quantum control & engineering with two-body interactions

Christiane Koch

WOMEN 4 QUANTUM

QUANTUM DYNAMICS & CONTROL

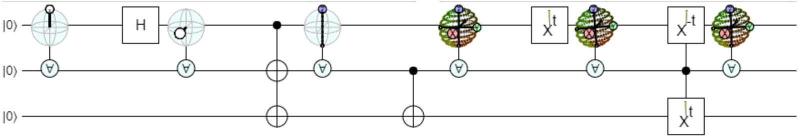
Freie Universität Berlin

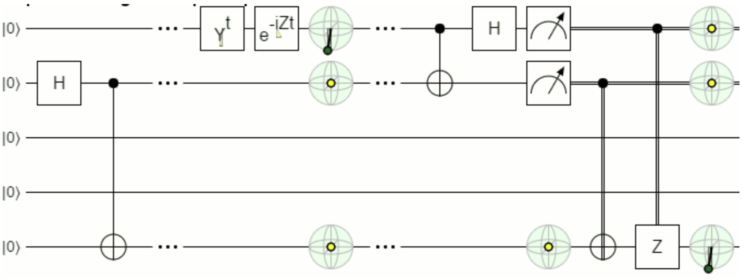
tout d'abord: merci !

quantum control & engineering with two-body interactions

quantum many-body dynamics

scaling number of “particles” & engineering interactions





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(algassert.com)

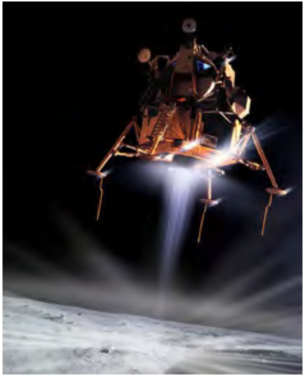
quantum control & engineering happen at the level of physical hardware

quantum control

= steering quantum systems with classical fields

what is (quantum) control?

steer dyn. system from initial to final state(s) using external knob



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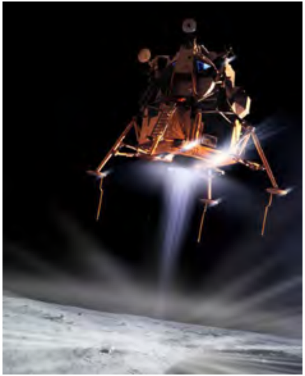

navigate spacecraft:

- Newton's eq.
- initial state: $\vec{r}_0, \vec{v}_0$
  final state: $\vec{r}_f, \vec{v}_f$
- knob: change acceleration

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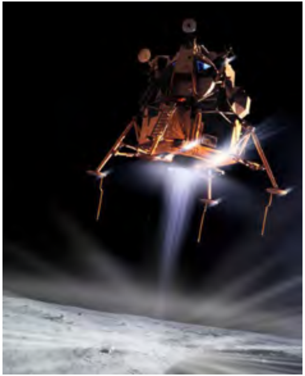

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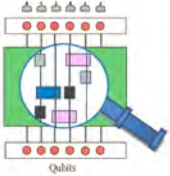
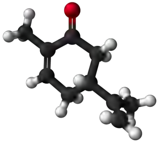
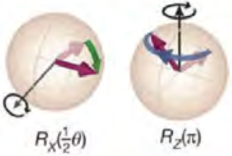
qubits



molecules





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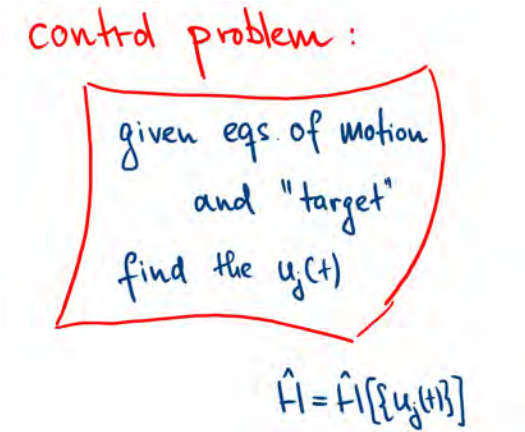
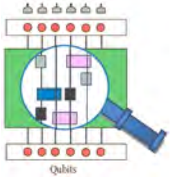
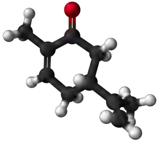
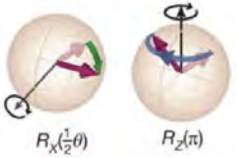


qubits *molecules*





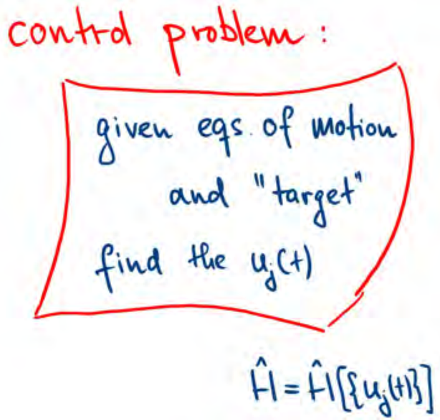


control theory

quantum dynamics — classical controls

Glaser et al., Eur. Phys. J. D (2015)

Koch et al., EPJ Quantum Technol. 9, 19 (2022)



1. is the problem solvable?

- controllability analysis

2. how to solve it?

optimal control theory

control theory

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Glaser et al., Eur. Phys. J. D (2015)

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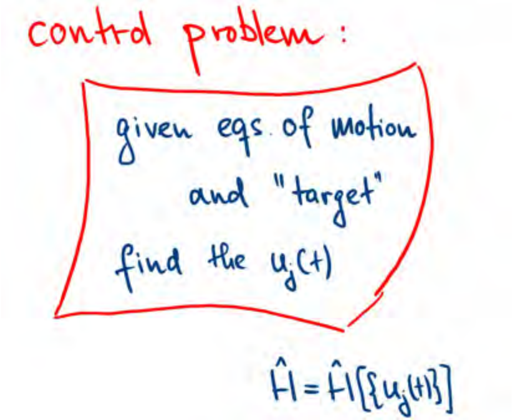


1. is the problem solvable?

- controllability analysis

2. how to solve it?

optimal control theory

- variational calculus (PMP)

  gradient-based optimization

  Python implementation of Krotov's method:
  https://github.com/qucontrol/krotov

  Goerz et al. SciPost Phys 7, 080 (2019)

  and many other variants (Tannor, Rabitz, Khaneja/Glaser,...)

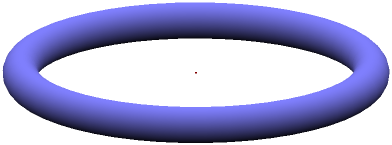
- parameter optimization

  gradient-free optimization

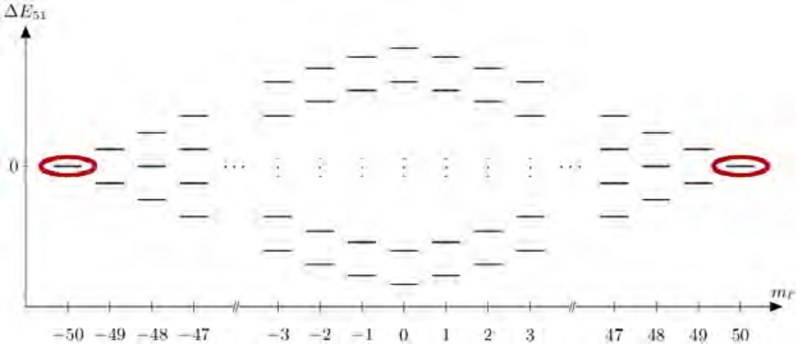
optimal control theory
for the shortest operation time

optimal control example #1

preparation of (circular) Rydberg states



Rb valence electron in $|n,(l),m_l^{max}\rangle$

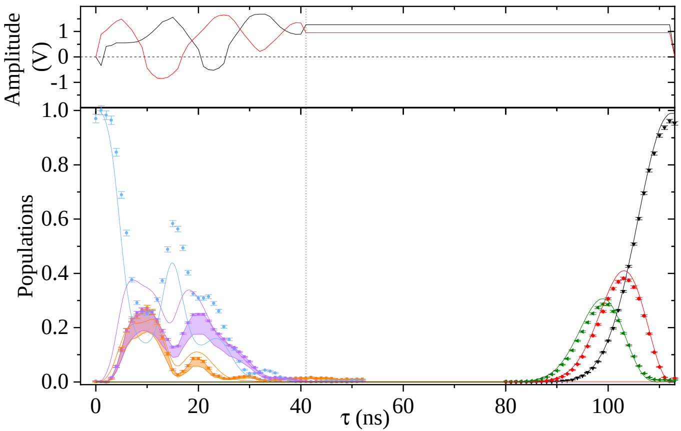


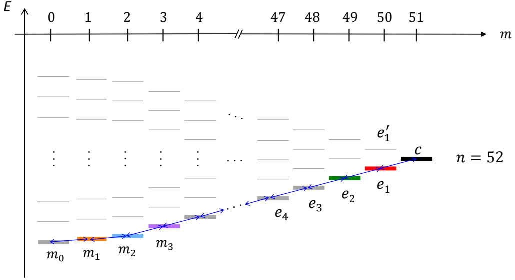
optimal control example #1

preparation of (circular) Rydberg states

Larrouy, Patsch . . ., Koch, Gleyzes, Phys Rev X 10, 021058 (2020) [experiment at Collège de France Paris]

with optimized RF drives: fast & accurate





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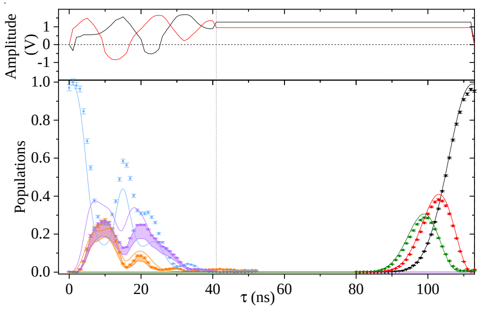
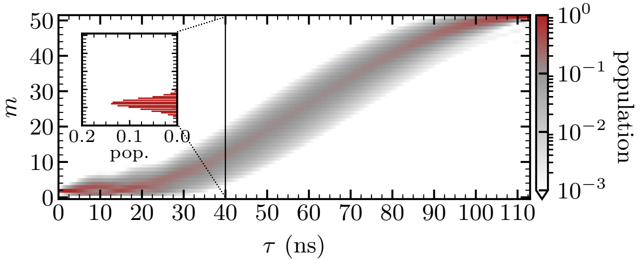
preparation of (circular) Rydberg states

Larrouy, Patsch . . ., Koch, Gleyzes, Phys Rev X 10, 021058 (2020) *[experiment at Collège de France Paris]*

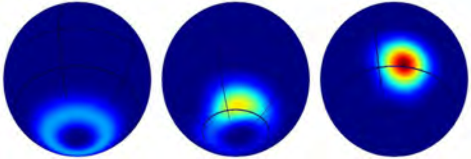
how do the optimized RF drives work? – via spin-coherent state





Husimi Q-function
(projection on spin-coh. state)

$$Q_\Psi(\theta,\varphi) = \frac{2j+1}{4\pi}\,|\langle\theta,\varphi|\Psi\rangle|^2$$



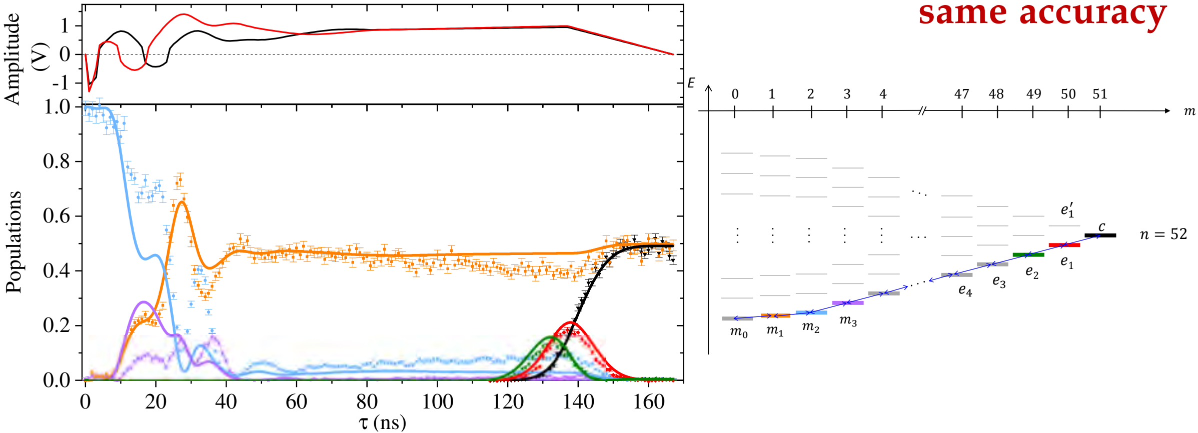
optimal control example #1

preparation of (circular) Rydberg states

Larrouy, Patsch . . ., Koch, Gleyzes, Phys Rev X 10, 021058 (2020)   [experiment at Collège de France Paris]

non-classical superposition – no previously known protocol

same accuracy



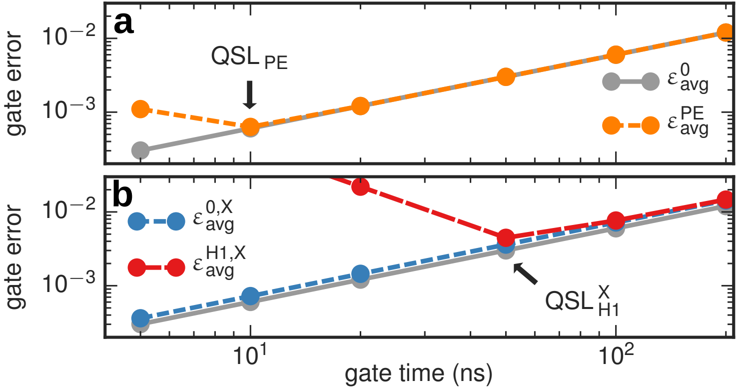
optimal control example #2

fastest universal set of gates

Goerz, Motzoi, Whaley, Koch, npj Quantum Inf. 3, 37 (2017)

two fixed-frequency transmons coupled to (driven) cavity

entangling: 10 ns **single-qubit: 50 ns**

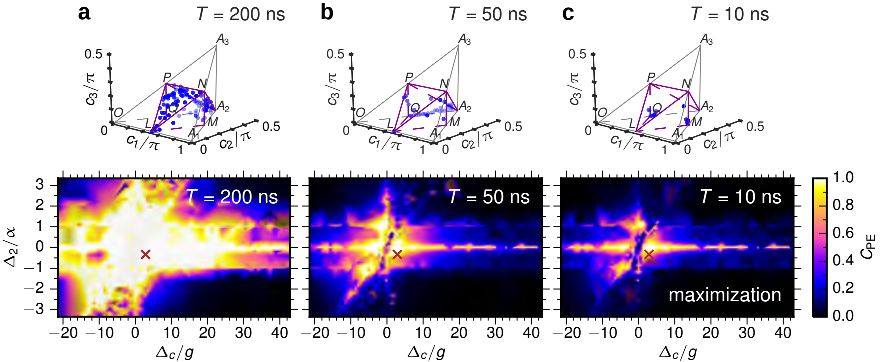


optimal control example #2

fastest universal set of gates

Goerz, Motzoi, Whaley, Koch, npj Quantum Inf. 3, 37 (2017)

two fixed-frequency transmons coupled to (driven) cavity – quasi-dispersive



almost all perfect entanglers

diagonal, $\sqrt{\text{SWAP}}$, $\sqrt{i\,\text{SWAP}}$

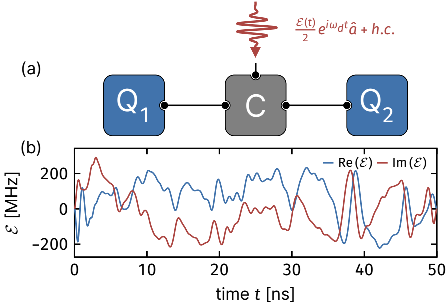
$\sqrt{i\,\text{SWAP}}$

caution !
the speed limit may be dangerous

optimal control example #2

chaotic instabilities in fast gates ?

Basilewitsch, Börner, Berke, Altland, Trebst, Koch, Phys Rev Lett 136, 170601 (2026)



Kullback-Leibler divergence for $\hat{\mathbf{U}}(t)$: compare distribution of eigenphase differences with $P_{POI/GUE}$

optimal control example #2

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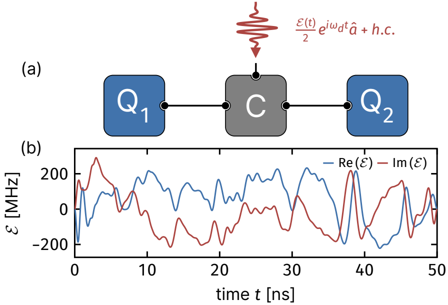

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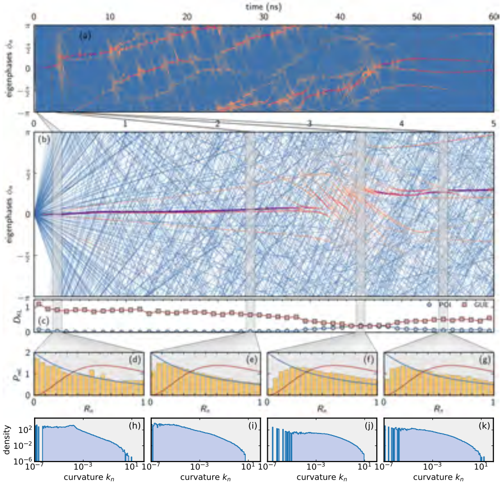


a more robust approach to control :

driven-dissipative evolutions

quantum-reservoir engineering

Poyatos, Cirac, Zoller, Phys Rev Lett 77, 4728 (1996)

$$\partial_t \rho = \mathcal{L}(\rho) = -i[H, \rho]_- + \mathcal{L}_D(\rho)$$

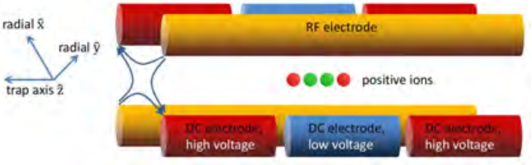
$$\text{steady state} \quad \longleftrightarrow \quad \partial_t \rho = 0$$

use external fields $\left(H = H_0 + \sum_j u_j(t) H_j\right)$ + unidirectional evolution due to $\mathcal{L}_D$ to create non-trivial steady state

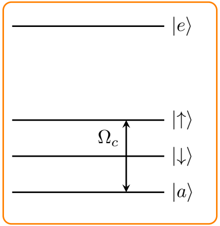
quantum-reservoir engineering

an experimental implementation (almost)

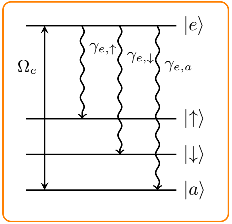
Lin, Gaebler, Reiter, Tan, Bowler, Sorensen, Leibfried, Wineland, Nature (2013)



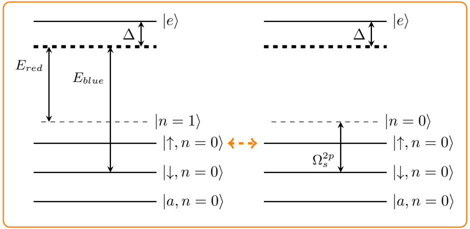
microwave



repump



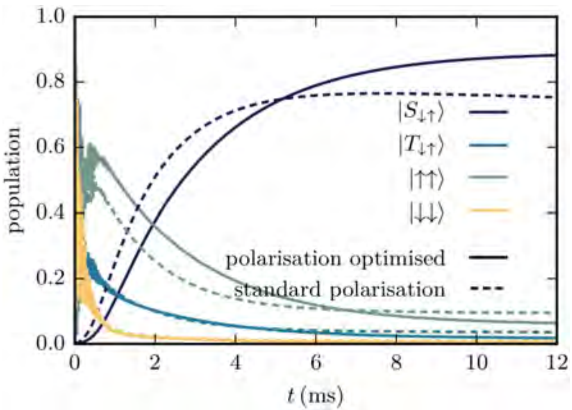
sideband

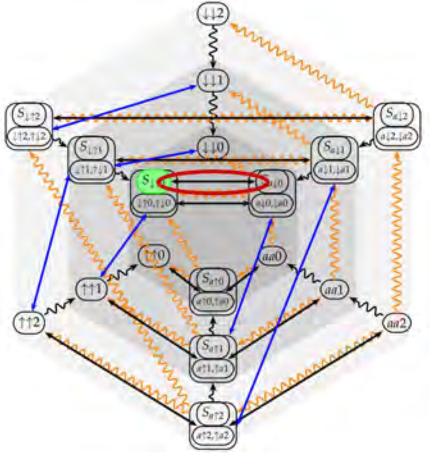


plus laser cooling on Mg^+

quantum reservoir engineering

an experimental implementation (almost)





leakage out of target state: steady state $\neq$ target state

optimal control of qu reservoir engineering

to ensure the desired steady state

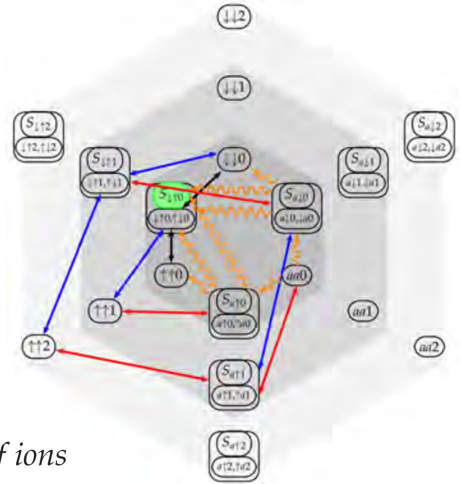
Horn, Reiter, Lin, Leibfried, Koch, New J Phys 20, 123010 (2018)

result of optimization

- keep repump & blue sideband
- different microwave transition
- replace cooling on Mg^+ by red sideband

and (of course) opt parameter values

↷ no transitions out of target state

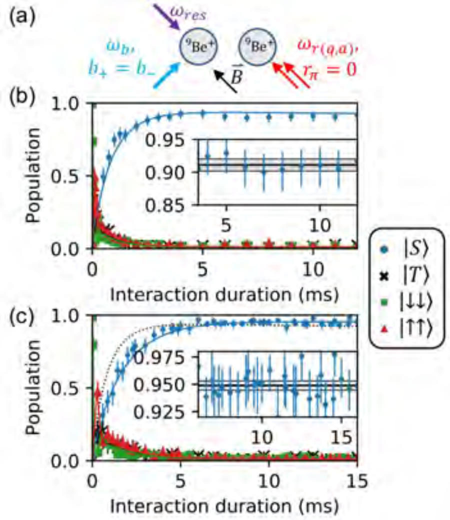


only remaining source of error: anomalous heating of ions

an experimental implementation ~~(almost)~~

steady state = target state

Cole, . . . Koch, Leibfried, Phys Rev Lett 128, 080502 (2022)
[experiment at NIST Boulder]



gain in exp. performance
due to optimal control !

quantum control vs quantum engineering

quantum control vs quantum engineering

so far:

- coherent control of quantum matter via classical controls ("light")
- similar: control of quantum light with classical drives
- key limitation:
  - "local"

quantum control vs quantum engineering

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what about...

- many (interacting) degrees of freedom ?

quantum control vs quantum engineering

so far:

- coherent control of quantum matter via classical controls ("light")
- similar: control of quantum light with classical drives
- key limitation:
  - "local"

what about...

- many (interacting) degrees of freedom ?

we need to

- engineer interactions
  "quantum controlers"
- create / design dissipation

excellent control of single & few-body quantum systems

Glaser et al., Eur. Phys. J. D 69, 279 (2015); Koch et al., Qu. Sci. Technol. 8, 045002 (2023)

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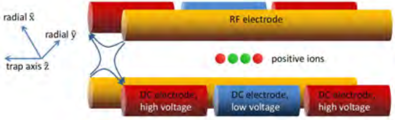
how can we take this to the many-body regime?

quantum control as quantum engineering

— creating dissipation via measurements —

trapped ion example



Horn, Reiter, Lin, Leibfried, Koch, New J Phys 20, 123010 (2018)

Cole et al. Phys Rev Lett 182, 080502 (2022)

'natural' dissipation:

spontaneous emission

limitations
- leakage
- local (one-body)

quantum control as quantum engineering

— creating dissipation via measurements —

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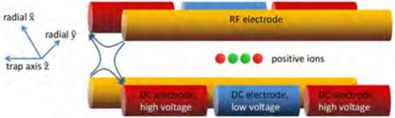

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PHYSICAL REVIEW A **78**, 042307 (2008)

Preparation of entangled states by quantum Markov processes

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[2]*Institute for Theoretical Physics III, University of Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart, Germany*
[3]*Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria*
(Received 1 April 2008; published 8 October 2008)

Article | Published: 07 September 2008

Quantum states and phases in driven open quantum systems with cold atoms

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Nature Physics 4, 878–883 (2008) | Cite this article

quantum control as quantum engineering

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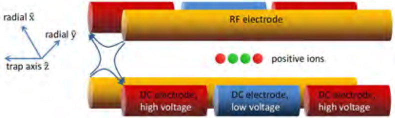

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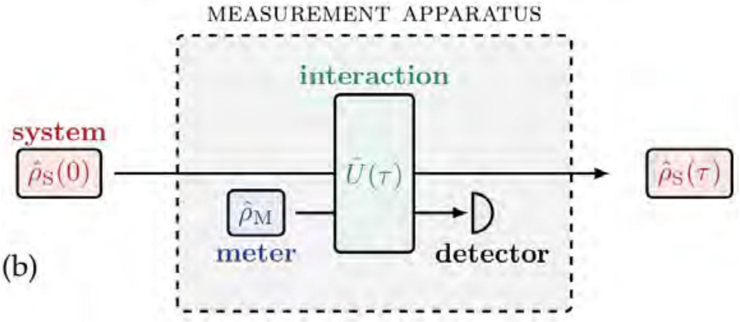
↷ engineer dissipation via coupling to "meters"

quantum measurements (recap)



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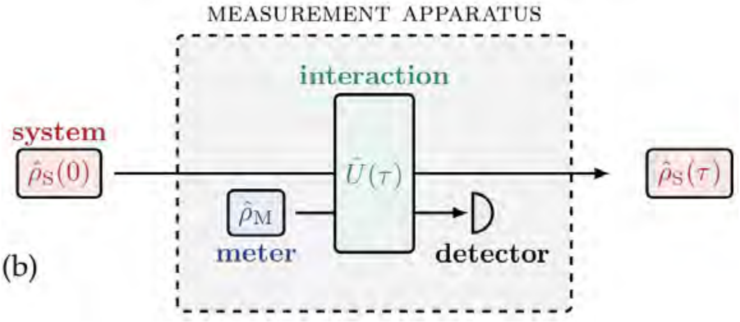
state of system after measurement $$\frac{\hat{\mathbf{M}}_a|\psi_S\rangle}{\sqrt{\langle\psi_S|\hat{\mathbf{M}}_a^+\hat{\mathbf{M}}_a|\psi_S\rangle}}$$

measurement operator $\hat{\mathbf{M}}_a = \langle a_M|\hat{\mathbf{U}}(\tau)|\psi_M\rangle$

Haroche & Raimond: Exploring the quantum; Wiseman, Milburn: Quantum measurement & control

quantum measurements (recap)



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state of system after measurement $\dfrac{\hat{\mathbf{M}}_a|\psi_S\rangle}{\sqrt{\langle\psi_S|\hat{\mathbf{M}}_a^{+}\hat{\mathbf{M}}_a|\psi_S\rangle}}$

measurement operator $\hat{\mathbf{M}}_a = \langle a_M|\hat{\mathbf{U}}(\tau)|\psi_M\rangle$

interaction with meter defines effective dissipators

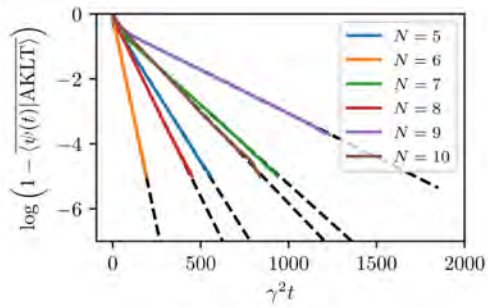
Haroche & Raimond: Exploring the quantum; Wiseman, Milburn: Quantum measurement & control

quantum control as quantum engineering

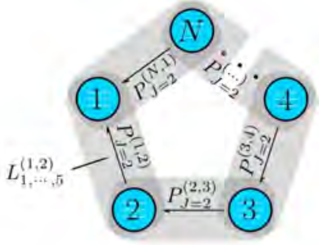
— creating dissipation via measurements in many-body systems —

Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

dilute “blind” cooling into ground state of AKLT model



$$L_1 = |1,1\rangle\langle 2,2|$$
$$L_2 = |1,0\rangle\langle 2,1|$$
$$L_3 = |0,0\rangle\langle 2,0|$$
$$L_4 = |1,-1\rangle\langle 2,-1|$$
$$L_5 = |1,-1\rangle\langle 2,-2|$$



attaching meter qubits to single link is sufficient !

quantum control as quantum engineering

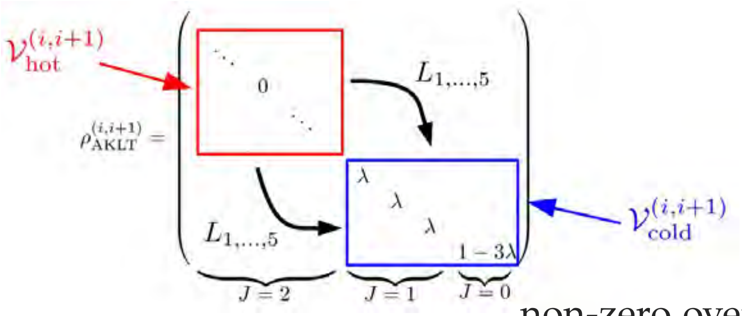
— creating dissipation via measurements —

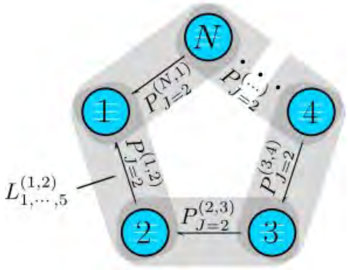
Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

dilute “blind” cooling into ground state of AKLT model

why does it work?

target state projected onto cooled link





all excited states have non-zero overlap with hot subspace

quantum control as quantum engineering

— creating dissipation via measurements —

Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

dilute "blind" cooling into many-body states: general recipe

Kernelizer

$$K_{|\psi_\ominus\rangle} \equiv \{A \in \operatorname{span} \mathcal{O} : A\,|\psi_\oplus\rangle = 0\}$$

$$\mathcal{O} = \operatorname{span} \cup_{i=1}^{N} \mathcal{O}^{(i,i+1)}$$

$$\mathcal{O}^{(i,i+1)} = \operatorname{span}\left\{\sigma_j^{(i)} \otimes \sigma_k^{(i+1)} : j,k \leq d^2\right\}$$

quasi-local op.s respecting $\rho_\oplus$

Sufficient condition for cooling:
Unitary controllability on the complement space of $|\psi_\ominus\rangle$

$$\dim \mathfrak{L}\left(K_{|\psi_\ominus\rangle}\right) = \left(d^N - 1\right)^2 - 1$$

Lie-Algebra generated by $K_{|\psi_\ominus\rangle}$

quantum control as quantum engineering

— creating dissipation via measurements —

Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

dilute "blind" cooling into many-body states: general recipe

Kernelizer

$K_{|\psi_\oplus\rangle} \equiv \{A \in \text{span}\,\mathcal{O} : A|\psi_\oplus\rangle = 0\}$

$\mathcal{O} = \text{span} \cup_{i=1}^{N} \mathcal{O}^{(i,i+1)}$

$\mathcal{O}^{(i,i+1)} = \text{span}\left\{\sigma_j^{(i)} \otimes \sigma_k^{(i+1)} : j,k \le d^2\right\}$

quasi-local op.s respecting $\rho_\oplus$

Target state $\rho_\oplus = |\psi_\oplus\rangle\langle\psi_\oplus|$

1. Check necessary condition $\mathcal{V}_{\text{hot}}^{(i,i+1)} \neq \emptyset$
2. Check sufficient condition $\dim \mathfrak{L}\left(K_{|\psi_\oplus\rangle}\right) = \left(d^N - 1\right)^2 - 1$
3. Choose $L_j = |\phi_{c,j}\rangle\langle\phi_{\text{h},j}|$
4. Choose some $H \in K_{|\psi_\oplus\rangle}$

works for frustration-free quasi-local H

Sufficient condition for cooling:
Unitary controllability on the complement space of $|\psi_\oplus\rangle$

$\dim \mathfrak{L}\left(K_{|\psi_\oplus\rangle}\right) = \left(d^N - 1\right)^2 - 1$

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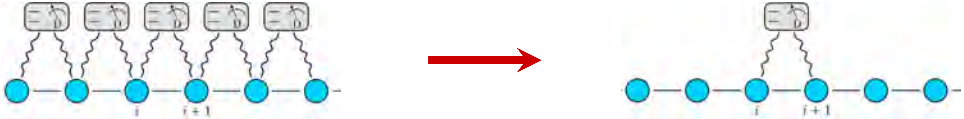

Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

- works for systems with ground state such that
$$\mathcal{V}_{hot}^{(i,i+1)} \neq \emptyset \text{ or equivalently } \mathcal{V}_{\text{hot}}^{(i,i+1)} \subsetneq \mathcal{H}^{(i,i+1)}$$
e.g. frustration-free quasi-local H but also PEPS
- requires engineering of $L_{1,\ldots,5}$ (three-body interactions)

quantum control as quantum engineering

— creating dissipation via measurements —

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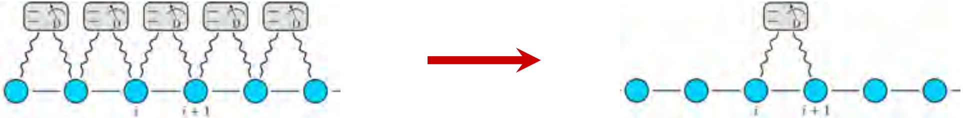

Langbehn, Snizhko, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

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  e.g. frustration-free quasi-local H but also PEPS
- requires engineering of $L_{1,\ldots,5}$ (three-body interactions)

can be simplified and made generic - random weak interactions

Langbehn, Mouloudakis, King, Menu, Gornyi, Morigi, Gefen, Koch, arXiv:2506.11964

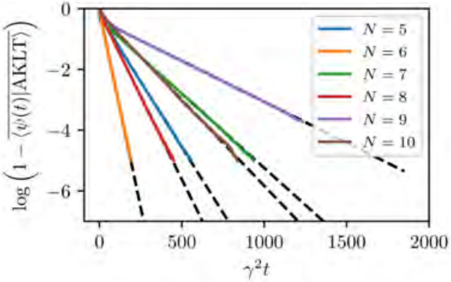
the difficulty:

“non-local” ($N \geq 2$) measurements

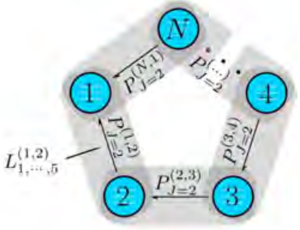
the real difficulty:

continuous "non-local" ($N \geq 2$) measurements

dilute "blind" steering into the AKLT state



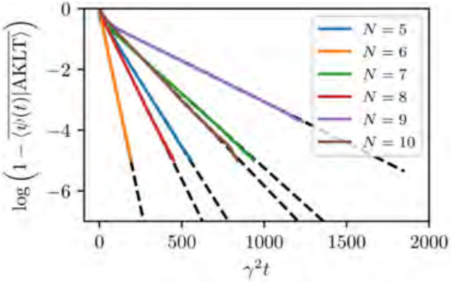
$$L_1 = |1,1\rangle\langle 2,2|$$
$$L_2 = |1,0\rangle\langle 2,1|$$
$$L_3 = |0,0\rangle\langle 2,0|$$
$$L_4 = |1,-1\rangle\langle 2,-1|$$
$$L_5 = |1,-1\rangle\langle 2,-2|$$



Langbehn, Snizhko, Gornyi, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

attaching 5 "meters" to a single link is sufficient

dilute "blind" steering into the AKLT state



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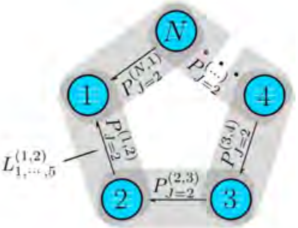


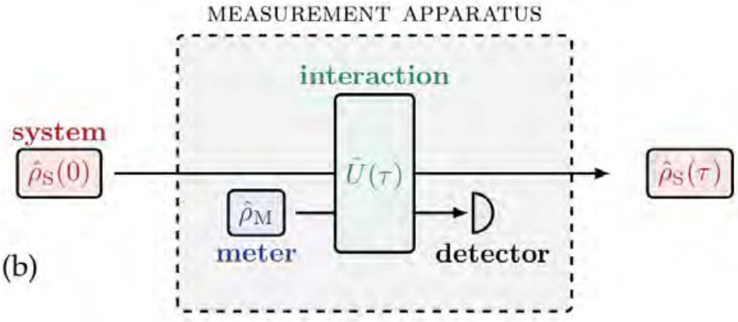
Langbehn, Snizhko, Gornyi, Morigi, Gefen, Koch, PRX Quantum 5, 030301 (2024)

attaching 5 "meters" to a single link is sufficient

5 weak but always-on (!) $\hat{\mathrm{A}} \otimes \hat{\mathrm{B}} \otimes \hat{\sigma}_i$-type interactions

spin 1 – spin 2 – meter

quantum measurements (recap)



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state of system after measurement $\dfrac{\hat{\mathbf{M}}_a|\psi_S\rangle}{\sqrt{\langle\psi_S|\hat{\mathbf{M}}_a^+\hat{\mathbf{M}}_a|\psi_S\rangle}}$

measurement operator $\hat{\mathbf{M}}_a = \langle a_M|\hat{\mathbf{U}}(\tau)|\psi_M\rangle$

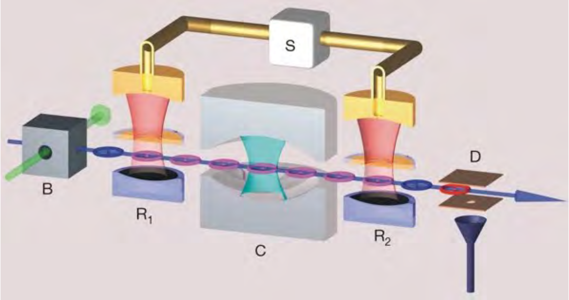
interaction with meter defines effective dissipators

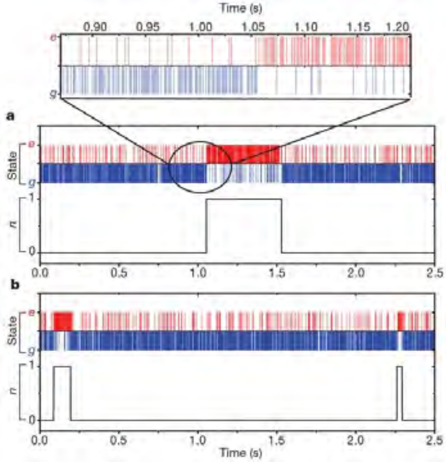
Haroche & Raimond: Exploring the quantum; Wiseman, Milburn: Quantum measurement & control

photon number measurements

— non-destructive quantum measurement —

Gleyzes et al, Nature 446, 297 (2007)





system = photons
meter = Rydberg atoms

photon number measurements

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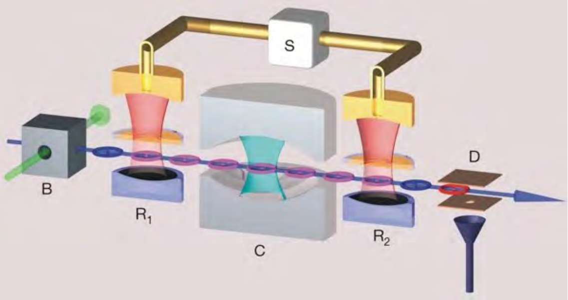

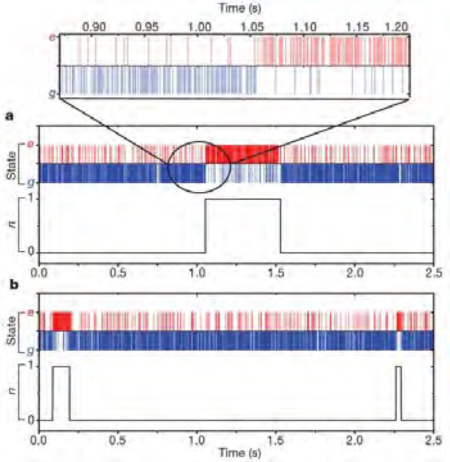

system = photons
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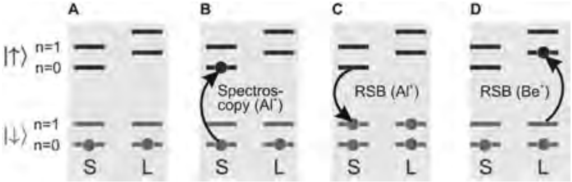
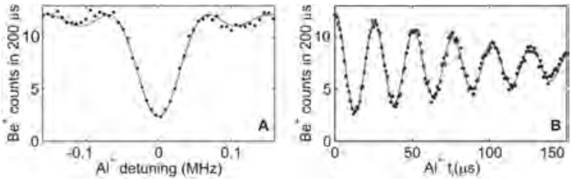
local measurement

quantum logic spectroscopy

— non-destructive quantum measurement —

Schmidt et al, Science 309, 749 (2005)



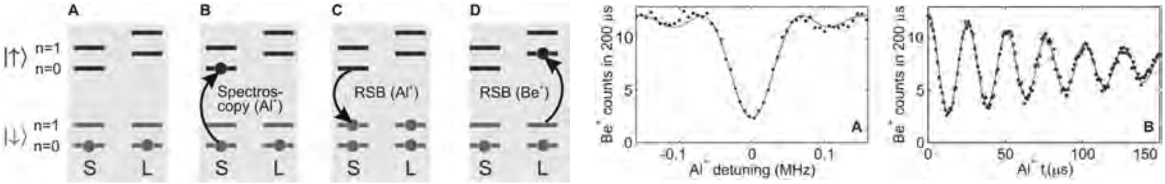


trapped atomic ions :
logic/clock ion & spectroscopy/meter ion

quantum logic spectroscopy

— non-destructive quantum measurement —

Schmidt et al, Science 309, 749 (2005)



trapped atomic ions :
logic/clock ion & spectroscopy/meter ion

local measurement

measurement of one-body operator via two-body interaction

don’t we need non-local measurements all the time ?

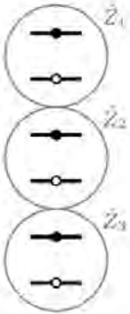
don’t we need non-local measurements all the time ?

e.g. in quantum error correction

in stabilizer QEC, each stabilizer is sequentially measured

non-local ($N \geq 2$) measurements in QEC

— example: three qubit bit flip code —



1. Encoding:

$|0\rangle_L = |000\rangle$

$|1\rangle_L = |111\rangle$

$\Rightarrow |\Psi\rangle_L = \alpha|0\rangle_L + \beta|1\rangle_L$

non-local ($N \geq 2$) measurements in QEC

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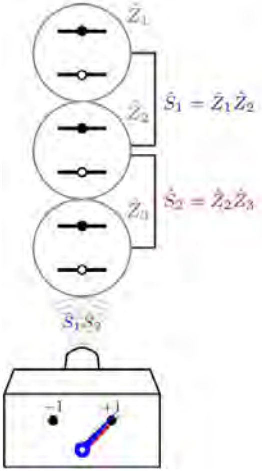

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$$\Longrightarrow |\Psi\rangle_L = \alpha|0\rangle_L + \beta|1\rangle_L$$

2. Syndrome measurements:

$$\hat{Z}_1\hat{Z}_2(\alpha|000\rangle + \beta|111\rangle) = +(\alpha|000\rangle + \beta|111\rangle) \Longrightarrow \text{Even parity}$$
$$\hat{Z}_2\hat{Z}_3(\alpha|000\rangle + \beta|111\rangle) = +(\alpha|000\rangle + \beta|111\rangle) \Longrightarrow \text{Even parity}$$

non-local ($N \geq 2$) measurements in QEC

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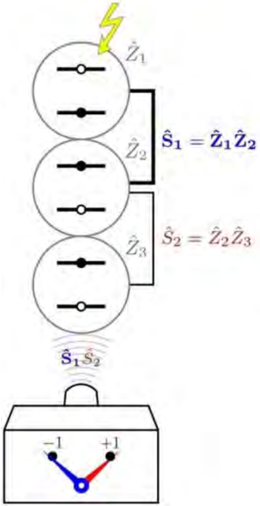

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2. Syndrome measurements:

$\hat{Z}_1\hat{Z}_2(\alpha|100\rangle + \beta|011\rangle) = -(\alpha|100\rangle + \beta|011\rangle)$ ⟹ Odd parity

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non-local ($N \geq 2$) measurements in QEC

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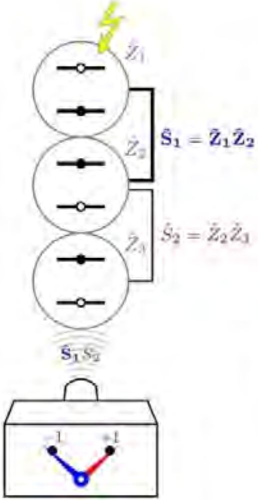

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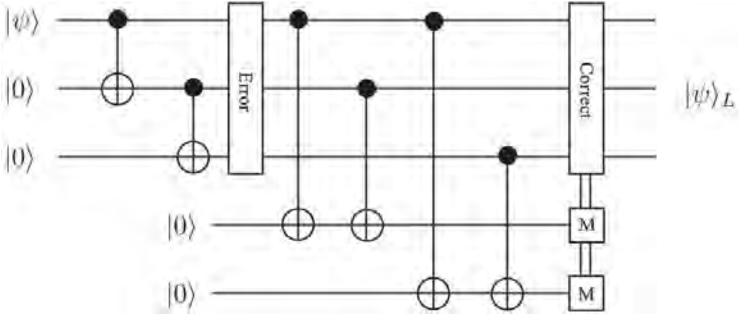
3. Correction operation (if necessary):

$\hat{X}_1(\alpha|100\rangle + \beta|011\rangle) \rightarrow \alpha|000\rangle + \beta|111\rangle$

non-local ($N \geq 2$) measurements in QEC

— example: three qubit bit flip code —



Devitt, Munroe, Nemoto: QEC for beginners, Rep. Prog. Phys. 76, 076001 (2013)

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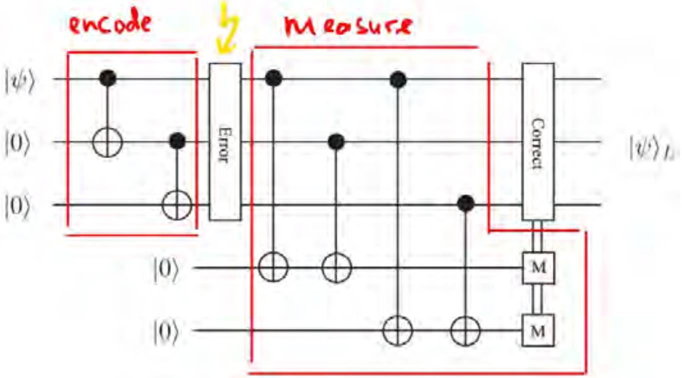

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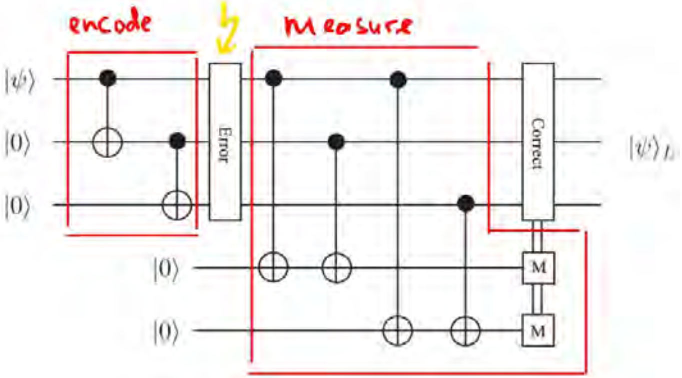

Devitt, Munroe, Nemoto: QEC for beginners, Rep. Prog. Phys. 76, 076001 (2013)

implicit assumption:
quasi-instantaneous error-correcting operations

continuous quantum error correction

Oreshkov, In: QEC, Eds. Lidar & Brun, 2013 *Paz & Zurek, Proc. R. Soc. London A 454, 355 (1998)*

unified description of errors & measurement as a GKLS master eq.

$$\frac{d\rho}{dt} = \mathscr{L}(\rho) + \kappa\,\mathscr{J}(\rho) \qquad \mathscr{J}(\rho) = \mathscr{R}(\rho) - \rho$$

$$\mathscr{L}(\rho) = -i[H,\rho] + \frac{1}{2}\sum_j \lambda_j (2L_j \rho L_j^\dagger - L_j^\dagger L_j \rho - \rho L_j^\dagger L_j)$$

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two possible approaches

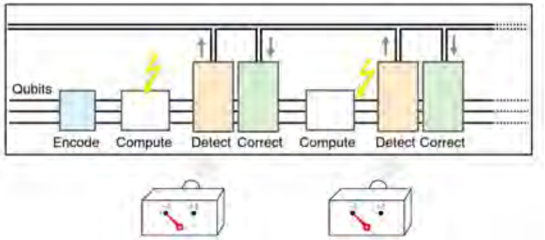
1. both measurement & correcting operations continuously
2. continuous measurement & correction conditioned on measurement outcome

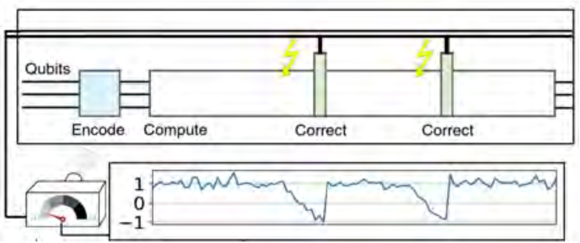
Ahn, Doherty, Landahl, PRA 65, 042301 (2002)

$\curvearrowright$ quantum feedback control (described by *stochastic* master eq.)

discrete vs continuous qu error correction

discrete vs continuous qu error correction





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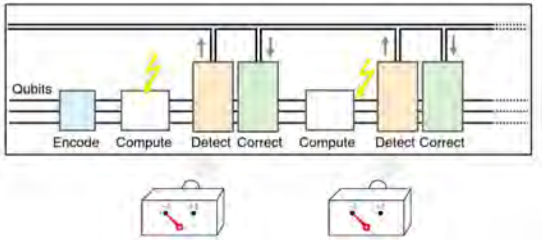
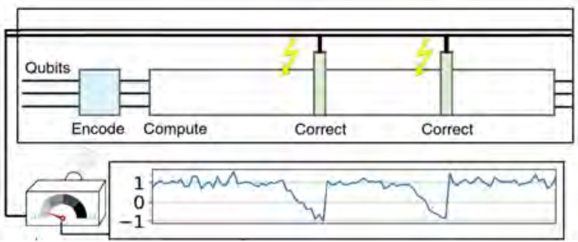
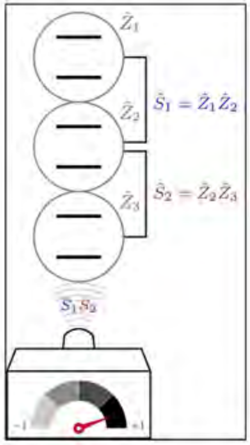




	Syndrome measurements	Measurement outcomes	Measure during computation?	Works for Quantum Annealing?
DQEC	projective	{-1,+1}	✘	✘
CQEC	continuous	[-1,+1]	✔	✔

how do we actally measure ?

— example: continuous parity measurements for superconducting qubits —



Lalumière, Gambetta, Blais, PRA 81, 040301 (2010)

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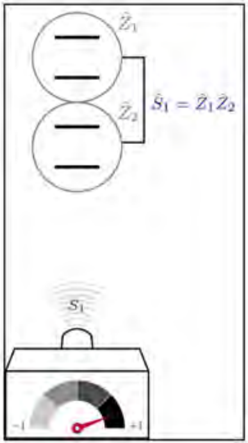

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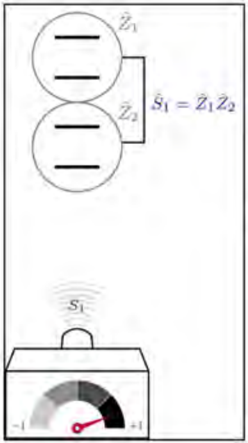

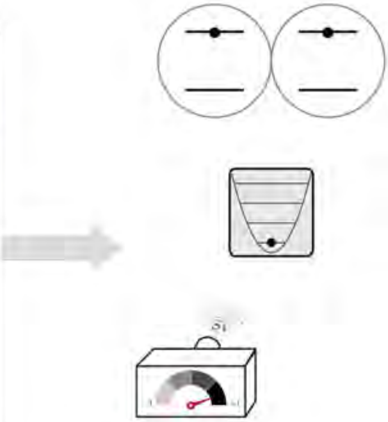

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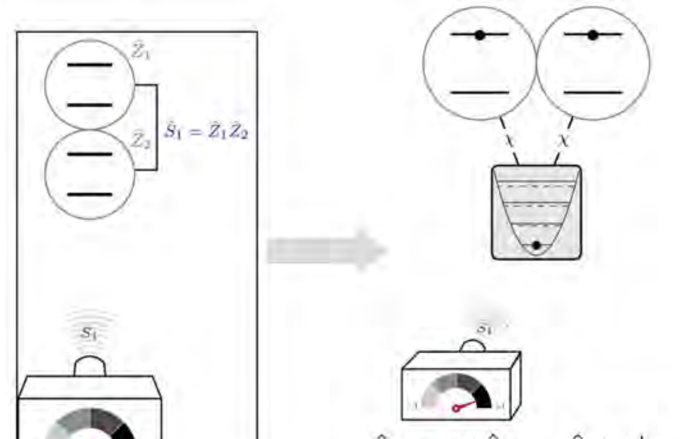

$$\hat{H} = \chi(\hat{Z}_1 + \hat{Z}_2)\hat{a}^\dagger \hat{a}$$

Lalumière, Gambetta, Blais, PRA 81, 040301 (2010)

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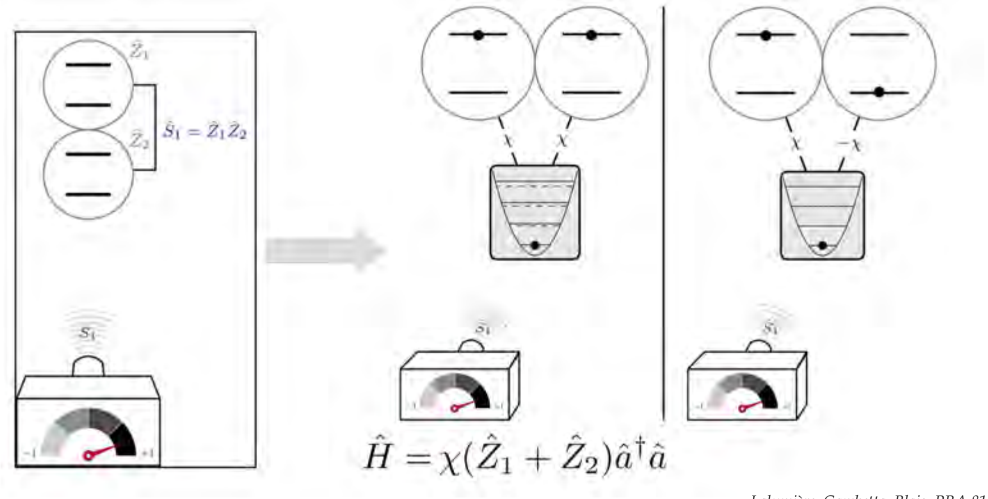

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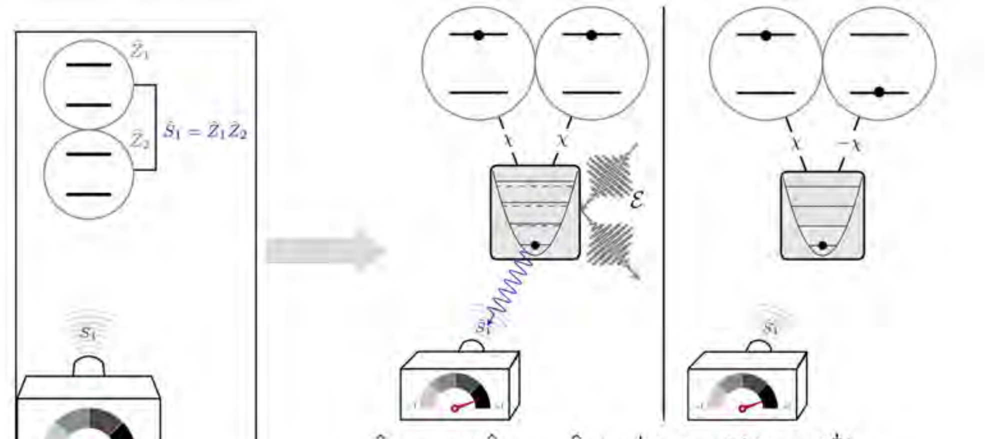

$$\hat{H} = \chi(\hat{Z}_1 + \hat{Z}_2)\hat{a}^\dagger\hat{a} + \mathcal{E}(\hat{a} + \hat{a}^\dagger)$$

Lalumière, Gambetta, Blais, PRA 81, 040301 (2010)

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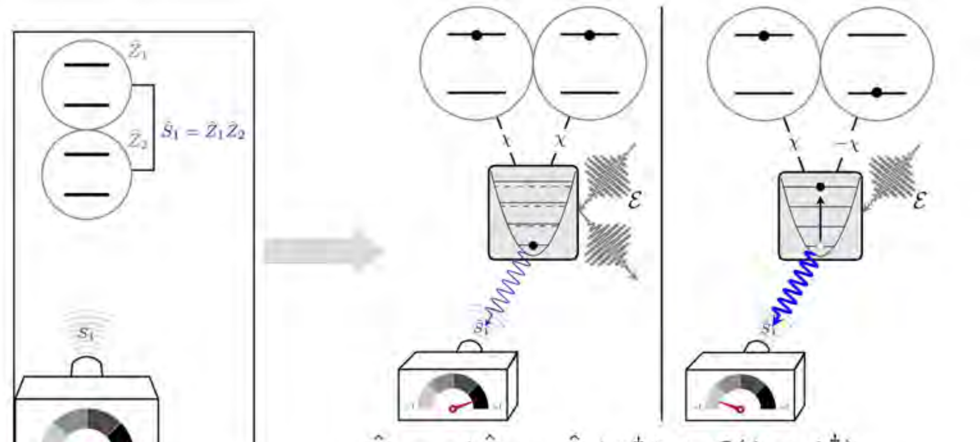

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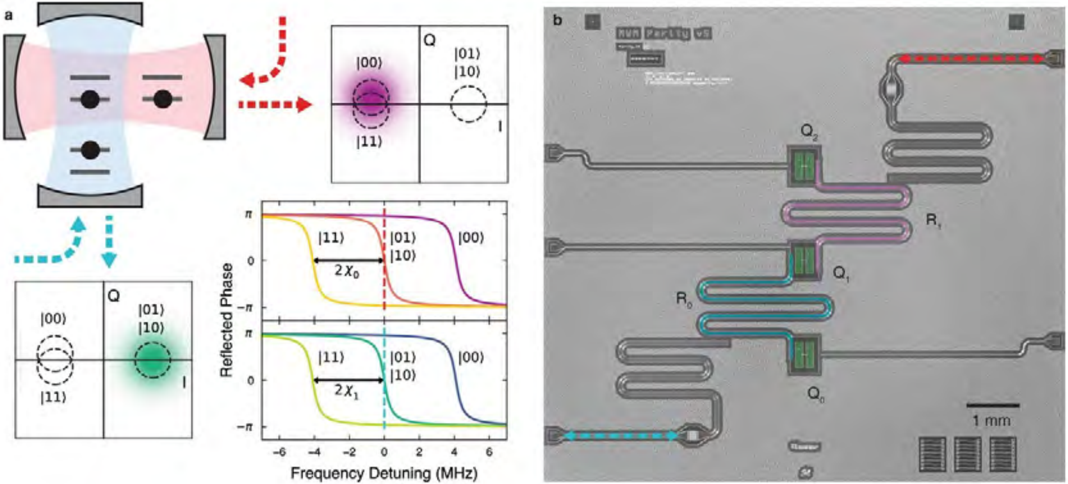
Lalumière, Gambetta, Blais, PRA 81, 040301 (2010)

continuous QEC experiment

Livingston, Blok, Flurin, Dressel, Jordan, Siddiqi, Nature Commun. 13, 2307 (2022)

From: Experimental demonstration of continuous quantum error correction



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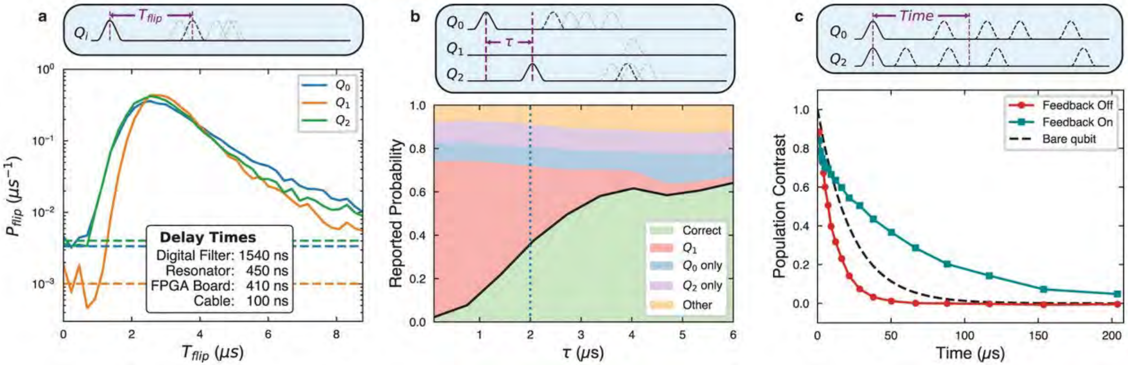

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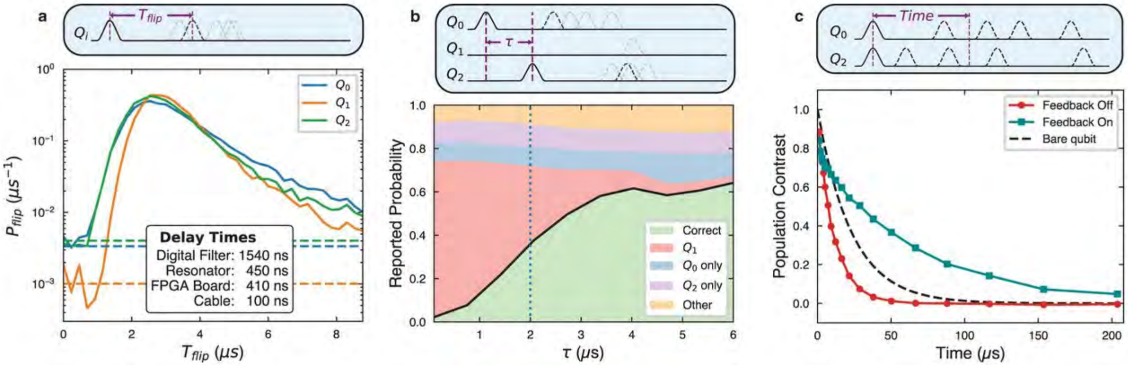
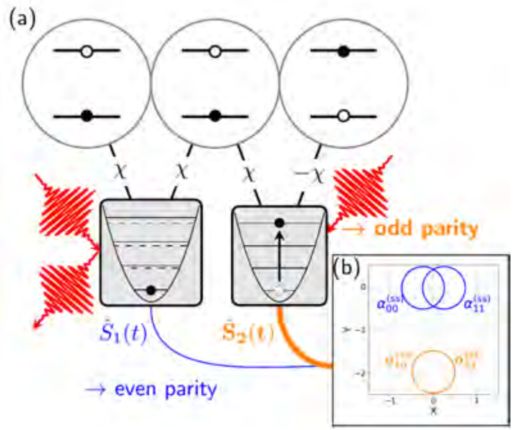


it works, but much less well than expected — why ?

odd-to-even dephasing

Halaski & Koch, arXiv:2603.02106



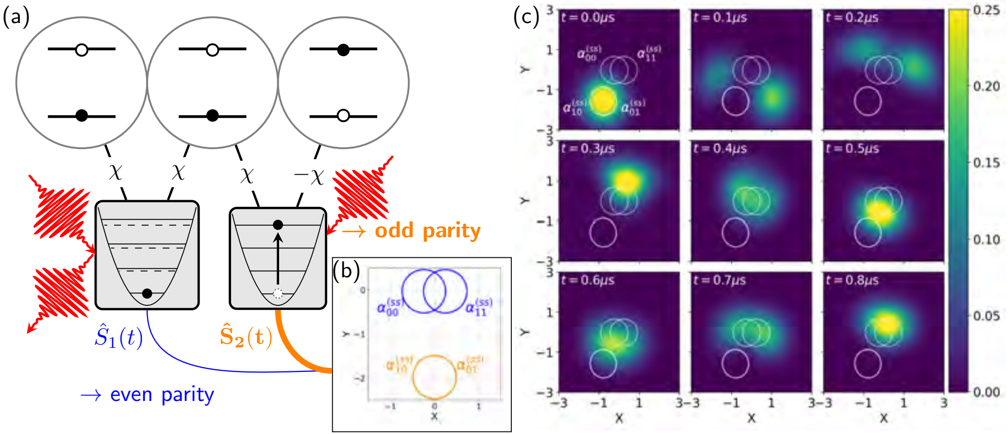
energy splitting:
interaction-induced phase

distinguishable steady-states:
information-induced phase

odd-to-even dephasing

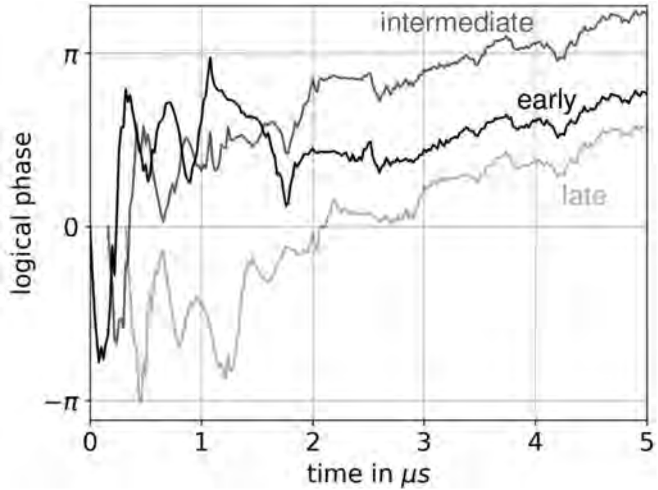
— it takes time to approach the new steady state after error occurred —

Halaski & Koch, arXiv:2603.02106



dephasing even with perfect detector

Halaski & Koch, arXiv:2603.02106



if time of bit flip known

(& detector perfect)

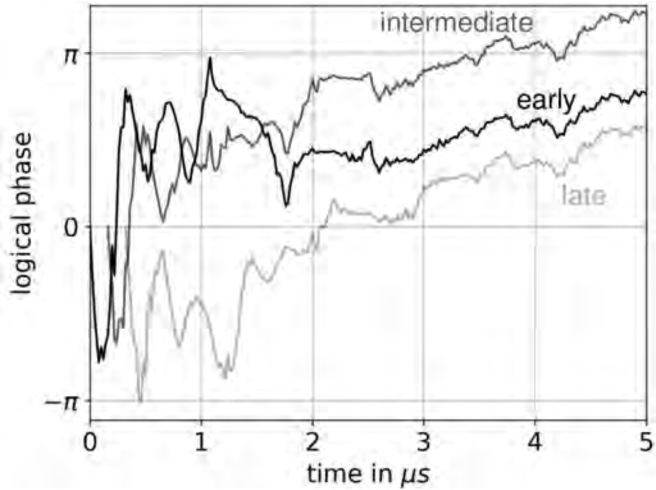
↷ undo the phase accumulated while evolving from odd-to-even steady state

but time of bit flip unknown

- mixture of trajectories
- large phase difference between trajectories

dephasing even with perfect detector

Halaski & Koch, arXiv:2603.02106



if time of bit flip known

(& detector perfect)

↷ undo the phase accumulated while evolving from odd-to-even steady state

but time of bit flip unknown

- mixture of trajectories
- large phase difference between trajectories

even-to-odd dephasing worse + subsequent errors uncorrectable

measurement-induced dephasing

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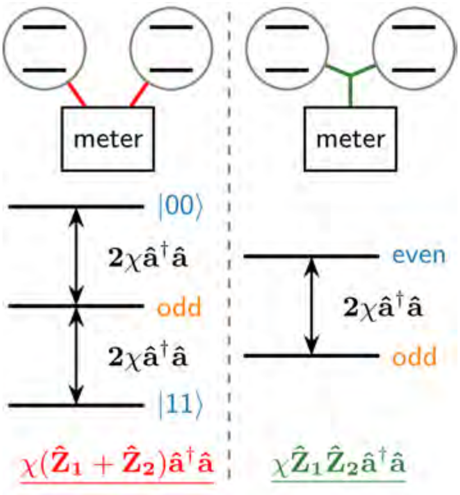

- native three-body coupling: ✓
  even/odd states indistinguishable

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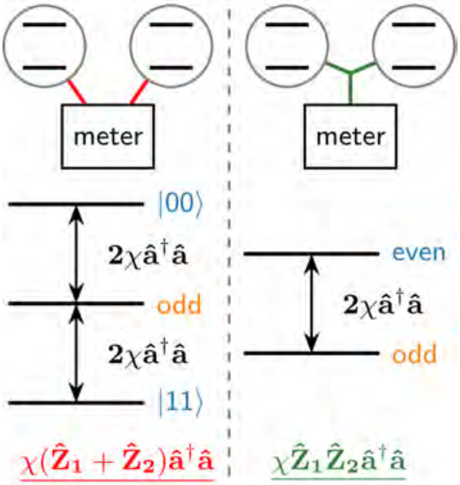

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  1. phase shift due to energy difference
  2. different effect on meter
     ↷ even states not indistinguishable

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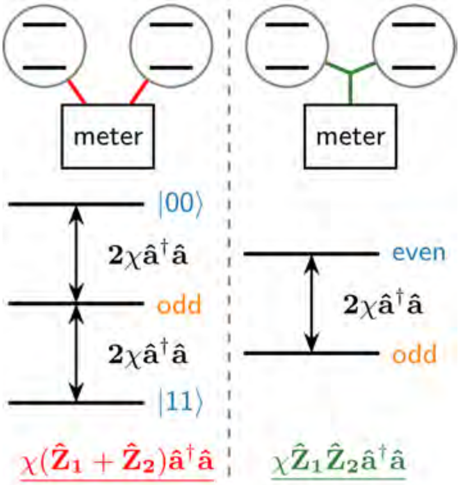

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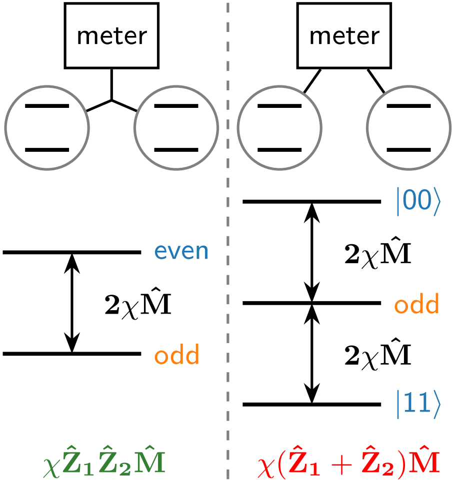
↷ **is it a general problem ??**

measurement-induced dephasing

— generalization —

Halaski & Koch, arXiv:2603.02106



- $\hat{H}_{int} = \hat{A} \otimes \hat{M}$, so far: $\hat{M} = \hat{a}^+\hat{a}$
- actual measurement: meter "decay" w/ finite time to approach steady state
- meter observable $\hat{O}$, so far $\hat{O} = \hat{Y}$ field quadrature

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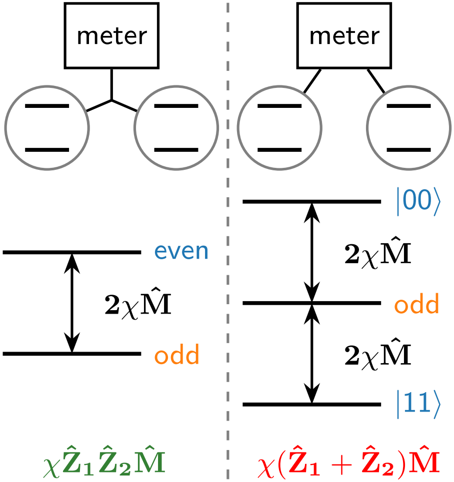

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- two cases
  1. $[\hat{\mathbf{M}}, \hat{\mathbf{H}}_M] = 0$ (so far with meter=cavity) ↷ eff meter frequency shift

     but: different shifts for even states in non-equil. dynamics ↷ dephasing

     also when coupling meter to meter-2 ...

measurement-induced dephasing

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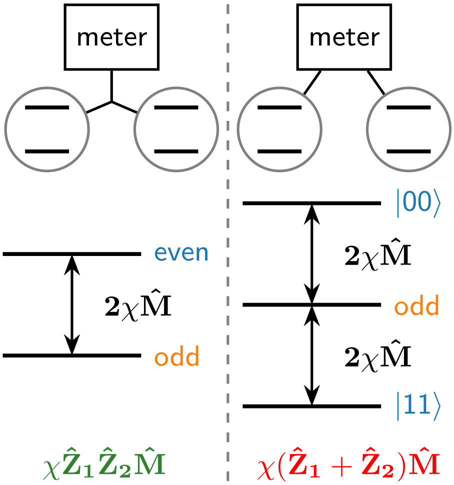

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- two cases
  2. $[\hat{\mathsf{M}}, \hat{\mathsf{H}}_M] \neq 0$ (more difficult to realize)
     e.g. $\hat{\mathsf{M}} = \hat{\mathsf{X}}_M$, $\hat{\mathsf{O}} = \hat{\mathsf{Z}}_M$
     but: meter in $|1\rangle_M$
     ↷ logical phase flips for even states
     also when coupling meter to meter-2 ...

measurement-induced dephasing

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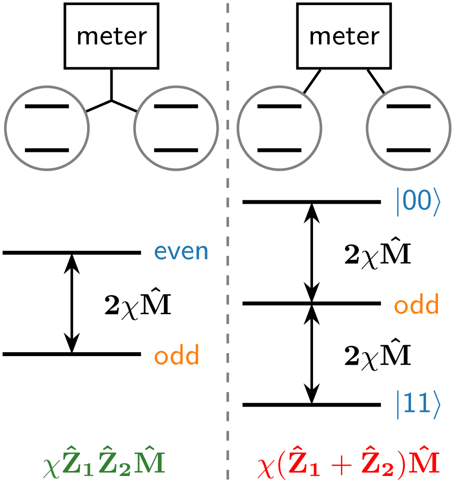

- unavoidable odd-to-even dephasing due to distinguishability of $|00\rangle, |11\rangle$ carries over to all larger codes !!

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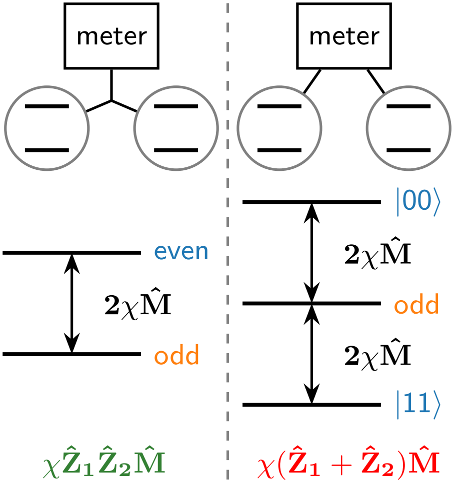

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one step back

- goal: measure $\hat{Z}_1\hat{Z}_2$

↷ we need qubit-qubit and qubit-meter couplings

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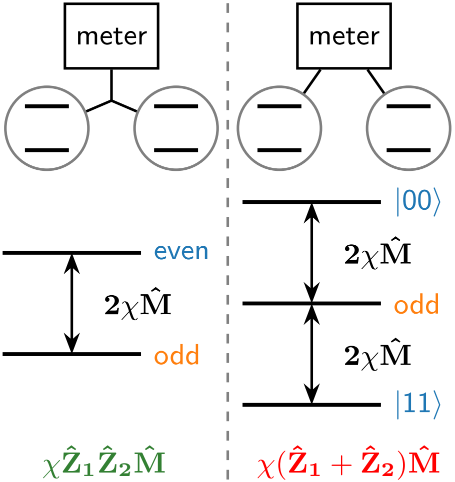

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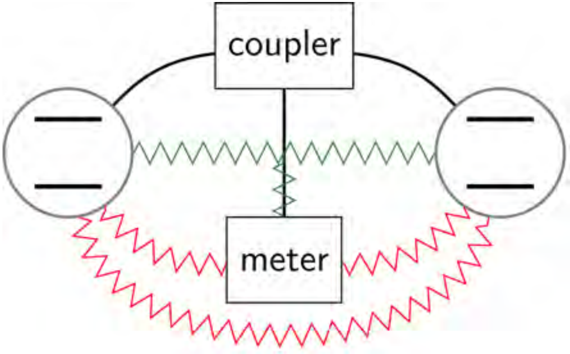
- what about engineering three-body interaction with separate coupler ?

engineering three-body interaction

— with a global tunable coupler —

Halaski & Koch, arXiv:2603.02106



when integrating out coupler:

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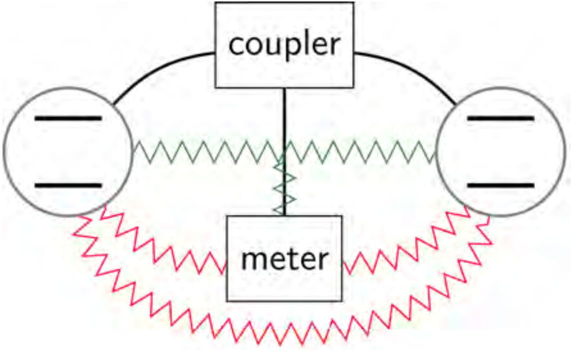
Halaski & Koch, arXiv:2603.02106



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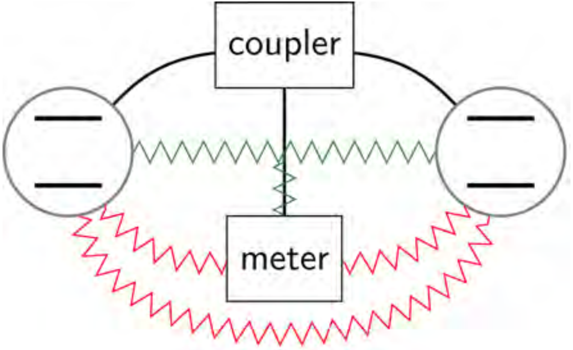

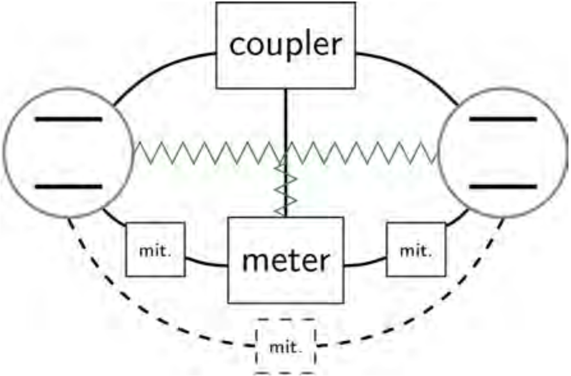

when integrating out coupler:

- eff three-body interaction
- eff two-body interactions

- at least one (tunable) mitigator per qubit needed

huge overhead

a better solution ?

— encoding inherently without measurement backaction —

Halaski & Koch, arXiv:2603.02106

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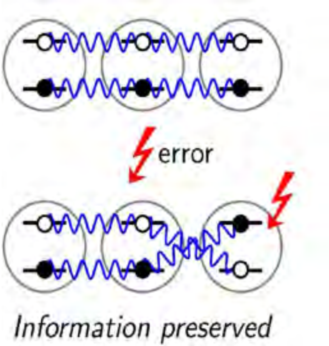

code subspace & error subspace
must be protected from measurement backaction

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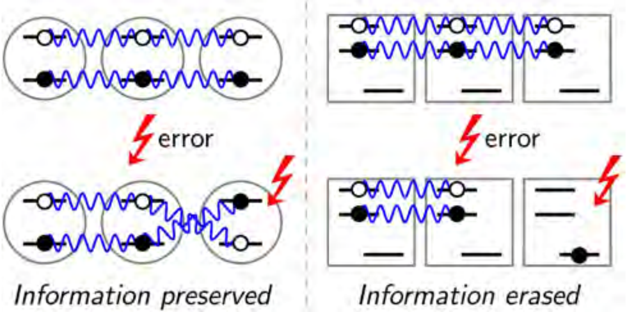
— encoding inherently without measurement backaction —

Halaski & Koch, arXiv:2603.02106

standard encoding | **erasure qubits**



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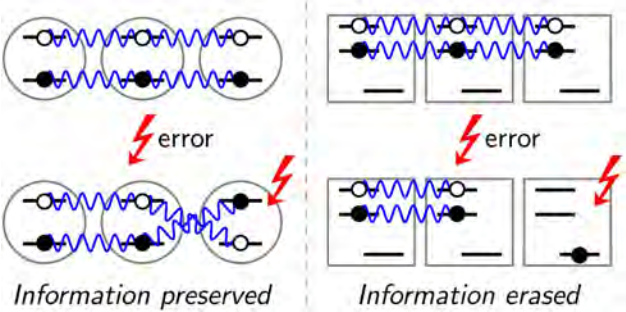

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single qubit correction op. | entangling correction operation

proper resource accounting

what can we consider "for free"? what comes with extra costs?

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1. what kind of "qubits" ?
   multi-level structure / nonlinearity
2. what kind of interactions / operations ?
   two-body vs N-body ($N > 2$) / Clifford vs magic
3. engineering dissipation / non-Hermicity
   extra degrees of freedom
4. actual clock time or space-time volume
   circuit depths, postselection

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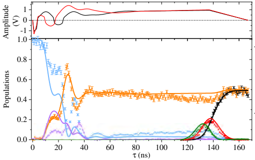
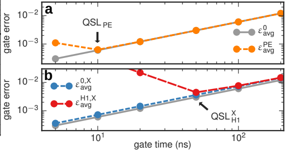
rethink optimization problem:

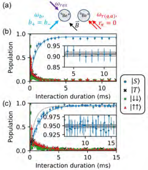
bias towards "free" physical resources & minimize extra costs

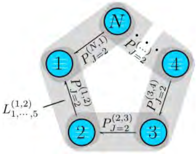
summary

- advanced state of quantum control & engineering









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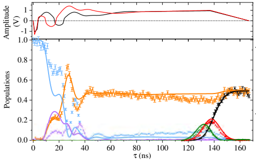

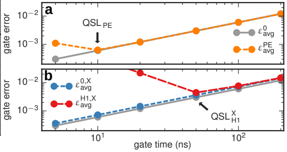

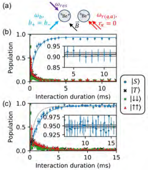

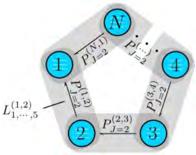

current challenge: taking this to true many-body regime

think about the resources!

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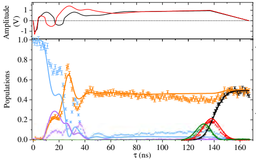

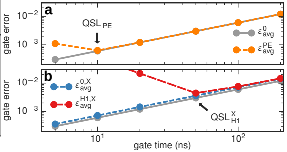

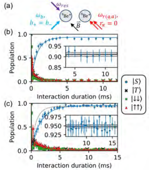

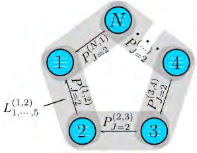

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continuous "non-local" ($N \geq 2$) measurements for QEC

- required $N+1$ interactions don't exist natively
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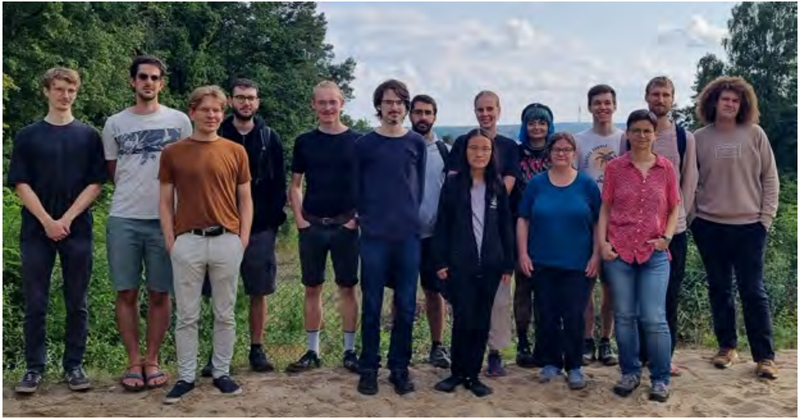
acknowledgements



George Mouloudakis
Josias Langbehn
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DFG

CRC183 ENTANGLED STATES OF MATTER

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collaborations: cavity-QED group Paris, NIST trapped ion group, B. Whaley, A. Altland & S. Trebst, Y. Gefen, I. Gornyi, G. Morigi, K. Snizhko

summary

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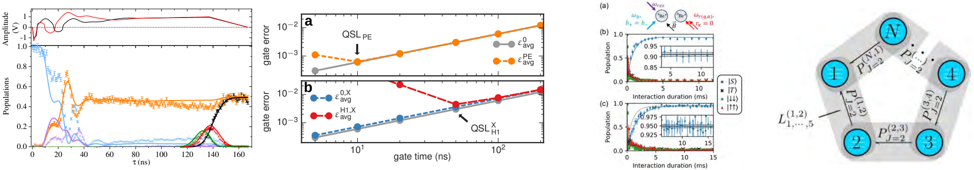

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