Quantum adiabatic theorem for unbounded Hamiltonians, with applications to superconducting circuits

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We present a new quantum adiabatic theorem that allows one to rigorously bound the adiabatic timescale for a variety of systems, including those described by unbounded Hamiltonians. Our bound is geared towards the qubit approximation of superconducting circuits, and presents a sufficient condition for remaining within the $2^n$-dimensional qubit subspace of a circuit model of $n$ qubits. The novelty of this adiabatic theorem is that unlike previous rigorous results, it does not contain $2^n$ as a factor in the adiabatic timescale, and it allows one to obtain an expression for the adiabatic timescale independent of the cutoff of the infinite-dimensional Hilbert space of the circuit Hamiltonian. As an application, we present an explicit dependence of this timescale on circuit parameters for a superconducting flux qubit, and demonstrate that leakage out of the qubit subspace is inevitable as the tunneling barrier is raised towards the end of a quantum anneal. We also discuss a method of obtaining a $2^n \times 2^n$ effective Hamiltonian that best approximates the true dynamics induced by slowly changing circuit control parameters.

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I. INTRODUCTION

The quantum adiabatic theorem is now more than 100 years old, dating back to Einstein [1] and Ehrenfest [2]. Yet, it still continues to inspire new interest and results, in large part due to its central role in adiabatic quantum computation and quantum annealing, where it can be viewed as providing a sufficient condition for the solution of hard computational problems via adiabatic quantum evolutions [3–5].

Consider a closed quantum system evolving for a total time \( t_f \) subject to the Hamiltonian \( H(t) \) acting on the Hilbert space \( \mathcal{H} \). Defining the rescaled (dimensionless) time \( s = t/t_f \), the evolution is governed by the unitary operator \( U_{\text{tot}}(s) \) which is the solution of

\[
U_{\text{tot}}'(s) = -i t_f H(s) U_{\text{tot}}(s), \quad U_{\text{tot}}(0) = I, \quad s \in [0, 1].
\]

Let \( P(s) \) be a finite-rank projection on the low-energy subspace of \( H(s) \), i.e., the (continuous-in-\( s \)) subspace spanned by the eigenvectors with the lowest \( d(s) \) eigenvalues. A unitary operator \( U_{\text{ad}}(s) \) can be constructed that preserves this subspace, i.e.:

\[
P(s) = U_{\text{ad}}(s) P(0) U_{\text{ad}}^\dagger(s).
\]

The adiabatic theorem is essentially the statement that there exists \( U_{\text{ad}} \) such that the following holds:

\[

\| [U_{\text{ad}}(s) - U_{\text{tot}}(s)] P(0) \| \leq \frac{\theta}{t_f} \equiv b;
\]

where \( \theta \) is a constant that does not depend on the final time \( t_f \), but typically (though not always [7, 8]) depends on the minimum eigenvalue gap \( \Delta \) of \( H(s) \) between \( P(s) \mathcal{H} \) and \( Q(s) \mathcal{H} \), where \( Q = I - P \). Since the right-hand side (r.h.s.) represents the deviation from adiabaticity, henceforth we refer to \( b \) as the “adiabatic evolution bound” and to \( \theta \) as the “adiabatic timescale”.

The total evolution time is adiabatic if it satisfies \( t_f \gg \theta \). Thus, the system evolves adiabatically (diabatically) if the diabatic evolution bound is small (large).

This version of the adiabatic theorem amounts to finding an expression for \( U_{\text{ad}} \), that contains information about the dynamic and geometric phase acquired along the evolution, which is missing in typical textbook expressions (e.g., Ref. [9]) that bound the overlap between \( U_{\text{ad}}(1)|\psi(0)\rangle \) and the final state \( U_{\text{tot}}(1)|\psi(0)\rangle \), where \( |\psi(0)\rangle \) is the lowest eigenstate of \( H(0) \). Instead, we consider any initial state \( |\psi(0)\rangle \in P(0) \mathcal{H} \), not just the ground state, and also compute the total phase. This is also more flexible in that in fact the projector \( P \) can single out any subspace of eigenstates of \( H \) (not necessarily the lowest), which may or may not be degenerate.

Techniques exist to improve the bound to \( \gamma_k/t_f^k \) for integers \( k > 1 \). This is done by requiring the time-dependent Hamiltonian to have vanishing derivatives up to order \( k \) at the initial and final time [10], or just the final time in the case of an open system [11]. It is even possible to make the bound exponentially small in \( t_f \) [12–17]. We will not be concerned with this problem here; instead, we focus on the constant \( \theta \) in the setting of unbounded Hamiltonians \( H(s) \). A paradigmatic example of such a system is a (perturbed) harmonic oscillator whose Hamiltonian changes slowly with time. Such systems are common in quantum computation, e.g., in the context of effective Hamiltonians of superconducting circuits [18] and in describing the coupling between trapped ions via motional degrees of freedom [19].

A large body of work exists on proofs of Eq. (3), including for unbounded Hamiltonians, starting with Kato [20], who improved upon the original proof of Born and Fock for simple discrete spectra [21] (e.g., a one-dimensional harmonic oscillator),

---

1 The norm we use in this work is the operator norm \( |A| = \sup_{|\psi\rangle} \langle A|\psi\rangle (\|\langle\psi\rangle\| = 1) \), which is unitarily invariant [6]: \( \|UAV\| = \|A\| \) for arbitrary \( A \) and unitary \( U \) and \( V \). Additionally, \( |A| = \|A^\dagger\|, \|U\| = 1 \). Unitarily invariant norms are also submultiplicative: \( \|AB\| \leq \|A\| \|B\| \). For Hermitian operators \( (A^\dagger = A) \) we have \( \|A\| = \sup_{\langle\psi\rangle} (\langle\psi|A|\psi\rangle) = \sup_{|\psi\rangle} \langle\psi|A|\psi\rangle \geq \langle\psi|A|\psi\rangle \).
allowing $P(s)$ to be a finite dimensional spectral projection associated with an isolated eigenvalue (e.g., the hydrogen atom). To the best of our knowledge all these proofs rely on $|X'|$ or higher derivatives being finite,ootnote{We use a prime to denote $\frac{\partial}{\partial s}$ in this work.} where $X$ is the Hamiltonian $H(s)$, the projector $P(s)$, or the resolvent $R(z, s) = (H(s) - z)^{-1}$; see, e.g., Refs. [7, 8, 22–26]. This means that the bound (3) diverges when these quantities do. Our main goal in this work is to formulate a version of the adiabatic theorem which is valid under a simpler ‘admissibility’ assumption, even for unbounded Hamiltonians where all of the aforementioned operator norms may diverge. This involves finding a new form of the bound (3), where the constant $\theta$ is expressed in terms of projected operators, i.e., unbounded operators $X$ will be replaced by $P(s)XP(s)$ (in fact, as we shall see, tighter bounds are obtained with $P(s)XQ(s)$). Moreover, we make the dependence on the gap $\Delta$ explicit by presenting a full expression for $\theta$, which we believe has not been done before for Hamiltonians with infinite $\|H'\|$.

This approach will also allow us to address the problem of deriving an error bound on the evolution generated by effective Hamiltonians $H_{\text{eff}}$ that are operators in a smaller Hilbert space corresponding to the low-energy subspace of the original problem. We identify the isometry $V(s)$ into that Hilbert space and the matrix $H_{\text{eff}}$, such that the solution of the Schrödinger equation $u'(s) = -itfH_{\text{eff}}(s)u(s)$ with $u(0) = I$ is close to the true evolution due to the same adiabatic theorem stated above:

$$\|u(s) - V(s)U_{\text{tot}}(s)V^\dagger(s)\| \leq b.$$ (4)

We apply our results to circuits of superconducting flux qubits [27, 28], of the type used, e.g., in quantum annealing [29–31]. Such qubits, with frequency $\omega_q$, are described by a circuit model (which includes capacitors, Josephson junctions, etc.), characterized by the capacitive energy $E_C$ and the Josephson junction energy $E_J \gg E_C$. We express the plasma frequency $\omega_{pl}(s)$ and the residual transverse field $\omega_{pl}\delta$ at the end of the anneal via the circuit parameters $E_J, E_C$ and the schedule of the control fluxes. We obtain a bound for the adiabatic timescale $\theta$ in Eq. (3): $\omega_q\theta \leq O(\omega_{pl}(1)\delta)(\ln \omega_{pl}(1))^{-1}$, while applying the existing rigorous form of the adiabatic theorem [25] yields $\omega_q\theta = O(\omega_q(\omega_{pl}(1)\delta))$ or diverges, depending on the type of the qubit. For these expressions written in terms of $E_J$ and $E_C$ see Sec. V B. Thus, our results include a new practical application of existing rigorous forms of the adiabatic theorem, as well as improvements over the latter.

The structure of this paper is as follows. We provide detailed definitions required to state our result, as well as compare it with previous work, in Sec. II. The proof is in two parts, a short argument for obtaining $O(1/tf)$ in Sec. III and a lengthier Sec. IV in which we compute the constant $\theta$. The application to flux qubits can be found in Sec. V. We give the definition of the effective (qubit) Hamiltonian in Sec. VI, along with a discussion of how the adiabatic theorem bounds we obtained apply in the effective Hamiltonian setting. We conclude in Sec. VII. Additional calculations in support of the flux qubit analysis are presented in Appendix A, and a proof of the intertwining relation is given in Appendix B.

II. ADIABATIC AND DIABATIC EVOLUTION

A. Previous work

To set the stage for our results on the adiabatic theorem for unbounded Hamiltonians, we first briefly review key earlier results. We note that unlike these earlier works, we will provide explicit expressions for the constants involved in the bound of our adiabatic theorem for unbounded Hamiltonians. This is an important aspect of the novelty of our contribution to the topic.

Jansen, Ruskai, and Seiler (JRS) gave several bounds, including [25, Theorem 3]:

Suppose that the spectrum of $H(s)$ restricted to $P(s)$ consists of $d(s)$ eigenvalues (each possibly degenerate, crossing permitted) separated by a gap $2\Delta(s)$ from the rest of the spectrum of $H(s)$, and $H$, $H'$, and $H''$ are bounded operators. Let $P_{s,s'}(s) \equiv U_{\text{tot}}(s)P(0)U_{\text{tot}}^\dagger(s)$. Then

$$\|P_{s,s'}(s^*) - P(s^*)\| \leq \frac{\theta(s^*)}{tf}$$ (5a)

$$\theta(s^*) = \frac{d[H']}{\Delta^2} \Big|_{s=s^*} + \frac{d[H']}{\Delta^2} \Big|_{s=s^*} + \int_{0}^{s} \left( \frac{d[H'']}{\Delta^2} + 7d\sqrt{\frac{d[H']^2}{\Delta^3}} \right) ds,$$ (5b)

The assumption of boundedness of $H$, $H'$, and $H''$ is the crucial one from our perspective, and the one we avoid in this work.

The earlier work by Avron and Elgart [7, Sec. 5] discussed the adiabatic theorem for unbounded Hamiltonians, but without an explicit expression for $\theta$ and only in the context of ‘admissible Hamiltonians’, which they defined as having the property
that both the resolvent \( R(z = i, s) \) and \( R'(z = i, s)H(s) \) are bounded. Essentially the same assumption was made by Abou Salem [32, Sec. 2], in the context of non-normal generators. Here we avoid such boundedness assumptions, and instead we make a physically motivated assumption of the form \( H'^2 < \sum_{k=0}^{k_{\max}} c_k H^{2k} \) (for certain constants \( c_k \); see Theorem 1 below for the precise statement) that does not rely on assuming boundedness of the operators involved \(^3\). For \( k_{\max} = 1 \) the boundedness of \( R'(z = i, s)H(s) \) follows from our assumption, as we show in Sec. IV E. Thus, in this special case the Avron-Elgart assumption is weaker than ours, but this is not the case for \( k_{\max} > 1 \). Moreover, proving \( H'^2 < cH^2 \) is easier than proving \( |R'H| < c \), so our result is a way to prove the latter in a manner that is more tractable in practice.

### B. Adiabatic intertwiner

Following Kato [20], we define an approximate evolution in the full Hilbert space \( \mathcal{H} \):

\[
U_{\text{ad}}(s) = -i H_{\text{ad}}(s) U_{\text{ad}}(s), \quad U_{\text{ad}}(0) = I, \quad s \in [0, 1]
\]

where \( U_{\text{ad}} \) is called the **adiabatic intertwiner** and the (dimensionless) adiabatic Hamiltonian is

\[
H_{\text{ad}}(s) = t_f H(s) + i [P'(s), P(s)].
\]

Note that both \( H_{\text{ad}} \) and \( U_{\text{ad}} \) are \( t_f \)-dependent. Here \( P(s) \) is a finite-rank projection on the low-energy subspace of \( H(s) \) (i.e., the continuous-in-\( s \) subspace spanned by the eigenvectors with the lowest \( d(s) \) eigenvalues\(^4\)). A property of this approximation is that the low-energy subspace is preserved:

\[
U_{\text{ad}}(s) P_0 = P(s) U_{\text{ad}}(s)
\]

where here and henceforth we denote \( P(0) \) by \( P_0 \), and drop the \( s \) time-argument from \( P(s) \) where possible. The proof of this intertwining property is well-known and has been given many times in various forms and subject to various generalizations; see, e.g., Refs. [22, 26, 32–34], as well as our Appendix B. The idea (due to Kato [20], who presented the original proof; see his Eq. (22)) is to show that both sides solve the same initial value problem, i.e., equality holds at \( s = 0 \), and they satisfy the same differential equation after differentiating by \( s \). The latter can be shown using Eqs. (9) and (10) below.

The operator \( P' \) has the following useful properties. Since \( P'^2 = P \), we have

\[
P' = P' P + PP'.
\]

Multiplying by \( P \) on the right, and letting \( Q \equiv I - P \), we obtain \( QP' P = P' P \), i.e.,

\[
PP' P = 0, \quad QP' Q = 0,
\]

where the proof of \( QP' Q = 0 \) is similar. Thus \( P' \) is block off-diagonal:

\[
P' = PP' Q + QP' P.
\]

### C. Bounds on states and physical observables

We would like to bound certain physical observables via the quantity \( b \) defined in Eq. (3). Since \( b \) bounds the difference between the actual and adiabatic evolution, we refer to \( b \) as the ‘adiabatic evolution bound’.

We note that Kato’s adiabatic theorem [20] established, for bounded Hamiltonians, that the quantity \( [U_{\text{ad}}(s) - U_{\text{tot}}(s)] P_0 \) tends to zero as \( 1/t_f \), but it will still take us most of the rest of this paper to arrive at the point where we can state with conviction that the bound in Eq. (3) is indeed finite for an unbounded Hamiltonian. This will require extra assumptions; indeed there are contrived unbounded Hamiltonians where Kato’s quantity is arbitrarily large for any finite evolution time \( t_f \).

Note that using unitary invariance we can rewrite Eq. (3) as \( \|x(s)\| \leq b \), where

\[
x(s) \equiv P_0 U_{\text{ad}}^\dagger(s) U_{\text{ad}}(s) - P_0.
\]

\(^3\) Indeed there are Hamiltonians that do not satisfy the assumption \( |R'(i, s)H(s)| < \infty \) of [7] while satisfying our assumption for \( k_{\max} > 1 \); consider a trivial example \( H = m + \sin s \hat{m}^2 \) (where \( m \) is a diagonal number operator with eigenvalues \( 0, 1, 2 \ldots \)) for which our \( \theta = 0 \) while \( |R'(i, s)H(s)| \), and thus \( \theta \) computed by following [7], diverge.

\(^4\) The number \( d_P \) of these eigenvectors is thus constant and equal to the the dimension of the subspace. Allowing for degeneracy, \( d_P \geq d(s) \), and we use \( d(s) \) until Sec. VI, at which point we switch to \( d_P \).
1. Bound on the final state difference

Consider an initial state $|\phi\rangle$ in the low-energy subspace ($P_0|\phi\rangle = |\phi\rangle$). We wish to compare the evolution generated by $U_{\text{tot}}$ with the one generated by $U_{\text{ad}}$. Dropping the $s$ time-argument from the $U$'s, the difference in the resulting final states is:

$$
\| (U_{\text{ad}} - U_{\text{tot}}) |\phi\rangle \|^2 = \| (U_{\text{ad}} - U_{\text{tot}}) P_0 |\phi\rangle \|^2 = \langle \phi | (U_{\text{ad}} - U_{\text{tot}})^\dagger (U_{\text{ad}} - U_{\text{tot}}) P_0 |\phi\rangle \\
\leq \| (U_{\text{ad}} - U_{\text{tot}}) P_0 \|^2 \leq \| (U_{\text{ad}} - U_{\text{tot}}) \|^2 = \| (U_{\text{tot}} U_{\text{ad}} - I) P_0 \|^2 \\
= \| (U_{\text{tot}} U_{\text{ad}} - I) P_0 \|^2 = \| P_0 (U_{\text{ad}} U_{\text{tot}} - I) \|^2 = \| x \|^2 \leq b^2.
$$

(13a) (13b) (13c)

We use this quantity because we would like to describe the error in both the amplitude and the acquired phase of the wavefunction.

2. Bound on leakage

If we are just interested in the leakage from the low-lying subspace, it can be expressed as:

$$
P_{\text{leak}} = \langle \phi | U_{\text{tot}}^\dagger Q U_{\text{tot}} |\phi\rangle = 1 - \langle \phi | U_{\text{tot}}^\dagger U_{\text{ad}} P_0 U_{\text{ad}}^\dagger U_{\text{tot}} |\phi\rangle.
$$

(14)

Then:

$$
1 - P_{\text{leak}} = \langle \phi | U_{\text{tot}}^\dagger U_{\text{ad}} P_0 U_{\text{ad}}^\dagger U_{\text{tot}} |\phi\rangle = \langle \phi | (P_0 + x)^\dagger (P_0 + x) |\phi\rangle = 1 + \langle \phi | x + x^\dagger + x^\dagger x |\phi\rangle,
$$

(15)

so that

$$
P_{\text{leak}} = -\langle \phi | x + x^\dagger + x^\dagger x |\phi\rangle \leq \| x + x^\dagger + x^\dagger x \| \leq 2b + b^2.
$$

(16)

3. Bound on the error in an observable $O$

The expectation value for an observable $O$ in the evolved state $U_{\text{tot}} |\phi\rangle$ as opposed to the approximate state $U_{\text{ad}} |\phi\rangle$ is different by:

$$
\langle \phi | U_{\text{tot}}^\dagger O U_{\text{tot}} |\phi\rangle - \langle \phi | U_{\text{ad}}^\dagger O U_{\text{ad}} |\phi\rangle \leq \| O \| (2b + b^2).
$$

(17)

To prove this, note that:

$$
U_{\text{tot}} |\phi\rangle = U_{\text{ad}} |\phi\rangle + \Delta U |\phi\rangle, \quad \Delta U \equiv U_{\text{tot}} - U_{\text{ad}}, \quad \Delta U |\phi\rangle = -U_{\text{tot}} x^\dagger |\phi\rangle.
$$

(18)

Therefore:

$$
\langle \phi | U_{\text{tot}}^\dagger O U_{\text{tot}} |\phi\rangle - \langle \phi | U_{\text{ad}}^\dagger O U_{\text{ad}} |\phi\rangle = \langle \phi | U_{\text{ad}}^\dagger O \Delta U |\phi\rangle + \langle \phi | \Delta U^\dagger O U_{\text{ad}} |\phi\rangle + \langle \phi | \Delta U^\dagger O \Delta U |\phi\rangle
$$

(19a)

$$
\leq \| U_{\text{ad}}^\dagger O x^\dagger \| + \| x U_{\text{ad}}^\dagger O U_{\text{ad}} \| + \| x U_{\text{tot}} U_{\text{tot}} x^\dagger \| \leq \| O \| \left( \| x^\dagger \| + \| x \| + \| x \| x^\dagger \right)
$$

(19b)

from which Eq. (17) follows.

One of the immediate consequences is that measuring $Z$ (or any other unit-norm observable) on one qubit in a $n$ qubit system after the evolution can be described by an approximate evolution $U_{\text{ad}}$ to within an error of $(2b + b^2)$ in the expectation value.

4. Bound on the JRS quantity

The quantity appearing in the JRS bound (5) satisfies

$$
\| P_{tf} - P \| = \| U_{\text{tot}} P_0 U_{\text{tot}}^\dagger - U_{\text{ad}} P_0 U_{\text{ad}}^\dagger \| = \| U_{\text{tot}}^\dagger U_{\text{tot}} P_0 - P_0 U_{\text{ad}}^\dagger U_{\text{ad}} P_0 \| = \| Q_0 U_{\text{ad}}^\dagger U_{\text{tot}} P_0 - P_0 U_{\text{ad}}^\dagger U_{\text{tot}} Q_0 \|,
$$

(20)

where in the last equality we used $Q_0 = I - P_0$ and added/subtracted $P_0 U_{\text{ad}}^\dagger U_{\text{tot}} P_0$.

Using the definition of $x$ [Eq. (12)], we can express:

$$
P_0 U_{\text{ad}}^\dagger U_{\text{tot}} = P_0 + x, \quad U_{\text{ad}}^\dagger U_{\text{tot}} P_0 = P_0 - U_{\text{ad}}^\dagger U_{\text{tot}} x^\dagger,
$$

(21)

so that Eq. (20) becomes:

$$
\| P_{tf} - P \| = \| Q_0 U_{\text{ad}}^\dagger U_{\text{tot}} x^\dagger P_0 + P_0 x Q_0 \| = \max(\| U_{\text{ad}}^\dagger U_{\text{tot}} x^\dagger \|, \| x \|) = \| x \| \leq b,
$$

(22)

where the second equality follows since $Q_0 U_{\text{ad}}^\dagger U_{\text{tot}} x^\dagger P_0$ and $P_0 x Q_0$ are two opposite off-diagonal blocks and their eigenvalues do not mix, and the last equality follows from the unitary invariance of the operator norm.

We proceed to explicitly express the bound $b$ in the next section.
D. Statement of the theorem

Collecting the definitions of the previous sections, we present our main result:

**Theorem 1** (Adiabatic theorem). Assume that \( \forall s \in [0, 1] \) there exist positive numbers \( \{c_k(s)\}_{k=0}^{k_{\text{max}}} \) such that the (possibly unbounded) Hamiltonian \( H(s) \) satisfies

\[
H'^2 \leq \sum_{k=0}^{k_{\text{max}}} c_k H^{2k} .
\]

Let \( P(s) \) denote the projection onto a continuous-in-\( s \) eigensubspace of the Hamiltonian \( H(s) \) corresponding to \( d(s) \) eigenvalues, that occupies an interval \( \sigma(s) \) in energy and is separated by a gap \( 2\Delta(s) \) from all other eigenvalues; see Fig. 1. Assume that the initial state \( \ket{\phi} \in P(0) \equiv P_0 \). Then the adiabatic intertwiner \( U_{\text{ad}} \) [the solution of Eq. (6)] satisfies the following bounds on its difference with the true evolution \( U_{\text{tot}} \):

\[
\| P_0 U_{\text{ad}} U_{\text{tot}} - P_0 \| \leq b, \quad \| (U_{\text{ad}} - U_{\text{tot}}) P_0 \| \leq b, \quad \| (U_{\text{ad}} - U_{\text{tot}}) \phi \| \leq b, \quad \| U_{\text{tot}} P_0 U_{\text{tot}} - U_{\text{ad}} P_0 U_{\text{ad}} \| \leq b,
\]

where \( b = \theta/t_f \) and \( \theta \) is given by

\[
\theta = \tau^2(0) [P_0 H'(0) Q_0] + \tau^2(s^*) [P(s^*) H'(s^*) Q(s^*)] + \int_0^{s^*} \int_0^{s^*} ds \left[ \tau^3(5|PH'Q| + 3|PH'P|) |PH'Q| + \tau^3 |PH''Q| \right] + 2^3 \sum_{k=0}^{k_{\text{max}}} c_k \| PH'H^k Q \|^2 \]

\[
\text{Here } t_f \text{ is the total evolution time, } s^* \in [0, 1] \text{ is the final value of } s \text{ and }
\]

\[
\tau = \min \left( \sqrt{\frac{\int_0^{s^*} \Delta(s)}{\int_0^{s^*} \Delta(s)}}, \sqrt{\frac{2r(s) + 2\pi \Delta(s)}{2\pi \Delta^2(s)}} \right).
\]

Note that the first three inequalities stated in Eq. (24) were already established in Eqs. (13), and the last in Eq. (20) along with Eq. (22). The new aspect of Theorem 1 is the value of the bound \( \theta \), which does not require \( H \) or its time derivatives to be bounded.

If \( \| H' \|_2 \) is finite the assumption (23) is automatically satisfied with \( k_{\text{max}} = 0 \) and \( c_0(s) = \| H' \|_2^2 \), since \( H'^2 - H'^2 I \leq 0 \) (a negative operator) by definition of the operator norm. Using this, let us write the finite \( \| H' \| \) version of the result (25) in the same form as Eq. (5) (from Ref. [25]) using \( \tau = \frac{\sqrt{2}}{\Delta} \):

**Corollary 1.** For finite \( \| H' \| \), the JRS adiabatic timescale \( \theta_{\text{JRS}}(s^*) \) and our new adiabatic timescale \( \theta_{\text{new}}(s^*) \) are:

\[
\theta_{\text{JRS}}(s^*) = \frac{d}{\Delta^2} \left| \frac{d}{\Delta^2} \right|_{s=0}^{s^*} \int_0^{s^*} \left( \frac{d}{\Delta^2} + 7d^2 \frac{\| H' \|^2}{\Delta^3} \right) ds,
\]

\[
\theta_{\text{new}}(s^*) = \frac{d}{\Delta^2} \left| \frac{d}{\Delta^2} \right|_{s=0}^{s^*} + \int_0^{s^*} \left( \frac{d}{\Delta^2} + 7d^2 \frac{\| H' \|^2}{\Delta^3} \right) ds,
\]

We see that though our new adiabatic timescale has slightly larger numerical coefficients, the projected form of the operators can provide a qualitative improvement over the JRS result. Note that we can also write a bound that is free of the dimension \( d \) if the second option for \( \tau \) in Eq. (26) is smaller than the first.

III. DIABATIC EVOLUTION BOUND

We will calculate a diabatic evolution bound \( b \) on the quantity in Eq. (3) for some \( s^* \in [0, 1] \):

\[
\| [U_{\text{ad}}(s^*) - U_{\text{tot}}(s^*)] P(0) \| = \| f(s^*) - P_0 \|,
\]
where
\[ f(s) \equiv P_0 U_{ad}^\dagger(s) U_{tot}(s) = x(s) + P_0. \] (29)

We would like to express \( f(s^*) \) via \( f'(s) \):
\[ f(s^*) = P_0 + \int_0^{s^*} f'(s) \, ds \] (30)

Recalling that \( U_{tot} \) satisfies Eq. (1) and \( U_{ad} \) satisfies Eq. (6), the derivative is:
\[ f'(s) = P_0 (U_{ad}^\dagger U_{tot} + U_{ad} U_{tot}^\dagger) = P_0 U_{ad}^\dagger (it_j H - [P', P] - it_j H) U_{tot} = -P_0 U_{ad}^\dagger [P', P] U_{tot} \] (31)

where we used \( P' = P' \). Note how the \( O(t_j) \) term cancelled, so the expression appears to be \( O(1) \). However, it is in fact \( O(1/t_j) \), as we show next.

For any operator \( X(s) \) define \( \tilde{X}(s) \) ("twiddle-\( X \)) [22] such that
\[ [X(s), P(s)] = [H(s), \tilde{X}(s)], \] (32)
and the diagonal of \( \tilde{X} \) in the eigenbasis of \( H(s) \) is zero. Note that \( \tilde{X} \) has units of time relative to \( X \).

For instance, \( P'' \) is defined via:
\[ [P'(s), P(s)] = [H(s), P''(s)] \] (33)
The details of why \( \tilde{X} \) exists and how it is expressed via \( X \) are given in Sec. IV. Proceeding with bounding Eq. (31), we can now rewrite it as:
\[ f'(s) = -P_0 U_{ad}^\dagger [H, P''] U_{tot}. \] (34)

Note that, using Eqs. (1) and (6):
\[ (U_{ad}^\dagger P'' U_{tot})' = U_{ad}^\dagger (it_j H P'' - [P', P] P'' + P'' - P'') U_{tot}, \] (35)
which we can rearrange as:
\[ U_{ad}^\dagger [H, P''] U_{tot} = \frac{1}{it_j} [(U_{ad}^\dagger P'' U_{tot})' + U_{ad}([P', P] P'' - P'') U_{tot}]. \] (36)

Using this in Eq. (31), we obtain the desired \( O(1/t_f) \) scaling:
\[ f'(s) = \frac{iP_0}{it_f} [(U_{ad}^\dagger P'' U_{tot})' - U_{ad}([P', P] P'' + P'') U_{tot}], \] (37)
where using Eq. (8) we simplified one term in the commutator as \( P_0 U_{ad}^\dagger P = P_0 U_{ad} \), and also using Eq. (10), we have \( P_0 U_{ad}^\dagger P'' P = U_{ad} P P' P = 0 \), so that the other term with \( P'' P \) in the commutator vanishes. Plugging this back into Eq. (30), we get:
\[ f(s^*) - P_0 = \frac{iP_0}{it_f} \left( (U_{ad}^\dagger P'' U_{tot})|s^*_{ad} - \int_0^{s^*} U_{ad}([P', P] P'' + P'') U_{tot} ds \right). \] (38)

Using \( P_0 U_{ad}^\dagger = U_{ad} P \) throughout, this results in the following bound on the quantity in Eq. (28) we set out to bound:
\[ \| [U_{ad}(s^*) - U_{tot}(s^*)] P(0) \| = \| f(s^*) - P_0 \| \leq b = \frac{\theta}{t_f} \] (39a)
\[ \theta = \| P_0 P''(0) \| + \| P(s^*) P''(s^*) \| + \int_0^{s^*} \| P P' P'' \| + \| P P'' P' \| \, ds. \] (39b)

The adiabatic timescale \( \theta \) given here is not particularly useful in its present form. Thus, we next set out to find bounds on each of the quantities involved. Our goal will be to bound everything in terms of block-off-diagonal elements of \( H \) and its derivatives, i.e., terms of the form \( \| PHQ \|, \| P'HQ \| \), etc.

---

5 Our convention is that the tilde takes precedence over derivatives, i.e., \( \tilde{X}' \equiv (\tilde{X})' \). When the derivative is to be taken first we write the tilde to the right of the operator, i.e., \( X'' \equiv (X')'' \).
IV. BOUNDS VIA THE RESOLVENT FORMALISM

Some of the material in this section closely follows Jansen et al. (JRS) [25], adjusted for clarity for our purposes. We start from the well-known resolvent formula, and then develop various intermediate bounds we need for the final result.

A. Twiddled operators

If $\Gamma$ is a positively oriented loop in the complex plane encircling the spectrum associated with an orthogonal eigenprojection $P$ of a Hermitian operator $H$, then [35]:

$$P = \frac{i}{2\pi} \oint_{\Gamma} (H - z)^{-1} dz,$$

(40)

where $(H - z)^{-1}$ is known as the resolvent.

Using this, it was shown in Lemma 2 of JRS [25] that for every operator $X$ there is a solution $\tilde{X}$ to Eq. (32) if the eigenvalues in $P$ are separated by a gap in $H$. This solution is written in terms of contour integrals involving the double resolvent:

$$\tilde{X} = \frac{1}{2\pi i} \oint_{\Gamma} (H - z)^{-1} X (H - z)^{-1} dz = -[(X^\dagger)^\sim]^\dagger,$$

(41)

where the contour $\Gamma$ again encircles the spectrum of $P$. Here $\tilde{X}$ is block-off-diagonal. The twiddle operation was introduced in Ref. [22], where it was defined via Eq. (41).

Note that since $P$ and $Q$ both commute with $H$, we can move both $P$ and $Q$ under the twiddle sign, i.e., using Eq. (41) we have

$$P \tilde{X} = (PX)^\sim, \quad Q \tilde{X} = (QX)^\sim, \quad \tilde{X} P = (XP)^\sim, \quad \tilde{X} Q = (XQ)^\sim$$

(42a)

$$P \tilde{X} Q = (PXQ)^\sim, \quad Q \tilde{X} P = (QXP)^\sim.$$

(42b)

Also note that $\tilde{X}$ is block-off-diagonal [25], i.e.:

$$P \tilde{X} P = Q \tilde{X} Q = 0$$

(43a)

$$P \tilde{X} = P \tilde{X} Q = \tilde{X} Q, \quad Q \tilde{X} = Q \tilde{X} P = \tilde{X} P.$$  

(43b)

B. Bound on $P'$

By definition, $[P, H] = 0$. Differentiating, we obtain:

$$[H', P] = [P', H].$$

(44)

We also know that $P'$ is block-off-diagonal, so by definition [Eq. (32)]

$$P' = -H^\sim.$$  

(45)

But the tilde operation only depends on the block-off-diagonal elements of $H'$, so that

$$P' = -(PH'Q + QH'P)^\sim,$$

(46)

which implies that as long as this quantity is bounded, $P'$ is as well: $\|P'\| = \|(PH'Q + QH'P)^\sim\|$.  

6 Eq. (41) is (up to a minus sign) how the twiddle operation was originally defined in Ref. [22, Eq. (2.11)].
C. Bound on $\tilde{X}$

Suppose that the spectrum of $H(s)$ (its eigenvalues $\{E_i(s)\}$) restricted to $P(s)$ consists of $d(s)$ eigenvalues (each possibly degenerate, crossing permitted) separated by a gap $2\Delta(s)$ from the rest of the spectrum of $H(s)$. I.e., $d(s) \leq d$, the dimension of the low energy subspace. Under these assumptions JRS proved the following bound in their Lemma 7:

$$\|\tilde{X}(s)\| \leq \frac{\sqrt{d(s)}}{\Delta(s)} \|X\|. \quad (47)$$

We will also use an alternative bound that did not appear in [25]. We start with:

$$\|(H(s) - z)^{-1}\| = \max_i \frac{1}{E_i(s) - z} \leq \frac{1}{\Delta(s)} \quad (48)$$

for $z$ on the contour $\Gamma$ in Eq. (41), illustrated in Fig. 1. This contour is of length $2r(s) + 2\pi \Delta(s)$ where $r$ is the spectral diameter of $P\mathcal{H}$ w.r.t $H$. Since $P(s)$ is a spectrum projector, $P\mathcal{H}$ has a basis of eigenvectors of $H(s)$ with eigenvalues $\lambda_i^P$, and we can define:

$$r(s) = \max_{\{\phi_{\min}, \lambda_{\max}\} \setminus \{0\}} \left( \langle \phi_{\max} | H(s) | \phi_{\max} \rangle - \langle \phi_{\min} | H(s) | \phi_{\min} \rangle \right) = \max_i \lambda_i^P - \min_i \lambda_i^P, \quad (49)$$

So, bounding the solution $\tilde{X}(s)$ from Eq. (41) directly results in:

$$\|\tilde{X}(s)\| \leq \frac{2r(s) + 2\pi \Delta(s)}{2\pi \Delta^2(s)} \|X\|. \quad (50)$$

This new bound can be tighter than Eq. (47) because it does not depend on $d$, though this can be offset by $\Delta$ and $r$.

As stated in Theorem 1, we define $\tau$ via Eq. (26) and combine the bounds (47) and (50) to write

$$\|\tilde{X}(s)\| \leq \tau(s) \|X\|. \quad (51)$$

Here, $\tau$ roughly means the adiabatic timescale. The bound (51) can be seen as one of the main reasons for introducing the twiddle operation. We will use it repeatedly below. We will omit the $s$-dependence of $\tau$ and $\tilde{X}$ whenever possible in what follows. Note that if $Y$ is any operator that commutes with $H$ then by Eq. (41) we have $\tilde{X}Y = (XY)^\tau$, $Y\tilde{X} = (YX)^\tau$. Therefore:

$$\|\tilde{X}Y\| \leq \tau \|XY\|, \quad \|Y\tilde{X}\| \leq \tau \|YX\| \quad \text{if} \quad [Y, H] = 0. \quad (52)$$

Likewise, using Eqs. (42), (43), and (51) we can remove a twiddle under the operator norm for the price of a factor of $\tau$ while inserting $P$ and $Q$ at will:

$$\|PX\| = \|\tilde{X}Q\| = \|P\tilde{X}Q\| = \|(P\tilde{X}Q)^\tau\| \leq \tau \|P\tilde{X}Q\|. \quad (53)$$
D. Combining everything into the diabatic evolution bound

We now combine the various intermediate results above to bound the r.h.s. of Eq. (39).
Together with \( |\vec{X}| \leq \tau |X| \) [Eq. (51)], Eq. (42) yields \( |P(s)P'\gamma(s)| \leq \tau |P(s)P'(s)| \). Thus, Eq. (39) becomes:

\[
\|f(s^*) - P_0\| \leq \frac{1}{L_f} \left( \tau(0)\|P_0P'(0)\| + \tau(s^*)\|P(s^*)P'(s^*)\| + \int_0^{s^*} \|PP'P''\| + \|PP''\| ds \right).
\]

(54)

Now, using \([P, H] = 0\) and \(PP'P = 0\), note that:

\[
PP'P''P = PP' \frac{1}{2\pi i} \oint (H - z)^{-1} P' P (H - z)^{-1} dz = \frac{1}{2\pi i} \oint (H - z)^{-1} (P' - PP') (H - z)^{-1} dz
\]

(55)

\[
= PP' \frac{1}{2\pi i} \oint (H - z)^{-1} P' (H - z)^{-1} dz = PP' P''.
\]

(56)

Also, \( \|PP'\| = \|(PP')^\dagger\| = \|P'P\| \) (since \(P\) and \(P'\) are Hermitian), so that using Eq. (42) we get:

\[
\|PPP''P\| = \|PP'(P'P)\| \leq \|PP'\| \|(P'P)\| \leq \|PP'\| \|\tau\| P'P\|^2.
\]

(57)

Thus

\[
\theta = \left( \tau(0)\|P_0P'(0)\| + \tau(s^*)\|P(s^*)P'(s^*)\| + \int_0^{s^*} \tau|PP'|^2 + \|PP''\| ds \right).
\]

(58)

We multiply Eq. (46) from the left by \(P\) to give

\[
PP' = -P(PH'Q + QH'P) = -(PH'Q)^\dagger,
\]

(59)

where we used Eq. (42). Therefore, using \( |\vec{X}| \leq \tau |X| \) again, we find:

\[
\|f(s^*) - P_0\| \leq \frac{\theta}{L_f}
\]

(60a)

\[
\theta = \tau^2(0)\|P_0H'(0)Q_0\| + \tau^2(s^*)\|P(s^*)H'(s^*)Q(s^*)\| + \int_0^{s^*} \tau^3|PH'Q|^2 + \|PP''\| ds.
\]

(60b)

We have nearly achieved the goal of expressing the diabatic evolution bound in terms of block-off-diagonal elements of \(H\) and its derivatives. The last term is not yet in this form and will require the development of additional tools, which we do next.

E. Derivative of the resolvent formula

To take derivatives of the twiddled expressions we need to differentiate the resolvent \(R(z, s) = (H(s) - z)^{-1}\). By differentiating the identity \((H(s) - z)R(z, s) = I\) we obtain

\[
\frac{\partial}{\partial s} R(z, s) = -R(z, s) H'(s) R(z, s).
\]

(61)

Using this, we can prove the relation between the assumption \(\|H(s)R'(z = i, s)\| < \infty\) that Ref. [7] used to prove an adiabatic theorem, and a subset of our assumptions \(H'^2 \leq c_0 + c_1 H^2\). Indeed:

\[
\|H(s)R'(z = i, s)\| = \|H R(z = i) H' R(z = i)\| \leq \|H R(z = i)\| \|H' R(z = i)\|,
\]

(62)

where we have omitted the \(s\)-dependence for brevity. The first term is:

\[
\|H R(z = i)\| = \|(i + (H - i)) R(z = i)\| \leq 1 + \|R(z = i)\| = 1 + (1 + \min_j \lambda_j^2)^{-1/2} \leq 2,
\]

(63)

where \(\lambda_j\) are the eigenvalues of \(H\), and we used \(\|R(z = i)\| = \max_j |(\lambda_j - i)^{-1}|\). For the second term, we use our assumption \(H'^2 \leq c_0 + c_1 H^2\):

\[
\|H' R(z = i)\| = \sqrt{\|R(z = i) H'^2 R(z = i)\|} \leq \sqrt{\|R(z = i)(c_0 + c_1 H^2) R(z = i)\|}
\]

(64a)

\[
\leq \sqrt{c_0(1 + \min_j \lambda_j^2)^{-1/2} + c_1(1 + (1 + \min_j \lambda_j^2)^{-1/2})^2} \leq \sqrt{c_0 + 4c_1}.
\]

(64b)
Combining the two expressions, we obtain the assumption of [7, Sec. 5]:

\[ |H(s)R'(z = i, s)| \leq 2\sqrt{c_0 + 4c_1}. \]  

(65)

We will also apply the derivative formula to our derivation. For example, using Eq. (41) we obtain

\[ P'' = \frac{1}{2\pi i} \oint (H - z)^{-1} P'(H - z)^{-1} dz \]  

(66)

and hence taking the derivative results in

\[ P'' = \frac{1}{2\pi i} \oint (H - z)^{-1} [-H'(H - z)^{-1}P' + P'' - P'(H - z)^{-1}H'](H - z)^{-1} dz. \]  

(67)

To bound this expression, we need to prove one more fact.

**F. Fact about a triple resolvent**

We will need to analyze expressions of the form

\[ F(A, B) = \frac{1}{2\pi i} \oint (H - z)^{-1} A(\bar{H} - z)^{-1} B(H - z)^{-1} dz; \]  

(68)

which we will use with \( A, B = H' \) for the norm of \( P'' \) and \( A, B = H', P' \) for the bound on \( P'' \) above. I.e.,

\[ P'' = -F(H', P') + P'' - F(P', H'). \]  

(69)

JRS proved a bound on \( F(A, B) \). Since \( F(A, B) \) has both diagonal and off-diagonal blocks, they found the bound for each block. We review their proof below, starting from a useful expression for the triple resolvent.

Consider the commutator with the Hamiltonian:

\[ [H, F(A, B)] = \frac{1}{2\pi i} \oint [H - z, (H - z)^{-1} A(\bar{H} - z)^{-1} B(H - z)^{-1}] dz = \bar{A}B - \bar{A}B, \]  

(70)

where we have inserted \( z \) since it is not an operator and therefore commutes with the other term, and where the second equality follows from Eq. (41).

Let us denote the off-diagonal block projection by \( o(X) = PXQ + QXP = [P, (P - Q)X] \). Note that \( P \) and \( Q \) commute with \( H \), so when we apply \([P, (P - Q) \cdot ]\) to both sides of the above equation, we get, after some simple algebra:

\[ [H, o(F(A, B))] = \{ -(P - Q)(\bar{A}B - \bar{A}B), P \}. \]  

(71)

Now we can apply the definition of the twiddle operation, \([H, \tilde{X}] = [X, P]\) [with \( X = -(P - Q)(\bar{A}B - \bar{A}B)\)], to Eq. (71). It follows that

\[ o[F(A, B)] = \{ -(P - Q)(\bar{A}B - \bar{A}B) \}. \]  

(72)

**Lemma 1.** Multiplication by \((P - Q)\) commutes with the twiddle operation, i.e., \((P - Q)X\) = \((P - Q)\tilde{X}\).

**Proof.** To prove this statement we need to show that \( Y' = ((P - Q)X)^{-} \) and \( Y' = (P - Q)\tilde{X} \) satisfy the same defining equation and are both block-off-diagonal. The defining equation of the first is \([H, Y] = [(P - Q)X, P] = (P - Q)XP - PX \). As for the second, note that if we multiply \([H, \tilde{X}] = [X, P] \) by \((P - Q)\) then, since \( H \) commutes with \( P - Q \), we obtain \([H, Y'] = (P - Q)XP - PX = [H, Y]\). Thus \( Y' \) satisfies the same defining equation as \( Y \). Moreover, by Eq. (32) \((P - Q)X\) is a block off-diagonal operator, and so is \( \tilde{X} \), so that \((P - Q)\tilde{X}\) is thus also block-off-diagonal. \( \square \)

Thus, by Eq. (72),

\[ o[F(A, B)] = (P - Q)(\bar{A}B - \bar{A}B) \]  

(73)

For the block-diagonal part, we need to apply a different strategy. By pole integrations identical to those in [25], which only require that there be a finite number of eigenvalues inside the low energy subspace, we can prove that

\[ F(A, B) - o[F(A, B)] = (P - Q)\tilde{A}\tilde{B} \]  

(74)
Combining the last two results, we finally obtain (the same as Eq. (13) in [25]):

\[ F(A, B) = (P - Q)[\hat{A}\hat{B} - (A\hat{B} - \hat{A}B)^\dagger]. \quad (75) \]

Now, using Eqs. (41), (45) and (61), we can express $P''$ as:

\[ P'' = -H'' = \frac{1}{\pi i} \int (H - z)^{-1} H'(H - z)^{-1} d\tau - H'''. \quad (76) \]

It then follows from Eq. (75) that:

\[ P'' = 2(P - Q)[(H'')^2 - [H', H'']] - H''' \quad (77) \]

**G. Bounding the last term in the diabatic evolution bound**

We are interested in bounding the last term in Eq. (60), which, using Eq. (69) we can write as:

\[ \|PP''\| = \|P(-F(H', P') - F(P', H') + P''')\|, \quad (78) \]

We now use $F(A, B) = (P - Q)[\hat{A}\hat{B} - (A\hat{B} - \hat{A}B)^\dagger]$ [Eq. (75)] to write

\[ \|PP''\| = \|P(-H'' P'' + (H' P'' - H'' P') - P'' H'') + (P'' H' - P'' H') + P''')\|. \quad (79) \]

Recall that $P' = -H''$ [Eq. (45)], so that

\[ \|PP''\| = \|P(-H'' P'' + (H' P'') - P'' H'') - (P'' H') + P''')\|. \quad (80) \]

Repeatedly using the fact that twiddled operators are block-off-diagonal and using Eq. (53):

\[ \|PH'' P''\| = \|PH'' Q P'' P'\| = \|PH'' Q P'' P'\| \leq \|PH'' Q\| \|PP''\| \leq \tau^2 \|PH'' Q\| \|PP''\|, \quad (81) \]

where in the last inequality we used Eq. (41) and the fact that both $P$ and $P'$ are Hermitian to write $\|PP''\| = \|(PP'')\| = \|PP''\|$. Similarly:

\[ \|P(H' P'') - Q\| \leq \tau \|PH''(P'' Q)\| = \tau \|PH''(P'' Q)\| \leq \tau \|PH''(P'' Q)\| \|PP''\| \leq \tau^2 \|PH''(P'' Q)\| \|PP''\|, \quad (82) \]

where in the second equality we used $\hat{X} = \hat{X} Q$ [Eq. (43b)]. The remaining terms in Eq. (80) are similarly bounded:

\[ \|PP'' H''\| = \|PP'' Q H''\| = \|PP'' Q H''\| \leq \|PP''\| \|PP''\| \leq \tau^2 \|PH'' Q\| \|PP''\| \quad (83a) \]

\[ \|P(P'' H')\| \leq \tau \|PP'' H'\| \quad (83b) \]

\[ \|PP''\| \leq \tau \|PP''\|. \quad (83c) \]

Combining these bounds yields:

\[ \|PP''\| \leq \tau^2 (2\|PH'' Q\| + \|PH'' P\|) \|PP''\| + \tau (\|PP'' H'\| + \|PP''\|) \quad (84a) \]

\[ \leq \tau^3 (2\|PH'' Q\| + \|PH'' P\|) \|PH'' Q\| + \tau (\|PP'' H'\| + \|PP''\|), \quad (84b) \]

where in the second line we used $\|PP''\| = \|PH'' Q\| = \|PH'' Q\| \leq \tau \|PH'' Q\|$. Finally, we use Eq. (77) for $P''$:

\[ \|PP''\| = 2\|P(H'')^2 - 2P[H', H''] - PH''\| \quad (85a) \]

\[ = 2\|PH'' Q H'' P\| + 2\|P(H' H'') - Q\| + 2\|P(H'' H')\| + \|PH''\| \quad (85b) \]

\[ \leq 2\|PH'' Q\| \|Q H'' P\| + 2\|P H'' Q\| + 2\|P H'' H'\| + \|PH''\| \quad (85c) \]

\[ \leq 2\tau^2 (\|PH'' Q\| + \|PH'' P\|) \|PH'' Q\| + 2\|P H'' H'\| + \tau \|PH'' Q\| \quad (85d) \]

To deal with the two terms that are not yet in the desired block-off-diagonal form ($\|PP'' H'\|$ and $\|PH'' H'\|$), we make the following assumption:

\[ H'^2 \leq cH^{2k}. \quad (86) \]
The inequality is to be understood as implying the existence of a positive constant $c$ such that the operator inequality holds, i.e., $c > 0$ can be found such that $H_{2k} - cH_{2}^2$ is a positive matrix for some integer $k > 0$.

We use this assumption as follows. First, it follows from the assumption that $PH'' H'^{2} H'' H^2 P \leq c PH'' H^{2k} H'' H^P$. Hence, upon taking norms of both sides:

$$
||PH'' H'||^2 = ||PH'' H'^{2} H'' H^P|| \leq c||PH'' H^{2k} H'' H^P|| = c||PH'' H'^{2}||^2 = c||P(H'H)^2||^2 \leq c \tau^2 ||PH'H^kQ||^2,
$$

where in the first equality we used $|A|^2 = \parallel AA\parallel$ and in the last equality we made use of $(XY)^\tau = 0$ when $[Y,H] = 0$, and then applied Eq. (53).

Similarly, using $P' = -H'':$

$$
||PP'' H'||^2 = ||PH'' H'^{2} H'' H^P|| \leq c||PH'' H^{2k} H'' H^P|| = c||PH'' H'^{2}||^2 \leq c \tau^2 ||PH'H^kQ||^2.
$$

More generally, we assume the existence of constants $c_k > 0$ such that:

$$
H'^2 \leq \sum_k c_k H^{2k}.
$$

Then:

$$
||PH'H'||^2 \leq \tau^2 \sum_k c_k ||PH'H^kQ||^2
$$

and

$$
||PP'' H'||^2 \leq \tau^4 \sum_k c_k ||PH'H^kQ||^2.
$$

Collecting all these bounds into Eqs. (84) and (85), we obtain:

$$
||PP''|| \leq \tau^3 (2||PH'Q|| + ||PH'P||) ||PH'Q|| + \sqrt{\sum_k c_k ||PH'H^kQ||^2 + 2||PH'Q||^2}
$$

$$
+ 2\tau^3 (||PH'P|| ||PH'Q|| + \sqrt{\sum_k c_k ||PH'H^kQ||^2}) + \tau^2 ||PH''Q||
$$

$$
= \tau^3 (4||PH'Q|| + 3||PH'P||) ||PH'Q|| + \tau^2 ||PH''Q|| + 3\tau^3 \sqrt{\sum_k c_k ||PH'H^kQ||^2}
$$

We are now ready to write down the diabatic evolution bound in its final form, by combining Eqs. (3), (28), (60), and (91):

$$
\parallel [U_{ad}(s^*) - U_{of}(s^*)]P_0 \parallel \leq \frac{\theta}{t_f}
$$

$$
\theta = \tau^2 (0||P_0 H'(0)Q_0|| + \tau^2(s^*) ||P(s^*) H'(s^*) Q(s^*)|| + \int_0^{s^*} ds [\tau^3 (5||PH'Q|| + 3||PH'P||) ||PH'Q|| + \tau^2 ||PH''Q||

+ 3\tau^3 \sqrt{\sum_k c_k ||PH'H^kQ||^2}],
$$

where the expression for $\theta$ coincides with the one in Eq. (25), and hence serves as the end of the proof of Theorem 1. It is worth recalling here also that $\tau$ contains a gap dependence via Eq. (26).

Note that despite appearances due to the block-off-diagonal form of this bound, all of the terms involved can be bounded by norms of some $dP \times dP$ matrices ($dP = \text{rank}(P)$):

$$
||PH'Q|| \leq \sqrt{||PH'^2 P||}, \quad ||PH'H^k Q|| \leq \sqrt{||PH'H^{2k} H' P||},
$$

where the inequalities follow by writing (for any Hermitian operator $A$): $PAAP = P[(P + Q)A(P + Q)]^2 P = PAPAP + PAP QAP$, so that $||PAQ||^2 \leq ||PA^2 P||$. This does not necessarily mean that our bounds are finite, but for physically realistic Hamiltonians we expect them to be. Indeed, $H'' H^{2k} H'$ can at least in principle be interpreted as a physical observable, and it is natural to expect it to be finite in the low-energy eigenspace of $H$ defined by the projection $P$. The key point is that the r.h.s. of Eq. (92) is finite even if $||H'||$ and $||H^{2k}||$ are unbounded.
Before we proceed, let us comment briefly on a physical consequence of the bound \( \parallel U_{ad}(s^*) - U_{tot}(s^*) \parallel P_0 \parallel \leq \frac{\theta_{tf}}{t_f} \) that we have just proven [Eq. (92)]. In Sec. II C 3 we gave a bound on the difference in expectation value of an observable \( O \) between the exact and the adiabatic evolution. Suppose that \( O \) is a unit norm observable such as the Pauli matrix \( \sigma^z \equiv Z \) or \( \sigma^x \equiv X \); measuring \( Z \) on a single qubit in an \( n \)-qubit system is a standard “computational basis” measurement. For this example, Eq. (17) then becomes:

\[
\langle \phi | U_{tot}^\dagger Z U_{tot} | \phi \rangle - \langle \phi | U_{ad}^\dagger Z U_{ad} | \phi \rangle \leq \frac{\theta_{tf}}{t_f} \left( 2 + \frac{\theta_{tf}}{t_f} \right),
\]

(94)

This means that a measurement of \( Z \) at \( t_f \) has an expectation value that – provided \( \frac{\theta_{tf}}{t_f} \ll 1 \) – is well described by an expectation value computed from the evolution \( U_{ad} \) that never leaves the low-energy subspace, which is the qubit subspace. The error between the two is given by the bound above. In Sec. VI we discuss the effective Hamiltonian (a qubit Hamiltonian for this example) generating this approximate evolution in more detail, with the aim of providing a recipe for numerical simulations of qubit Hamiltonians that can predict the outcomes of superconducting circuit experiments.

V. EXAMPLES

We consider examples motivated by adiabatic quantum computing and quantum annealing with flux qubits [31, 36–39]. We first discuss inductively coupled flux qubits in terms of generic circuit Hamiltonians. We use Theorem 1 to derive general bounds on the deviation between the actual evolution described by these circuit Hamiltonians and the evolution in the desired low-energy subspace defined by \( P \). Next we discuss specific models of single flux qubits, for which we can explicitly exhibit the dependence of our bounds on the circuit parameters.

A. Application to coupled flux qubits

An interesting example is the circuit Hamiltonian describing inductively coupled superconducting flux qubits [40]:

\[
H_{\text{flux}}(s) = \sum_i \hat{p}_i^2 + B_i(s) \cos(\hat{x}_i + \varphi_i(s)) + \sum_{ij} M_{ij}(s) \hat{x}_i \hat{x}_j,
\]

(95)

where \( \hat{p}_i \) and \( \hat{x}_i \) are canonically conjugate momentum and position operators, respectively. The remaining quantities are scalar control parameters: \( \varphi_i \) are control fluxes, \( M_{ij} \) are matrix elements of the mutual inductance matrix, and \( B_i \) are barrier heights depending on more control fluxes [28]. A simplified circuit described by this equation is shown in Fig. 2. For notational simplicity we drop the hat (operator) notation below.

1. Constant mutual inductance matrix

We first consider the case \( M_{ij}(s) = M_{jj} \). As we shall see, in this case just \( c_0 \) is sufficient, and previously developed bounds such as JRS’s will apply directly since \( \parallel H' \parallel \) is finite, though recall that by Corollary 1 we can obtain a tighter bound.
The derivative is:

\[ H'_{\text{flux}}(s) = \sum_i B_i'(s) \cos(x_i + \varphi_i(s)) - B_i(s)\varphi'_i(s) \sin(x_i + \varphi_i(s)), \]  

and we note that

\[ \|H'_{\text{flux}}(s)\| \leq \sum_i |B_i'(s)| + B_i(s)|\varphi'_i(s)| = \sqrt{c_0(s)}, \]

where as long as \( B_i(s) \) and \( \varphi_i(s) \) are smooth functions of \( s \) then \( c_0(s) \) is finite and has dimensions of energy:

\[ c_0(s) = \left( \sum_i |B_i'(s)| + B_i(s)|\varphi'_i(s)| \right)^2. \]

The final error upper bound [Eq. (92)] simplifies to:

\[
\theta = \tau^2(0) \| P_0 H'(0) Q_0 \| + \tau^2(s^*) \| P(s^*) H'(s^*) Q(s^*) \| + \int_0^{s^*} ds [\tau^3(5\|PH'Q\| + 3\|PH'P\|) \|PH'Q\|] + \tau^2 \| PH''Q \| + 3\tau^3 \sqrt{c_0(s)} \|PH'Q\| \]

Now, since in this example \( \|H'(s)\| \) is finite \( \forall s \), in fact the projection is not necessary and known bounds are already finite. Indeed, the JRS bound for \( \theta(s^*) \) quoted in Eq. (5) is clearly finite for the present example [recall Corollary 1]. Thus in the next subsection we consider an example where \( \|H'(s)\| \) is unbounded.

2. Time-dependent mutual inductance matrix

Generally, to implement a standard adiabatic quantum computing or quantum annealing protocol, the mutual inductance matrix \( M_{ij} \) cannot be constant (e.g., see Ref. [37]). Thus we consider a second example of a circuit Hamiltonian of superconducting flux qubits, more appropriate for both quantum annealing and our purpose of demonstrating the case of unbounded Hamiltonians. Consider the Hamiltonian in Eq. (95) and its derivative:

\[ H'_{\text{flux}}(s) = \sum_i B_i'(s) \cos(x_i + \varphi_i(s)) - B_i(s)\varphi'_i(s) \sin(x_i + \varphi_i(s)) + \sum_{ij} M'_{ij}(s) x_i x_j. \]

The term \( M'_{ij}(s) x_i x_j \), containing the derivative of the time-dependent mutual inductance matrix, is now unbounded in norm due to the \( x_i x_j \) terms (recall that \( x_i \) are operators), so that the JRS version of the adiabatic theorem [Eq. (5)] does not apply and we need to resort to Theorem 1. Note that \( M_{ij}(s) \) is always a positive matrix. Denote its lowest eigenvalue by \( l = \min l_M \). Then we can bound:

\[ M \geq l I, \quad \Rightarrow \quad \sum_{ij} M_{ij}(s) x_i x_j \geq l \sum_i x_i^2. \]

Note also that

\[ \| M' \| I \geq M' \quad \Rightarrow \quad \| M' \| \sum_i x_i^2 \geq \sum_{ij} M'_{ij}(s) x_i x_j, \]

so that we obtain:

\[ \frac{\| M' \|}{l} \sum_{ij} M_{ij}(s) x_i x_j \geq \sum_{ij} M'_{ij}(s) x_i x_j. \]

Substituting this inequality into Eq. (100) we have:

\[ H'_{\text{flux}}(s) \leq \sum_i |B_i'(s)| + B_i(s)|\varphi'_i(s)| + \| M' \| \frac{1}{l} \sum_{ij} M_{ij}(s) x_i x_j. \]

We now add a (positive) \( p^2 \) term and add and subtract the \( \cos \) term to complete the Hamiltonian:

\[ H'_{\text{flux}}(s) \leq \sum_i (|B_i'(s)| + B_i(s)|\varphi'_i(s)|) + \| M' \| \frac{1}{l} H_{\text{flux}}(s) - \| M' \| \frac{1}{l} B_i(s) \cos(x_i + \varphi_i(s)). \]
The final numerator in the diabatic evolution bound [Eq. (92)] becomes:

\[
\tilde{a} = \text{Denote in Ref. [30, Supplementary Material, p.17], which also explains how harmonic oscillators, with bias } \zeta \text{ and tunneling } \xi \text{ between the groundstates of the wells. The relationship between } \varphi_1, \varphi_2 \text{ and } \phi \text{ is discussed in Ref. [30, Supplementary Material, p.17], which also explains how } H_{\text{CSFQ}} \text{ can be obtained by analyzing the circuit shown here.}
\]

Bounding the last term in the same way as the first two, we obtain:

\[
H'_\text{flux}(s) \leq \sum_i |B_i(s) + B_i(s)| \varphi_i(s)) + \frac{M'}{l} H_{\text{flux}}(s) + \frac{M'}{l} \sum_i |B_i(s)|.
\]

(106)

Denote \(a_0 = \sum_i (|B_i(s) + B_i(s)| \varphi_i(s)) + \frac{M'}{l} |B_i(s)| \) and \(a_1 = \frac{M'}{l}\), then \(H'_\text{flux} \leq a_0 + a_1 H_{\text{flux}}\). For the square of the derivative, we obtain:

\[
H'^2_{\text{flux}} \leq (a_0 + a_1 H_{\text{flux}})^2 \leq (a_0 + a_1 H_{\text{flux}})^2 + (a_0 - a_1 H_{\text{flux}})^2 \leq 2a_0^2 + 2a_1^2 H_{\text{flux}}^2
\]

(107)

Thus the constants we defined in the general notation of Eq. (89) are \(\sqrt{c_0} = \sqrt{2a_0} \) and \(\sqrt{c_1} = \sqrt{2a_1}\), or, explicitly:

\[
\sqrt{c_0} = \sqrt{2} \sum_i (|B_i(s) + B_i(s)| \varphi_i(s)) + \frac{M'}{l} |B_i(s)|, \quad \sqrt{c_1} = \sqrt{2} \frac{M'}{l}
\]

(108)

The final numerator in the diabatic evolution bound [Eq. (92)] becomes:

\[
\theta = \tau^2(0) \| P_0 H'(0) Q_0 \| + \tau^2(s') \| P(s^+) H'(s^+) Q(s^+) \| + \int_0^{s'} ds [\tau^3(5) \| PH'Q \| + 3 \| PH'P \|] \| PH'Q \|
\]

\[
+ \tau^2 \| PH'Q \| + 3\tau^3 \sqrt{c_0} \| PH'Q \| + c_1 \| PH'Q \|^2.
\]

(109)

Contrasting this with Eq. (99) for the case of a constant mutual inductance matrix, we see that the only differences are the appearance of the new term \(c_1 \| PH'Q \|^2\) and an extra contribution from \(M'_{ij}\) to every \(H'\).

**B. Adiabatic timescale via superconducting qubit circuit parameters**

The bounds above are stated in terms of the circuit parameters \(B_i\) and \(M_{ij}\) but are too abstract to be practically useful. In this subsection we consider more specific models and arrive at practically useful bounds which also illustrate the utility of our approach for dealing with unbounded operators.

We consider two types of flux-qubit circuit Hamiltonians:

\[
H_{\text{CJJ}} = E_C \hat{n}^2 + E_J b \cos \phi + E_L (\phi_f - f)^2, \quad \phi \in [-\infty, \infty],
\]

(110a)

\[
H_{\text{CSFQ}} = E_C \hat{n}^2 + E_J b \cos \phi - E_\alpha \cos \frac{1}{2}(\phi_f - f), \quad \phi \in [-2\pi, 2\pi].
\]

(110b)

As we explain below, \(H_{\text{CJJ}}\) describes a compound Josephson junction (CJJ) rf SQUID qubit [29], while \(H_{\text{CSFQ}}\) describes a capacitively shunted flux qubit (CSFQ) [30]. \(H_{\text{CSFQ}}\) can be obtained by analyzing the circuit displayed in Fig. 3. Note that in the notation of Eq. (95), the canonically conjugate operators \(\hat{n}\) (charge stored in the capacitor \(C\)) and \(\hat{\phi}\) (flux threading the circuit) are identified with \(\hat{\rho}\) and \(\hat{x}\), respectively, and that in the transmon case \(E_L = E_\alpha = 0\) [41] [note a factor of 4 difference in the definition of \(E_C\) between the latter and our Eq. (110)].
The quadratic self-inductance term \( E_L(\dot{\phi} - \theta)^2 \) is responsible for the divergence of \( |H_{\text{CJJ}}| \), just like the time-dependent mutual inductance in Eq. (95). Thus, the JRS adiabatic theorem once again does not apply and the bound we derived in Eq. (109) can be used instead. To make this bound explicit in terms of the parameters appearing in \( H_{\text{CJJ}} \) requires quite a bit of additional work. We set the stage for this work using \( H_{\text{CJJ}} \) by explaining how this Hamiltonian can be reduced to an effective qubit Hamiltonian, and then borrow the same set of tools to explicitly compute our bounds for the capacitively shunted flux qubit described by a simpler Hamiltonian \( H_{\text{CSFQ,sin}} \) where we retain just one of the trigonometric terms:

\[
H_{\text{CSFQ,sin}} = E_C\dot{n}^2 + E_J b \cos \dot{\phi} - E_\alpha \sin \frac{\dot{\phi}}{2} \sin \frac{f}{2}, \quad \phi \in [-2\pi, 2\pi].
\] (111)

Note that both \( H_{\text{CSFQ}} \) and \( H_{\text{CSFQ,sin}} \) and their derivatives are bounded, so in this case the JRS adiabatic theorem does apply, but as explained below we will obtain a somewhat tighter bound.

The quantities \( b \geq 1 \) and \( f \geq 0 \) are time-dependent controls that can be chosen at will. Ideally we would like the effective qubit Hamiltonian (Sec. VI) to match a desired quantum annealing “schedule” \( \omega_q((1 - s)X + sZ) \) where \( s = t/t_f \) is the dimensionless time. However in practice for calibration of the annealing schedule an approximate method for choosing \( b(s), f(s) \) is used instead. Here we will also follow this approximate method for simplicity; thus we will not know the true effective qubit Hamiltonian \( H_{\text{eff}} \) the schedule is implementing, but we will be able to accurately bound the error of that qubit description. This is in line with our goal of providing a useful theoretical result to guide current experiments with superconducting circuits: the error would characterize, e.g., the leakage to the non-qubit states for fast anneals. The true effective Hamiltonian \( H_{\text{eff}} \), and correspondingly a precise method for choosing \( b(s), f(s) \), can be found straightforwardly in a numerical simulation, which we leave for future work.

The approximate method is as follows.

**Definition 1.** Using the exact circuit description, we compute a 2×2 operator \( H_q \) defined as follows. \( H_q \) acts on a 2-dimensional Hilbert space corresponding to the low-energy subspace of the circuit Hamiltonian. The basis for \( H_q \) in that subspace is chosen to diagonalize the low-energy projection of \( \delta \). The energy levels of \( H_q \) are chosen to exactly match the two levels of \( \q \) Hamiltonians, up to a constant shift. Once we obtain the relationship between \( b(s), f(s) \) and \( H_q \), we find \( b(s), f(s) \) by requiring:

\[
H_q = \omega_q((1 - s + \delta)X + sZ),
\] (112)

where \( \delta > 0 \) is a certain precision parameter we discuss below (ideally \( \delta = 0 \)).

Note that the true effective Hamiltonian \( H_{\text{eff}} \) is isospectral to \( H_q \), and is a rotation of \( H_q \) to the basis determined by \( U_{\text{eff}} \) as will be prescribed in Sec. VI. In this section we only obtain explicit values of \( \theta \) [the timescale in the error bounds (27)] for an evolution up to \( s = s^* \), and demonstrate a small improvement relative to the JRS version, which yields

\[
\theta_{\text{JRS}}(s^*) = O\left( \frac{1}{\omega_{\text{pl}}(s^*)(1 - s^* + \delta)} \right),
\] (113)

while our new bound yields

\[
\theta_{\text{new}} = O\left( \frac{1}{\omega_{\text{pl}}(s^*)(1 - s^* + \delta)\ln \frac{\omega_q(s^*)}{\omega_{\text{pl}}(s^*)}} \right).
\] (114)

Here the qubit approximation starts at \( b(0) = 1 \) and ends at \( b(s^*) > 1 \). In the Introduction [below Eq. (4)] these results were reported for the special case of \( s^* = 1 \), \( b(1) = B > 1 \). The gap \( 2\Delta(s) \) separating the qubit subspace from the rest of the Hilbert space (recall Fig. 1) will turn out to be well approximated by the plasma frequency \( \omega_{\text{pl}}(s) = \sqrt{E_C E_J b(s)} \). To leading order only the final value of that gap \( \omega_{\text{pl}}(s^*) = \sqrt{E_C E_J b(s^*)} \) enters our bound. These results hold in the relevant regime \( E_J/E_C \gg 1, 1 - s^* + \delta \ll 1 \). The quantities appearing in our result for the adiabatic timescale are illustrated in Fig. 4.

For notational simplicity we again drop the hat (operator) symbols from now on. The goal of the rather lengthy calculations that follow in the remainder of this section is to assign a physical significance to the various quantities that appear in Eqs. (27a) and (27b), expressed in terms of the parameters of CJJ and CSFQ circuits, so as to eventually derive Eqs. (113) and (114).

1. **Compound Josephson junction (CJJ) rf SQUID**

Consider a D-Wave (CJJ rf SQUID) qubit [29]. It consists of a large (main) loop and a small (CJJ) loop subjected to external flux biases \( \Phi_2^\pi \) and \( \Phi_{CJJ}^\pi \), respectively. The CJJ loop is interrupted by two identical Josephson junctions connected in parallel
frequency obtained at zero bias at the beginning and the end of the anneal respectively. Maximum bias also yields charge stored in the capacitance, $\phi$ divides.alt0 in a circuit diagram in Figs. 2 and 5. The two counter-circulating persistent current states along the main loop comprise the qubit $C$ with total capacitance $\xi$ oscillators, with bias $\omega$.

**FIG. 5.** The circuit corresponding to Eq. (110a), and the potential for the phase variable $\phi$. The lowest two wells are approximated as harmonic oscillators, with bias $\zeta$ and tunneling $\xi$ between the groundstates of the wells.

with total capacitance $C$. For illustration purposes we represent this loop as a single junction with some external phase control in a circuit diagram in Figs. 2 and 5. The two counter-circulating persistent current states along the main loop comprise the qubit $|0\rangle$ and $|1\rangle$ states, and can be understood as the states localized in the two wells of a double well potential, described below.

The circuit Hamiltonian of this qubit can be written as in Eq. (110a), where $\omega_q$ denotes the (normalized) quantized charge stored in the capacitance, $\phi = \frac{2\pi}{Q_0} \Phi$ is the (normalized) quantized total flux threading the main loop, $f = (2\pi/\Phi_0)\Phi_2^f$ and $E_J b = -E_J^{\text{conventional}} \cos (\pi \Phi_0^C/\Phi_0)$ depend on the fluxes threading the main and small loops, respectively, $\Phi_0 = h/(2e)$ is the flux quantum (we use units of $h = 1$ throughout), and $E_\text{cc} = 2e^2/C$, $E_L = (\Phi_0/(2\pi))^2/(2L)$, and $E_J$ are the charging, (normalized) inductive, and Josephson energy, respectively. Note that the conventional notation for the Josephson energy translates to ours as $E_J^{\text{conventional}} = E_J B$. The fluxes $\Phi_0^C$ and $\Phi_0^f$ (and hence the parameters $b$ and $f$) are time-dependent and controllable, while the rest are fixed parameters set by the hardware.

While $H_{\text{cir}}$ describes the physical circuit, we wish to implement the low energy Hamiltonian of a qubit with frequency $\omega_q$, as defined by Eq. (112), using the approximate method given in Def. 1. We now discuss how to make this transition. Treating the term $E_J b \cos \phi + E_L (\phi - f)^2$ as a classical potential in the variable $\phi$, it represents a cosine potential superimposed on a parabolic well. The two lowest states in this potential are the qubit states, separated by $\omega_q$. These two states need to be separated from non-qubit states, and the corresponding gap $\Delta$ is given by half the plasma frequency $\omega_{pl}$.

For a transmon, where $E_L = 0$, one has $\omega_q = \omega_{pl} - E_C$ [41], where the plasma frequency is given by

$$\omega_{pl}(s) = 2\sqrt{E_CE_J b(s)}. \quad (115)$$

Note that $b = 1$ corresponds to when the cosine potential is shallowest, i.e., when the tunneling barrier is lowest, which is the initial point of the anneal with $s = 0$. At the other extreme, when $b = B$, the tunneling barrier is at its maximum and this corresponds to the end of the anneal with $s = 1$.

In the presence of the parabolic well there are additional levels in local minima of the raised cosine potential. For $f = 0$ the two degenerate global minima appear at $\phi = \pm \pi$ and the lowest local minima at $\phi = \pm 3\pi$. Thus, to ensure that the additional levels in the local minima are higher than the qubit frequency we can set $\min \omega_{pl}(s) = \omega_{pl}(0) \approx (3\pi)^2 E_L - (\pm \pi)^2 E_L = 8E_L \pi^2$. 

**FIG. 4.** For various target Hamiltonians between $+\omega_q Z$ and $-\omega_q Z$ the anneal paths in the parameter space $b(s), f(s)$ occupy the white triangle. The yellow triangle indicates the range of applicability of the qubit approximation for anneals with $t_J \gg \theta(s^*)$. The splittings $\omega_q$ and $\omega_{pl}$ are obtained at zero bias at the beginning and the end of the anneal respectively. Maximum bias also yields $\omega_q$ at the end of the anneal. The plasma frequency $\omega_{pl}$ is the frequency of each well, and increases throughout the anneal towards the value $\omega_{pl}(s^*)$ that enters $\theta(s^*)$ in Eq. (113).
Next, using \( b(0) = 1 \), if \( E_C \ll E_J \) (as it must, to ensure \( \omega_q \ll \omega_p \)) then \( E_L = O(\sqrt{E_CE_J}) \ll E_J \), which we will assume:

\[
E_C, E_L \ll E_J. \tag{116}
\]

We now wish to choose the controls of \( H_{\text{CSFQ}} \) so that \( H_q \) in Definition 1 takes the form:

\[
H_q(s) = \xi(s)X + \zeta(s)Z, \tag{117}
\]

so that \( \zeta(s) = \omega_q s \) [compare to Eq. (112)]. Focusing just on the minima at \( \phi = \pm \pi \), but now allowing \( f > 0 \), we have \( \zeta(s) = E_L(-\pi - f(s))^2 - E_L(\pi - f(s))^2 \), so that, upon neglecting the \( f^2 \) term:

\[
f(s) = \frac{\zeta(s)}{4E_L\pi} = s \frac{\omega_q}{4E_L\pi}, \tag{118}
\]

subject to \( f(1) < \pi \), i.e., we have the additional constraint \( \omega_q < 4E_L\pi^2 \).

Following Ref. [41], we can identify the bandwidth (peak-to-peak value for the charge dispersion of the energy levels in the periodic potential) of the \( E_L = 0 \) Hamiltonian with the coefficient \( \xi(s) \) in the effective qubit Hamiltonian. Under the assumed inequality (116), Eq. (2.5) of Ref. [41] with \( m = 0 \) yields

\[
\xi(s) = 8E_C \sqrt{\frac{2}{\pi}} \left( \frac{2E_Jb(s)}{E_C} \right)^{3/4} e^{-\sqrt{\frac{32b(s)E_J}{E_C}}} \tag{119}
\]

Thus, a sufficiently large \( b(1) = B \) ensures an exponentially small \( \xi(1) \), which shows that we can operate the system in the annealing regime, i.e., the regime where \( H_q(s) \) interpolates smoothly from \( X \) to \( Z \). Recall that \( b(0) = 1 \), thus \( \xi(0) = \omega_q \) serves as a definition of \( \omega_q \). Let \( \xi(1)/\omega_q = \delta \) be the desired precision. Then we can choose the remaining time dependent control \( b(s) \) by solving Eq. (119) for \( b(s) \) and setting \( \xi(s) = \omega_q(1 - s + \delta) \) [again compare Eq. (117) to Eq. (112)]. This together with Eq. (118) fully defines the schedule.

This mathematical model in fact describes a family of qubits, different by \( \omega_q, \omega_p(1) \) and \( \delta \). The family is spanned by varying the ratio \( E_J/E_C \) and \( B \), in the region where both are \( \gg 1 \) to ensure the applicability of Eq. (119) and the smallness of the precision parameter \( \delta \). Note that in the \( E_J/E_C \gg 1, B \gg 1 \) regime the aforementioned conditions \( \omega_q < \omega_p, 4E_L\pi^2 \) are automatically satisfied. Among the qubits in the family, a smaller \( \omega_q/\omega_p(1) \) will allow a (relatively) faster anneal while the qubit approximation is maintained, but exactly how \( E_J/E_C \) and \( B \) (or equivalently, \( \omega_q/\omega_p(1) \) and \( \delta \)) enter needs to be investigated via the adiabatic theorem, which we will only do for the simpler CSFQ case below.

We have thus shown how to reduce the circuit Hamiltonian \( H_{\text{CSFQ}} \) to an effective qubit Hamiltonian \( H_q \), and how the circuit control functions \( b(s) \) and \( f(s) \) relate to the effective qubit annealing schedule functions \( \xi(s) \) and \( \zeta(s) \).

2. Capacitively shunted flux qubit (CSFQ)

We now repeat the analysis for a periodic \( \phi \), i.e., for \( H_{\text{CSFQ}} \) [Eq. (110b)]. In this case the potential \( E_Jb \cos \phi - E_\alpha \cos \frac{1}{2}(\phi - f) \) exhibits only two wells. For simplicity of the analysis, we instead choose to work with the Hamiltonian \( H_{\text{CSFQ,\alpha}} \) given in Eq. (111). Recall that this Hamiltonian omits one of the terms in the trigonometric decomposition of \( \cos \frac{1}{2}(\phi - f) \) and has the benefit that the wells are centered exactly at \( \phi = \pm \pi \) for all \( f \). Thus it ignores the diabatic effects from the wells shifting along the \( \phi \) axis in the complete CSFQ Hamiltonian (110b). That effect can be included in the calculation straightforwardly, but for our example we choose the simplest nontrivial case. Each well independently experiences narrowing as \( b \) grows, leading to diabatic transitions out of the well’s ground state. The physical meaning of the adiabatic timescale is to characterize the dynamics associated with this deformation of the harmonic oscillator, but by using the general machinery of our and the JRS bounds, we can obtain the result via algebra alone, without having to rely on physical intuition.

To apply the different versions of the adiabatic theorem expressed in Corollary 1 we will need bounds on the derivatives of the simplified CSFQ Hamiltonian (111) (we drop the subscript and hat symbols for simplicity):

\[
H' = E_Jb' \cos \phi - \frac{E_\alpha}{2} f' \sin \frac{\phi}{2} \cos \frac{f}{2}, \tag{120a}
\]

\[
H'' = E_Jb'' \cos \phi - \frac{E_\alpha}{2} f'' \sin \frac{\phi}{2} \left( f'' \cos \frac{f}{2} - \frac{f'^2}{2} \sin \frac{f}{2} \right). \tag{120b}
\]

In the JRS case one directly bounds the operator norm:

\[
\|H'\| \leq E_J|b'| + \frac{E_\alpha}{2} |f'| \tag{121a}
\]

\[
\|H''\| \leq E_J|b''| + \frac{E_\alpha}{2} (|f''| + \frac{1}{2} |f'|^2). \tag{121b}
\]
FIG. 6. The region in the space of control parameters \( b(s), f(s) \) where quantum annealing of a flux qubit is analytically tractable within the well approximation.

In the case of our new version of the adiabatic theorem we will need bounds on the projected quantities. In any case, it is clear that we need to find bounds on the derivatives of \( b \) and \( f \), which we now proceed to derive.

a. The effective Hamiltonian. Define the well basis as the low energy basis diagonalizing \( \phi \) projected into the low-energy subspace. The qubit Hamiltonian in the well basis (see Definition 1) is:

\[
H_q(s) = \xi(s)X + \zeta(s)Z,
\]

(122)

In the limit \( E_\alpha \ll E_J \) we can approximate the width of the wells as equal, which leads to

\[
\zeta(s) \approx E_\alpha \sin \frac{\pi}{2} \sin \frac{f}{2} - E_\alpha \sin \frac{-\pi}{2} \sin \frac{f}{2} = 2E_\alpha \sin \frac{1}{2} f(s)
\]

(123)

[in this case the same result is obtained with the complete potential \( E_\alpha \cos \frac{1}{2} (\phi - f) \)]. We can also neglect the adjustment to the tunneling amplitude through the barrier of height \( bE_J \) coming from the bias \( \zeta(s) \leq 2E_\alpha \) between wells. This again uses \( E_\alpha \ll E_J \). Repeating the argument leading to Eq. (119), the zero-bias expression [Eq. (2.5) of Ref. [41] with \( m = 0 \)] holds for the tunneling amplitude, so we can reuse Eq. (119). This expression also uses \( E_C \ll E_J \). The more rigorous statement of the approximate equality in Eq. (119) is postulated in the conjecture below. In Fig. 6 we contrast the special regime of these approximations, which we call the well approximation, with the traditional schedule for quantum annealing.

b. Reducing the number of parameters. We choose the following notation for the ranges of \( b \) and \( f \):

\[
b : [0, 1] \to [0, B], \quad f : [0, 1] \to [0, F]
\]

(124)

In total, our CSFQ Hamiltonian has five parameters \( E_C, E_J, E_\alpha, B, F \), i.e., four dimensionless parameters, since \( B \) and \( F \) are already dimensionless. We take \( E_C \) to represent an overall energy scale, and define the dimensionless parameter \( A \) as the ratio appearing in \( \xi(s) \),

\[
A = \sqrt{\frac{32E_J}{E_C}},
\]

(125)

rewriting Eq. (119) as:

\[
\xi(s) \approx E_\alpha \sqrt{2} \pi (A \sqrt{b(s)})^{3/2} e^{-A \sqrt{b(s)}}.
\]

(126)

The parameter space can be reduced by setting \( F = \pi/3 \). Note that the maximum allowed \( F \) is \( \pi \), at which \( f'|_{s=1} \) required to fit the schedules will diverge. Making \( F \) really small just makes the qubit worse by adding additional constraints on other parameters, which Justifies our choice. Then \( f(1) = \pi/3 \), so by Eq. (123) we have \( E_\alpha = \zeta(1) \).

We now make use of \( \omega_q = \xi(0) = \zeta(1) \). This means that the annealing schedule is such that the start and end energy approximately coincide, as is traditional for the idealized qubit model of annealing \((1 - s)X + sZ\). This allows us to write:

\[
\omega_q = E_\alpha = \zeta(1) = \xi(0) = E_C \sqrt{\frac{2}{\pi}} A^{3/2} e^{-A},
\]

(127)
i.e., the ratio $E_α/E_C$ is also determined by $A$. Having fixed the dimensionless parameters $E_J/E_C$ and $E_α/E_C$ in terms of the single parameter $A$, and having fixed $F$ at a numerical value, we are left only with $A$ and $B$, i.e., we have reduced the original four dimensionless parameters to two. Let us now state the conjecture that replaces Eq. (119) by a rigorous statement:

**Conjecture 1.** For a desired multiplicative precision $ε$, there exists a minimum $A_0(ε)$ such that $∀ A ≥ A_0$:

$$\xi(s) = E_C \sqrt{\frac{2}{π}} (A\sqrt{b(s)})^{3/2} e^{-A/\sqrt{B(s)}}(1 + ε), \quad |ε| ≤ ε. \quad (128)$$

The two derivatives $ξ'$, $ξ''$ are also given by the derivatives of Eq. (126) to the same multiplicative precision $ε$.

The final transverse field needs to be negligible in quantum annealing. If our tolerance to a finite transverse field is $δ$, the final transverse field needs to be negligible in quantum annealing. If our tolerance to a finite transverse field is $\delta$, then denote:

$$δ = \frac{ξ(1)}{ξ(0)} = (B_0)^{3/4} e^{-A(\sqrt{B} - 1)}. \quad (129)$$

This implicitly defines $B_0(δ, A) > 1$. So our two dimensionless parameters live in a range $A ∈ [A_0(ε), ∞]$ and $B ∈ [B_0(δ, A), ∞]$. Their physical meaning is: $A$ is the (root of the) area under the barrier in appropriate dimensionless units at the beginning of the anneal, and $B$ is how much the barrier has been raised at the end relative to the beginning. We note that both $B_0, A_0$ are rather large numbers for reasonable $ε$ and $δ$, thus we intend to investigate the scaling of the adiabatic timescale $θ$ in the limit $A, B → ∞$. The relationship between $A$ and $B$ as they approach that limit may be arbitrary; we don’t make any additional assumptions about this.

The gap to the non-qubit states is, to the leading order, determined by the plasma frequency:

$$ω_{pl}(b) = 2\sqrt{E_CE_J}b = E_C A \sqrt{b(s)/8}, \quad (130)$$

which is the same as Eq. (115) for the D-Wave qubit. Even though $ω_{pl}(b)$ attains its minimum value at $b(1) = 1$, we will find that the terms in the numerator of the adiabatic theorem overwhelm it in such a way that only $ω_{pl}(B)$ at the end of the anneal matters.

Repeating the reasoning of the CJJ qubit case above, $ξ(0) = ω_{pl}$ serves as the definition of $ω_{pl}$, and the time dependent controls $f(s), b(s)$ should be [approximately, using Eq. (126)] chosen as:

$$\frac{ξ(s)}{ξ(1)} = 2 \sin \frac{1}{2} f(s) = s, \quad (131a)$$

$$\frac{ξ(s)}{ξ(0)} = b(s)^{3/4} e^{-A/\sqrt{b(s)}} + A = 1 - s + δ_B. \quad (131b)$$

Here $δ_B ≤ δ^2$ is the precision we get for this choice of $B$. The quantity $δ_B$ together with the ratio of the qubit frequency $ω_{pl} = ξ(0) = E_α$ [Eq. (127)] to the plasma frequency at the end of the anneal $ω_{pl}(B) = E_α A \sqrt{B}/8$, are the two independent parameters we will use to present the final answer for $θ_{\text{new}}$. The relationship of these two parameters with $A, B$ is given by:

$$δ_B = B^{3/4} e^{-A(\sqrt{B} - 1)}, \quad \frac{ω_{pl}}{ω_{pl}(B)} = 4 \sqrt{π} \sqrt{A/B} e^{-A}. \quad (132)$$

**c. The derivatives $b', b'', f', f''$.** First, from Eq. (131a):

$$f'(s) = \frac{1}{\cos(f/2)} = \frac{1}{\sqrt{1 - (s/2)^2}} ≤ \frac{2}{\sqrt{3}} \quad (133a)$$

$$f''(s) = \frac{s/4}{(1 - (s/2)^2)^{3/2}} ≤ \frac{2}{3\sqrt{3}} \quad (133b)$$

Second, from Eq. (131b):

$$b\left(\frac{3}{4b} - \frac{A}{2\sqrt{b}}\right) b(s)^{3/4} e^{-A/\sqrt{b(s)}} + A = -1 \quad ⇔ \quad b\left(\frac{3}{4b} - \frac{A}{2}\right) = -b(s)^{-1/4} e^{A/\sqrt{b(s)} - A}. \quad (134)$$

---

7 For $ε = 10^{-1}, δ = 10^{-9}$ we are free to choose $A_0$ satisfying Eq. (128). For $b = 1$, if we assume $ε = 1/A_0$, as well as subleading exponential terms, this would lead to an estimate $A_0 = 10$. Now solving Eq. (129) for $B_0$, we find $B_0 = 10.6$

8 This holds since $δ = δ_B$, and $B > B_0 > 1$, and the function $δ_B$ is monotonically decreasing in $B$ for $B > Θ(1/A^2)$. 
Since $A \gg 1$, $b \geq 1$, we can neglect the subleading term $\frac{3}{4\sqrt{b}}$, i.e.,

$$b' \approx \frac{2}{Ab^{1/4}(s)} e^{A\sqrt{b(s)}-A}.$$  \hfill (135)

We do the same in the calculation of the second derivative:

$$b'' \approx \frac{b'}{b(s)^{3/4}} e^{A(\sqrt{b(s)}-1)} \approx \frac{2}{Ab(s)} e^{2A(\sqrt{b(s)}-1)}.$$  \hfill (136)

We will use a change of integration variable

$$ds = \frac{Ab^{1/4}(s)}{2} e^{-A(\sqrt{b(s)}-1)} db.$$  \hfill (137)

We also note that $b'$, $b''$ are exponentially large in $A(\sqrt{b(s)} - 1)$, thus they have the potential of becoming the leading terms in our estimate for the adiabatic timescale.

\[ d \text{. Completing the proof of the result claimed in Eq. (113).} \quad \]  

We show below that $\|H'\|$ is finite, so that Corollary 1 applies. Using the JRS formula (27a) with $d = 2$ and $\Delta \approx \omega_{pl}/2$, we have:

$$g_{RS}^{(s^*)} \approx \frac{8\|H'(0)\|}{\omega_{pl}^2(b(0))} + \frac{8\|H'(s^*)\|}{\omega_{pl}^2(b(s^*))} + I, \quad I \equiv \int_0^s \left( \frac{8\|H''(s)\|}{\omega_{pl}^2(b(s))} + 7 \cdot 2^4 \sqrt{2} \frac{\|H'(s)\|^2}{\omega_{pl}^2(b(s))} \right) ds.$$  \hfill (138)

Returning to Eq. (121a), we now substitute the derivatives of $b$ and $f$ we found in terms of $A, b$, using Eqs. (125), (127), (133a), and (135):

\[ \|H'(s)\| \leq \frac{E_C}{32} A^2 \left( \frac{2}{Ab^{1/4}(s)} e^{A(\sqrt{b(s)}-1)} \right) (1 + o(1)) + E_C \sqrt{\frac{2}{\pi}} A^{3/2} e^{-A} \frac{2}{\sqrt{3}}. \]  \hfill (139)

where the $o(1)$ accounts for the term we neglected in approximating $b'$ to arrive at Eq. (135). The second term in Eq. (139) (arising from $f'$) is subleading, and since we only kept the leading term in the derivatives of $b$, we should omit it. The same happens for the second derivative, for which we use Eqs. (121b) and (136). Thus:

\[ \|H'(s)\| \leq \frac{E_C}{32} A \frac{2}{b(s)} e^{A(\sqrt{b(s)}-1)} (1 + o(1)) \]  \hfill (140a)

\[ \|H''(s)\| \leq \frac{E_C}{32} A \frac{2}{b(s)} e^{2A(\sqrt{b(s)}-1)} (1 + o(1)). \]  \hfill (140b)

Here $o(1)$ means going to zero in the limit $A \to \infty$, or $b \to \infty$. We will omit the $(1 + o(1))$ clause below when working with leading order expressions.

Let us substitute the expressions obtained so far into the integral $I$ [Eq. (138)], and change variables to $db$ using Eq. (137):

\[ I \leq \int_1^{b(s^*)} \left( \frac{8E_C}{32} A^2 \frac{e^{2A(\sqrt{b(s)}-1)}}{e^{E_C A^2 b/8}} + 7 \cdot 2^4 \sqrt{2} \frac{E_C^3 A^4 e^{2A(\sqrt{b(s)}-1)}}{E_C A^4 (b/8)^{3/2}} \right) A^{1/4} db, \]  \hfill (141)

where we also used Eq. (130). The two terms depend on $A$ and $b$ in exactly the same way:

\[ E_C I \leq 9 \int_1^{b(s^*)} b^{-7/4} e^{A(\sqrt{b(s)}-1)} db = 18A^{3/2} e^{-A} \int_A^{A^{1/4}(s^*)} w^{-5/2} e^w dw. \]  \hfill (142)

The integral can be computed analytically in terms of the exponential integral function, but it is more insightful to observe that it is dominated by the upper integration limit, under the assumption that $b'(s^*) 

\[ \int_A^{A^{1/4}(s^*)} w^{-5/2} e^w dw = \int_{-\infty}^{A^{1/4}(s^*)} \frac{1}{(A \sqrt{b(s^*)})^{3/2}} e^w dw = \frac{e^{A \sqrt{b(s^*)}}}{(A \sqrt{b(s^*)})^{3/2}}. \]  \hfill (143)

Hence:

\[ I \leq 18 \frac{e^{A(\sqrt{b(s^*)}-1)}}{E_C A b(s^*)^{3/4}}. \]  \hfill (144)
The full bound for $\theta$ is thus, using Eqs. (130), (138), (140), and (144):

$$\theta^{\text{RS}}(s^*) \leq \frac{4}{E_{C\mathcal{A}}} \left( 1 + \frac{e^{A(\sqrt{s^*(s^*)^{-1})}}}{b(s^*)^{5/4}} + \frac{9}{2} \frac{e^{A(\sqrt{s^*(s^*)^{-1})}}}{b(s^*)^{5/4}} \right) \approx \frac{22}{E_{C\mathcal{A}}b(s^*)^{5/4}} = \frac{1}{(1 - s^* + \delta_B)E_{C\mathcal{A}}b(s^*)}, \quad (145)$$

where neglecting the subleading first term (arising from $s = 0$) means that only the end of the annel matters, and we used Eq. (132) to obtain the last equality. Reintroducing $\omega_p(b(s^*)) = E_{C\mathcal{A}}/b(s^*)^{3/8}$ [Eq. (130)], we obtain:

$$\omega_q \theta^{\text{RS}}(s^*) \leq \frac{11}{\sqrt{2}} \frac{1}{(1 - s^* + \delta_B) \omega_p(b(s^*))}. \quad (146)$$

The ratio of qubit frequency over gap is what one would intuitively expect from the adiabatic theorem, but the other factors can only be obtained after a detailed calculation such as the one performed here.

e. Completing the proof of the result claimed in Eq. (114). Since we have already shown that $H'$ is a bounded operator [Eq. (140a)] we now use Eq. (27b) [Corollary 1] for the CSFQ Hamiltonian.

It turns out that there is no benefit from $\|P(H'P) - \|H'\|P$, so we just use $\|P(H'P) \leq \|H'\|$, and focus on the off-diagonal terms $\|PH''Q\|$ and $\|PH'Q\|$ to obtain an improvement over the JRS bound (146). Starting from Eq. (120), we have:

$$PH'Q = E_j b' P \cos \dot{\phi}Q - \frac{E_j}{2} P \sin \dot{\phi}Q \cos \frac{f}{2} \cos \frac{f}{2}$$

Thus we need to estimate the leading order of the bound on $\|P \cos \dot{\phi}Q\|$ and $\|P \sin \dot{\phi}Q\|$. For this estimate, we make use of the well approximation: the eigenstates are approximately the states of a harmonic oscillator centered at each well (Fig. 6). Indeed, recalling that $H_{\text{CSFQ,sin}}$ [Eq. (111)] is a Hamiltonian representing a double-well potential centered exactly at $\phi = \pm \pi$ for all $f$. We thus approximate as the sum of

$$H_L = E_C \hat{n}^2 + \frac{1}{2} E_j b(\dot{\phi} + \pi)^2, \quad H_R = E_C \hat{n}^2 + \frac{1}{2} E_j b(\dot{\phi} - \pi)^2. \quad (148)$$

$P$ projects onto the span of the ground states of these two Hamiltonians, while $Q$ projects onto the span of the first and higher excited states. Denote $\delta \phi_{L,R} \equiv \phi \pm \pi$, then the expression for the position operators $\delta \phi$ in terms of the corresponding harmonic oscillator creation and annihilation operators is:

$$\delta \hat{\phi}_{L,R} = O \left( \frac{E_C}{E_j b} \right)^{1/4} (\hat{a}_{L,R} + \hat{a}^\dagger_{L,R}). \quad (149)$$

We can now estimate:

$$\|P \cos \dot{\phi}Q\| = \|g_L \langle gL | \cos \delta \hat{\phi}_L (1 - |g_L \rangle \langle gL |) \cos \delta \hat{\phi}_R (1 - |g_R \rangle \langle gR |) \|, \quad (150)$$

where $|g_{L,R}\rangle$ are the ground states in the corresponding wells, and we neglected the matrix elements of $\cos \phi$ that mix the wells. We proceed as follows:

$$\|P \cos \dot{\phi}Q\| \approx \|g_L \langle gL | (1 - \frac{1}{2} \delta \hat{\phi}_L^2 (1 - |g_L \rangle \langle gL |) + |g_R \rangle \langle gR | (1 - \frac{1}{2} \delta \hat{\phi}_R^2 (1 - |g_R \rangle \langle gR |) \| \quad (151a)$$

$$= \frac{1}{2} \|g_L \langle gL | \delta \hat{\phi}_L^2 (1 - |g_L \rangle \langle gL |) + |g_R \rangle \langle gR | \delta \hat{\phi}_R^2 (1 - |g_R \rangle \langle gR |) \| \quad (151b)$$

$$\leq \frac{1}{2} \|g_L \langle gL | \delta \hat{\phi}_L^2 (1 - |g_L \rangle \langle gL |) \| + \|g_R \langle gR | \delta \hat{\phi}_R^2 (1 - |g_R \rangle \langle gR |) \|. \quad (151c)$$

---

9 To see this, consider the standard 1D quantum harmonic oscillator Hamiltonian $H = \alpha \hat{x}^2 + \beta \hat{p}^2$, where $\alpha = \frac{1}{2m}$ and $\beta = \frac{1}{2} m \omega^2$, which after the introduction of the standard creation and annihilation operators gives $\hat{x} = \gamma (\hat{a} + \hat{a}^\dagger)$, where $\gamma = (\frac{\omega^2}{4})^{1/4} = \sqrt{\frac{\omega}{2m}}$; in our case $\alpha = E_C$ and $\beta = \frac{1}{2} E_j b$, so that $\gamma = \Theta \left( \frac{E_C}{E_j b} \right)^{1/4}$, where the big-$\Theta$ notation is defined by $y = \Theta(x) \iff (y = O(x) \text{ and } x = O(y))$ which includes proportionality up to a constant.
Plugging in Eq. (149),\(^{10}\) and repeating the same calculation for \( |P \cos \frac{\delta \phi}{2} Q| \), we get:

\[
\|P \cos \frac{\delta \phi}{2} Q\| = O\left(\frac{E_C}{E_J b}\right)^{1/2} \quad (152a)
\]

\[
\|P \sin \frac{\delta \phi}{2} Q\| = \|P \cos \frac{\delta \phi}{2} Q\| = O\left(\frac{E_C}{E_J b}\right)^{1/2} \quad (152b)
\]

Thus the expressions (121) and (140) get multiplied by the same factor \(O\left(\frac{E_C}{E_J b}\right)^{1/2}\):

\[
\|P H'(s) Q\| \approx \|H'(s)\| O\left(\frac{E_C}{E_J b(s)}\right)^{1/2} \quad (153a)
\]

\[
\|P H''(s) Q\| \approx \|H''(s)\| O\left(\frac{E_C}{E_J b(s)}\right)^{1/2} \quad (153b)
\]

Note that since \(\sqrt{E_C/E_J} = \sqrt{32} A [\text{Eq. (125)}]\) and \(b(s) \in [1, B]\), we have

\[
\left(\frac{E_C}{E_J b(s)}\right)^{1/2} \ll 1 \quad \forall s. \quad (154)
\]

We can carry the \(O\left(\frac{E_C}{E_J b}\right)^{1/2}\) factor through the calculations all the way until the integration, as in Eq. (138), except that now the integral is the one appearing in Eq. (27b). Thus, again using \(d = 2\) and \(\Delta \approx \omega_p l/2\), and absorbing all numerical factors into \(O(1)\) when convenient:

\[
I \approx \int_0^s \left(8\frac{|P H''(s) Q|}{\omega_p^2 b(s)} + 2^4 \sqrt{2} \frac{|P H'(s) Q| (5 |P H'(s) Q| + 3 |P H'(s) P| + 3 |H'(s)|)}{\omega_p^3 (b(s))}\right) ds \quad (155a)
\]

\[
\leq O(1) \int_0^s \left(\frac{|P H''(s) Q|}{\omega_p^2 b(s)} + \frac{|P H'(s) Q| (|P H'(s) Q| + |H'(s)|)}{\omega_p^3 (b(s))}\right) ds. \quad (155b)
\]

It follows from Eqs. (153a) and (154) that we may neglect \( |P H'(s) Q| \) compared to \( |H'(s)| \). We may thus proceed from Eq. (142) but multiply the right-hand side by \( O\left(\frac{E_C}{E_J b(s)}\right)^{1/2} = O(1) \frac{1}{A \sqrt{b(s)}} \):

\[
E_C I \leq O(1) \left(\frac{E_C}{E_J}\right)^{1/2} \int_1^{b(s*)} b^{-9/4} e^{A(\sqrt{b(s*)}-1)} db = O(1) A^{3/4} e^{-A} \int_A^{A \sqrt{b(s*)}} w^{-7/4} e^w dw \approx O(1) \frac{e^{A(\sqrt{b(s*)}-1)}}{A^2 b(s*)^{7/4}}, \quad (156)
\]

where in the last approximate equality we applied the same reasoning as in Eq. (143).

Comparing to the latter, we see that the expression gained an overall factor of \(\frac{1}{A \sqrt{b(s*)}}\). The same happens with the leading boundary term. Using Eq. (140a):

\[
\left. \left\|\frac{d}{\Delta^2} \frac{d}{\Delta^2} \frac{d}{\Delta^2} \right\| \right|_{s=0} + \left. \left\|\frac{d}{\Delta^2} \frac{d}{\Delta^2} \right\| \right|_{s=s*} \leq O(1) \left( \left(\frac{E_C}{E_J b(0)}\right)^{1/2} \left\|\frac{H'(0)}{\omega_p^2 b(0)}\right\| + \left(\frac{E_C}{E_J b(1)}\right)^{1/2} \left\|\frac{H'(s*)}{\omega_p^2 b(s*)}\right\| \right) \quad (157a)
\]

\[
= O(1) \frac{1}{E_C A^2} \left( 1 + \frac{e^{A(\sqrt{b(s*)}-1)}}{b(s*)^{7/4}} \right) \approx O(1) \frac{e^{A(\sqrt{b(s*)}-1)}}{E_C A^2 b(s*)^{7/4} b(s*)^{7/4} \quad (157b)}
\]

which is of the same order as the integral term. Thus:

\[
\theta_{new}(s*) = \left. \left\|\frac{d}{\Delta^2} \frac{d}{\Delta^2} \frac{d}{\Delta^2} \right\| \right|_{s=0} + \left. \left\|\frac{d}{\Delta^2} \frac{d}{\Delta^2} \right\| \right|_{s=s*} + I \leq O(1) \frac{e^{A(\sqrt{b(s*)}-1)}}{E_C A^2 b(s*)^{7/4} \quad (158a)}
\]

\[
= O(1) \frac{1}{A \sqrt{b(s*)}} \theta_{BS}(s*) \quad (158b)
\]

\[
= O(1) \frac{1}{(1 - s* + \delta_B) E_C A^2 b(s*)} = O(1) \frac{1}{(1 - s* + \delta_B) \omega_p^2 b(s*)}. \quad (158c)
\]

\(^{10}\) In the number basis we have \(|g)(g(a + a^*)^2 (1 - |g)(g) = |0\rangle \langle 0 | (a + a^*)^2 \sum_{n=1}^{\infty} |n\rangle \langle n | = \sqrt{2} |0\rangle \langle 0 | 2\rangle, and \| |0\rangle \langle 0 | 2\rangle \| = 1 \) (largest eigenvalue of \(|2\rangle \langle 2|\)).
where in the second line we used Eq. (145) and \( \omega_{pl}(b(s^*)) = \Theta(1) E_C A \sqrt{b(s^*)} \) [Eq. (130)].

Now, using \( \omega_{pl}(b(0)) = E_C A \sqrt{1/8} \) we have \( E_C = \Theta(1) \omega_{pl}(b(0))/A \). Also, from Eqs. (127) and (130) we have \( A^{1/2} e^{-A} = \Theta(\omega_q/\omega_{pl}(b(0))) \), which we can solve approximately as \( A = \Theta \left( \ln(\omega_{pl}(b(0))/\omega_q) \right) \). Combining this with Eq. (158c), we get:

\[
\theta^\text{new}(s^*) \lesssim O(1) \left( \frac{1}{1 - s^* + \delta_B} \frac{E_C}{\omega_{pl}^2(b(s^*))} \right) = O(1) \left( \frac{1}{1 - s^* + \delta_B} \frac{\omega_{pl}(b(0))}{\omega_{pl}(b(s^*)) \ln(\omega_{pl}(b(0))/\omega_q)} \right) 
\]

\[
= O(1) \theta^{\text{RS}}(s^*) \omega_{pl}(b(0)) / \omega_{pl}(b(s^*)) \ln(\omega_{pl}(b(0))/\omega_q),
\]

where the JRS result is given in Eq. (146).

3. Comparison of the two bounds for the CSFQ

To compare the two bounds, it is useful to express everything via two parameters at \( s^* \) only: \( 1 - s^* + \delta_B \) and \( \frac{\omega_q}{\omega_{pl}(b(s^*))} \). Note, combining Eqs. (127), (130) and (131b), that:

\[
(1 - s^* + \delta_B) \frac{\omega_q}{\omega_{pl}(b(s^*))} = \frac{4}{\sqrt{\pi}} (A \sqrt{b(s^*)})^{1/2} e^{-A \sqrt{b(s^*)}} \Rightarrow A \sqrt{b(s^*)} = -(1 + o(1)) \ln \left[ \left( 1 - s^* + \delta_B \right) \frac{\omega_q}{\omega_{pl}(b(s^*))} \right].
\]

Thus, since Eq. (158b) shows that the new bound is related to the JRS bound by the factor \( 1/(A \sqrt{b(s^*)}) \), using the new bound leads to a logarithmic correction of the original adiabatic timescale:

\[
\theta^\text{new}(s^*) = \theta^{\text{RS}}(s^*) \left( \frac{O(1)}{- \ln \left[ \left( 1 - s^* + \delta_B \right) \frac{\omega_q}{\omega_{pl}(b(s^*))} \right]} \right).
\]

We conclude that there are two competing small numbers, \( 1 - s^* + \delta_B \) and \( \frac{\omega_q}{\omega_{pl}(b(s^*))} \). The gap to the third state should be much larger than the qubit frequency, i.e., \( \omega_{pl}(b(s)) \gg \omega_q \forall s \). The expression \( 1 - s^* + \delta_B \) [recall its definition in Eq. (131b)], times \( \omega_q \), can be interpreted as a residual transverse field \( h_x \) at \( s = s^* \). This residual transverse field should satisfy \( h_x/\omega_q = 1 - s^* + \delta_B \ll 1 \) in the regime where the expression \( \theta(s^*) \) for the adiabatic timescale over the interval \([0, s^*]\) is valid. Using Eqs. (146) and (161) we may rewrite the two bounds as:

\[
\omega_q \theta^{\text{RS}}(s^*) = O(1) \left. \frac{\omega_q^2}{\omega_{pl} h_x} \right|_{s=s^*}, \quad \omega_q \theta^\text{new}(s^*) = O(1) \left. \frac{\omega_q^2}{\omega_{pl} h_x \ln(\omega_q/\omega_{pl}(s^*) \right|_{s=s^*}.
\]

Thus, if the geometric mean \( \sqrt{h_x/\omega_{pl}} \gg \omega_q \), then the effective dynamics stays within the qubit approximation well. Our new bound adds a logarithmic correction to this estimate, and is tighter than the JRS bound since \( \omega_{pl}(b(s^*)) > h_x \). Finally, we note that a brute-force calculation we present in Appendix A obtains an equivalent bound.

Since the adiabatic timescale increases as \( s^* \) approaches 1, there is a regime of intermediate anneal times \( t_f \) such that:

\[
\theta(0) \leq t_f \leq \theta(1) \Rightarrow \frac{11/\sqrt{2}}{\omega_{pl}(0)} \leq t_f \leq \frac{11/\sqrt{2}}{\delta_B \omega_{pl}(1)} ,
\]

where we dropped the logarithmic corrections, and also for the purposes of estimation used \( \theta(0) \) even though this is outside the range of applicability of our expression for \( \theta \). In this regime there is \( s^* \) such that \( t_f = \theta(s^*) \), and the physical intuition is that the anneal over the interval \([0, s^*]\) stays within the qubit approximation, while the anneal beyond that in the interval \([s^*, 1]\) leaves the qubit subspace. We do not know if there is still an effective qubit description of this dynamics, but we note that it is not likely to be given by the dynamics of the lowest levels alone. Indeed, although there will still be tunneling between the wells in \([s^*, 1]\), there is no clear way to define a phase of the state in each well, since that state involves several energy levels of that well. Thus the pattern of interference that emerges when the populations of two wells meet after tunneling will no longer be governed by a single phase parameter. This intuition suggests that either a full multilevel description should be utilized instead of a qubit description, or possibly there is an effective stochastic description that arises after we neglect any interference effects but keep the dimension of the qubit model. The development of such a theory is beyond the scope of this work.
VI. EFFECTIVE HAMILTONIAN

In this section we will show that the effective evolution in a $d_P$-dimensional low-energy subspace that is an image of $P(s)$ is best described by a $d_P \times d_P$ effective Hamiltonian:

$$H_{\text{eff}}(s) = V(s)H(s)V^\dagger(s), \quad V(s) = V_0U^\dagger_{\text{eff}}(s), \quad \frac{\partial}{\partial s}U_{\text{eff}}(s) = [P', P]U_{\text{eff}}(s), \quad U_{\text{eff}}(0) = I$$

(164)

where the isometry $V_0$ describes a freedom of choice of basis in the low-energy subspace at $s = 0$.

Consider the equation of the approximate evolution $U_{\text{ad}}(s)|\phi_0\rangle = |\phi(s)\rangle$ generated by $H_{\text{ad}}(s)$ [Eq. (7)]:

$$\frac{\partial}{\partial s}|\phi(s)\rangle = -iH_{\text{ad}}(s)|\phi(s)\rangle.$$  

(165)

This is written in the full Hilbert space even though we know that $\forall s > 0$, $P(s)|\phi(s)\rangle = |\phi(s)\rangle$ as long as the same holds for the initial state $|\phi_0\rangle$.

This suggests that we could write the evolution as generated by a $d_P \times d_P$ matrix in the low-energy subspace - the effective Hamiltonian. Of course, one can trivially do this by first undoing the evolution generated by $U_{\text{ad}}$, i.e., by first changing the basis in a time-dependent manner via

$$|\zeta(s)\rangle = U_{\text{ad}}^\dagger|\phi(s)\rangle \implies \frac{\partial}{\partial s}|\zeta(s)\rangle = \frac{\partial}{\partial s}|\phi_0\rangle = 0.$$  

(166)

Let the eigenvectors of $H(0)$ in the low energy subspace be $\{|\lambda_i\rangle\}_{i=1}^{d_P}$, and let the basis vectors defining the new $d_P$-dimensional Hilbert space we map into be $\{|e_i\rangle\}_{i=1}^{d_P}$. Then the isometry $V_0$ corresponding to the projection $P_0 \equiv P(0)$ can be chosen as:

$$V_0 = \sum_{i=1}^{d_P} |e_i\rangle|\lambda_i\rangle.$$  

(167)

We use $V_0$ to form a $d_P$-dimensional Schrödinger equation

$$|\psi(s)\rangle = V_0|\zeta(s)\rangle \implies \frac{\partial}{\partial s}|\psi(s)\rangle = 0.$$  

(168)

Thus the effective $d_P \times d_P$ Hamiltonian governing the dynamics of $|\psi(s)\rangle$ is zero in this basis. The observables $O$ of the original system have to be transformed accordingly:

$$O_V(s) = V_0U_{\text{ad}}^\dagger(s)OU_{\text{ad}}(s)V_0^\dagger,$$  

(169)

which is $t_f$-dependent.

We would now like to present another time-dependent basis in which this $t_f$-dependence disappears. There are some additional reasons to consider a different effective Hamiltonian, to be discussed below. Define $U_{\text{eff}}^G(s)$ via:

$$\frac{\partial}{\partial s}U_{\text{eff}}^G(s) = (G + [P', P])U_{\text{eff}}^G(s),$$  

(170)

where $G = G(s)$ is a gauge (geometric connection) term in the generator for the basis change, which we assume to be block-diagonal ($G = PGP + QGQ$). We prove in Appendix B that any such $U_{\text{eff}}^G$ will satisfy the intertwining property much like Eq. (8) for $U_{\text{ad}}$:

$$U_{\text{eff}}^G(s)P_0 = P(s)U_{\text{eff}}^G(s).$$  

(171)

We then let $U_{\text{eff}}^G$ be our time-dependent change of basis transformation:

$$|\zeta(s)\rangle = U_{\text{eff}}^G(\zeta)|\phi(s)\rangle = U_{\text{eff}}^G(s)|\phi_0\rangle.$$  

(172)

Now, $\frac{\partial}{\partial s}U_{\text{eff}}^G = U_{\text{eff}}^G([G^\dagger + [P, P']], \text{ so that, using Eq. (165):}$

$$\frac{\partial}{\partial s}|\zeta(s)\rangle = U_{\text{eff}}^G([G^\dagger + [P, P'] - iH_{\text{ad}}])|\phi\rangle = U_{\text{eff}}^G([G^\dagger + [P, P'] - iT_fH + IT_f[P', P']])U_{\text{eff}}^G|\zeta(s)\rangle = U_{\text{eff}}^G([G^\dagger - iT_fH])U_{\text{eff}}^G|\zeta(s)\rangle,$$  

(173)
where $H(s)$ is the full Hamiltonian in Eq. (7). Note that combining Eqs. (8) and (171), we see that $|\zeta(s)\rangle$ remains in the $s = 0$ low-energy subspace: $|\zeta(s)\rangle = P_0 |\zeta(s)\rangle$ for all $s$. Thus the isometry $V_0$ defined as before completes the mapping into the effective (e.g., qubit) $d_P$-dimensional Hilbert space:

$$ |\psi(s)\rangle = V_0 |\zeta(s)\rangle \tag{174} $$

Thus:

$$ \frac{\partial}{\partial s} |\psi(s)\rangle = -i t_f H_{\text{eff}}^G(s) |\psi(s)\rangle, \tag{175} $$

where

$$ H_{\text{eff}}^G(s) = V^G(s) \left( H(s) + \frac{i}{t_f} G^\dagger \right) V^G_{\dagger}(s), \tag{176} $$

and we defined the time-dependent isometry

$$ V^G(s) = V_0 U_{\text{eff}}^{G_{\dagger}}(s) \tag{177} $$

into the effective basis at any $s$. Note that, combining our notation, we can write:

$$ |\psi(s)\rangle = V^G |\phi(s)\rangle, \quad |\phi(s)\rangle = V^G_{\dagger} |\psi(s)\rangle \tag{178} $$

The adiabatic theorem (Theorem 1) we have proven gives the bound [recall Eq. (24)]

$$ \| |\phi(s)\rangle - |\phi_{\text{tot}}(s)\rangle \| \leq b = \frac{\theta}{t_f}, \tag{179} $$

where $|\phi(s)\rangle$ is the approximate evolution from Eq. (165), while $|\phi_{\text{tot}}(s)\rangle = U_{\text{tot}}(s) |\phi_0\rangle$ is the true evolution generated by the Hamiltonian $H(s)$ in the full Hilbert space. Applying the expression for $|\phi(s)\rangle$ in terms of $|\psi(s)\rangle$, we get:

$$ \| V^G_{\dagger} |\psi(s)\rangle - |\phi_{\text{tot}}(s)\rangle \| \leq b = \frac{\theta}{t_f}. \tag{180} $$

This inequality means that $|\psi(s)\rangle$, the state evolving according to the effective Hamiltonian, after an isometry back to the total Hilbert space is close to the true state $|\phi_{\text{tot}}(s)\rangle$. Since $V_0 V_0^\dagger = I$ and since $V_0$ is an isometry (hence norm reducing), we have

$$ \| |\psi(s)\rangle - V^G(s) |\phi_{\text{tot}}(s)\rangle \| = \| V^G(s) (V^G_{\dagger}(s) |\psi(s)\rangle - |\phi_{\text{tot}}(s)\rangle) \| \leq \| V^G_{\dagger}(s) |\psi(s)\rangle - |\phi_{\text{tot}}(s)\rangle \| \leq b = \frac{\theta}{t_f}. \tag{181} $$

Let $u(s)$ be generated by $t_f H_{\text{eff}}(s)$, i.e., $|\psi(s)\rangle = u(s) |\psi(0)\rangle$ [Eq. (175)]. Note that $|\phi(0)\rangle = V^G_{\dagger} |\psi(0)\rangle$. We can rewrite Eq. (181) as:

$$ \forall |\psi(0)\rangle : \quad \| (u(s) - V^G(s) U_{\text{tot}}(s) V^G_{\dagger}(s) |\psi(0)\rangle \| \leq b = \frac{\theta}{t_f}. \tag{182} $$

It follows immediately that the same bound holds for the evolution operators, as stated in the Introduction [recall Eq. (4)]:

$$ \| (u(s) - V^G(s) U_{\text{tot}}(s) V^G_{\dagger}(s)) \| \leq b. \tag{183} $$

The observables of the original system transform as:

$$ O_{\text{eff}}^G(s) = V^G(s) O V^G_{\dagger}(s). \tag{184} $$

In practice, $H_{\text{eff}}$ and $O_{\text{eff}}$ can be found by truncation of the total Hilbert space to some large cutoff, and working with truncated finite dimensional matrices $O, H, U, V$. The error introduced by the cutoff may be estimated by trying several cutoffs and extrapolating. We defer a more rigorous treatment of this error to future work.

Let us now discuss the gauge $G$. There are two natural reasons for choosing $G = 0$. The first is that if we wish to keep the basis change (and thus the operators $O_{\text{eff}}^G = V^G(s) O V^G_{\dagger}(s)$) $t_f$-independent, then $G$ itself must be $t_f$-independent. Thus, by Eq. (176), the only choice that leads to $t_f$-independent $H_{\text{eff}}^G$ is $G = 0$.

The second is that the choice $G = 0$ is the one that minimizes the norm of the derivative of any observable. This can be interpreted as the desirable consequence of not imparting any additional geometric phases that artificially speed up the evolution of observables in the given observation frame. To show this explicitly, note first that since we assumed that $G$ is block-diagonal, we cannot choose the block-off-diagonal form $G = -[P^G, P]$ to cancel the time-dependence of the operators. Now, by Eq. (170):

$$ \frac{\partial}{\partial s} O_{\text{eff}}^G = V^G[O, G + [P^G, P]] V^G_{\dagger}. \tag{185} $$

When an operator $X$ is block-diagonal so that in particular $P X P = 0$, then also $V^G X V^G_{\dagger} = 0$ since $V^G$ just maps onto the space the projector selects. With this, it is clear that since $P^G P = P = 0$, we have:

$$ \| \frac{\partial}{\partial s} O_{\text{eff}}^G \| = \| V^G[O, G] V^G_{\dagger} \| \geq 0, \tag{186} $$

with the norm vanishing in general only when $G = 0$. 

VII. CONCLUSIONS

Starting with Kato’s work in the 1950’s, work on the adiabatic theorem of quantum mechanics has resulted in rigorous bounds on the convergence between the actual evolution and the approximate, adiabatic evolution. These bounds were initially derived for Hamiltonians with bounded-norm derivatives, then conjectured without presenting the explicit form for the unbounded case, subject to assumptions restricting the class of Hamiltonians to being ‘admissible’, which essentially meant that norms of certain functions of $H$ and its derivatives were not allowed to diverge. In this work we obtained new bounds which are presented in the explicit form, and applied to Hamiltonians whose derivatives are unbounded. To achieve this we introduced a different assumption, relating $H'$ to a power of $H$ via a simple-to-check positivity condition [Eq. (86)]. With this assumption, we derived a new form of the adiabatic theorem. We expect this adiabatic theorem to prove to be useful in a variety of situations, e.g., in the context of adiabatic quantum computing using superconducting qubits or trapped ions, where the physical degrees of freedom correspond to (perturbed) harmonic oscillators.

To demonstrate and illustrate the latter, we performed a calculation of the adiabatic timescale characterizing the accuracy of the qubit approximation of the circuit Hamiltonian of a capacitively shunted flux qubit. Specifically we considered a time evolution fashioned after quantum annealing that attempts to reduce the qubit transverse field $X$ linearly as $(1-s)X$. The result shows that after some $s^*$ close to 1 the state generally escapes from the qubit approximation. Specifically, higher oscillator states become populated in each well. We do not expect this leakage effect to introduce a significant change in the outcome of a single-qubit quantum anneal, since the end-measurement is just a binary measurement of which well the flux is in, not the projection onto the lowest eigenstates. Thus, the non-qubit eigenstates become categorized as 0 or 1 depending on the sign of the flux. It remains an open question what the effect of this type of leakage is in the case of multi-qubit quantum dynamics, and whether it impacts the prospects of a quantum speedup.

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Appendix A: Time-dependent harmonic oscillator: a brute-force estimate vs. the bound of Sec V B

To obtain a meaningful expression for the adiabatic timescale $\theta$ in Sec. V B, we had to use a “well approximation”: the two wells of the $\phi$-potential of the Hamiltonian

$$H_{\text{CSFQ,sin}} = E_C \hat{n}^2 + E_J b \cos \hat{\phi} - E_\alpha \sin \frac{\hat{\phi}}{2} \sin \frac{f}{2} \phi \in [-2\pi, 2\pi]$$

are separated by a large enough barrier $\sim b E_J$ throughout the anneal, so that the low energy subspace is approximately given by the ground states of the harmonic approximation of the left and right wells:

$$H_{\text{CSFQ,L}} = E_C \hat{n}^2 + E_J b \frac{(\hat{\phi} + \pi)^2}{2}, \quad \phi \in [-\infty, \infty],$$

$$H_{\text{CSFQ,R}} = E_C \hat{n}^2 + E_J b \frac{(\hat{\phi} - \pi)^2}{2}, \quad \phi \in [-\infty, \infty].$$

Note that we neglected the adjustment of the harmonic potential by the last term, and made a constant energy shift $\pm E_\alpha \sin \frac{f}{2}$. If we choose $b(s)$ and $f(s)$ the same way as in Eq. (131), the Hamiltonians $H'_{\text{CSFQ,L}}$ and $H'_{\text{CSFQ,R}}$ are unbounded, so we cannot apply JRS anymore. We will need to use the relation

$$(H'_{\text{CSFQ,L}})^2 \leq \frac{b^2}{b^2} H_{\text{CSFQ,L}}.$$
FIG. 7. For this figure, we assume that up to \( s_1 \) the evolution was fully adiabatic, but then the instantaneous approximation is applied to go from \( s_1 \) to \( s_2 \). The wavefunction is preserved, but since the eigenstates change it gets projected into the excited states. In the text, a more careful calculation of the leakage is carried out.

Applying our adiabatic theorem [Eq. (25)] to staying in the ground state of \( H_{\text{CSFQ}} \) and \( H_{\text{CSFQR}} \), we will find that a term with this extra factor \( b'/b \) turns out to be subleading. We do not present the entire calculation here, since it follows that of Sec. V B almost identically. One obtains exactly the same estimate as for \( \omega_q \theta_{\text{new}} \) in Eq. (162):

\[
\omega_q \theta_L = \omega_q \theta_R = O(1) \left( \frac{\omega_q^2}{\omega_q \hbar \ln \frac{\omega_q}{\hbar}} \right)_{s=1}, \quad \omega_q \theta_{\text{new}} = O(1) \left( \frac{\omega_q^2}{\omega_q \hbar \ln \frac{\omega_q}{\hbar}} \right)_{s=1}
\]  

(A4)

We note however, that Eq. (A2) at every point \( s \) along the anneal contains just harmonic potentials of different width, thus the leading order of leakage can be well described by changing the width of the harmonic potential by a dilation to \( 1/\sqrt{b(s)} \) of the \( s = 0 \) width. We illustrate the leakage due to this effect in Fig. 7. The diabatic evolution subject to the corresponding Hamiltonian

\[
H_{\text{CSFQ,0}} = E_C \hat{n}^2 + E_J \hat{\phi}^2, \quad \phi \in [-\infty, \infty],
\]  

(A5)

where we shifted the minimum to \( \phi = 0 \), can be investigated in a brute-force manner, since we know the eigenstates \( |m \rangle \) at every \( s \), as well as their derivatives \( |m' \rangle \). Indeed if we use the dilation operator:

\[
U_d = e^{-\frac{ib}{\hbar} (\hat{n} + \hat{\phi})}, \quad U_d \psi(\phi) = b^{-1/4} \psi(\phi/\sqrt{b})
\]  

(A6)

we can express:

\[
|m_s \rangle = U_d |m_{s=0} \rangle, \quad |m'_s \rangle = U_d \left[ -\frac{ib'}{4b} (\hat{n} + \hat{\phi}) \right] |m_{s=0} \rangle.
\]  

(A7)

We now write the time-dependent Schrödinger equation in the time-dependent eigenbasis, thus acquiring a geometric term:

\[
|\psi'(s)\rangle = -it_f H |\psi(s)\rangle, \quad |\psi(s)\rangle = \sum_m c_m(s) |m_s \rangle
\]  

(A8)

\[
\sum_m c'_m(s) |m_s \rangle + c_m(s) |m'_s \rangle = -\sum_m it_f H c_m(s) |m_s \rangle
\]  

(A9)

\[
c'_m(s) + \sum_m c_m(s) \langle k_s | m'_s \rangle = -\sum_m it_f c_m(s) \langle k_s | H | m_s \rangle
\]  

(A10)

\[
|c'(s)\rangle = -\frac{ib'}{4b} (\hat{n}_{s=0} \hat{\phi}_{s=0} + \hat{\phi}_{s=0} \hat{n}_{s=0}) |c(s)\rangle = -it_f \omega_{pl} \hat{n} |c(s)\rangle,
\]  

(A11)

where \( \hat{n} \) is just a diagonal matrix with 0, 1, 2 \ldots \ on the diagonal, and

\[
\hat{\phi}_{s=0} \sim \left( \frac{E_C}{E_J} \right)^{1/4} (a + a^*) \quad \hat{n}_{s=0} \sim \left( \frac{E_J}{E_C} \right)^{1/4} i(a - a^*).
\]  

(A12)
and \(a, a'^*\) are the usual bosonic annihilation and creation operators. With this, we can estimate the leakage. Let us call

\[
V(s) = \frac{-b'}{4t_f b'} (\hat{n}_{s=0} \phi_{s=0} + \hat{\phi}_{s=0} \hat{n}_{s=0})
\]  

(A13)

a perturbation to the Hamiltonian. We split the interval \([0, t_f]\) into periods \(2\pi/\omega_{pl}^s\). Over one period, we approximately consider \(\omega_{pl}^s\) to be constant. We transform into the interaction picture:

\[
V(t) = \frac{i O(1) b'}{t_f b'} \left( a^2 e^{i2\omega_{pl}^s t} - a'^* e^{-i2\omega_{pl}^s t} \right).
\]  

(A14)

We do not keep track of the numerical factors at this point. The leakage over one period is given by

\[
|\delta c_s| = i \int_0^{2\pi/\omega_{pl}^s} V(t) dt |0\rangle, \quad |\delta c_s| = O(1) \left| \left( \frac{\partial}{\partial t} \frac{b'}{2t f b'} \right) \int_0^{2\pi/\omega_{pl}^s} e^{-i2\omega_{pl}^s t} dt \right| = O(1) \frac{1}{t_f} (\ln b')'' \frac{1}{\omega_{pl}^s},
\]  

(A15)

where the constant-in-\(t\) term cancels in the rotating integral. Now what remains is to add contributions of all \(s\) from intervals \(2\pi/\omega_{pl}^s t_f\):

\[
|\delta c| = \int_0^{1} ds (2\pi/\omega_{pl}^s t_f)^{-1} |\delta c_s| = O(1) \frac{1}{t_f} \int_0^{1} ds (\ln b')'' \frac{1}{\omega_{pl}^s} = O(1) \frac{1}{t_f \omega_{pl}(0)} \int_0^{1} ds (\ln b')'' \frac{1}{\sqrt{b}}.
\]  

(A16)

Taking the integral using Eqs. (135) and (137):

\[
\int_0^{1} ds (\ln b')'' \frac{1}{\sqrt{b}} = (\ln b')' \left| \frac{1}{\sqrt{b}} \right|_0^1 - \int_0^{1} ds \frac{b'}{b} \left( \frac{1}{\sqrt{b}} \right)' \left|_0^1 + \int_0^{1} ds \frac{b'^2}{2b^{3/2}} \right|
\]  

(A17)

\[
= \frac{2}{A(b)^1} e^{A(\sqrt{b})-1} \left|_0^1 + \int_1^B \frac{2}{A^2 b^3} e^{2A(\sqrt{b})-1} \frac{A(b)^{1/4}}{2} e^{-A(\sqrt{b})-1} \right.
\]  

(A18)

\[
= \frac{2 + o(1)}{AB^{7/4}} e^{A(\sqrt{b})-1} + \frac{1 + o(1)}{AB^{7/4}} e^{A(\sqrt{b})-1}.
\]  

(A19)

The second term is subleading, thus

\[
E_C \theta = O(1) \frac{1}{A^2 B^{7/4}} e^{A(\sqrt{b})-1},
\]  

(A20)

which exactly matches Eq. (158) for \(s^* = 1, b(s^*) = B\). In other words, our brute-force calculation produces the same result as our bound.

**Appendix B: Proof of the intertwining relation, Eqs. (8) and (171)**

**Proof.** It suffices to prove that \(J(s)\) defined via

\[
J(s) \equiv U_{eff}^G(s) P_0 - P(s) U_{eff}^G(s)
\]  

(B1)

vanishes for all \(s\). Thus \(J(s)\) is the “integral of motion” of the differential equation satisfied by \(U_{ad}(s)\).

We can find the derivative using Eq. (170):

\[
J' = U_{eff}^G P_0 - P' U_{eff}^G - PU_{eff}^G
\]  

(B2a)

\[
= GJ + [P', G] U_{eff}^G P_0 - P' U_{eff}^G - P[ P', G] U_{eff}^G,
\]  

(B2b)

where in the second equality we used \([P, G] = 0\), which follows from \(G\) being block-diagonal \((G = PGP + QGQ)\). Using the fact that \(P'\) is block-off-diagonal [Eqs. (10) and (11)], we simplify the last two terms as

\[
P' + P[ P', G] = P' - PP' = QP'Q + QP'P = P'P,
\]  

(B3)
where in the last equality we used \( P'P = (PP' + QP')P = QP'P \). Thus:

\[
J' - GJ = [P', P]U_{\text{eff}}^G P_0 - P'PU_{\text{eff}}^G = [P', P]U_{\text{eff}}^G P_0 - (P'P - PP')PU_{\text{eff}}^G = [P', P]J,
\]

(B4a)

i.e.,

\[
J' = (G + [P', P])J.
\]

(B5)

Since \( J(s) = 0 \) satisfies this equation and by definition of \( J(s) \) [Eq. (B1)] we have \( J(0) = 0 \), by uniqueness of the solution of a linear differential equation we obtain that \( J(s) = 0 \) is the unique solution. This proves the desired property of \( U_{\text{eff}}^G \).

In the special case of \( G(s) = -it J(s)H(s) \) we have \( U_{\text{eff}} = U_{\text{int}} \), thus proving Eq. (171) also proves Eq. (8). \( \square \)

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