Quantum Computation and Simulation with Trapped Ions

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1. Trapping and Cooling Ions

1.1 How to trap an ion

1.2 Ion strings for quantum computation

1.3 Choosing an ion

1.4 Laser-ion interaction

1.5 Laser cooling in ion traps

1.6 Gate Operations & Decoherence

1.7 Entanglement

2. Quantum Computation and Simulation

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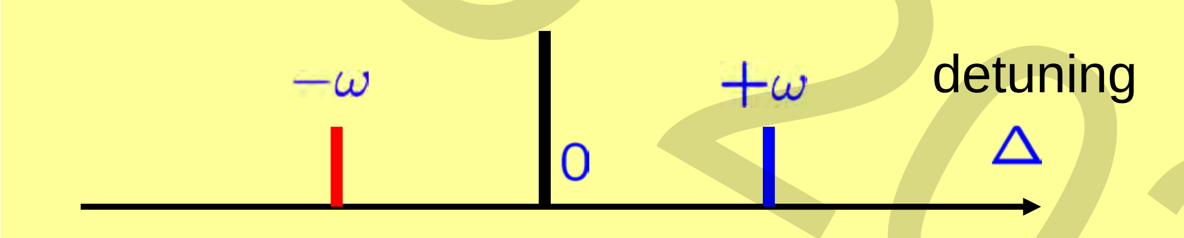
Recall: Laser-ion interaction

In the Lamb-Dicke regime $\eta^2(2n+1) \ll 1$

we expand $\exp(i\eta(\hat{a}^\dagger + \hat{a})) = 1 + i\eta(\hat{a}^\dagger + \hat{a}) + \mathcal{O}(\eta^2)$

Carrier

$$\Omega_{n,n} = \Omega(1 - \eta^2 n)$$
$$H_I = \tfrac{1}{2}\hbar\Omega_{n,n}(\sigma^+ + \sigma^-)$$



Red sideband

$$\Omega_{n-1,n} = \eta\sqrt{n}\Omega$$
$$H_I = \tfrac{1}{2}i\hbar\Omega_{n-1,n}(\hat{a}\sigma^+ - \hat{a}^\dagger\sigma^-)$$

Blue sideband

$$\Omega_{n+1,n} = \eta\sqrt{n+1}\Omega$$
$$H_I = \tfrac{1}{2}i\hbar\Omega_{n+1,n}(\hat{a}^\dagger\sigma^+ - \hat{a}\sigma^-)$$

D. Leibfried et al, Rev. Mod. Phys. 75, 281-324 (2003)

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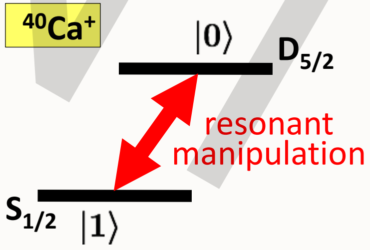
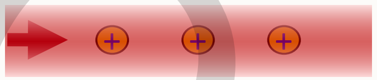
Quantum computing with global and local operations

Global

Collective Local Operations



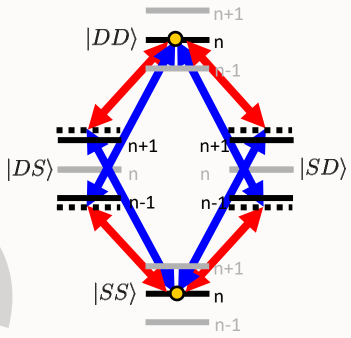
$S_{x,y}(\theta)$



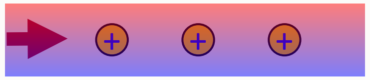
τ = 20µs

F > 99.9%

Global Mølmer- Sørensen entangling gate



$S^2_{x,y}(\theta)$

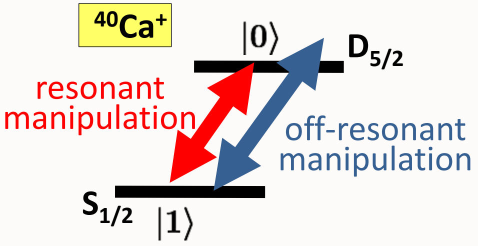


τ = 50µs

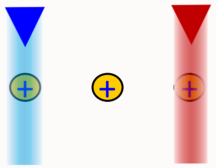
F_2 > 99%

Local

Individual (and parallel) local operations



$S_z(\theta)$ $S_{x,y}(\theta)$

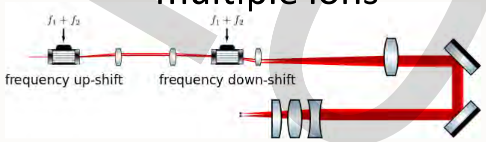


τ = 20µs

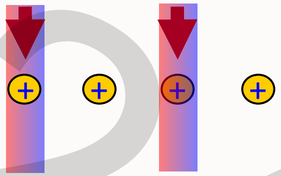
F > 99.9%

Local Mølmer- Sørensen entangling gate

Simultaneous addressing of multiple ions



$S^2_{x,y}(\theta)$



τ = 100µs

F_2 > 99%

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P. Schindler, at al., New. J. Phys. 15, 123012 (2013)

M. Ringbauer, et al., Nature Physics 18, 1053 (2022)

2. Quantum Computation and Simulation

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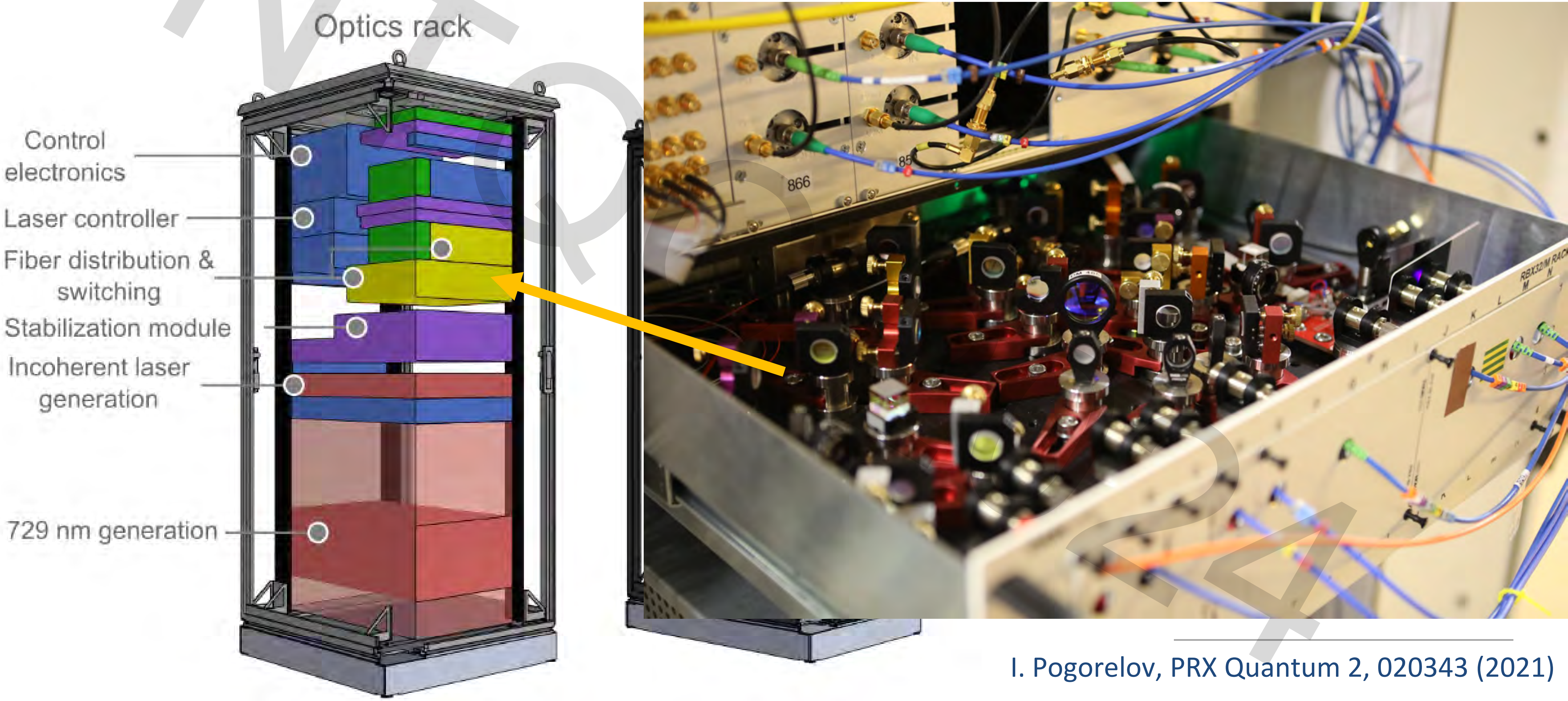
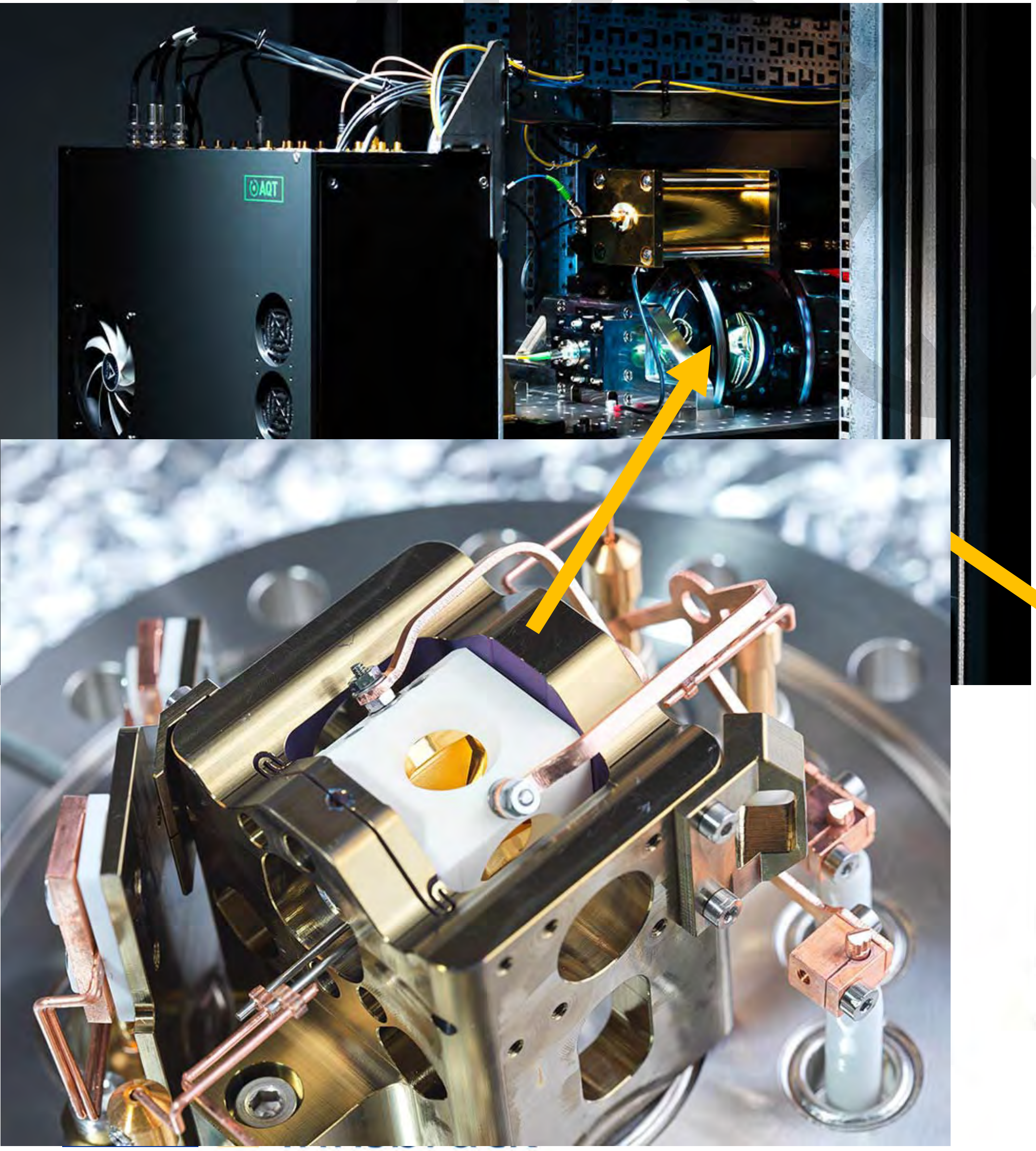
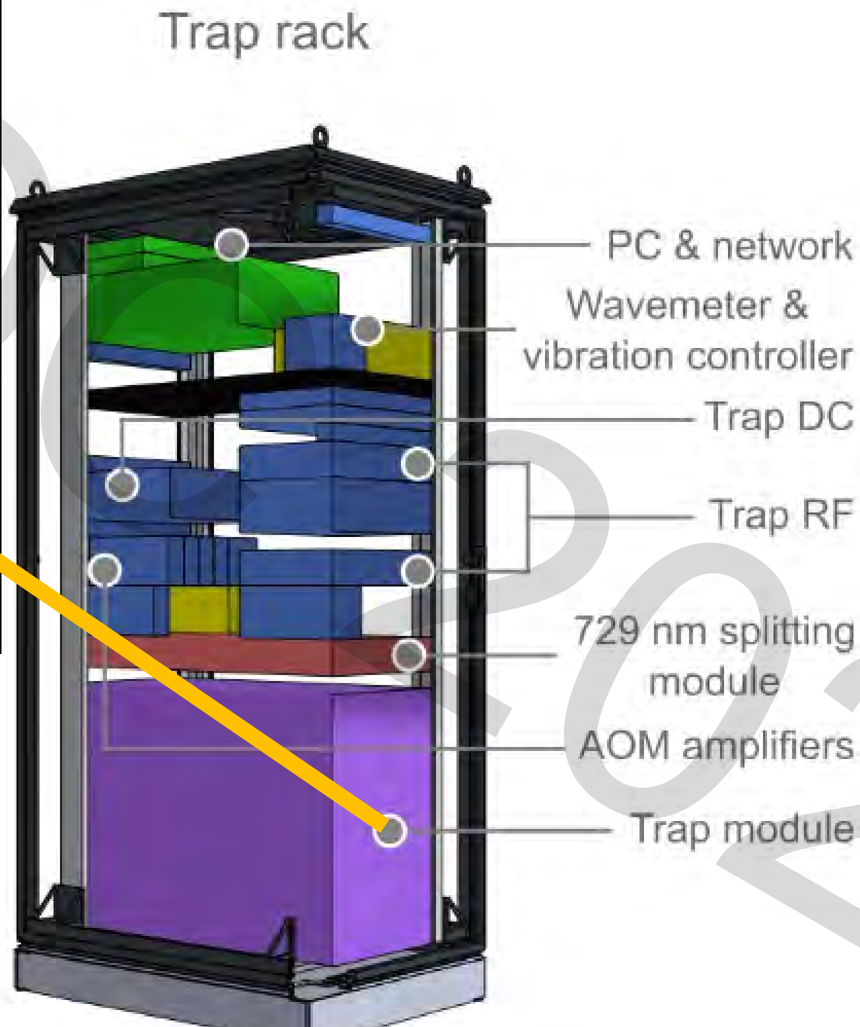
To a Compact, Modular System



I. Pogorelov, PRX Quantum 2, 020343 (2021)

To a Compact, Modular System





I. Pogorelov, PRX Quantum 2, 020343 (2021)

2. Quantum Computation and Simulation

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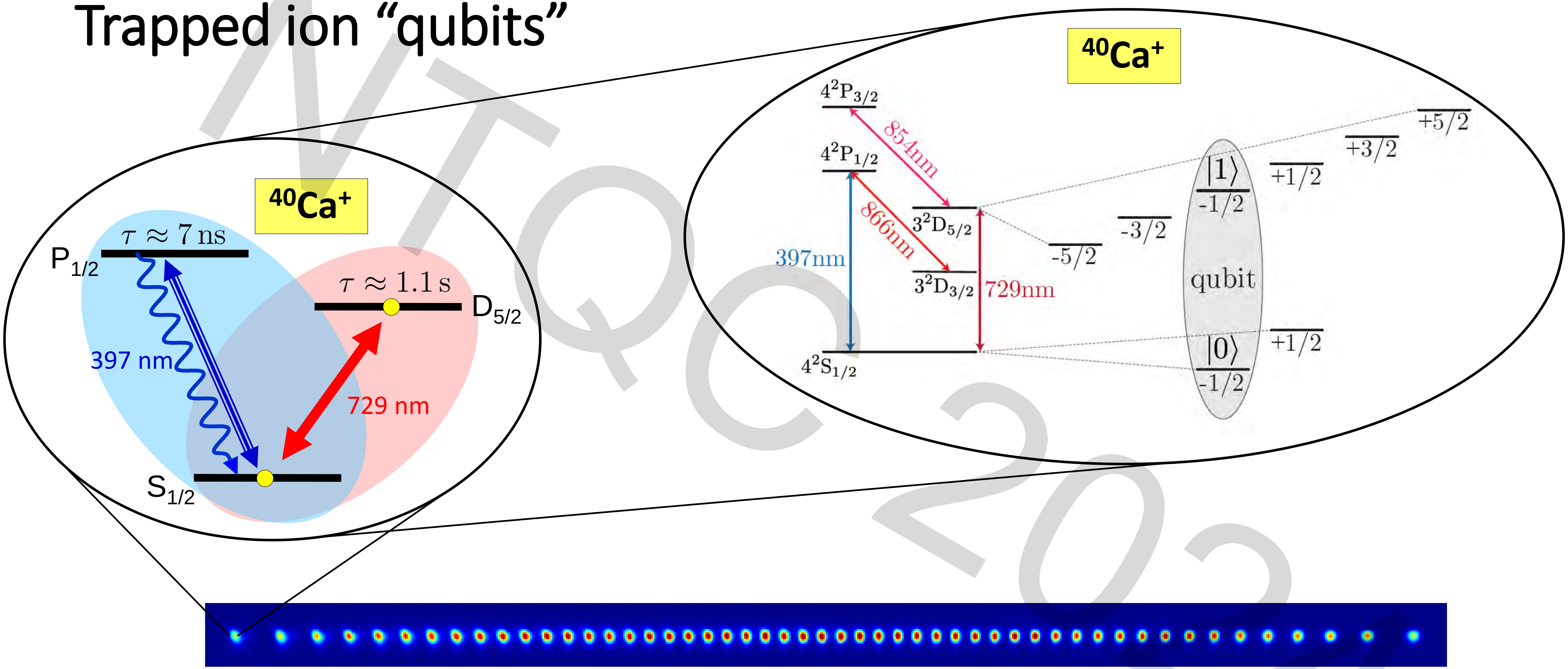
Trapped ion "qubits"



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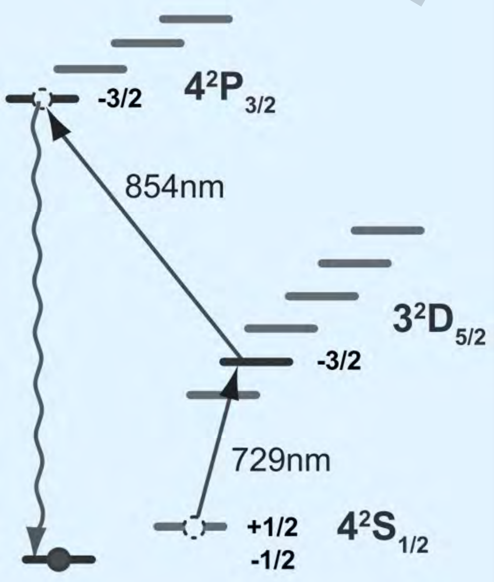
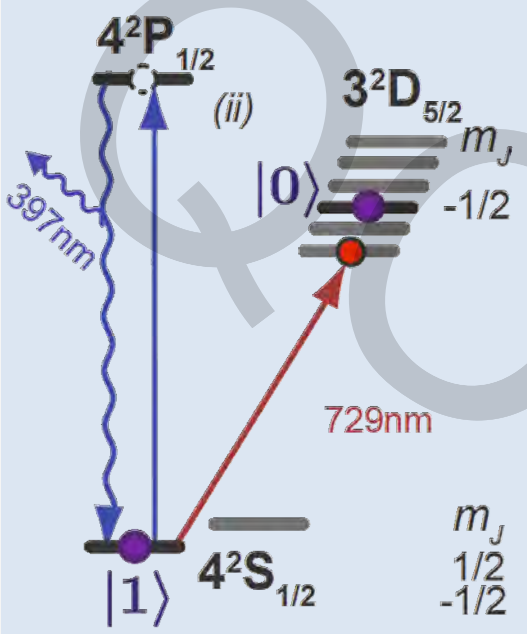
Capabilities beyond Qubits

Optical pumping



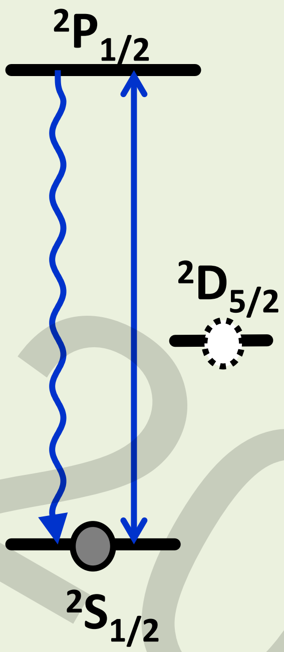
Initializes qubit in one Zeeman state

Decoupling



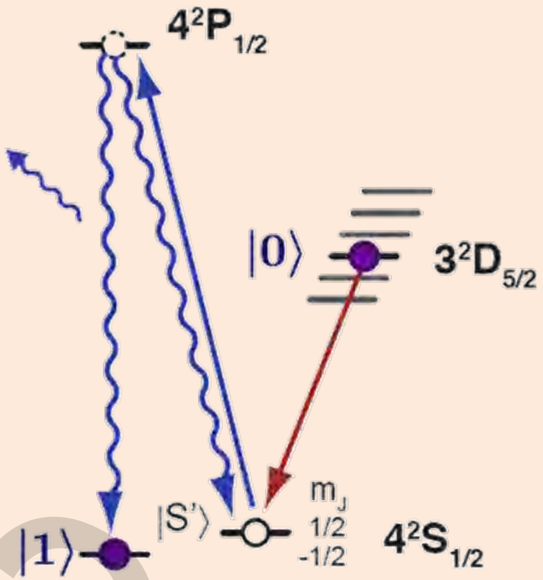
reduces, enlarges the computational subspace

Dephasing



controlled dissipation

Resetting



resets the qubit

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P. Schindler et al., New. J. Phys. 15, 123012 (2013)

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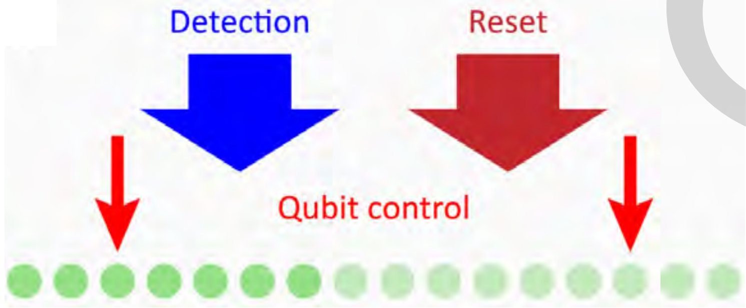
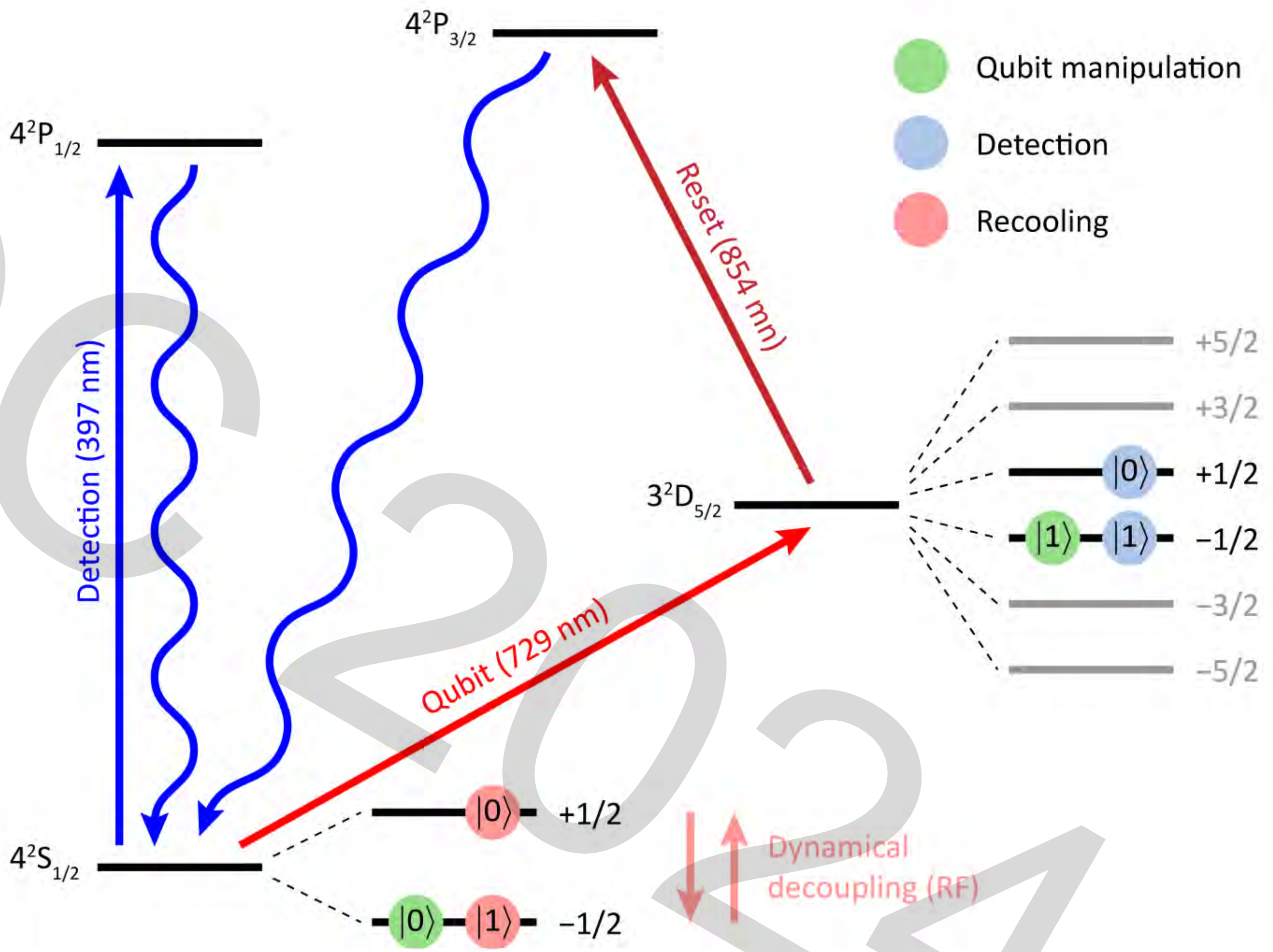
Mid-Circuit Measurement & Reset



Measure & Reset some qubits

Leave the others alone



L. Postler, et al., arXiv:2312.09745 (2023)

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2. Quantum Computation and Simulation

2.1 New Generation

2.2 Operations beyond Qubits

2.3 Quantum Error Correction

2.4 QIP with Qudits

2.5 Digital Quantum Simulation

2.6 Scaling

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Quantum error correction will be mandatory for large scale quantum computing!

Why small-scale QEC?

- Validate assumptions on errors
- Inform future trap architectures

Ion trap QEC implementations:

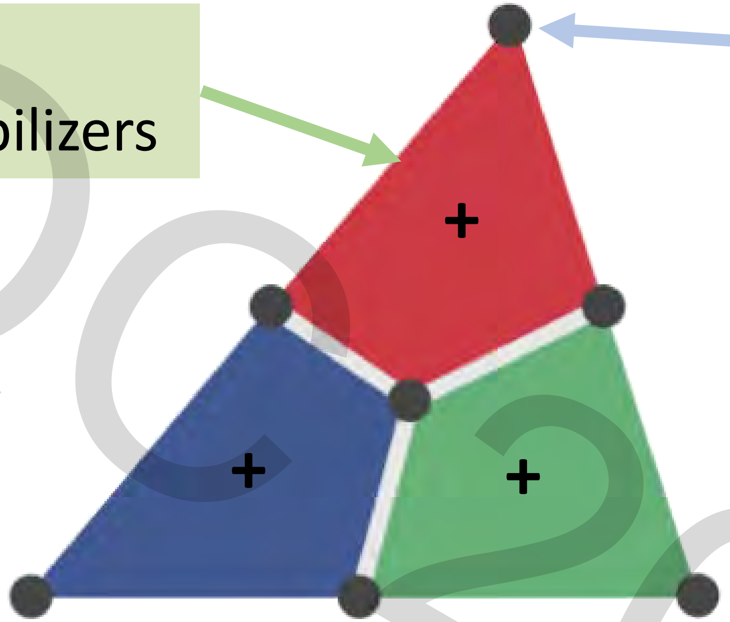
J. Chiaverini, Nature 432, 602 (2004)
P. Schindler, Science 332, 1059 (2011)
D. Nigg, Science 345, 302 (2014)
N. Linke Sci. Adv. 3, e1701074 (2017)
C. Flühmann, Nature 566, 513 (2019)
A. Erhard, Nature 589, 220 (2021)
C. Ryan-Anderson, PRX 11, 041058 (2021)
L. Egan, Nature 598, 281 (2021)
De Neeve, Nature Physics 18, 296 (2022)
J. Hilder, PRX 12, 011032 (2022)
Da Silva, arxiv: 2404.02280 (2024)
→ See also: Work by Mainz (Schmidt-Kaler)

The 7-qubit color code (Steane code)

Plaquette with two associated 4-body stabilizers

$S_x^{(1)} = X_1X_3X_5X_7$

$S_z^{(1)} = Z_1Z_3Z_5Z_7$



Physical qubit

Initializing the logical qubit requires the system to be in the +1 eigenstate of each stabilizer

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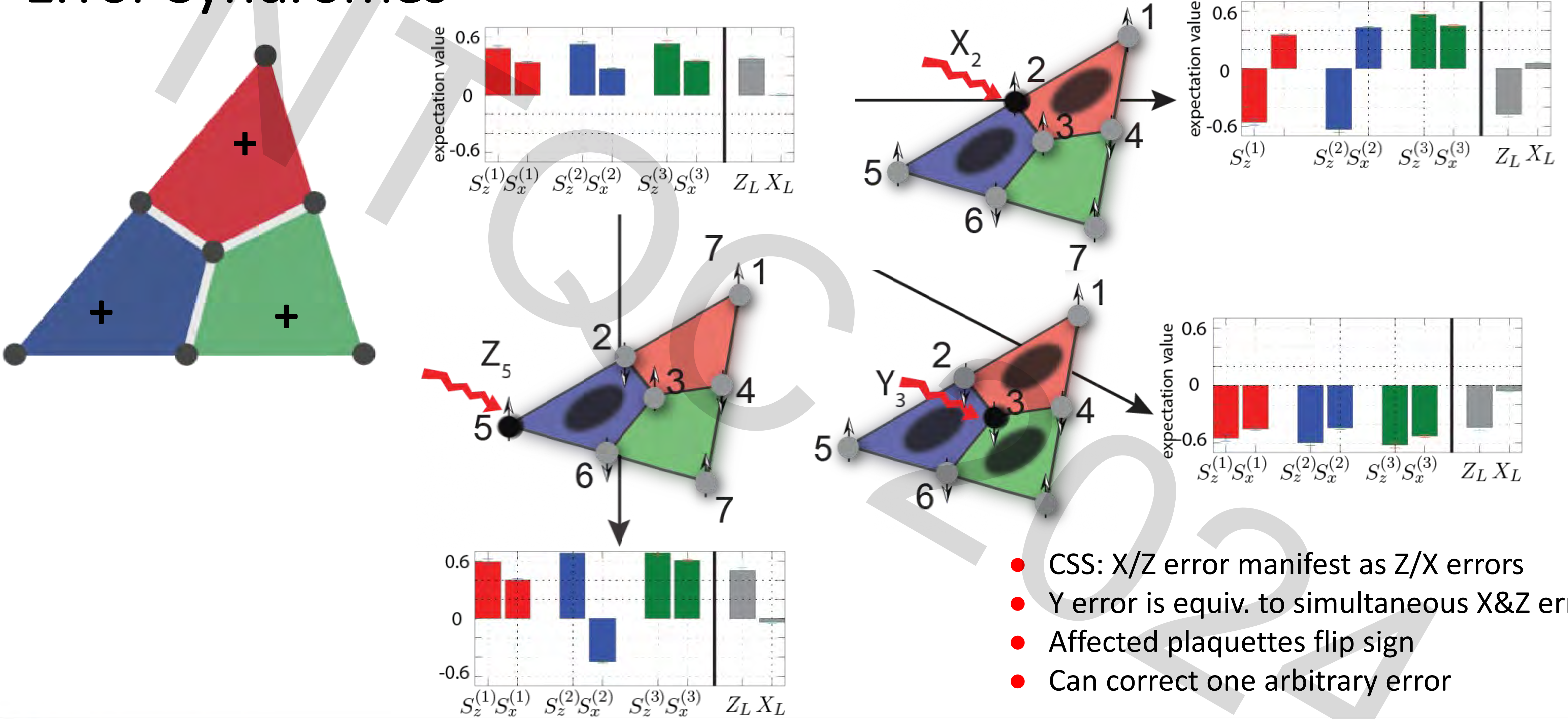
A. Bermudez et al., PRX 7, 041061 (2017)

Error Syndromes



- CSS: X/Z error manifest as Z/X errors
- Y error is equiv. to simultaneous X&Z error
- Affected plaquettes flip sign
- Can correct one arbitrary error

D. Nigg, M. Müller et al., Science **345**, 302 (2014)

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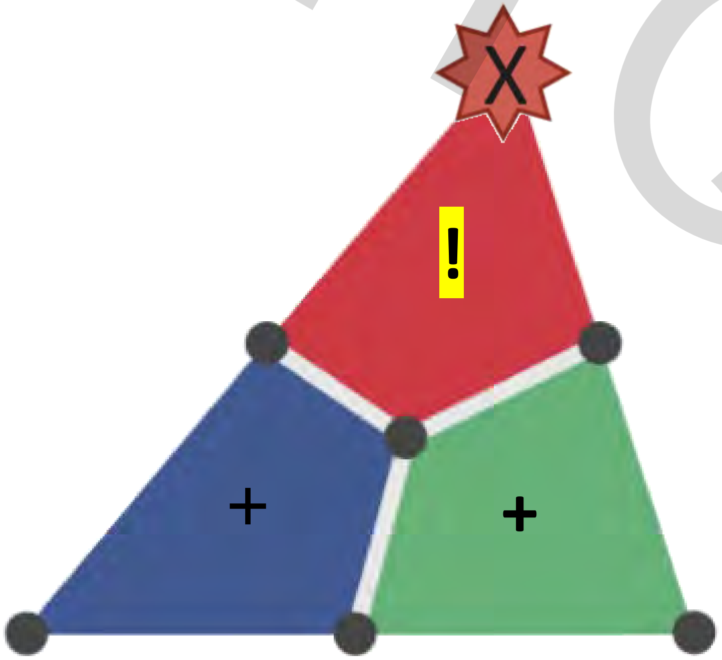
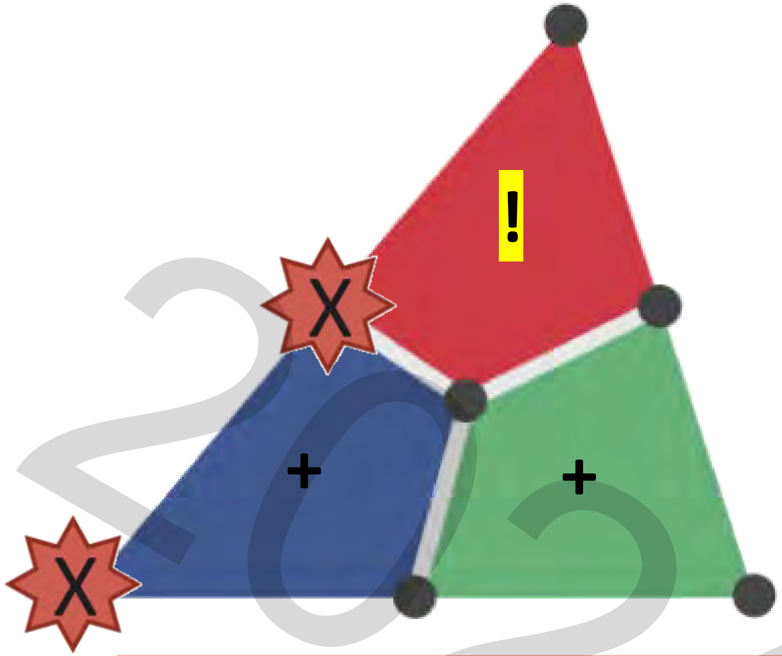
Correctable and Uncorrectable Errors

Any single error can be detected and corrected



Correctable error

Two physical errors cannot be detected correctly



Uncorrectable error

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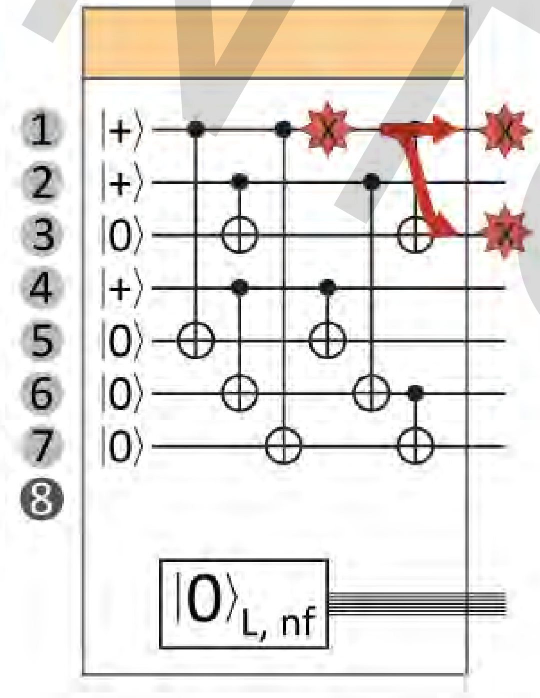
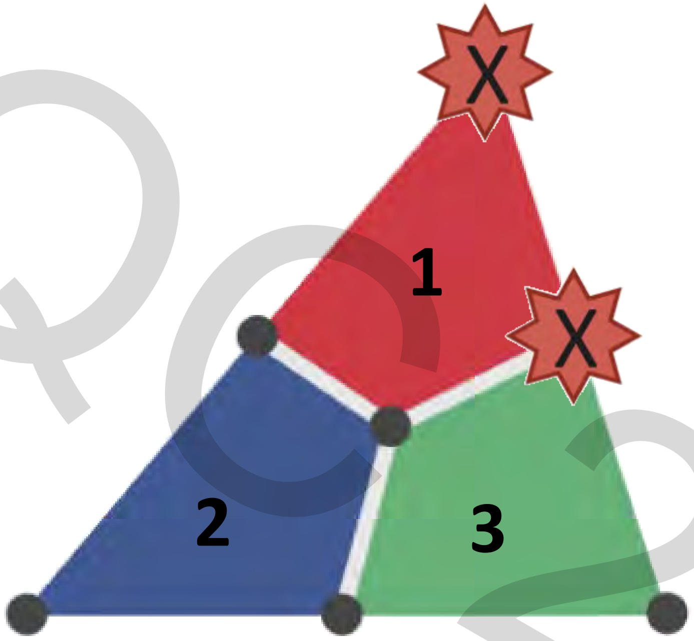
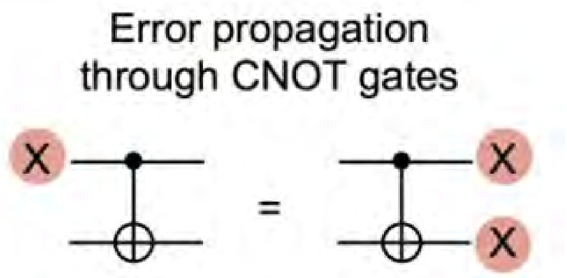
Error Propagation and Fault Tolerance







A single physical error can cause an uncorrectable logical error → **Non fault-tolerant**

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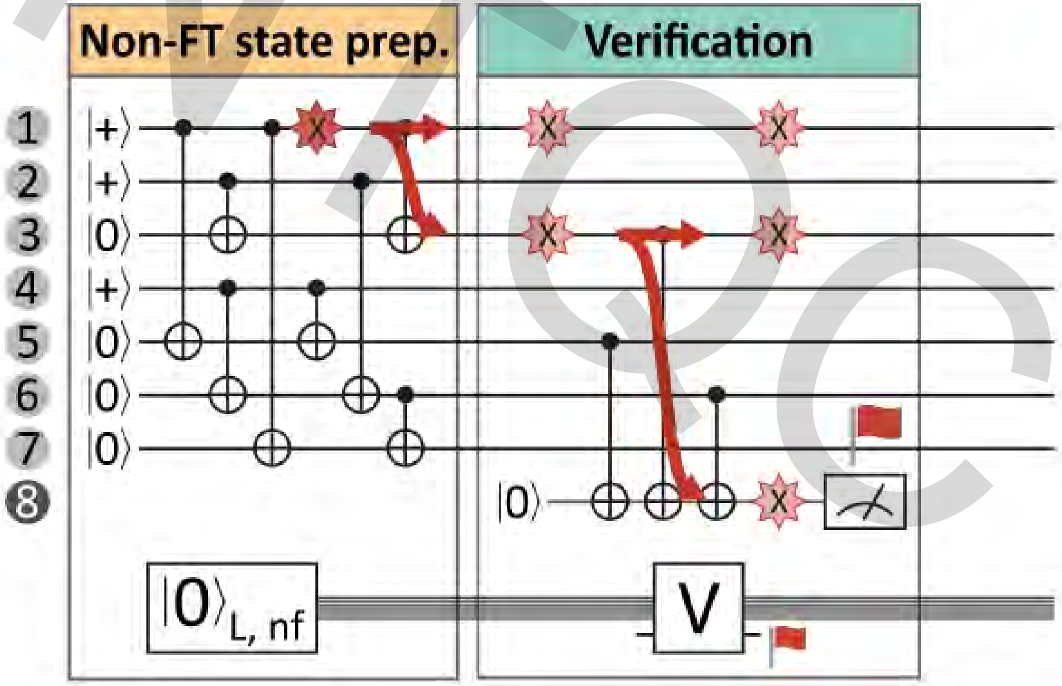
Error Propagation and Fault Tolerance



Add a single "flag qubit" to herald uncorrectable errors when preparing the logical ground state

A **single** physical error leads **always** to a correctable error → **Fault-tolerant** ✓

Chao, PRL. 121, 050502 (2018)
Yoder , Quantum 1, 2 (2017)
Reichardt, arXiv:1804.06995 (2018)
C. Chamberland, Quantum 2, 53 (2018).
C. Chamberland, NJP 22, 023019, (2020)
C. Chamberland, Quantum 3, 143 (2019)

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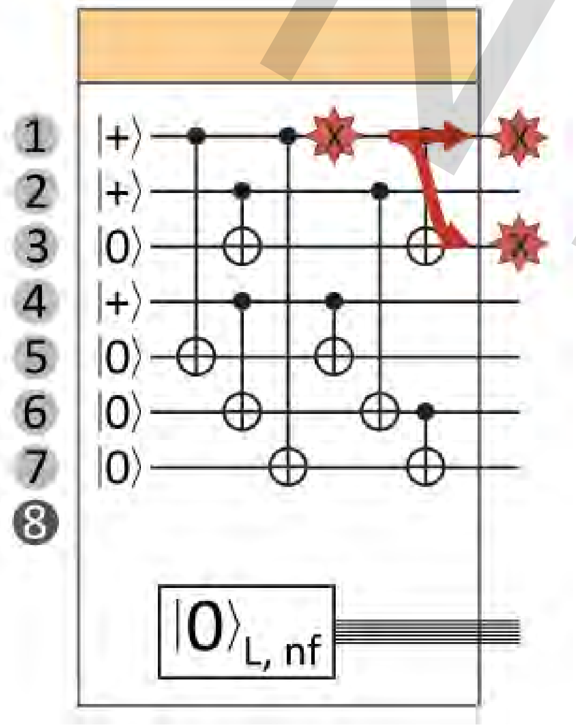
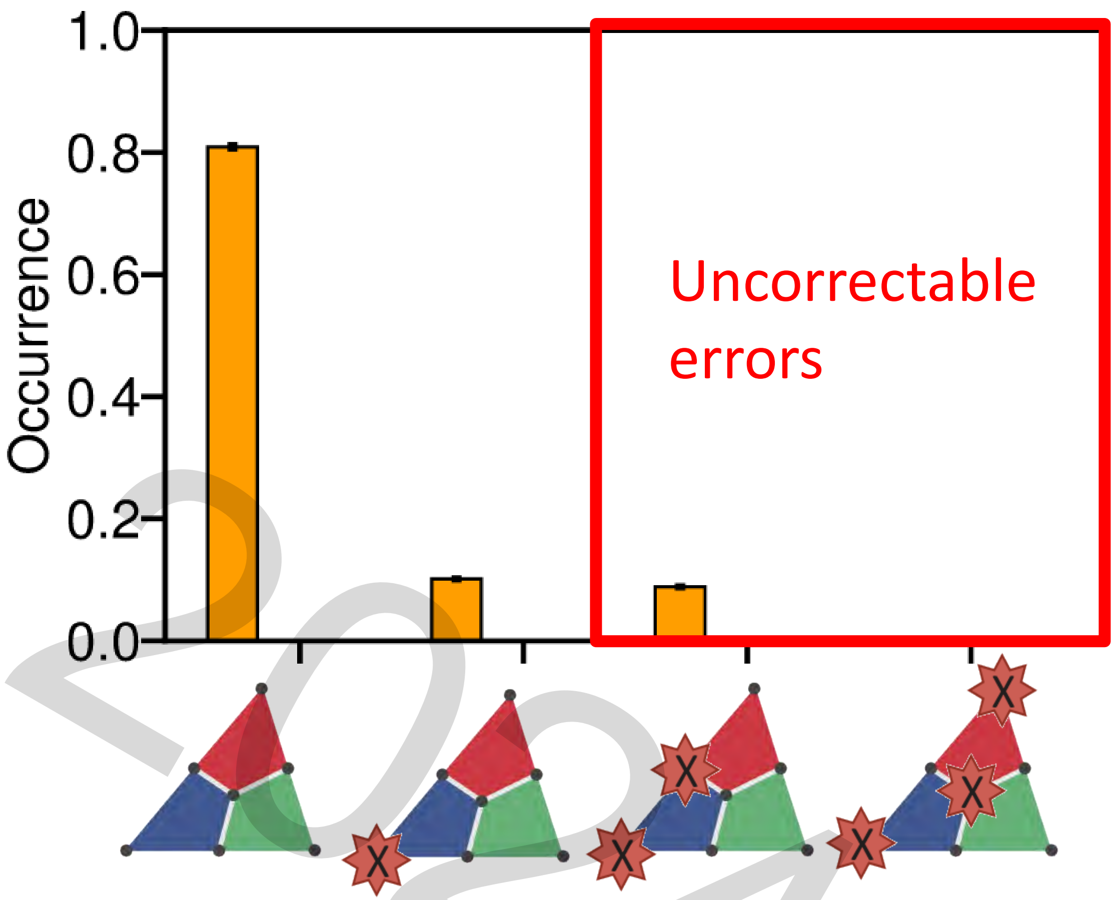
Experimental Results: Non-Fault-Tolerant State Preparation



Correctable and uncorrectable errors occur with similar probability



Analyze # of physical errors

L. Postler et al, Nature **605** 675-680 (2022)

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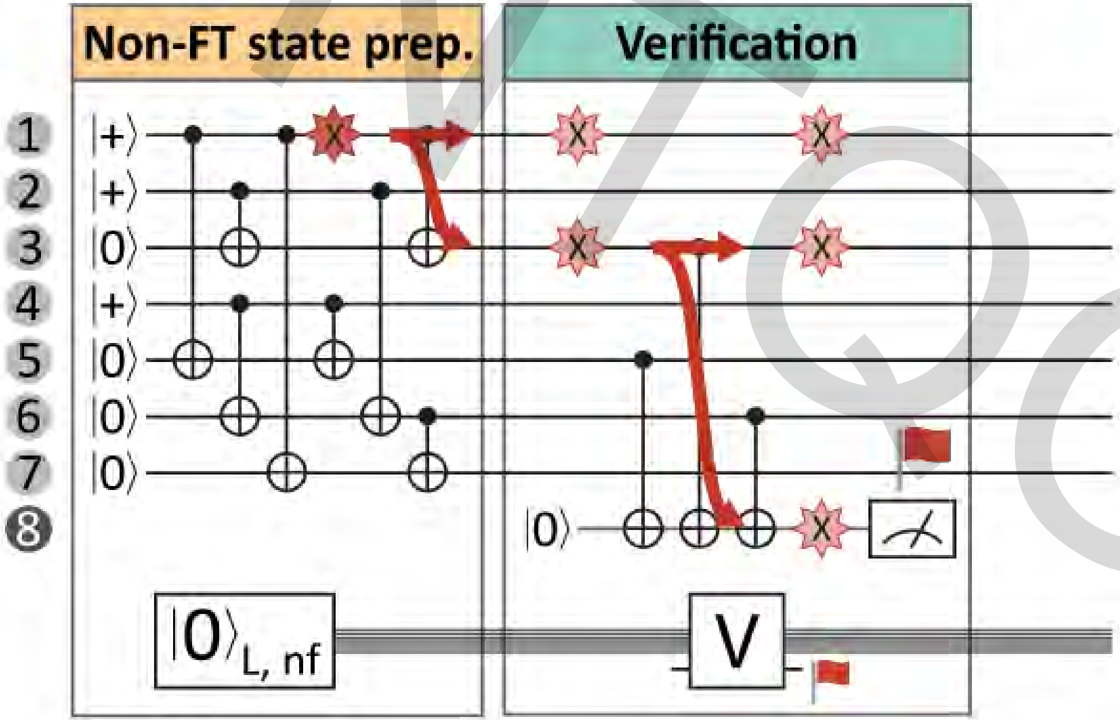
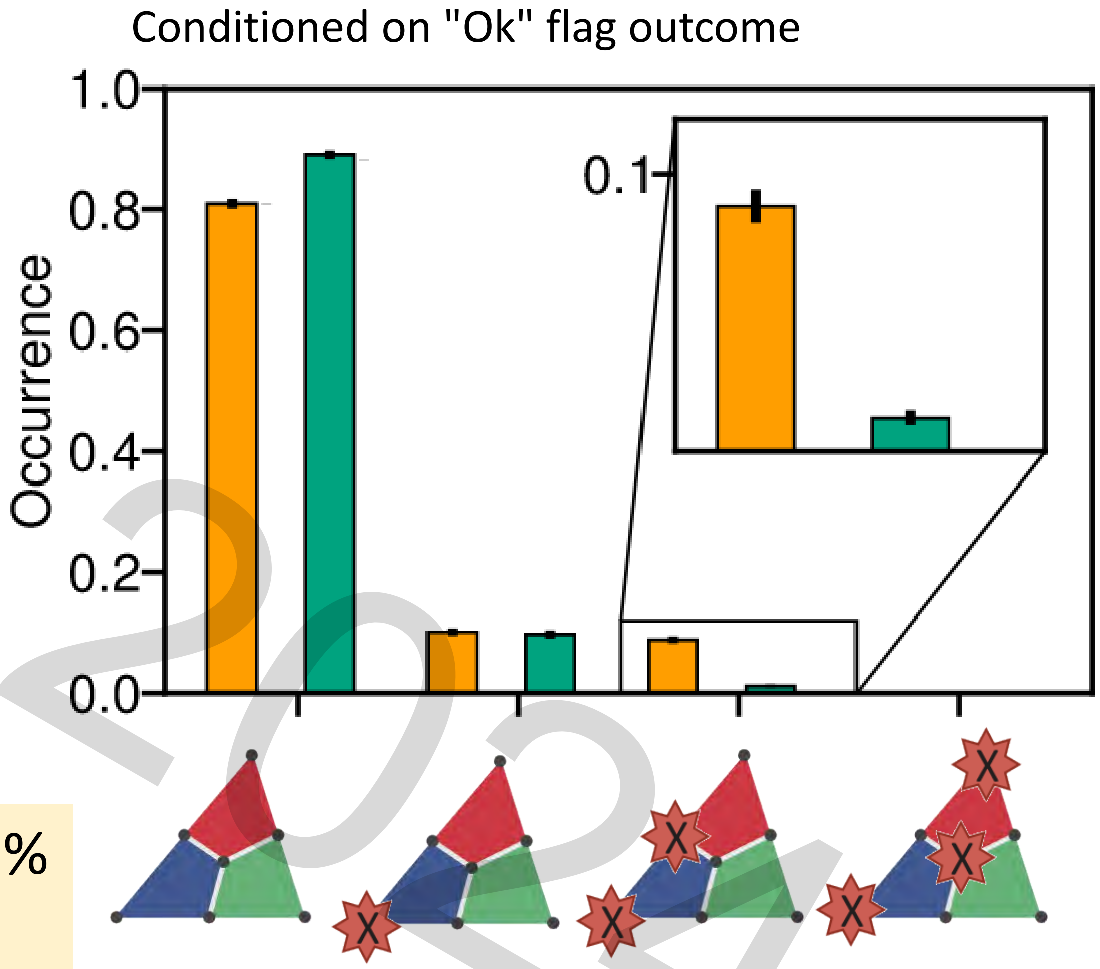
Experimental Results: Fault-Tolerant State Preparation





Uncorrectable errors are strongly suppressed

Logical infidelity: 1%
Survival rate: 78%

L. Postler et al, Nature **605** 675-680 (2022)

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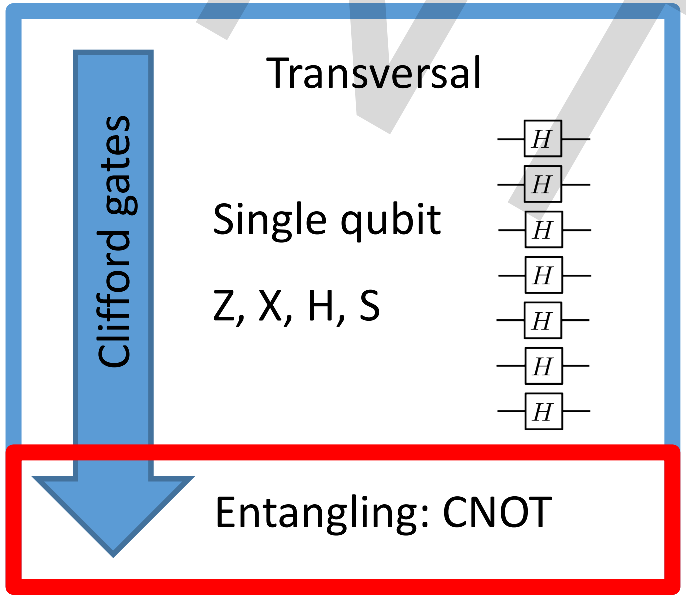
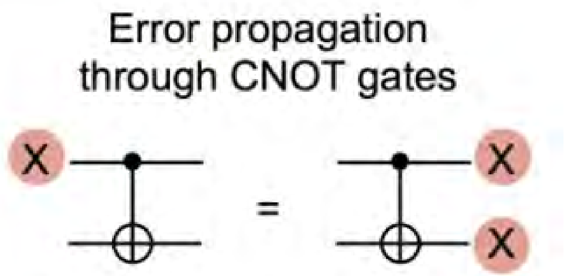
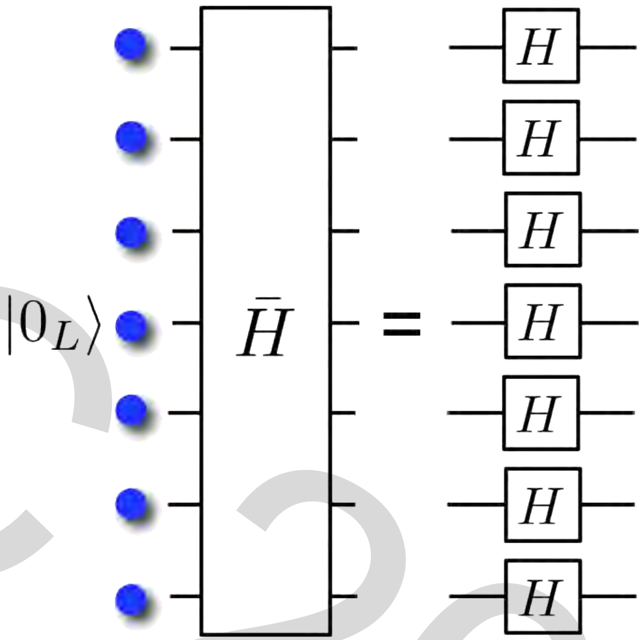
Operations on Encoded Qubits Need to be Fault-Tolerant!







$$|0_L\rangle + |1_L\rangle$$

Transversal operations are fault-tolerant ✓

The entire set of Clifford operations
is transversal for the color code

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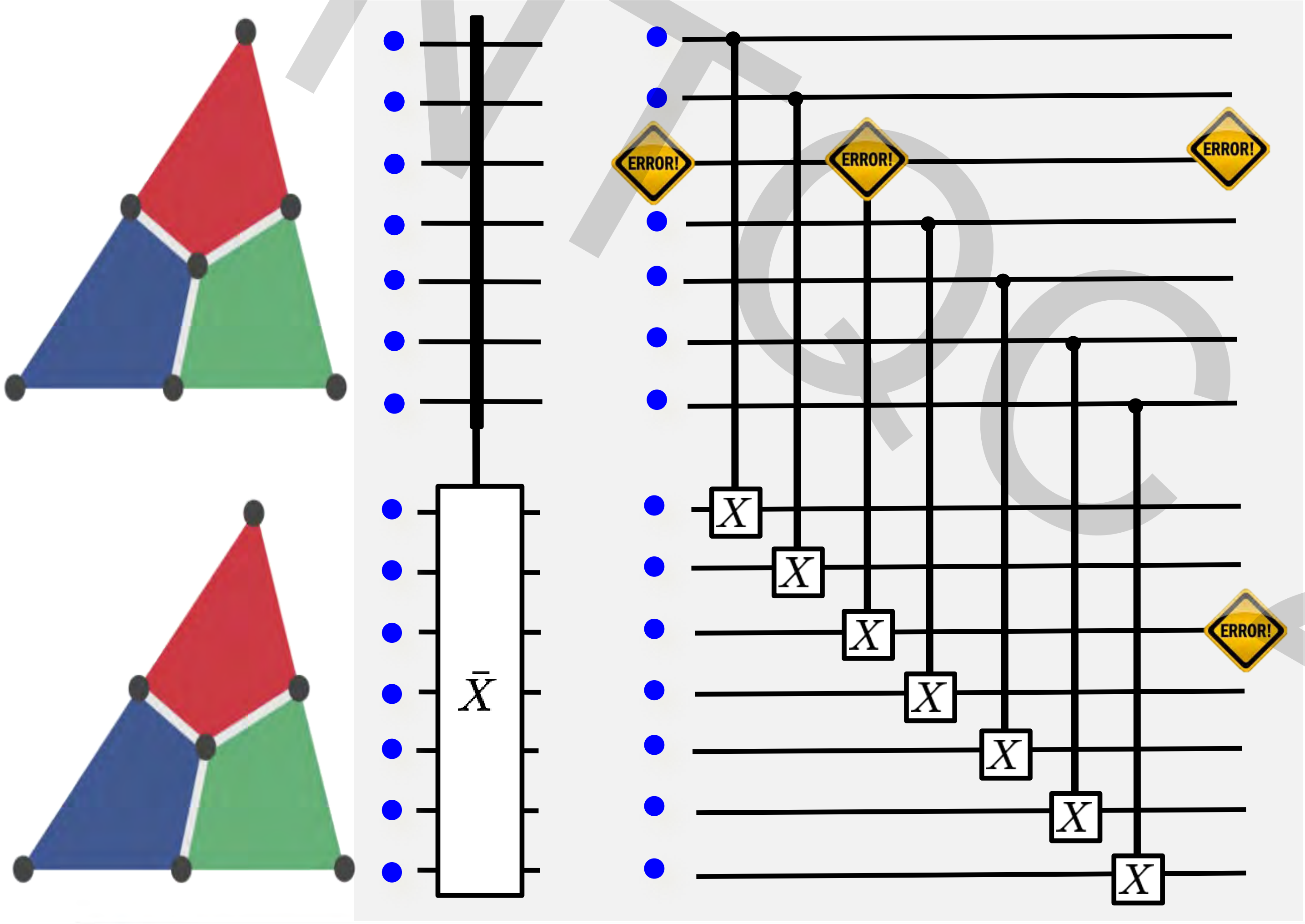
Fault-Tolerant CNOT



Single physical error maps onto two physical errors on different logical qubits!

A **single** physical error leads **always** to a correctable error

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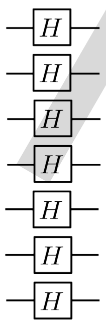
A Universal Gate-Set

Clifford gates

Transversal

Single qubit

Z, X, H, S

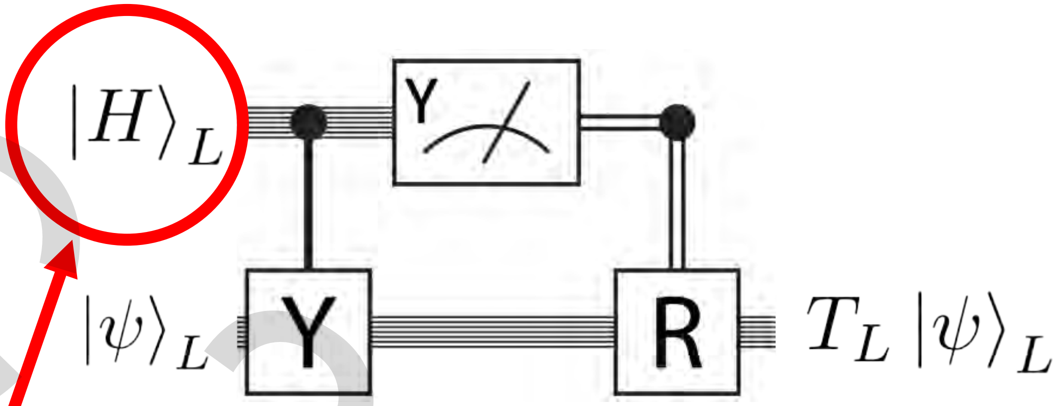


Entangling: CNOT

Universality

T-gate through magic state injection

Solution: Gate teleportation with a fault-tolerant magic state



Challenge: Requires fault tolerant operations on two logical qubits

Magic state – hard to create

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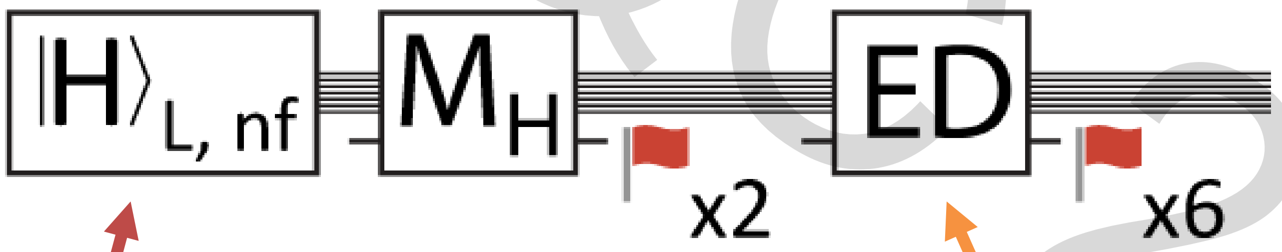
Fault-Tolerant Magic State Preparation

Project in eigenbasis
to reject -1 eigenstates



Guaranteed
magic state with
at most one error

Non-FT preparation

Error detection of
all 6 stabilizers

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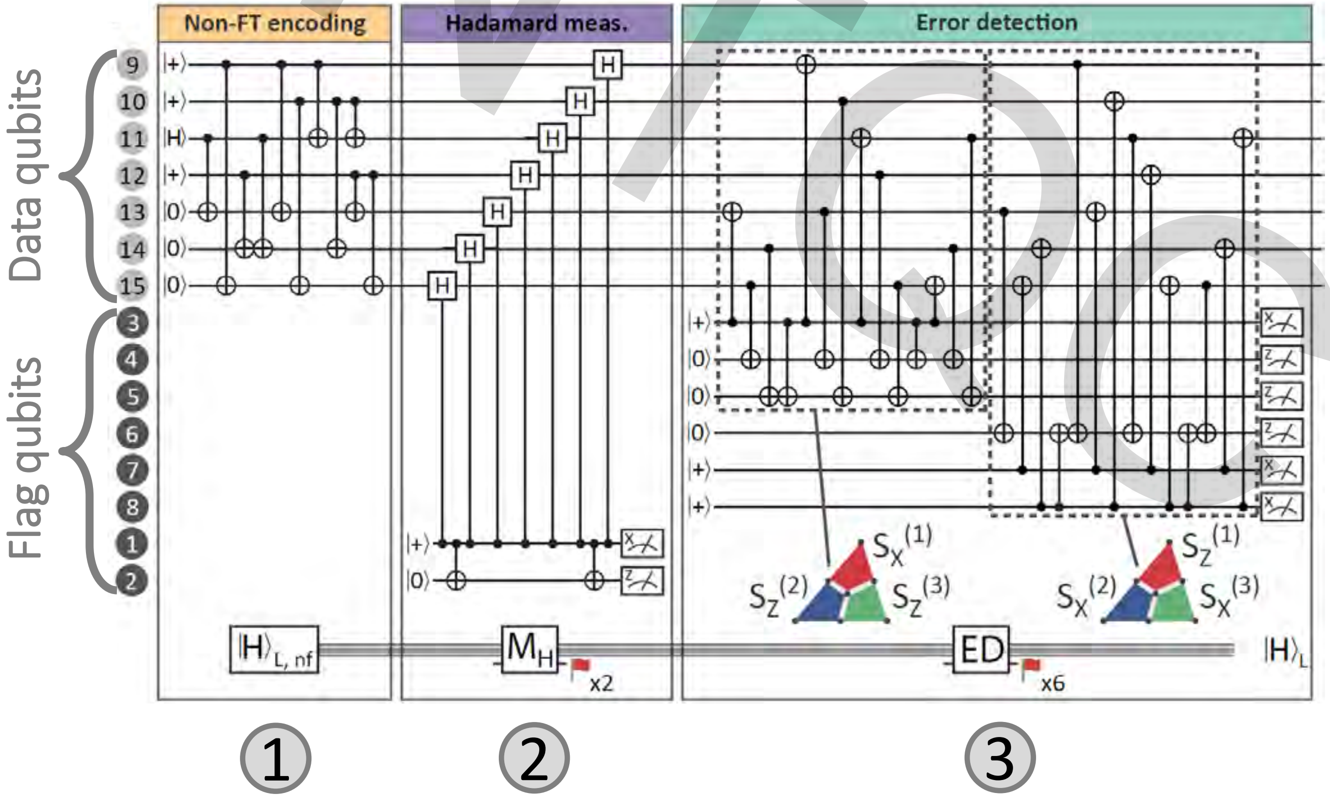
Goto, Scientific Reports 6(1):19578 (2016)

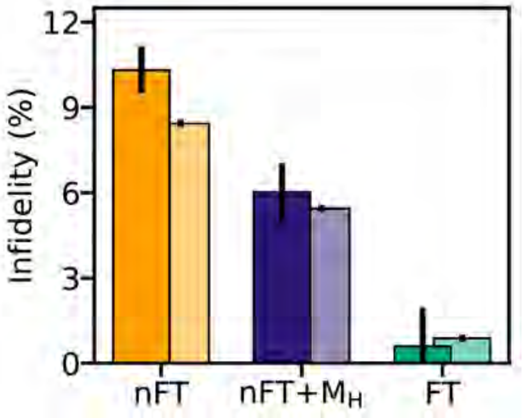
Fault-Tolerant Magic State Preparation



1 Non-FT prepate magic state

2 Measure Hadamard: Magic state is +1-eigenstate

3 Error detection



$$\mathcal{F}_{\mathrm{FT}} = 0.994^{+5}_{-14}$$

Survival rate = 13%

L. Postler et al, Nature **605** 675-680 (2022)

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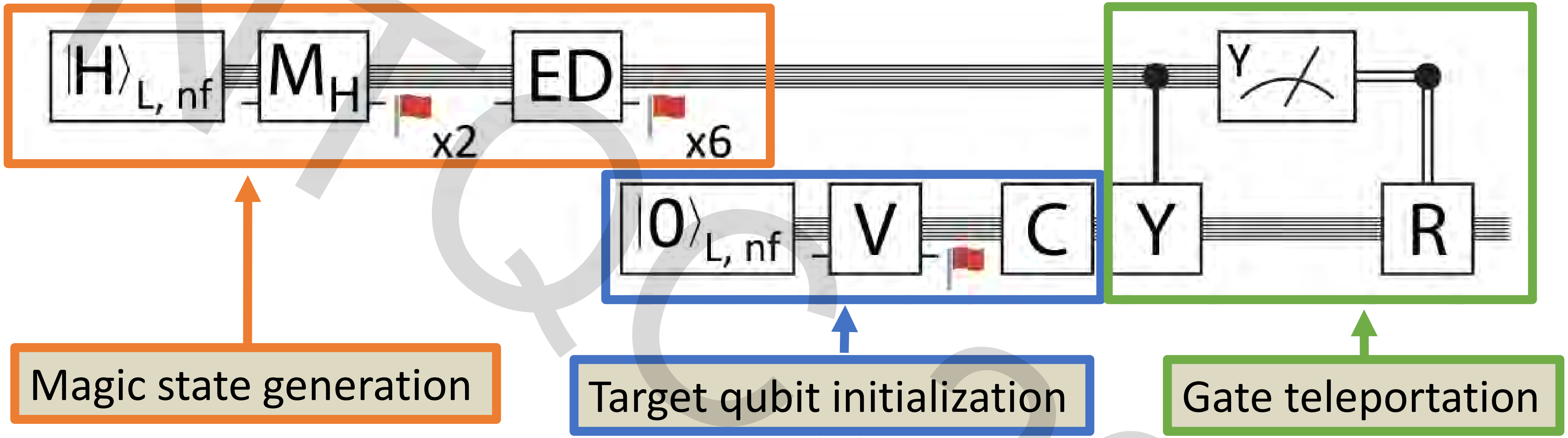
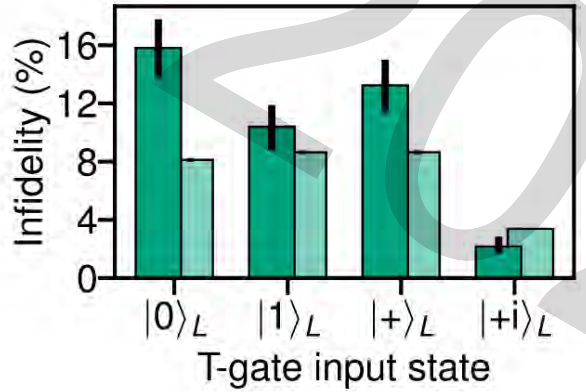
And Gate teleportation



Required resources:

- 2 logical qubits (14 physical qubits)
- 9 Flag-qubits
- 66 entangling operations



Logical error: 10%
Survival rate: 9%

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L. Postler et al, Nature **605** 675-680 (2022)

→ See also: M.P. da Silva et al, arXiv:2404.02280 (2024)

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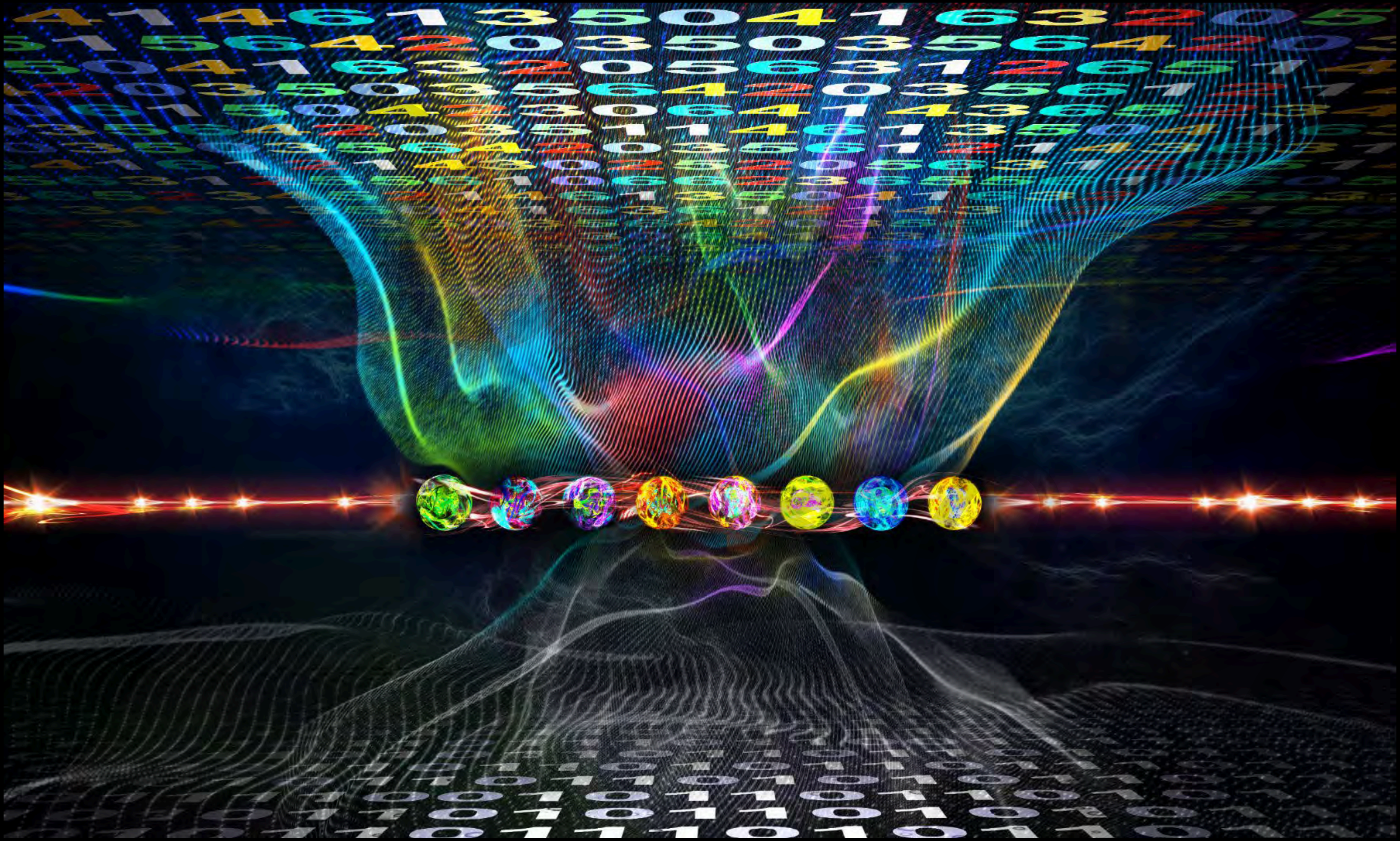
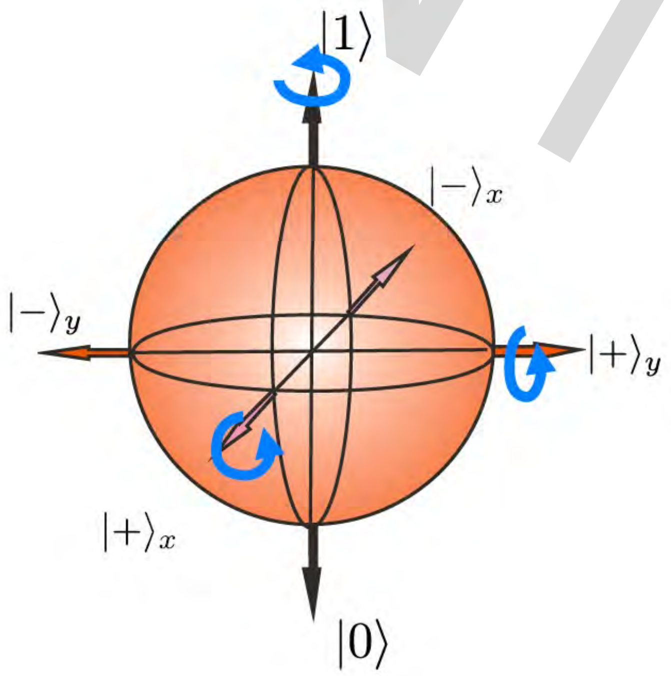
Quantum Information Processing with trapped-ion qudits



Credit: H. Ritsch

Universal Gate Set



Operations on qubits are elements of SU(2).

The Lie algebra is generated by

$$X_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad Y_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad Z_2 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

→ Pauli group: $\langle X_2, Y_2, Z_2 \rangle$

→ Clifford group: $\langle S_2, H_2, \mathrm{CNot} \rangle$ + $T_2 = \begin{pmatrix} 1 & 0 \\ 0 & e^{\frac{i\pi}{4}} \end{pmatrix}$

Universal !

$$S_2 = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \qquad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

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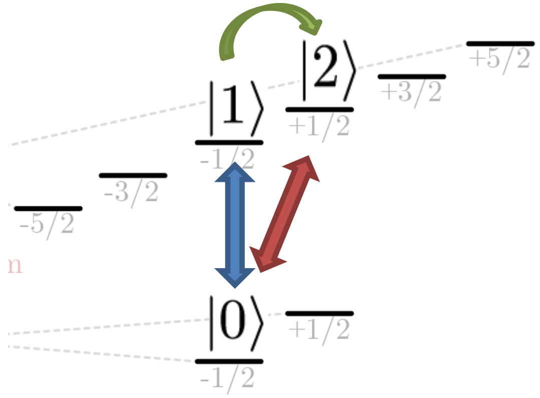
Operations on a qudit



Qudit operations are described by SU(d)

For d=3 the Lie algebra is generated by the Gell-Mann matrices:

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix},$$

$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

su(2) sub-algebras

$$\{\lambda_1, \lambda_2, \lambda_3\}$$

$$\{\lambda_4, \lambda_5, (\lambda_3 + \sqrt{3}\lambda_8)/2\}$$

$$\{\lambda_1, \lambda_2, (-\lambda_3 + \sqrt{3}\lambda_8)/2\}$$

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Qudit operations

"Pauli"

$$Z_d = \omega_d^j |j\rangle\langle j|$$

$$Z_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{2\pi i}{3}} & 0 \\ 0 & 0 & e^{\frac{4\pi i}{3}} \end{pmatrix}$$

$$X_d = |j+1 \pmod{d}\rangle\langle j|$$

$$X_3 = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Clifford

$$S_d = \sum_j \omega_d^{j(j+1)/2} |j\rangle\langle j|$$

$$S_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{2\pi i}{3}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$H_d = \frac{1}{\sqrt{d}} \sum_{j,k} \omega_d^{jk} |k\rangle\langle j|$$

$$H_3 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & e^{\frac{2\pi i}{3}} & e^{-\frac{2\pi i}{3}} \\ 1 & e^{-\frac{2\pi i}{3}} & e^{\frac{2\pi i}{3}} \end{pmatrix}$$

Universal

+

$$T_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{2\pi i}{9}} & 0 \\ 0 & 0 & e^{-\frac{2\pi i}{9}} \end{pmatrix}$$

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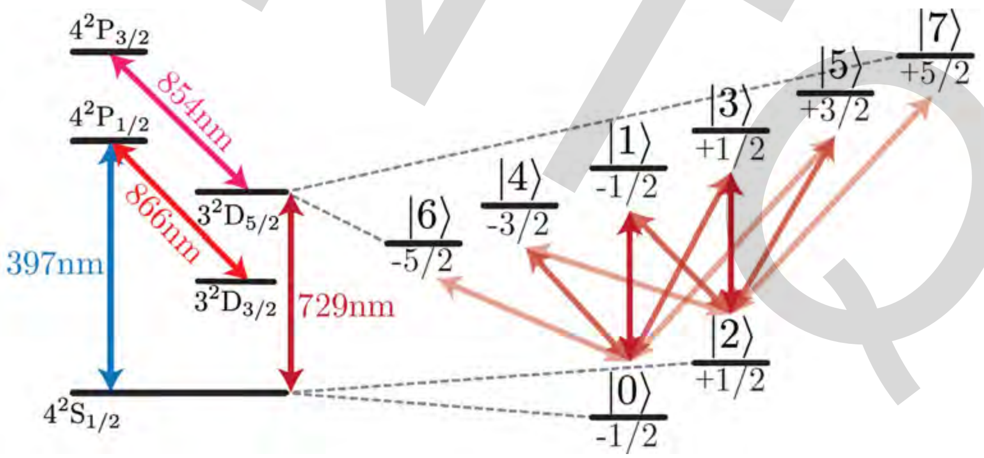
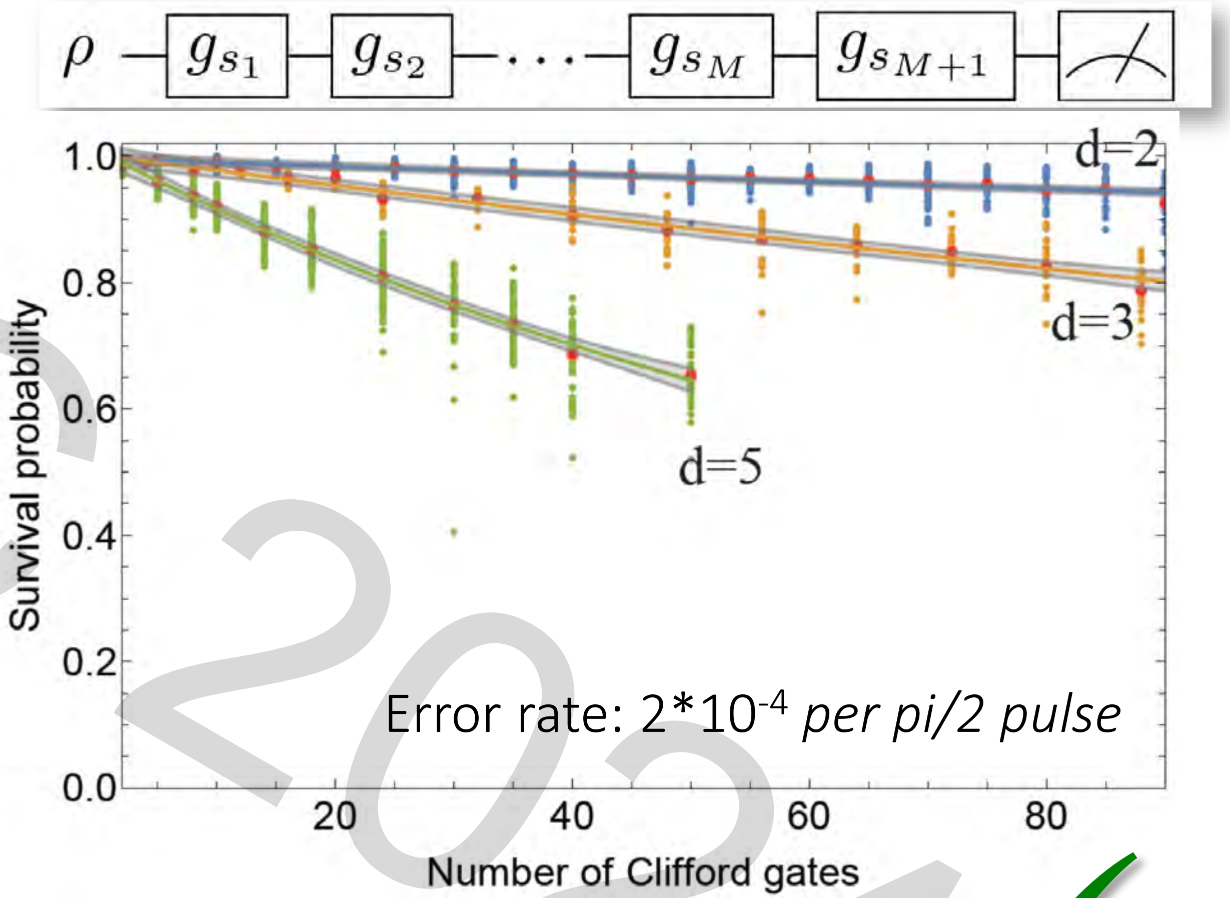
Benchmarking Single Qudit Operations





Efficient decomposition of all local gates

Universal computation with Clifford + T

Consistent performance for all *d*!

MR et al., Nature Physics **18**, 1053 (2022)
K. Mato, et al., QCE 2022

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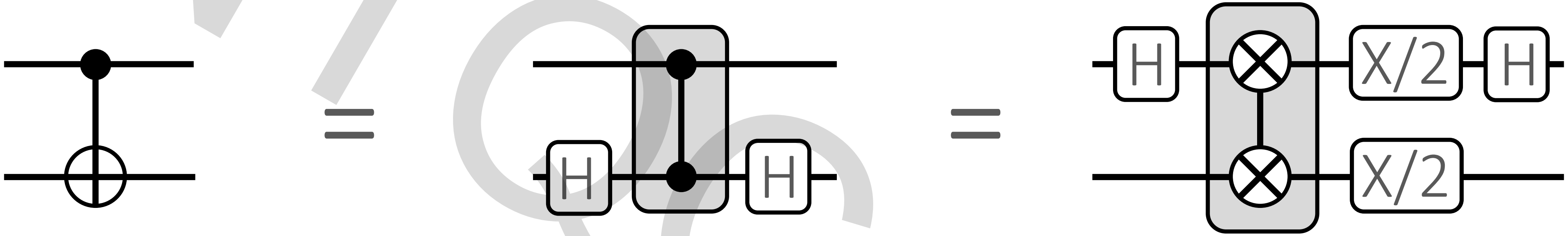
Entangling gates

Universal qubit/qudit QC requires arbitrary local gates + any 1 entangling gate!



$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \qquad \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad \frac{e^{i\pi/4}}{\sqrt{2}}\begin{pmatrix} 1 & 0 & 0 & -i \\ 0 & 1 & -i & 0 \\ 0 & -i & 1 & 0 \\ -i & 0 & 0 & 1 \end{pmatrix}$$

For qubits all entangling gates are equal

For qudits, some are more equal than others

MR et al., Nature Physics **18**, 1053 (2022)

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Qudit entangling gates

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Embedded qubit gates

States such as

$$|00\rangle + |11\rangle$$

Genuine qudit gates

States such as

$$|00\rangle + |11\rangle + |22\rangle$$

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X. Gao, et al., Quantum 7, 1141 (2023)

Qudit entangling gates

QUDITS

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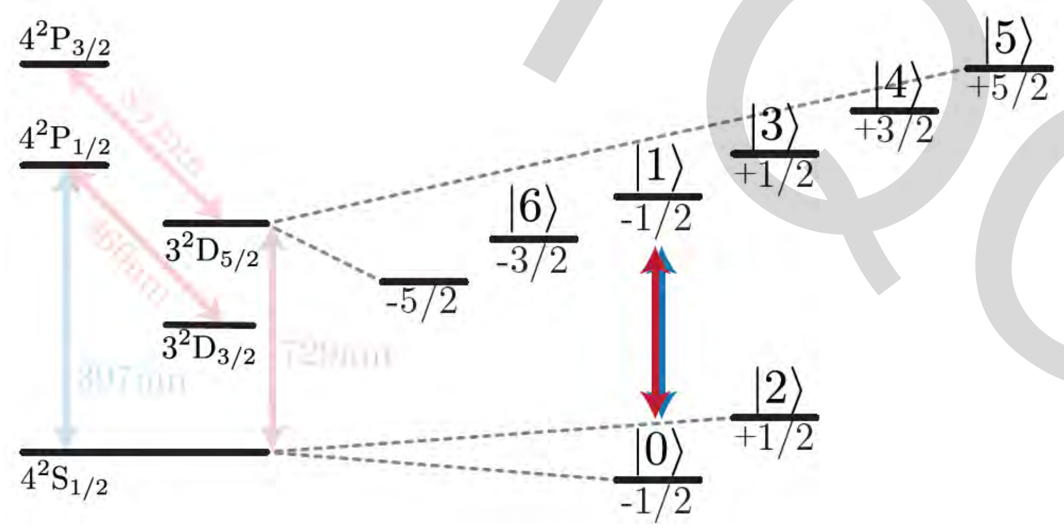
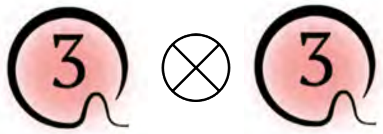
Embedded qubit gates



Two-level entanglement in qudit Hilbert space

→ No drop in fidelity due to larger Hilbert space ✓

Genuine qudit gates



States such as

$$|00\rangle + |11\rangle + |22\rangle$$

MR et al., Nature Physics **18**, 1053 (2022)

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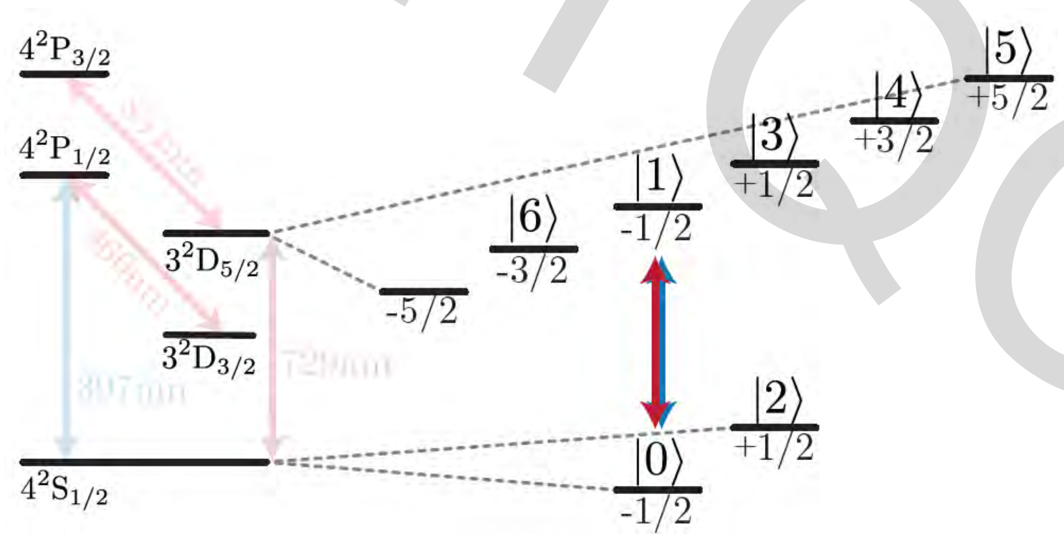
QUDITS

Qudit entangling gates

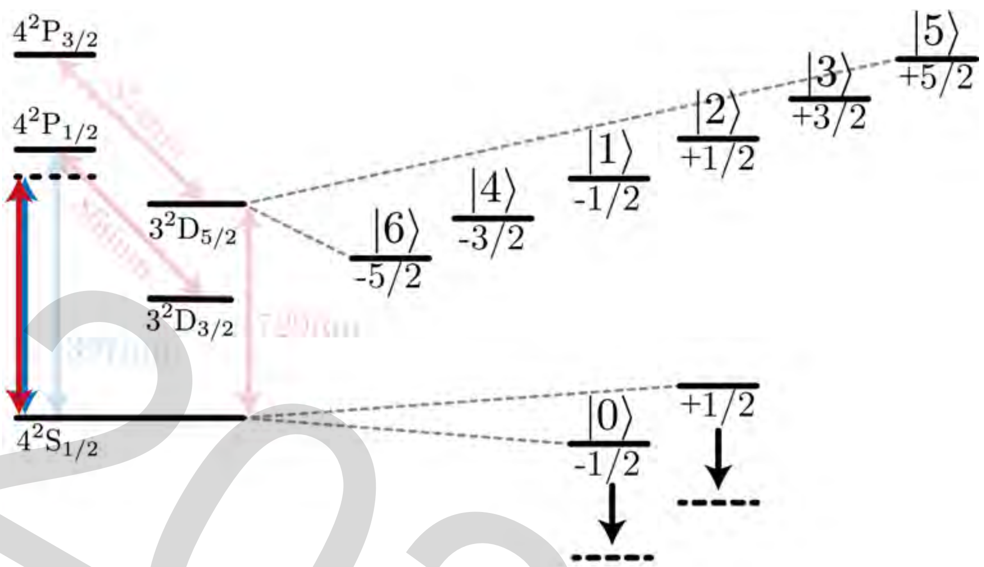
Embedded qubit gates



Two-level entanglement in qudit Hilbert space

→ No drop in fidelity due to larger Hilbert space ✓

Genuine qudit gates



Genuine qutrit gate with F=0.990(4) %

→ One control parameter independent of dim ✓

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MR et al., Nature Physics **18**, 1053 (2022)

P. Hrmo, et al., Nature Commun. **14**, 2242 (2023)

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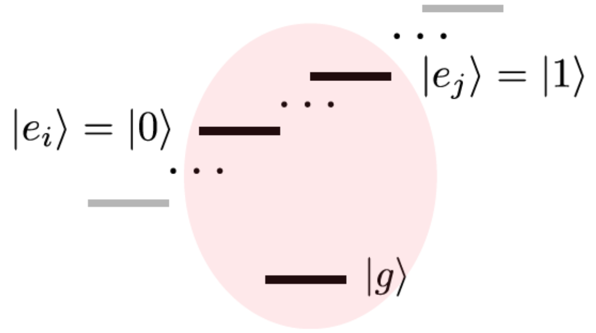
Mixed-dimensional controlled-rotation gates

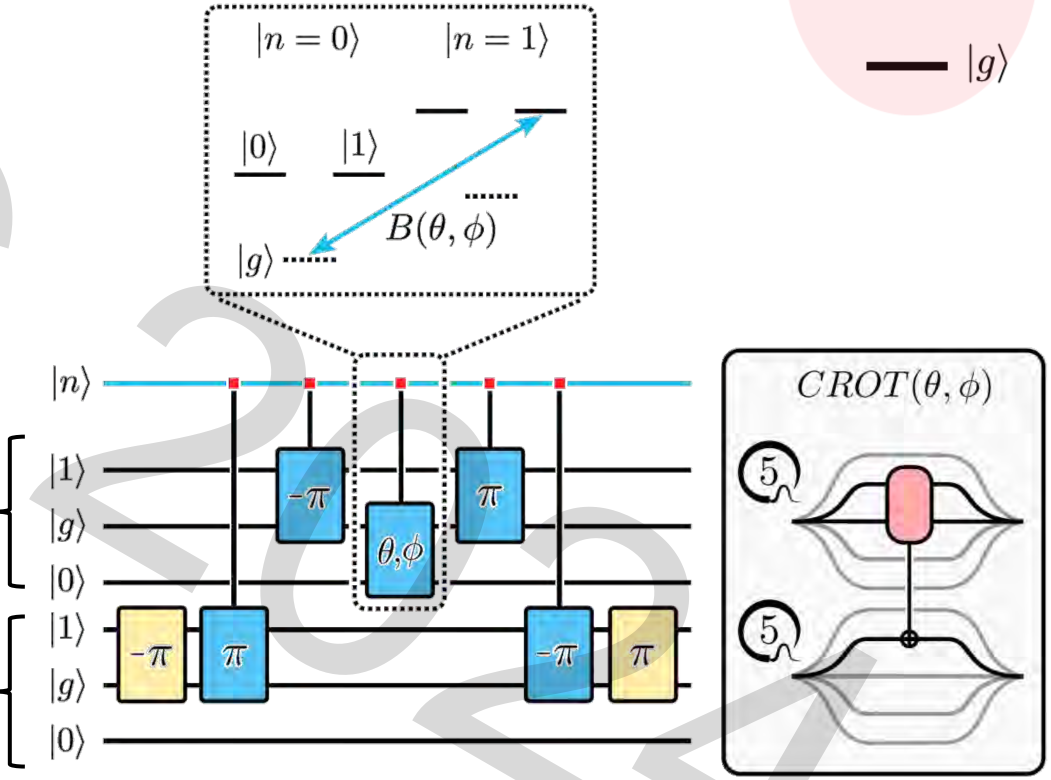
Encode qudit in excited state manifold of $^{40}Ca^{+}$

ground state is (generally) not populated

local blue sideband pulses to mediate interaction



- Any qudit state can serve as control state
- Arbitrary rotation on target qudit
- Mediated via motional mode



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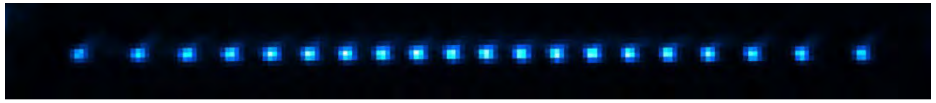
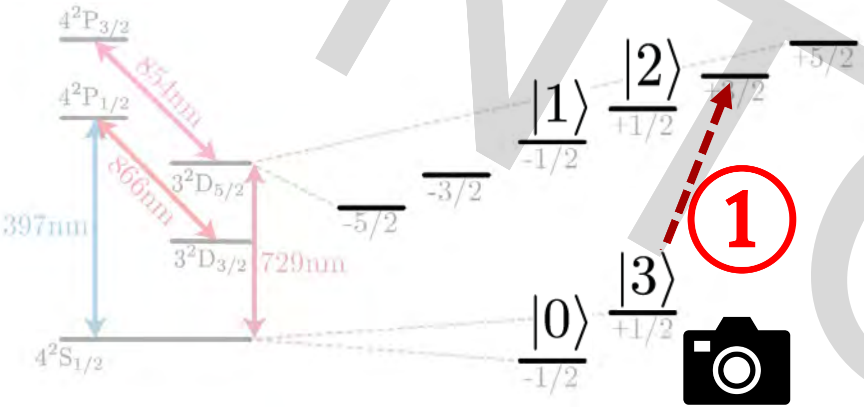
M. Meth, et al., arxiv:2310.12110 (2023)

Qudit Measurement





$\{|0\rangle\langle 0|, \mathbb{1} - |0\rangle\langle 0|\}$

$\{|1\rangle\langle 1|, \mathbb{1} - |1\rangle\langle 1|\}$

$\{|2\rangle\langle 2|, \mathbb{1} - |2\rangle\langle 2|\}$

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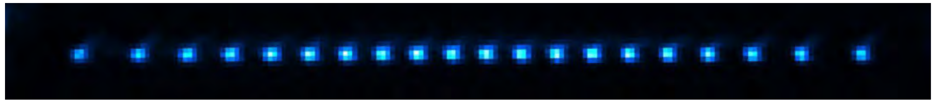
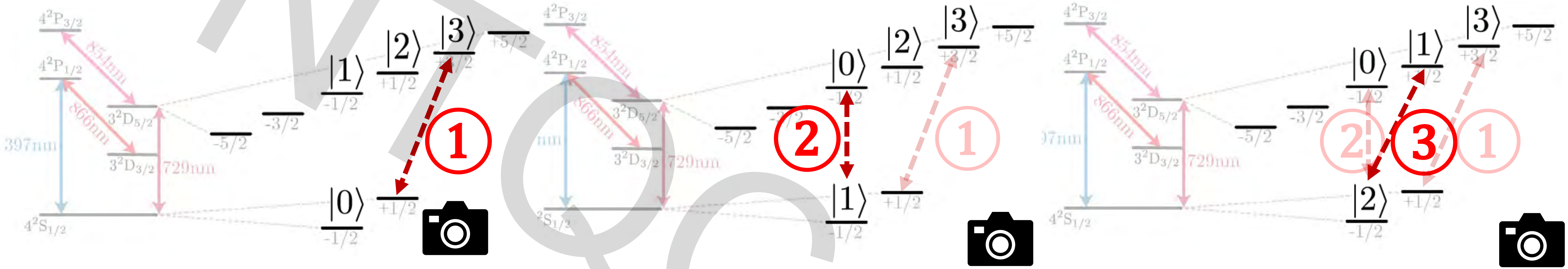
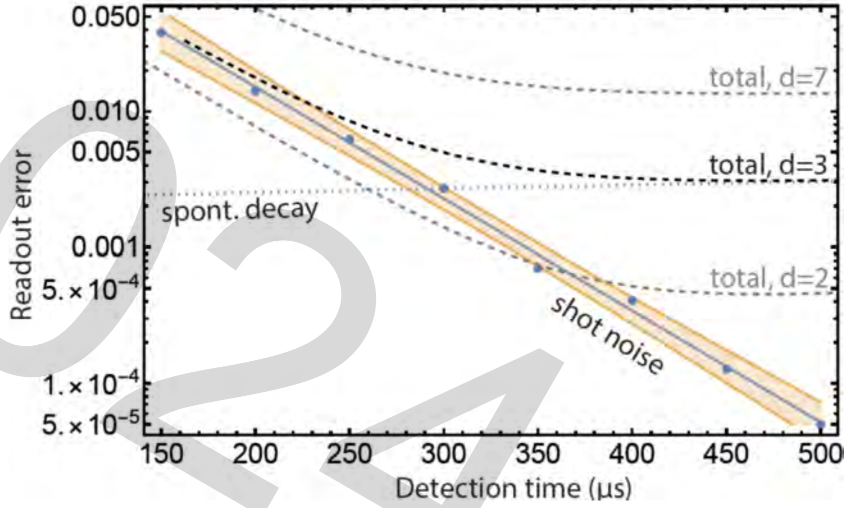
Qudit Measurement





$\{|0\rangle\langle 0|, \mathbb{1} - |0\rangle\langle 0|\}$

$\{|1\rangle\langle 1|, \mathbb{1} - |1\rangle\langle 1|\}$



MR et al., Nature Physics **18**, 1053 (2022)

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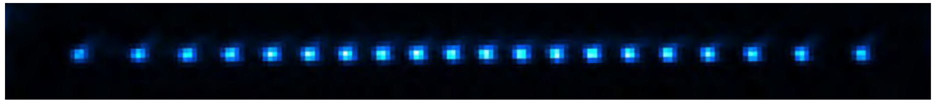
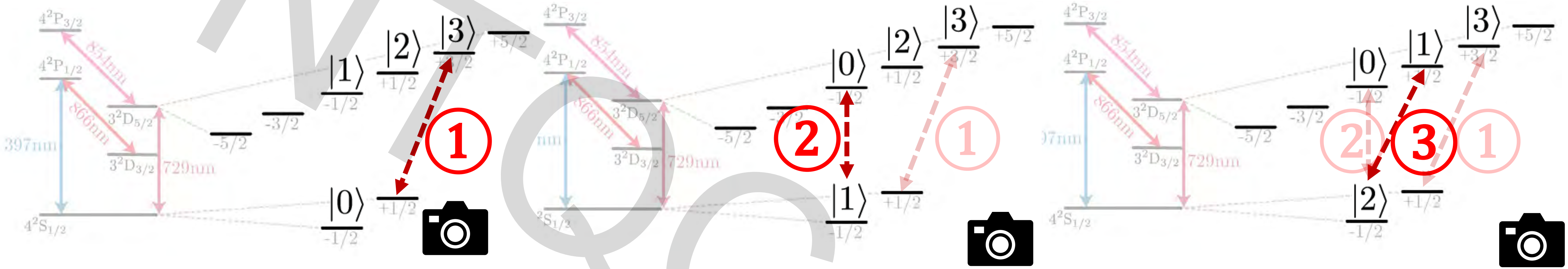
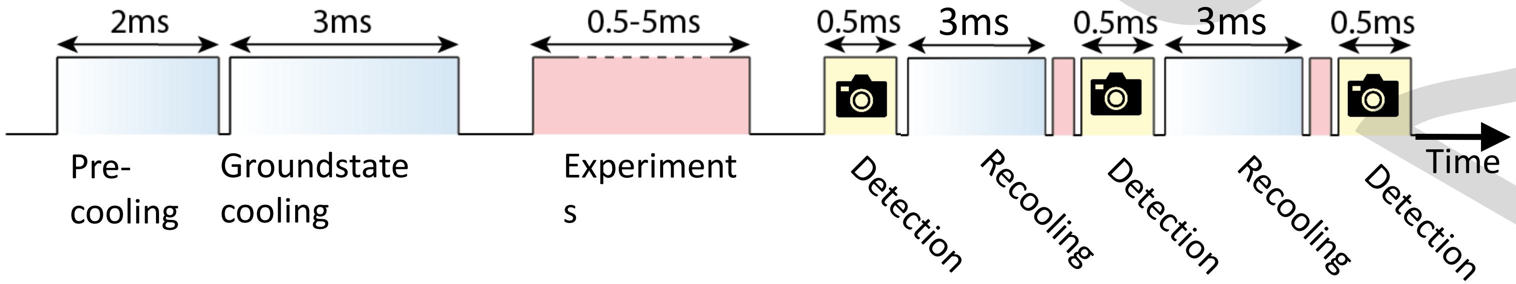
QUDITS

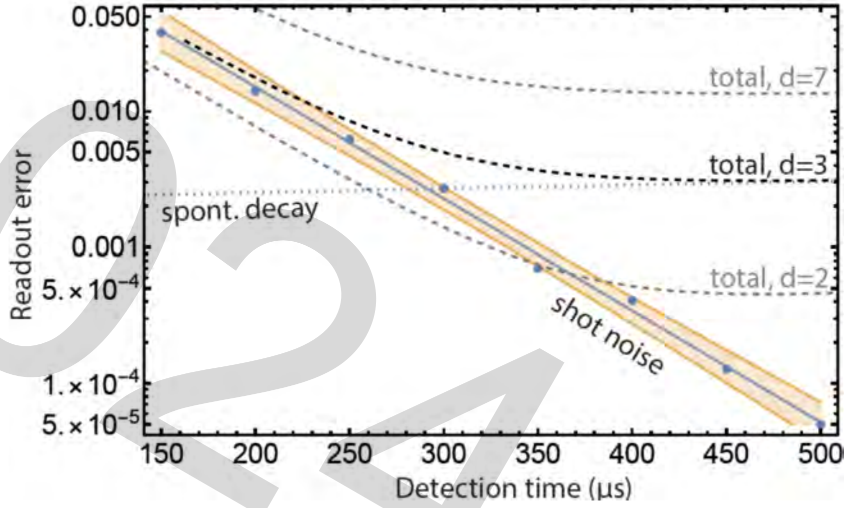
Qudit Measurement







Requires fast detection & recooling!



MR et al., Nature Physics **18**, 1053 (2022)

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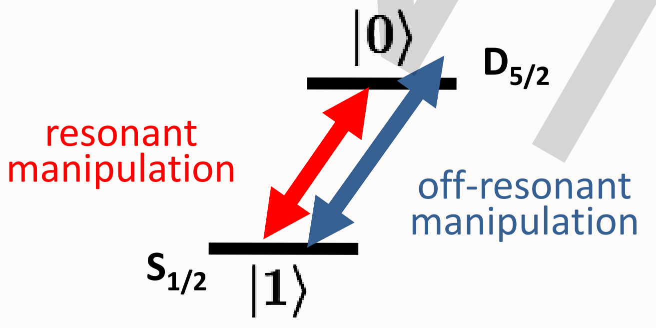
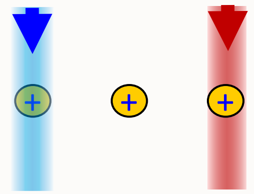
Quantum computing with qudits

Local Operations

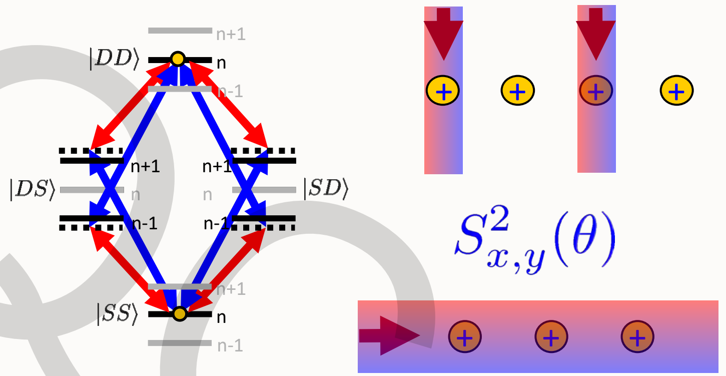


$S_z(\theta)$ $S_{x,y}(\theta)$



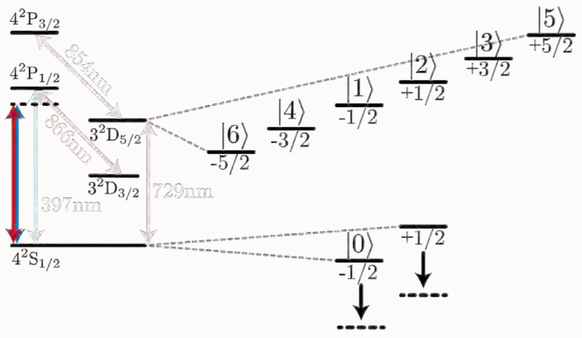
τ = 20µs
F > 99.9%

Qubit Entanglement



F_2 > 99% τ = 100µs

Qudit Entanglement



F_2 > 99% τ = 100µs

Mixed-dimensional Entanglement

F_2 > 99%
τ = 100µs

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M. Ringbauer, et al., Nature Physics 18, 1053 (2022)
P. Hrmo, et al., Nature Commun. 14, 2242 (2023)
M. Meth, et al., arxiv:2310.12110 (2023)

MTQC 2024

2. Quantum Computation and Simulation

2.1 New Generation

2.2 Operations beyond Qubits

2.3 Quantum Error Correction

2.4 QIP with Qudits

2.5 Digital Quantum Simulation

2.6 Scaling

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AG Quantenoptik und Spektroskopie

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Digital Simulation – Universal Quantum Simulator

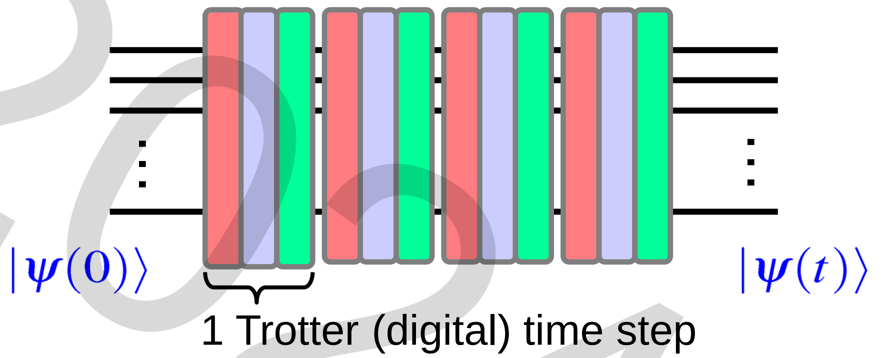
$H = \sum_k h_k$ ⟵ model of some local system to be simulated for a time t

1) build each local evolution operator separately, for small time steps $u_k = e^{-ih_k t/n}$

2) approximate global evolution operator using the Trotter approximation $U = e^{-iHt} \approx \left(e^{-ih_1 \frac{t}{n}} e^{-ih_2 \frac{t}{n}} e^{-ih_3 \frac{t}{n}} \dots e^{-ih_k \frac{t}{n}}\right)^n$

“Efficient for local quantum systems“

S. Lloyd,
Science **273**, 1073 (1996)

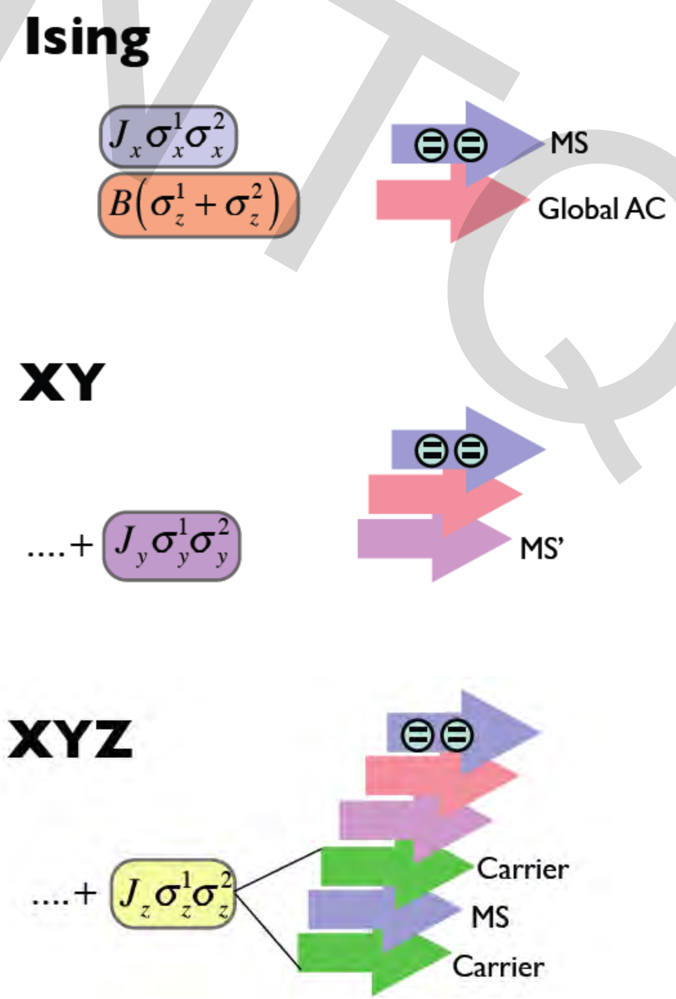


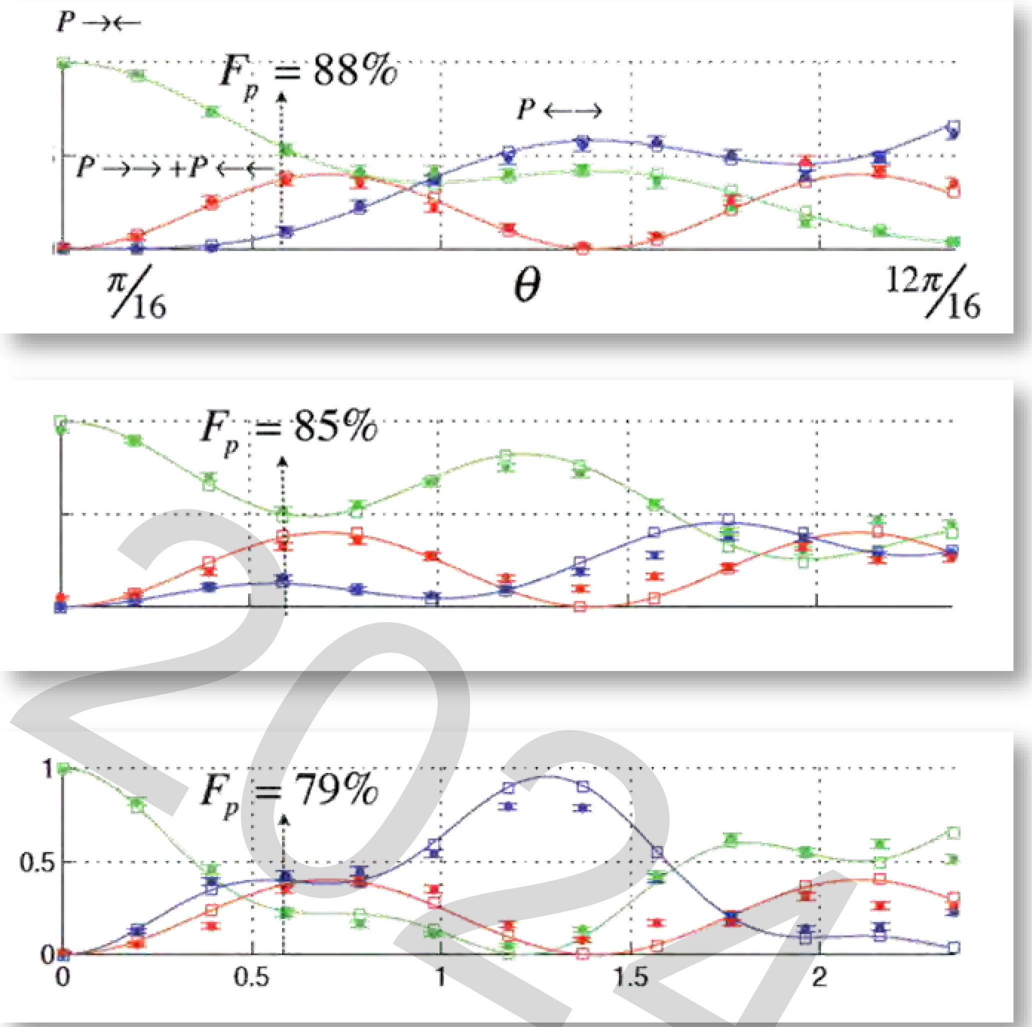
Discretization errors are well behaved
M. Heyl et al, Sci. Adv. **5**, eaau8342 (2019)

R. Blatt, C. Roos, Nat Phys 8, 277 (2012)

NTQC 2024

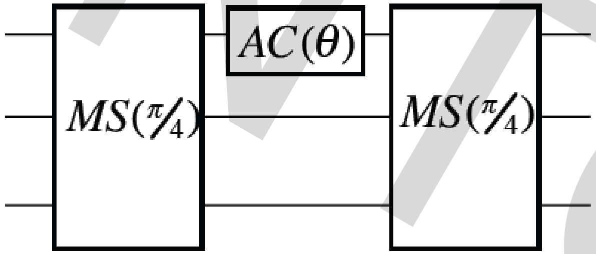
Digital Simulators are flexible





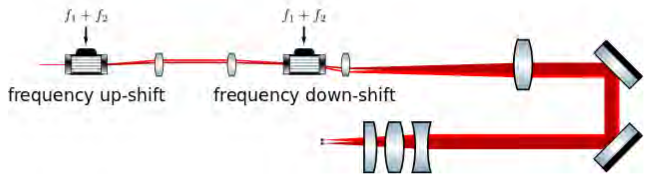
B. Lanyon et al., Science 334, 6052 (2011)

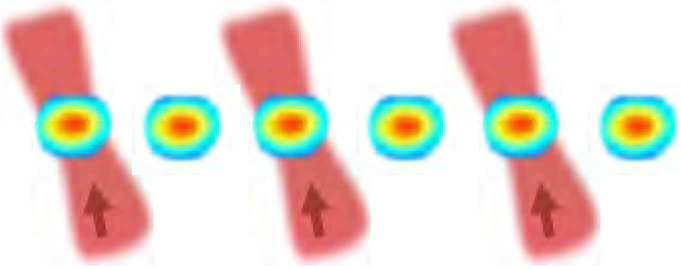
Many-body Interactions

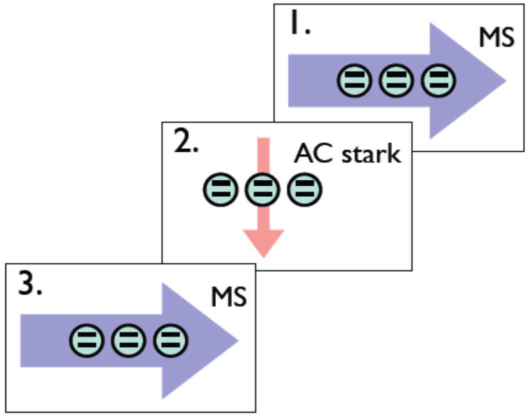


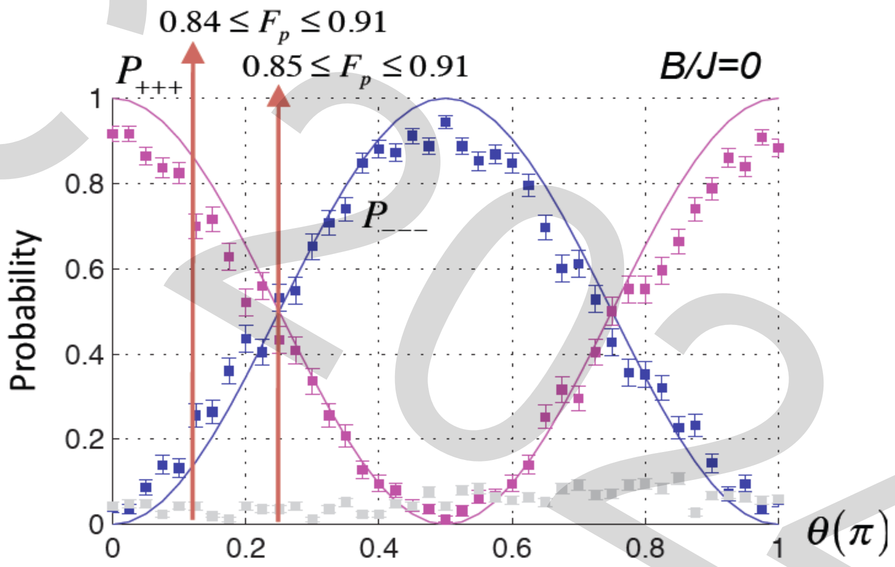
$$= e^{i\sigma_z^1\sigma_x^2\sigma_x^3\theta}$$

Effective 3-body Hamiltonian









M. Müller et al, NJP 13, 085007 (2011)

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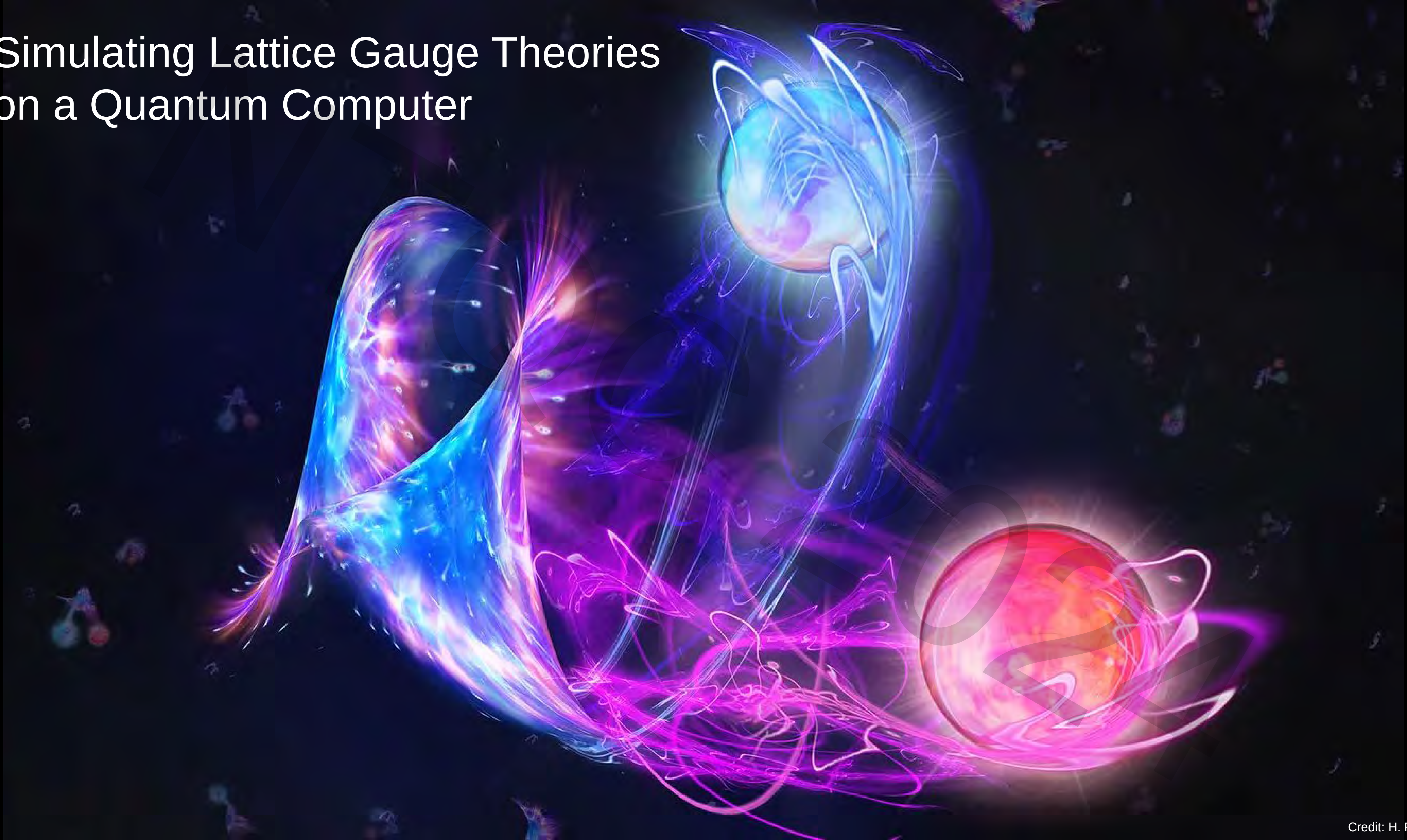
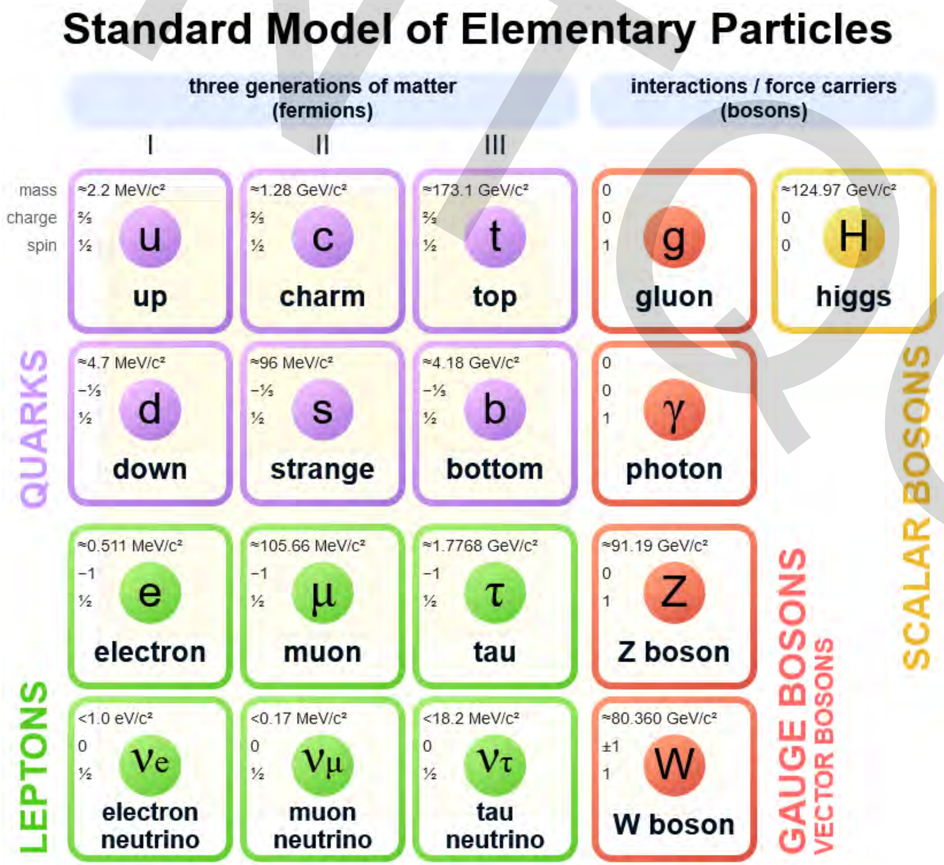
Simulating Lattice Gauge Theories on a Quantum Computer



Credit: H. Ritsch

Gauge Theories



gauge theories describe interactions between particles and forces

e.g. Quantum Electrodynamics

Hard to simulate classically due to sign problems

⬇

quantum simulation

Image source: Uploaded by MissMJ, created by Fermilab, https://en.wikipedia.org/wiki/Standard_Model

Dalmonte, M., & Montangero, S. Contemporary Physics, 57(3), 388–412 (2016)
Banuls, M.C., et al, European Physical Journal D 74, 165 (2020)

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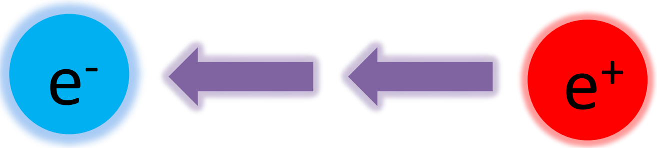
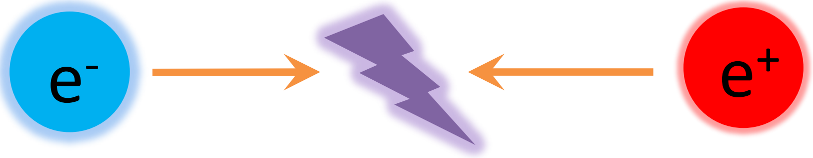
Quantum electrodynamics

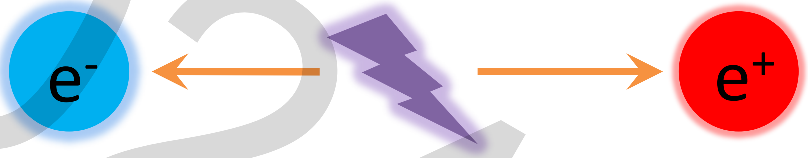
Charged particles (electrons, e^-) and antiparticles ($positrons$, e^+) interact via electromagnetic force fields.



Particles and antiparticles can mutually annihilate.



spontaneous creation of particle-antiparticle pairs in strong static fields (Schwinger mechanism).



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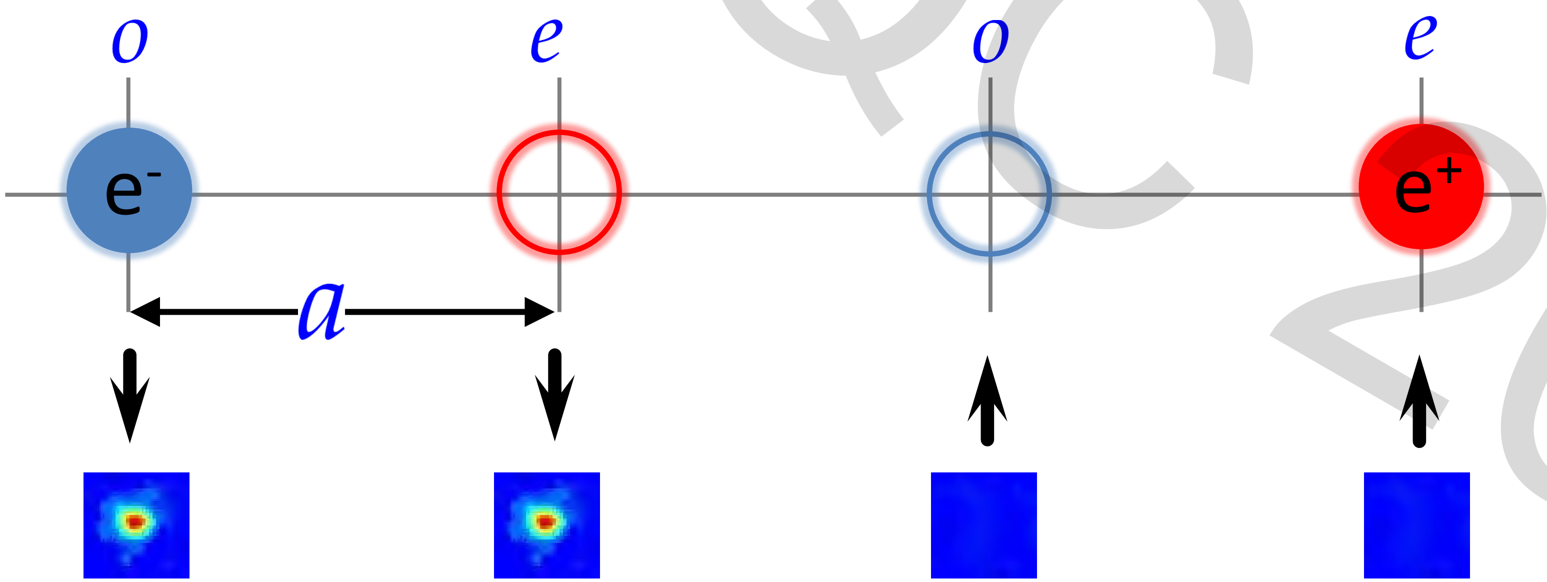
Encoding Fermions into two-level systems

- Fermions (e^-, e^+) and holes are encoded in two-level systems (of ions)
- **Odd(o)** sites: e^-, **even(e)** sites: e^+



Hilbert space

$$|0000\rangle = |\uparrow\downarrow\uparrow\downarrow\rangle$$
$$|e^- e^+ 00\rangle = |\downarrow\uparrow\uparrow\downarrow\rangle$$
$$|0 e^+ e^- 0\rangle = |\uparrow\uparrow\downarrow\downarrow\rangle$$
$$|00 e^- e^+\rangle = |\uparrow\downarrow\downarrow\uparrow\rangle$$
$$|e^- 00 e^+\rangle = |\downarrow\downarrow\uparrow\uparrow\rangle$$
$$|e^- e^+ e^- e^+\rangle = |\downarrow\uparrow\downarrow\uparrow\rangle$$

→ Error detection

C. Muschik et al., NJP 19, 103020 (2017)

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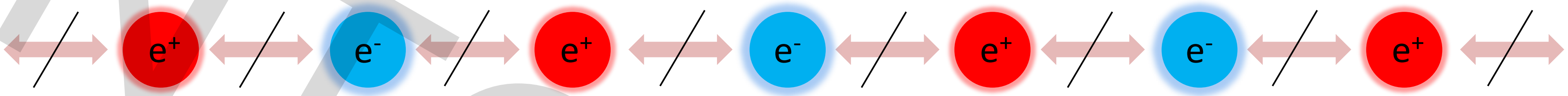
Quantum Simulating Lattice Gauge Theories

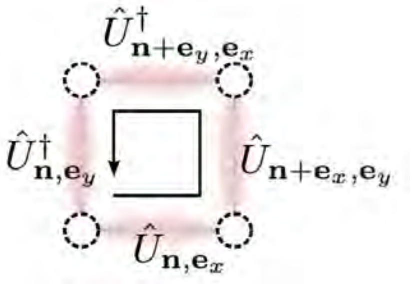


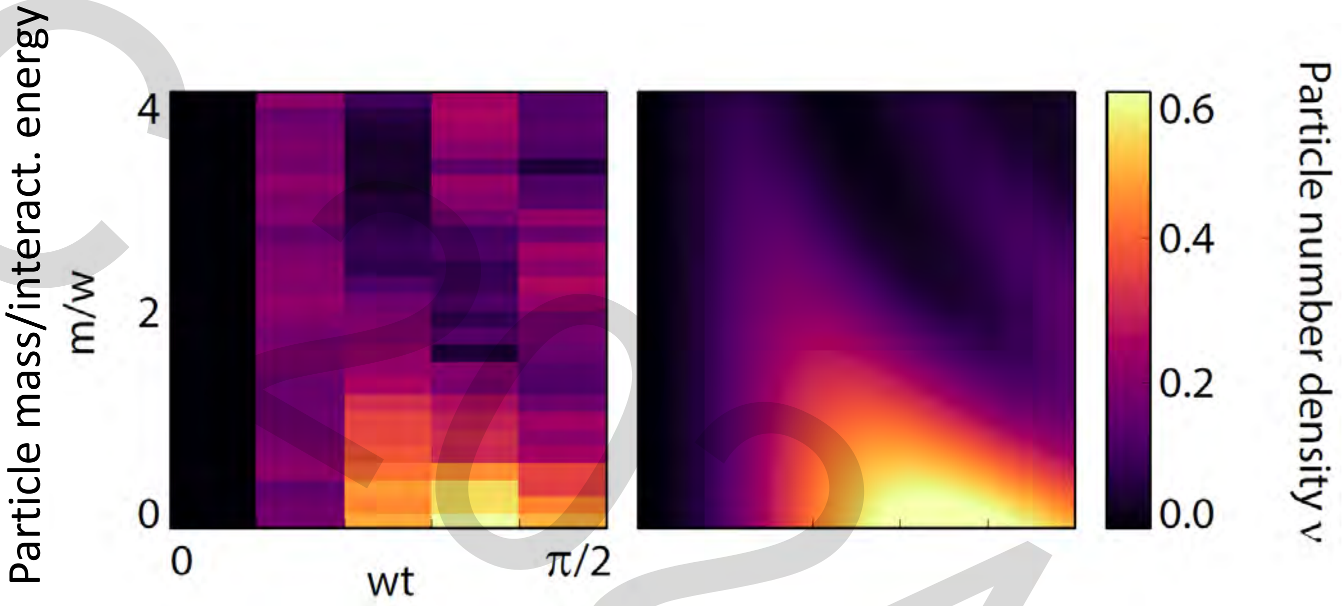
Example: 1D QED

→ Gauge fields can be eliminated

→ No gauge field dynamics

→ No magnetic fields





Physics is different beyond 1D!

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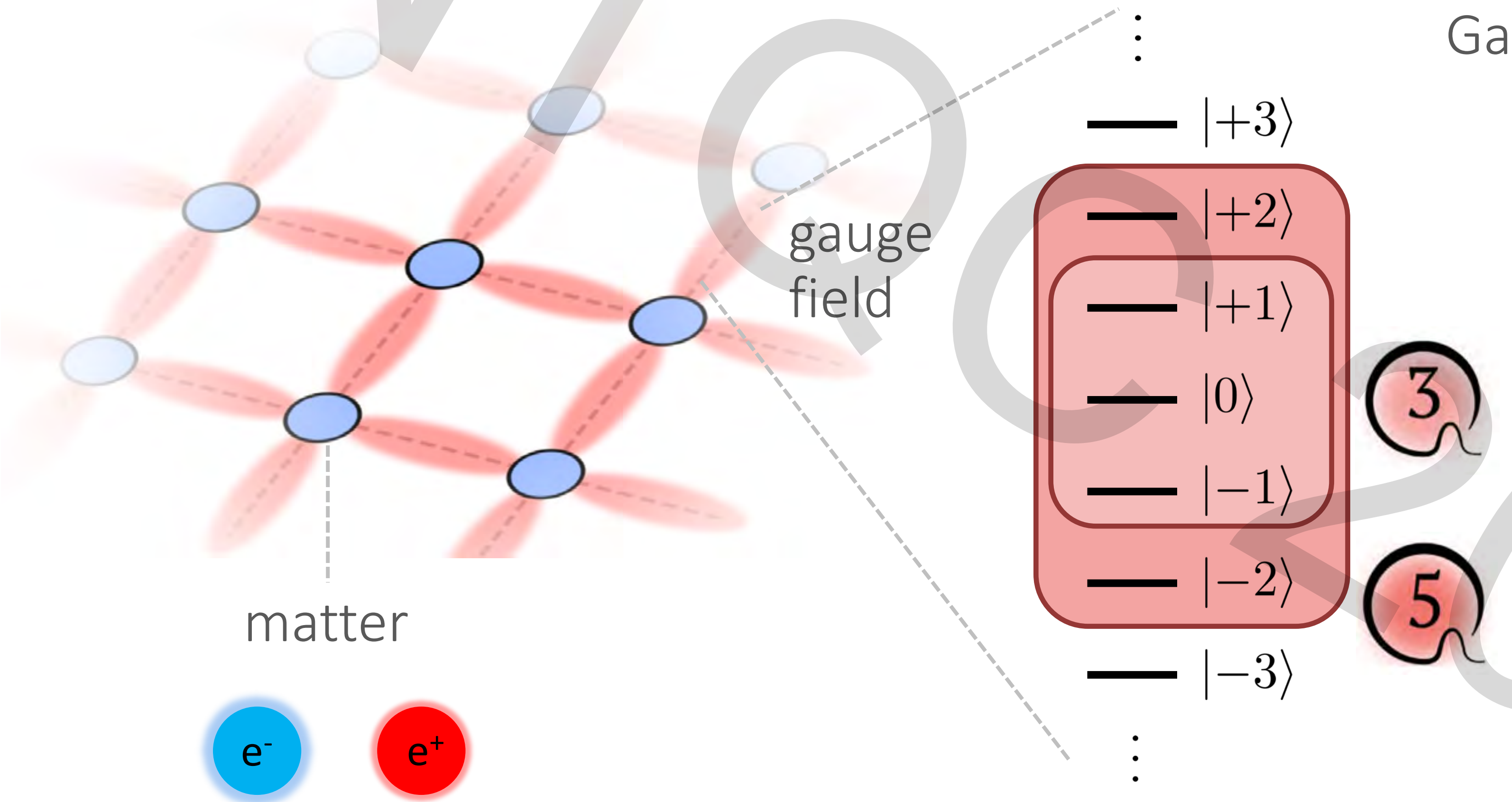
E. Martinez et al., Nature 534, 516 (2016)

C. Muschik et al., NJP 19, 103020 (2017)

Quantum Simulating Gauge Theories



In classical and quantum simulation:

Gauge fields must be truncated

Minimal truncation: d=3

- field in pos direction
- zero
- field in neg direction

Better truncation: d=5

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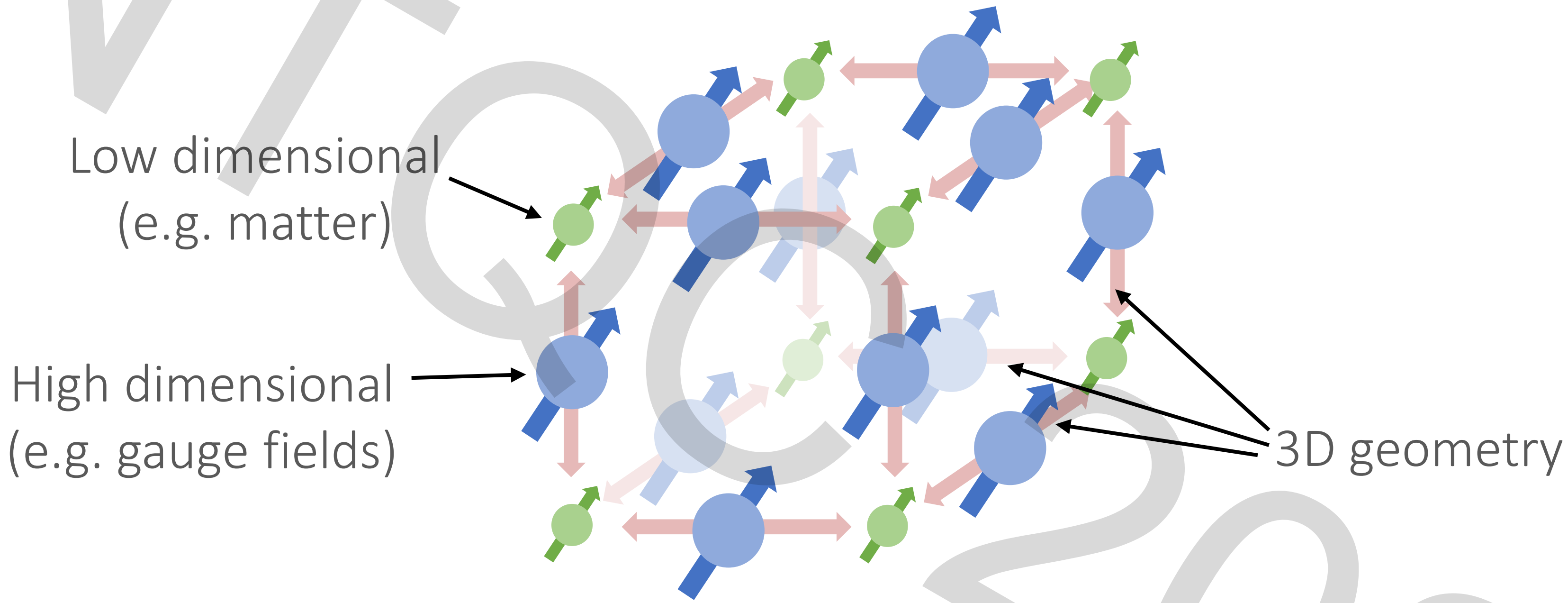
Quantum Simulation of LGTs beyond 1D



✓ Native support for mixed-dimensional systems w/o loss of fidelity

✓ Arbitrary geometries through all-to-all connectivity

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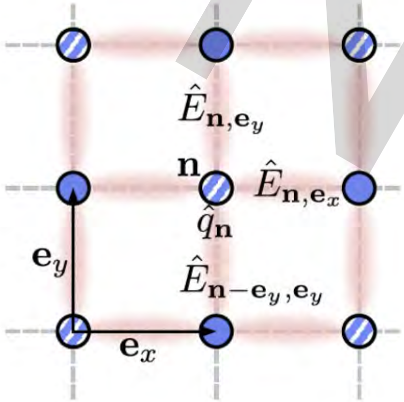
Simulating 2D QED on a Qudit Quantum Computer



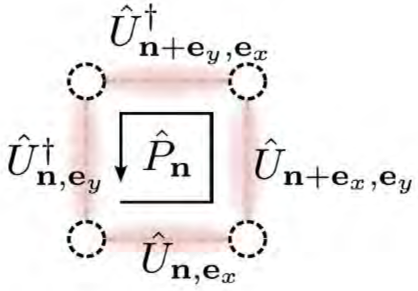
$$\hat{H} = g^2 \hat{H}_E + \frac{1}{g^2}\hat{H}_B + m\hat{H}_m + \Omega\hat{H}_k$$

Electric Field Energy

Particle Rest Mass

Kinetic Energy Term

Magnetic Field Energy



Gauss Law:

$$\hat{G}_{\mathbf{n}} = \sum_{\mu}\left(\hat{E}_{\mathbf{n},\mathbf{e}_\mu} - \hat{E}_{\mathbf{n}-\mathbf{e}_\mu,\mathbf{e}_\mu}\right) - \hat{q}_{\mathbf{n}}$$

J. Haase, et al., Quantum 5, 393 (2021)

D. Paulson, et al., PRX Quantum 2, 030334 (2021)

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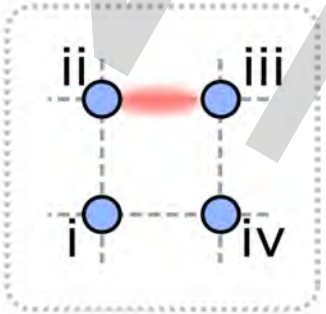
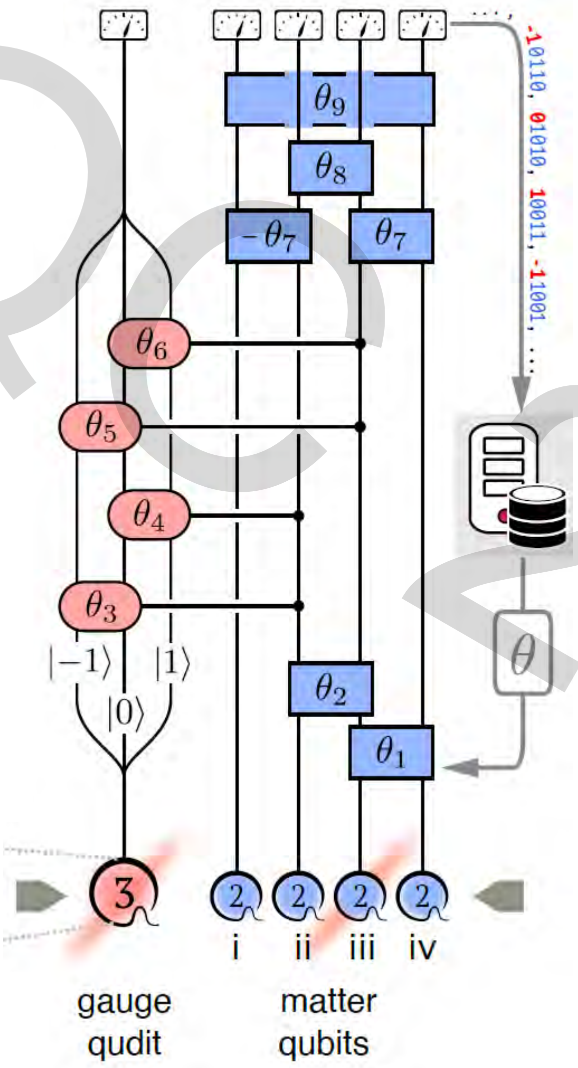
Variational Quantum Simulation of 2D QED

Elementary building block:
Plaquette

$$\hat{H} = g^2 \hat{H}_E + \frac{1}{g}\hat{H}_B + m\hat{H}_m + \Omega\hat{H}_k$$

Goal: prepare groundstate of H by variationally minimizing the energy





<u>**Quantum Computer:**</u>

- Parametrized circuit
- Energy measurement

Classical Computer:

- Hamiltonian
- Parameter optimization

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Simulating 2D QED on a qudit quantum computer

QUDITS

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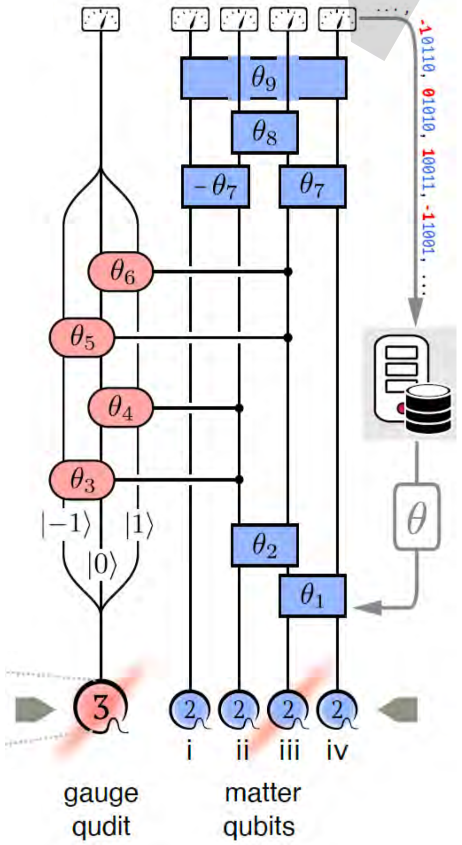
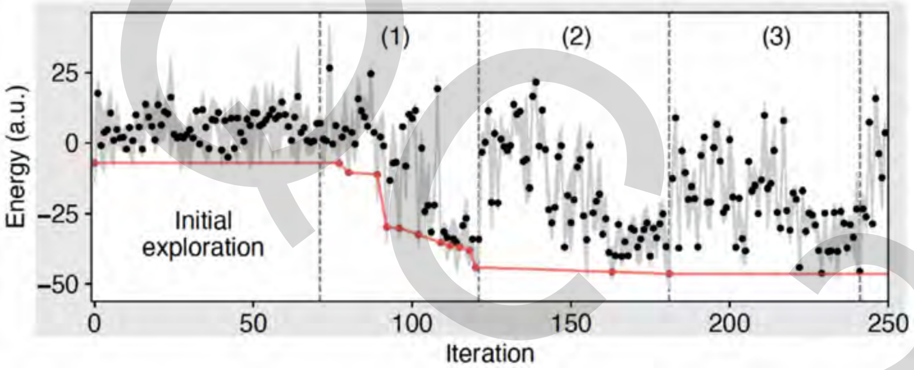
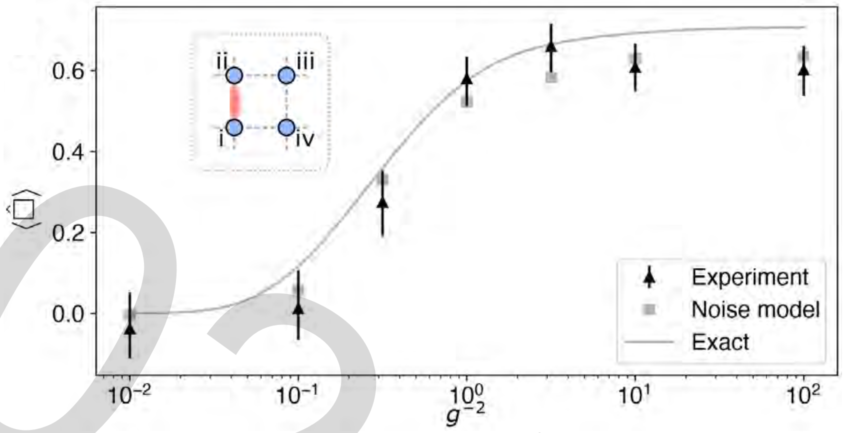
Mixed-dimensional VQE



Ground-state preparation



Plaquette expectation value



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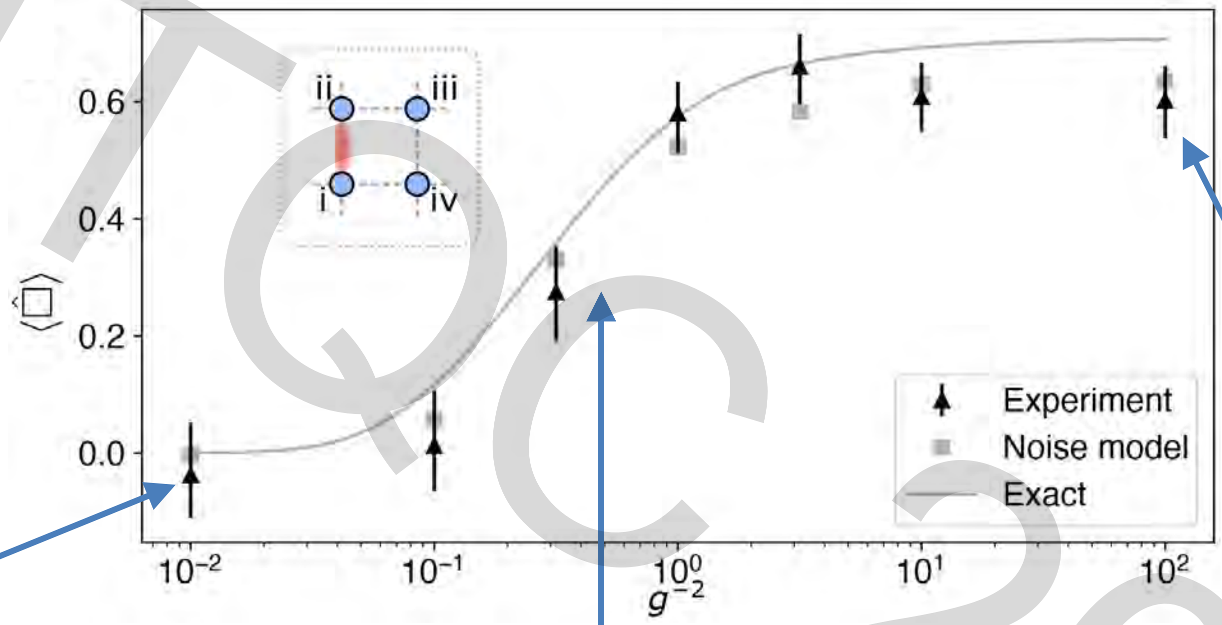
M. Meth, et al., arxiv:2310.12110 (2023)

Simulating 2D QED on a qudit quantum computer



Strong-coupling regime
- Pair generation suppressed
- No Magnetic fields

Intermediate regime
- Competition between pair generation and field energy terms
- Dynamical magnetic fields

Weak-coupling regime
- Magnetic-field dominated
- No entanglement with matter

M. Meth, et al., arxiv:2310.12110 (2023)

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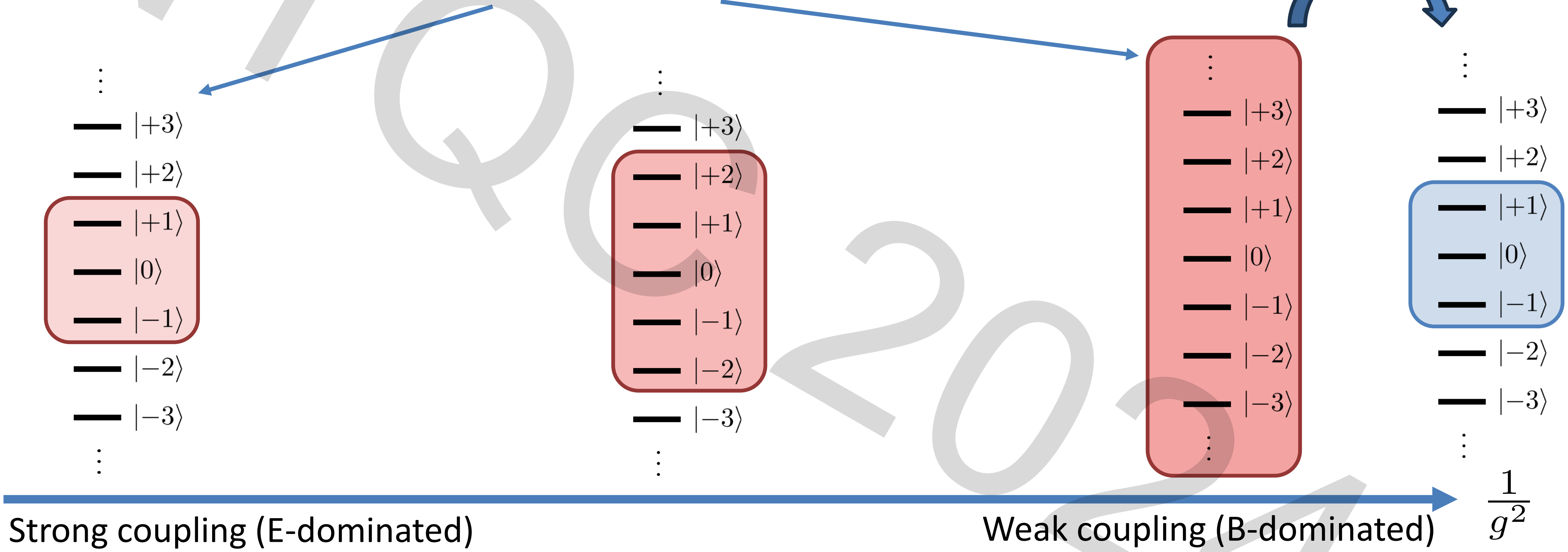
Truncation strategies for a pure gauge plaquette

$$\hat{H} = g^2 \hat{H}_E + \frac{1}{g^2} \hat{H}_B + m\hat{H}_m + \Omega \hat{H}_k$$



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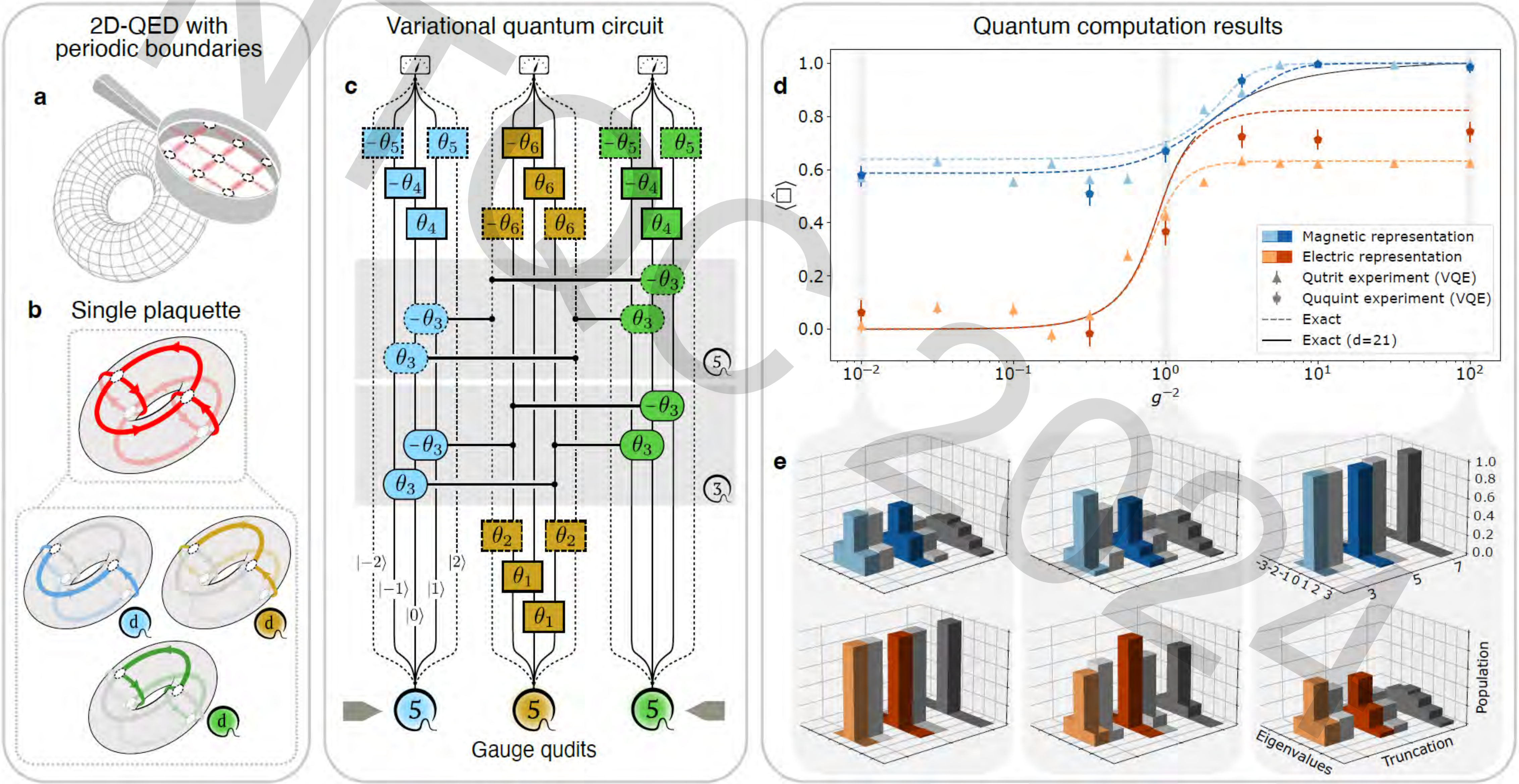
J. Haase, et al., Quantum 5, 393 (2021)

D. Paulson, et al., PRX Quantum 2, 030334 (2021)

Pure gauge 2D QED



Hardware efficient encoding

	Qudit encoding			Qubit encoding		
dimension d	3	5	7	3	5	7
register size	5	5	5	7	9	11
CNOT count	26	34	42	90	162	234
CNOT fidelity	99%					
approx. circ. fid.	77%	71%	66%	40%	20%	10%
CNOT fidelity	99.5%					
approx. circ. fid.	88%	84%	81%	64%	44%	31%

← Gauge+Matter

Pure gauge →

	Qudit encoding			Qubit encoding		
dimension d	3	5	7	3	5	7
register size	3	3	3	9	15	21
CNOT count	8	8	8	84	108	132
CNOT fidelity	99%					
approx. circ. fid.	92%	92%	92%	43%	34%	27%
CNOT fidelity	99.5%					
approx. circ. fid.	96%	96%	96%	66%	58%	52%

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2. Quantum Computation and Simulation

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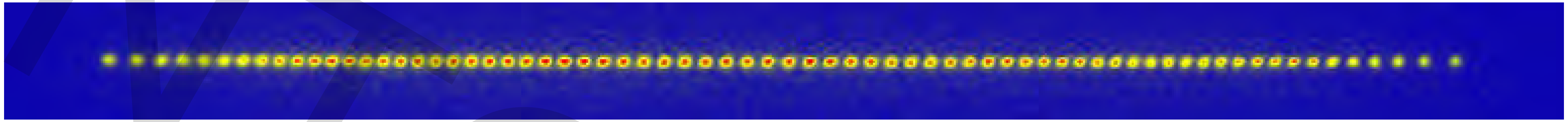
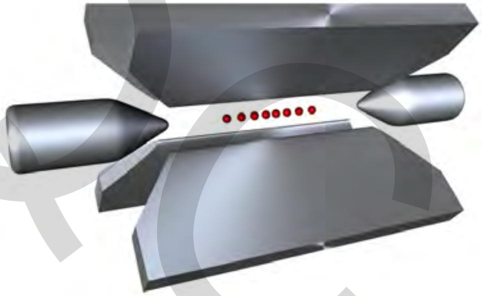
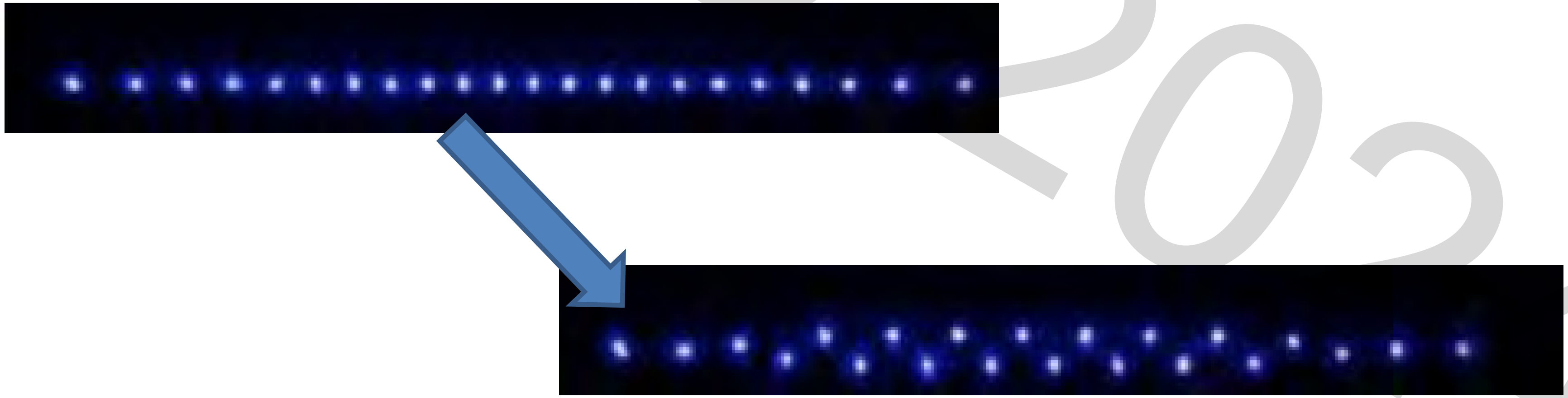
Are ion traps scalable?







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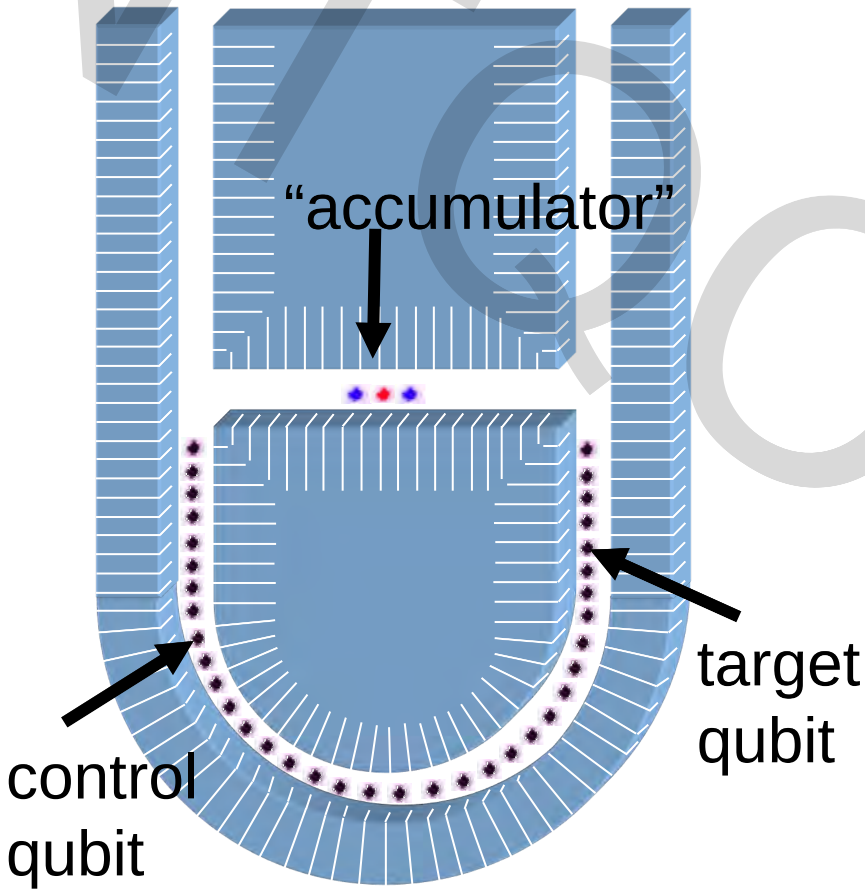
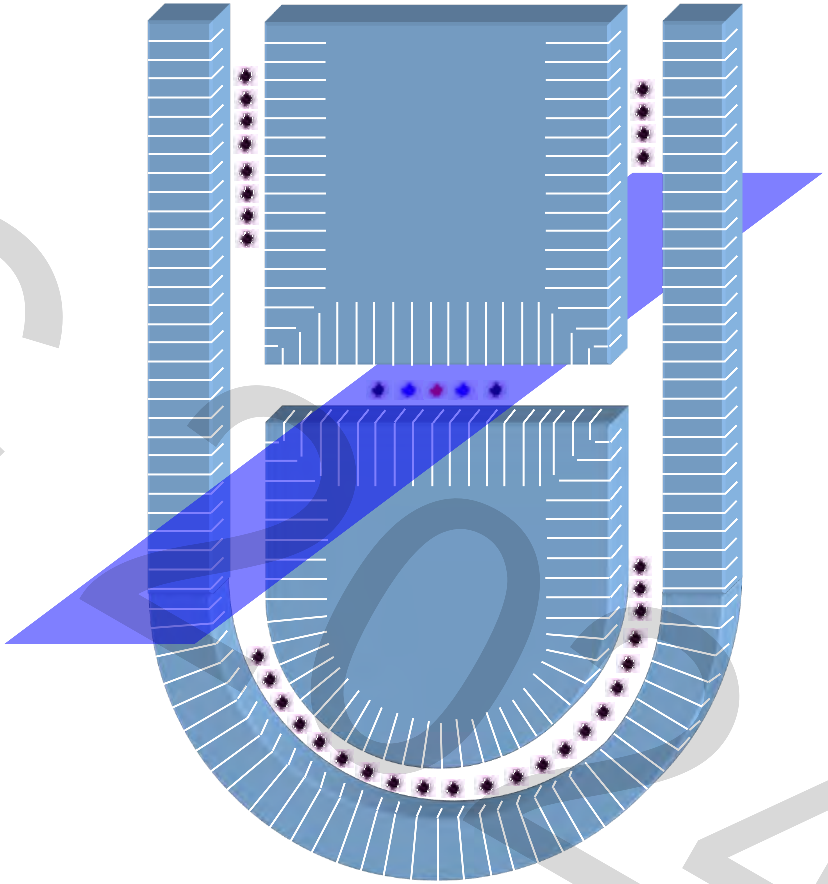
Ion shift register (CCD)





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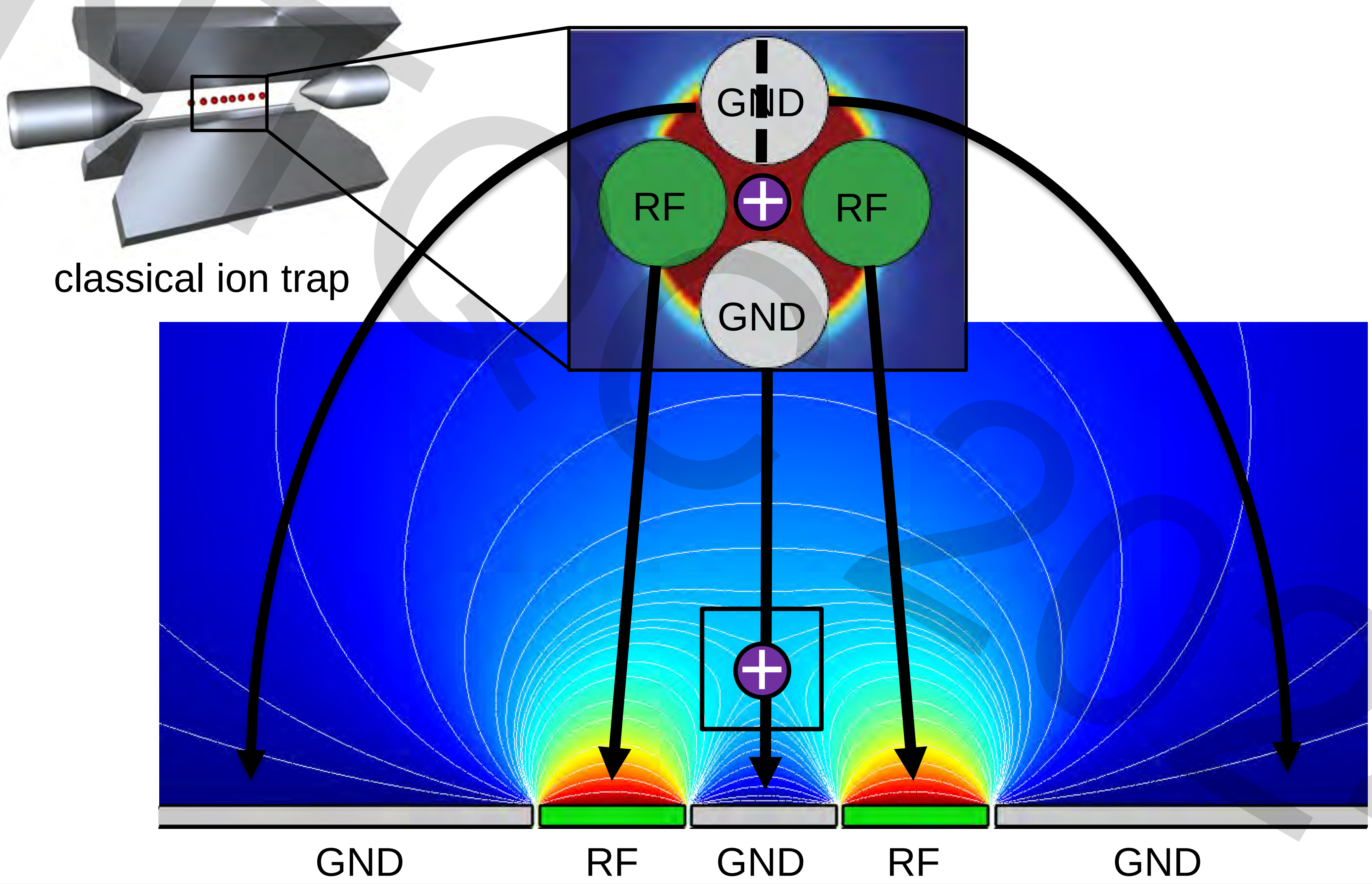
D. Wineland, Boulder, USA
Kieplinski et al, Nature 417, 709 (2002)

Planar Ion Traps



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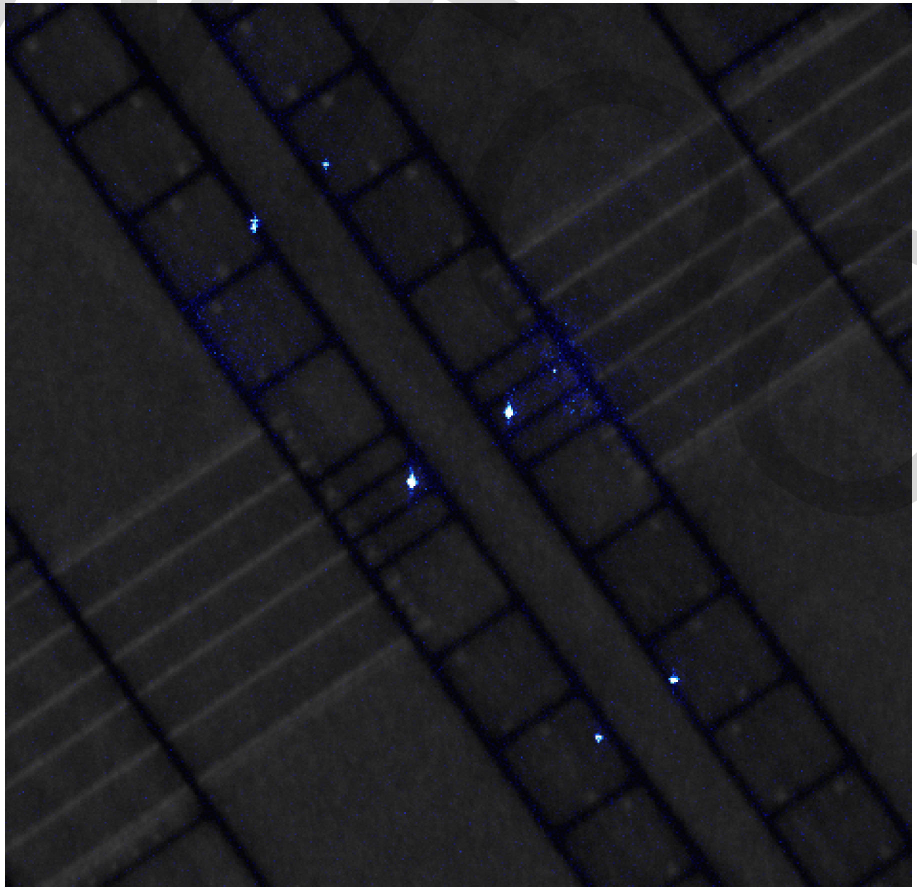
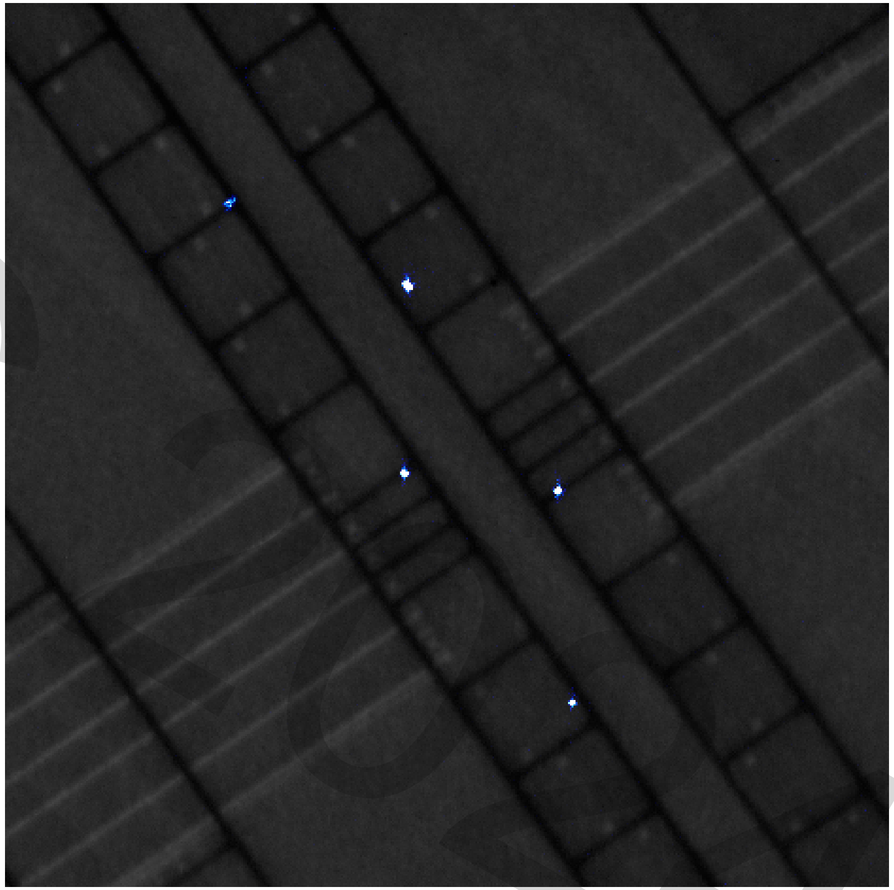
2D ion trap arrays

PIEDMONS





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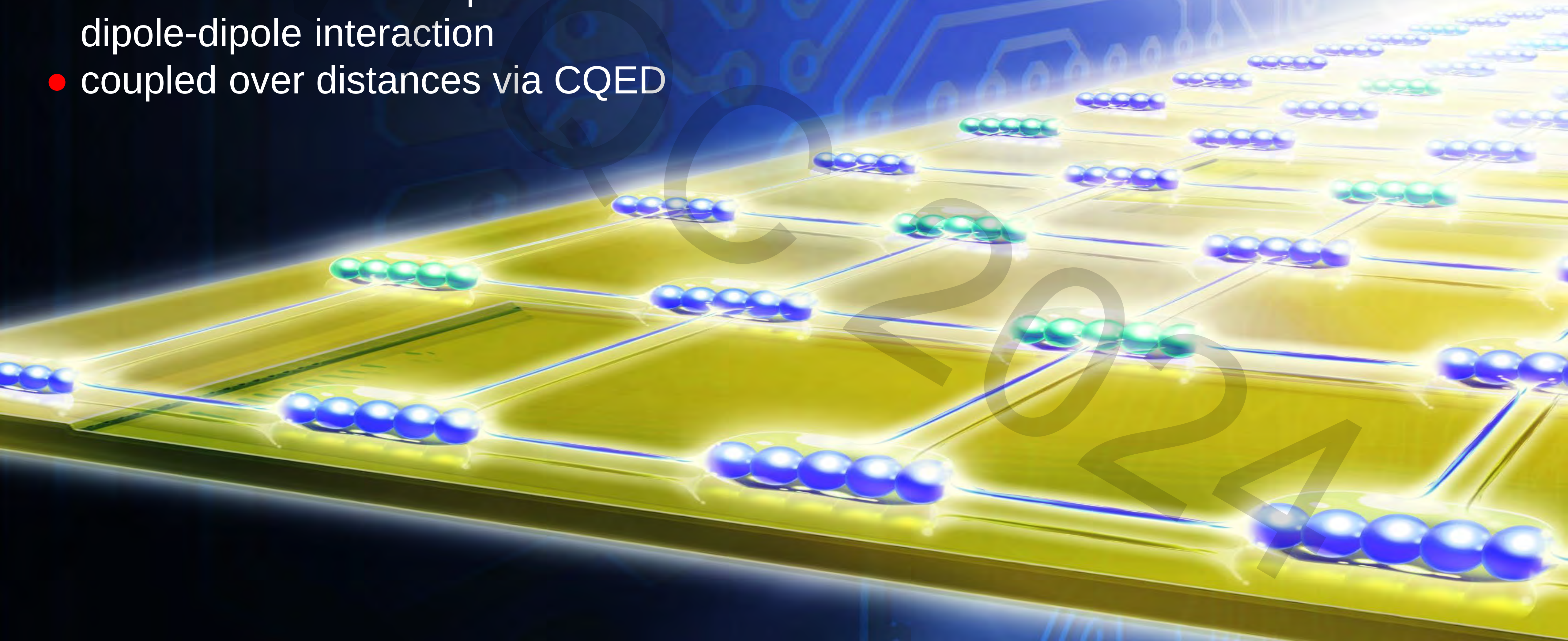
The vision:

- local logical qubits,
- protected by error correction,
- interconnected on-chip via dipole-dipole interaction
- coupled over distances via CQED



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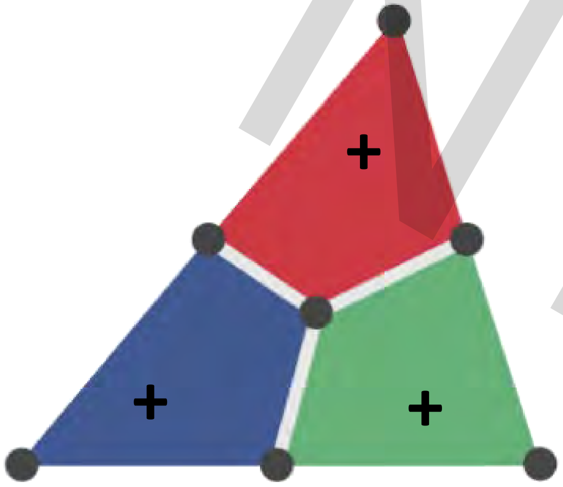
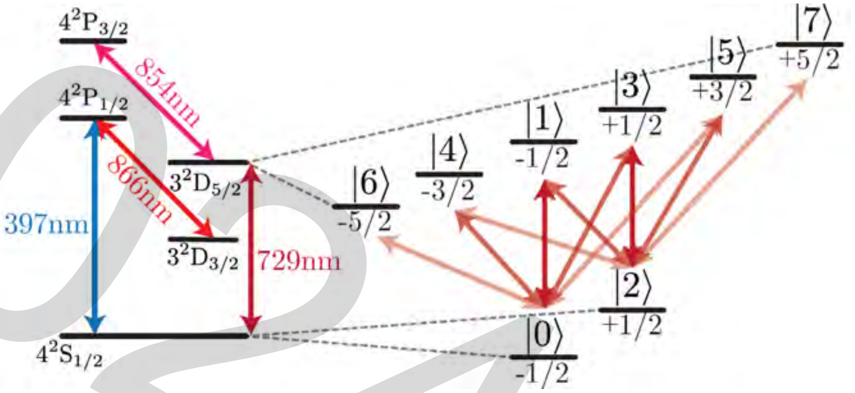
Take-home message



- ✓ The trapped-ion toolbox goes much beyond qubit gates
- ✓ Quantum Error Correction suppresses errors through redundancy
- ✓ Universal mixed-dimensional quantum computing
- ✓ Natural platform for gauge theory simulations



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The Innsbruck Ion Trappers 2023

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PhDs and PostDocs wanted !

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