

optimal control theory for quantum gates in open quantum systems

Christiane P. Koch

**U N I K A S S E L
V E R S I T 'A' T**

**some terminology
&
basics of optimal control**

principle of coherent / quantum control

wave properties of matter (superposition principle)

variation of phase between
different, but indistinguishable quantum pathways:

constructive *interference*
in desired channel

destructive *interference*
in all other channels

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how to solve the inversion problem?

'intuitive' approaches

optimal control theory

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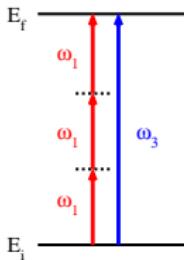
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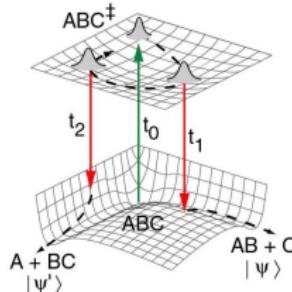
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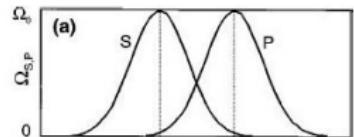
Brumer & Shapiro



Tannor & Rice



STIRAP



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optimal control theory

- bichromatic control
- pump-dump/probe
- STIRAP
 - ~~ DFS & other symmetry-adapted control

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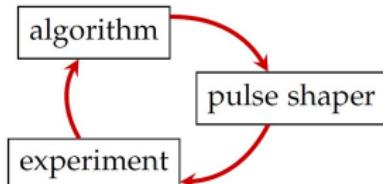
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~~ DFS & other
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- theory: iterative solution of control equations
- exp.: 

optimal control theory

time/frequency 'phase space' picture

$$t = 0 \quad | \varphi_i \rangle \quad \rightsquigarrow \quad t = T \quad | \varphi_f \rangle$$

define the objective :

$$\text{GOAL} \equiv \| \langle \varphi_i | \hat{\mathbf{U}}^+(T, 0; \boldsymbol{\varepsilon}) | \varphi_f \rangle \|^2 = -J_T$$

as a functional of the field $\boldsymbol{\varepsilon}$

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include additional constraints:

$$J = J_T + \int_0^T J_t(\boldsymbol{\varepsilon}, \varphi) dt$$

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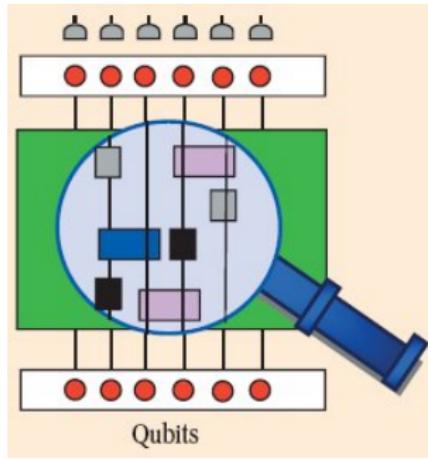
optimize J :

$$\partial_{\boldsymbol{\varepsilon}} J = 0 \quad \partial_{\varphi(t)} J = 0 \quad \partial_{\boldsymbol{\varepsilon}}^2 J > 0$$

$| \varphi(t) \rangle = \hat{\mathbf{U}}(t, 0; \boldsymbol{\varepsilon}) | \varphi_i \rangle$ can only be fulfilled **locally!**

control tasks
in an ideal quantum world
(w/o decoherence)

optimal control for quantum gates

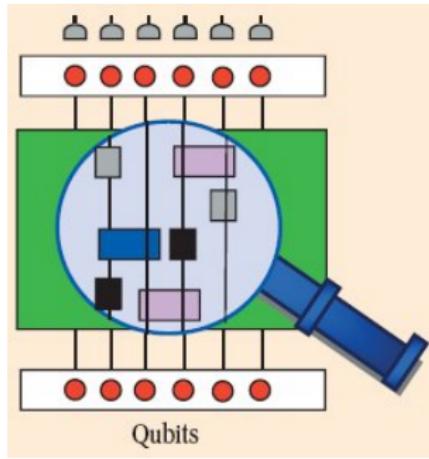


$$\text{Tr} \left\{ \hat{\mathbf{O}}^+ \hat{\mathbf{P}}_N \hat{\mathbf{U}}(T, 0; \varepsilon) \hat{\mathbf{P}}_N \right\}$$

Palao & Kosloff, PRA 68, 062308 (2003)

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

optimal control for quantum gates



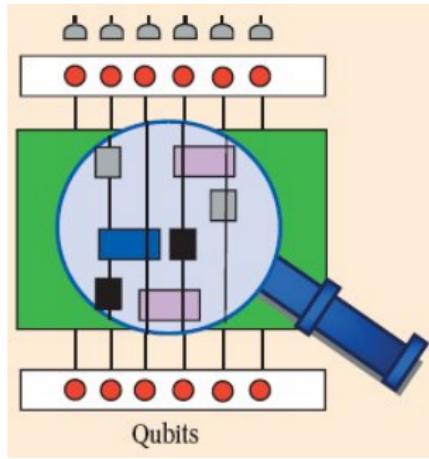
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$$\Delta \boldsymbol{\epsilon}(t) = \frac{S(t)}{2\alpha} \Im \mathfrak{m} \left[\sum_{k=1}^N \langle \varphi_{k,ini} | \hat{\mathbf{O}}^+ \hat{\mathbf{U}}^+(T, t; \boldsymbol{\epsilon}^{old}) \hat{\mu} \hat{\mathbf{U}}(t, 0; \boldsymbol{\epsilon}^{new})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

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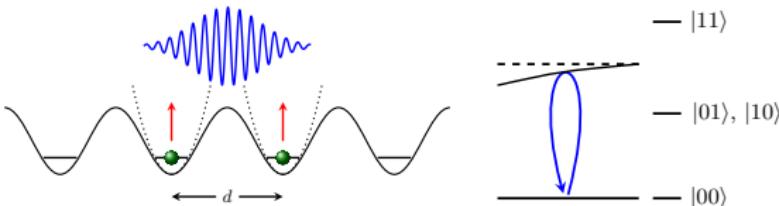
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- what gate time T needed ?
- best choice of target $\hat{\mathbf{O}}$?

minimum gate time

example: controlled phasegate $\hat{O} = \text{diag}(e^{i\chi}, 1, 1, 1)$
for atoms in an optical lattice

Goerz, Calarco, Koch, J Phys B 44, 154011 (2011)



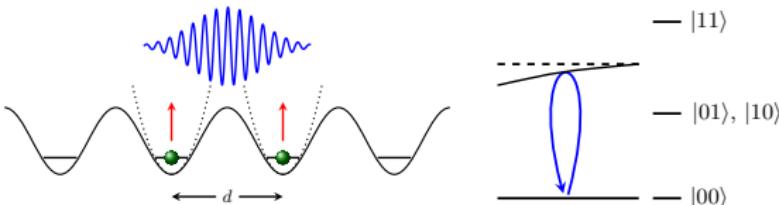
goal: perform a
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while restoring the motional state of the atoms

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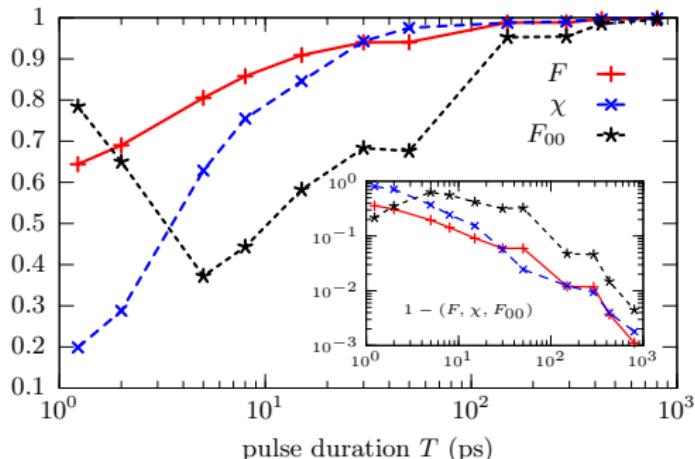
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best choice of target

Müller, Reich, Murphy, Yuan, Vala, Whaley, Calarco, Koch, PRA 84, 042315 (2011)

optimize for the entangling content of a two-qubit gate
rather than for a specific gate

local invariants functional

$$J_T = \Delta g_1^2 + \Delta g_2^2 + \Delta g_3^2$$

with $\Delta g_i^2 = |g_i(\hat{\mathbf{O}}) - g_i(\hat{\mathbf{U}})|^2$ and $g_i(\hat{\mathbf{O}})$ the local invariants of $\hat{\mathbf{O}}$

optimization determines *that* gate out of a local equivalence class that can best be implemented in an *automated* fashion

$$\hat{\mathbf{U}} = \hat{\mathbf{k}}_1 e^{-\frac{i}{2} \sum_{j=x,y,z} c_j \hat{\sigma}_j^1 \hat{\sigma}_j^2} \hat{\mathbf{k}}_2$$

$$g_1, g_2, g_3 \iff c_x, c_y, c_z$$

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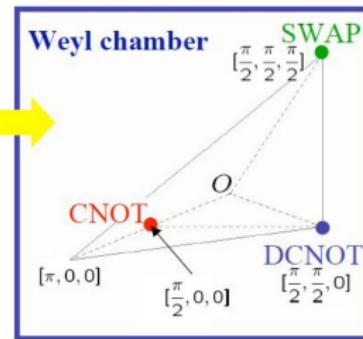
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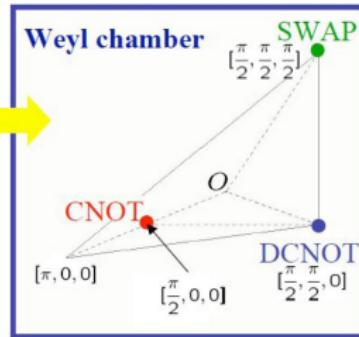
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J_T 8th degree polynomial in $\{|\varphi_k\rangle\}$

~~ nonlinear Krotov method

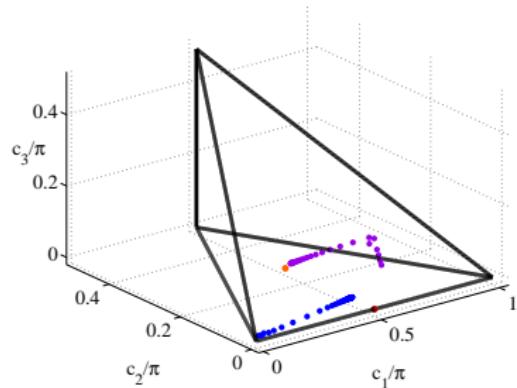
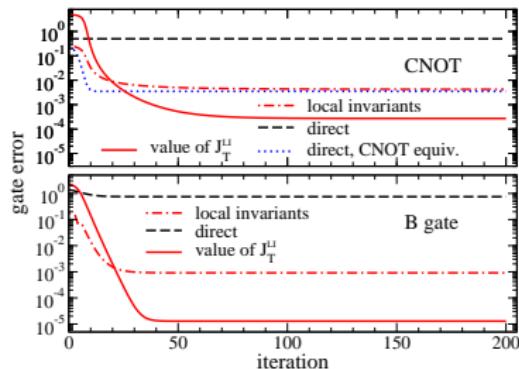
Reich, Ndong, Koch, J. Chem. Phys. 136, 104103 (2012)



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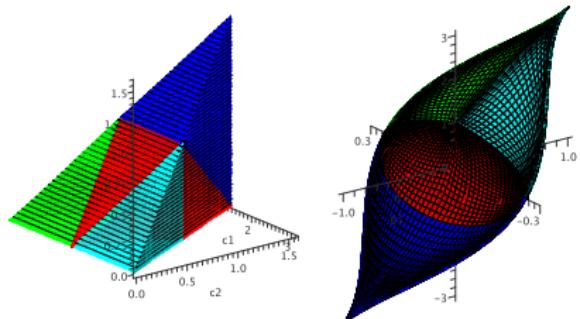
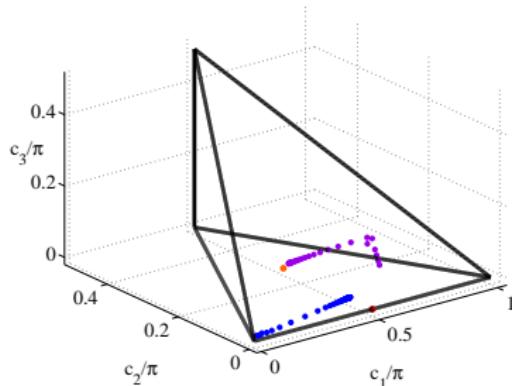
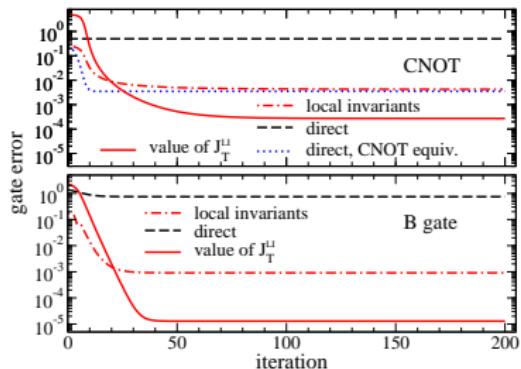
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can be generalized to all perfect entanglers

P. Watts & J. Vala

combination of g_i which vanishes on boundary of W_{PE} , e.g.

$$J_T = g_3 \sqrt{g_1^2 + g_2^2 - g_1 g_2}$$

how to tackle control tasks
in the real world ?
(with decoherence)

OCT for open quantum systems

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

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\Rightarrow maximize $\text{Tr}[\rho(T)\rho_{target}]$

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Kallush & Kosloff, Phys. Rev. A 73, 032324 (2006)

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

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using concepts 'commutant space' and 'total rotation'

differentiating unitaries: commutant space assume unitary time evolution

set of states $\{\rho_i = \rho_i(t=0)\}$ and $\{\rho_i^U(T) = U\rho_i U^\dagger\}$

$$U \in PU(d) = U(d)/U(1)$$

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**commutant space $K(\rho)$ = set of all linear operators
that commute with ρ**

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can always find U with common eigenbasis with ρ \longrightarrow need a
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$\mathcal{K}(\{\rho_i\})$ = intersection of all $K(\rho_i)$
= set of all linear operators that commute with **each** ρ_i

differentiating unitaries: commutant space

**commutant space $K(\rho)$ = set of all linear operators
that commute with ρ**

unitaries in $K(\rho)$ cannot be distinguished from $\mathbb{1}$ by inspection
of ρ : $U\rho U^+ = UU^+\rho = \rho$

if we can distinguish U from $\mathbb{1}$, we can distinguish any U from
any other U' (follows from $U, U' \in PU(d)$) \longleftrightarrow **M injective**
can always find U with common eigenbasis with ρ \longrightarrow need a
set of at least two states

$\mathcal{K}(\{\rho_i\})$ = intersection of all $K(\rho_i)$
= set of all linear operators that commute with **each** ρ_i

$$\mathcal{K}(\{\rho_i\}) = \{\mathbb{1}\} \\ \hat{=}$$

$\mathbb{1}$ is only time evolution that leaves ***all*** $\{\rho_i\}$ unchanged

minimal set of states: total rotation

given a ρ , 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

$$\Rightarrow \rho = \sum_{i=1}^d \lambda_i P_i, \lambda_i \neq \lambda_j$$

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 $\implies \rho = \sum_{i=1}^d \lambda_i P_i, \lambda_i \neq \lambda_j$
- ② construct a ρ' guaranteed to have no common eigenspace with any P_i : **total rotation**
 $\implies \rho' = P_{TR}$ 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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$$P_{TR} P_i \neq 0 \quad \forall P_i \in \{P_i\}$$

(note: d P_{TR} 's = mutually unbiased basis)

$\Rightarrow \rho(T), \rho'(T)$ 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

$$J_T = \sum_{j=1}^3 [1 - \text{Tr}[O\rho_j O^\dagger \rho_j(T)]]$$

$$\rho_{1,ij} = \frac{2(d-i+1)}{d(d+1)}\delta_{ij} \quad \rho_{2,ij} = \frac{d^2-2}{d^2}\delta_{i1}\delta_{1j} + \frac{1}{d^2}\delta_{1j} + \frac{1}{d^2}\delta_{i1} \quad \rho_{3,ij} = \frac{1}{d}\delta_{ij}$$

fix the basis totally rotated state check unitarity
on logical subspace

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fix the basis totally rotated state check unitarity
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J_T attains its minimum only if

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

gate optimization

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

gate optimization

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→ propagation of 3 states sufficient, irrespective of $\dim \mathcal{H}$
 → implications for device characterization

gate optimization with 3 states

theorem:

Let $\text{DM}(d)$ be the space of $d \times d$ density matrices and $\mathcal{D} : \text{DM}(d) \mapsto \text{DM}(d)$ a dynamical map.

The following statements are equivalent:

- ① \mathcal{D} is unitary.
- ② \mathcal{D} maps a set \mathcal{A} of d one-dimensional orthogonal projectors onto a set of d one-dimensional orthogonal projectors and a totally rotated projector P_{TR} (w.r.t. \mathcal{A}) onto a one-dimensional projector.
- ③ \mathcal{D} is unital and leaves the spectrum of a complete and totally rotating set of density matrices invariant.

→ important for optimization of complex systems (d large)

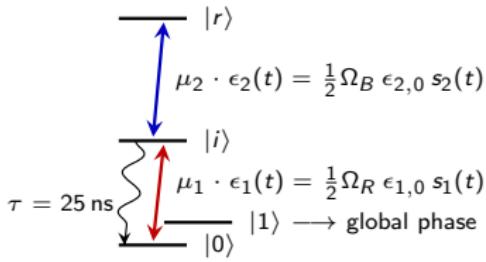
examples:

can OCT help us find better gates ?

example 1:

**Rydberg C-phase gate
for trapped atoms**

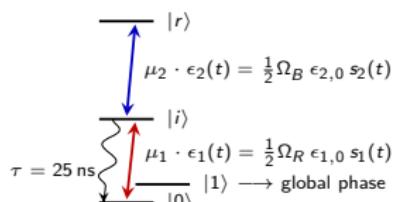
Rydberg gate



$$\hat{\mathbf{H}}_{1q} = \begin{pmatrix} 0 & 0 & \mu\epsilon_1(t) & 0 \\ 0 & E_1 & 0 & 0 \\ \mu\epsilon_1(t) & 0 & \Delta_1 & \mu\epsilon_2(t) \\ 0 & 0 & \mu\epsilon_2(t) & \Delta_1 + \Delta_2 \end{pmatrix}$$

$$\hat{\mathbf{H}}_{2q} = \hat{\mathbf{H}}_{1q} \otimes \mathbb{1} + \mathbb{1} \otimes \hat{\mathbf{H}}_{1q} - \mathcal{U}|rr\rangle\langle rr|$$

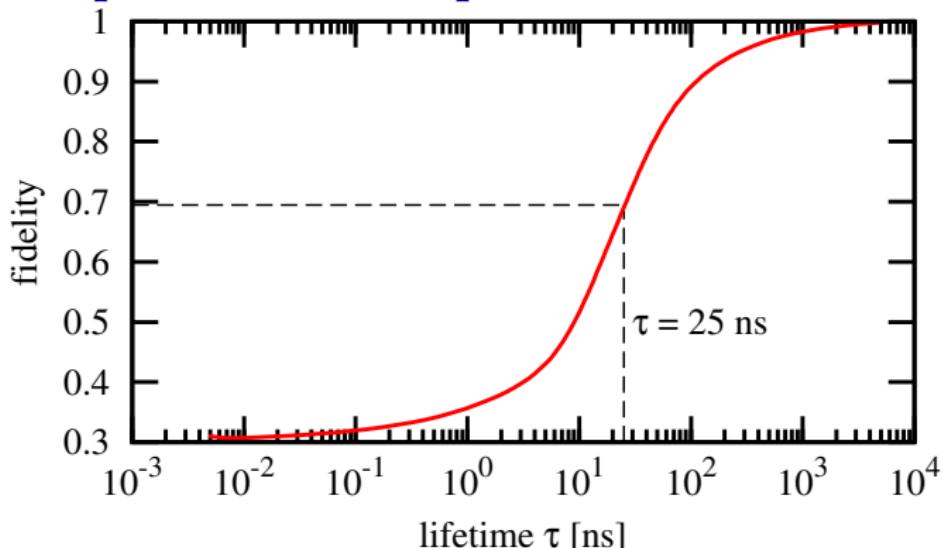
Rydberg gate



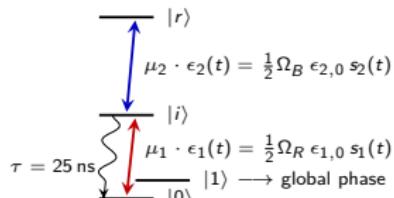
$$\hat{H}_{1q} = \begin{pmatrix} 0 & 0 & \mu\epsilon_1(t) & 0 \\ 0 & E_1 & 0 & 0 \\ \mu\epsilon_1(t) & 0 & \Delta_1 & \mu\epsilon_2(t) \\ 0 & 0 & \mu\epsilon_2(t) & \Delta_1 + \Delta_2 \end{pmatrix}$$

$$\hat{H}_{2q} = \hat{H}_{1q} \otimes \mathbb{1} + \mathbb{1} \otimes \hat{H}_{1q} - U|rr\rangle\langle rr|$$

optimization w/o spontaneous emission



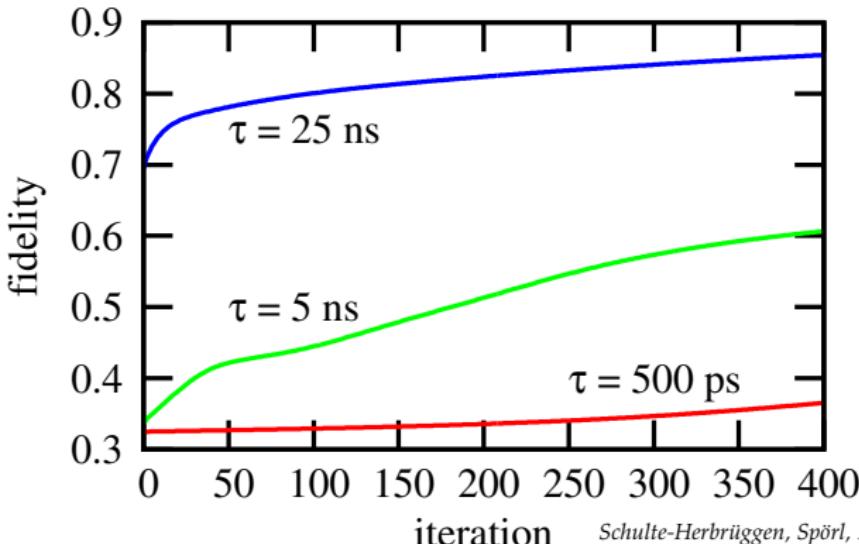
Rydberg gate



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$$\hat{H}_{2q} = \hat{H}_{1q} \otimes \mathbb{1} + \mathbb{1} \otimes \hat{H}_{1q} - U|rr\rangle\langle rr|$$

optimization including spontaneous emission



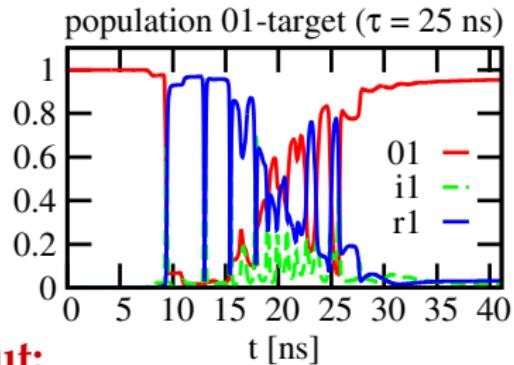
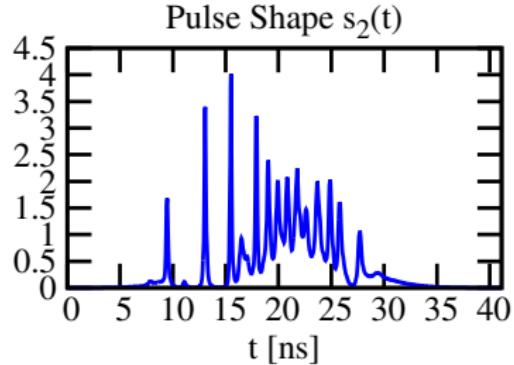
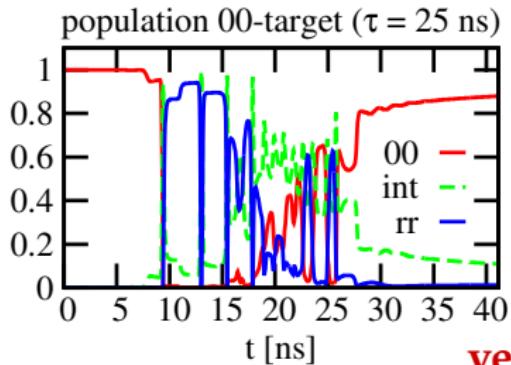
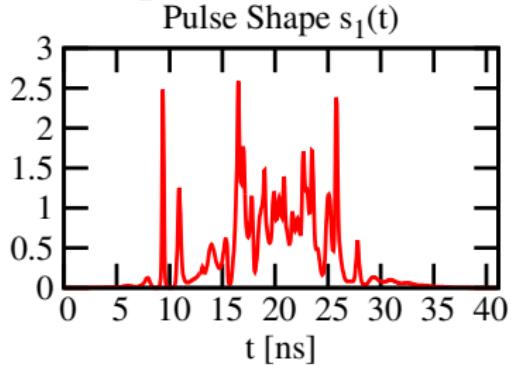
yes!
fidelity:
 $0.7 \rightarrow 0.85$

similar observation for different examples:

Schulte-Herbrüggen, Spörl, Khaneja, Glaser, J. Phys. B 44 154013 (2011)

Rydberg gate

optimization including spontaneous emission

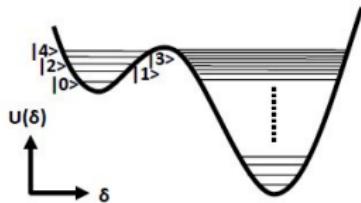
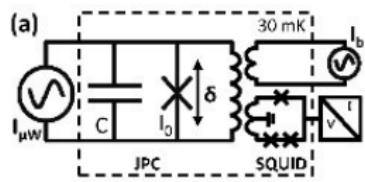


yes! ... but:

fidelity improvement at the price of bang-like solutions

example 2: state preparation of superconducting qutrits

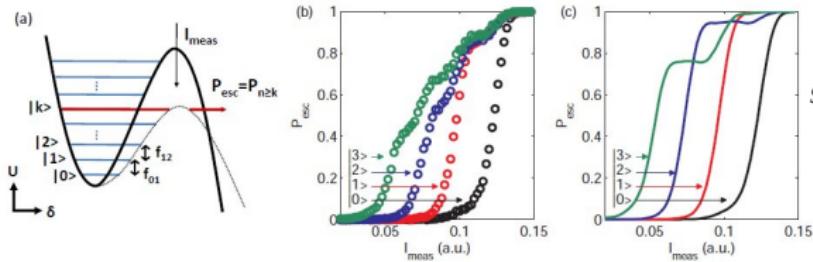
superconducting qubits 1: phase qutrit



Shalibo, Rofe, Barth, Friedland, Bialczak, Martinis, Katz,
Phys. Rev. Lett. 108, 037701 (2012)

Shalibo, PhD thesis (2012)

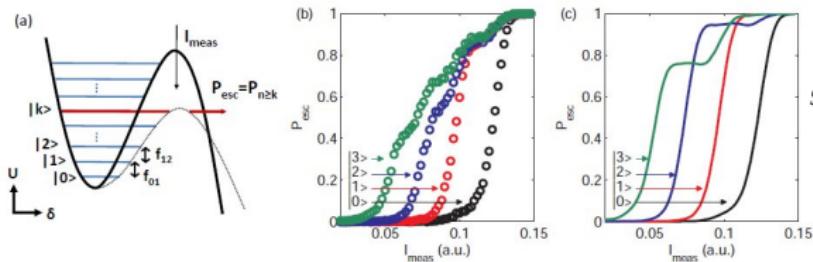
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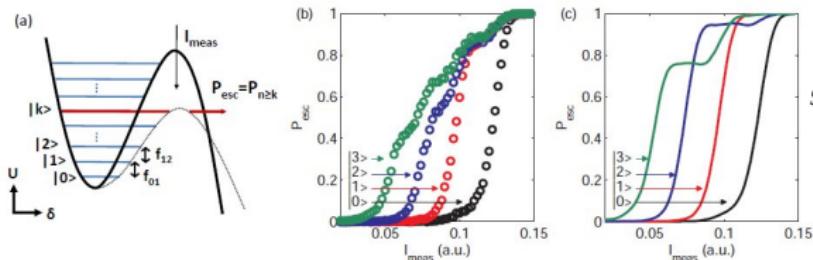
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optimization of state preparation for tomography

$$T_1^{|1\rangle} = 170 \text{ ns}, T_1^{|2\rangle} = 86 \text{ ns} \quad (\Gamma_{n,n-1} \sim n)$$

$$T_2^{|0\rangle\langle 1|} = 75 \text{ ns}, T_2^{|1\rangle\langle 2|} = 65 \text{ ns}, T_2^{|0\rangle\langle 2|} = 25 \text{ ns}$$

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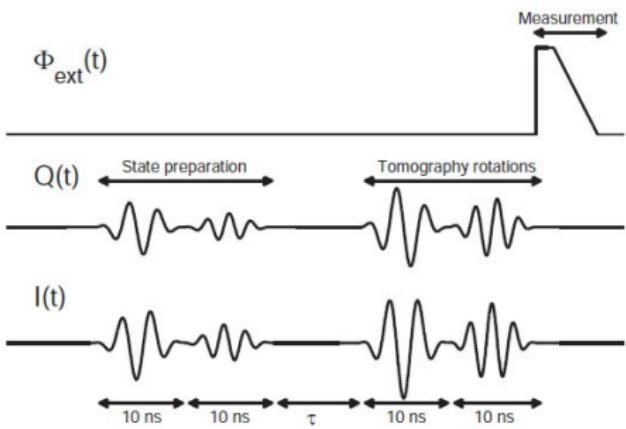
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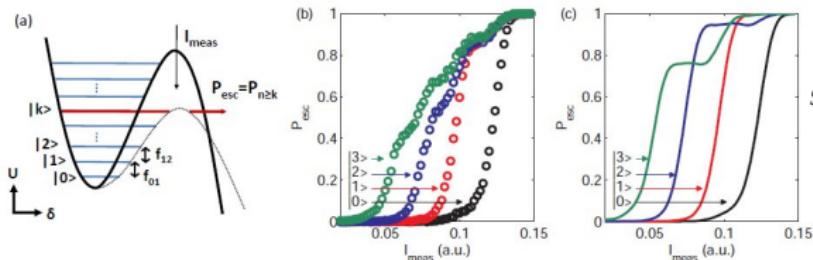
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experiment

sequence of π and $\pi/2$ pulses
with $S(t) = (1 - \cos[2\pi t/T]) / 2$

superconducting qubits 1: phase qutrit



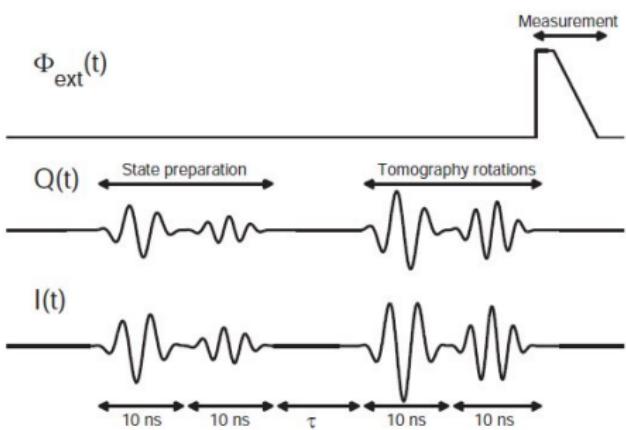
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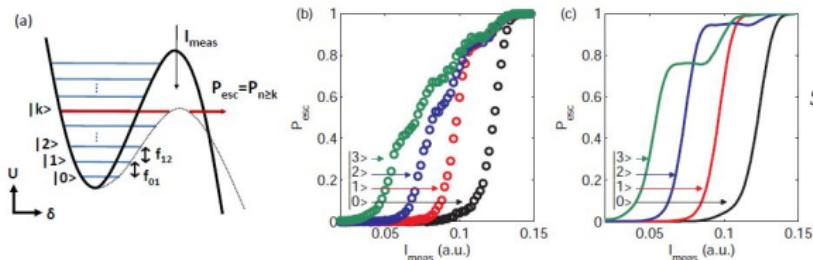
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experiment

sequence of π and $\pi/2$ pulses
with $S(t) = (1 - \cos[2\pi t/T])/2$
 $T = 10 \text{ ns}$

superconducting qubits 1: phase qutrit



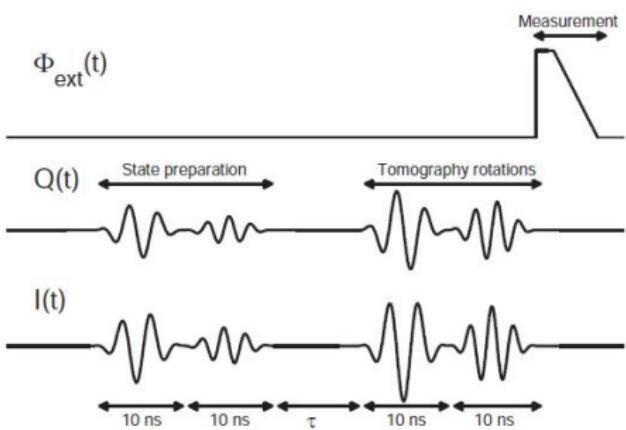
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experiment

sequence of π and $\pi/2$ pulses
with $S(t) = (1 - \cos[2\pi t/T])/2$
 $T = 10 \text{ ns}$

implementing
 $\hat{\mathbf{O}} = \exp[-i\phi\hat{\lambda}_i/2]$

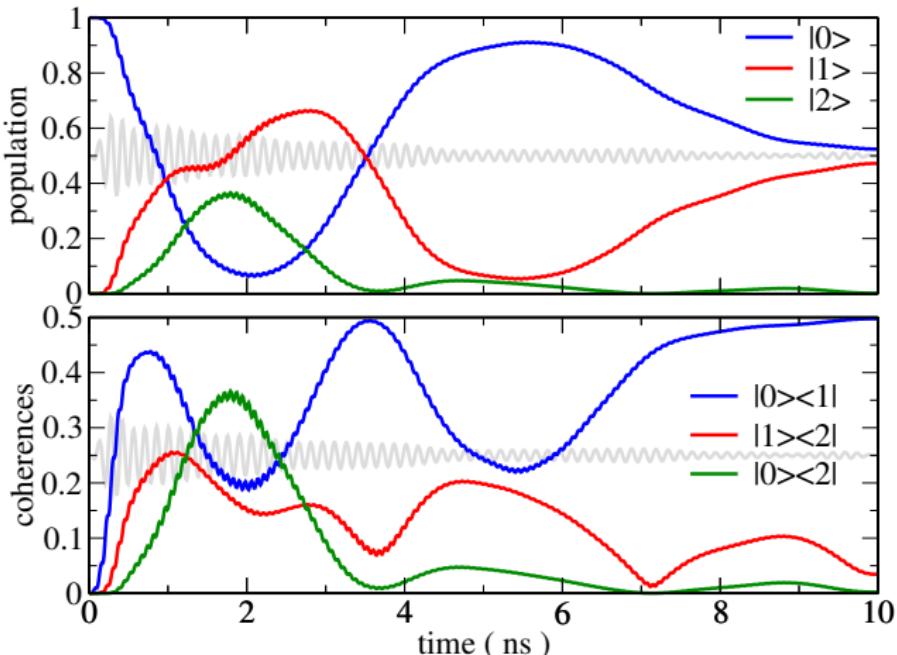
superconducting qubits 1: phase qutrit

optimization of state preparation for tomography: $\hat{\lambda}_1$

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fidelity: 99.3% (no decoherence)



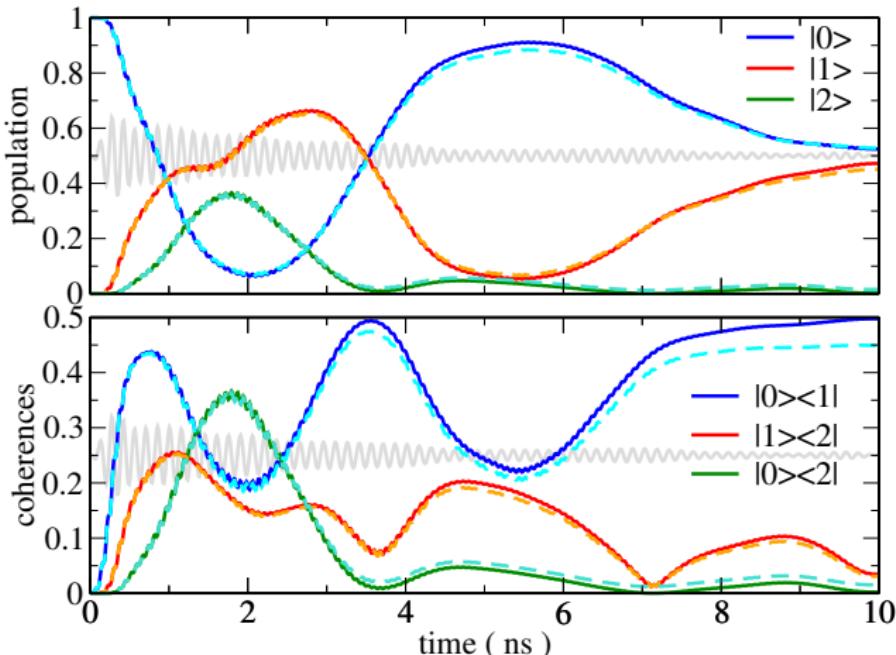
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fidelity: 99.3% \rightsquigarrow 91.7% (with decoherence)



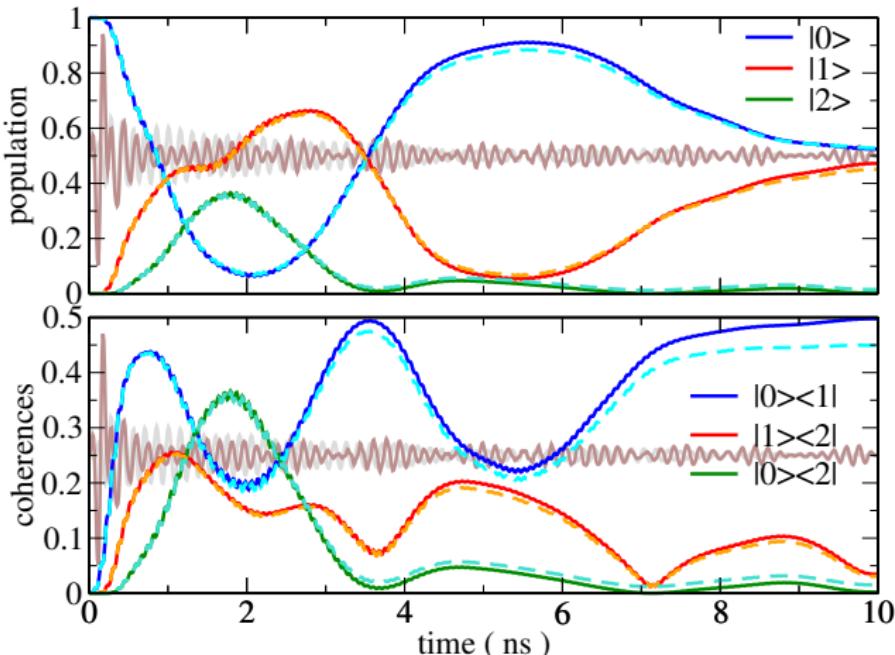
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fidelity: 99.3% \rightsquigarrow 91.7% vs 92.2% (optimized under decoherence)



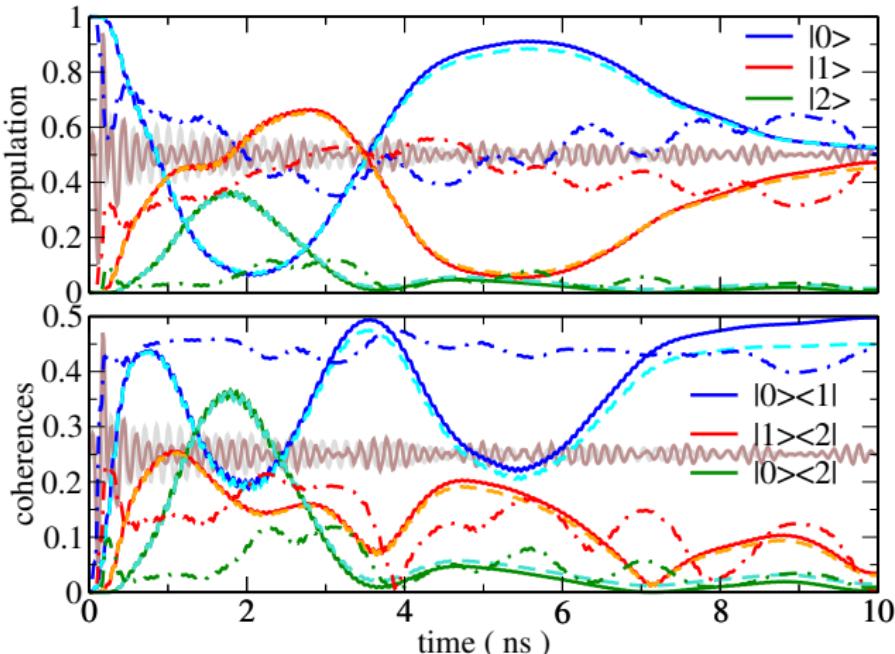
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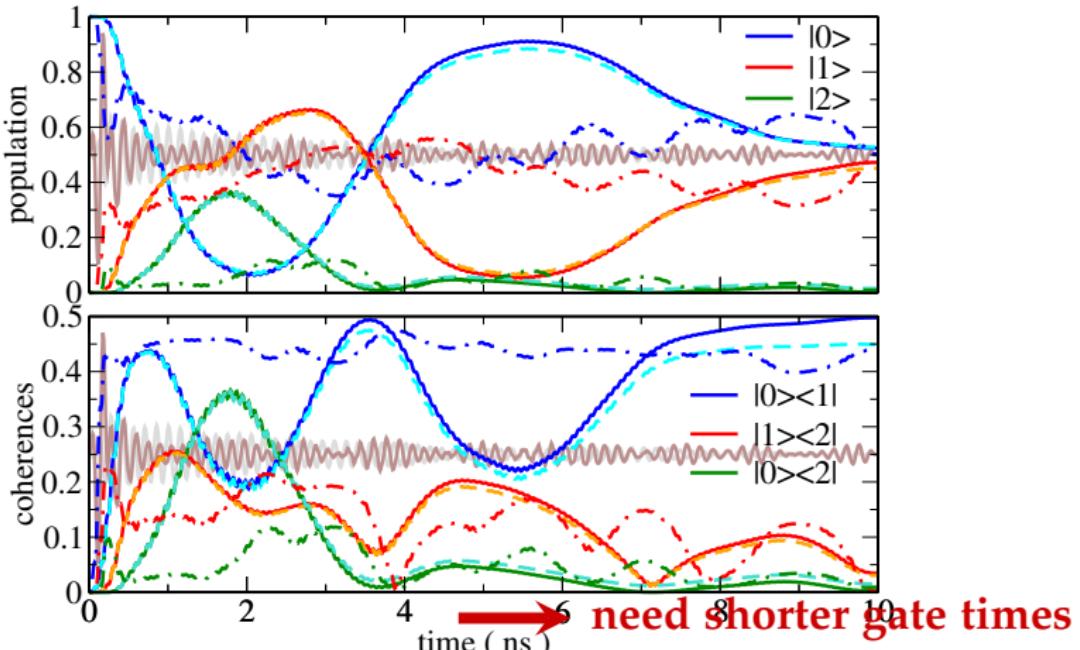
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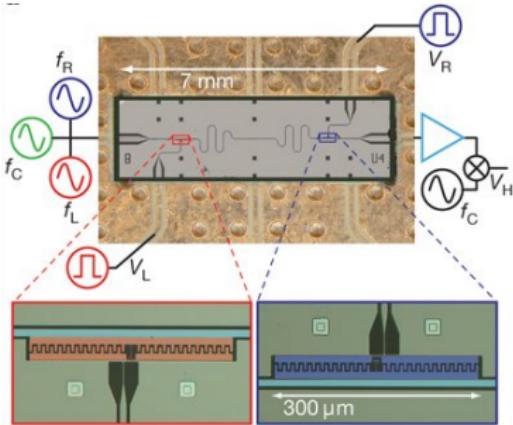
fidelity: 99.3% \rightsquigarrow 91.7% vs 92.2% (optimized under decoherence)



example 3:

C-phase gate for transmon qubits

superconducting qubits 2: transmon qubits



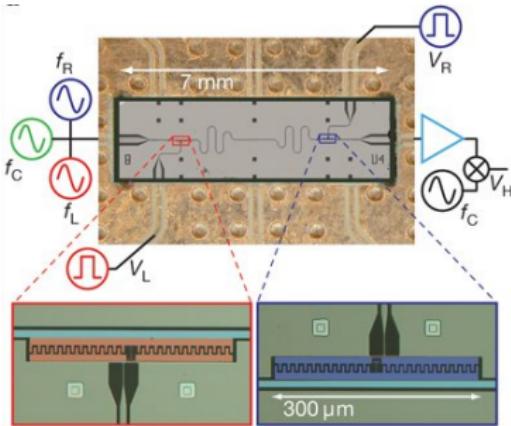
J Koch, Yu, Gambetta, Houck, Schuster, Majer, Blais, Devoret, Girvin, Schoelkopf,
Phys. Rev. A 76, 042319 (2007)

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

comparatively long decoherence times

$$T_2 = 20 \dots 100 \mu\text{s}$$

superconducting qubits 2: transmon qubits



J Koch, Yu, Gambetta, Houck, Schuster, Majer, Blais, Devoret, Girvin, Schoelkopf,
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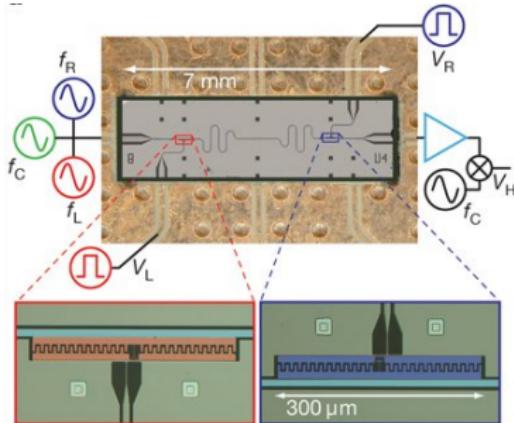
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$$T_2 = 20 \dots 100 \mu\text{s}$$

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

will 'beat' decoherence

superconducting qubits 2: transmon qubits



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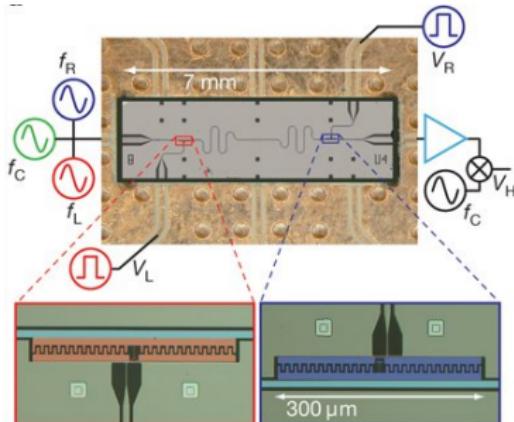
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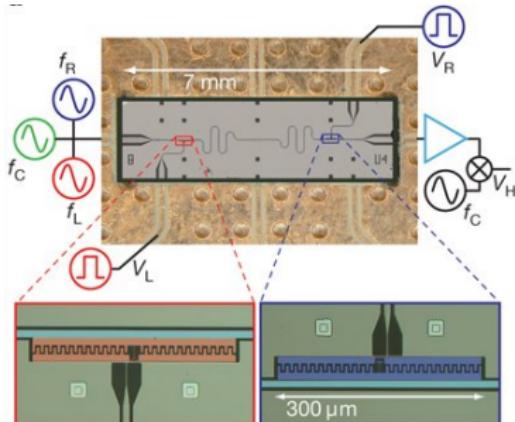
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 \curvearrowright qubit-qubit & qubit-cavity coupling too weak for fast gates

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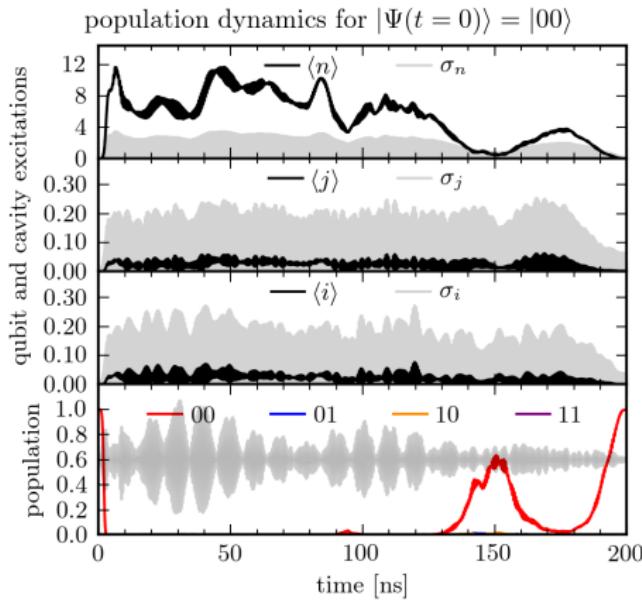
usually treated in dispersive regime \Rightarrow effective qubit-qubit $\hat{\mathbf{H}}$
 \curvearrowright qubit-qubit & qubit-cavity coupling too weak for fast gates

$$\begin{aligned} \hat{\mathbf{H}} = & \sum_{i=1,2} \left[\omega_i \hat{\mathbf{b}}_i^\dagger \hat{\mathbf{b}}_i - \alpha_i \hat{\mathbf{b}}_i^\dagger \hat{\mathbf{b}}_i^\dagger \hat{\mathbf{b}}_i \hat{\mathbf{b}}_i \right] + \textcolor{green}{J} \left(\hat{\mathbf{b}}_1^\dagger \hat{\mathbf{b}}_2 + \hat{\mathbf{b}}_1 \hat{\mathbf{b}}_2^\dagger \right) \\ & + \omega_c \hat{\mathbf{a}}^\dagger \hat{\mathbf{a}} + \epsilon^*(t) \hat{\mathbf{a}} + \epsilon(t) \hat{\mathbf{a}}^\dagger + \sum_{i=1,2} g_i \left(\hat{\mathbf{b}}_i^\dagger \hat{\mathbf{a}} + \hat{\mathbf{b}}_i \hat{\mathbf{a}}^\dagger \right) \end{aligned}$$

superconducting qubits 2: transmon qubits

optimization of C-Phase w/o dissipation

fast gate: $F_{av} = 99.72\%$

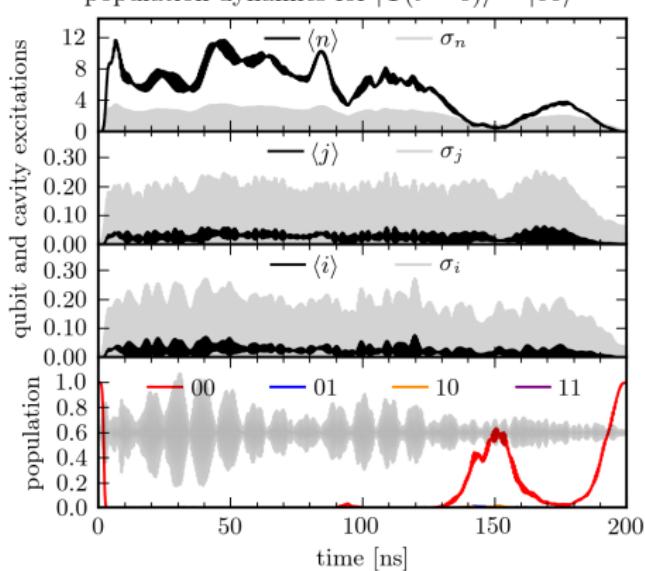


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superconducting qubits 2: transmon qubits

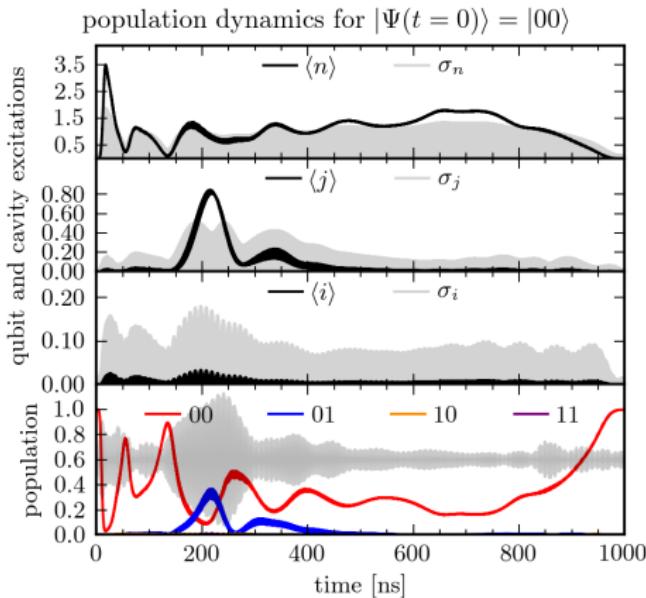
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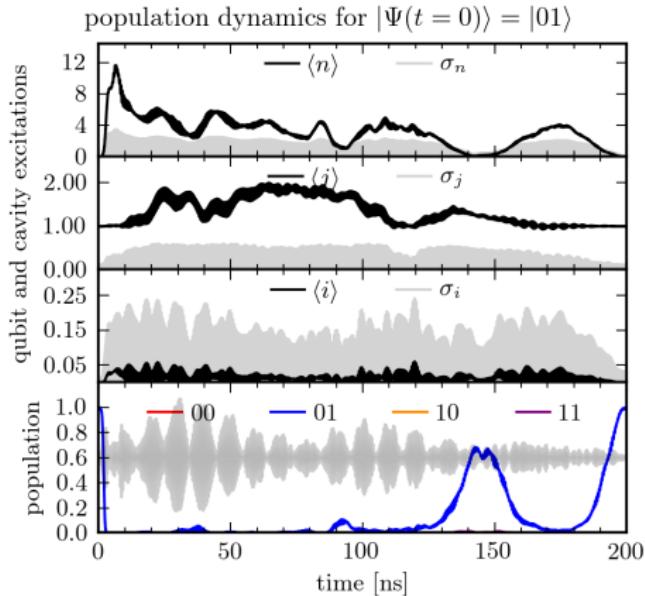


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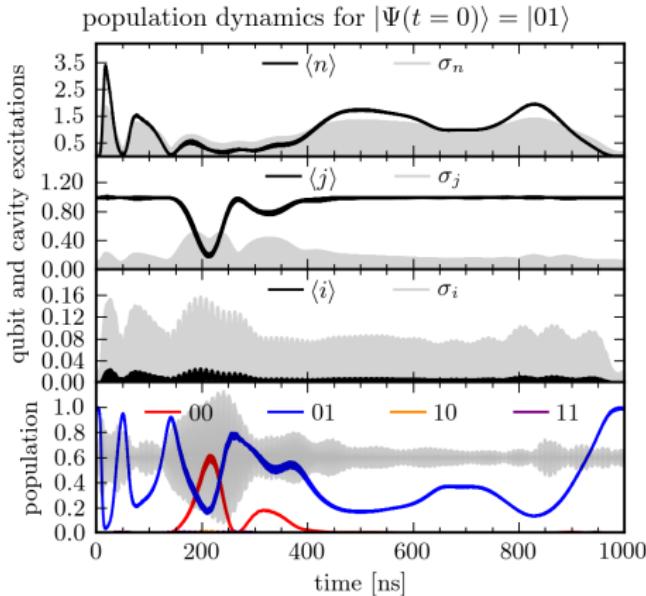
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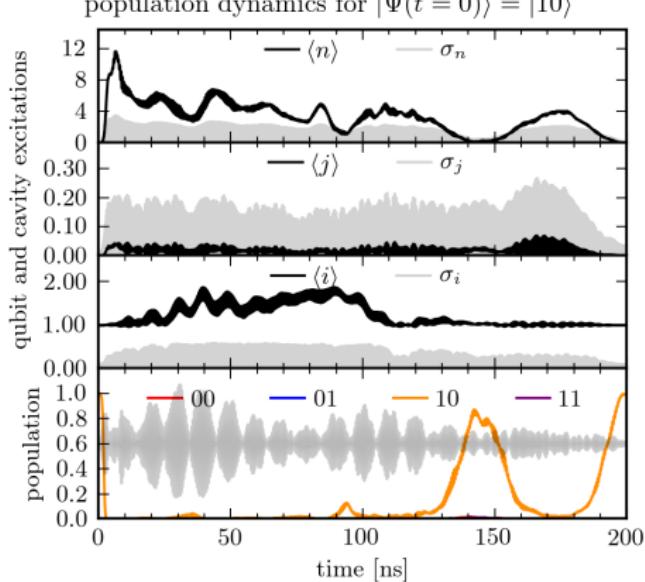


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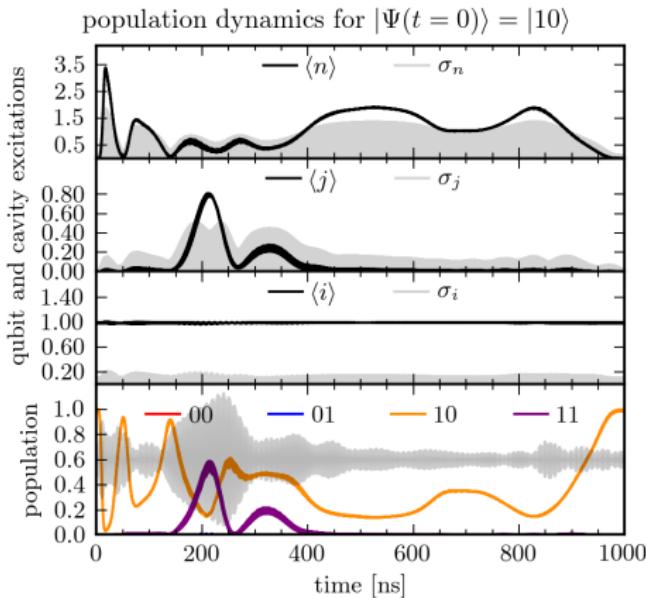
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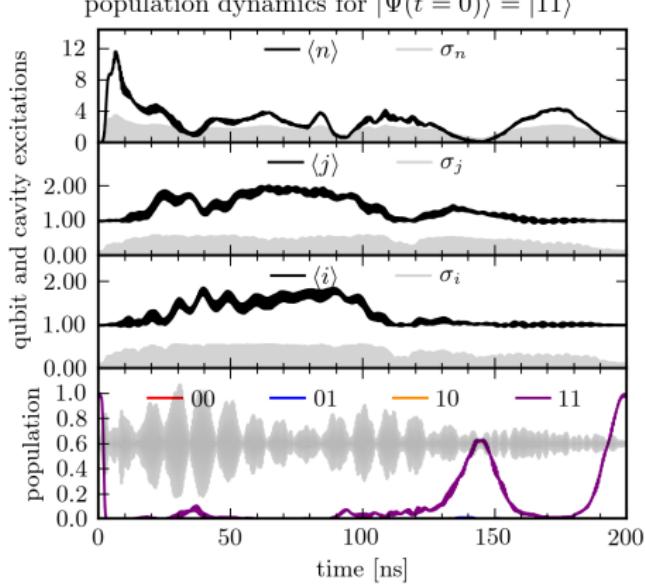


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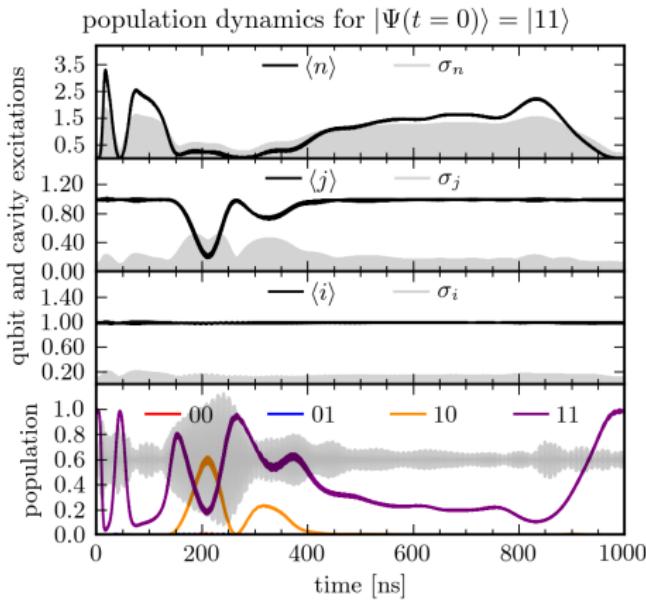
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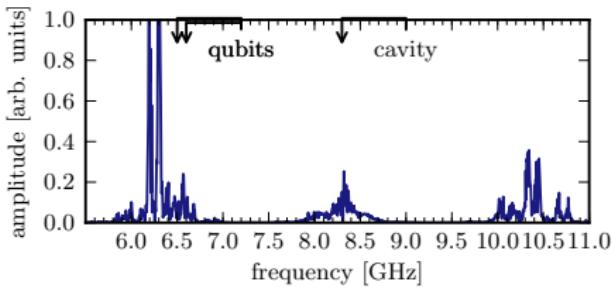


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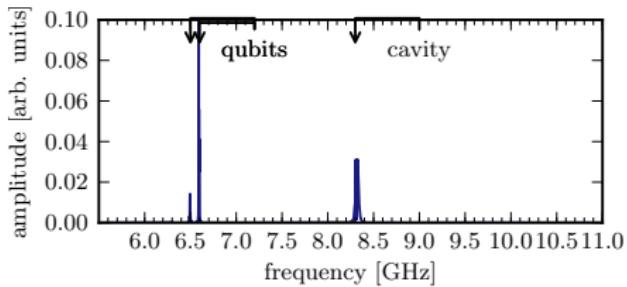
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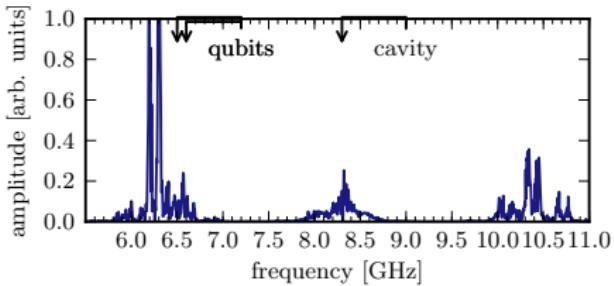
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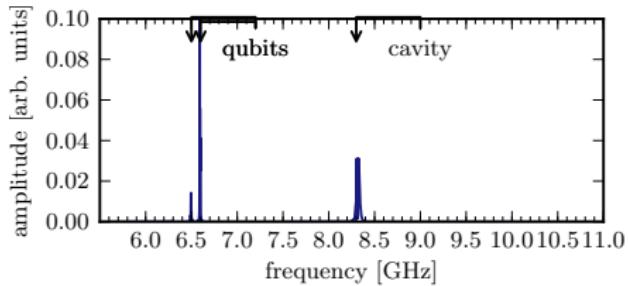
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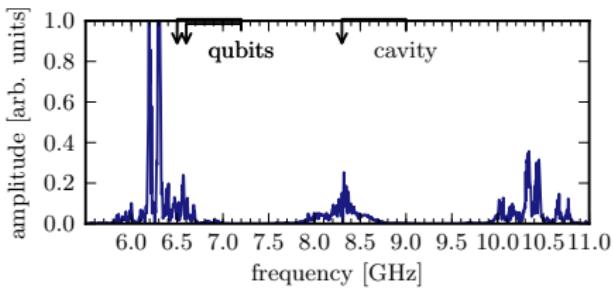
fast gate with additional transitions involving

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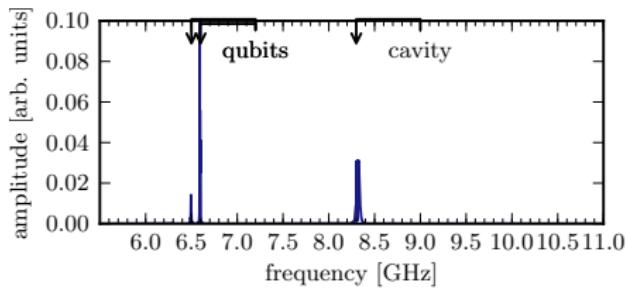
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→ OCT using full complexity of \hat{H} :
gates fast enough to beat decoherence

summary

- OCT can be adapted to QIPC tasks
by proper choice of functional
- OCT yields **fast high-fidelity gates** for complex systems
ex: transmons in the non-dispersive regime
- optimizing under dissipation yields **improved gates**
provided some regions of Hilbert space
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ex: Rydberg gate for trapped atoms
- gate optimization requires **only 3 (and not d^2) states**
 \implies paving the way for OCT for complex systems
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acknowledgments

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thank you!

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