Quantum Error Correction by Dissipation

F. Reiter, A. Sørensen, P. Zoller, and C. Muschik

UNIVERSITY OF WATERLOO

IQC Institute for Quantum Computing

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Exploring Open Quantum Systems in Quantum Simulators

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Scientific Advisors: Tilman Esslinger, Christian Roos, Irfan Siddiqi, and Christine Silberhorn

Quantum Optics Theory

UNIVERSITY OF WATERLOO

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Quantum Interactions

Postdoc position available

Quantum Optics Theory

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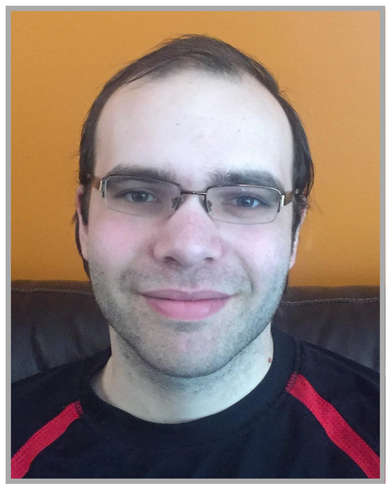
Postdoc position available



Ryan Ferguson

Danny Paulson

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Dr. Jinglei Zhang

Dr. Yasar Atas

Dr. Christine Muschik

Quantum Optics Theory

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How can we we use quantum systems to achieve a **quantum advantage?**

How can this be done **in practice?**

Quantum Optics Theory

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Quantum Networks

Quantum Simulations

Quantum Optics Theory

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Quantum Networks

Quantum Simulations

Entanglement distribution

New design concepts for 2D quantum networks

Robust quantum repeater architectures

- Quest: faithfully transfer quantum states
- Vision: ‘quantum internet’

Entanglement distribution

New design concepts for 2D quantum networks

Robust quantum repeater architectures

➡ Quest: faithfully transfer quantum states
➡ Vision: ‘quantum internet’

Self-stabilizing quantum systems

Autonomous quantum error correction

Nat. Commun. 8, 1822 (2017).

Entanglement distribution

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Self-stabilizing quantum systems

Autonomous quantum error correction

Nat. Commun. 8, 1822 (2017).

- Quest: keep a qubit alive
- Vision: self-correcting quantum technology

Quantum Optics Theory

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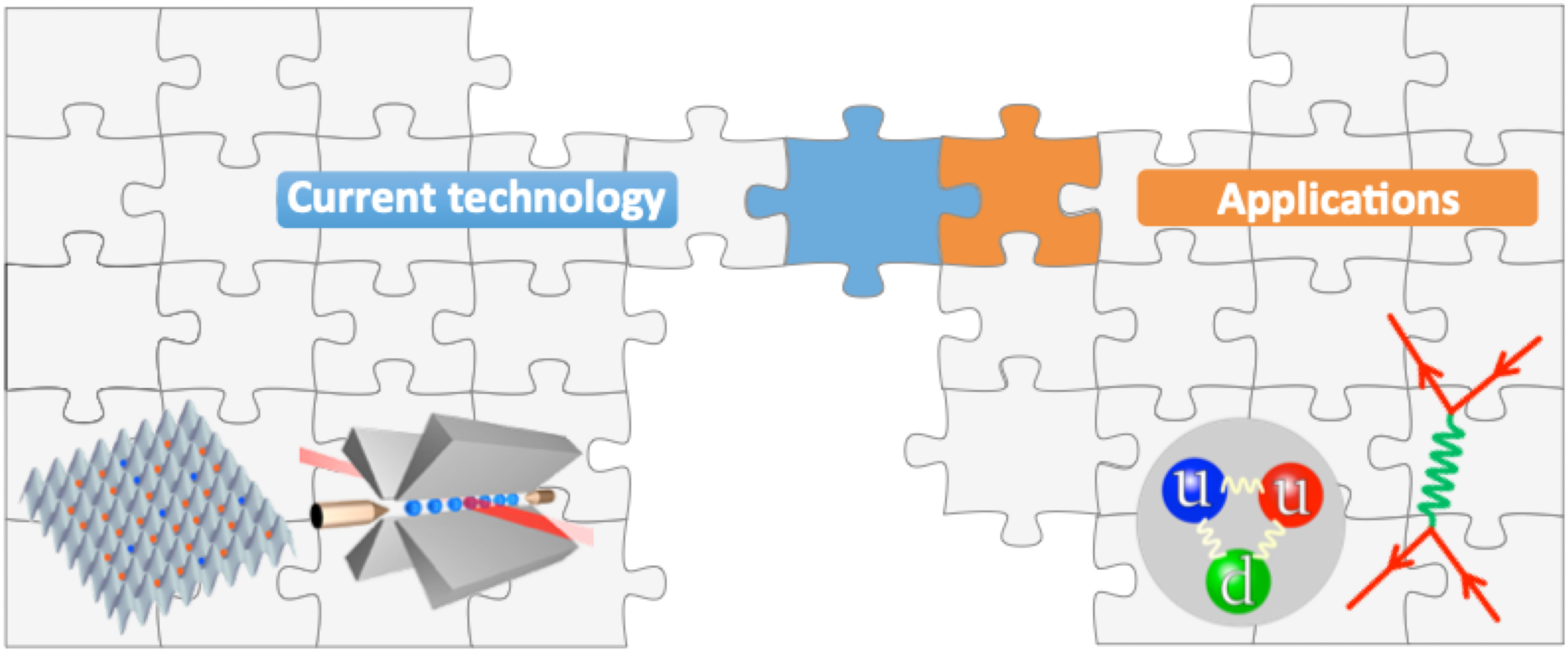
Quantum Networks

Quantum Simulations

Quantum technologies **High energy physics**



Nature 534, 516 (2016).

Nature (in press), arXiv:1810.03421.

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Autonomous quantum error correction

Nat. Commun. 8, 1822 (2017).

- Quest: keep a qubit alive
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Autonomous quantum error correction with application to quantum metrology

F. Reiter, A. Sørensen, P. Zoller, and C. Muschik

See also:
Work by David Schuster: PRL 119, 150502 (2017).
Work by Martin Plenio: PRL 119, 010801 (2017).
Work by John Preskill and Liang Jiang: Nature Commun. 9, 78 (2018).

Quantum error correction

Quantum computing

Fault-tolerant quantum gates

Quantum annealing
[F. Pastawski and J. Preskill, PRA 93, 052325 (2016).]

Quantum communication

Entanglement distribution
in 2D quantum networks

Encoded quantum repeaters

Quantum simulations

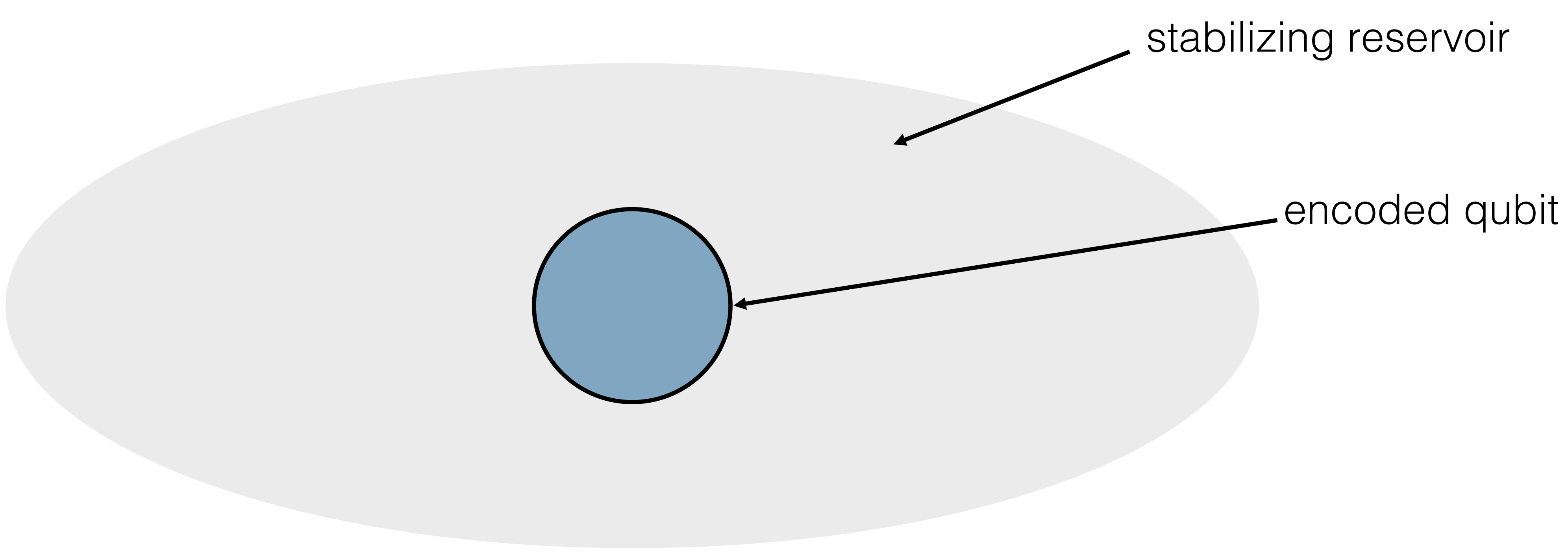
Digital quantum simulations

Black hole physics in quantum error correcting codes

➡➡➡ Explore new strategies for quantum error correction

Autonomous error correction by reservoir engineering

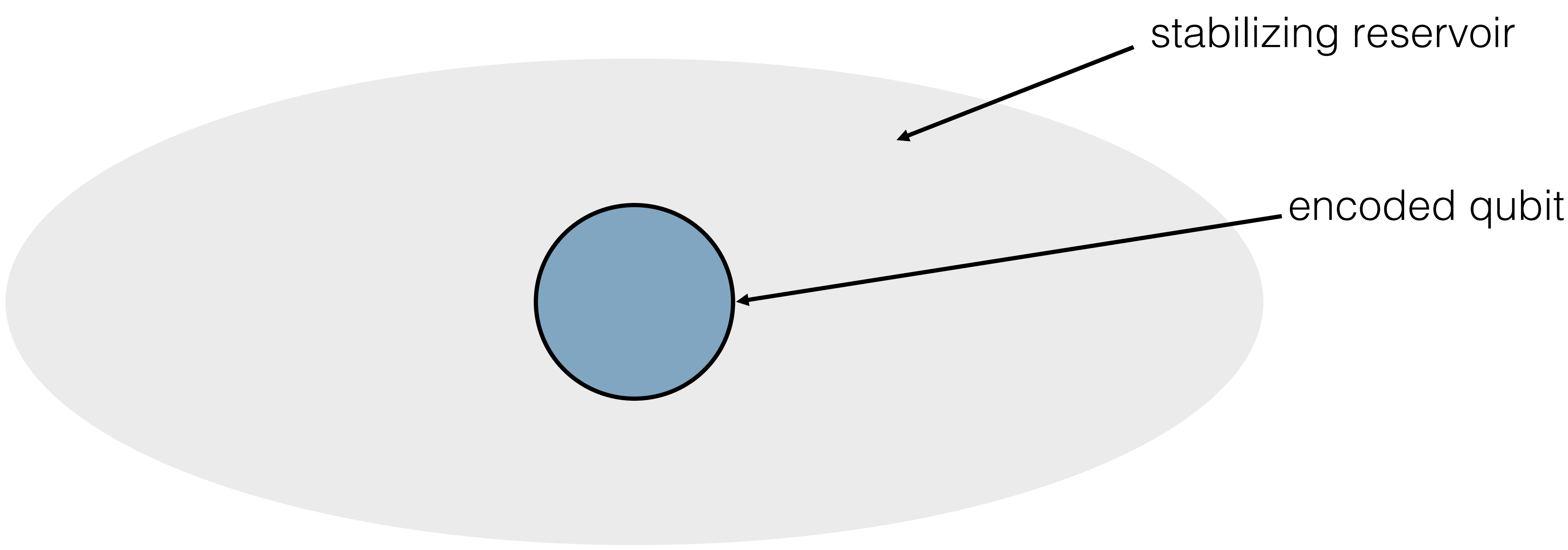
Vision:
Keep a qubit alive by coupling it to an engineered reservoir that stabilises it and coherently corrects errors if they occur



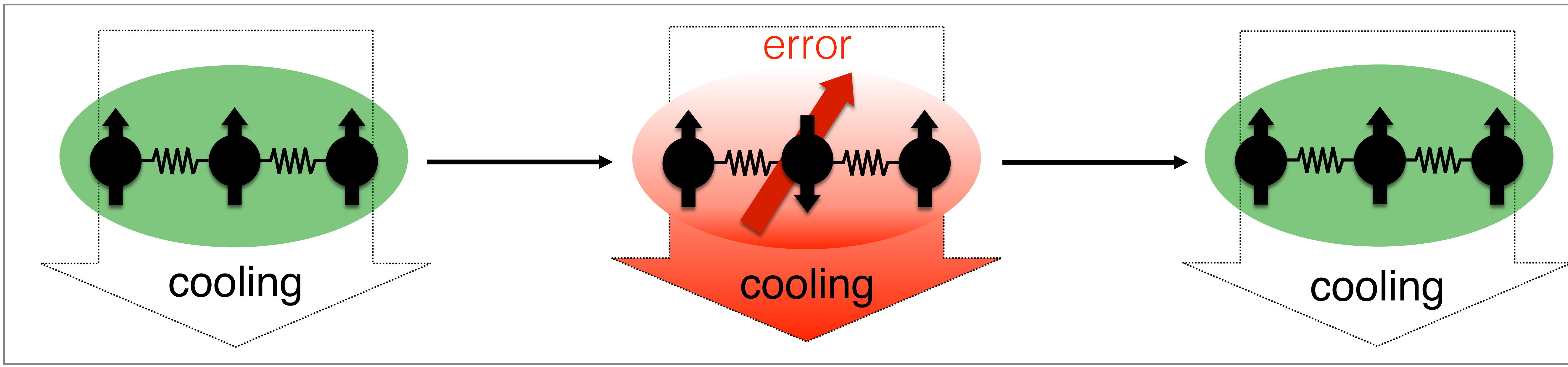
Autonomous error correction by reservoir engineering

Vision:
Keep a qubit alive by coupling it to an engineered reservoir that stabilises it and coherently corrects errors if they occur

Here:
Platform: trapped ions
Qubit: encoded in electronic degrees of freedom
Reservoir:motional modes of the ions
3-qubit code: protection against spin flips (or phase flips).



Autonomous error correction by reservoir engineering

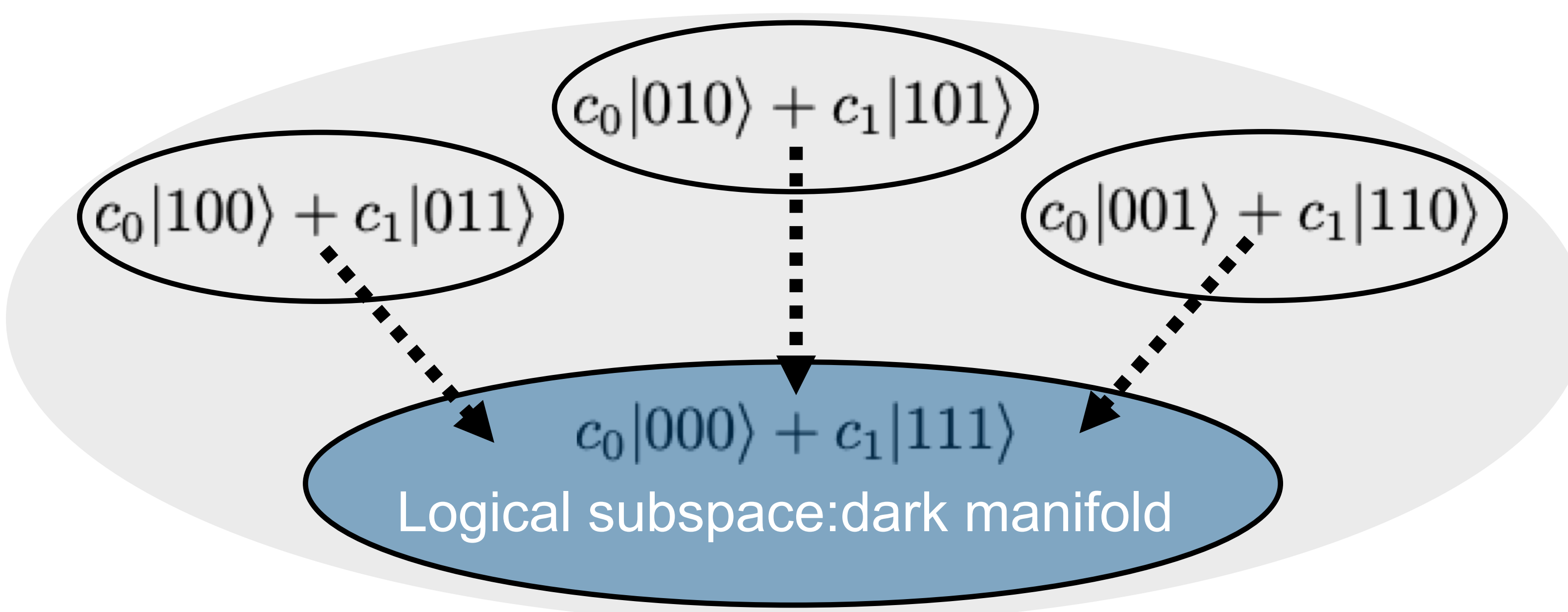


Autonomous error correction by reservoir engineering

Vision:
Keep a qubit alive by coupling it to an engineered reservoir that stabilises it and coherently corrects errors if they occur

Here:

- Uses only always-on couplings
- Runs continuously in time
- Operates in a fully autonomous fashion based on built-in feedback mechanism



Autonomous error correction by reservoir engineering

Vision:
Keep a qubit alive by coupling it to an engineered reservoir that stabilises it and coherently corrects errors if they occur

Our application: Improve high-precision sensing
Quantum error correction —> improved effective coherence times —> improved sensitivity

➡ Towards self-stabilising quantum information processing

Overview

1. Motivation
2. Error correction scheme
3. Application to sensing
4. Conclusions

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Motivation

Textbook approach to quantum error correction:

- Encode logical qubit in several physical qubits
- Map error syndromes to ancilla qubits
- Read-out the error syndrome through measurements on the ancillas
- Perform feedback operations on the encoded qubit

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Three-qubit code:

$$|0\rangle_L \equiv |000\rangle$$

$$|1\rangle_L \equiv |111\rangle$$

$$|\Psi\rangle = c_0|000\rangle + c_1|111\rangle$$

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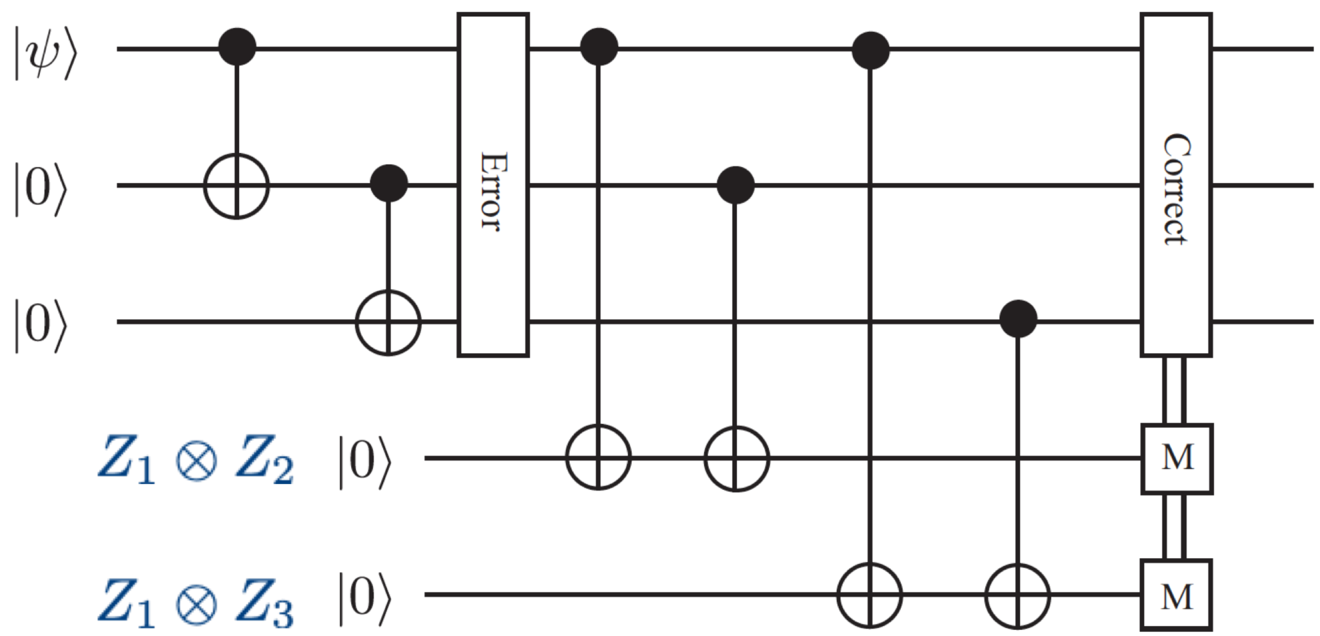
Gate-based implementation:



Example: spin flip on the first qubit:

$$|\Psi'\rangle = c_0|100\rangle + c_1|011\rangle$$

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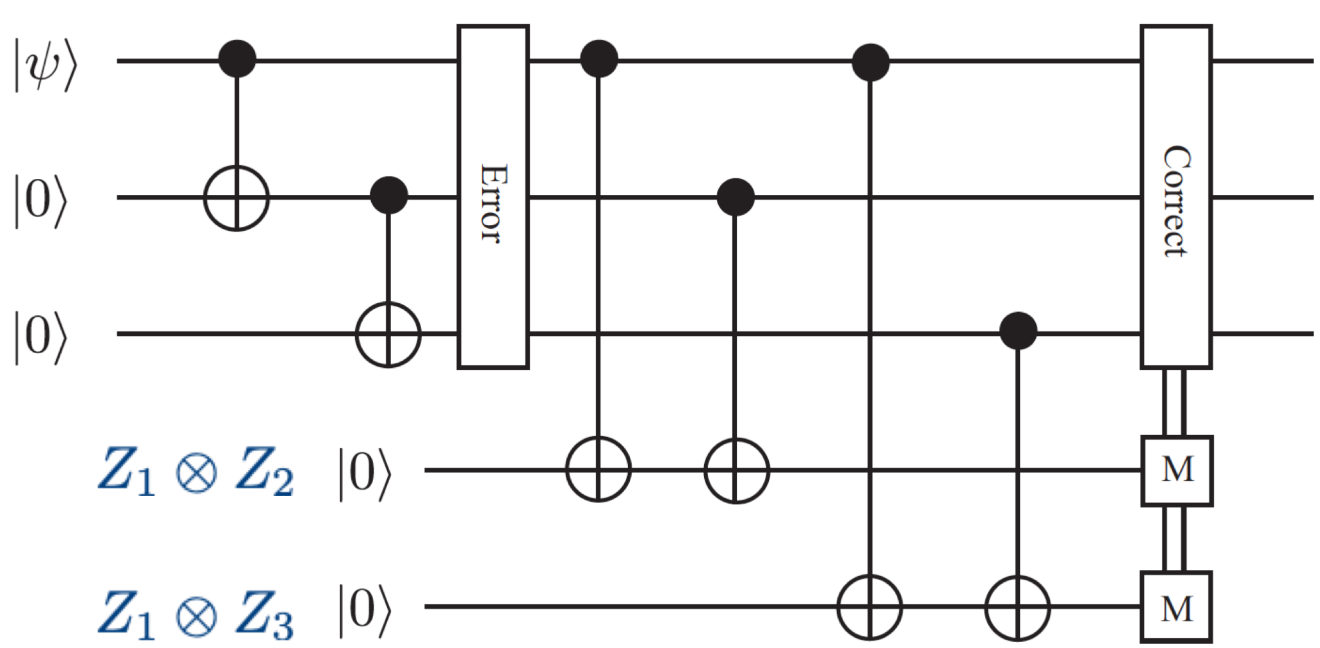

Example: spin flip on the first qubit:

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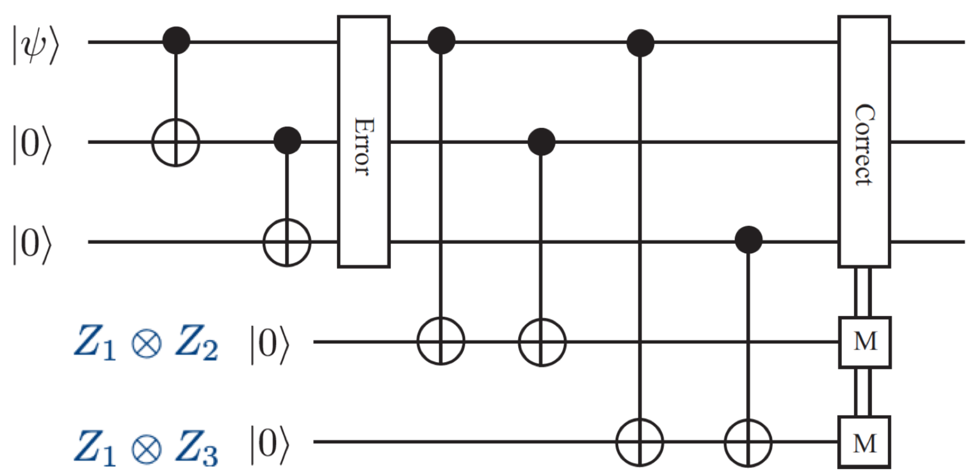
Majority vote + correction

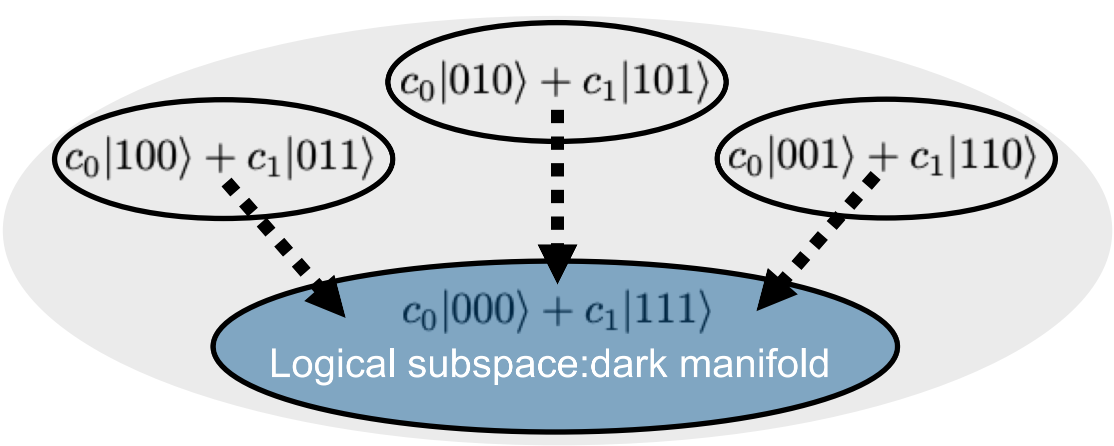
$$|\Psi\rangle = c_0|000\rangle + c_1|111\rangle$$

Motivation

Gate-based implementation of the three-qubit code



Error correction by reservoir engineering



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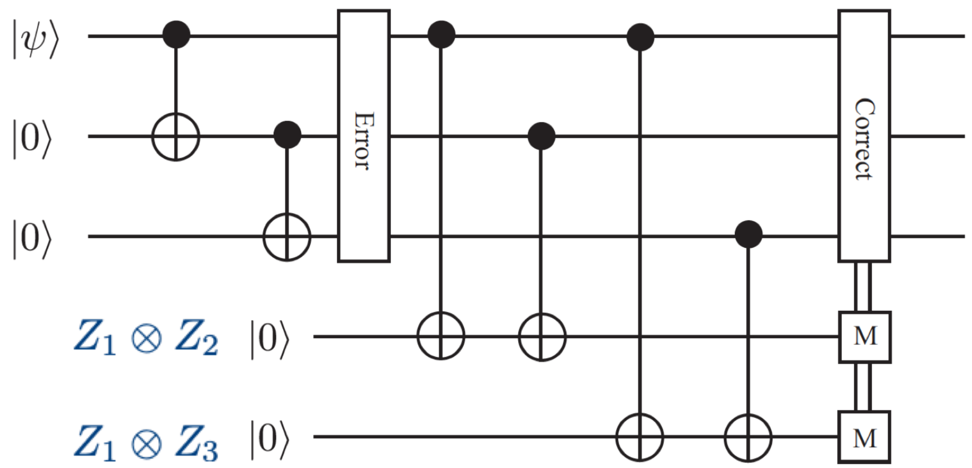

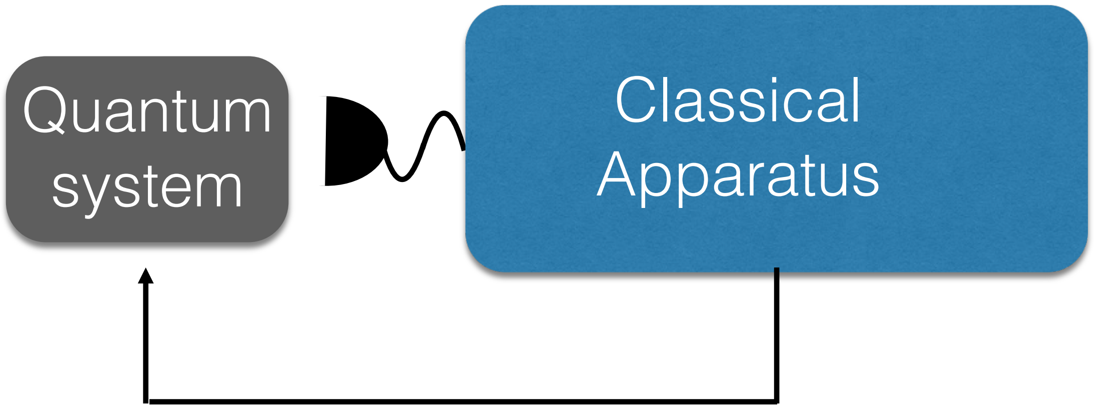

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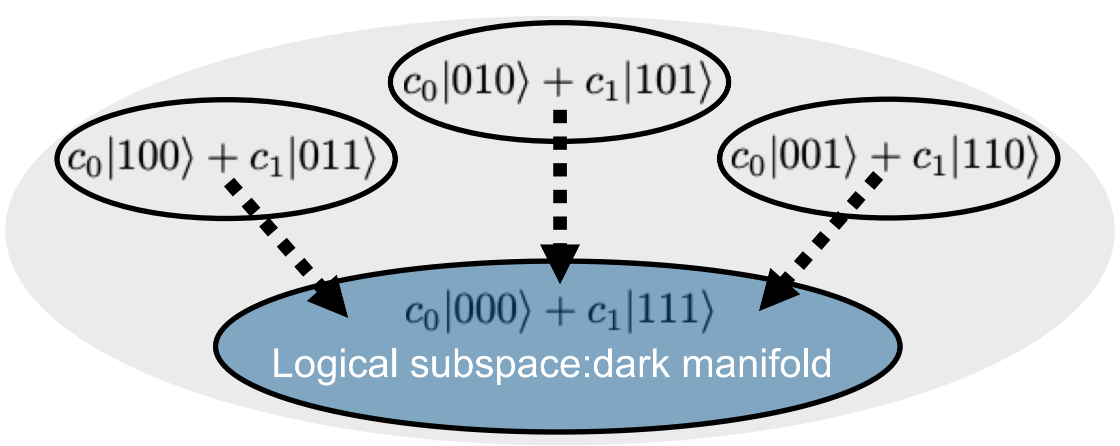
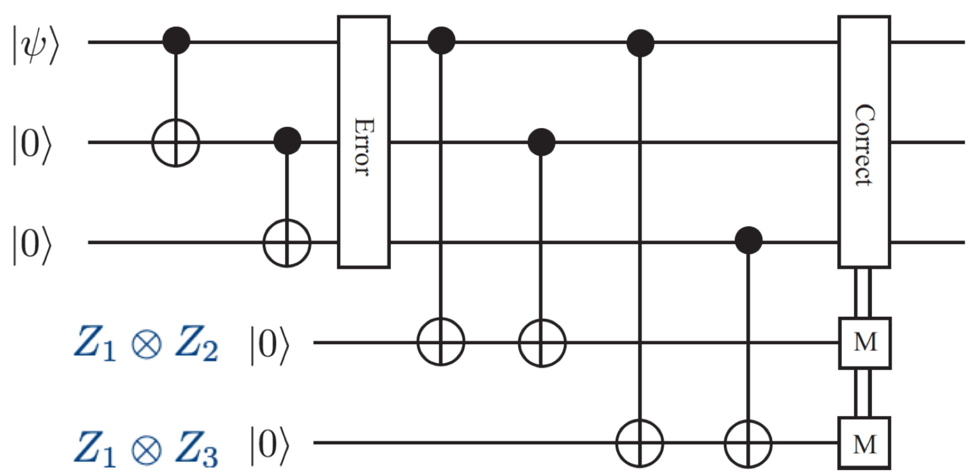


- Measurement-free error correction
  Error correction takes places entirely at the microscopic level

Motivation

Gate-based implementation of the three-qubit code



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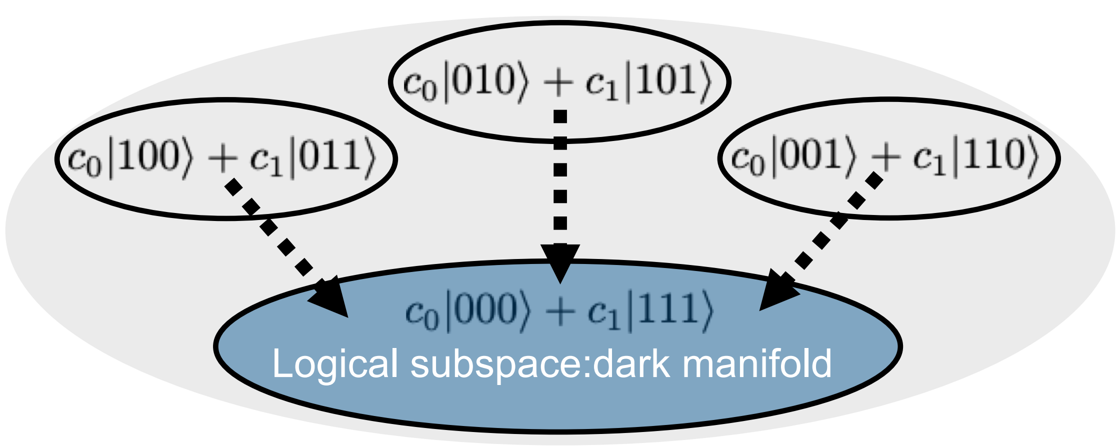

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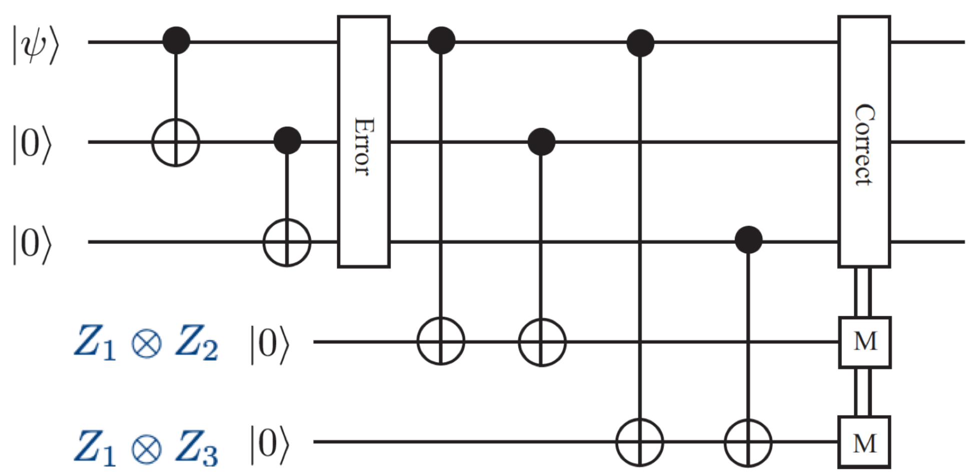

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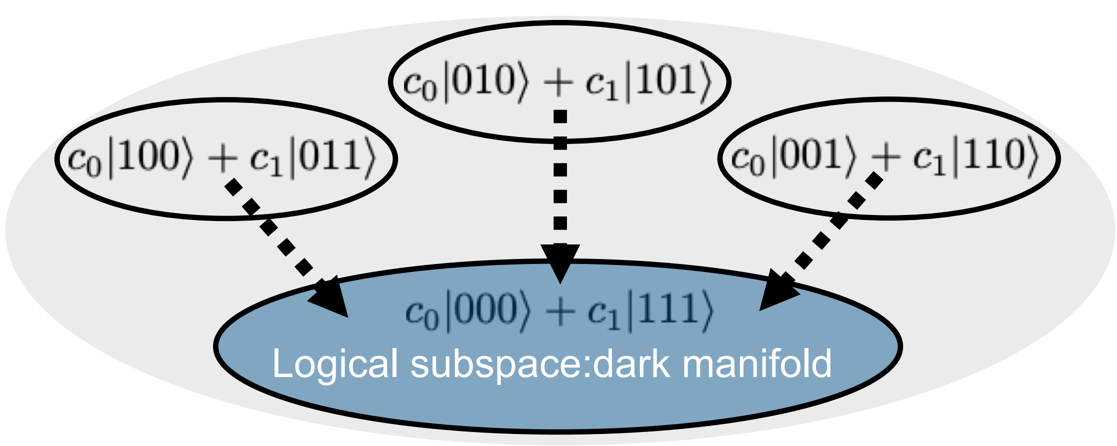

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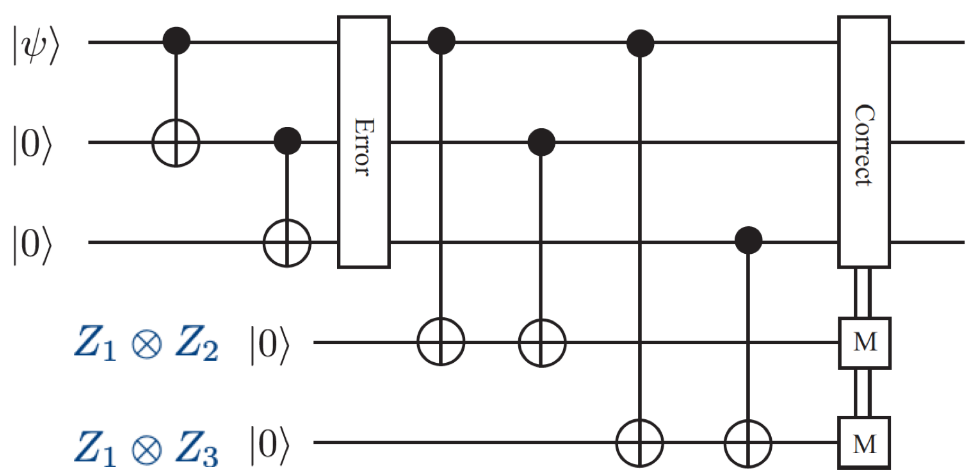

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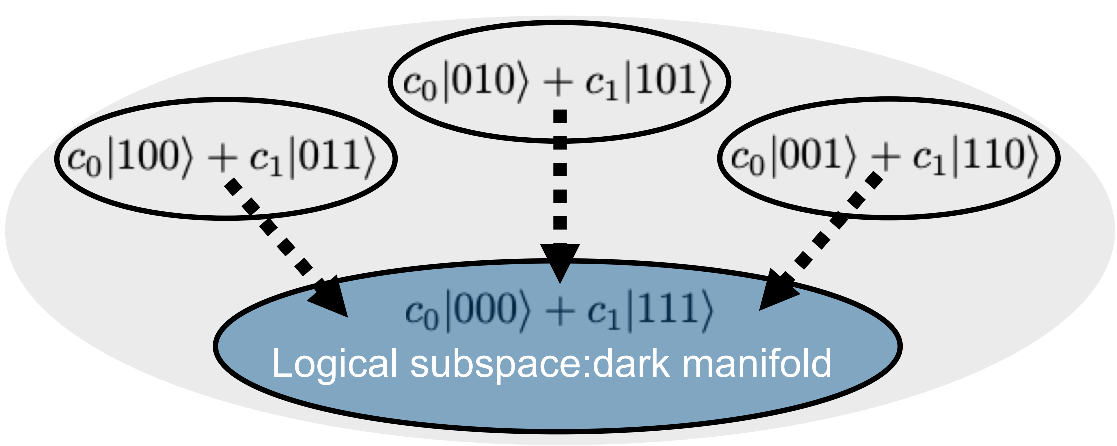

- Measurement-free error correction
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New paradigm: self-correcting quantum systems
Couple a quantum system to a quantum reservoir that automatically corrects for errors

Motivation

Taking dissipative methods to a new stage

Harnessing dissipative processes for quantum information processing —> allows for features different from established schemes.

S. Diehl, et al. Nature Phys. 4, 878 (2008).
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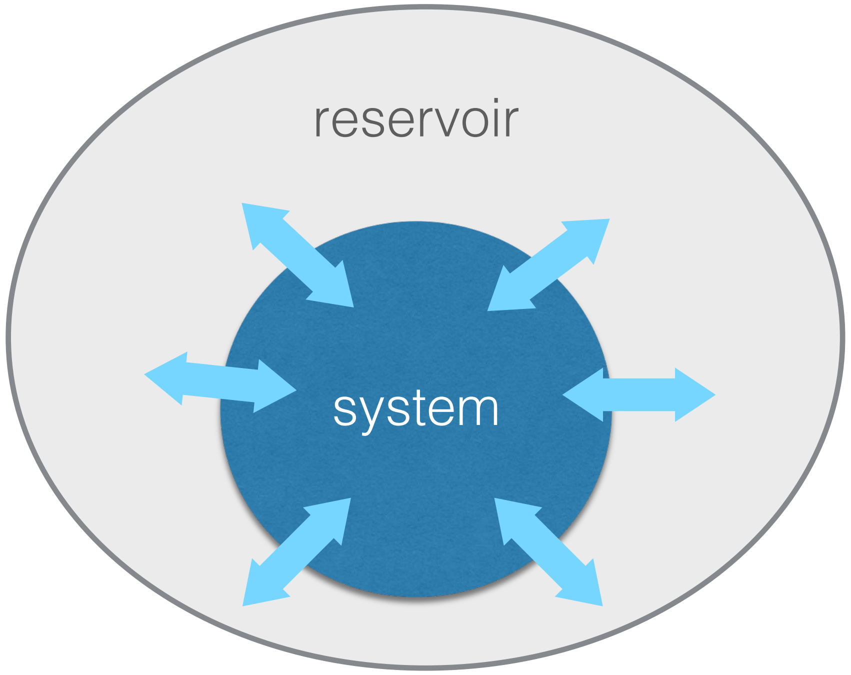

So far: dissipative state preparation

—> Entanglement by dissipation

PRL 107, 080503 (2011), Nature 470, 486 (2011), Nature 504, 415 (2013), Nature 504, 419 (2013), Science 347, 52 (2015), arXiv:1902.06946

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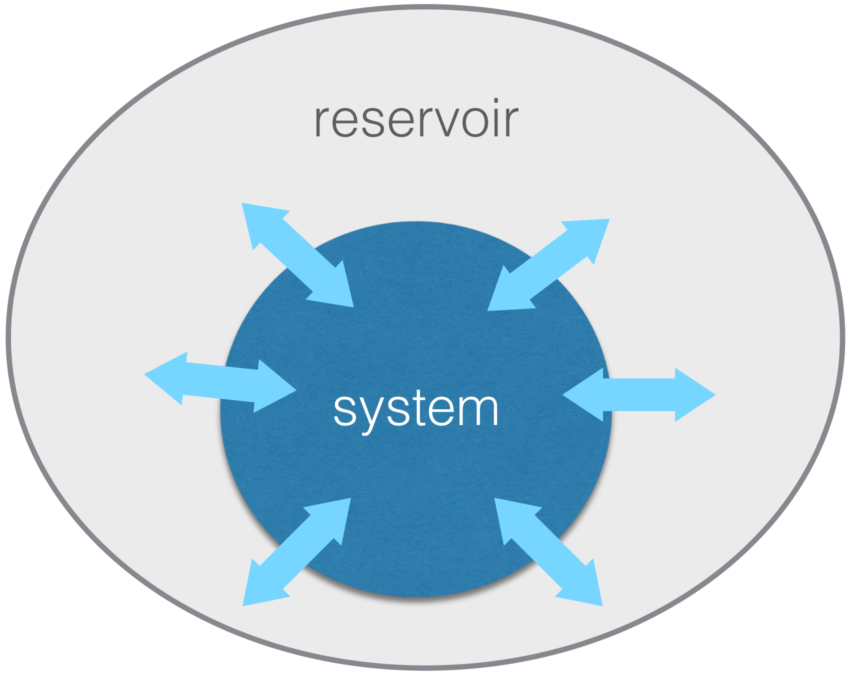

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—> Extend the life-time of entangled resource states by several orders of magnitude.

Experiment:

H. Krauter, C. Muschik, K. Jensen, W. Wasilewski, J. Petersen, I. Cirac, E. Polzik, PRL 107, 080503 (2011).

Theory:

C. Muschik, E. Polzik, I. Cirac, PRA 83, 052312 (2011).

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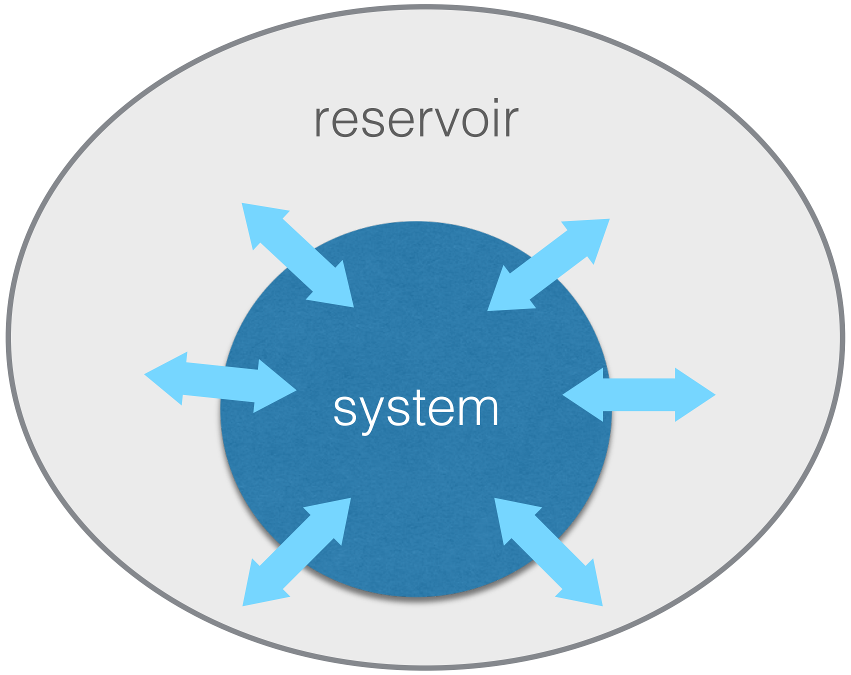

$$|\Psi\rangle = c_0|000\rangle + c_1|111\rangle$$

Next step:
Dissipative processing of an unknown quantum state: preserve coherences i.e. stabilize a whole manifold (not a single state)

Phys. Rev. A 83, 012304 (2011), Phys. Rev. X 4, 041039 (2014) 111, 120501 (2013), PRA 91,062324 (2015), PRL 116, 150501 (2016), PRA 90, 062344 (2014),arXiv:1603.05005 (2016), Science 347, 853 (2015).

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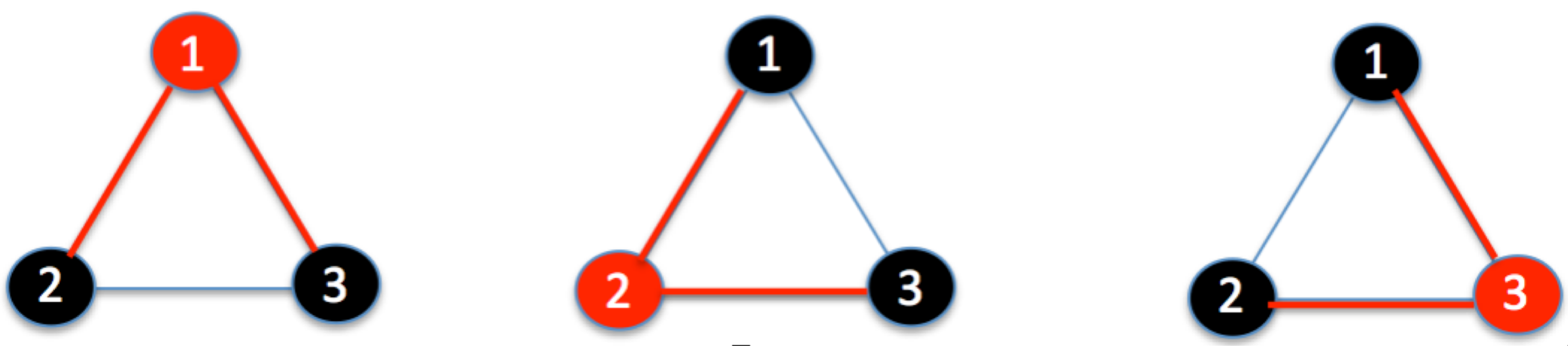
Error correction scheme

Master equation:

$$\mathcal{L}(\rho) = \sum_k \mathcal{D}[L_k](\rho)$$
$$= \sum_k L_k^\dagger \rho L_k - \frac{1}{2}\left(L_k^\dagger L_k \rho + \rho L_k^\dagger L_k\right)$$

Error correction scheme

3 qubit code: $|\Psi\rangle = c_0|000\rangle + c_1|111\rangle$



$|\Psi_1'\rangle = c_0|100\rangle + c_1|011\rangle$ $|\Psi_2'\rangle = c_0|010\rangle + c_1|101\rangle$ $|\Psi_3'\rangle = c_0|001\rangle + c_1|110\rangle$

Error correction scheme

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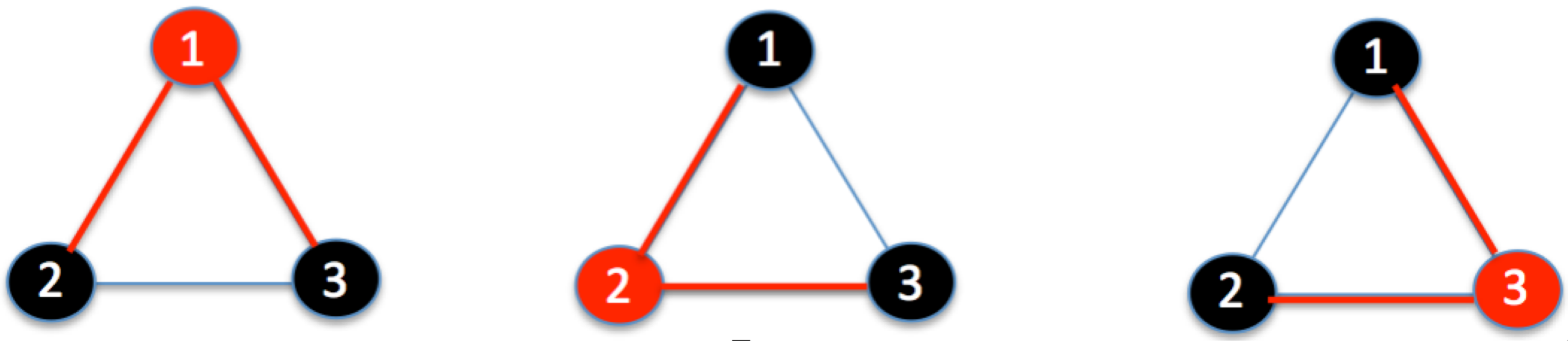

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Conditional Lindblad operators:

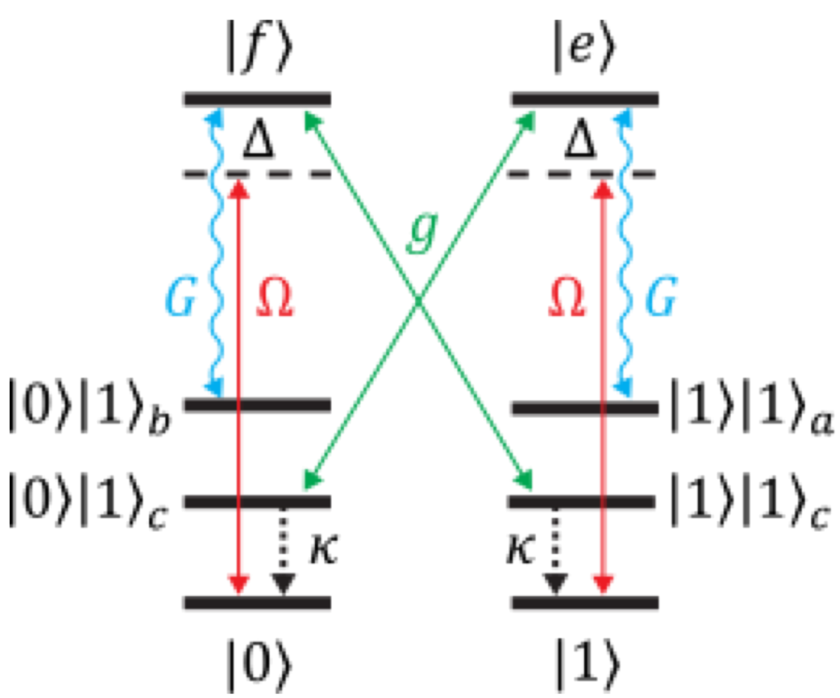
$$L_{\mathrm{corr}}^{X_1} = \sqrt{\Gamma_{\mathrm{corr}}} X_1 \frac{\mathbb{1} - Z_1 Z_3}{2} \frac{\mathbb{1} - Z_1 Z_2}{2}$$

$$L_{\mathrm{corr}}^{X_2} = \sqrt{\Gamma_{\mathrm{corr}}} X_2 \frac{\mathbb{1} - Z_2 Z_1}{2} \frac{\mathbb{1} - Z_2 Z_3}{2}$$

$$L_{\mathrm{corr}}^{X_3} = \sqrt{\Gamma_{\mathrm{corr}}} X_3 \frac{\mathbb{1} - Z_3 Z_2}{2} \frac{\mathbb{1} - Z_3 Z_1}{2}$$

Error correction scheme

Level scheme:



Interactions:

$$H_{\text{drive}} = \frac{\Omega}{2}\sum_{j=1}^{N}\left(|e\rangle_j\langle 1| + |f\rangle_j\langle 0|\right) + H.c.$$

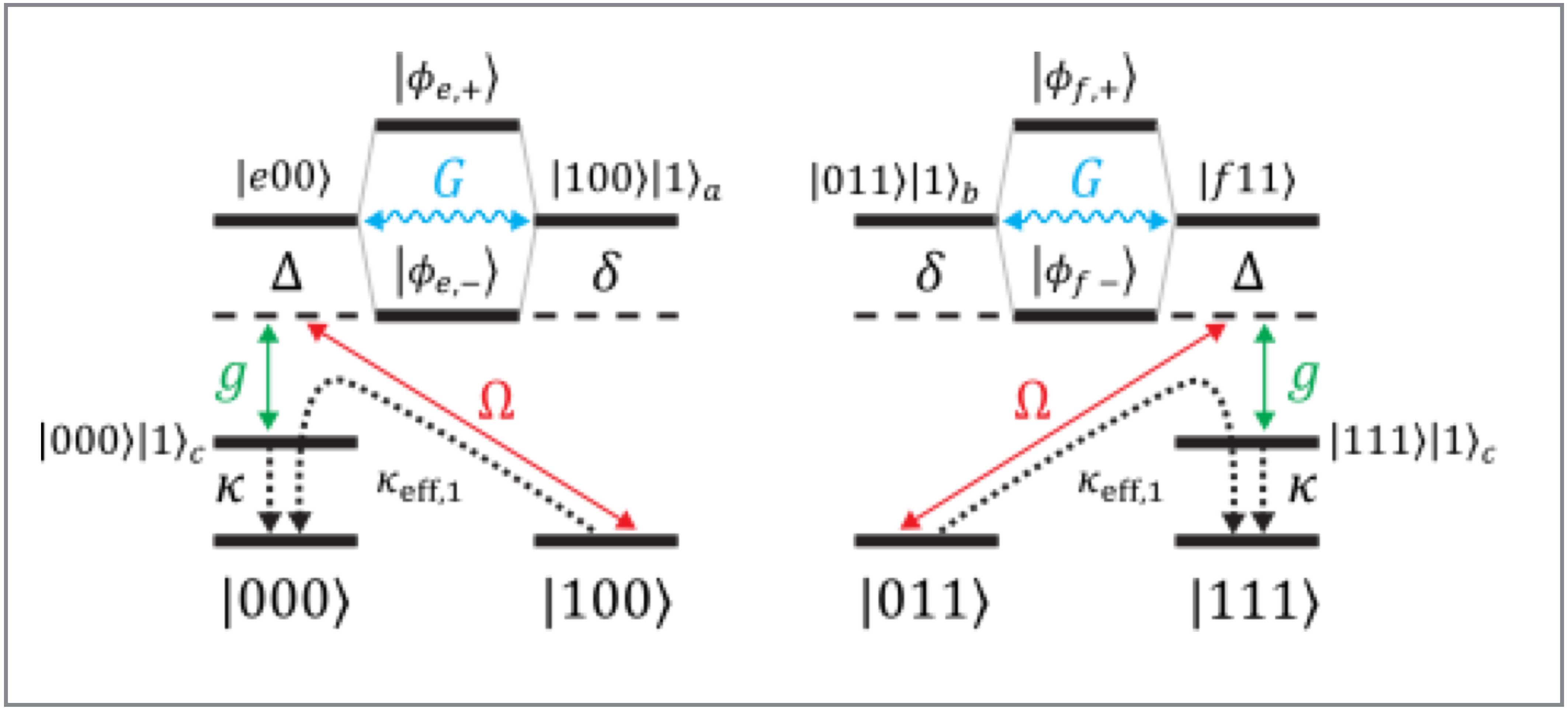
$$H_{\text{osc}} = G\left(a^\dagger|1\rangle\langle e| + b^\dagger|0\rangle\langle f|\right) + H.c.$$

$$H_{\text{anc}} = g\sum_{j=1}^{N} c_j^\dagger\left(|0\rangle_j\langle e| + |1\rangle_j\langle f|\right) + H.c.,$$

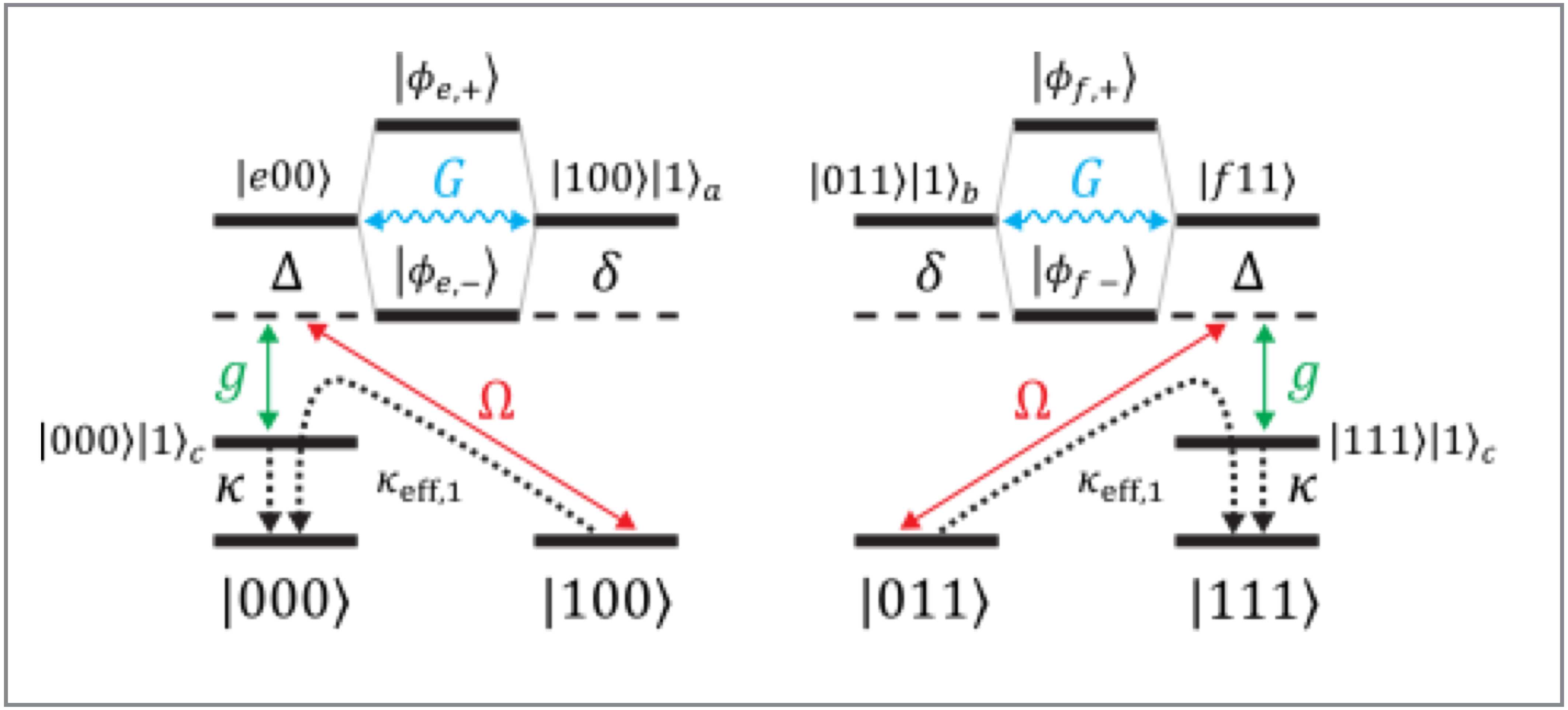
Motional modes a, b 'Interrogation' modes (perform majority vote)

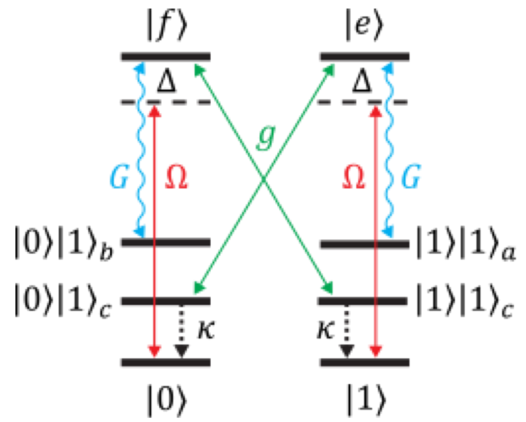
Motional modes c_1, c_2, c_3 : 'Cooling' modes

Error correction scheme



Error correction scheme

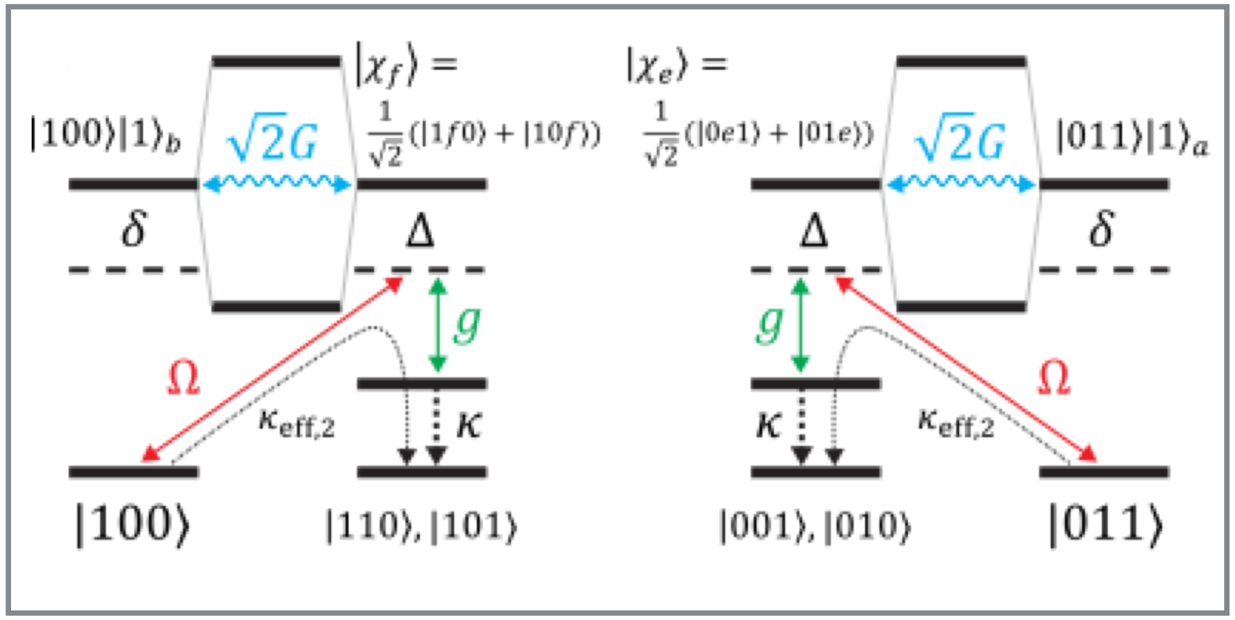


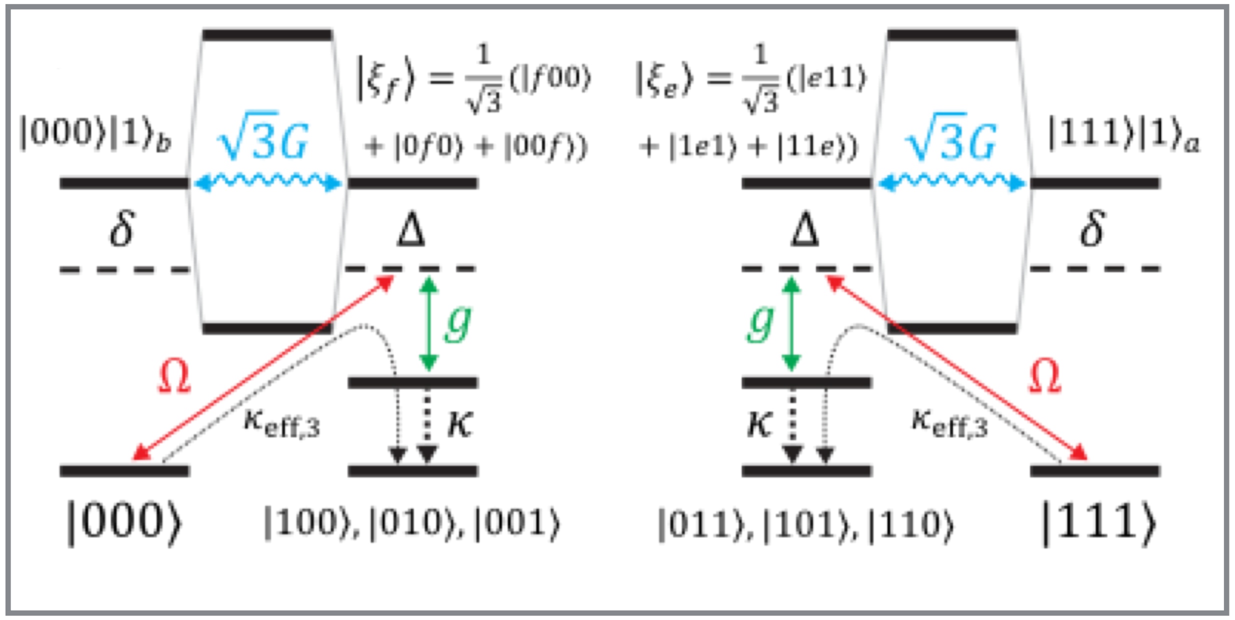


level scheme for a single ion

Error correction scheme

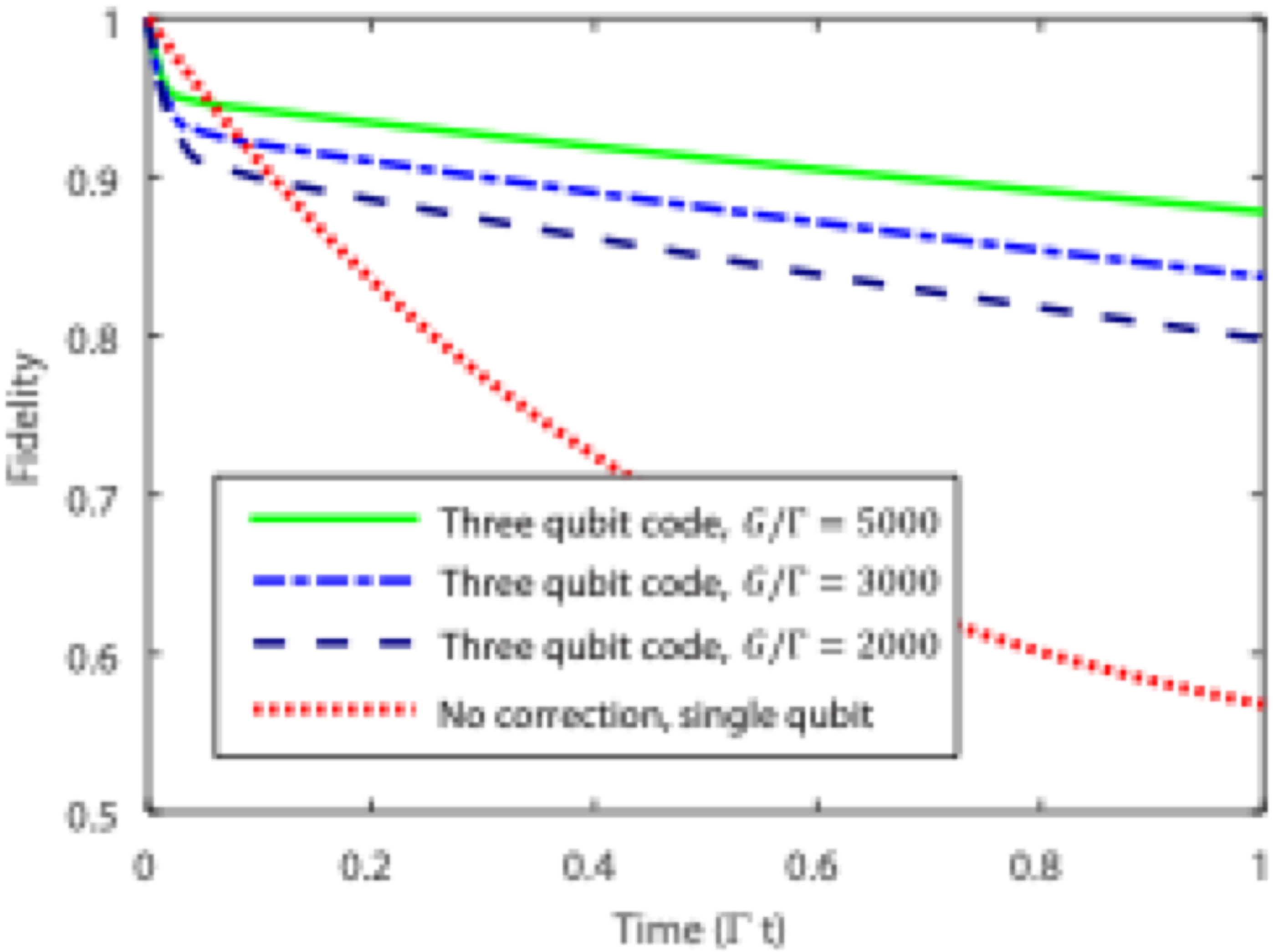
Undesired processes (suppressed)





Error correction scheme

Performance of the protocol



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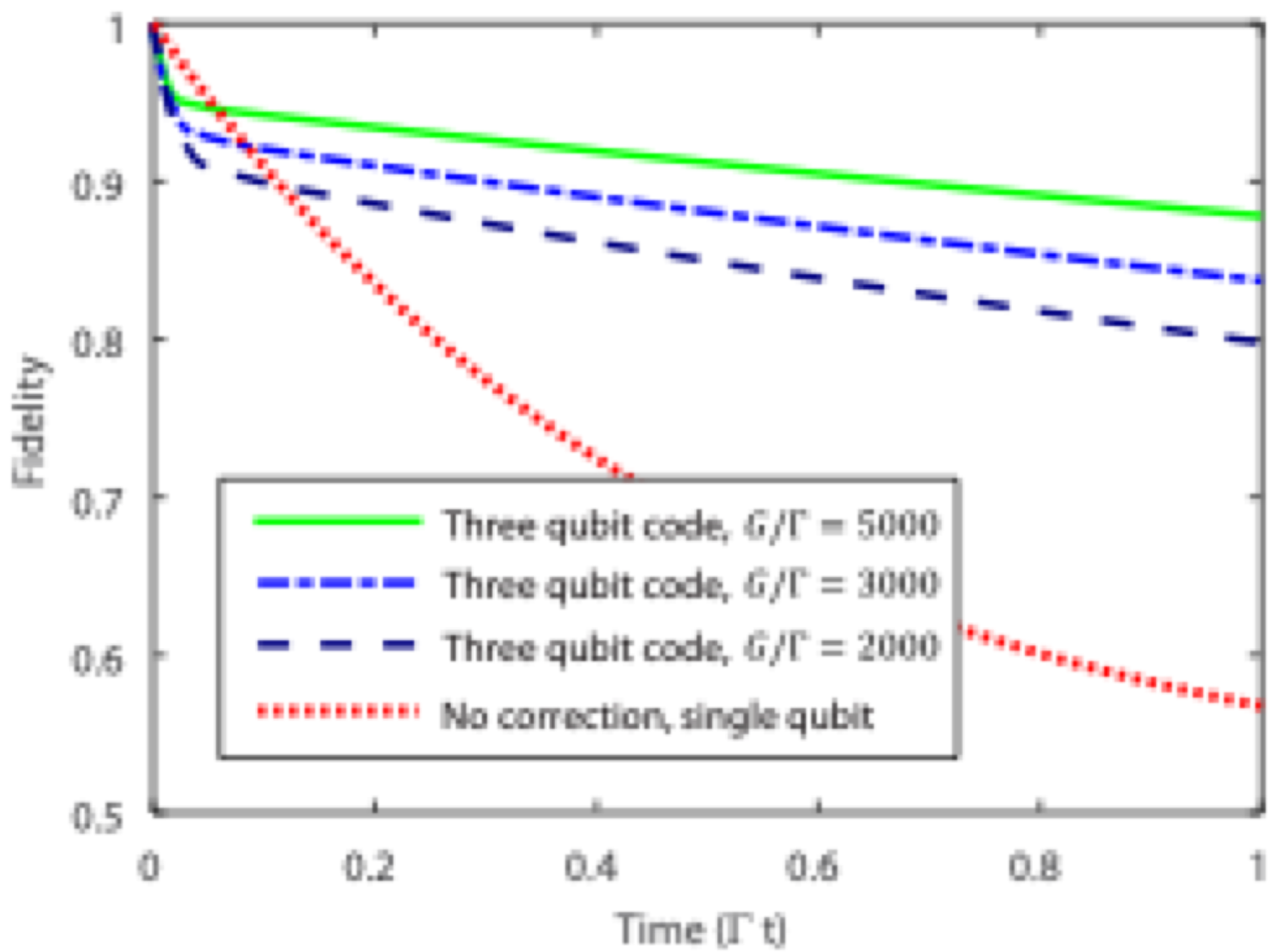

Analysis in terms of experimental imperfections:
The effect of dephasing is moderate for $\Gamma_{\mathrm{deph}} < \Gamma/50$

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Application to quantum metrology

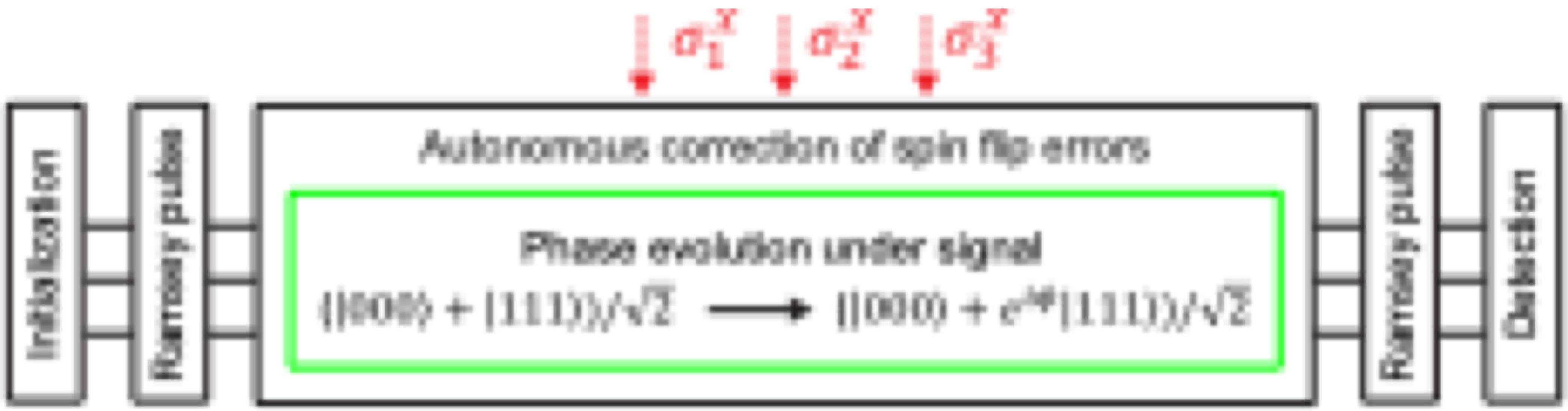
Quantum error correction for quantum sensing:

Precision ~ $\frac{1}{\sqrt{T_{\mathrm{coh}}}}$ ⟶ enhancing T_{coh} is a key goal

Improve effective coherence times through error correction

PRL 112, 080801 (2014).
PRL 112, 150802 (2014).
PRL 112, 150801 (2014).
arXiv:1310.3432 (2013).
PRL 116, 230502 (2016).

Application to quantum metrology



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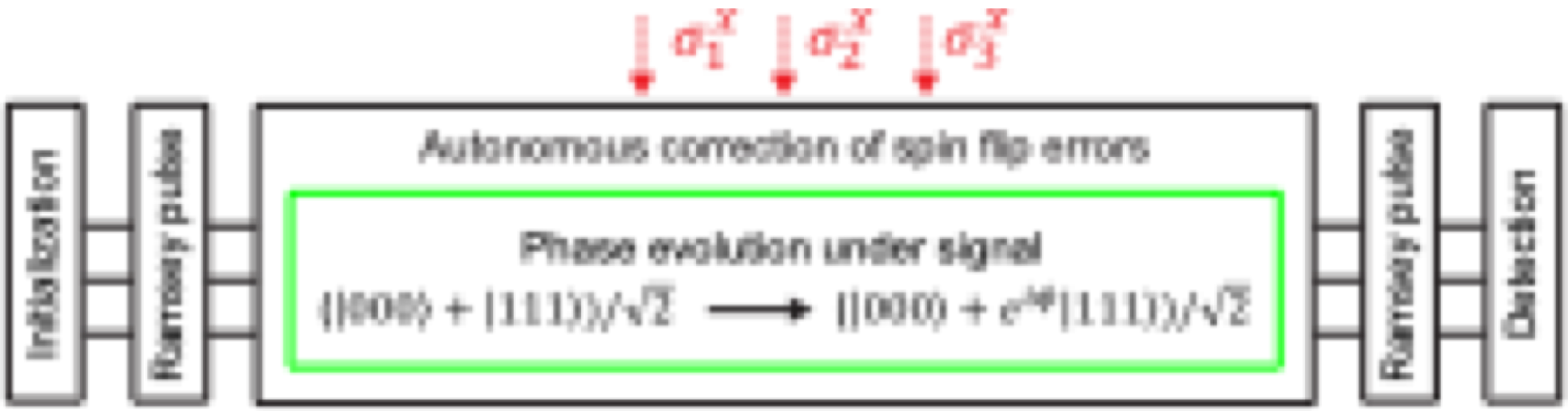
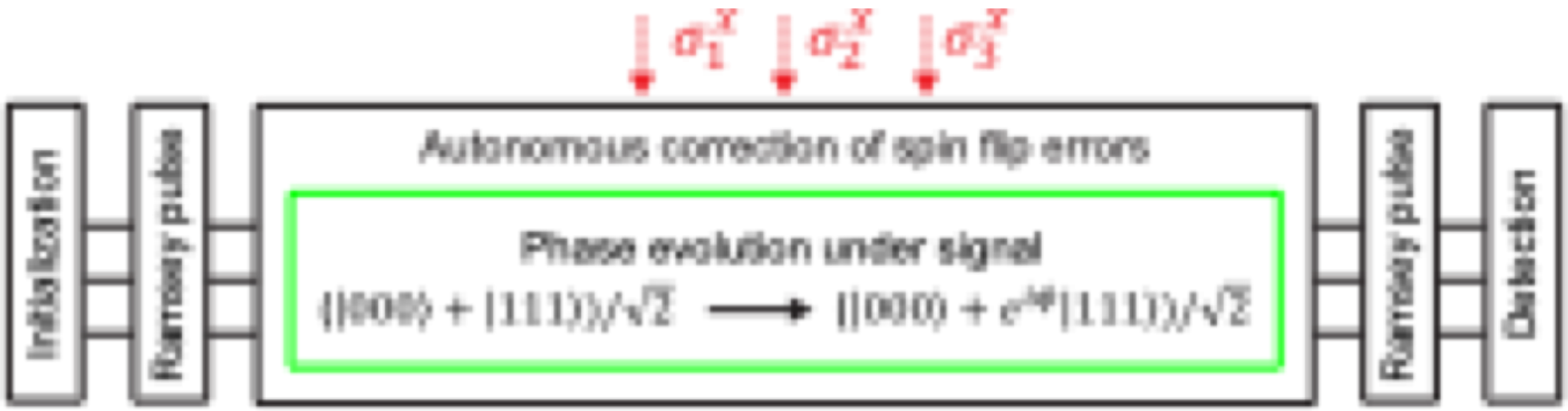


First Ramsey pulse:

$$|\Psi(0)\rangle = (|000\rangle + |111\rangle)/\sqrt{2}.$$

Application to quantum metrology



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Free evolution:

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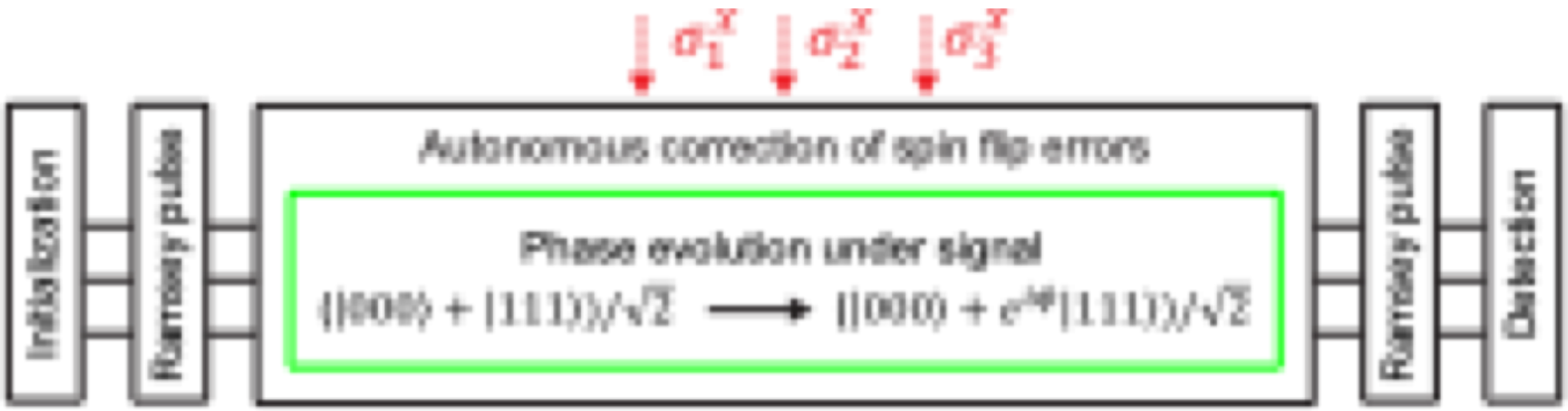
Application to quantum metrology



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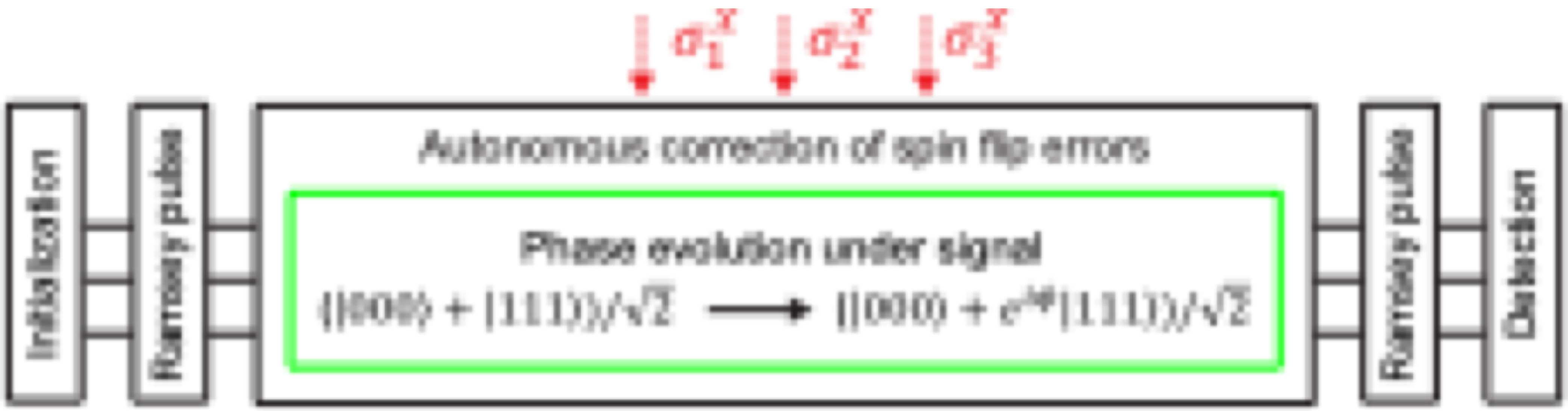
Second Ramsey pulse:

$$|\Psi'(\tau_{\mathrm{R}})\rangle \quad = \quad \cos(\phi(\tau_{\mathrm{R}}))|000\rangle \ + \ i\sin(\phi(\tau_{\mathrm{R}}))|111\rangle$$

Application to quantum metrology



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$$|\Psi(\tau_R)\rangle \quad = \quad (|000\rangle \ + \ e^{-i\phi(\tau_R)}|111\rangle)/\sqrt{2}.$$

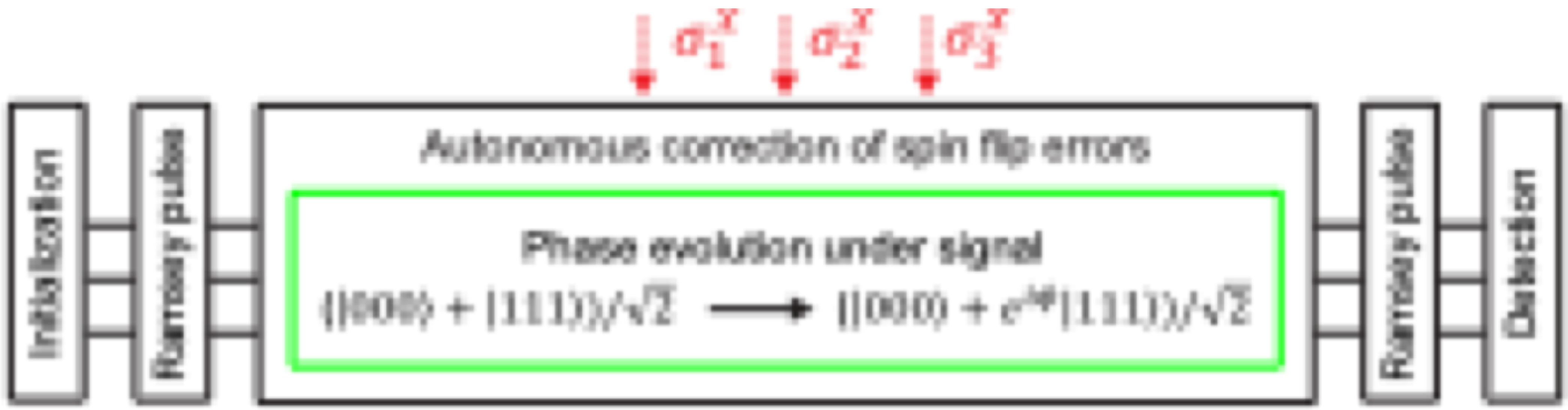
Second Ramsey pulse:

$$|\Psi'(\tau_R)\rangle \quad = \quad \cos(\phi(\tau_R))|000\rangle \ + \ i\sin(\phi(\tau_R))|111\rangle$$

Measurement:

$$P_0 \ = \ \cos^2(\phi(\tau_R))$$

Application to quantum metrology



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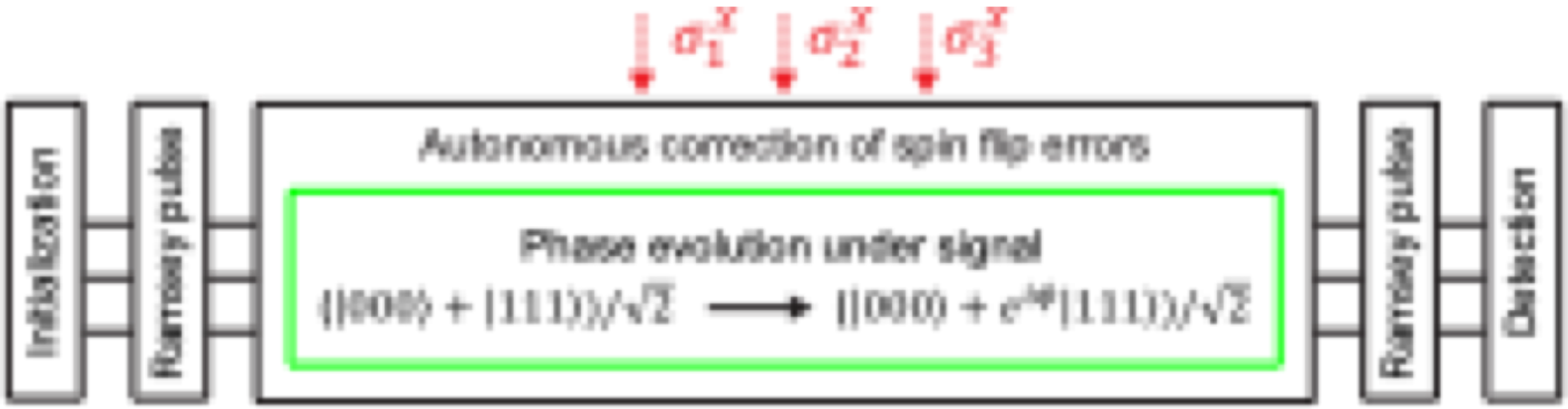
Precision:

$$|\delta\omega_0| = \frac{1}{n\sqrt{\tau_{\mathrm{R}}}\sqrt{T}},$$

$$T = m\tau_{\mathrm{R}}$$

# of exp. runs

Application to quantum metrology



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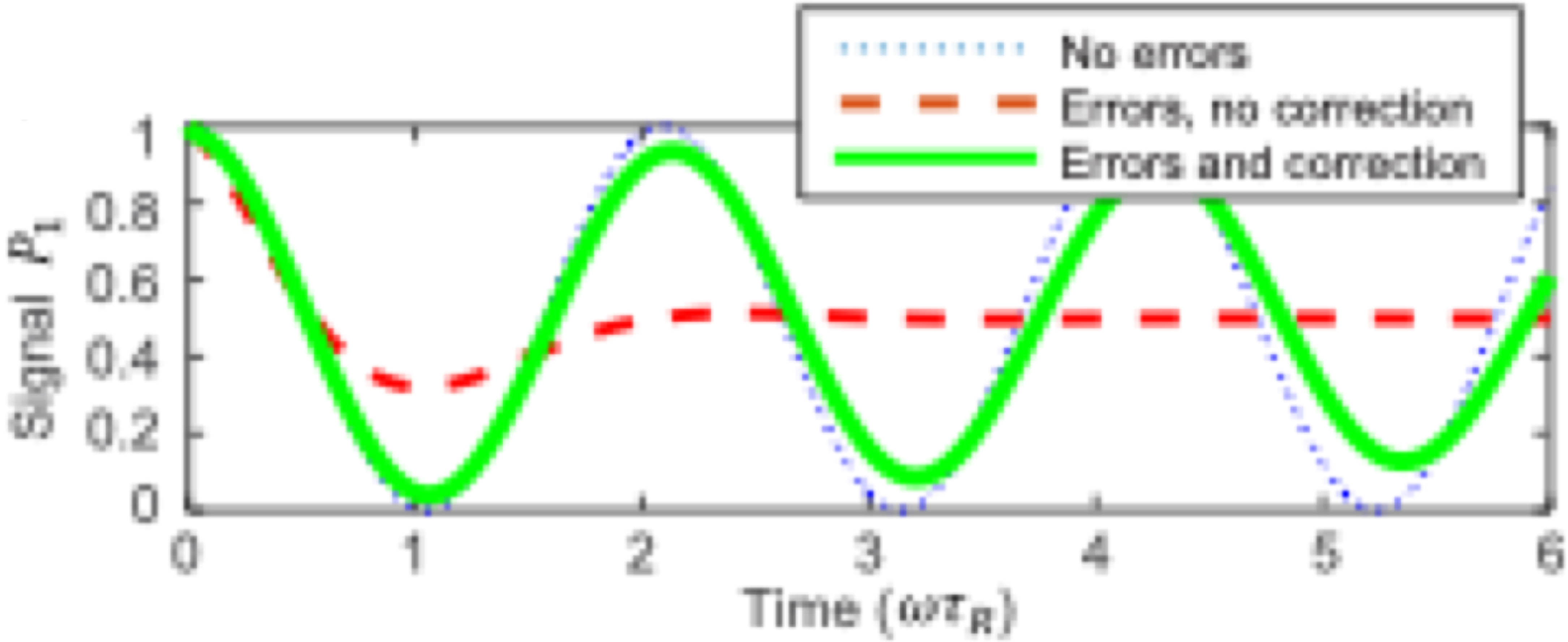
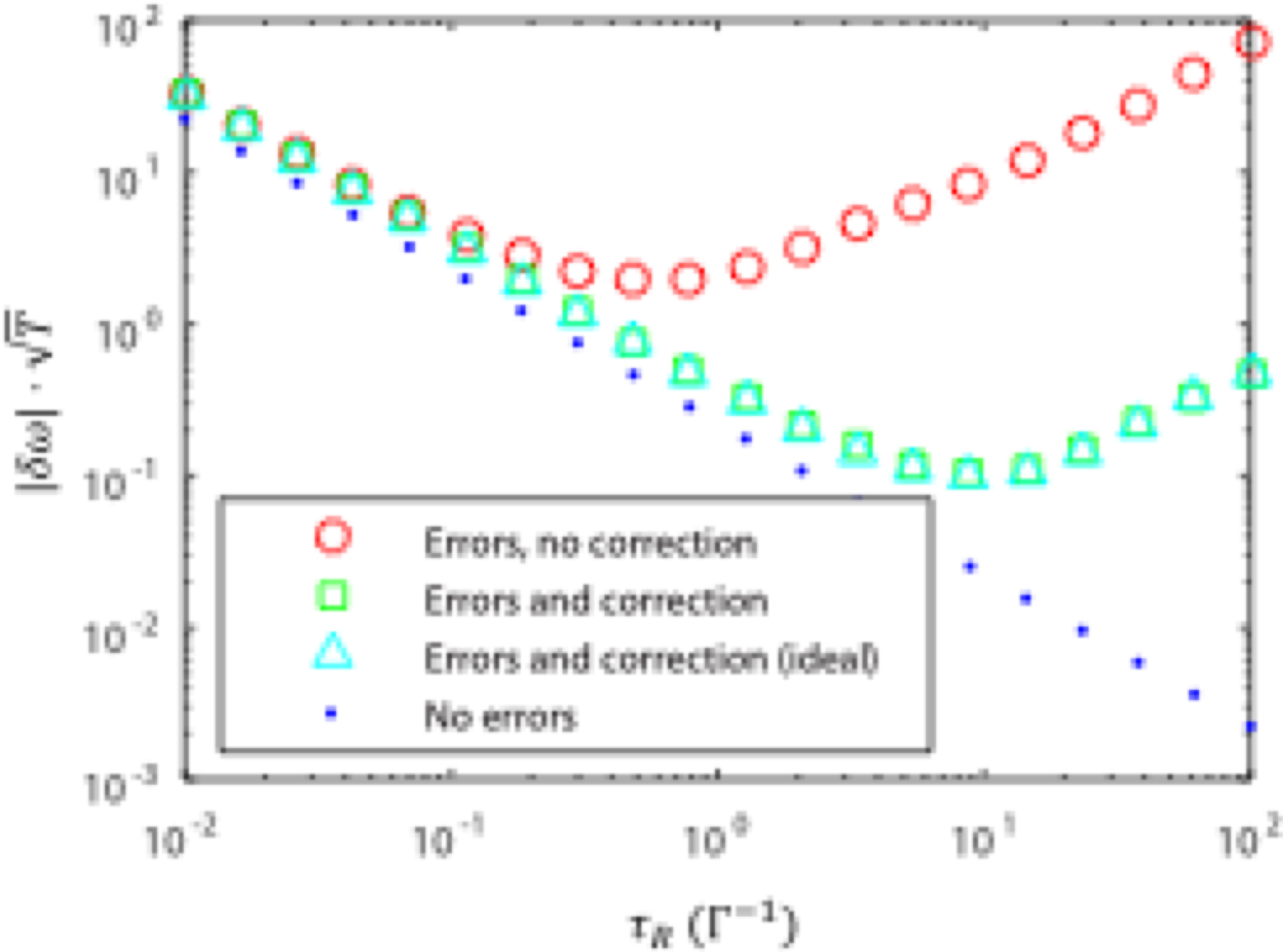


Application to quantum metrology

Sensitivity



Overview

1. Motivation
2. Error correction scheme
3. Application to sensing
4. Conclusions

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Summary

Dissipative quantum error correction scheme for trapped ions:
Stabilises an encoded qubit by coupling it to a reservoir.

Correction mechanism results from a build-in back action mechanism induced by engineered dissipative processes.

Instead of using a gate base approach:

- use the interaction between internal degrees of freedom and motional modes directly
- always-on couplings act simultaneously and continuously on an encoded qubit.
- remove errors by means of standard sympathetic cooling of the motional modes.

Application to quantum sensing

For scaling up: use segmented ion traps that accommodate several several logical qubits in different trap segments

Vision

Goal: perform autonomously stabilised quantum information processing tasks.

- Protocols for proof-of-concept demonstrations: stepping stone for exploring the use of quantum reservoir engineering for quantum information processing.
- Towards dissipative protocols that manipulate non-orthogonal quantum states while maintaining their coherence

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Some open questions:

Can we find practical dissipative implementations for
- transversal codes, topological quantum error correction?
- quantum error correction of loss errors (e.g. for applications in quantum networks)?

How can we use dissipative processes to engineer exotic quantum channels (*)?
- Could variational algorithms provide a viable route to design dissipative maps?
- Could machine learning be useful to engineer dissipative maps?

Could dissipative methods be used for
- robust and experimentally feasible quantum simulations of lattice gauge theories?
- for robust and experimentally feasible entanglement distillation?

(*) e.g. for:
- dissipative quantum simulations
- dissipative annealing, i.e. for classical optimization problems (Tamascelli and others…)
- dissipative quantum algorithms (Susana Huelga & Martin Plenio: arXiv:1903.05443)
- dissipative preparation of complex quantum many-body states (e.g. J. Simon, P. Zoller, M. Lukin…)
- etc…

Thank you very much for your attention

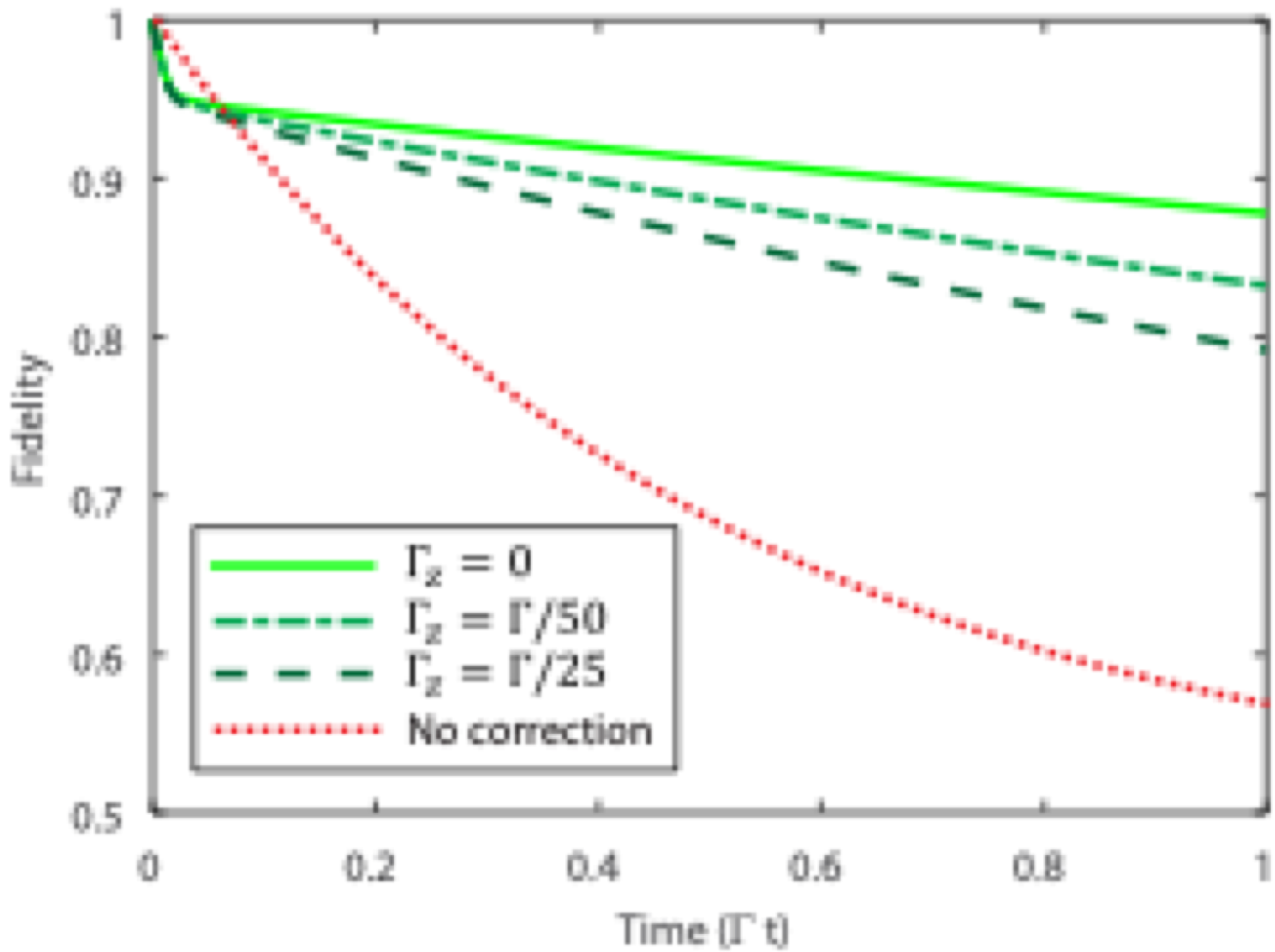
Autonomous quantum error correction with application to quantum metrology

F. Reiter, A. Sørensen, P. Zoller, and C. Muschik

Autonomous quantum error correction

Nat. Commun. 8, 1822 (2017).

- Quest: keep a qubit alive
- Vision: self-correcting quantum technology



1
0.9
0.8
0.7
0.6
0.5
Fidelity
0
0.2
0.4
0.6
0.8
1
Time (Γ t)
Γz = 0
Γz = Γ/50
Γz = Γ/25
No correction

Quantum error correction

Quantum computing

Fault-tolerant quantum gates

Quantum annealing
[F. Pastawski and J. Preskill, PRA 93, 052325 (2016).]

Quantum communication

Entanglement distribution
in 2D quantum networks

Encoded quantum repeaters

Quantum simulations

Digital quantum simulations

Black hole physics in quantum
error correcting codes

→ → → Explore new strategies for quantum error correction