

Pre-thermal Time Crystals and Floquet topological phases without disorder

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We show that both discrete and continuous time-translation symmetry can be broken in the pre-thermal regime of quantum systems that eventually thermalize. We prove a theorem that states that such “time crystals” persist until times that are nearly exponentially-long in the couplings and, in driven systems, the drive frequency. After this thermalization time, the time-translational symmetry breaking oscillations fade away. However, during the time interval prior to that, a time crystal can exist even without disorder, and its properties are encapsulated by a field theory analogous to that of equilibrium spontaneous symmetry-breaking phases. When coupled to a cold bath, the pre-thermal regime could potentially persist to infinite time. Similar conclusions hold for topological phases of driven systems.

I. INTRODUCTION

The concept of *spontaneous symmetry breaking* forms an integral part of our understanding of emergent phases of matter. Ferromagnets spontaneously break spin-rotation symmetry, crystals spontaneously break translation symmetry, and superfluids spontaneously break global gauge symmetry. But what about *time-translation symmetry*? This symmetry is arguably the most fundamental symmetry of all, since, for example, the notion of “thermal equilibrium” implicitly assumes a system that is invariant with respect to time-translation. This makes it hard to imagine, at least initially, how it could be spontaneously broken. Nevertheless, the term “time crystal” has been coined to refer to a system in which time translation is spontaneously broken^{1–9}. However, the original model of Ref. 1 proved to be unsatisfactory for exhibiting time crystal behavior⁴. Later, no-go theorems were proven that seemed to rule out the possibility of a time crystal, at least for particular definitions of time crystal^{6,10}.

Eventually, however, it was realized¹¹ that in *periodically-driven (Floquet)* systems, time translation symmetry can indeed be spontaneously broken. In Floquet systems, time-translation symmetry has already been explicitly broken down to a discrete subgroup \mathbb{Z} due to the time-dependent, but periodic, external drive. This discrete time translation symmetry can then be spontaneously broken down even further, $\mathbb{Z} \rightarrow N\mathbb{Z}$. In such systems, the system is driven at frequency ν but, for any physical initial state, the expectation values of observables oscillate at *fractional* frequency ν/N for infinitely long times (in the thermodynamic limit). Such systems have been dubbed *Floquet time crystals*. Armed with this understanding, the models of Refs. 12–15 can be re-interpreted as examples of *Floquet time crystals*; the free-fermion models of Ref. 16 and 17 also map to Floquet time crystals under a Jordan-Wigner transformation. For an alternative view of such systems that focuses on spontaneous breaking of other symmetries of the Floquet operator, see Refs. 13–15.

The Floquet time crystals of Refs. 11, 13–15 had strong

quenched disorder in order to ensure that they exhibited many-body localization (MBL)^{18–28}. In the absence of fine-tuning to integrable points¹², MBL seems to be a necessary condition to find a Floquet time crystal in which the oscillations persist to infinitely-large times^{29–33}, because without MBL a driven isolated many-body system will generically absorb energy from the drive and heat to an infinite temperature state at large times^{34–36} (the “heating problem”), and this state is clearly invariant under time translations. However, relying on MBL has some drawbacks. In experimental realizations, it might be difficult to achieve sufficiently strong disorder. Furthermore, MBL is stable only in isolated systems and will be destroyed by any coupling to an environment^{37–45}.

A loophole in this heating problem was pointed out in Refs. 46–50, and numerically observed in Refs. 51–53: At frequencies ν that are large compared to all local energy scales in the instantaneous Hamiltonian, the time-scale t_* at which an isolated system heats to infinite temperature scales nearly exponentially, $t_* \sim e^{O(\nu/\ln^3 \nu)}$. This raises the hope of finding “pre-thermal” Floquet time crystals in which the oscillations persist until the very late time t_* . Unfortunately, it can be shown that precisely in this limit when ν is larger than *all* local energy scales in the instantaneous Hamiltonian, the state of the system in the pre-thermal epoch $t \ll t_*$ is described by a time-invariant steady state $\rho \approx \frac{1}{2}e^{-\beta D}$, where D is a quasi-local time-independent Hamiltonian. This excludes the occurrence of novel Floquet phenomena such as Floquet time crystals. Here we will show, however, that this limit is overly restrictive. Indeed, we will see that pre-thermalization – by which we mean that the heating time scales as $t_* \sim e^{O(\alpha/\ln^c \alpha)}$ for some large parameter α and some $c \geq 0$ – can also occur in certain cases where the drive frequency ν is not large compared to *all* local energy scales in the instantaneous Hamiltonian. This is closely related to results in Ref. 47, in which pre-thermalization results were proven for *stationary* systems as a consequence of a separation of energy scales.

In this paper, we will explicitly construct models that display robust Floquet time crystal behavior in a pre-

thermalized regime. In the driven versions of these models, one local coupling strength is large and the others are small; the drive frequency is large compared to the small couplings, and the parameter α is the ratio of the drive frequency to the largest of the small local couplings. The term in the Hamiltonian with large coupling must take a special form, essentially that of a symmetry generator, that allows it to avoid heating the system. In fact, our methods are not restricted to Floquet systems. We can also construct *undriven* systems that spontaneously break *continuous* time-translation symmetry in a pre-thermal regime, thus evading the no-go theorem of Ref. 10. In these un-driven systems, one of the couplings is much larger than the others, and α is the ratio of the large coupling to the largest small couplings, as in the static systems considered in Ref. 48.

Because we have lifted the requirement of MBL, it is conceivable that our pre-thermal time crystals models can be robust even in the presence of coupling to an environment. In fact, as we will argue, we expect that the pre-thermal Floquet time crystals can actually be *stabilized* by coupling to a sufficiently cold thermal bath, such that the system remains in the pre-thermal regime even at infinite time.

Our methods can also be applied to other Floquet phases of matter. The classification of many-body *symmetry-protected topological (SPT)*^{54–72} and *symmetry-enriched topological (SET)* phases^{73–79} is enriched in the Floquet context compared to the stationary case, because one needs to take into account the discrete time translation symmetry^{80–83}. So far, the new Floquet-SPT and Floquet-SET phases have only been constructed in MBL systems, because of the heating problem. However, we will argue that all of these phases (even the ones without a stationary analog) can exist as long-lived states in a pre-thermalized regime, with a lifetime on the order of the nearly exponentially-large heating time t_* . These phases can also be stabilized by coupling to a cold thermal bath.

II. RESULTS ON PRE-THERMALIZATION

Several works^{46–50} have now demonstrated that many-body systems driven at very high frequency ν exhibit a pre-thermalized regime for times much less than the heating time $t^* \sim e^{O(\nu/[\log \nu]^3)}$. Specifically, Ref. 47 constructs an approximate representation of the Floquet evolution operator as $U_f \approx \tilde{U}_f = \exp(-iT H_{\text{eff}})$, where H_{eff} is a quasi-local Hamiltonian, and \tilde{U}_f well describes the dynamics at stroboscopic times $t = nT \ll t^*$. However, these results are not sufficient to allow us to find a Floquet time crystal, or non-stationary Floquet SPT, in the pre-thermalized regime; if the dynamics are described (at stroboscopic times) by a time-independent local Hamiltonian, then we will never find any phases that do not exist in stationary systems. Indeed, it was argued in Ref. 11 that in Floquet time crystals, no such quasi-local effective

Hamiltonian H_{eff} exists. Similarly, one can show that in a Floquet SPT without a stationary analog, a quasi-local effective Hamiltonian potentially exists, but it cannot be made symmetry-respecting.

However, as was already found in Ref. 46, high frequency driving is not a necessary condition to achieve pre-thermalization; it can also be achieved as a consequence of a separation of energy scales. Accordingly, we will consider a time-dependent Hamiltonian of the form $H(t) = H_0(t) + V(t)$, where $H_0(t)$ and $V(t)$ are periodic with period T . We assume that $\lambda T \ll 1$, where λ is the local energy scale of V . We further assume that $H_0(t)$ has the property that it generates a trivial time evolution over N time cycles: $U_0(NT, 0) = U_0(T, 0)^N = 1$, where

$$U_0(t_2, t_1) = \mathcal{T} \exp \left(-i \int_{t_1}^{t_2} H_0(t) dt \right), \quad \mathcal{T} = \text{time-ordering.} \quad (1)$$

We claim that such a time evolution will exhibit pre-thermalizing behavior for $\lambda T \ll 1/N$ even if the local energy scale of $H_0(t)$ is comparable to $1/T$. In other words, such a system exhibits pre-thermalizing behavior when the frequency is large compared some of the couplings (those in $V(t)$) but not others (those in $H_0(t)$), as promised in the introduction.

An easy way to see that this claim is true is to work in the interaction picture (treating V as the “interaction”). Then we see that the time evolution of the total Hamiltonian $H(t)$ over N time cycles is given by

$$U(NT, 0) = \mathcal{T} \exp \left(-i \int_0^{NT} V^{\text{int}}(t) dt \right), \quad (2)$$

where $V^{\text{int}}(t) = U_0(0, t)^\dagger V(t) U_0(0, t)$ is the representation of $V(t)$ in the interaction picture, and $U_0(0, NT) = 1$ ensures that the time evolution operator Eq. (2) is the same in the interaction and Schrödinger pictures. If we rescale time as $t \rightarrow t/\lambda$, then Eq. (2) describes a system being driven at the large frequency $\nu = 1/(\lambda NT)$ by a drive of local strength 1, which by the results of Refs. 46–50 will exhibit pre-thermalizing behavior for $\nu \gg 1$.

On the other hand, since the above argument for pre-thermalization required coarse-graining the time period from T to NT , it prevents us from identifying time-crystalline or Floquet-SPT order in the original drive. In order to proceed further, we will need to analyze $U(T, 0)$ itself, rather than $U(NT, 0)$. Such an analysis leads us to a generalization of the results of Abanin et al.⁴⁷. A more precise version of our theorem will be given momentarily, and the proof will be given in Appendix A; the theorem essentially states that there exists a time-independent local unitary rotation \mathcal{U} such that $U_f \approx \tilde{U}_f = \mathcal{U}^\dagger (X e^{-iDT}) \mathcal{U}$, where $X = U_0(T, 0)$ is the time evolution of H_0 over one time cycle, and D is a quasi-local Hamiltonian that commutes with X . The dynamics at stroboscopic times are well-approximated by \tilde{U}_f for times $t \ll t_*$, where $t_* = e^{O(1/(\lambda T [\log(1/\lambda T)]^3))}$.

This result combines ideas in Ref. 47 about (1) the high-frequency limit of driven systems and (2) approximate symmetries in systems with a large separation of scales. Recall that, in the high-frequency limit of a driven system, the Floquet operator can be approximated by the evolution (at stroboscopic times) due a time-independent Hamiltonian, $U_f \approx \exp(-iT H_{\text{eff}})$. Meanwhile, in a static system with a large separation of scales, $H = -uL + D_0$, where u is much larger than the couplings in D_0 but $[L, D_0] \neq 0$, Ref. 47 shows that there is a unitary transformation \mathcal{U} such that $\mathcal{U}H\mathcal{U}^\dagger \approx -uL + D$ where $[L, D] = 0$, i.e. the system has an approximate symmetry generated by $\mathcal{U}^\dagger L \mathcal{U}$. Our theorem states that a periodic Hamiltonian $H(t) = H_0(t) + V(t)$, with $H_0(t)$ satisfying the condition given above, can be approximated, as far as the evolution at stroboscopic times is concerned, by a binary drive that is composed of two components: (1) the action of $H_0(t)$ over one cycle, namely $U_0(T, 0)$ and (2) a static Hamiltonian that is invariant under the symmetry generated by $U_0(T, 0)$.

The preceding paragraph summarizes the physical meaning of our theorem. A more precise statement of the theorem, although it is a bit more opaque physically, is useful because it makes the underlying assumptions manifest. The statement of the theorem makes use of an operator norm $\|O\|_n$ that measures the average over one Floquet cycle of the size of the local terms whose sum makes up a Hamiltonian; the subscript n parametrizes the extent to which the norm suppresses the weight of operators with larger spatial support. An explicit definition of the norm is given in Appendix A. The theorem states the following.

Theorem 1. *Consider a periodically-driven system with Floquet operator:*

$$U_f = \mathcal{T} \exp\left(-i \int_0^T H(t) dt\right) \quad (3)$$

where $H(t) = H_0(t) + V(t)$, and $X \equiv U_0(0, T)$ satisfies $X^N = 1$ for some integer N . We assume that $H_0(t)$ can be written as a sum $H_0(t) = \sum_i h_i(t)$ of terms acting only on single sites i . Define $\lambda \equiv \|V\|_1$. Assume that

$$\lambda T \leq \frac{\gamma \kappa_1^2}{N+3}, \quad \gamma \approx 0.14. \quad (4)$$

Then there exists a (time-independent) unitary \mathcal{U} such that

$$\mathcal{U} U_f \mathcal{U}^\dagger = X \mathcal{T} \exp\left(-i \int_0^T [D + E + V(t)] dt\right) \quad (5)$$

where D is local and $[D, X] = 0$; D, E are independent of time; and

$$\|V\|_{n_*} \leq \lambda \left(\frac{1}{2}\right)^{n_*} \quad (6)$$

$$\|E\|_{n_*} \leq \lambda \left(\frac{1}{2}\right)^{n_*} \quad (7)$$

The exponent n_* is given by

$$n_* = \frac{\lambda_0/\lambda}{[1 + \log(\lambda_0/\lambda)]^3}, \quad \lambda_0 = \frac{(\kappa_1)^2}{72(N+3)(N+4)T} \quad (8)$$

Furthermore,

$$\|D - \bar{V}\|_{n_*} \leq \mu(\lambda^2/\lambda_0), \quad \mu \approx 2.9, \quad (9)$$

where

$$\begin{aligned} \bar{V} &= \frac{1}{NT} \int_0^{NT} V^{\text{int}}(t) dt \\ &= \frac{1}{N} \sum_{k=0}^{N-1} X^{-k} \left(\frac{1}{T} \int_0^T V^{\text{int}}(t) dt \right) X^k. \end{aligned} \quad (10)$$

The proof is given in Appendix A. The statement of the theorem makes use of a number κ_1 . It is chosen so that $\|H\|_1$ is finite; the details are given when the norm is given in Appendix A.

Unpacking the theorem a bit in order to make contact with the discussion above, we see that it states that there is a time-independent unitary operator \mathcal{U} that transforms the Floquet operator into the form $X e^{-iDT}$ with $[D, X] = 0$ and local D , up to corrections that are exponentially small in $n_* \sim 1/(\lambda T [\ln(1/\lambda T)]^3)$. These ‘‘error terms’’ fall into two categories: time-independent terms that do not commute with X , which are grouped into E ; and time-dependent terms, which are grouped into $V(t)$. Both types of corrections are exponentially-small in n_* . Since they are exponentially-small $\|E\|_{n_*}, \|V\|_{n_*} \sim (1/2)^{n_*}$, these terms do not affect the evolution of the system until exponentially-long times, $t_* \sim e^{C n_*}$ (for some constant C). It is not possible to find a time-independent unitary transformation that exactly transforms the Floquet operator into the form $X e^{-iDT}$ because the system must, eventually, heat up to infinite temperature and the true Floquet eigenstates are infinite-temperature states, not the eigenstates of an operator of the form $X e^{-iDT}$ with local D . In the interim, however, the approximate Floquet operator $X e^{-iDT}$ leads to Floquet time crystal behavior, as we will discuss in the next Section.

The proof of Theorem 1 constructs \mathcal{U} and D through a recursive procedure, which combines elements of the proofs of pre-thermalization in driven and undriven systems given by Abanin et al. 47.

In the case of pre-thermal undriven systems, the theorem we need has essentially already been given in Ref. 47, but we will restate the result in a form analogous with Theorem 1, which entails some slightly different bounds (however, they are easily derivable using the techniques of Ref. 47).

Theorem 2. *Consider a time-independent Hamiltonian H of the form*

$$H = -uL + V, \quad (11)$$

where $e^{2\pi iL} = 1$. We assume that L can be written as a sum $L = \sum_i L_i$ of terms acting only on single sites i . Define $\lambda \equiv \|V\|_1$, and assume that

$$\lambda/u \leq \gamma\kappa_1^2, \quad \gamma \approx 0.14. \quad (12)$$

Then there exists a local unitary transformation \mathcal{U} such that

$$\mathcal{U}H\mathcal{U}^\dagger = -uL + D + \hat{V} \quad (13)$$

where $[L, D] = 0$ and \hat{V} satisfies

$$\|\hat{V}\|_{n_*} \leq \lambda \left(\frac{1}{2}\right)^{n_*} \quad (14)$$

where

$$n_* = \frac{\lambda_0/\lambda}{[1 + \log(\lambda_0/\lambda)]^3}, \quad \lambda_0 = \frac{u\kappa_1^2}{144}. \quad (15)$$

Furthermore,

$$\|D - \langle V \rangle\|_{n_*} \leq \mu(\lambda^2/\lambda_0), \quad \mu \approx 2.9, \quad (16)$$

Here, we have defined, following Ref. 47, the symmetrized operator $\langle V \rangle$ according to

$$\langle V \rangle \equiv \int_0^{2\pi} \frac{d\theta}{2\pi} e^{iL\theta} V e^{-iL\theta} \quad (17)$$

which, by construction, satisfies $[L, \langle V \rangle] = 0$.

III. PRE-THERMALIZED FLOQUET TIME CRYSTALS

A. Basic Picture

The results of the previous section give us the tools that we need to construct a model which is a Floquet time crystal in the pre-thermalized regime. Our approach is reminiscent of Ref. 15, where the Floquet-MBL time crystals of Ref. 11 were reinterpreted in terms of a spontaneously broken “emergent” \mathbb{Z}_2 symmetry. Here, “emergent” refers to the fact that the symmetry is in some sense hidden – its form depends on the parameters on the Hamiltonian in a manner that is not *a priori* known. Furthermore, it is not a symmetry of the Hamiltonian, but is a symmetry of the Floquet operator.

In particular, suppose that we have a model where we can set $X = \prod_i \sigma_i^x$. (Thus $N = 2$.) We then have $U_f \approx \tilde{U}_f = \mathcal{U}^\dagger (X e^{-iDT}) \mathcal{U}$, where the quasi-local Hamiltonian D by construction respects the Ising symmetry generated by X . This Ising symmetry corresponds to an *approximate* “emergent” symmetry $\mathcal{U}X\mathcal{U}^\dagger$ of U_f (“emergent” for the reason stated above and approximate because it is an exact symmetry of \tilde{U}_f , not U_f , and therefore is approximately conserved for times $t \ll t_*$.) Suppose that

D spontaneously breaks the symmetry X below some finite critical temperature τ_c . For example, working in two dimensions or higher, we could have $D = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z$ plus additional smaller terms of strength which break integrability. We will be interested in the regime where the heating time $t_* \gg t_{\text{pre-thermal}}$, where $t_{\text{pre-thermal}}$ is the thermalization time of D .

Now consider the time evolution $|\psi(t)\rangle$, starting from a given short-range correlated state $|\psi(0)\rangle$. We also define the rotated states $|\tilde{\psi}(t)\rangle = \mathcal{U}|\psi(t)\rangle$. At stroboscopic times $t = nT$, we find that $|\tilde{\psi}(nT)\rangle = (X e^{-iDT})^n |\tilde{\psi}(0)\rangle$. Since $(X e^{-iDT})^2 = e^{-2iDT}$, we see that at even multiples of the period, $t = 2nT$, the time evolution of $|\tilde{\psi}(t)\rangle$ is described by the time-independent Hamiltonian D . Thus, we expect that, after the time $t_{\text{pre-thermal}}$, the system appears to be in a thermal state of D at temperature τ . Thus, $|\tilde{\psi}(2nT)\rangle \langle \tilde{\psi}(2nT)| \approx \tilde{\rho}$, where $\tilde{\rho}$ is a thermal density matrix for D at some temperature τ , and the approximate equality means that the expectation values of local observables are approximately the same. Note that for $\tau < \tau_c$, the Ising symmetry of D is spontaneously broken and $\tilde{\rho}$ must either select a nonzero value for the order parameter $M_{2n} = \langle \sigma_i^z \rangle_{\tilde{\rho}}$ or have long-range correlations. The latter case is impossible given our initial state, as long-range correlations cannot be generated in finite time. Then, at odd times $t = (2n+1)T$, we have

$$\begin{aligned} |\tilde{\psi}((2n+1)T)\rangle \langle \tilde{\psi}((2n+1)T)| &\approx (X e^{-iDT}) \tilde{\rho} (e^{iDT} X) \\ &= X \tilde{\rho} X \end{aligned} \quad (18)$$

(since $\tilde{\rho}$ commutes with D .) Therefore, at *odd* times, the order parameter

$$M_{2n+1} = \langle \sigma_i^z \rangle_{X \tilde{\rho} X} = -M_{2n}. \quad (20)$$

Thus, the state of the system at odd times is different from the state at even times, and time translation by T is spontaneously broken to time translation by $2T$.

The above analysis took place in the frame rotated by \mathcal{U} . However, we can also consider the expectation values of operators in the original frame, for example $\langle \psi(t) | \sigma_i^z | \psi(t) \rangle = \langle \tilde{\psi}(t) | \mathcal{U}^\dagger \sigma_i^z \mathcal{U} | \tilde{\psi}(t) \rangle$. The rotation \mathcal{U} is close to the identity in the regime where the heating time is large⁸⁴, so σ_i^z has large overlap with $\mathcal{U}^\dagger \sigma_i^z \mathcal{U}$ and therefore will display fractional frequency oscillations. We recall that the condition for fractional frequency oscillations in the pre-thermalized regime is that (a) D must spontaneously break the Ising symmetry X up to a finite critical temperature τ_c ; and (b) the energy density with respect to D of $\mathcal{U}|\psi(0)\rangle$ must correspond to a temperature $\tau < \tau_c$. In Figure 1, we show the expected behavior at low temperatures τ and contrast it with the expected behavior in a system which is not a time crystal in the pre-thermal regime.

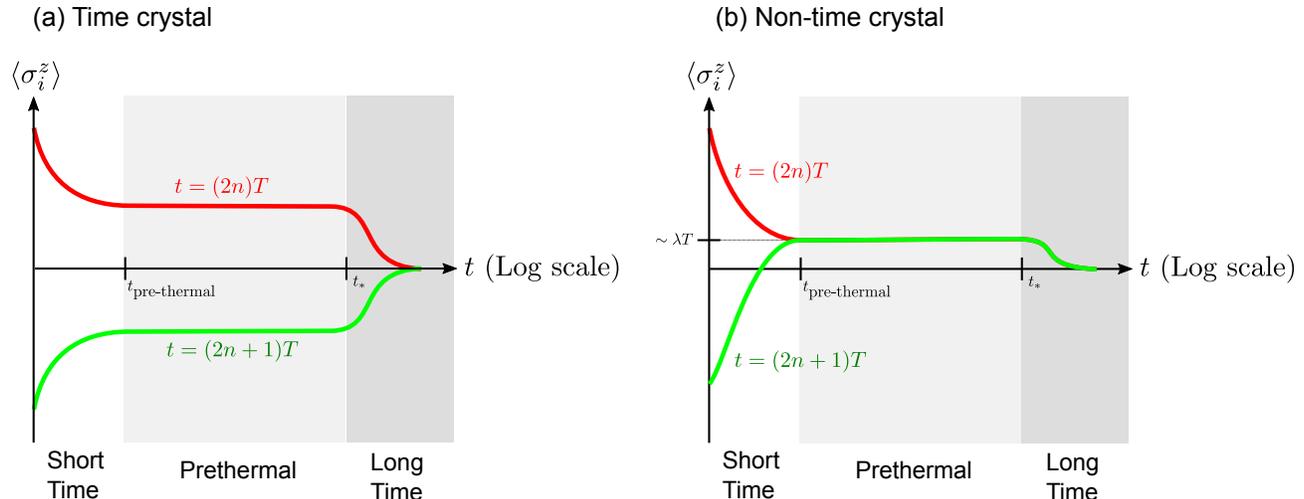


FIG. 1. The expected time dependence of $\langle \sigma_i^z \rangle$ at stroboscopic times, starting from a state which is low-temperature with respect to $\mathcal{U}DU^\dagger$ (for example, for a state with all spins polarized in the z direction.), in (a) the pre-thermal time crystal phase, and (b) the non-time crystal pre-thermal phase.

B. Example: periodically-driven Ising spins

Let us now consider a concrete model which realizes the behavior described above. We consider an Ising ferromagnet, with a longitudinal field applied to break the Ising symmetry explicitly, and driven at high frequency by a very strong transverse field. Thus, we take

$$H(t) = H_0(t) + V, \quad (21)$$

where

$$H_0(t) = - \sum_i h^x(t) \sigma_i^x \quad (22)$$

$$V = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - h^z \sum_i \sigma_i^z, \quad (23)$$

and we choose the driving profile such that

$$\int_0^T h^x(t) dt = \frac{\pi}{2}, \quad (24)$$

ensuring that the “unperturbed” Floquet operator U_0 implements a π pulse, $X = \prod_i \sigma_x^i$, and we can set $N = 2$. (If the driving does not exactly implement a π pulse, this is not a significant problem since we can just incorporate the difference into V .) This implies that $h_x \sim 1/T$, and we assume that $h^z \lesssim J \ll 1/T$.

Then by the results of Section II (with J playing the role of λ here), we find a quasi-local Hamiltonian $D = \bar{V} + \frac{1}{T} O((JT)^2)$, where

$$\bar{V} = \frac{1}{2T} \int_0^{2T} V_{\text{int}}(t) dt. \quad (25)$$

In particular, in the case where the π pulse acts instantaneously, so that

$$h^x(t) = \frac{\pi}{2} \sum_{k=-\infty}^{\infty} \delta(t - kT), \quad (26)$$

we find that

$$\bar{V} = -J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z \quad (27)$$

(this Hamiltonian is integrable, but in general the higher order corrections to D will destroy integrability.) More generally, if the delta function is smeared out so that the π pulse acts over a time window δ , the corrections from Eq. (27) will be at most of order $\sim J\delta/T$. Therefore, so long as $\delta \ll T$, then in two dimensions or higher, the Hamiltonian D will indeed spontaneously break the Ising symmetry up to some finite temperature τ_c , and we will observe the time-crystal behavior described above.

C. Field Theory of the Pre-Thermal Floquet Time Crystal State

The universal behavior of a pre-thermal Floquet time crystal state can be encapsulated in a field theory. For the sake of concreteness, we derive this theory from the model analyzed in the previous section. The Floquet operator can be written, up to nearly exponential accuracy, as:

$$U_f \approx \mathcal{U}(X e^{-iDT}) \mathcal{U}^\dagger \quad (28)$$

Consequently, the transition amplitude from an initial state $|\psi_i\rangle$ at time t_0 to a final state $|\psi_f\rangle$ at time

$t_0 + mT$ can be written in the following form, provided $t_{\text{pre-thermal}} < t_0 < t_0 + mT < t_*$:

$$\begin{aligned} \langle \psi_f | (U_f)^m | \psi_i \rangle &= \langle \psi_f | \mathcal{U}(X e^{-iDT})^m \mathcal{U}^\dagger | \psi_i \rangle \\ &= \langle \tilde{\psi}_f | e^{-iDmT} | \tilde{\psi}_i \rangle \end{aligned} \quad (29)$$

where $|\tilde{\psi}_i\rangle \equiv \mathcal{U}^\dagger |\psi_i\rangle$ and $|\tilde{\psi}_f\rangle \equiv X^m \mathcal{U}^\dagger |\psi_f\rangle$; recall that X^m is 1 or X for, respectively, m even or odd.

The second line of Eq. (29) is just the transition amplitude for the quantum transverse field Ising model in $(d+1)$ -dimensional spacetime, with $d \geq 2$. The model has nearest-neighbor interaction (27) together with higher-order terms that are present in the full expression for D . Hence, it can be represented by the standard functional integral for the continuum limit of the Ising model:

$$\langle \tilde{\psi}_f | e^{-iDmT} | \tilde{\psi}_i \rangle = \int \mathcal{D}\varphi e^{i \int d^d x dt \left[\frac{1}{2} K (\partial_t \varphi)^2 - \frac{v^2}{2} K (\nabla \varphi)^2 - U(\varphi) \right]} \quad (30)$$

where $U(\varphi)$ has minima at $\varphi = \pm\varphi_0$ when the parameters in the Ising model place it in the ordered phase. This functional integral is only valid for wavevectors that are less than a wavevector cutoff: $|q| < \Lambda$, where $\Lambda \ll 1/a$ and a is the spatial lattice spacing. Although the right-hand side of (30) has a continuous time variable, it is only equal to the original periodically-driven problem for stroboscopic times $t = mT$ for $m \in \mathbb{Z}$. Note the left-hand side of (30) is also well-defined for arbitrary times, i.e. for continuous m , although it, too, only corresponds to the original problem for integer m . Thus the continuous-time effective field theory has a frequency cutoff Λ_ω that we are free to choose. Although the functional integral only corresponds to the original problem for stroboscopic times, the functional integral is well-defined for all times. As a result of the factor of X in U_f , the field φ is related to the Ising spin according to $\varphi(x, kT) \sim (-1)^k \sigma(x, kT)$. In other words, the field φ in the functional integral has the interpretation of the temporally-staggered magnetization density, just as, in the corresponding description of an Ising anti-ferromagnet, this field would be the spatially-staggered magnetization. Discrete time-translation symmetry, $t \rightarrow t + T$ has the following action: $\varphi \rightarrow -\varphi$. Thus, the symmetry-breaking phase, in which $\varphi = \pm\varphi_0$, is a pre-thermal Floquet time crystal, in which TTTSB occurs, as expected.

The rotated Floquet operator $\mathcal{U}^\dagger U_f \mathcal{U}$ has an approximate \mathbb{Z}_2 symmetry generated by the operator X since $\mathcal{U}^\dagger U_f \mathcal{U} \approx X e^{-iDT}$ and $[D, X] = 0$. Hence, $\mathcal{U}^\dagger X \mathcal{U}$ commutes with the (unrotated) Floquet operator U_f . It is not a microscopic symmetry in the conventional sense, since $\mathcal{U}^\dagger X \mathcal{U}$ does not commute with the time-dependent Hamiltonian $H(t)$, except for special fine-tuned points in the Floquet time crystal phase. However, since it commutes with the Floquet operator, it is a symmetry of the continuum-limit field theory (30). (See Ref. 15 for a discussion of Floquet time crystals in the MBL context that focuses on such symmetries, sometimes called

“emergent symmetries”.) Within the field theory (30), this symmetry acts according to $\varphi \rightarrow -\varphi$, i.e. it acts in precisely the same way as time-translation by a single period. Again, this is analogous to the case of an Ising anti-ferromagnet, but with the time-translation taking the place of spatial translation. Thus, it is possible to view the symmetry-breaking pattern as $\mathbb{Z}_{\text{TTS}} \times \mathbb{Z}_2 \rightarrow \mathbb{Z}$. The unbroken \mathbb{Z} symmetry is generated by the combination of time-translation by one period and the action of $\mathcal{U}^\dagger X \mathcal{U}$.

However, there is an important difference between a Floquet time crystal and an Ising antiferromagnet. In the latter case, it is possible to explicitly break the the Ising symmetry without breaking translational symmetry (e.g. with a uniform longitudinal magnetic field) and vice versa (e.g. with a spatially-oscillating exchange coupling). In a Floquet time crystal, this is not possible because there is always a \mathbb{Z}_2 symmetry $\mathcal{U}^\dagger X \mathcal{U}$ regardless of what small perturbation (compared to the drive frequency) is added to the Hamiltonian. The only way to explicitly prevent the system from having a \mathbb{Z}_2 symmetry is to explicitly break the time-translation symmetry. Suppose the Floquet operator is $\mathcal{U} X e^{-iDT} \mathcal{U}^\dagger$. When a weak perturbation with period $2T$ is added, the Floquet operator can be written in the approximate form $\mathcal{U}' e^{-2i(D+Y)T} (\mathcal{U}')^\dagger$ where Y is due to the doubled-period weak perturbation, but it is not possible to guarantee that $[X, Y] = 0$. Thus there is a symmetry generated by an operator of the form $\mathcal{U}^\dagger X \mathcal{U}$ only if time-translation symmetry is present – i.e. it is a consequence of time-translation symmetry and pre-thermalization.

This functional integral is computed with boundary conditions on φ at $t = t_0$ and $t_0 + mT$. Time-ordered correlation functions can be computed by inserting operators between the factors of U_f . However, if we are interested in equal-time correlation functions (at stroboscopic times $t = kT$),

$$\begin{aligned} \langle \psi | \hat{O}(x, kT) \hat{O}(0, kT) | \psi \rangle &\equiv \\ \langle \psi | (U_f)^{-k} \hat{O}(x, 0) \hat{O}(0, 0) (U_f)^k | \psi \rangle \end{aligned} \quad (31)$$

then we can make use of the fact that the system rapidly pre-thermalizes to replace $(U_f)^k | \psi \rangle$ by a thermal state:

$$\begin{aligned} \langle \psi | (U_f)^{-k} \hat{O}(x, 0) \hat{O}(0, 0) (U_f)^k | \psi \rangle &= \\ \text{tr}(e^{-\beta D} \hat{O}(x) \hat{O}(0)) \end{aligned} \quad (32)$$

where β is determined by $\text{tr}(e^{-\beta D} D) = \langle \psi | D | \psi \rangle$. The latter has an imaginary-time functional integral representation:

$$\begin{aligned} \text{tr}(e^{-\beta D} \hat{O}(x) \hat{O}(0)) &= \\ \int \mathcal{D}\varphi e^{-\int d^d x d\tau \left[\frac{1}{2} K (\partial_\tau \varphi)^2 + \frac{v^2}{2} K (\nabla \varphi)^2 + U(\varphi) \right]} \end{aligned} \quad (33)$$

This equation expresses equal-time correlation functions in a pre-thermal Floquet time crystal in terms of the

standard imaginary-time functional integral for the Ising model but with the understanding that the field φ in the functional integral is related to the Ising spins in the manner noted above.

In order to compute unequal-time correlation functions, it is convenient to use the Schwinger-Keldysh formalism^{85,86} (see Ref. 87 for a modern review). This can be done by following the logic that led from the first line of Eq. (29) to the second and thence to Eq. (30). This will be presented in detail elsewhere⁸⁸.

We close this subsection by noting that the advantage of the field theory formulation of a pre-thermal Floquet time crystal is the salience of the similarity with the equilibrium Ising model; for instance, it is clear that the transition out of the Floquet time crystal (e.g. as a function of the energy of the initial state) in the pre-thermal regime is an ordinary Ising phase transition. The disadvantage is that it is difficult to connect it to measurable properties in a quantitative way because the field φ has a complicated relationship to the microscopic degrees of freedom.

D. Relation to formal definitions of time crystals

In the above discussion, we have implicitly been adopting an “operational” definition of time-crystal: it is a system in which, for physically reasonable initial states, the system displays oscillations at a frequency other than the drive frequency forever (or at least, in the pre-thermal case, for a nearly exponentially long time.) This is a perfectly reasonable definition of time crystal, but it has the disadvantage of obscuring the analogies with spontaneous breaking of other symmetries, which tends not to be defined in this way. (Although in fact it could be; for example, an “operational” definition of spontaneously broken Ising symmetry, say, would be a system in which the symmetry-breaking order parameter does not decay with time for physically reasonable initial states⁸⁹.) It was for this reason that in Ref. 11 we introduced a formal definition of time-translation symmetry-breaking in MBL systems in terms of eigenstates (two equivalent formulations of which we called TTSB-1 and TTSB-2.)

The definitions TTSB-1 and TTSB-2 of Ref. 11 are natural generalizations of the notion of “eigenstate order” used to define spontaneous breaking of other symmetries in MBL^{89,90}. On the other hand they, like the notion of eigenstate order in general, are not really appropriate outside of the MBL context. In this subsection, we will review the usual formal definitions of spontaneous symmetry breaking in equilibrium. Then we will show how they can be extended in a natural way to time-translation symmetries, and that these extended versions are satisfied by the pre-thermal Floquet time crystals constructed above.

Let us first forget about time-translation symmetry, and consider a time-independent Hamiltonian H with an Ising symmetry generated by X . Let ρ be a steady state of the Hamiltonian; that is, it is invariant under

the time evolution generated by H . (Here, we work in the thermodynamic limit, so by ρ we really mean a function which maps local observables to their expectation values; that is, we define a state in the C^* -algebra sense⁹¹.) Generically, we expect ρ to be essentially a thermal state. If the symmetry is spontaneously broken, then ρ can obey the cluster decomposition (i.e. its correlations can be short-ranged), or it can be invariant under the symmetry X , but *not* both. That is, any state invariant under the symmetry decomposes as $\rho = \frac{1}{2}(\rho_{\uparrow} + \rho_{\downarrow})$, where ρ_{\uparrow} and ρ_{\downarrow} have opposite values of the Ising order parameter, and are mapped into each other under X . Thus, a formal definition of spontaneously broken Ising symmetry can be given as follows. We call a symmetry-invariant steady state ρ state an *extremal symmetry-respecting state* if there do not exist states ρ_1 and ρ_2 such that $\rho = p\rho_1 + (1-p)\rho_2$ for some $p \in (0, 1)$, where ρ_1 and ρ_2 are symmetry-invariant steady states. We say the Ising symmetry is spontaneously broken if extremal symmetry-invariant steady states do not satisfy the cluster decomposition. Similar statements can be made for Floquet systems, where by “steady state” we now mean a state that returns to itself after one time cycle.

We can now state the natural generalization to time-translation symmetry. For time-translation symmetry, “symmetry-invariant” and “steady state” actually mean the same thing. So we say that time-translation symmetry is spontaneously broken if extremal steady states do not satisfy the cluster decomposition. This is similar to our definition TTSB-2 from Ref. 11 (but not exactly the same, since TTSB-2 was expressed in terms of eigenstates, rather than extremal steady states in an infinite system), so we call it TTSB-2'. We note that TTSB-2' implies that any short-range correlated state ρ , i.e. a state ρ which satisfies the cluster decomposition, must not be an extremal steady state. Non-extremal states never satisfy the cluster decomposition, so we conclude that short-range correlated states must not be steady states at all, so they cannot simply return to themselves after one time cycle. (This is similar to, but again not identical with, TTSB-1 in Ref. 11.)

We note that, for clean systems, the only steady state of the Floquet operator U_f is believed to be the infinite temperature state³⁴⁻³⁶ which always obeys the cluster property, and hence time translation symmetry is not broken spontaneously. This does not contradict our previous results, since we already saw that time translation symmetry is only spontaneously broken in the pre-thermal regime, not at infinitely long times. Instead, we should examine the steady states of the *approximate* Floquet operator \tilde{U}_f which describes the dynamics in the pre-thermal regime. We recall that, after a unitary change of basis, $\tilde{U}_f = X e^{-iDT}$, where D commutes with X and spontaneously breaks the Ising symmetry generated by X (for temperatures $\tau < \tau_c$). Hence $\tilde{U}_f^2 = e^{-2iDT}$. Any steady state ρ of \tilde{U}_f must be a steady state of \tilde{U}_f^2 , which implies (if its energy density corresponds to a temperature $\tau < \tau_c$) that it must be of the

form $\rho = t\rho_{SB} + (1-t)X\rho_{SB}X$, where ρ_{SB} is an Ising symmetry-breaking state of temperature τ for the Hamiltonian D . Hence, we see (since ρ_{SB} is invariant under e^{-iDT}) that $\tilde{U}_f\rho\tilde{U}_f^\dagger = tX\rho_{SB}X + (1-t)\rho_{SB}$. So if ρ is a steady state of \tilde{U}_f and not just \tilde{U}_f^2 , we must have $t = 1/2$. But then the state ρ clearly violates the cluster property. Hence, time translation is spontaneously broken.

IV. SPONTANEOUSLY-BROKEN CONTINUOUS TIME-TRANSLATION SYMMETRY IN THE PRE-THERMAL REGIME

A. Basic Picture

The pre-thermalized Floquet time crystals discussed above have a natural analog in undriven systems with *continuous* time translation symmetry. Suppose we have a time-independent Hamiltonian

$$H = -uL + V, \quad (34)$$

where the eigenvalues of L are integers; in other words, for time $T = 2\pi/u$, the condition $e^{inuLT} = 1$ holds for all $n \in \mathbb{Z}$. We also assume that L is a sum of local terms of local strength $O(1)$; and V is a local Hamiltonian of local strength $\lambda \ll u$. Then by Theorem 3.1 of Ref. 47, restated in Theorem 2 in Section II), there exists a local unitary \mathcal{U} such that $\mathcal{U}H\mathcal{U}^\dagger = -uL + D + \hat{V}$ such that $[D, L] = 0$ and the local strength of \hat{V} is $\sim \lambda e^{-O([\log \lambda T]^3/[\lambda T])}$. As noted in Theorem 2 in Section II), the first term in the explicit iterative construction of D in Ref. 47 is $D = \langle V \rangle + \frac{1}{T}O(\lambda T)^2$, where

$$\langle V \rangle \equiv \frac{1}{2\pi} \int_0^{2\pi} d\theta e^{iL\theta} V e^{-iL\theta}. \quad (35)$$

As a result of this theorem, such a system has an approximate $U(1)$ symmetry generated by $\mathcal{U}^\dagger L \mathcal{U}$ that is explicitly broken only by nearly exponentially-small terms. Consequently, $\mathcal{U}^\dagger L \mathcal{U}$ is conserved by the dynamics of H for times $t \ll t_* = e^{O([\log \lambda T]^3/[\lambda T])}$. We will call the Hamiltonian $-uL + D$ the ‘‘pre-thermal’’ Hamiltonian, since it governs the dynamics of the system for times short compared to t_* . We will assume that we have added a constant to the Hamiltonian such that L is positive-definite; this will allow us to abuse terminology a little by referring to the expectation value of L as the ‘‘particle number’’, in order to make analogies with well-known properties of Bose gases, in which the generator of the $U(1)$ symmetry is the particle number operator. In this vein, we will call u the electric potential, in analogy with (negatively) charged superfluids.

We will further suppose that D is neither integrable nor many-body localized, so that the dynamics of D will cause an arbitrary initial state $|\psi_0\rangle$ with non-zero energy density and non-zero $\langle \psi_0 | L | \psi_0 \rangle$ to rapidly thermalize on some short (compared to t_*) time scale $t_{\text{pre-thermal}} \sim$

λ^{-1} . The resulting thermalized state can be characterized by the expectation values of D and L , both of which will be the same as in the initial state, since energy and particle number are conserved. Equivalently, the thermalized state can be characterized by its temperature β (defined with respect to D) and effective chemical potential μ . In other words, all local correlation functions of local operators can be computed with respect to the density matrix $\rho = e^{-\beta(D-\mu L)}$. The chemical potential μ has been introduced to enforce the condition $\text{tr}(\rho L) = \langle \psi_0 | L | \psi_0 \rangle$.

Now suppose that we choose V such that D spontaneously breaks the $U(1)$ symmetry in some range of temperature $1/\beta$ and chemical potential μ . Suppose, further, that we prepare the system in a short-range correlated initial state $|\psi_0\rangle$ such that the energy density (and hence, its temperature) is sufficiently low, and the number density sufficiently high, so that the corresponding thermalized state spontaneously breaks the $U(1)$ symmetry generated by L . Then, the preceding statement must be slightly revised: all local correlation functions of local operators can be computed with respect to the density matrix $\rho = e^{-\beta(D-\mu L-\epsilon X)}$ for some X satisfying $[X, L] \neq 0$. The limit $\epsilon \rightarrow 0$ is taken after the thermodynamic limit is taken; the direction of the infinitesimal symmetry-breaking field X is determined by the initial state. To avoid clutter, we will not explicitly write the ϵX in the next paragraph, but it is understood.

Consider an operator Φ that satisfies $[L, \Phi] = \Phi$. (For example, if we interpret L as the particle number, we can take Φ to be the particle creation operator.) Its expectation value at time t is given by

$$\begin{aligned} & \langle \psi_0 | e^{-i(-uL+D)t} \Phi e^{i(-uL+D)t} | \psi_0 \rangle \\ &= \text{tr} \left(\left[e^{-i(-uL+D)t} \Phi e^{i(-uL+D)t} \right] e^{-\beta(D-\mu L)} \right) \\ &= e^{i(\mu-u)t} \text{tr} \left(\left[e^{-i(-\mu L+D)t} \Phi e^{i(-\mu L+D)t} \right] e^{-\beta(D-\mu L)} \right) \end{aligned} \quad (36)$$

According to the discussion in Appendix B, which makes use of the result of Watanabe and Oshikawa¹⁰, the trace on the right-hand-side of the second equality must be independent of time. Hence, so long as $\text{Tr}(\Phi e^{-\beta(D-\mu L)}) \neq 0$ (which we assume to be true for some order parameter Φ in the symmetry-breaking phase), we find that the expectation value of Φ oscillates with frequency given by the ‘‘effective electrochemical potential’’ $\mu - u$ due to the winding of the phase of Φ .

If the dynamics were exactly governed by $-uL + D$, then the system would oscillate with period $2\pi/(u - \mu)$ forever. As it is, these oscillations will be observed until the exponentially late time t_* . At infinitely long times, the system approaches a thermal state of the full Hamiltonian $-uL + D + \hat{V}$. Since \hat{V} is small, this is approximately the same as a thermal state of $-uL + D$. However, because \hat{V} is not exactly zero, the particle number is not

conserved and in equilibrium the system chooses the particle number that minimizes its free energy, which corresponds to the “electrochemical potential” being zero, $\mu - u = 0$. Since this corresponds to zero frequency of oscillations, it follows that no oscillations are observed at infinite time.

The above discussion is essentially the logic that was discussed in Refs. 8, 10, and 92, where it was pointed out that a superfluid at non-zero chemical potential is a time crystal as a result of the well-known time-dependence of the order parameter⁹³. However, there is an important difference: the U(1) symmetry is not a symmetry of the Hamiltonian of the problem and, therefore, does not require fine-tuning but, instead, emerges in the $u \rightarrow \infty$ limit, thereby evading the criticism^{8,10,94–96} that the phase winds in the ground state only if the U(1) symmetry is exact.

B. Example: XY Ferromagnet in a Large Perpendicular Field

Consider the concrete example of a spin-1/2 system in three spatial dimensions, with Hamiltonian

$$H = -h^z \sum_i S_i^z - h^x \sum_i S_i^x - \sum_{i,j} [J_{ij}(S_i^x S_j^x + S_i^y S_j^y) + J_{ij}^z S_i^z S_j^z] - h^x \sum_i S_i^x, \quad (37)$$

We take $L = S^z \equiv \sum_i S_i^z$, and the longitudinal magnetic field h^z plays the role of u in the preceding section. We take J_{ij} and J_{ij}^z to vanish except for nearest neighbors, for which $J_{ij} = J$ and $J_{ij}^z = J^z$. The local scale of V is given by $\lambda = \max(J, h^x)$, so that the condition $\lambda \ll T^{-1} \sim h^z$ is satisfied if $J, h^x \ll h^z$. In this case, D is (to first order) the Hamiltonian of an XY ferromagnet:

$$D = - \sum_{i,j} [J_{ij}(S_i^x S_j^x + S_i^y S_j^y) + J_{ij}^z S_i^z S_j^z] + \frac{1}{T} O(\lambda/h^z)^2. \quad (38)$$

Then, starting from a short-range correlated state with appropriate values of energy and $\langle S^z \rangle$, we expect that time evolution governed by D causes the system to “pre-thermalize” into a symmetry-breaking state with some value of the order parameter $\langle S_i^+ \rangle = n_0 e^{i\phi}$. According to the preceding discussion, the order parameter will then rotate in time with angular frequency $\omega = h^z + \mu$ (where $\mu \lesssim \lambda$ is determined by the initial value of $\langle S^z \rangle$) for times short compared to the thermalization time t_* .

Note, however, that we have assumed that the system is completely isolated. If the system is not isolated, then the periodic rotation of the order parameter will cause the system to emit radiation, and this radiation will cause the system to decay to its true ground state^{4,97}.

C. Field Theory of Pre-Thermal Continuous-TTSB Time Crystal

For simplicity we will give only the imaginary-time field theory for equal-time correlation functions deep within the pre-thermal regime; the Schwinger-Keldysh functional integral for unequal-time correlation functions, with nearly exponentially-small thermalization effects taken into account, will be discussed elsewhere⁸⁸. Introducing the field $\phi \sim (S_x + iS_y)e^{i(\mu-u)t}$, we apply Eq. (36) to the XY ferromagnet of the previous section, thereby obtaining the effective action:

$$S_{\text{eff}} = \int d^d x d\tau [\phi^* \partial_\tau \phi - \mu \phi^* \phi + g(\phi^* \phi)^2 + \dots] \quad (39)$$

The ... represents higher-order terms. The U(1) symmetry generated by S^z acts according to $\phi \rightarrow e^{i\theta} \phi$. Time-translation symmetry acts according to $\phi(t) \rightarrow e^{i(\mu-u)a} \phi(t+a)$ for any a . Thus, when ϕ develops an expectation value, both symmetries are broken and a combination of them is preserved according to the symmetry-breaking pattern $\mathbb{R}_{\text{TTS}} \times U(1) \rightarrow \mathbb{R}$, where the unbroken \mathbb{R} is generated by a gauge transformation by θ and a time-translation $t \rightarrow t + \frac{\theta}{\mu-u}$.

From the mathematical equivalence of Eq. (39) to the effective field theory of a neutral superfluid, we see that (1) in 2D, there is a quasi-long-range-ordered phase – an ‘algebraic time crystal’ – for initial state energies below a Kosterlitz-Thouless transition; (2) the TTSB phase transition in 3D is in the ordinary XY universality class in 3D; (3) the 3D time crystal phase has Goldstone boson excitations. If we write $\phi(x, t) = \sqrt{\left(\frac{\mu}{2g} + \delta\rho(x, t)\right)} e^{i\theta(x, t)}$, and integrate out the gapped field $\delta\rho(x, t)$, then the effective action for the gapless Goldstone boson $\theta(x, t)$ is of the form discussed in Ref. 95.

V. OPEN SYSTEMS

So far, we have considered only isolated systems. In practice, of course, some coupling to the environment will always be present. One can also consider the effect of classical noise, for example some time-dependent randomness in the parameters of the drive, so that successive time steps do not implement exactly the same time evolution. The Floquet-MBL time crystals of Ref. 11 are not expected to remain robust for open systems, because such a coupling will destroy MBL. This limits the timescales over which one could expect to observe Floquet-MBL time crystals experimentally.

However, as we discuss in this section, we expect the pre-thermal time crystals of this work to be more robust. In fact, we expect that (at least in the Floquet case) the time-crystals can actually be *stabilized* in open systems so that the oscillations actually continue *forever* for *any* initial state (in contrast to the case of isolated systems, in

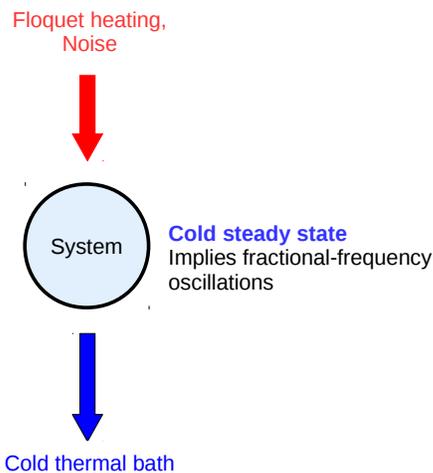


FIG. 2. So long as the energy inflow due to noise and periodic driving is balanced by the outflow to a cold thermal bath, giving a low-energy steady state, oscillations at a fraction of the drive frequency will be observed.

which, as discussed previously, the oscillations continue only up to some very long time, and only for some initial states). The idea, as depicted in Figure 2, is that the heating due to the periodic driving, as well as classical noise sources and other stray couplings to an environment, can be counteracted by cooling from a coupling to a sufficiently cold thermal bath. Provided that the resulting steady-state has sufficiently low energy (for some appropriate measure of “energy” in the driven system), we will argue that that oscillations at a fraction of the drive frequency will be observed in this steady state.

First we need to clarify what we mean by “energy” and “steady state” in the Floquet context. Let $H_S(t)$ be the time-evolution of the system alone (not taking to account the coupling to the environment.) We define the Floquet operator $U_f = \mathcal{T} \exp\left(-i \int_0^T H_S(t) dt\right)$. Recall that in the regime discussed in Section III, where λ as defined there satisfies $\lambda T \ll 1$, we can write $H_S(t) = \tilde{H}_S(t) + V(t)$. Here $V(t)$ is a very weak residual perturbation, and $\tilde{H}_S(t)$ is such that, if we define the approximate Floquet operator by $\tilde{U}_f = \mathcal{T} \exp\left(-i \int_0^T \tilde{H}_S(t) dt\right)$, then it can be expressed, following a local unitary time-independent change of basis (which we will here set to 1 for notational simplicity), as $\tilde{U}_f = X e^{-iDT}$, where $X^2 = 1$ and D is a quasi-local Hamiltonian D that commutes with X . In particular, we have $\tilde{U}_f^2 = e^{-2iDT}$. This implies that we can make a time-dependent local unitary change of basis $W(t)$, periodic with period $2T$ and satisfying $W(0) = 1$, such that the transformed Hamiltonian, which is related to $\tilde{H}_S(t)$ according to

$$\tilde{H}'_S = W H_S W^\dagger + i[\partial_t W] W^\dagger, \quad (40)$$

is time-independent and equal to D . Therefore, in this

new reference frame, it is clear that we should refer to the expectation value of D as “energy”. We emphasize that we have not gotten rid of the time-dependence completely: even in the new reference frame the residual driving term $V(t)$, as well as any couplings to the environment, will still be time-dependent. (Due to the time-dependent change of basis, the latter will gain a time-dependence even if it was originally time-independent.)

The steady state is now determined by some balance between the residual periodic driving $V(t)$, the classical noise, and the coupling to the environment. We leave a detailed analysis of this open system process for future work⁹⁸, but we expect that in a suitable regime the energy-density of the steady state will be low. We will now explain why this implies oscillations (which are observed in the *original* reference frame, not the rotating one defined above.)

Consider a short-range correlated steady state ρ whose energy density with respect to D is small. Recall that in Section III A we argued that if ρ is a thermal state it must spontaneously break the symmetry generated by X , and it follows that under \tilde{U}_f it oscillates at twice the drive frequency. Of course, for an open system the steady-state need not be thermal, and time evolution of the open system is not exactly given by \tilde{U}_f . However, as we prove in Appendix C, even non-thermal states must fail to be invariant under the symmetry X if their energy density with respect to D is sufficiently small, provided that they satisfy a physically reasonable “thermalizability” condition. Moreover, if $\lambda T \ll 1$ (so that we can approximate $\tilde{U}_f \approx X$), and the coupling to the environment sufficiently weak, then the resulting state after one time period is approximately given by $X\rho X^\dagger$, which by the preceding discussion is *not* the same as ρ . (We make this argument more precise in Appendix C.) Thus, provided that the energy of the steady-state is sufficiently small, it does not return to itself after one time period, and oscillations with period $2T$ will be observed.

Generic baths will destroy continuous-time time crystals. The difference with the discrete-time case is the existence of an extra variable characterizing thermal states of D ; namely, the chemical potential μ . This extra variable is needed because of the presence of the hidden $U(1)$ symmetry in the continuous-time regime. (There is no analogous variable when the hidden symmetry is *discrete*.) Thus, one certainly cannot make any statement that all low-energy states of D oscillate, because, in particular, a *thermal* state of D in which the electrochemical potential $\mu - u = 0$ does not oscillate. A coupling to a generic bath will not preserve the hidden $U(1)$ symmetry, and thus to the extent that the steady state of an open system process is close to a thermal state of D , we in fact expect it to have $\mu - u = 0$, since this corresponds to minimizing the free energy.

In principle, one could fine-tune the bath so that it respects the symmetry. This would allow the time crystal to survive, but is clearly contrived. One might wonder whether the bath itself could also pre-thermalize: if we

could consider the bath to be included in the Hamiltonian (34) then it could have an approximate U(1) symmetry along with the rest of the system. This would require the local terms in the bath Hamiltonian to be much smaller than the coupling u in Eq. (34). However, for most of the physically relevant baths that one would want to consider (for example, phonons), the local terms in the bath Hamiltonian are in fact unbounded.

VI. PRE-THERMALIZED FLOQUET TOPOLOGICAL PHASES

We can also apply our general results of Section II to Floquet symmetry-protected (SPT) and symmetry-enriched (SET) topological phases, even those which don't exist in stationary systems. (We will henceforth use the abbreviation SxT to refer to either SPT or SET phases.)

As was argued in Refs. 81 and 82, any such phase protected by symmetry G is analogous to a topological phase of a *stationary* system protected by symmetry $\mathbb{Z} \rtimes G$, where the extra \mathbb{Z} corresponds to the time translation symmetry. Here the product is semi-direct for anti-unitary symmetries and direct for unitary symmetries. For simplicity, here we will consider only unitary symmetries. Similar arguments can be made for anti-unitary symmetries.

We will consider the class of phases which can still be realized when the \mathbb{Z} is refined to \mathbb{Z}_N . That is, the analogous stationary phase can be protected by a unitary representation $W(\tilde{g})$ of the group $\tilde{G} = \mathbb{Z}_N \times G$. Then, in applying the general result of Section II, we will choose $H_0(t)$ such that its time evolution over one time cycle is equal to $X \equiv W(\mathbb{T})$, where \mathbb{T} is the generator of \mathbb{Z}_N . Then it follows that, for a generic perturbation V of small enough local strength λ , there exists a local unitary rotation \mathcal{U} (commuting with all the symmetries of U_f) such that $U_f \approx \tilde{U}_f$, where $\tilde{U}_f = \mathcal{U} X e^{-iDT} \mathcal{U}^\dagger$, D is a quasi-local Hamiltonian which commutes with X , and \tilde{U}_f well describes the dynamics until the almost exponentially large heating time t_* .

Now let us additionally assume (since we want to construct a Floquet-SxT protected by the symmetry G , plus time-translation) that the Floquet operator U_f is chosen such that it has the symmetry G . Specifically, this means that it is generated by a periodic time evolution $H(t)$ such that, for all $g \in G$, $W(g)H(t)W(g)^{-1}$. By inspection of the explicit construction for \mathcal{U} and D (see Appendix A), it is easy to see that in this case \mathcal{U} is a symmetry-respecting local unitary with respect to $W(g)$, and D commutes with $W(g)$. That is, the rotation by \mathcal{U} *preserves* the existing symmetry G as well as revealing a new \mathbb{Z}_N symmetry generated by X (which in the original frame was “hidden”).

Therefore, we can choose D to be a Hamiltonian whose ground state is in the *stationary* SxT phase protected by $\mathbb{Z}_N \times G$. It follows (by the same arguments discussed in

Ref. 81 for the MBL case) that the ground state D will display the desired Floquet-SxT order under the time evolution generated by $\mathcal{U}^\dagger U_f \mathcal{U} = X e^{-iDT}$. Furthermore, since Floquet-SxT order is invariant under symmetry-respecting local unitaries, the ground state of $\mathcal{U} D \mathcal{U}^\dagger$ will display the desired Floquet-SxT order under U_f .

We note, however, that topological order, in contrast to symmetry-breaking order, does not exist at nonzero temperature (in clean systems, for spatial dimensions $d < 4$). Thus, for initial state mean energies $\langle D \rangle$ that corresponds to temperatures β^{-1} satisfying $0 < \beta^{-1} \ll \Delta$, where Δ is the bulk energy gap, the system will exhibit exponentially-small corrections $\sim e^{-\beta\Delta}$ to the quantized values that would be observed in the ground state. This is no worse than the situation in thermal equilibrium where, for instance, the Hall conductance is not precisely quantized in experiments, but has small corrections $\sim e^{-\beta\Delta}$. However, preparing such an initial state will be more involved than for a simple symmetry-breaking phase. For this reason it is more satisfactory to envision cooling the system by coupling to a thermal bath, as discussed in Section V, which is analogous to how topological phases are observed in thermal equilibrium experiments – by refrigeration.

VII. DISCUSSION

In this paper, we have described how time crystal behavior can be observed in the pre-thermal regime of driven and undriven quantum systems. This greatly increases the set of experimental systems in which time crystal behavior can be observed, since, as opposed to previous proposals, we do not require many-body localization to robustly prevent the system from heating to infinite temperature. While many-body localization has been observed in experiments^{99–101}, the ideas put forward in this paper significantly reduce experimental requirements as strong disorder is not required.

Our Theorem 1 states that oscillations can be observed to nearly exponentially-late times, provided that the drive frequency is sufficiently high. However, the rigorous bound given in the theorem – which requires a drive frequency $\sim 10^3$ times larger than the local couplings in the time-dependent Hamiltonian – may not be tight. Therefore, it would be interesting to check numerically whether long-lived oscillations are observed in systems with drive frequency only moderately larger than the local couplings. This may be challenging in small systems, in which there isn't a large separation of energy scales between the local coupling strength and the width of the many-body spectrum (which the frequency should certainly not exceed). In one-dimensional systems, oscillations will not be observed to exponentially-long (in the drive frequency) times, but will have a finite correlation time for any non-zero energy density initial state. However, there will be a universal quantum critical regime in which the correlation time will be the inverse effective

temperature.

Although naive application of Theorem 1 suggests that the ideal situation is the one in which the drive frequency becomes infinitely large, in practice very high-frequency driving will tend to excite high energy modes that were ignored in constructing the model lattice Hamiltonian. For example, if the model Hamiltonian describes electrons moving in a periodic potential in the tight-binding approximation, high frequency driving would excite higher orbitals that were excluded. Thus, the driving frequency Ω needs to be much greater than the local energy scales of the degrees of freedom included in the model Hamiltonian (except for one particular coupling, as discussed in Section III), but also much less than the local energy scales of the degrees of freedom not included. (One cannot simply include *all* degrees of freedom in the model Hamiltonian, because then the norm of local terms would be unbounded, and Theorem 1 would not apply.)

In the case of undriven systems, we have shown that continuous time-translation symmetry breaking can similarly occur on nearly exponentially-long time intervals even without any fine-tuning of the Hamiltonian, provided that there is a large separation of scales in the Hamiltonian. We show how in certain cases this can be described in terms of approximate Goldstone bosons associated with the spontaneously-broken time-translation symmetry.

Our analysis relied on the construction of hidden approximate symmetries that are present in a pre-thermal regime. The analogous symmetries in MBL systems, where they are exact, were elucidated in the interesting work of von Keyserlingk et al.¹⁵. In the pre-thermal Floquet time crystal discussed here, the symmetry generated by the operator $U^\dagger XU$ is enslaved to time-translation symmetry since, in the absence of fine-tuning, such a symmetry exists only if time-translation symmetry is present. (That is, if we add fields to the Hamiltonian that are periodic with period nT and not period T , then the hidden symmetry no longer exists.) Moreover, this symmetry is broken if and only if time-translation symmetry is broken. (Similar statements hold in the MBL case¹⁵.) Since the hidden symmetry generated by $U^\dagger XU$ acts on the order parameter at stroboscopic times in the same way as time-translation by T (a single period of the drive), it does not constrain correlation functions any more than they already are by time-translation symmetry. The same observation holds for the approximate symmetry generated by L_z in the undriven case.

However, there are systems in which the time crystal behavior actually does “piggyback” off another broken symmetry. This does require fine-tuning, since it is necessary to ensure that the system possesses the “primary” symmetry, but such tuning may be physically natural (e.g. helium atoms have a very long lifetime, leading to a U(1) symmetry). The broken symmetry allows a many-body system to effectively become a few-body system. Thus, time crystal behavior can occur in such systems for the same reason that oscillations can per-

sist in few-body systems. Oscillating Bose condensates (e.g. the AC Josephson effect and the model of Ref. 102) can, thus, be viewed as fine-tuned time crystals. They are not stable to arbitrary time-translation symmetry-respecting perturbations; a perturbation that breaks the “primary” symmetry will cause the oscillations to decay. Indeed, most few-body systems are actually many-body systems in which a spontaneously-broken symmetry approximately decouples a few degrees of freedom. A pendulum is a system of 10^{23} atoms that can be treated as a single rigid body due to spontaneously-broken spatial translational symmetry: its oscillations owe their persistence to this broken symmetry, which decouples the center-of-mass position from the other degrees of freedom.

With the need for MBL obviated by pre-thermalization, we have opened up the possibility of time crystals in open systems, in which MBL is impossible^{37–45}. In fact, since the results of Appendix C show that TTSB can occur in non-thermal states, it is possible for the coupling to a cold bath to counteract the heating effect that would otherwise bring an end to the pre-thermal state at time t_* . This raises the possibility of time crystals that survive to infinite times in non-equilibrium steady states; the construction of such states is an interesting avenue for future work.

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Appendix A: Rigorous proof of pre-thermalization results

a. Definition of the norm

Let’s suppose, for the sake of concreteness, that we have a spin system with a local time-dependent Hamiltonian of the form:

$$\begin{aligned} H(t) &= \sum_{i,j} J_{i,j}^{\alpha\beta}(t) S_i^\alpha S_j^\beta + \sum_{i,j,k} K_{i,j,k}^{\alpha\beta\gamma}(t) S_i^\alpha S_j^\beta S_k^\gamma + \dots \\ &= \sum_p \sum_{p\text{-tuples}} A_{i_1, \dots, i_p} \end{aligned} \tag{A1}$$

Here $\alpha = x, y, z$ are the components of the spins, and i, j, k are lattice sites. In the first line, we have explicitly written the 2-site and 3-site terms; the \dots represents terms up to n -site terms, for some finite n . It is assumed that these interactions have finite range $r \geq n$ such that all of the sites in a k -site term are within distance r . In

the second line, we have re-expressed the Hamiltonian in a more generic form in terms of p -site terms A_{i_1, \dots, i_p} with $i_1 \neq \dots \neq i_p$. To avoid clutter, we have not explicitly denoted the t -dependence of A_{i_1, \dots, i_p} . We define the local instantaneous norm $\|A_{i_1, \dots, i_p}\|_n$ according to

$$F\|A_{i_1, \dots, i_p}\|_n^{\text{inst}} \equiv e^{p\kappa_n} \|A_{i_1, \dots, i_p}\| \quad (\text{A2})$$

where $\|A_{i_1, \dots, i_p}\|$ is the operator norm of A_{i_1, \dots, i_p} at a given instant of time t and

$$\kappa_n \equiv \kappa_1/[1 + \ln n]. \quad (\text{A3})$$

We make this choice of n -dependence of κ_n , following Ref. 47 for reasons that will be clear later. We then average the instantaneous norm over one cycle of the drive:

$$\|A_{i_1, \dots, i_p}\|_n \equiv \frac{1}{T} \int_0^T dt \|A_{i_1, \dots, i_p}\|_n^{\text{inst}} \quad (\text{A4})$$

It is only in this step that we differ from Abanin et al.⁴⁷, who consider the supremum over t rather than the average. In analyzing the Floquet operator, i.e. the evolution due to H at stroboscopic times, it is the total effect of H , which is determined by its integral over a cycle, that concerns us. Error terms that act over a very short time, even if they are relatively strong, have little effect on the Floquet operator so long as their norm, as defined above, is small. Finally, we define the global time-averaged norm of the Hamiltonian H :

$$\|H\|_n \equiv \sup_j \sum_p \sum_{p\text{-tuples}} \left[\sum_k \delta_{j, i_k} \right] \|A_{i_1, \dots, i_p}\|_n \quad (\text{A5})$$

The term in square braces restricts the sum to p -tuples that contain the site j .

b. More technical statement of Theorem 1

Theorem 1 stated above will follow from the following slightly more technical formulation. For notational simplicity we work in units with $T = 1$.

Theorem 1'. *Consider a periodically-driven system with Floquet operator:*

$$U_f = \mathcal{T} \exp \left(-i \int_0^1 [H_0(t) + V(t)] dt \right), \quad (\text{A6})$$

where $X \equiv \mathcal{T} \exp \left(-i \int_0^1 H_0(t) \right)$ satisfies $X^N = 1$ for some integer N , and we assume that H_0 can be written as a sum $H_0(t) = \sum_i h_i(t)$ of terms acting on single sites i . Define $\lambda \equiv \|V\|_1$. Then there exists a sequence of quasi-local A_n such that, defining $\mathcal{U}_n = e^{-iA_n} \dots e^{-iA_1}$, we have

$$\mathcal{U}_n U_f \mathcal{U}_n^\dagger = X \mathcal{T} \exp \left(-i \int_0^1 [D_n + E_n + V_n(t)] dt \right), \quad (\text{A7})$$

where $[D_n, X] = 0$; D_n, E_n are independent of time; and

$$\|V_n\|_n, \|E_n\|_n \leq 2K_n \lambda^n, \quad (\text{A8})$$

$$\|A_n\|_n \leq (N+1)K_n \lambda^n, \quad (\text{A9})$$

$$\|D_n - D_{n-1}\|_n \leq K_n \lambda^n, \quad (\text{A10})$$

where we have defined $\lambda \equiv \|V\|_1$, and

$$K_n = C^{n-1} \prod_{k=1}^{n-1} m(k), \quad C = 2(N+3)(N+4),$$

$$m(n) = \frac{18}{\kappa_{n+1}(\kappa_n - \kappa_{n+1})}. \quad (\text{A11})$$

These bounds hold provided that $n \leq n_*$, with

$$n_* = \frac{\lambda_0/\lambda}{[1 + \log(\lambda_0/\lambda)]^3}, \quad \lambda_0 = (36C)^{-1} \quad (\text{A12})$$

and provided that

$$\lambda < \frac{\mu}{N+3}, \quad \mu \approx 0.07. \quad (\text{A13})$$

Theorem 1 follows from Theorem 1', because n_* is chosen such that $n \leq n_*$ implies $Cm(n) \leq \frac{1}{2\lambda}$. It then follows that $K_{n+1}\lambda^{n+1}/(K_n\lambda^n) = Cm(n)\lambda \leq \frac{1}{2}$, and hence that $K_n\lambda^n \leq \lambda/2^{n-1}$. Moreover, we obtain Eq. (9) by summing Eq. (A10), from which we see that $\|D_n - D_1\|_n \leq \sum_{k=2}^{\infty} K_k \lambda^k \leq K_2 \lambda^2 \sum_{k=2}^{\infty} (\frac{1}{2})^{k-2} = 2K_2 \lambda^2 = 2Cm(1)\lambda^2 \approx 2.9\lambda^2/\lambda_0$. (Here we use the fact that $\|\cdot\|_{n+1} \leq \|\cdot\|_n$.)

In the next subsections, we will give a proof of Theorem 1'.

c. Iterative construction

The idea is to construct the D_n, V_n, E_n, A_n discussed above iteratively. That is, suppose that at the n -th step, we have

$$\mathcal{U}_n U_f \mathcal{U}_n^\dagger \equiv U_f^{(n)} = X \mathcal{T} \exp \left(-i \int_0^1 \mathcal{H}_n(t) dt \right), \quad (\text{A14})$$

where $\mathcal{H}_n(t) = F_n + V_n(t)$, with $F_n = \int_0^T \mathcal{H}_n(t) dt$ time-independent. We will choose to separate the time-independent piece F_n according to $F_n = D_n + E_n$, where $D_n = \langle F_n \rangle$, and we have defined the symmetrization

$$\langle O \rangle = \frac{1}{N} \sum_{k=0}^{N-1} X^{-k} O X^k. \quad (\text{A15})$$

In particular, this implies that $[D_n, X] = 0$ and $\langle D_n \rangle = D_n$, and therefore $\langle E_n \rangle = \langle F_n \rangle - \langle D_n \rangle = D_n - D_n = 0$.

We will now introduce a local unitary $\mathcal{A}_n = e^{-iA_n}$, which we use to rotate the Floquet operator $U_f^{(n)}$, giving a new Floquet operator

$$U_f^{(n+1)} \equiv \mathcal{A}_n U_f^{(n)} \mathcal{A}_n^\dagger = X \mathcal{T} \exp \left(-i \int_0^1 \mathcal{H}_{n+1}(t) dt \right). \quad (\text{A16})$$

The ultimate goal, decomposing $\mathcal{H}_{n+1}(t) = D_{n+1} + E_{n+1} + V_{n+1}(t)$ as before, is to ensure that the residual error terms E_{n+1} and V_{n+1} are much smaller than E_n and V_n . This goal is achieved in two separate steps. The first step ensures that E_{n+1} is small (that is, the time-independent part of $\mathcal{H}_{n+1}(t)$ nearly commutes with X), and the second step ensures that V_{n+1} is small.

Step One.– This step proceeds similarly to the recursion relation of Abanin et al⁴⁷ for the *time-independent* case (Section 5.4 of Ref. 47). There the recursion relation was designed to make the Hamiltonian commute with its zero-th order version. This is analogous to our present goal of making the Floquet operator commute with X . Here, we adapt the analysis of Ref. 47 to the Floquet case.

We observe that

$$U_f^{(n+1)} = \mathcal{A}_n U_f^{(n)} \mathcal{A}_n^\dagger \quad (\text{A17})$$

$$= X \left[X^\dagger \mathcal{A}_n X \times \mathcal{T} \exp \left(-i \int_0^1 \mathcal{H}_n(t) dt \right) \times \mathcal{A}_n^\dagger \right], \quad (\text{A18})$$

$$= X \left[e^{-X^\dagger i A_n X} \times \mathcal{T} \exp \left(-i \int_0^1 \mathcal{H}_n(t) dt \right) \times e^{i A_n} \right] \quad (\text{A19})$$

$$= X \times \mathcal{T} \exp \left(-i \int_0^1 \mathcal{H}'_n(t) dt \right), \quad (\text{A20})$$

where

$$\mathcal{H}'_n(t) = \begin{cases} \frac{1}{a}(-A_n) & 0 \leq t \leq a \\ \frac{1}{1-2a} \mathcal{H}_n(3t-1) & a \leq t \leq (1-a), \\ \frac{1}{a}(X^\dagger A_n X) & (1-a) \leq t \leq 1, \end{cases} \quad (\text{A21})$$

(for some constant $a \in [0, 1/2]$ which can be chosen arbitrarily.) Let us decompose $\mathcal{H}'_n(t) = D'_n + V'_n(t)$, where $D'_n = \frac{1}{T} \int_0^1 \mathcal{H}'_n(t)$. Our goal will be to ensure that the time-independent part D'_n commutes with X . It turns out this can actually be achieved exactly, and in particular we can choose A_n such that $D'_n = D_n$.

To this end, we first observe that

$$D'_n = D_n + E_n + X^\dagger A_n X - A_n \quad (\text{A22})$$

We now claim that $D'_n = D_n$ if we choose

$$A_n := \frac{1}{N} \sum_{k=0}^{N-1} \sum_{p=0}^k E_n^{(p)}, \quad E_n^{(p)} = X^{-p} E X^p. \quad (\text{A23})$$

To see this, note that, by construction,

$$X^\dagger A_n X - A_n = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{p=0}^k [E_n^{(p+1)} - E_n^{(p)}] \quad (\text{A24})$$

$$= \frac{1}{N} \sum_{k=0}^{N-1} [E_n^{(k+1)} - E_n^{(k)}] \quad (\text{A25})$$

$$= -E_n + \langle E_n \rangle, \quad (\text{A26})$$

$$= -E_n, \quad (\text{A27})$$

since $\langle E_n \rangle = 0$.

Step Two.– The next step is now to find a new time-dependent Hamiltonian $\mathcal{H}_{n+1}(t)$ which gives the same unitary evolution as $\mathcal{H}'_n(t)$ over the time interval $[0, 1]$, while making the time-dependent part smaller. That is, making the decomposition $\mathcal{H}_{n+1}(t) = D_{n+1} + E_{n+1} + V_{n+1}(t)$ as before, the goal is to make V_{n+1} small. In fact, this is precisely the problem already considered by Abanin et al⁴⁷, and we can use the procedure described in Section 4.1 of that paper.

One might worry whether Step Two undoes the good work done by Step One. That is, does making V_{n+1} small come at the cost of making E_{n+1} larger again? However, this turns out not to be a problem, as the bounds we derive below will make clear.

d. Bounds on Error terms

Now we will derive bounds that quantify the success of the iterative procedure described in the previous subsection at making the residual error terms E_n and V_n small. Analysis proceeds in similar way to Abanin et al⁴⁷. We define

$$d(n) = \|D_n\|_n, \quad v(n) = \|V_n\|_n, \quad v'(n) = \|V'_n\|_n, \\ e(n) = \|E_n\|_n, \quad \delta d(n) = \|D_{n+1} - D_n\|_{n+1}, \quad (\text{A28})$$

First of all, from Eq. (A23) we have a bound on A_n :

$$\|A_n\|_n \leq \frac{N+1}{2} e(n) \quad (\text{A29})$$

From Eq. (A21) we observe that

$$V'_n(t) = \begin{cases} \frac{1}{a}(-A_n) - D_n & 0 \leq t \leq a \\ \frac{1}{1-2a}(2aD_n + E_n + V_n(3t-1)) & a \leq t \leq (1-a), \\ \frac{1}{a}(X^\dagger A_n X) - D_n & (1-a) \leq t \leq 1, \end{cases} \quad (\text{A30})$$

and hence

$$v'(n) \leq 2\|A_n\|_n + \|E_n\|_n + \|V_n\|_n + 4a\|D_n\|_n \quad (\text{A31})$$

Hence, we can send $a \rightarrow 0$ to give (using Eq. (A29))

$$v'(n) \leq (N+2)e(n) + v(n). \quad (\text{A32})$$

Then, as our construction of \mathcal{H}_{n+1} from \mathcal{H}'_n is the one described in Section 4.1 of Abanin et al, we can use their bounds

$$\|D_{n+1} + E_{n+1} - D_n\|_{n+1} \leq \epsilon_n/2 \quad (\text{A33})$$

$$v(n+1) \leq \epsilon_n \quad (\text{A34})$$

where

$$\epsilon_n = m(n)v'(n)(d(n) + 2v'(n)), \quad (\text{A35})$$

$$m(n) = \frac{18}{(\kappa_{n+1} - \kappa_n)\kappa_{n+1}}. \quad (\text{A36})$$

These bounds hold provided that

$$3v'(n) \leq \kappa_n - \kappa_{n+1} \quad (\text{A37})$$

Since $D_{n+1} - D_n = \langle D_{n+1} + E_{n+1} - D_n \rangle$, we see that

$$\delta d(n) \leq \|D_{n+1} + E_{n+1} - D_n\|_{n+1} \leq \epsilon_n/2 \quad (\text{A38})$$

and

$$e(n+1) \leq \|D_{n+1} + E_{n+1} - D_n\|_{n+1} + \|D_{n+1} - D_n\|_{n+1} \leq \epsilon_n \quad (\text{A39})$$

e. Proof of Theorem 1' by induction

The idea now is to apply the bounds of the previous subsection recursively to give bounds expressed in terms of the original Floquet operator,

$$U_f = U_f^{(1)} = \mathcal{T} \exp \left(-i \int_0^1 [H_0(t) + V(t)] dt \right) \quad (\text{A40})$$

$$= X\mathcal{T} \exp \left(-i \int_0^1 V_{\text{int}}(t) dt \right), \quad (\text{A41})$$

and in particular the quantity $\lambda \equiv \|V_{\text{int}}\|_1 = \|V\|_1$. First of all, we write $\mathcal{H}_1(t) \equiv V_{\text{int}}(t) = F_1 + V_1(t)$, where $F_1 = \int_0^1 V_{\text{int}}(t) dt$, and then separate $F_1 = D_1 + E_1$, where $D_1 = \langle F_1 \rangle$. We note that $\|F_1\|_1 \leq \lambda$, which implies that $v(1) \leq \|V_{\text{int}}\|_1 + \|F_1\|_1 \leq 2\lambda$, and $d(1) \leq \lambda$. In turn this gives $e(1) \leq \|D_1\|_1 + \|F_1\|_1 \leq 2\lambda$.

Now we proceed by induction. Suppose that we have some n such that, for all $1 \leq k \leq n$, we have

$$e(k), v(k) \leq 2K_k \lambda^k, \quad (\text{A42})$$

and for all $1 \leq k < n$,

$$\delta d(k) \leq K_{k+1} \lambda^{k+1} \quad (\text{A43})$$

where the coefficients K_k satisfy $K_{k+1}/K_k \leq \frac{1}{2\lambda}$. (The preceding discussion shows that this induction condition is satisfied for $n = 1$ with $K_1 = 1$.)

Then from Eq. (A32) we find that

$$v'(n) \leq 2c_N K_n \lambda^n, \quad c_N = N + 3, \quad (\text{A44})$$

and hence

$$\epsilon_n \leq m(n) 2c_N K_n \lambda^n (d(n) + 2c_N K_n \lambda^n). \quad (\text{A45})$$

We note that the triangle inequality and the fact that $\|\cdot\|_n$ decreases with n ensures that $d(n+1) - d(n) \leq \delta d(n)$.

Hence we can bound $d(n)$ by

$$d(n) \leq d(1) + \sum_{k=1}^{n-1} \delta d(k) \quad (\text{A46})$$

$$\leq \lambda + \sum_{k=1}^{n-1} K_{k+1} \lambda^{k+1} \quad (\text{A47})$$

$$= \sum_{k=1}^n K_k \lambda^k \quad (\text{A48})$$

$$\leq \sum_{k=1}^n \lambda \left(\frac{1}{2} \right)^{k-1} \quad (\text{A49})$$

$$\leq 2\lambda \quad (\text{A50})$$

In Eq. (A49), we used the inequality $K_{k+1}/K_k \leq 1/(2\lambda)$. This same inequality also ensures that $K_n \lambda^n \leq \lambda$, so inserting into Eq. (A45) gives

$$\begin{aligned} \epsilon_n &\leq m(n) 2c_N K_n (2 + 2c_N) \lambda^{n+1} \\ &\equiv 2Cm(n) K_n \lambda^{n+1} \\ &\equiv K_{n+1} \lambda^{n+1}. \end{aligned} \quad (\text{A51})$$

Here we chose

$$K_{n+1} = Cm(n) K_n, \quad C = 2c_N(1 + c_N). \quad (\text{A52})$$

Next we need to examine the conditions under which Eq. (A37) holds. Given the bounds on $v'(n)$ and using the inequality $K_n \lambda^n \leq \lambda(1/2)^{n-1}$, it is sufficient to demand that

$$3c_N (1/2)^{n-1} \lambda \leq \kappa_{n+1} - \kappa_n, \quad (\text{A53})$$

or in other words

$$\lambda \leq \frac{1}{3c_N} \max_{n \in \mathbb{N}} [2^{n-1} (\kappa_{n+1} - \kappa_n)] = \frac{1}{3c_N} (\kappa_2 - \kappa_1) \approx \frac{0.14\kappa_1}{N+3}. \quad (\text{A54})$$

Provided that Eq. (A54) holds, we then find that

$$\delta d(n), v(n+1)/2, e(n+1)/2 \leq K_{n+1} \lambda^{n+1}. \quad (\text{A55})$$

Therefore, we can continue the induction provided that $K_{n+1}/K_n \leq \frac{1}{2\lambda}$. Since $K_{n+1}/K_n = Cm(n)$, this is true provided that $n \leq n_*$. This completes the proof of Theorem 1'.

Appendix B: Proof of phase-winding when a U(1) symmetry is spontaneously broken

Here we intend to prove the claim made in Section IV A above that the expectation value

$$\text{Tr}(\rho_X e^{itK} \Phi e^{-itK}) \equiv g_X(t) \quad (\text{B1})$$

must be independent of time t , where we have defined $K \equiv D - \mu L$ and $\rho_X \equiv \lim_{\epsilon \rightarrow 0^+} \frac{1}{Z} e^{-\beta(K + \epsilon X)}$. The idea

is to make a connection with results of Ref. 10; however, these were expressed in terms of *two-point* correlation functions, and also did not have the ϵX term in the definition of the density matrix. To make a connection, we assume that the symmetric density matrix $\rho = \frac{1}{Z} e^{-\beta K}$ can be recovered by symmetrizing a symmetry-breaking

state,

$$\rho = \frac{1}{2\pi} \int_0^{2\pi} e^{-i\theta L} \rho_X e^{i\theta L} d\theta, \quad (\text{B2})$$

and that the symmetry-breaking state ρ_X is short-range correlated. Now we calculate the two-point correlation function (where $\Phi(x)$ and $\Phi(y)$ are two operators acting at different spatial locations x and y)

$$f(t) = \text{Tr}[\rho e^{itK} \Phi(x) e^{itK} \Phi^\dagger(y)] \quad (\text{B3})$$

$$= \frac{1}{2\pi} \int_0^{2\pi} d\theta \text{Tr}[e^{-i\theta L} \rho_X e^{i\theta L} e^{itK} \Phi(x) e^{-itK} \Phi(y)] \quad (\text{B4})$$

$$= \frac{1}{2\pi} \int_0^{2\pi} d\theta \text{Tr}[\rho_X e^{itK} \{e^{i\theta L} \Phi(x) e^{-i\theta L}\} e^{-itK} \{e^{i\theta L} \Phi^\dagger(y) e^{-i\theta L}\}] \quad (\text{B5})$$

$$= \text{Tr}[\rho_X \{e^{-itK} \Phi(x) e^{itK}\} \Phi^\dagger(y)] \quad (\text{B6})$$

$$= g_X(t) [g_X(0)]^*, \quad (\text{B7})$$

where we used the fact that L and K commute and that $e^{i\theta L} \Phi e^{-i\theta L} = e^{i\theta} \Phi$. In the last line we sent $|x - y| \rightarrow \infty$ and used the assumption that ρ_X has short-range correlations.

Now, the theorem of Ref. 10 rigorously proves that the function $f(t)$ must be independent of time. Hence, unless $g_X(0) = 0$, we conclude that $g_X(t)$ must be independent of time. (If $g_X(0) = 0$ but $g_X(t)$ is not independent of time then there must be some t such that $g_X(t) \neq 0$. Then we can just relabel the time-coordinate so that $g_X(0) \neq 0$ and repeat the argument.)

Appendix C: Spontaneous symmetry-breaking for non-thermal states

Let D be a quasi-local Hamiltonian for which the thermal states spontaneously break an on-site \mathbb{Z}_N symmetry generated by X for energy densities $e < e_c$. More precisely, what we mean is the following, where we define the local distance between two states on a region A according to

$$\|\rho_1 - \rho_2\|_A = \|(\rho_1)_A - (\rho_2)_A\|_1 \quad (\text{C1})$$

where $\|\cdot\|_1$ is the trace norm, and $(\rho)_A = \text{Tr}_{A^c} \rho$ is the reduced state of ρ on A .

Assumption 1 (Spontaneous symmetry-breaking). There exists some finite region A and some $\gamma > 0$, such that, for any short-range correlated thermal state ρ_τ with energy density $e < e_c$, we have $\|\rho_\tau - X^k \rho_\tau X^{-k}\|_A \geq \gamma$ for all $0 < k < N$.

Now let ρ be *any* state (not necessarily thermal) such that the energy density $\epsilon \equiv \langle D \rangle_\rho / V < e_c$ (with V the volume of the system.) We assume the following *thermalizability* condition, which roughly states that ρ can thermalize when time-evolved under D . More precisely:

Assumption 2 (Thermalizability). There exist a time t_1 and a short-range correlated thermal state ρ_τ with the same energy density as ρ , such that $\|\rho(t_1) - \rho_\tau\|_A \leq \gamma/8$, where $\rho(t) = e^{-iDt_1} \rho e^{iDt_1}$.

From Assumptions 1 and 2 we derive the following lemma, which quantifies the sense in which the state ρ must break the symmetry.

Lemma 1. *There exists a finite region A' such that $\|\rho - X^k \rho X^{-k}\|_{A'} \geq 3\gamma/4$.*

Proof. From the triangle inequality it follows that

$$\|\rho(t_1) - X^k \rho(t_1) X^{-k}\|_A \quad (\text{C2})$$

$$\geq \|\rho_\tau - X^k \rho_\tau X^{-k}\|_A - \|\rho(t_1) - X^k \rho(t_1) X^{-k} - (\rho_\tau - X^k \rho_\tau X^{-k})\|_A \quad (\text{C3})$$

$$\geq \gamma - 2\gamma/8 \quad (\text{C4})$$

$$= 3\gamma/4. \quad (\text{C5})$$

Using the characterization of the trace norm as

$$\|\rho\|_1 = \sup_{\hat{\delta}: \|\hat{\delta}\|=1} |\langle \hat{\delta} | \rho \rangle|, \quad (\text{C6})$$

it follows that there exists an operator $\hat{\delta}_A$ supported on A , with $\|\hat{\delta}_A\| = 1$, such that $|\langle X^{-k} \hat{\delta}_A X^k - \hat{\delta}_A \rangle_{\rho(t_1)}| \geq 3\gamma/4$. Now, since D is quasi-local, it must obey a Lieb-Robinson bound^{103,104}, which implies that there exists a local operator $\hat{O}_{A'}$ supported on a finite region A' such that $\|\hat{\delta}(t_1) - \hat{O}_{A'}\| \leq \gamma/8$, where $\hat{\delta}(t_1) = e^{iDt_1} \hat{\delta} e^{-iDt_1}$. Hence we see that

$$|\langle X^{-k} \hat{O}_{A'} X^k - \hat{O}_{A'} \rangle_{\rho}| \quad (\text{C7})$$

$$\geq -\gamma/4 + |\langle X^{-k} \hat{\delta}_A(t_1) X^k - \hat{\delta}_A(t_1) \rangle_{\rho}| \quad (\text{C8})$$

$$= -\gamma/4 + |\langle X^{-k} \hat{\delta}_A X^k - \hat{\delta}_A \rangle_{\rho(t_1)}| \quad (\text{C9})$$

$$\geq -\gamma/4 + 3\gamma/4. \quad (\text{C10})$$

$$= \gamma/2. \quad (\text{C11})$$

To get to line Eq. (C9), we used the fact that X and D commute. The lemma follows. \square

Now consider a system which in isolation would evolve under a time-dependent Hamiltonian $H(t)$, which is periodic with period T . We assume that $H(t)$ exhibits the pre-thermalization phenomena discussed in the main text. That is, we assume that the Floquet operator can be approximated according to $U_f \approx \tilde{U}_f = X e^{-iDT}$, where D is quasi-local and commutes with X , and where U_f is close to \tilde{U}_f in the sense that

$$\|U_f^\dagger O_{A'} U_f - \tilde{U}_f^\dagger O_{A'} \tilde{U}_f\| \leq \frac{\gamma}{8} \|O_{A'}\| \quad (\text{C12})$$

for any operator $O_{A'}$ supported on A' .

Let $\rho_{\text{open}}(t)$ be the reduced state of the system (tracing out the bath) at time t , taking into account the system-bath coupling, and we assume that $\rho_{\text{open}}(0) \equiv \rho$ satisfies Assumption 2 above. We assume the coupling to the bath is sufficiently weak, in the following sense:

Assumption 3 (Weak coupling). For any time $0 \leq t \leq T$, we have $\|\rho_{\text{open}}^{\text{int}}(t) - \rho\|_{A'} \leq \gamma/8$.

Here we defined the interaction picture state $\rho_{\text{open}}^{\text{int}}(t) = U(0, t)^{-1} \rho_{\text{open}}(t) U(0, t)$, where $U(0, t)$ is the time evolution generated by $H(t)$. If we were to set the coupling to the bath to zero then the state $\rho_{\text{open}}^{\text{int}}(t)$ would be constant in time, so Assumption 3 corresponds to weak coupling. Finally, we will assume that the strength of DT is small enough so that

Assumption 4. For any observable $O_{A'}$ supported on A' , we have

$$\|e^{-iDT} O_{A'} e^{iDT} - O_{A'}\| \leq \frac{\gamma}{8} \|O_{A'}\| \quad (\text{C13})$$

This will always be true in the regime of interest, $\lambda T \ll 1$ (where λ is as defined in Section II), because $\|D\|_{n_*}$ is $O(\lambda)$ [see Eq. (9) in Theorem 1].

From the above assumptions we can now derive our main result:

Theorem 3.

$$\|\rho_{\text{open}}(T) - \rho\|_{A'} \geq \gamma/8. \quad (\text{C14})$$

Proof.

$$\|\rho_{\text{open}}(T) - \rho\|_{A'} \quad (\text{C15})$$

$$= \|U_f \rho_{\text{open}}^{\text{int}}(T) U_f^\dagger - \rho\|_{A'} \quad (\text{C16})$$

$$\geq -\gamma/8 + \|\tilde{U}_f \rho_{\text{open}}^{\text{int}}(T) \tilde{U}_f^\dagger - \rho\|_{A'} \quad (\text{C17})$$

$$= -\gamma/8 + \|e^{-iDT} \rho_{\text{open}}^{\text{int}}(T) e^{iDT} - X^\dagger \rho X\|_{A'} \quad (\text{C18})$$

$$\geq -\gamma/8 - \gamma/8 + \|\rho_{\text{open}}^{\text{int}}(T) - X^\dagger \rho X\|_{A'} \quad (\text{C19})$$

$$\geq -\gamma/8 - \gamma/8 - \gamma/8 + \|\rho - X^\dagger \rho X\|_{A'} \quad (\text{C20})$$

$$\geq -\gamma/8 - \gamma/8 - \gamma/8 + \gamma/2. \quad (\text{C21})$$

$$= \gamma/8. \quad (\text{C22})$$

\square

In other words, the state of the open system at times $t = T$ and $t = 0$ are locally distinguishable. That is, for the stated assumptions, the state of the system does not synchronize with the drive and time translation symmetry is spontaneously broken.

¹ F. Wilczek, Phys. Rev. Lett. **109**, 160401 (2012), arXiv:1202.2539 [quant-ph].

² A. Shapere and F. Wilczek, Phys. Rev. Lett. **109**, 160402 (2012), arXiv:1202.2537 [cond-mat.other].

³ T. Li, Z.-X. Gong, Z.-Q. Yin, H. T. Quan, X. Yin, P. Zhang, L.-M. Duan, and X. Zhang, Phys. Rev. Lett. **109**, 163001 (2012).

⁴ P. Bruno, Phys. Rev. Lett. **110**, 118901 (2013).

⁵ P. Bruno, Phys. Rev. Lett. **111**, 029301 (2013).

⁶ P. Bruno, Phys. Rev. Lett. **111**, 070402 (2013), arXiv:1306.6275.

⁷ P. Nozières, Eur. Phys. Lett. **103**, 57008 (2013).

⁸ G. E. Volovik, JETP Lett. **98**, 491 (2013),

arXiv:1309.1845.

⁹ K. Sacha and D. Delande, “Anderson localization in the time domain,” arXiv:1603.05827.

¹⁰ H. Watanabe and M. Oshikawa, Phys. Rev. Lett. **114**, 251603 (2015), arXiv:1410.2143 [cond-mat.stat-mech].

¹¹ D. V. Else, B. Bauer, and C. Nayak, “Floquet Time Crystals,” (2016), arXiv:1603.08001.

¹² A. Chandran and S. L. Sondhi, “Interaction stabilized steady states in the driven O(N) model,” (2015), arXiv:1506.08836.

¹³ V. Khemani, A. Lazarides, R. Moessner, and S. L. Sondhi, “On the phase structure of driven quantum systems,” arXiv:1508.03344.

- ¹⁴ C. W. von Keyserlingk and S. L. Sondhi, “1D Many-body localized Floquet systems II: Symmetry-Broken phases,” ([arXiv:1602.06949](#)).
- ¹⁵ C. W. von Keyserlingk, V. Khemani, and S. L. Sondhi, “Emergent Symmetries and Absolutely Stable phases of Floquet systems,” (2016), [arXiv:1605.00639](#).
- ¹⁶ L. Jiang, T. Kitagawa, J. Alicea, A. R. Akhmerov, D. Pekker, G. Refael, J. I. Cirac, E. Demler, M. D. Lukin, and P. Zoller, *Physical Review Letters* **106**, 220402 (2011), [arXiv:1102.5367 \[cond-mat.quant-gas\]](#).
- ¹⁷ M. Thakurathi, A. A. Patel, D. Sen, and A. Dutta, *Phys. Rev. B* **88**, 155133 (2013), [arXiv:1303.2300 \[cond-mat.mes-hall\]](#).
- ¹⁸ D. M. Basko, I. L. Aleiner, and B. L. Altshuler, *Annals of Physics* **321**, 1126 (2006).
- ¹⁹ D. M. Basko, I. L. Aleiner, and B. L. Altshuler, “On the problem of many-body localization,” [arXiv:cond-mat/0602510](#).
- ²⁰ V. Oganesyan and D. A. Huse, *Phys. Rev. B* **75**, 155111 (2007).
- ²¹ M. Žnidarič, T. Prosen, and P. Prelovšek, *Phys. Rev. B* **77**, 064426 (2008).
- ²² A. Pal and D. A. Huse, *Phys. Rev. B* **82**, 174411 (2010).
- ²³ J. H. Bardarson, F. Pollmann, and J. E. Moore, *Phys. Rev. Lett.* **109**, 017202 (2012).
- ²⁴ D. A. Huse and V. Oganesyan, *Phys. Rev. B* **90**, 174202 (2013), [arXiv:1305.4915](#).
- ²⁵ B. Bauer and C. Nayak, *J. Stat. Mech: Theor. Exp.* **9**, 09005 (2013), [arXiv:1306.5753 \[cond-mat.dis-nn\]](#).
- ²⁶ M. Serbyn, Z. Papić, and D. A. Abanin, *Phys. Rev. Lett.* **110**, 260601 (2013), [arXiv:1304.4605](#).
- ²⁷ M. Serbyn, Z. Papić, and D. A. Abanin, *Phys. Rev. Lett.* **111**, 127201 (2013), [arXiv:1305.5554 \[cond-mat.dis-nn\]](#).
- ²⁸ D. A. Huse, R. Nandkishore, and V. Oganesyan, *Phys. Rev. B* **90**, 174202 (2014).
- ²⁹ D. A. Abanin, W. D. Roeck, and F. Huveneers, “A theory of many-body localization in periodically driven systems,” (2014), [arXiv:1412.4752](#).
- ³⁰ P. Ponte, A. Chandran, Z. Papić, and D. A. Abanin, *Ann. Phys.* **353**, 196 (2015), [arXiv:1403.6480 \[cond-mat.dis-nn\]](#).
- ³¹ P. Ponte, Z. Papić, F. Huveneers, and D. A. Abanin, *Phys. Rev. Lett.* **114**, 140401 (2015), [arXiv:1410.8518 \[cond-mat.dis-nn\]](#).
- ³² A. Lazarides, A. Das, and R. Moessner, *Phys. Rev. Lett.* **115**, 030402 (2015), [arXiv:1410.3455 \[cond-mat.stat-mech\]](#).
- ³³ T. Iadecola, L. H. Santos, and C. Chamon, *Phys. Rev. B* **92**, 125107 (2015), [arXiv:1503.07871 \[cond-mat.str-el\]](#).
- ³⁴ L. D’Alessio and M. Rigol, *Phys. Rev. X* **4**, 041048 (2014), [arXiv:1402.5141](#).
- ³⁵ A. Lazarides, A. Das, and R. Moessner, *Phys. Rev. E* **90**, 012110 (2014), [arXiv:1403.2946](#).
- ³⁶ P. Ponte, A. Chandran, Z. Papić, and D. A. Abanin, *Ann. Phys.* **353**, 196 (2015), [arXiv:1403.6480](#).
- ³⁷ E. Levi, M. Heyl, I. Lesanovsky, and J. P. Garrahan, Preprint (2015), [arXiv:1510.04634](#).
- ³⁸ M. H. Fischer, M. Maksymenko, and E. Altman, *Physical Review Letters* **116**, 160401 (2016), [arXiv:1512.02669 \[cond-mat.str-el\]](#).
- ³⁹ R. Nandkishore, S. Gopalakrishnan, and D. A. Huse, *Phys. Rev. B* **90**, 064203 (2014).
- ⁴⁰ S. Gopalakrishnan and R. Nandkishore, *Phys. Rev. B* **90**, 224203 (2014).
- ⁴¹ S. Johri, R. Nandkishore, and R. N. Bhatt, *Phys. Rev. Lett.* **114**, 117401 (2015).
- ⁴² R. Nandkishore, *Phys. Rev. B* **92**, 245141 (2015), [arXiv:1506.05468](#).
- ⁴³ X. Li, S. Ganeshan, J. H. Pixley, and S. Das Sarma, *Phys. Rev. Lett.* **115**, 186601 (2015), [arXiv:1504.00016](#).
- ⁴⁴ R. Nandkishore and S. Gopalakrishnan, “General theory of many body localized systems coupled to baths,” [arXiv:1606.08465](#).
- ⁴⁵ K. Hyatt, J. R. Garrison, A. C. Potter, and B. Bauer, “Many-body localization in the presence of a small bath,” [arXiv:1601.07184](#).
- ⁴⁶ D. A. Abanin, W. De Roeck, and F. Huveneers, *Phys. Rev. Lett.* **115**, 256803 (2015), [arXiv:1507.01474](#).
- ⁴⁷ D. A. Abanin, W. De Roeck, and W. W. Ho, “Effective Hamiltonians, prethermalization and slow energy absorption in periodically driven many-body systems,” (2015), [arXiv:1510.03405](#).
- ⁴⁸ D. Abanin, W. De Roeck, F. Huveneers, and W. W. Ho, “A rigorous theory of many-body prethermalization for periodically driven and closed quantum systems,” (2015), [arXiv:1509.05386](#).
- ⁴⁹ T. Kuwahara, T. Mori, and K. Saito, *Ann. Phys.* **367**, 96 (2016), [arXiv:1508.05797](#).
- ⁵⁰ T. Mori, T. Kuwahara, and K. Saito, *Physical Review Letters* **116**, 120401 (2016), [arXiv:1509.03968](#).
- ⁵¹ M. Bukov, S. Gopalakrishnan, M. Knap, and E. Demler, *Phys. Rev. Lett.* **115**, 205301 (2015).
- ⁵² E. Canovi, M. Kollar, and M. Eckstein, *Phys. Rev. E* **93**, 012130 (2016).
- ⁵³ M. Bukov, M. Heyl, D. A. Huse, and A. Polkovnikov, *Phys. Rev. B* **93**, 155132 (2016).
- ⁵⁴ Z.-C. Gu and X.-G. Wen, *Phys. Rev. B* **80**, 155131 (2009), [arXiv:0903.1069](#).
- ⁵⁵ F. Pollmann, A. M. Turner, E. Berg, and M. Oshikawa, *Phys. Rev. B* **81**, 064439 (2010), [arXiv:0910.1811](#).
- ⁵⁶ F. Pollmann, E. Berg, A. M. Turner, and M. Oshikawa, *Phys. Rev. B* **85**, 075125 (2012), [arXiv:0909.4059](#).
- ⁵⁷ L. Fidkowski and A. Kitaev, *Phys. Rev. B* **81**, 134509 (2010), [arXiv:0904.2197](#).
- ⁵⁸ X. Chen, Z.-C. Gu, and X.-G. Wen, *Phys. Rev. B* **82**, 155138 (2010), [arXiv:1004.3835](#).
- ⁵⁹ X. Chen, Z.-C. Gu, and X.-G. Wen, *Phys. Rev. B* **83**, 035107 (2011), [arXiv:1008.3745](#).
- ⁶⁰ N. Schuch, D. Pérez-García, and I. Cirac, *Phys. Rev. B* **84**, 165139 (2011), [arXiv:1010.3732](#).
- ⁶¹ L. Fidkowski and A. Kitaev, *Phys. Rev. B* **83**, 075103 (2011), [arXiv:1008.4138](#).
- ⁶² X. Chen, Z.-X. Liu, and X.-G. Wen, *Phys. Rev. B* **84**, 235141 (2011), [arXiv:1106.4772](#).
- ⁶³ X. Chen, Z.-C. Gu, Z.-X. Liu, and X.-G. Wen, *Phys. Rev. B* **87**, 155114 (2013), [arXiv:1106.4772](#).
- ⁶⁴ M. Levin and Z.-C. Gu, *Phys. Rev. B* **86**, 115109 (2012), [arXiv:1202.3120](#).
- ⁶⁵ A. Vishwanath and T. Senthil, *Phys. Rev. X* **3**, 011016 (2013), [arXiv:1209.3058](#).
- ⁶⁶ C. Wang, A. C. Potter, and T. Senthil, *Science* **343**, 629 (2014), [arXiv:1306.3238](#).
- ⁶⁷ A. Kapustin, “Symmetry Protected Topological Phases, Anomalies, and Cobordisms: Beyond Group Cohomology,” (2014), [arXiv:1403.1467](#).
- ⁶⁸ Z.-C. Gu and X.-G. Wen, *Phys. Rev. B* **90**, 115141 (2014), [arXiv:1201.2648](#).

- ⁶⁹ D. V. Else and C. Nayak, Phys. Rev. B **90**, 235137 (2014), arXiv:1409.5436.
- ⁷⁰ F. J. Burnell, X. Chen, L. Fidkowski, and A. Vishwanath, Phys. Rev. B **90**, 245122 (2014), arXiv:1302.7072.
- ⁷¹ J. C. Wang, Z.-C. Gu, and X.-G. Wen, Phys. Rev. Lett. **114**, 031601 (2015), arXiv:1405.7689.
- ⁷² M. Cheng, Z. Bi, Y.-Z. You, and Z.-C. Gu, “Towards a Complete Classification of Symmetry-Protected Phases for Interacting Fermions in Two Dimensions,” (2015), arXiv:1501.01313.
- ⁷³ J. Maciejko, X.-L. Qi, A. Karch, and S.-C. Zhang, Phys. Rev. Lett. **105**, 246809 (2010), arXiv:1004.3628.
- ⁷⁴ A. M. Essin and M. Hermele, Phys. Rev. B **87**, 104406 (2013), arXiv:1212.0593.
- ⁷⁵ Y.-M. Lu and A. Vishwanath, “Classification and Properties of Symmetry Enriched Topological Phases: A Chern-Simons approach with applications to Z2 spin liquids,” (2013), arXiv:1302.2634.
- ⁷⁶ A. Mesaros and Y. Ran, Phys. Rev. B **87**, 155115 (2013), arXiv:1212.0835.
- ⁷⁷ L.-Y. Hung and X.-G. Wen, Phys. Rev. B **87**, 165107 (2013), arXiv:1212.1827.
- ⁷⁸ M. Barkeshli, P. Bonderson, M. Cheng, and Z. Wang, “Symmetry, Defects, and Gauging of Topological Phases,” (2014), arXiv:1410.4540.
- ⁷⁹ M. Cheng, M. Zaletel, M. Barkeshli, A. Vishwanath, and P. Bonderson, “Translational symmetry and microscopic constraints on symmetry-enriched topological phases: a view from the surface,” (2015), arXiv:1511.02263.
- ⁸⁰ C. W. von Keyserlingk and S. L. Sondhi, “Phase Structure of 1d Interacting Floquet Systems I: Abelian SPTs,” (), arXiv:1602.02157.
- ⁸¹ D. V. Else and C. Nayak, “On the classification of topological phases in periodically driven interacting systems,” arXiv:arXiv:1602.04804.
- ⁸² A. C. Potter, T. Morimoto, and A. Vishwanath, “Topological classification of interacting 1D Floquet phases,” arXiv:1602.05194.
- ⁸³ R. Roy and F. Harper, “Abelian Floquet SPT Phases in 1D,” arXiv:1602.08089.
- ⁸⁴ Specifically, it follows from the construction of \mathcal{U} that $\mathcal{U} = 1 + O(\lambda T)$, and $\lambda T \ll 1$ is the regime where the heating time is large.
- ⁸⁵ J. Schwinger, J. Math. Phys. **2**, 407 (1961).
- ⁸⁶ L. V. Keldysh, Zh. Eksp. Teor. Fiz. **47**, 1515 (1964), [Sov. Phys. JETP **20**, 1018 (1965)].
- ⁸⁷ A. Kamenev, “Many-body theory of non-equilibrium systems,” Eprint arXiv:cond-mat/0412296.
- ⁸⁸ D. V. Else, B. Bauer, and C. Nayak, To appear.
- ⁸⁹ D. Pekker, G. Refael, E. Altman, E. Demler, and V. Oganesyan, Phys. Rev. X **4**, 011052 (2014), arXiv:1307.3253.
- ⁹⁰ D. A. Huse, R. Nandkishore, V. Oganesyan, A. Pal, and S. L. Sondhi, Phys. Rev. B **88**, 014206 (2013), arXiv:1304.1158.
- ⁹¹ R. Haag, *Local Quantum Physics: Fields, Particles, Algebras* (Springer, 1996).
- ⁹² F. Wilczek, Physical Review Letters **111**, 250402 (2013), arXiv:1308.5949 [cond-mat.supr-con].
- ⁹³ C. J. Pethick and H. Smith, *Bose-Einstein Condensation in Dilute Gases* (Cambridge University Press, 2008).
- ⁹⁴ A. Nicolis and F. Piazza, J. High Energy Phys. **2012** (2012), 10.1007/JHEP06(2012)025, arXiv:1112.5174 [hep-th].
- ⁹⁵ E. Castillo, B. Koch, and G. Palma, (2014), arXiv:1410.2261.
- ⁹⁶ M. Thies, (2014), arXiv:1411.4236.
- ⁹⁷ P. Bruno, Phys. Rev. Lett. **111**, 070402 (2013), arXiv:1306.6275.
- ⁹⁸ For one study of steady states of many-body Floquet systems coupled to a bath, see Ref. 105.
- ⁹⁹ M. Schreiber, S. S. Hodgman, P. Bordia, H. P. Lüschen, M. H. Fischer, R. Vosk, E. Altman, U. Schneider, and I. Bloch, Science **349**, 842 (2015), arXiv:1501.05661 [cond-mat.quant-gas].
- ¹⁰⁰ J. Smith, A. Lee, P. Richerme, B. Neyenhuis, P. W. Hess, P. Hauke, M. Heyl, D. A. Huse, and C. Monroe, Nat Phys **advance online publication**, (2016).
- ¹⁰¹ J.-y. Choi, S. Hild, J. Zeiher, P. Schauß, A. Rubio-Abadal, T. Yefsah, V. Khemani, D. A. Huse, I. Bloch, and C. Gross, Science **352**, 1547 (2016).
- ¹⁰² K. Sacha, Phys. Rev. A **91**, 033617 (2015), arXiv:1410.3638 [cond-mat.quant-gas].
- ¹⁰³ E. H. Lieb and D. W. Robinson, Commun. Math. Phys. **28**, 251 (1972).
- ¹⁰⁴ B. Nachtergaele and R. Sims, Commun. Math. Phys. **265**, 119 (2006), arXiv:math-ph/0506030 [math-ph].
- ¹⁰⁵ T. Shirai, J. Thingna, T. Mori, S. Denisov, P. Hänggi, and S. Miyashita, New J. Phys. **18**, 053008 (2016), arXiv:1511.06864.