role, as the long-range signatures are encoded exclusively in

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the low-momentum modes, while interactions among different fermionic species remain local [23].

We start by demonstrating that the density of states (DOS) of the Fermi-Hubbard model for a single fermion in the lattice is in exact correspondence to the DOS of an XX model with long-range interactions and a single spin flip on top of a magnetized background. We then provide numerical evidence on how this equivalence imprints the same dynamical behavior for more than one initially localized excitation in both systems. Finally, we consider the dynamics under global quenches. In this case, the large-time dynamics can only be accessed for the Hubbard Hamiltonian, where UPT and DMFT calculations apply.

As an example of a global quench, we consider the case where the local density-density interactions between different fermionic species, initially absent, are suddenly ignited in the whole system. For purely long-range couplings, the system's observables remain mostly unchanged after the quench, a phenomenon often referred to as *freezing*. We analytically connect the existence of such a phenomenon with the survival of low-energy single-particle spectral gaps and the appearance of a high-energy accumulation point in the quasiparticle spectrum. Once disorder is introduced in the couplings, the degeneracy of the accumulation point is lifted, generating the celebrated semicircular density of states [24].

The appearance of the continuous part of the spectrum unfreezes the dynamics, and the effect of long-range couplings remains confined to a few low-energy discrete states, whose very limited impact on the global dynamics leads to the phenomenon of *shielding*. These dynamical effects can be demonstrated exactly only in the thermodynamic limit, making them truly many-body phenomena. Finally, we discuss the differences between rescaled and unscaled long-range interactions under Kac's prescription and determine their effect on the dynamics of fermionic systems [25].

The models. As discussed in the introduction, our study focuses on two long-range Hamiltonians, which share the same low-energy features. The spin Hamiltonian describes two long-range interacting spin chains with local interchain exchange terms:

$$H_0 = - \sum_{i=1}^L \sum_{r=1}^{L/2-1} t_r (\sigma_i^+ \sigma_{i+r}^- + \text{H.c.}) - h \sum_i \sigma_i^z - \sum_{i=1}^L \sum_{r=1}^{L/2-1} t_r (\bar{\sigma}_i^+ \bar{\sigma}_{i+r}^- + \text{H.c.}) - h \sum_i \bar{\sigma}_i^z, \quad (1a)$$

$$H_{\text{int}} = U \sum_{i=1}^L \sigma_i^z \bar{\sigma}_i^z, \quad (1b)$$

where $\sigma_i^\alpha, \bar{\sigma}_i^\alpha$ are the Pauli matrices acting at site i for the first and second chains, respectively. The second Hamiltonian describes a one-dimensional Fermi-Hubbard model with two distinct fermionic species labeled by $\tau \in \{\uparrow, \downarrow\}$ decorated with long-range hopping amplitudes:

$$H_0 = - \sum_{\tau=\uparrow, \downarrow, i=1}^L \left(\sum_{r=1}^{L/2-1} t_r (\hat{c}_{i\tau}^\dagger \hat{c}_{i+r\tau} + \text{H.c.}) + \mu \hat{c}_{i\tau}^\dagger \hat{c}_{i\tau} \right), \quad (2a)$$

$$H_{\text{int}} = U \sum_{i=1}^L \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}. \quad (2b)$$

In both cases, the total Hamiltonian is $H = H_0 + H_{\text{int}}$. Under certain approximations, the two models can be connected via a Jordan-Wigner transformation [26].

The spins in Eq. (1a) are coupled by an intrachain long-range exchange term with couplings t_r and feel a homogeneous transverse magnetic field h . A local interchain transverse exchange coupling completes the analogy with the case of the Fermi-Hubbard Hamiltonian in Eq. (2a). Indeed, Hamiltonian (2) features power-law decaying hopping amplitudes t_r and a local density-density interaction term between the two fermionic species. At $U = 0$, the fermionic Hamiltonian admits an analytic solution [27], while for $U > 0$, integrability is disrupted. As we argue in the following, both Hamiltonians in Eqs. (2a) and (1a) are described by locally interacting quasiparticles with the nonanalytic spectrum characteristic of long-range couplings. The latter description is a low-energy effective theory for the spin Hamiltonian (1a) and applies only to quenches with low quasiparticle density.

In addition to the conventional long-range envelope, we allow the exchange couplings t_r to have Gaussian fluctuations around a mean value that decays as a power law of the distance:

$$\langle t_r \rangle = \frac{M_\alpha}{r^\alpha}, \quad \langle t_r t_{r'} \rangle = \sigma^2 \delta_{rr'} \equiv \frac{J^2}{L} \delta_{rr'}. \quad (3)$$

For the spin Hamiltonian in Eq. (1a), a rescaling of the long-range exchange term is needed to maintain the internal energy of the system extensive, a procedure referred to as Kac's rescaling [2]. The same rescaling of the hopping amplitudes in the long-range fermionic model in Eq. (2a) will instead result in a subextensive kinetic energy [28]. However, in order to draw connections with most of the existing literature, we will consider both Kac-scaled and unscaled strong long-range interactions.

Density of states. Let us first consider Hamiltonian (2a) with $\alpha = 0$. There, the quasiparticle spectrum features $L - 1$ degenerate states with energy $\varepsilon_{k>0} = \mu$, which we refer to as the high-energy accumulation point [29]. A finite disorder strength $\sigma > 0$ lifts the degeneracy and leads to a continuous DOS with semicircular shape plus the low-energy isolated state at $k = 0$, in analogy to the problem of a single impurity in a crystal [30]. Similarly, for $0 \leq \alpha < 1$ in the absence of disorder, the low-energy part of the spectrum remains discrete while the high-energy modes accumulate near a single point in the thermodynamic limit. The presence of disorder mainly mixes the accumulated high-energy modes while keeping the low-energy ones gapped; the DOS takes the generic form valid at any $\alpha < 1$ [31],

$$\rho(\lambda) = \frac{\sqrt{4J^2 - \lambda^2}}{2\pi J^2} + \frac{1}{L} \sum_{n < n^*} \delta(\lambda - \lambda_n), \quad (4)$$

where $\lambda_n = M_\alpha \varepsilon_n + J^2/(M_\alpha \varepsilon_n)$, ε_n correspond to the eigenenergies of the free long-range hopping model ($\alpha < 1$) in the absence of disorder, and n^* is a critical n for which $|\lambda_{n^*}| \leq 2J$ and $|\lambda_{n^*-1}| > 2J$, where $n \in \mathbb{Z}$ and $-\frac{L}{2} \leq n < \frac{L}{2}$. The eigenenergies in the absence of disorder ε_n read

$$\varepsilon_n = -L_\alpha^{-1} \sum_{r=1}^{L/2} \frac{\cos(2\pi nr/L)}{r^\alpha} \approx -c_\alpha \int_0^{1/2} ds \frac{\cos(2\pi ns)}{s^\alpha} \quad (5)$$

with $L_\alpha^{-1} = c_\alpha L^{\alpha-1} = (1-\alpha)2^{(1-\alpha)}L^{\alpha-1}$ [23]. The latter equality in Eq. (5) is strictly valid in the thermodynamic limit $L \rightarrow \infty$, and the omission of Kac's renormalization L_α leads to eigenenergies increasing with the volume L :

$$\varepsilon_n \propto \begin{cases} O(1), & \text{Kac on,} \\ O(L^{1-\alpha}), & \text{Kac off.} \end{cases} \quad (6)$$

It is worth reminding that in Eq. (4) the summation over discrete energy states only includes the n^* eigenvalues whose energy lies outside the continuous portion of the spectrum, which, for Kac-scaled interactions, remains finite in the thermodynamic limit while it diverges in the Kac unscaled case.

Without disorder, the spin Hamiltonian (1a) at $\alpha = 0$ corresponds to the fully connected XX model. There, the many-body spectrum can be computed exactly. The Hamiltonian eigenstates ($|S, S_z\rangle$) correspond to the eigenstates of the total spin S and total magnetization S_z [32]. Assuming L to be even and considering the total magnetization to be fixed to $S_z = (L/2 - 1)$, the spectrum consists of $L - 1$ energetically degenerate states and a single gapped state with the energy gap given by $\Delta\varepsilon = M_0$. The unique gapped state corresponds to the state with maximal total spin $S = L/2$, while the $L - 1$ degenerate eigenstates are composed of the different $S \in \{0, \dots, L/2 - 1\}$ eigenstates. Such degeneracies come from the different possible ways to arrange the microscopic $1/2$ spins in order to form a total spin S [33]. In analogy to the fermionic model, disorder primarily affects the $S = L/2 - 1$ eigenstates, altering their energy and lifting the degeneracy, but leaves the isolated $S = L/2$ state almost unaltered.

Although formulated for the case $\alpha = 0$, the analogy between the quasiparticle spectra of the two models extends to arbitrary values of α in the low-energy region of the spectrum [see Figs. 1(e) and 1(f) and Ref. [34]]. Consequently, it is natural to expect that any low-energy state with sufficiently low quasiparticle density will exhibit similar dynamical behavior under Hamiltonians (1a) and (2a). Figure 1(a) illustrates the dynamics of Hamiltonian (1a) in the presence of disorder but without long-range interactions ($M_\alpha = 0$), starting from a state fully polarized along the magnetic field except for three isolated spin flips. Panel (b) shows the dynamics when long-range interactions are included ($M_\alpha > 0$, $\alpha \simeq 1/4$). The correspondence between spin dynamics and fermionic dynamics becomes evident when comparing Figs. 1(a) and 1(b) with Figs. 1(c) and 1(d), which present the evolution under Hamiltonian (2). This similarity was anticipated from the comparison of the low-energy DOS of the two models [see Figs. 1(e) and 1(f)].

As we demonstrate in the following, the discreteness of the long-range quasiparticle spectrum lies at the root of the shielding phenomenon. Our calculations will be performed for the Hamiltonian (2), where, owing to the applicability of DMFT and UPT, we are going to prove that long-range interactions are shielded for any initial state. Due to the correspondence between the quasiparticle dynamics of the Fermi-Hubbard and XX Hamiltonians, our conclusions will also apply to the Hamiltonian (1a), at least for initial states in the low-energy regime considered also in Ref. [12].

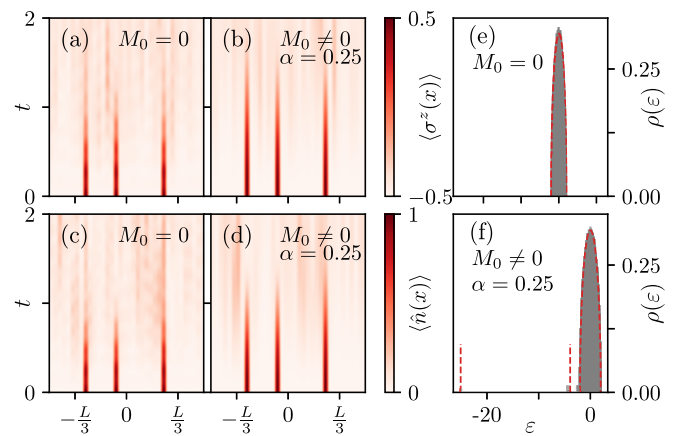


FIG. 1. (a), (b) Evolution of the magnetization profile under H_0 from Eq. (1a) for three initially localized perturbations (spin flips on top of a magnetized background). Panel (a) corresponds to the dynamics under purely off-diagonal disorder ($M_0 = 0$), while panel (b) in addition to disorder contains the long-range envelope with $M_0 = -4\pi$ and $\alpha = 0.25$. (c), (d) Dynamics for three initially localized fermions under H_0 from Eq. (2a) under the same parameters as panels (a) and (b), respectively. Both calculations were performed with $L = 36$. (e), (f) Density of states of a single-particle excitation. Panel (e) shows the DOS with Gaussian disorder, as specified in Eq. (3). Panel (f) includes additional long-range hoppings with $M_0 = -4\pi$ and $\alpha = 0.25$. In both panels, the shaded area corresponds to a normalized eigenvalue histogram for $L = 2^{13}$, while the red line sketches the theoretical prediction given by Eq. (4), with the dashed line corresponding to the continuous predictions, and the tiny red columns highlight the discrete eigenvalues.

Freezing and its relation with the accumulation point. Shielding and freezing are two sides of the same coin. In the case of *shielding*, the dynamical evolution of observables is unaffected by the presence of long-range couplings. Conversely, *freezing* refers to observables remaining mostly unchanged after a quantum quench. Both phenomena occur in the strong long-range regime, so we focus on $\alpha < d$: Initially, the system is prepared in the noninteracting ground state, i.e., the lowest-energy state of the Hamiltonian H_0 . The chemical potential is therefore tuned to ensure that we are at half filling, $N_\uparrow = N_\downarrow = L/2$, where $N_{\uparrow(\downarrow)}$ is the number of distinct electron species. This corresponds to a filled Fermi sea up to the middle of the semicircle in Eq. (4).

At $t = 0$, the on-site interactions are turned on and the noninteracting ground state evolves according to H [Eq. (2)]. The result of this procedure is reported in Fig. 2 for $\alpha = 0$. For the clean long-range system (dotted line), the double occupancy, $d \equiv \sum_i \langle \hat{n}_{i\uparrow} \hat{n}_{i\downarrow} \rangle$, remains fixed to its initial value after the interaction quench, so the electrons effectively behave as if they were not allowed to hop between sites in agreement with the expected suppression of excitation propagation evidenced for local quenches in long-range systems [12,13].

For $\alpha < d$, the absence of dynamical signatures after turning on the interaction can be justified analytically within the DMFT formalism [35]. The idea behind DMFT is to simplify the many-body problem by approximating it with the problem of a single impurity coupled to a bath. Therefore, the single-electron Green's function $G(i\omega_n)$ loses its momentum

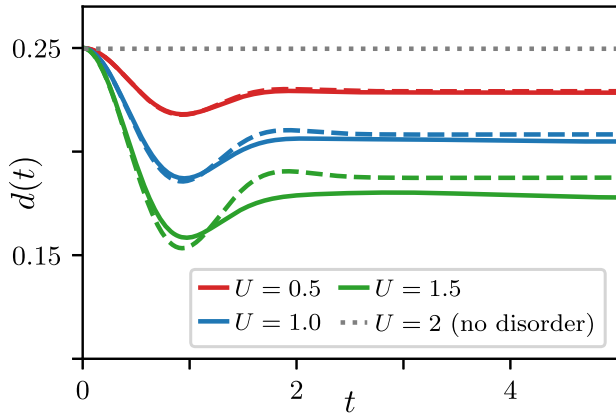


FIG. 2. Double occupancy after a sudden quench. Continuous and dashed lines correspond, respectively, to DMFT and UPT computations for the disordered case in the absence of long-range tails ($M_\alpha = 0$) for different on-site interactions $U = 0.5, 1.0, 1.5$, while the dotted line is a DMFT computation of the clean fully connected Fermi-Hubbard model ($\alpha = 0$) at $U = 2$. We observe the freezing of dynamics in the absence of disorder and a relaxation to an equilibrium value, which decreases as U increases, in the presence of it [36].

dependence and depends only on the imaginary frequency. In order to obtain the impurity Green's function, one has to solve a self-consistent equation for the impurity self-energy $\Sigma(i\omega_n) = \mathcal{G}_0^{-1}(i\omega_n) - G^{-1}(i\omega_n)$, where $\mathcal{G}_0(i\omega_n)$ is the bare Green's function of the impurity, also referred to as the Weiss effective field [17].

As the thermodynamic limit is approached, the kinetic energy contribution from long-range couplings with $\alpha < d$ vanishes, due to the kinetic energy contribution being dominated by the accumulation point. Thus, the impurity Green's function $\mathcal{G}_0(i\omega_n)$ converges to the atomic limit [35]:

$$\mathcal{G}_0^{-1}(i\omega_n) = i\omega_n + \mu + \mathcal{O}(1/L). \quad (7)$$

The many-body/cooperative nature of the shielding effect is evident by the requirement of a large number of particles to ensure that the $\mathcal{O}(L^{-1})$ in Eq. (7) is negligible and, thus, the kinetic energy effect vanishes. In fact, in the thermodynamic limit, the kinetic and interaction terms effectively commute, leading to the simultaneous conservation of kinetic and potential energies [37]. At $t \geq 0$, as the local density-density interactions in Eq. (2b) are ignited, a finite potential energy is suddenly imprinted onto the system, which cannot be dispersed in any way.

In other words, the energy gaps between quasiparticle states remain finite even at large L due to the strong long-range nature of the tunneling. This suppresses the proliferation of fluctuations following the quench, thereby preventing mode dephasing, which is fundamental to equilibration in many-body systems [38]. As the thermodynamic limit is approached ($L \rightarrow \infty$), the dominant quasiparticle contribution to the dynamics becomes increasingly concentrated in the highest-energy region of the spectrum—specifically, near the accumulation point. This leads to the erasure of all dynamical features, as illustrated by the dotted line in Fig. 2. A similar reasoning applies to spatial fluctuations, which are also suppressed by the strong long-range tunneling term [2].

This justifies the applicability of DMFT even in the one-dimensional case.

From freezing to shielding. As previously argued, long-range couplings suppress spatial fluctuations, guaranteeing the applicability of mean-field approaches. In a similar way, Gaussian disorder ensures that momentum and energy conservation do not generate divergences in the unitary perturbation theory treatment of the problem. Thus, at half filling, both in the DMFT and in the UPT study of the disordered case, turning on local density-density interactions at $t > 0$ only triggers scattering processes that involve transitions between states within the continuous semicircular portion of the spectrum. Therefore, the dynamics are shielded from long-range couplings, which only affect the discrete low-energy states in the DOS (see Fig. 1).

Indeed, the continuous semicircular portion of the spectrum in Eq. (4) induced by disorder corresponds to the DOS of the local system in the Bethe lattice. By comparing the dynamics in the presence and absence of disorder (see Fig. 2), we can conclude how disorder is necessary in order to break the *freezing* mechanism and have dynamical signatures. The addition of the long-range coupling amplitudes in Eq. (4) causes the appearance of a discrete set of low-energy quasiparticle states. However, these discrete states become statistically irrelevant in the thermodynamic limit, which removes the effect of long-range couplings. This is readily shown by the self-consistent condition between the Weiss function and the single-electron Green's function within DMFT $\mathcal{G}_0^{-1}(i\omega_n) = i\omega_n + \mu - J^2 G(i\omega_n) + \mathcal{O}(1/L)$ for the DOS in Eq. (4) [39].

Similarly to the case of local quenches in the long-range spin models discussed in Fig. 1 and Refs. [12,13], the dynamics induced by Hamiltonian (2) is not influenced by the discrete low-energy states and its thermalization timescales are solely determined by energies near the Fermi surface. The thermodynamic limit procedure is essential to obtain exact shielding of long-range couplings. Thus, in order to investigate the finite-size signatures of shielding, we employ the UPT approach, which has already been successfully applied to the local case [40]. In UPT, the time evolution of an observable $\hat{A}$ can be computed by the expression

$$\langle A \rangle_t = \langle A \rangle_0 + 4U^2 \int_{-\infty}^{\infty} d\omega \frac{\sin^2(\omega t/2)}{\omega^2} J(\omega) + \mathcal{O}(U^3), \quad (8)$$

where $J(\omega) = \langle \hat{H}_{\text{int}}(\hat{A} - \langle A \rangle_0) \delta(\hat{H}_0 - \langle H_0 \rangle - \omega) \hat{H}_{\text{int}} \rangle_0$ captures scattering processes up to second order in U . In the local case $\alpha \rightarrow \infty$, UPT predicts a prethermalization plateau and the appearance of quasiconserved charges, which lead to a generalized Gibbs distribution [22].

In Fig. 3 (left panel), we present the results for the $\alpha = 0.5$ case at half filling for different system sizes $L = 2^3, 2^6, 2^9$ for both scaled and unscaled couplings. By comparing the blue line at the bottom of Fig. 3(a) with the blue dashed line in the middle of Fig. 2, we observe how, as long as the system is considerably big, we recover the qualitative behavior of the infinite-dimensional Bethe lattice [36]. At small sizes, the spectrum can be considered discrete everywhere and Poincaré revivals are observed (black diamonds in Fig. 3). The presence or absence of the Kac's renormalization factor influences the

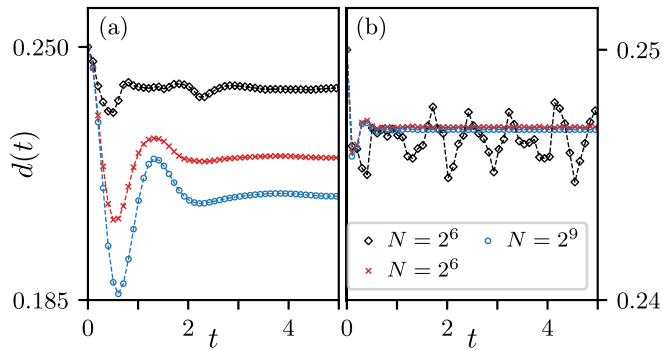


FIG. 3. Double occupancy after a sudden quench to $U = 1$ for $\alpha = 0.5$, $\sigma = 1$, and $M_0 = -4\pi$. In panel (a), the couplings have been rescaled using Kac's prescription, while for panel (b) the couplings are unscaled. Three different system sizes are shown $L = 2^3, 2^6, 2^9$ (black diamonds, red crosses, and blue dots) from top to bottom close to $t = 0$. For the smallest size $L = 2^3$, we observe the presence of Poincaré recurrences, which already dephase for both $L = 2^6$ and 2^9 .

magnitude of the relative change of the double occupancy before and after the quench, without adding any temporal structure, as we can see by comparing the Kac-scaled result [Fig. 3(a)] with the unscaled one [Fig. 3(b)]. The quantitative discrepancy between the Kac-scaled and unscaled cases originates from the change in spectral weight outside the semicircular DOS due to the Kac's factor.

Conclusions and perspectives. Our analysis demonstrates that the dynamical evolution following local quenches of Fermi-Hubbard models with long-range hoppings mimics the one of spin chains with long-range exchange interactions, due to the correspondence between their quasiparticle spectra. The key characteristic of this dynamical evolution is *shielding*: In the presence of off-diagonal disorder, local perturbations spread rapidly in both models, and at the same time, both systems become insensitive to the inclusion of long-range couplings.

In the Fermionic model, shielding is demonstrated to extend also to global quenches, where a repulsive on-site interaction is suddenly ignited in the system. In the absence of disorder, electrons localize, a phenomenon that we refer to as *freezing*. Disorder unfreezes the dynamics, but the system is shown to remain insensitive to additional long-range couplings, leading back to the phenomenology of shielding. We conclude that shielding is fundamentally linked to the low-energy (universal) spectral features of systems with long-range couplings.

The correspondence between the low-energy spectra of Hamiltonians (1a) and (2) has been demonstrated exactly in the Supplemental Material [34], but our picture for local quenches applies to any model whose quasiparticle spectrum displays coexistence of continuous and discrete regions akin to the one described in Fig. 1, including the model studied in Refs. [12,13].

For global quenches, the appearance of freezing and shielding is peculiar to Fermi quasiparticles, where the effects of interactions are suppressed by the combined effects of statistics and spectral discreteness. For systems with Bose quasiparticles, such as long-range quantum spin Hamiltonians, spectral discreteness appears to affect only specific states, i.e., the quantum scars [41], while most of the spectrum becomes chaotic [42]. A clearer picture of the many-body spectrum of long-range spin Hamiltonians in the finite-energy regime may be obtained by developing a quantum kinetic theory of long-range models.

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Data availability. The data that support the findings of this article are openly available [43]; embargo periods may apply.

- [1] A. Polkovnikov, K. Sengupta, A. Silva, and M. Vengalattore, *Colloquium: Nonequilibrium dynamics of closed interacting quantum systems*, *Rev. Mod. Phys.* **83**, 863 (2011).
- [2] N. Defenu, T. Donner, T. Macrì, G. Pagano, S. Ruffo, and A. Trombettoni, Long-range interacting quantum systems, *Rev. Mod. Phys.* **95**, 035002 (2023).
- [3] N. Defenu, A. Leroise, and S. Pappalardi, Out-of-equilibrium dynamics of quantum many-body systems with long-range interactions, *Phys. Rep.* **1074**, 1 (2024).
- [4] M. Saffman, T. G. Walker, and K. Mølmer, Quantum information with Rydberg atoms, *Rev. Mod. Phys.* **82**, 2313 (2010).
- [5] L. Chomaz, I. Ferrier-Barbut, F. Ferlaino, B. Laburthe-Tolra, B. L. Lev, and T. Pfau, Dipolar physics: A review of experiments with magnetic quantum gases, *Rep. Prog. Phys.* **86**, 026401 (2023).
- [6] L. D. Carr, D. DeMille, R. V. Krems, and J. Ye, Cold and ultracold molecules: Science, technology and applications, *New J. Phys.* **11**, 055049 (2009).
- [7] C. Monroe, W. C. Campbell, L.-M. Duan, Z.-X. Gong, A. V. Gorshkov, P. W. Hess, R. Islam, K. Kim, N. M. Linke, G. Pagano, P. Richerme, C. Senko, and N. Y. Yao, Programmable quantum simulations of spin systems with trapped ions, *Rev. Mod. Phys.* **93**, 025001 (2021).
- [8] H. Ritsch, P. Domokos, F. Brennecke, and T. Esslinger, Cold atoms in cavity-generated dynamical optical potentials, *Rev. Mod. Phys.* **85**, 553 (2013).
- [9] T. D. Farokh Mivehvar, F. Piazza, and H. Ritsch, Cavity QED with quantum gases: New paradigms in many-body physics, *Adv. Phys.* **70**, 1 (2021).
- [10] Z. Wu, J. Fan, X. Zhang, J. Qi, and H. Wu, Signatures of prethermalization in a quenched cavity-mediated long-range interacting Fermi gas, *Phys. Rev. Lett.* **131**, 243401 (2023).
- [11] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O'Brien, Quantum computers, *Nature (London)* **464**, 45 (2010).

- [12] G. L. Celardo, R. Kaiser, and F. Borgonovi, Shielding and localization in the presence of long-range hopping, *Phys. Rev. B* **94**, 144206 (2016).
- [13] L. F. Santos, F. Borgonovi, and G. L. Celardo, Cooperative shielding in many-body systems with long-range interaction, *Phys. Rev. Lett.* **116**, 250402 (2016).
- [14] E. H. Lieb and D. W. Robinson, The finite group velocity of quantum spin systems, *Commun. Math. Phys.* **28**, 251 (1972).
- [15] M. Foss-Feig, Z.-X. Gong, C. W. Clark, and A. V. Gorshkov, Nearly linear light cones in long-range interacting quantum systems, *Phys. Rev. Lett.* **114**, 157201 (2015).
- [16] J. Hubbard, Electron correlations in narrow energy bands, *Proc. R. Soc. London, Ser. A* **276**, 238 (1963).
- [17] A. Georges, G. Kotliar, W. Krauth, and M. J. Rozenberg, Dynamical mean-field theory of strongly correlated fermion systems and the limit of infinite dimensions, *Rev. Mod. Phys.* **68**, 13 (1996).
- [18] M. Rigol, V. Dunjko, and M. Olshanii, Thermalization and its mechanism for generic isolated quantum systems, *Nature (London)* **452**, 854 (2008).
- [19] N. Tsuji, M. Eckstein, and P. Werner, Nonthermal antiferromagnetic order and nonequilibrium criticality in the Hubbard model, *Phys. Rev. Lett.* **110**, 136404 (2013).
- [20] H. Aoki, N. Tsuji, M. Eckstein, M. Kollar, T. Oka, and P. Werner, Nonequilibrium dynamical mean-field theory and its applications, *Rev. Mod. Phys.* **86**, 779 (2014).
- [21] M. Moeckel and S. Kehrein, Interaction quench in the Hubbard model, *Phys. Rev. Lett.* **100**, 175702 (2008).
- [22] M. Kollar, F. A. Wolf, and M. Eckstein, Generalized Gibbs ensemble prediction of prethermalization plateaus and their relation to nonthermal steady states in integrable systems, *Phys. Rev. B* **84**, 054304 (2011).
- [23] N. Defenu, Metastability and discrete spectrum of long-range systems, *Proc. Natl. Acad. Sci. USA* **118**, e2101785118 (2021).
- [24] M. L. Mehta, *Random Matrices, Pure and Applied Mathematics* (Elsevier/Academic Press, Amsterdam, 2004), Vol. 142.
- [25] M. Kac, G. E. Uhlenbeck, and P. C. Hemmer, On the van der Waals theory of the vapor-liquid equilibrium. I. Discussion of a one-dimensional model, *J. Math. Phys.* **4**, 216 (1963).
- [26] See Sec. I of the Supplemental Material [34].
- [27] E. Lieb, T. Schultz, and D. Mattis, Two soluble models of an antiferromagnetic chain, *Ann. Phys.* **16**, 407 (1961).
- [28] As an example, if the hoppings are purely nonlocal ($\alpha = 0$), the kinetic energy is solely carried by the $k = 0$ momentum mode [37].
- [29] L. Dell’Anna, S. Fantoni, P. Sodano, and A. Trombettoni, Critical temperature of non-interacting Bose gases on disordered lattices, *J. Stat. Mech.* (2008) P11012.
- [30] S. F. Edwards and R. C. Jones, The eigenvalue spectrum of a large symmetric random matrix, *J. Phys. A: Math. Gen.* **9**, 1595 (1976).
- [31] See Sec. II of the Supplemental Material [34].
- [32] H. Lipkin, N. Meshkov, and A. Glick, Validity of many-body approximation methods for a solvable model: I. Exact solutions and perturbation theory, *Nucl. Phys.* **62**, 188 (1965).
- [33] L. Del Re, M. Fabrizio, and E. Tosatti, Nonequilibrium and non-homogeneous phenomena around a first-order quantum phase transition, *Phys. Rev. B* **93**, 125131 (2016).
- [34] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevB.104.L042010> for see Sec. II of the supplemental material for an analytic derivation of the DOS.
- [35] See Sec. III of the Supplemental Material [34].
- [36] M. Eckstein, M. Kollar, and P. Werner, Interaction quench in the Hubbard model: Relaxation of the spectral function and the optical conductivity, *Phys. Rev. B* **81**, 115131 (2010).
- [37] P. van Dongen and D. Vollhardt, Exact solution and thermodynamics of the Hubbard model with infinite-range hopping, *Phys. Rev. B* **40**, 7252 (1989).
- [38] G. Jona-Lasinio and C. Presilla, Chaotic properties of quantum many-body systems in the thermodynamic limit, *Phys. Rev. Lett.* **77**, 4322 (1996).
- [39] See Sec. III B of the Supplemental Material [34].
- [40] A. Hackl and S. Kehrein, A unitary perturbation theory approach to real-time evolution problems, *J. Phys.: Condens. Matter* **21**, 015601 (2009).
- [41] T. Comparin, F. Mezzacapo, and T. Roscilde, Robust spin squeezing from the tower of states of U(1)-symmetric spin Hamiltonians, *Phys. Rev. A* **105**, 022625 (2022).
- [42] A. Lerose, T. Parolini, R. Fazio, D. A. Abanin, and S. Pappalardi, Theory of robust quantum many-body scars in long-range interacting systems, *Phys. Rev. X* **15**, 011020 (2025).
- [43] D. Arrufat Vicente and N. Defenu, Data and code for “Freezing and shielding under global quenches for many-body systems with long-range couplings” [Computer software], Zenodo (2024), <https://doi.org/10.5281/zenodo.18434265>.