controlling open quantum systems: tools, achievements, limitations

Christiane P. Koch

UNI KASSEL
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control

steer a dynamical system from an initial to a final state using an external knob

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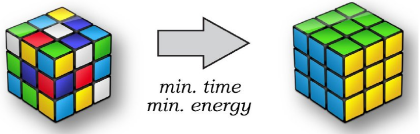
steer a dynamical system from an initial to a final state using an external knob

navigate spacecraft:

- Newton's eq.
- knob: change acceleration

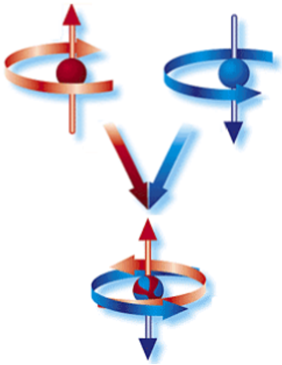
optimal control

reach desired accuracy with minimal expenditure of effort



quantum control

matter waves → superposition principle



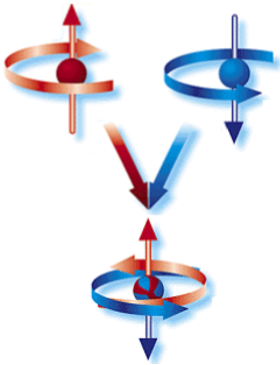
$$|\,\Psi\,\rangle = \frac{1}{\sqrt{2}}\,(|\uparrow\rangle \pm |\downarrow\rangle)$$

$$+1 = e^{2\pi i} \quad -1 = e^{\pi i}$$

variation of relative phases:
interference

quantum control

matter waves → superposition principle



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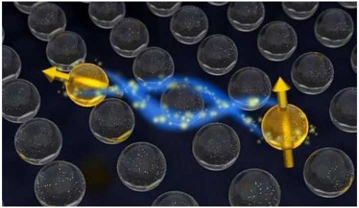

we can utilize interference (and entanglement)
to realize desired control
knobs: external fields (electric, magnetic)

our tool: quantum optimal control

define the objective :

$$\mathsf{GOAL} \equiv \| \langle \varphi_{\mathrm{ini}} | \hat{\mathbf{U}}^{+}(T, 0; \epsilon) | \varphi_{\mathrm{target}} \rangle \|^2 = -J_T$$

as a functional of the external field ϵ

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include additional constraints:

$$J = J_T + \int_0^T J_t(\epsilon, \varphi)\, \mathrm{d}t$$

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optimize J:

$$\partial_\epsilon J = 0 \qquad \partial_{\varphi(t)} J = 0 \qquad \partial^2_\epsilon J > 0$$

$$|\varphi(t)\rangle = \hat{\mathbf{U}}(t, 0; \epsilon)|\varphi_{\text{ini}}\rangle \quad \hat{\mathbf{H}} = \hat{\mathbf{H}}_0 + \epsilon(t)\hat{\mathbf{H}}_1$$

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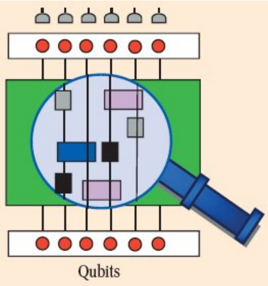
$$|\varphi(t)\rangle = \hat{\mathbf{U}}(t, 0; \epsilon)|\varphi_{\text{ini}}\rangle \qquad \hat{\mathbf{H}} = \hat{\mathbf{H}}_0 + \epsilon(t)\hat{\mathbf{H}}_1$$

$$\Delta\epsilon(t) \sim \mathfrak{Im}\left[\langle \varphi_{\text{target}} | \hat{\mathbf{U}}^{+}(T, t; \epsilon^{old}) \hat{\mathbf{H}}_1 \hat{\mathbf{U}}(t, 0; \epsilon^{new}) | \varphi_{\text{ini}} \rangle \right]$$

Reich, Ndong, CPK, J Chem Phys 136, 104103 (2012)
and many other variants (Tannor, Rabitz, Khaneja/Glaser,...)

an example: realize a unitary / gate



$$J_T = -\Re e\left[\mathsf{Tr}\left\{\hat{\mathbf{O}}^{+}\hat{\mathbf{P}}_N\hat{\mathbf{U}}(T,0;\epsilon)\hat{\mathbf{P}}_N\right\}\right]$$

Palao & Kosloff, Phys Rev A 68, 062308 (2003)

- desired unitary operation : $\hat{\mathbf{O}}$
- desired accuracy/fidelity :
  $1 - \varepsilon$ where $\varepsilon < 10^{-4}$

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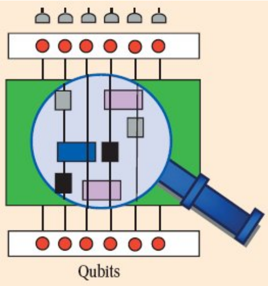

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$$\Delta\epsilon(t) = \frac{S(t)}{2\alpha} \Im m \left[\sum_{k=1}^{N} \langle \varphi_{k,ini} | \hat{\mathbf{O}}^{+} \hat{\mathbf{U}}^{+}(T,t;\epsilon^{old}) \hat{\mathbf{H}}_1 \hat{\mathbf{U}}(t,0;\epsilon^{new}) | \varphi_{k,ini} \rangle \right]$$

- **what gate time T needed ?**
- **best choice of target $\hat{\mathbf{O}}$?**

Müller, Reich, Murphy, Yuan, Vala, Whaley, Calarco, CPK, Phys Rev A 84, 042315 (2011)
Watts, Vala, Müller, Calarco, Whaley, Reich, Goerz, CPK, Phys Rev A 91, 062306 (2015)
Goerz, Gualdi, Reich, CPK, Motzoi, Whaley, Vala, Müller, Montangero, Calarco, Phys Rev A 91, 062307 (2015)

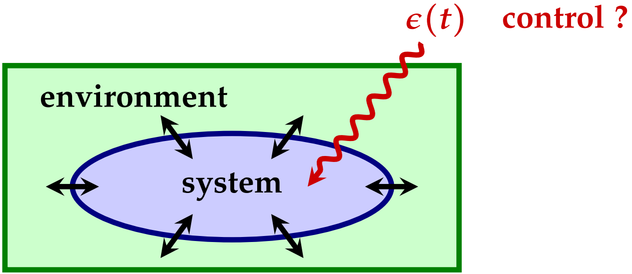
but wait a minute!

open quantum systems !?

decoherence!

control vs decoherence

$$\hat{\mathsf{H}} = \hat{\mathsf{H}}_S(\epsilon) + \hat{\mathsf{H}}_{SE} + \hat{\mathsf{H}}_E$$



- what are viable quantum control strategies ?
- dependence on properties of environment / coupling ?
- fundamental limits to quantum control ?

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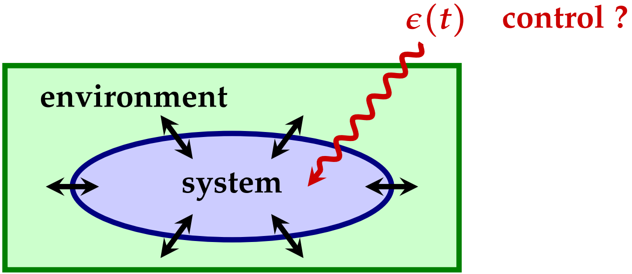

- what are viable quantum control strategies ?
- dependence on properties of environment / coupling ?
- fundamental limits to quantum control ?

but also: dissipation-enabled control (e.g. cooling)

overview

- Markovian vs non-Markovian dynamics
- controllability
- how to measure success of control
  in open quantum systems ?
- strategy 1: fighting decoherence
- strategy 2a: utilizing the environment
  (Markovian dynamics)
- strategy 2b: utilizing the environment
  (non-Markovian dynamics)
- summary & outlook

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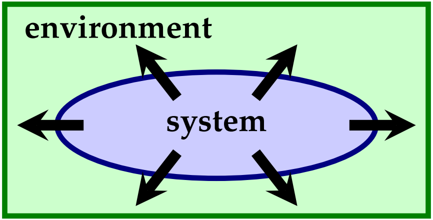
Markovian vs non-Markovian dynamics

Markovian evolution



fully irreversible loss
of energy and phase

non-Markovian evolution

overall loss
of energy and phase

but some 'back-flow' possible

Breuer, Laine, Piilo, Phys. Rev. Lett. 103, 210401 (2009)
Rivas, Huelga, Plenio, Phys. Rev. Lett. 105, 050403 (2010)

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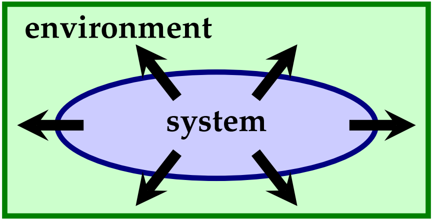

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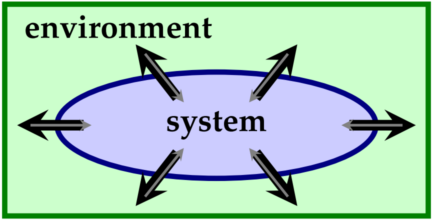

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modelling open system dynamics

- most often employed: Markovian bath model

$$\frac{\partial \rho}{\partial t} = \frac{i}{\hbar}[H, \rho]_{-} + \mathcal{L}_D(\rho)$$

- non-Markovian variants
  - time-local non-Markovian master eqs.
  - stochastic approaches (under certain assumptions)

    e.g. Piilo, Maniscalco, Härkönen, Suominen, Phys. Rev. Lett. 100, 180402 (2008)
    Koch, Großmann, Stockburger, Ankerhold, Phys. Rev. Lett. 100, 230402 (2008)
  - poor (wo)man's non-Markovian bath: single TLF

    e.g. Rebentrost, Serban, Schulte-Herbrüggen, Wilhelm, Phys. Rev. Lett. 102, 090401 (2009)
  - small-size spin bath / effective modes

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small-size bath approximation can be made rigorous:
open system dynamics is quasi-local

open system dynamics quasi-local

Gualdi & CPK, Phys Rev A 88, 022122 (2013)

$$\hat{H} = \hat{H}_S + \sum_{i=1}^{N_S^{int}} \sum_{j=1}^{N_B^{int}} \hat{\Phi}_{ij}^{SB} + \sum_{i \leq j=1}^{N_B} \hat{\Phi}_{ij}^{B}$$

with $\hat{\Phi}_{ij} = \sum_{\mu=0}^{dim(\mathcal{B}(\mathcal{H}_i))-1} \sum_{\nu=0}^{dim(\mathcal{B}(\mathcal{H}_j))-1} J_{ij}^{\mu\nu} \hat{O}_i^{\mu} \hat{O}_j^{\nu}$

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represent couplings $J_{ij}^{\mu\nu}$ on graph & reorder bath modes according to graph distance:

$$\hat{H} = \sum_{d=0}^{\infty} \left(\hat{h}_d + \hat{h}_{d,d+1} \right)$$

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bound: $\left\| \hat{A}_S(t) - \hat{A}_S^{H_n}(t) \right\| \leq 2 \left\| \hat{A}_S \right\| e^{-(n-vt)}$ with $v = 2\mathcal{O}\bar{c}^2 \|J\| e$

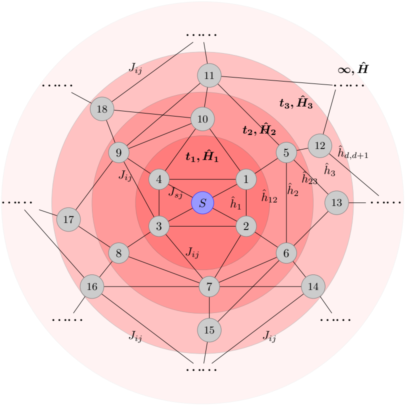
$\bar{c}$ max. connectivity and $\mathcal{O} = \max_{(i,j)\in N;\mu,\nu} \left\| \hat{O}_i^{\mu} \hat{O}_j^{\nu} \right\|$

Lieb-Robinson-type bound limits spread of system-bath correlations

dynamical renormalization of SB coupling

Gualdi & CPK, Phys Rev A 88, 022122 (2013)

discrete environments



➡ given t, size of finite approximate bath known *a priori*

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Gualdi & CPK, Phys Rev A 88, 022122 (2013)

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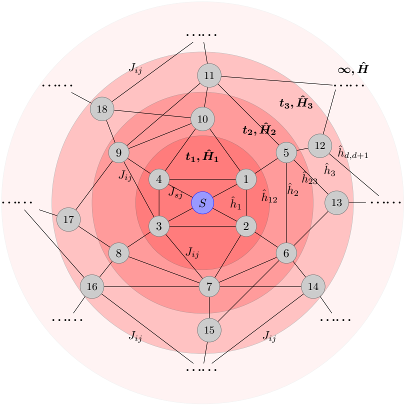
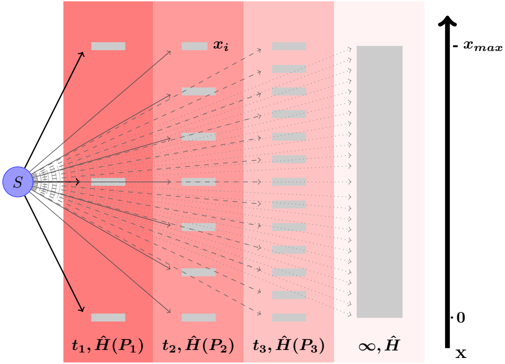


continuous environments



prerequisite: finite support of SB coupling
discrete approximation by partitioning

→ given t, size of finite approximate bath known *a priori*

overview

- Markovian vs non-Markovian dynamics
- controllability
- how to measure success of control
  in open quantum systems ?
- control strategy 1: fighting decoherence
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controllability: can we reach the target?

– assuming closed system & sufficient resources –

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = \left[\hat{\mathsf{H}}_0 + \sum_l \varepsilon_l(t) \hat{\mathsf{H}}_l \right] |\psi(t)\rangle$$

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- $\hat{\mathbf{H}}_0$ has a *finite* spectrum
- state-to-state transitions

→ It is possible to completely control evolution from initial to target state

Huang, Tarn, Clarke, J Math Phys 24, 2608 (1983); Ramakrishna et al., Phys Rev A 51, 960 (1995)

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controllability retained for some systems w/ infinitely many states using Galerkin-type methods

Boscain et al., J Math Phys 43, 2107 (2002)

intuition: adjust an external field (ion trap) s.t. system separated into finite and infinite subsystem

Rangan, Bloch, Monroe, Bucksbaum, Phys Rev Lett 92, 113004 (2004)

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$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = \left[\hat{\mathbf{H}}_0 + \sum_l \varepsilon_l(t)\hat{\mathbf{V}}_l\right]|\psi(t)\rangle$$

for simplicity: assume piecewise const. controls & single $\varepsilon(t)\hat{\mathbf{V}}$

$$\begin{aligned}|\psi(t)\rangle &= e^{-\frac{i}{\hbar}(\hat{\mathbf{H}}_0+\epsilon\hat{\mathbf{V}})t}\,|\psi(0)\rangle \\ &= e^{-\frac{i}{\hbar}\hat{\mathbf{H}}_0 t}\,e^{-\frac{i}{\hbar}\epsilon\hat{\mathbf{V}}t}\,e^{-\frac{i}{\hbar}\frac{1}{2}\left[\hat{\mathbf{H}}_0,\epsilon\hat{\mathbf{V}}\right]t^2}\,e^{-\frac{i}{\hbar}\frac{1}{12}\left[\hat{\mathbf{H}}_0,\left[\hat{\mathbf{H}}_0,\varepsilon\hat{\mathbf{V}}\right]\right]t^3}\,\cdot \\ &\qquad \cdot\, e^{\frac{i}{\hbar}\frac{1}{12}\left[\varepsilon\hat{\mathbf{V}},\left[\hat{\mathbf{H}}_0,\varepsilon\hat{\mathbf{V}}\right]\right]t^3}\,\cdot\ldots\cdot\,|\psi(0)\rangle\end{aligned}$$

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generators determine directions in Hilbert space:

$$\hat{\mathbf{H}}_0,\ \hat{\mathbf{V}},\ \left[\hat{\mathbf{H}}_0, V\right], \ldots$$

controllability $\Longleftrightarrow$ all directions can be generated

still depends on $|\psi(0)\rangle$

complete (unitary) controllability

– assuming closed system & sufficient resources –

$$i\hbar\frac{\partial}{\partial t}\hat{\mathbf{U}}(t) \quad = \quad \left[\hat{\mathbf{H}}_0 + \sum_l \varepsilon_l(t)\hat{\mathbf{V}}_l\right]\hat{\mathbf{U}}(t) \qquad \hat{\mathbf{U}}(0) = \mathbb{1}$$

$$\hat{\mathbf{U}}(t,0) = e^{Ct} = e^{\sum_{i=1}^{N^2}\alpha_i C_i t}$$

$C, C_i : N \times N$ skew-Hermitian, C_i linearly independent

any $\hat{\mathbf{U}}(t,0) \Longleftrightarrow$ all N^2 generators $\{C_i\}$ available

full rank condition

dim(algebra of iterated commutators) $= N^2$

controllability $\leftrightarrow$ connectivity

symmetry = enemy of controllability

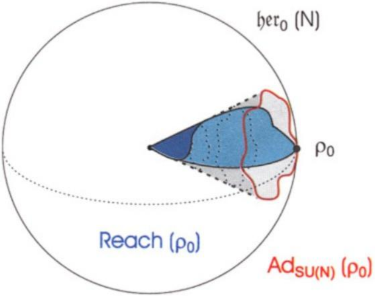
controllability of open quantum systems

review: Glaser et al., Eur Phys J D 69, 279 (2015)

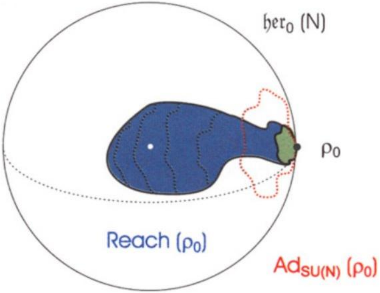
- for Markovian dynamics

  & assuming $\varepsilon(t)$ does not change $\mathcal{L}_D$
  - time evolution: Lie group $\Longrightarrow$ Lie semi-group

$\mathcal{L}_D \sim \mathbb{1}$



generic



Dirr, Helmke, Kurniawan, Schulte-Herbrüggen, Rep Math Phys 64, 93 (2009)

- no rigorous results for non-Markovian dynamics

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our tool: optimal control theory

$$t = 0 \qquad |\varphi_{\text{ini}}\rangle \rightsquigarrow |\varphi_{\text{target}}\rangle \qquad t = T$$

define the objective :

$$\mathsf{GOAL} \equiv \| \langle \varphi_{\text{ini}} | \hat{\mathbf{U}}^{+}(T, 0; \epsilon) | \varphi_{\text{target}} \rangle \|^2 = -J_T$$

as a functional of the field ϵ

include additional constraints:

$$J = J_T + \int_0^T J_t(\epsilon, \varphi)\, \mathrm{d}t$$

optimize J:

$$\partial_\epsilon J = 0 \qquad \partial_{\varphi(t)} J = 0 \qquad \partial^2_\epsilon J > 0$$

$$|\varphi(t)\rangle = \hat{\mathbf{U}}(t, 0; \epsilon) |\varphi_{\text{ini}}\rangle$$

$$J_T = -\Re e \left[\mathrm{Tr} \left\{ \hat{\mathbf{O}}^{+} \hat{\mathbf{P}}_N \hat{\mathbf{U}}(T, 0; \epsilon) \hat{\mathbf{P}}_N \right\} \right]$$

optimal control for open quantum systems

review: CPK, J Phys Condens Matter 28, 213001 (2016)

$t = 0$ $\rho_{\text{ini}} \rightsquigarrow \rho_{\text{target}}$ $t = T$

define the objective :

$$\mathsf{GOAL} \equiv \mathsf{Tr}\left\{\mathcal{D}_{\epsilon}(\rho_{\text{ini}})\,\rho_{\text{target}}\right\} = -J_T$$

as a functional of the field ϵ

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OCT for open quantum systems

$$\rho(T) = \mathcal{D}(\rho(0)) \qquad \text{e.g.}: \quad \frac{\partial \rho}{\partial t} = \frac{i}{\hbar}[H, \rho]_- + \mathcal{L}_D(\rho)$$

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   $\Rightarrow$ maximize $\mathsf{Tr}\left\{\rho(T)\,\rho_{\text{target}}\right\}$

   Bartana, Kosloff, Tannor, J Chem Phys 106, 1435 (1997)
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2. gates: lift $\mathsf{Tr}\left\{O^+ P_N U(T, 0; \varepsilon) P_N\right\}$ to Liouville space

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   but: $U \Leftrightarrow \mathcal{D}(\rho)$ **!?**

characterizing open quantum systems

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how many states ρ_j really need to be propagated?

only $N = 3!$ (not $N = d^2$)

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using concepts 'commutant space' and 'total rotation'

minimal set of states: total rotation

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given a $\rho(T) = U\rho(0)U^{+}$, we cannot distinguish those U with common eigenbasis with ρ from $\mathbb{1}$

1. fix a basis: basis-complete projectors $\{P_i\}$
   d orthonormal one-dimensional projectors
   $\Longrightarrow \rho = \sum_{i=1}^{d} \lambda_i P_i$, $\lambda_i \neq \lambda_j$

provided time evolution coherent

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2. construct a ρ' *guaranteed* to have no common eigenspace with any P_i: **total rotation**
   $\Longrightarrow \rho' = P_{TR}$ with
   $P_{TR} P_i \neq 0 \quad \forall\, P_i \in \{P_i\}$
   (note: d P_{TR}'s = mutually unbiased basis)

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$\Longrightarrow \rho(T), \rho'(T)$ **are sufficient to distinguish any two unitaries (and thus measure success of control) provided time evolution coherent**

gate optimization

third state sufficient to check whether time evolution is unitary

Goerz, Reich, CPK, New J Phys 16, 055012 (2014)

$$J_T = \sum_{j=1}^{3} \left[1 - \mathsf{Tr}\left\{ O \rho_j O^+ \rho_j(T) \right\} \right]$$

$$\rho_{1,ij} = \frac{2\left(d - i + 1\right)}{d\left(d+1\right)} \delta_{ij}$$

fix the basis

$$\rho_{2,ij} = \frac{1}{d}$$

totally rotated state

$$\rho_{3,ij} = \frac{1}{d} \delta_{ij}$$

check unitality on logical subspace

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J_T attains its minimum if and only if

1. $\mathcal{D}$ is a unitary dynamical map on the logical subspace
2. $\mathcal{D}(\rho_1) = O\rho_1 O^+$ and $\mathcal{D}(\rho_2) = O\rho_2 O^+$

➡ propagation of 3 states sufficient, irrespective of $\dim \mathcal{H}$

overview

- Markovian vs non-Markovian dynamics
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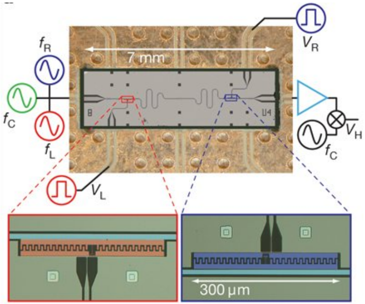
example: superconducting transmon qubits



Koch, Yu, Gambetta, Houck, Schuster, Majer, Blais, Devoret, Girvin,Schoelkopf, Phys. Rev. A 76, 042319 (2007)

DiCarlo, Chow, Gambetta, Bishop, Johnson, Schuster, Majer, Blais, Frunzio, Girvin, Schoelkopf, Nature 460, 240 (2009)

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$T_2 = 20 \ldots 100\,\mu\text{s}$

gate times $T < 250\,\text{ns}$
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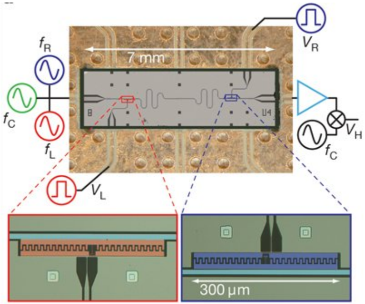

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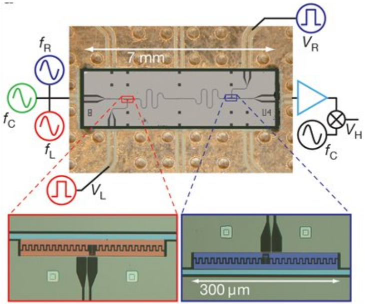

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$$\hat{\mathbf{H}} = \sum_{i=1,2} \left[\omega_i \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i - \frac{\alpha_i}{2} \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i \hat{\mathbf{b}}_i \right] + J \left(\hat{\mathbf{b}}_1^+ \hat{\mathbf{b}}_2 + \hat{\mathbf{b}}_1 \hat{\mathbf{b}}_2^+ \right)$$

$$+ \omega_c \hat{\mathbf{a}}^+ \hat{\mathbf{a}} + \epsilon^*(t) \hat{\mathbf{a}} + \epsilon(t) \hat{\mathbf{a}}^+ + \sum_{i=1,2} g_i \left(\hat{\mathbf{b}}_i^+ \hat{\mathbf{a}} + \hat{\mathbf{b}}_i \hat{\mathbf{a}}^+ \right)$$

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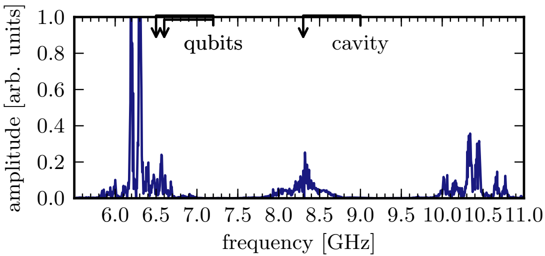
200 ns C-phase gate: $F_{av} = 99.72\% \rightsquigarrow 99.06\%$



fast gate with additional transitions involving

- qubit $|1\rangle \to |2\rangle$
- cavity $|0\rangle \to |2\rangle$ simultaneous with qubit $|1\rangle \to |0\rangle$

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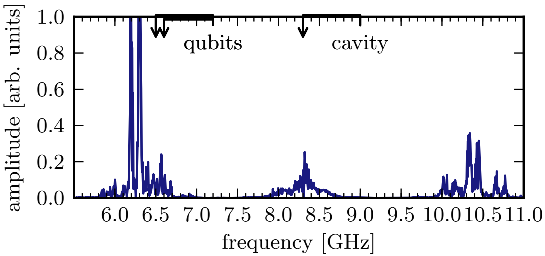

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⟶ **OCT using full complexity of $\hat{\mathsf{H}}$: gates fast enough to beat decoherence**

which gate? shortest duration? which system parameters?

charting the circuit QED design landscape
with quantum optimal control

Goerz, Motzoi, Whaley, CPK, arXiv:1606.08825

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$$\hat{\mathsf{H}} = \sum_{i=1,2}\left[\omega_i \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i - \alpha_i \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i^+ \hat{\mathbf{b}}_i \hat{\mathbf{b}}_i\right] + J\left(\hat{\mathbf{b}}_1^+ \hat{\mathbf{b}}_2 + \hat{\mathbf{b}}_1 \hat{\mathbf{b}}_2^+\right)$$

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which gates? a universal set!

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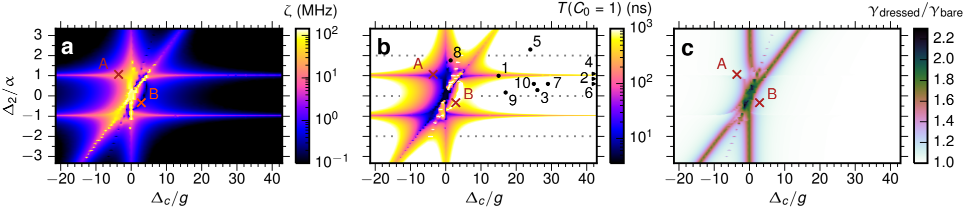
field-free ($\epsilon(t) = 0$) dynamics

entanglement creation — effective decay



interesting parts of parameter space unexplored !

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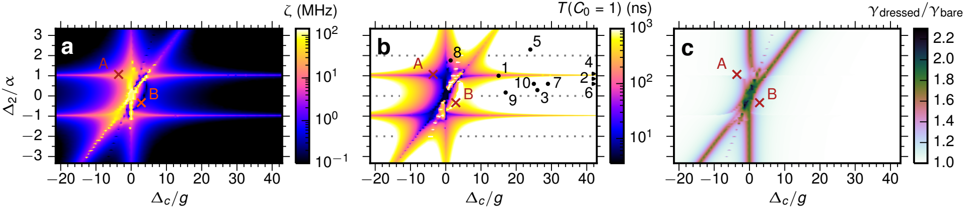

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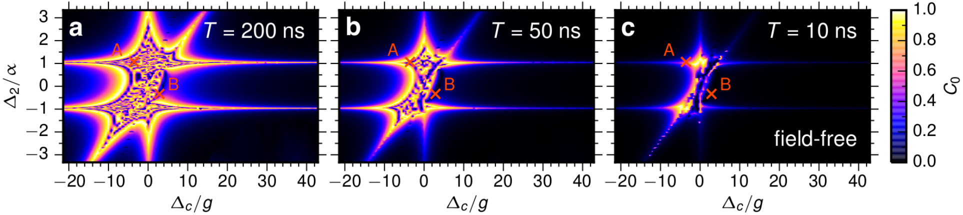

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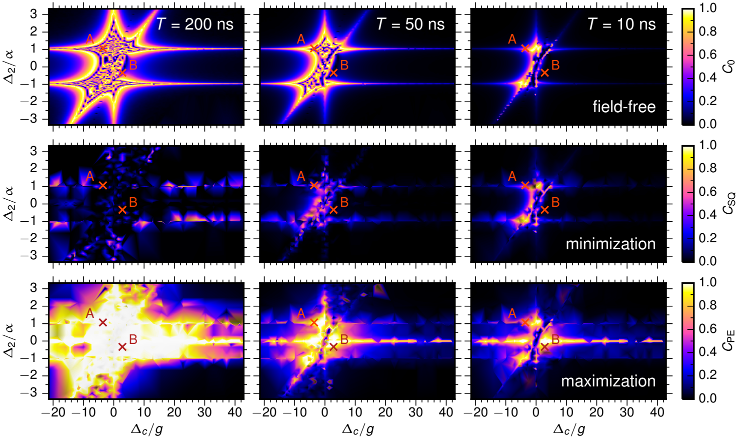
Goerz, Motzoi, Whaley, CPK, arXiv:1606.08825

controlling entanglement creation



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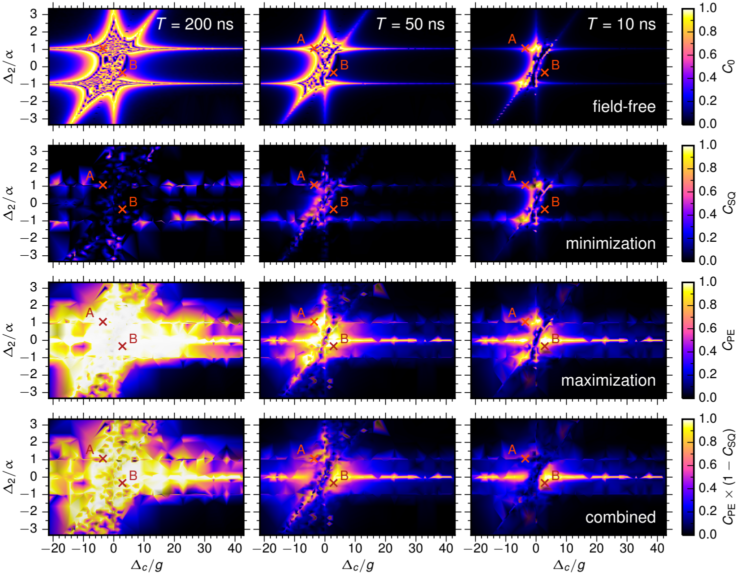

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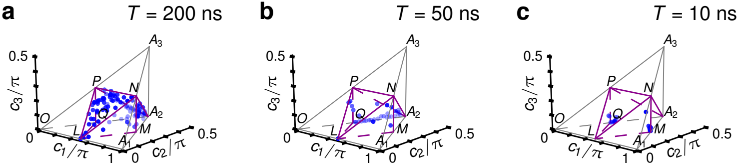
searching for arbitrary perfect entangler (in universal set)



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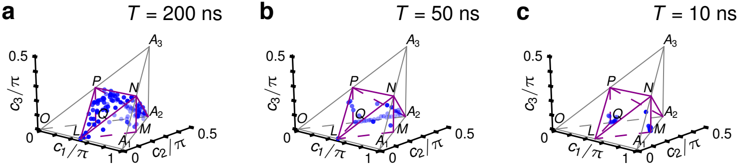
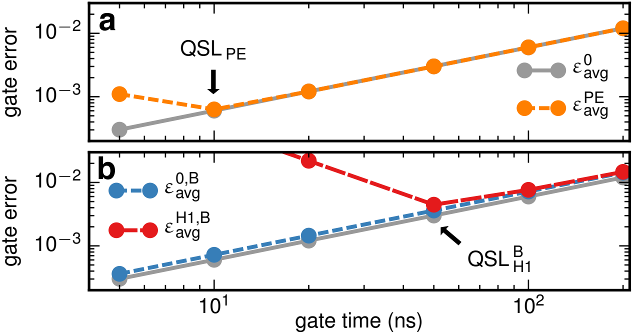


identifying the quantum speed limit: 50 ns



control strategy 1: fighting decoherence

avoiding decoherence

- our example:

beat decoherence by fastest possible operation

use optimal control theory to identify 'quantum speed limit'

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- steer dynamics through regions of state space less affected by decoherence
  - relaxation-optimized dynamics

Khaneja, Luy, Glaser, Proc Natl Acad Sci USA 100, 13162 (2003)

Khaneja, Reiss, Luy, Glaser, J Magnet Reson 162, 311 (2005)

- decouple the system from its environment
  - dynamical decoupling *Viola, Knill, Lloyd, Phys Rev Lett 82, 2417 (1999)*
  - spectral engineering *Clausen, Bensky, Kurizki, Phys Rev Lett 104, 040401 (2010)*

- use symmetry protection (e.g. decoherence-free subspaces)

Lidar, Chuang, Whaley, Phys Rev Lett 81, 2594 (1998)

Knill, Laflamme, Viola, Phys Rev Lett 84, 2525 (2000)

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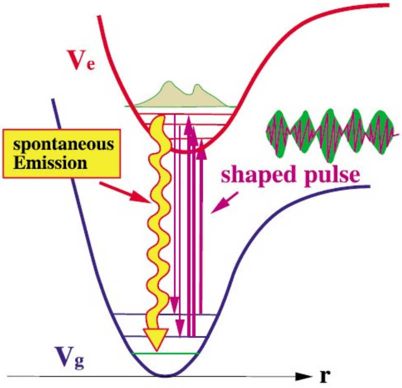
vibrational cooling – theory

Tannor, Kosloff, Bartana, Faraday Discuss. 113, 365 (1999)

Bartana, Kosloff, Tannor, Chem. Phys. 267, 195 (2001)



cooling = maintaining a dark ground state

many cycles of
shaped laser excitation
and spontaneous emission
without
reexcitation of ground state
↷
accumulation in ground state

vibrational cooling – experiment

Optical Pumping and Vibrational Cooling of Molecules

Matthieu Viteau,[1] Amodsen Chotia,[1] Maria Allegrini,[1,2] Nadia Bouloufa,[1] Olivier Dulieu,[1]
Daniel Comparat,[1] Pierre Pillet[1]*

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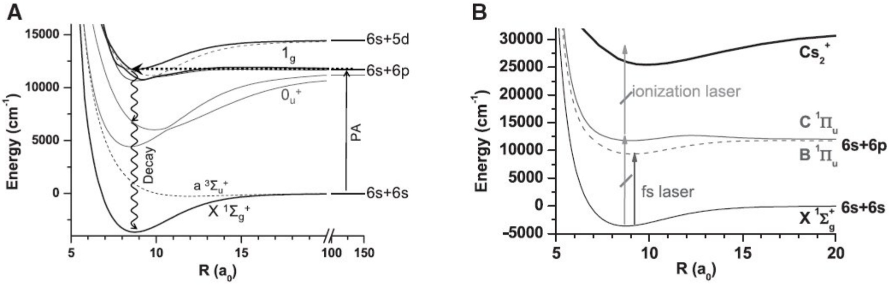
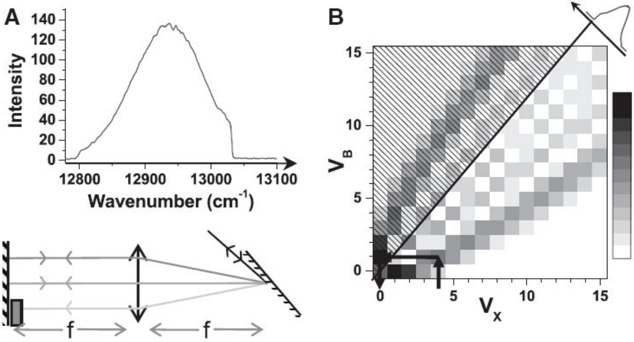


vibrational cooling – experiment

Viteau et al., Science 321, 232 (2008)

a crude way of maintaing a dark ground state . . .



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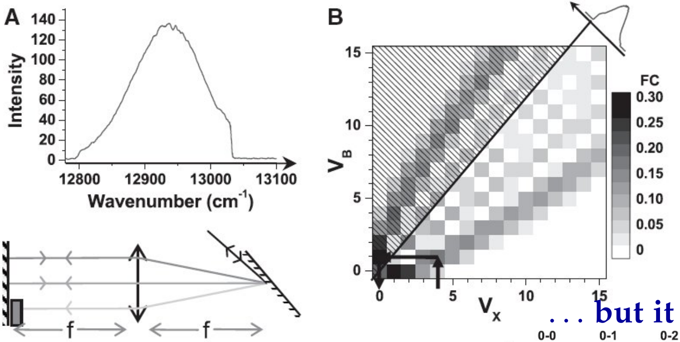
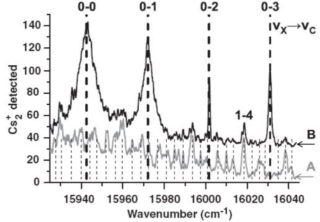


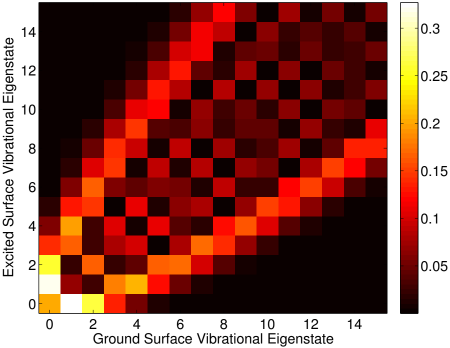
. . . but it works!



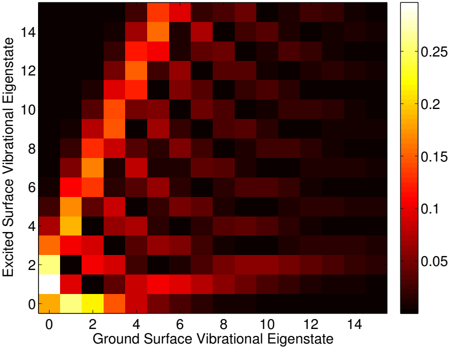
vibrational cooling – the crude way

dependence on molecular structure?

'good' case: Cs_2 cooling



'bad' case: LiCs heating



Reich & CPK, New J Phys 15, 125028 (2013)

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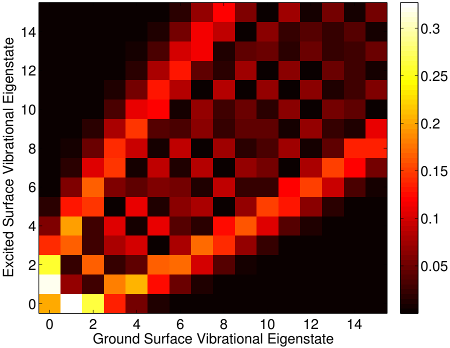

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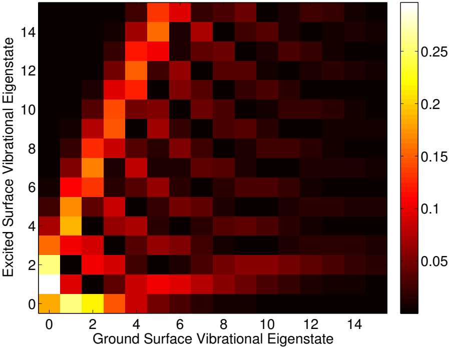

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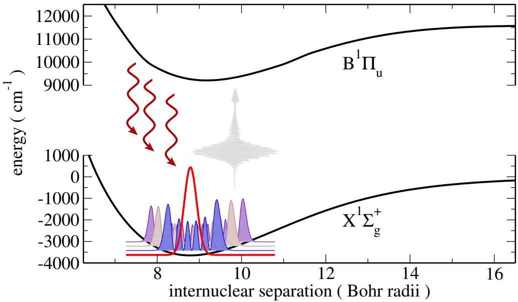
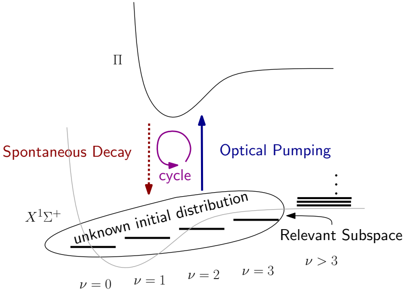
seek to cool many molecules with the same optimized fs pulse irrespective of molecular structure

controlling vibrational laser cooling

utilizing timescale separation of excitation & spontaneous emission





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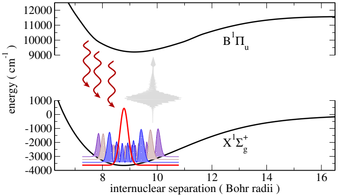
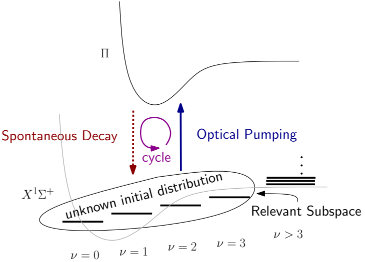
controlling vibrational laser cooling

relying on spontaneous emission

Reich & CPK, New J Phys 15, 125028 (2013)

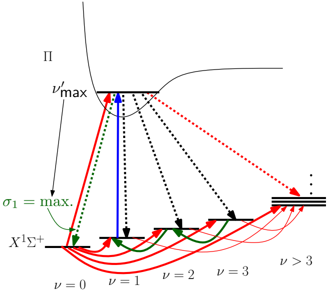




assembly-line cooling

- keep target state dark
- pump up doorway state
- reshuffle all other states towards doorway

$\Longrightarrow$ tailored OC functional



controlling vibrational laser cooling

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'bad' case: cold & trapped LiCs molecules

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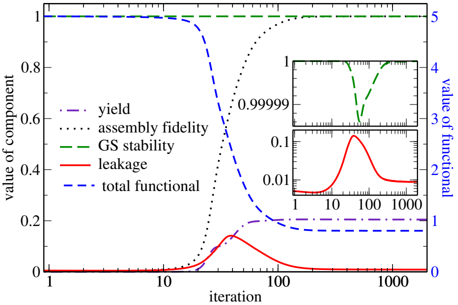

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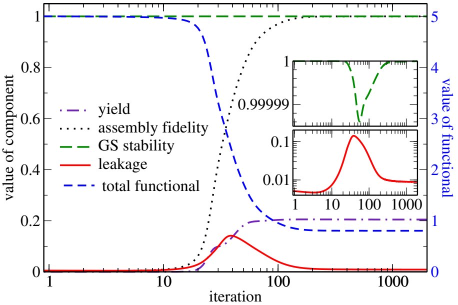
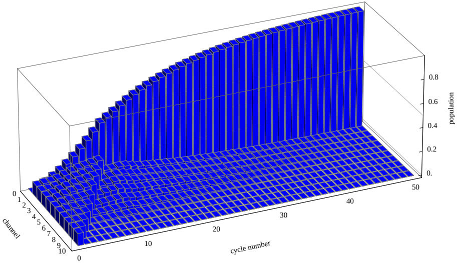


accumulation in dark state



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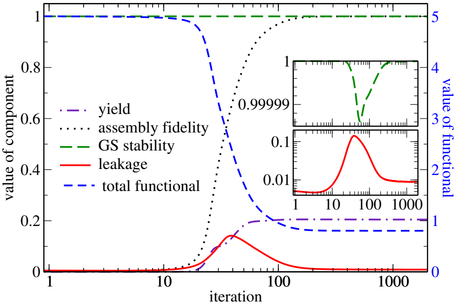

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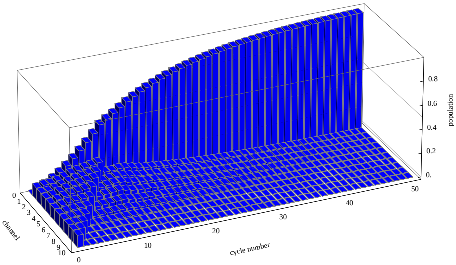


minimal requirement on molecular structure for cooling?

- a single excited state level favorable to cooling not heating

overview

- Markovian vs non-Markovian dynamics
- how to measure success of control
  in open quantum systems ?
- control strategy 1: fighting decoherence
- control strategy 2(a): utilizing the environment
  (Markovian dynamics)
- control strategy 2(b): utilizing the environment
  (non-Markovian dynamics)
- summary & outlook

Markovian vs non-Markovian evolution

non-Markovian evolution:
loss of energy and phase not monotonic

- distinguishability of two optimal states
  (recovery of previously lost information)

  Breuer, Laine, Piilo, Phys Rev Lett 103, 210401 (2009)

- divisability of the dynamical map
  (increase of correlations in a bi/multi-partite system)

  Rivas, Huelga, Plenio, Phys Rev Lett 105, 050403 (2010)

- ...

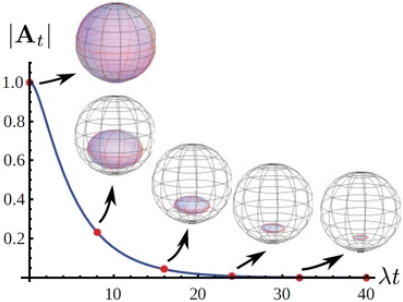
- accessible volume in Liouville (state) space

  Lorenzo, Plastina, Paternostro, Phys Rev A 88, 020102 (2013)

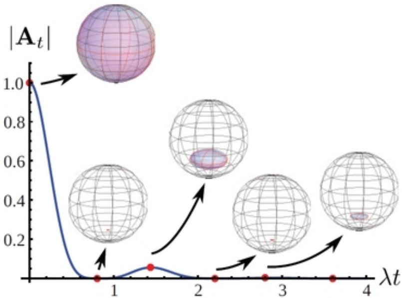
Markovian vs non-Markovian evolution

set of reachable states and Liouville space determinant

Lorenzo, Plastina, Paternostro, Phys Rev A 88, 020102 (2013)



Markovian evolution:
volume always shrinks



non-Markovian evolution:
volume may re-expand

non-Markovian evolution should allow for more control than Markovian evolution

superconducting phase qudit with control

Hamiltonian of a flux-biased phase qudit with control

$$\hat{\mathsf{H}} = \hbar\omega_0 \hat{\mathsf{n}} + \frac{\beta}{2} \hat{\mathsf{n}} \left(\hat{\mathsf{n}} - 1\right) + \underbrace{\kappa_1 I_c(t) \hat{\mathsf{n}}}_{\text{low frequency}} + \underbrace{\kappa_2 I_c(t) \left(\hat{\mathsf{a}} + \hat{\mathsf{a}}^{+}\right)}_{\text{high frequency}}$$

high frequency:
all SO(4) operations
(Pythagorean couplings)

$\beta \ll \omega_0$

Svetitsky et al. Nature Commun. 5, 5617 (2014)

what is missing for full SU(4) controllability?

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Cartan decomposition of $\mathfrak{su}(N)$

$$\forall\, U \in SU(N): \qquad U = k_1\, A\, k_2 \qquad k_1, k_2 \in SO(N)$$

A diagonal, unitary matrix

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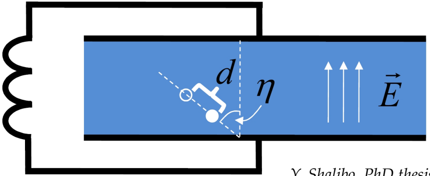
$\curvearrowright$ **diagonal unitaries (with 'non-local' phases)**

decoherence of the phase qudit

main source of decoherence in Josephson junctions: charge defects

- defects switch between two spatial configurations in electric field
- two configurations $\longrightarrow$ effective TLS: 'natural' spin bath



Y. Shalibo, PhD thesis (Katz group, Hebrew U Jerusalem)

$$\hat{\mathbf{H}}^{(i)} = \Delta^{(i)}\sigma_z^{(i)} \qquad \hat{\mathbf{H}}_{int}^{(i)} = \frac{S^{(i)}}{2}\left(\hat{\mathbf{a}}\hat{\sigma}_i^{+} + \hat{\mathbf{a}}^{+}\hat{\sigma}_i^{-}\right)$$

1. $\Delta^{(i)} \gg \omega_0 \Longrightarrow$ no effect on qudit
2. $\Delta^{(i)} \ll \omega_0 \Longrightarrow T_2$: pure dephasing of qudit
3. $\Delta \simeq \omega_0$, S weak $\Longrightarrow T_1$: relaxation of qudit
4. $\Delta \simeq \omega_0$, S strong $\Longrightarrow$ non-Markovian dynamics

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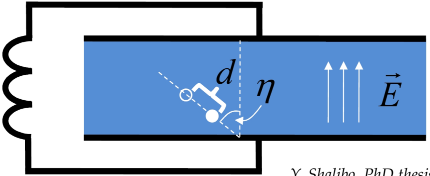

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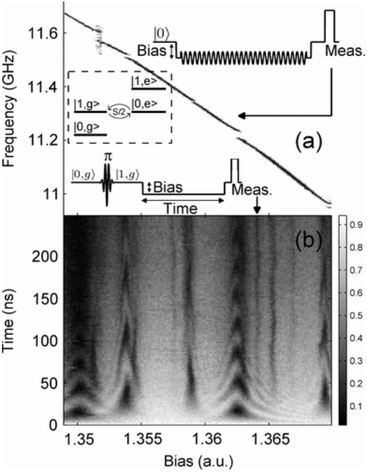


PRL 105, 177001 (2010) PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2010

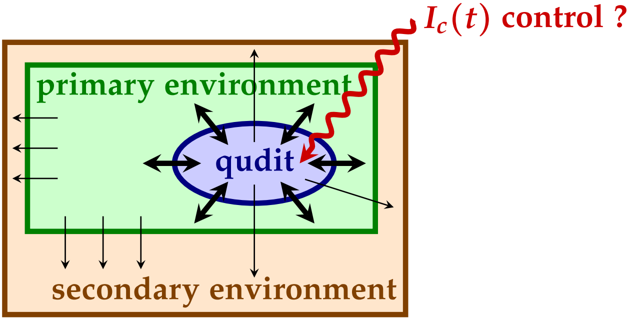
Lifetime and Coherence of Two-Level Defects in a Josephson Junction

Yoni Shalibo,[1] Ya'ara Rofe,[1] David Shwa,[1] Felix Zeides,[1] Matthew Neeley,[2] John M. Martinis,[2] and Nadav Katz[1]
[1]*Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[2]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
(Received 14 July 2010; published 19 October 2010)

$$\curvearrowright \Delta^{(i)}, S^{(i)}, T_1^{(i)}, T_2^{(i)}$$

strongly coupled TLS can be characterized experimentally

qudit strongly coupled to a few TLS and weakly coupled to T_1/T_2 background



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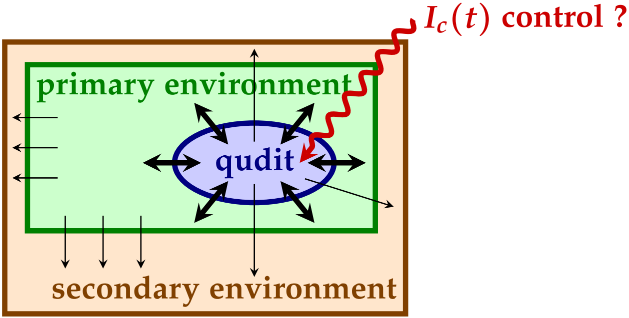
} secondary environment

4. $\Delta \simeq \omega_0$, S strong $\Longrightarrow$ non-Markovian dynamics — primary env.

qudit strongly coupled to a few TLS and weakly coupled to T_1 background



$$\frac{d}{dt}\hat{\boldsymbol{\rho}}_{QP} = -i[\hat{\mathbf{H}}_{QP}, \hat{\boldsymbol{\rho}}_{QP}] + \mathcal{L}_S(\hat{\boldsymbol{\rho}}_{QP})$$

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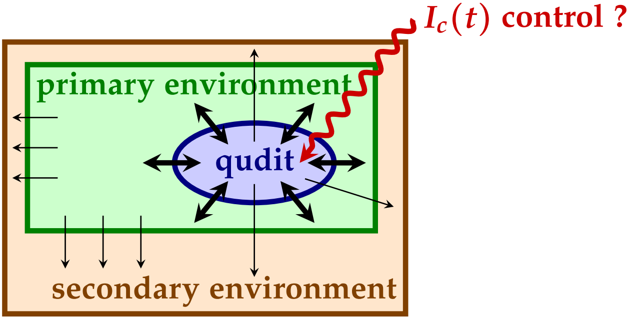

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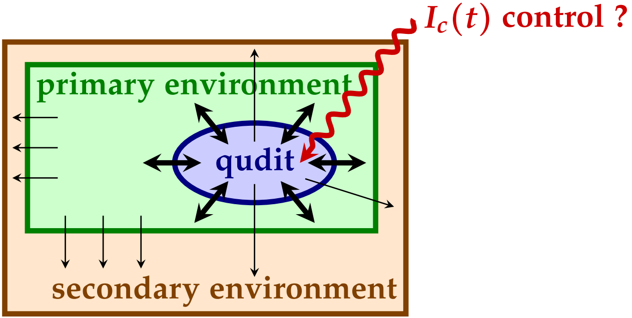

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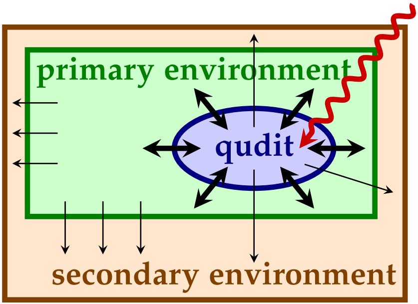

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$$\hat{\mathbf{A}}_i = \sqrt{1/T_1^{(i)}}\,\sigma_i^-$$

SU(4) controllability: phasegates

Reich, Katz, CPK, Sci Rep 5, 12430 (2015)

$\hat{\mathsf{H}}_Q = \hbar\omega_0 \hat{\mathbf{n}} + \frac{\beta}{2}\hat{\mathbf{n}}\left(\hat{\mathbf{n}} - 1\right) + \kappa_1 I_c(t)\hat{\mathbf{n}}$ $\quad \hat{\mathsf{H}}_P = \Delta\sigma_z$ $\quad \hat{\mathsf{H}}_{int} = \frac{S}{2}\left(\hat{\mathbf{a}}\hat{\sigma}^{+} + \hat{\mathbf{a}}^{+}\hat{\sigma}^{-}\right)$

error after optimization for $\mathrm{diag}(1, -1, 1, 1)$ w/ single primary bath TLS

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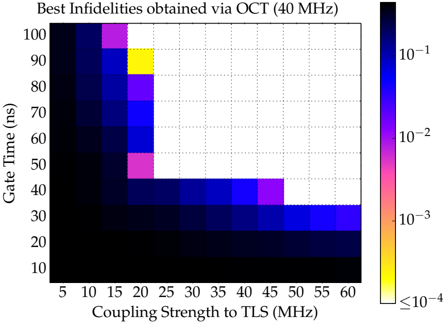

infinite T_1 (no loss)

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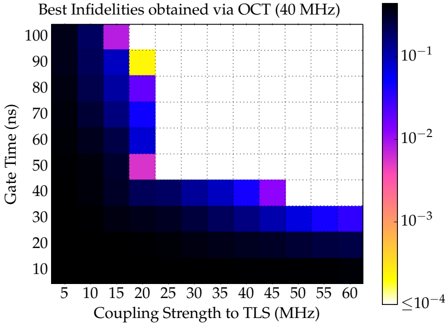

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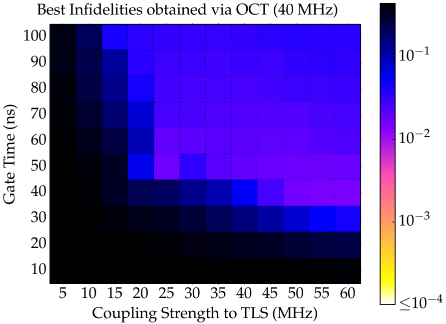

$T_1 = 5\mu s$, $T_1^{TLS} = 1\mu s$

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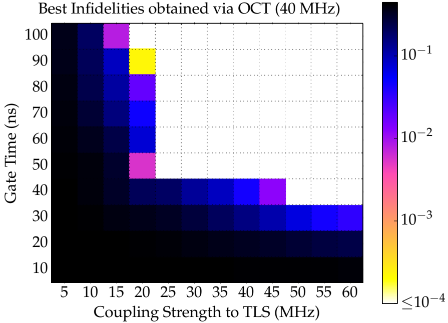

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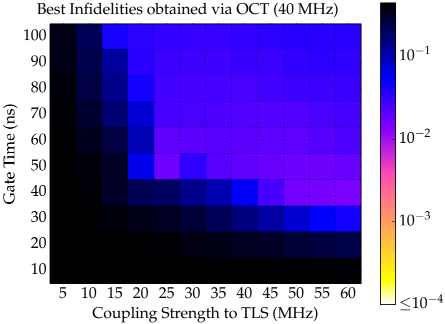

$T_1 = 5\mu s$, $T_1^{TLS} = 1\mu s$

→ **for strong enough coupling error small even for lossy TLS**

→ **for weak coupling no control**

role of non-Markovianity

Reich, Katz, CPK, Sci Rep 5, 12430 (2015)

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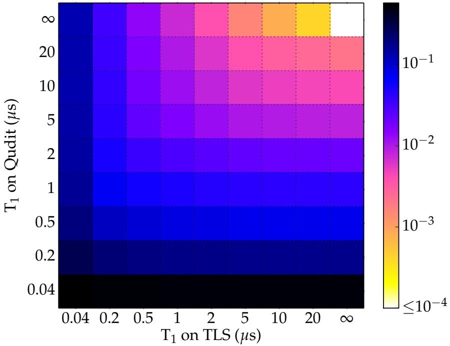

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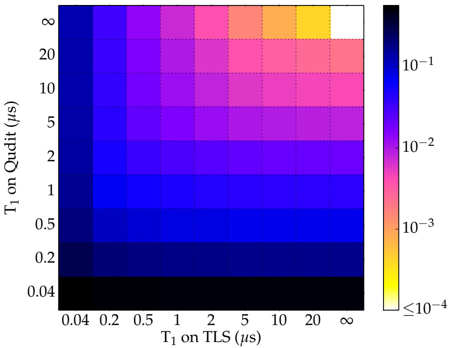

control lost once Markovian decay too fast: $T_1 < 1/S$

what about additional primary bath TLS?

$\Delta^{(2)}$	$S^{(2)}$	$T_1^{(2)}$	error
50 MHz	40 MHz	2000 ns	$3.076 \cdot 10^{-2}$
50 MHz	40 MHz	200 ns	$4.052 \cdot 10^{-2}$
50 MHz	40 MHz	40 ns	$7.867 \cdot 10^{-2}$
50 MHz	10 MHz	2000 ns	$3.196 \cdot 10^{-2}$
50 MHz	10 MHz	200 ns	$3.564 \cdot 10^{-2}$
50 MHz	10 MHz	40 ns	$4.241 \cdot 10^{-2}$
450 MHz	40 MHz	2000 ns	$1.659 \cdot 10^{-2}$
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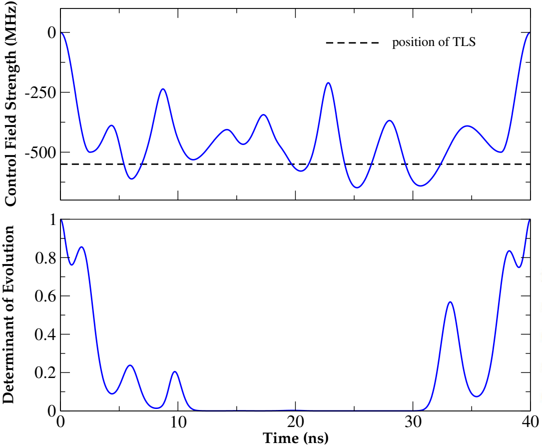
similar errors for up to 4 TLS

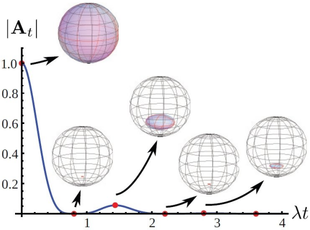
only strongly coupled, very lossy TLS very close by make life difficult

how does the control work?

Reich, Katz, CPK, Sci Rep 5, 12430 (2015)

ramp system into resonance with TLS and back acquiring non-local phase due to interaction





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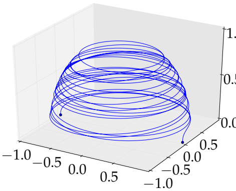
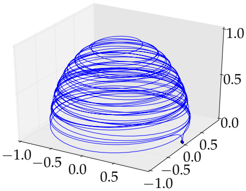
evolution of $|1\rangle$



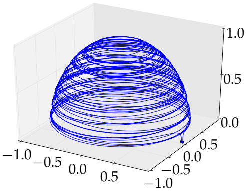
non-local phase acquired

evolution of $|2\rangle$



original phase restored

evolution of $|3\rangle$



original phase restored

proper phase alignment possible thanks to optimal control

opportunities & fundamental limits

3 rules for controlling open quantum systems

review: CPK, J Phys Condens Matter 28, 213001 (2016)

1. detrimental case: unwanted Markovian dynamics
   $\Longrightarrow$ do things as fast as you can (OCT)
2. beneficial case: desired Markovian dynamics
   target must be fixed state of Liouvillian
   $\Longrightarrow$ quantum reservoir engineering
3. non-Markovian dynamics: beneficial & detrimental effects
   beneficial $\Longleftrightarrow$ few strongly coupled,
   sufficiently isolated modes

directly applicable in current experiments
with superconducting circuits

also applicable to other small 'natural' spin baths
(NV centers)

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is it possible to exploit other features of non-Markovianity?

acknowledgments

Michael Goerz, Daniel Reich

Giulia Gualdi

€€€:

DFG, DAAD

QUAINT Optimal Control Technologies in Quantum Information Processing

MARIE CURIE ACTIONS

Birgitta Whaley, Berkeley
Nadav Katz, HUJI

opportunities & fundamental limits

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