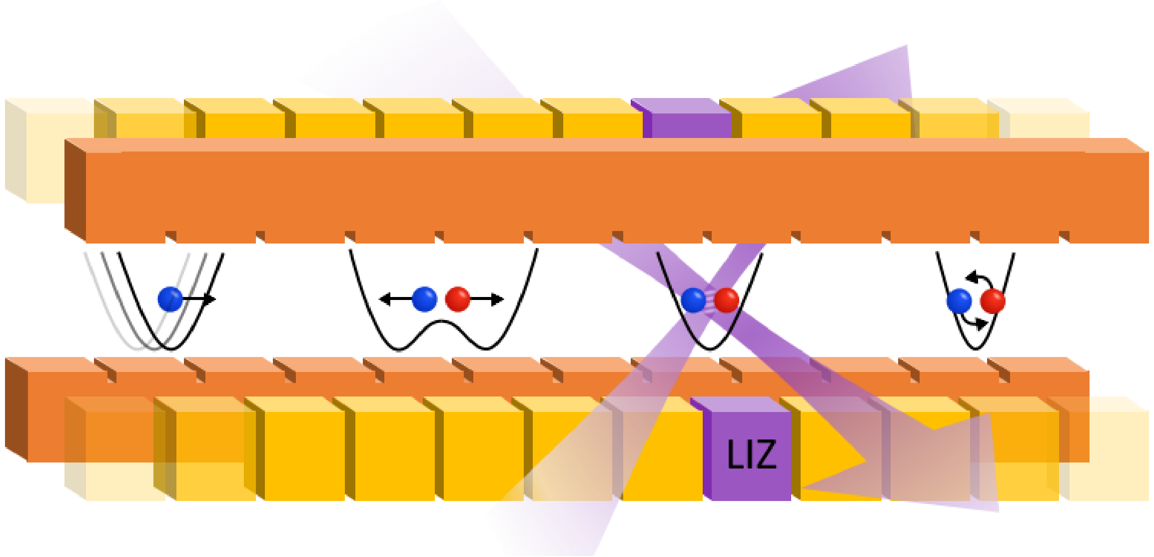
Towards quantum chemistry with trapped ion qubits



Dissipative Phases of Entangled Quantum Matter

- Trapped-ion quantum computer platform
- Fault tolerant quantum error correction building blocks
- Single spin heat engine
- Outlook

Trapped ion platform

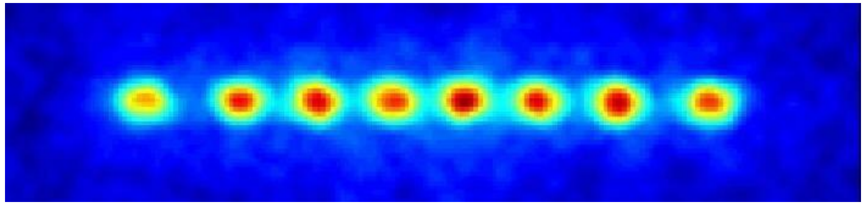
Atomic ions in radiofrequency traps

Few-body to
mesoscopic systems

Tight harmonic
confinement

High-fidelity state readout

High-fidelity gate
operations

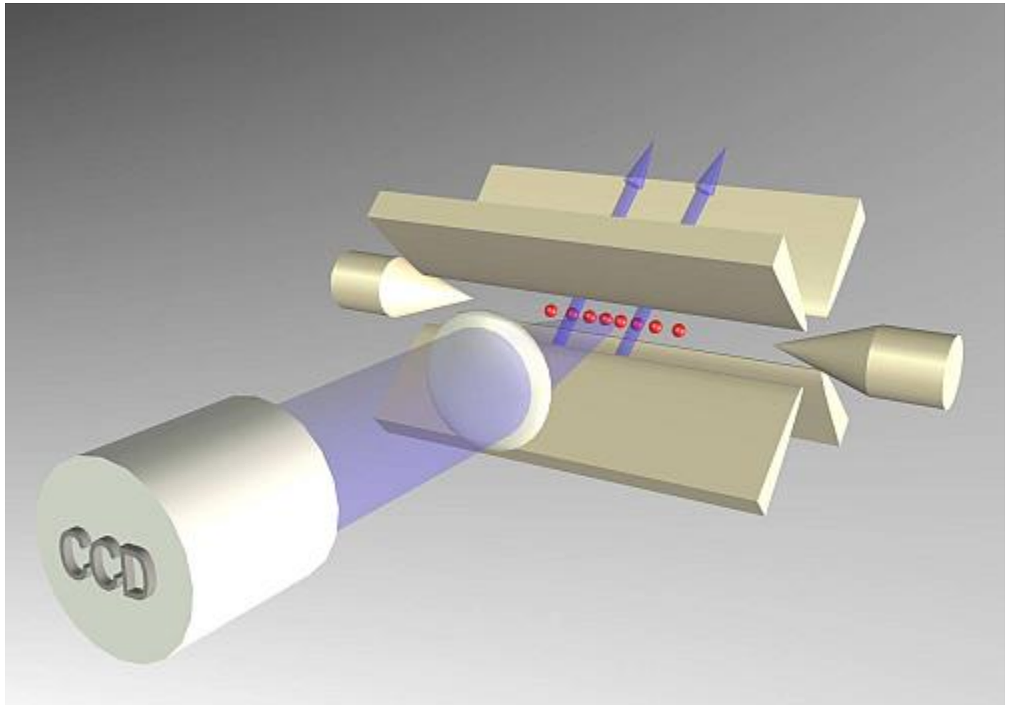


Engineered
dissipation

Long qubit lifetimes

Quantum control of
harmonic oscillator
degrees of freedom

Trapped ion QC



Group of Rainer Blatt, Universität Innsbruck

“Traditional” approach:

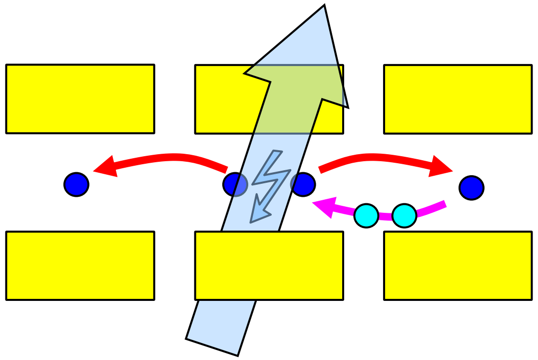
- Static ion string
- 3D harmonic confinement
- Static & ponderomotive potentials
- Spin/spin coupling via collective modes
- Laser addressing

Scalability limits:

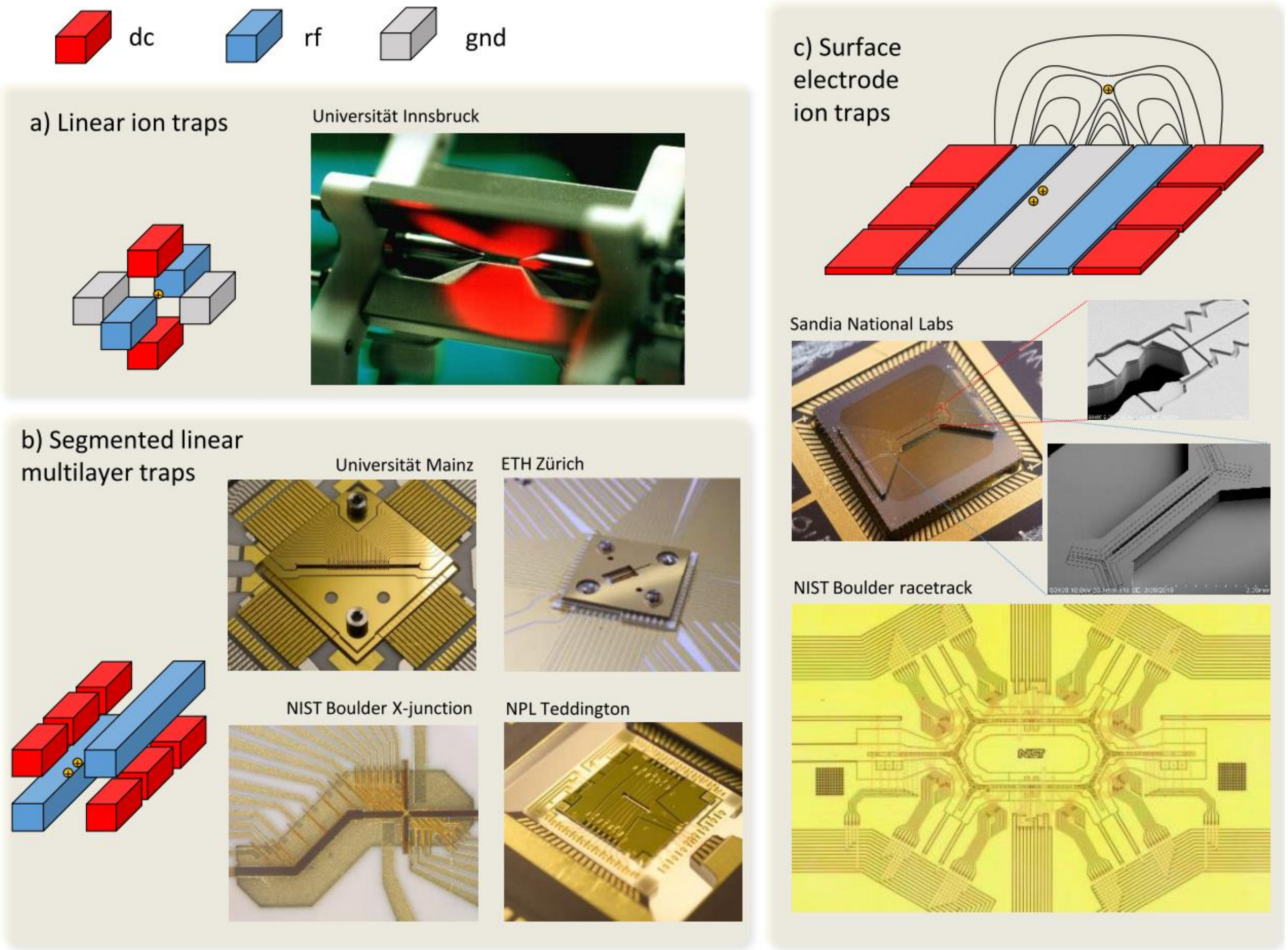
- Crystal stability
- Spatial crowding
- Spectral crowding
- Addressing range
- …

"Quantum CCD"

"Divide et impera"



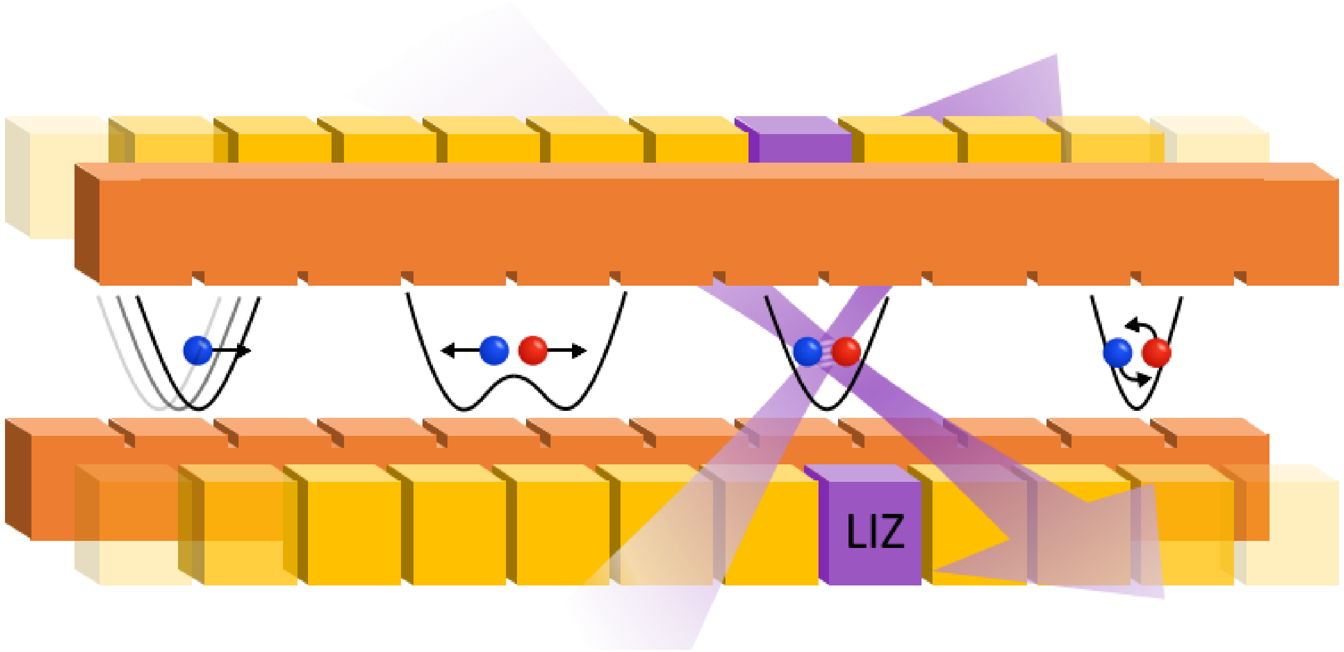
Original proposal:
Kielpinsky et al., Nature **417**, 709 (2002



UGP, FSK, "Quantum Computing Experiments with Cold Trapped Ions",
in *Quantum Information: From Foundations to Quantum Technology Applications*,
Bruss, Leuchs (eds.), Wiley VCH (2016)

Trapped Ion Qubit Reconfiguration QC

- Reconfigurable QB register
- 1D architecture
- Laser-driven gates @ laser interaction zone
- Shuttling operations: transport, swap rotate, split/merge
- Motion: axial / Gates: radial



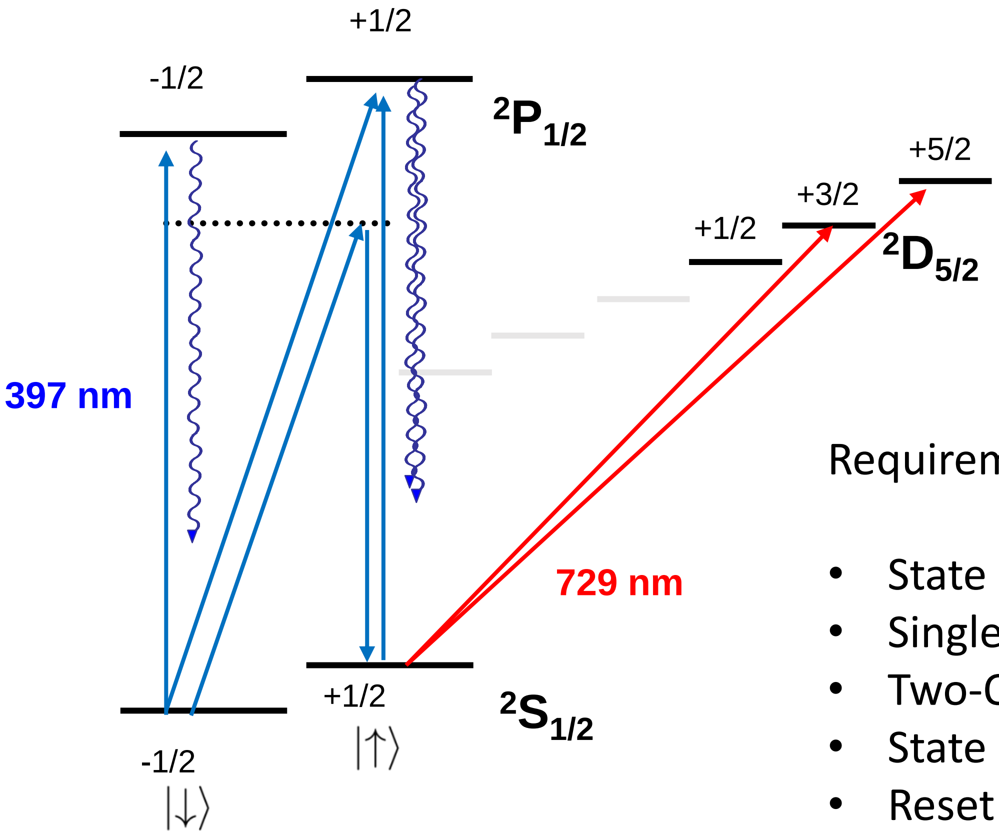
Requirements:

- QB Cooling / readout / reset
- Gates: Single QB, two QB
- QB memory integrity
- Shuttling

V. Kaushal et al., „Shuttling-based trapped-ion quantum information processing“, AVS Quantum Science **2** (1), 014101

The $^{40}Ca^{+}$ spin qubit

[illegible]ations



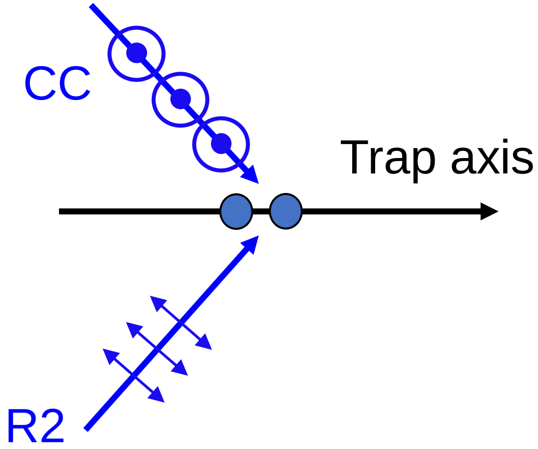
Requirements:

- State preparation
- Single Qubit rotations
- Two-Qubit entangling gates
- State readout
- Reset

UGP et al., J. Phys. B **42** 154013 (2009)

Entangling gate

Collective vibrations of two ions:

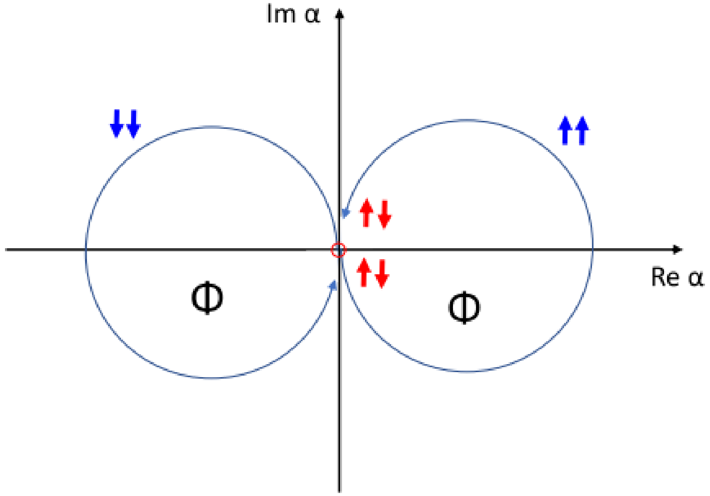


Spin-selective optical dipole force

Frequency difference tuned to COM mode:

-equal oscillating force on the two ions required

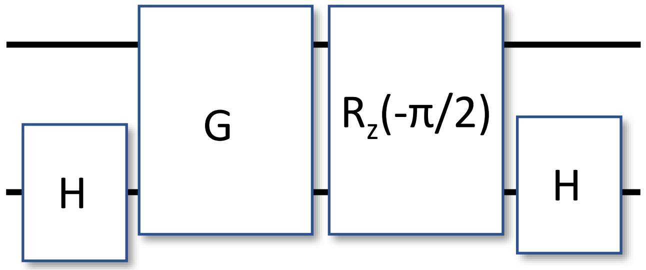
-only even parity states excited



Phase gate unitary:

$$\hat{G} = \begin{pmatrix} e^{i\Phi} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\Phi} \end{pmatrix}$$

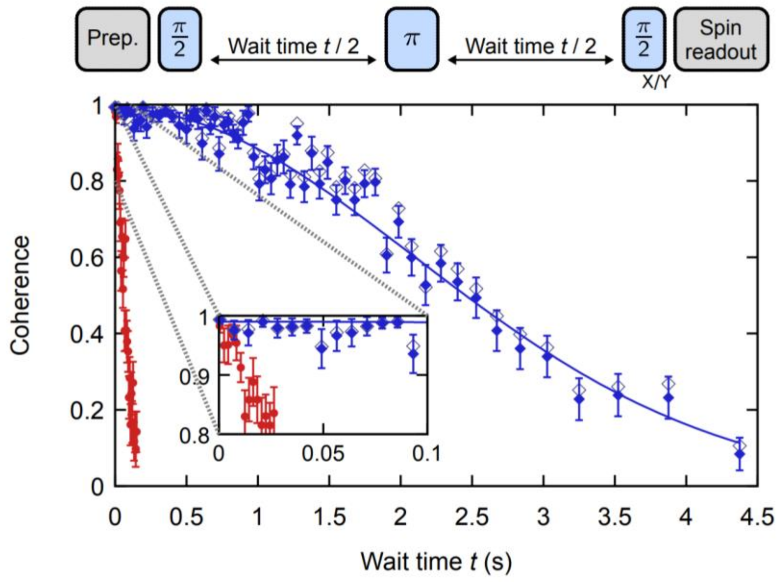
CNOT:



D. Leibfried et al., Nature **422**, 412 (2002)
P.J. Lee et al., J. Opt. B. **7**, 371 (2005)

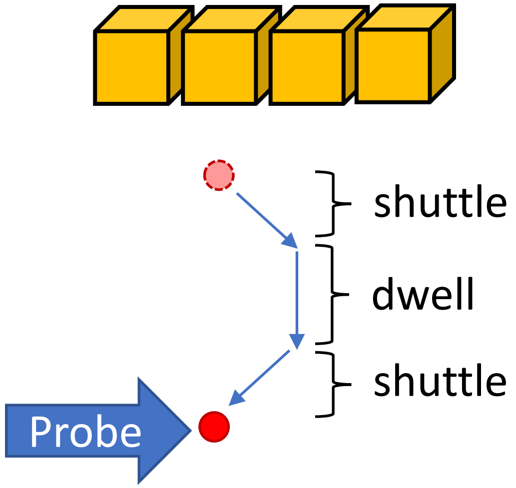
Long lived spin state qubits

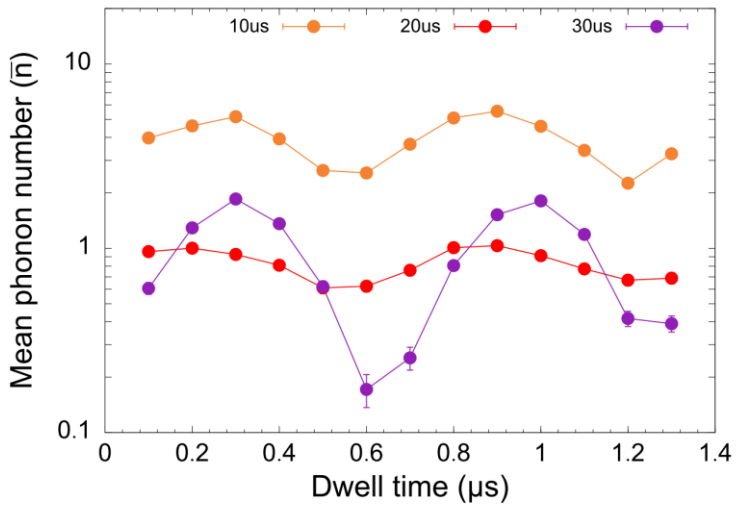
- Current setup achieves coherence times on the order of 2 sec
- Simple 2-layer Mu-Metal chamber
- Requires additional active compensation
- Limited by B-field noise



T. Ruster et al., Appl. Phys. B, 122(10) (2016)

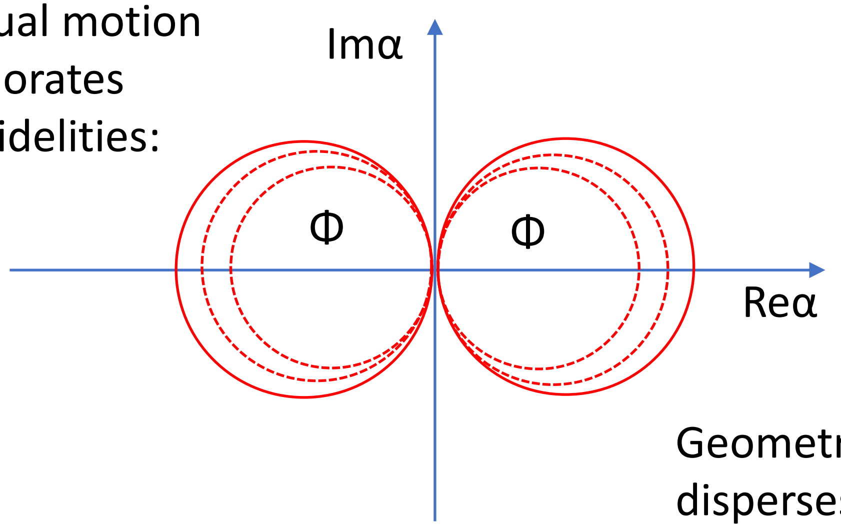
Shuttling operations





- Modulation of excitation with dwell time indicates excitation
- Precise control required

Residual motion deteriorates gate fidelities:

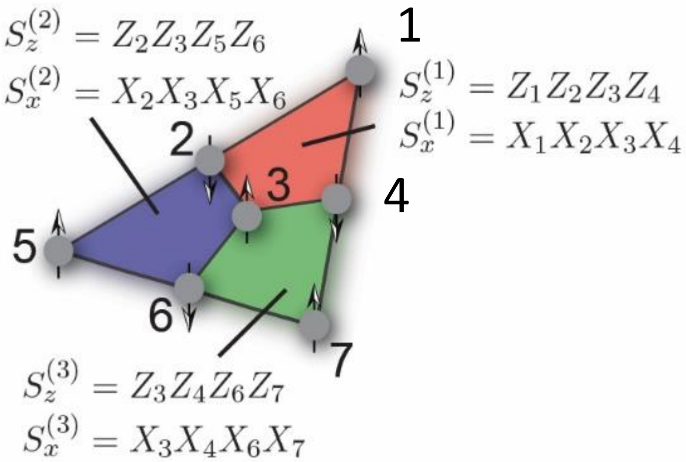


Geometric phase disperses with phonon#

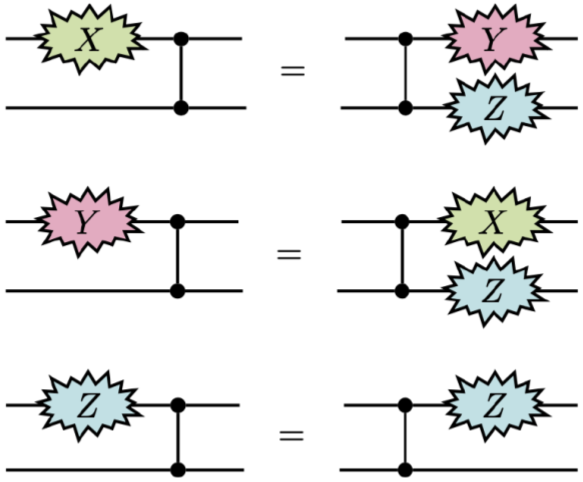
A. Walther et al., PRL **109**, 080501 (2012)

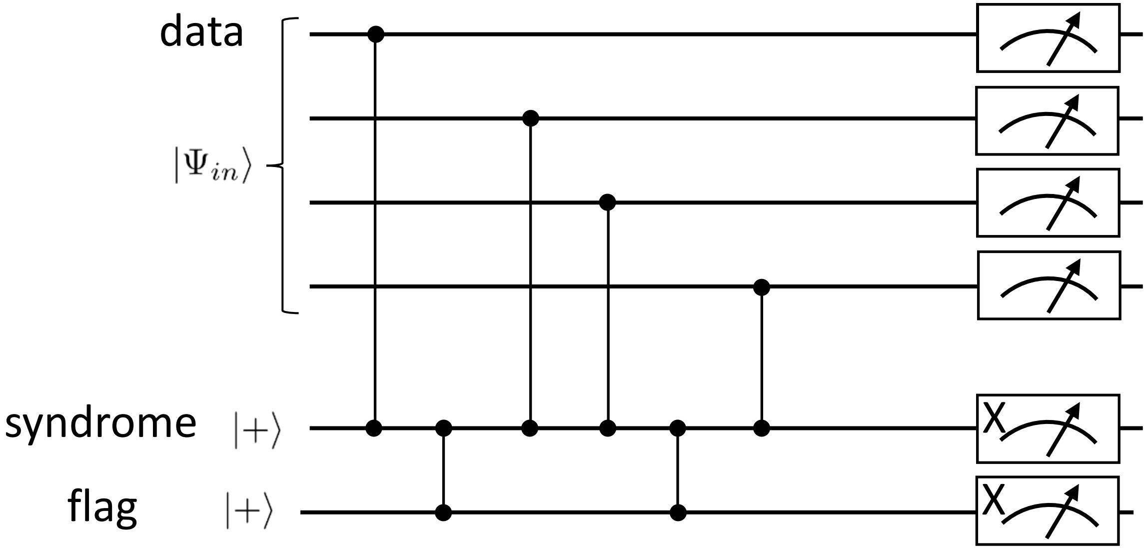
Fault Tolerant Quantum Error Correction

- Ongoing work on 7 QB topological error correction code
- Fault-tolerant syndrome extraction from 4 QB plaquette
- Parity measurement based on 2 qubit gates
- Flag qubit detects hook error



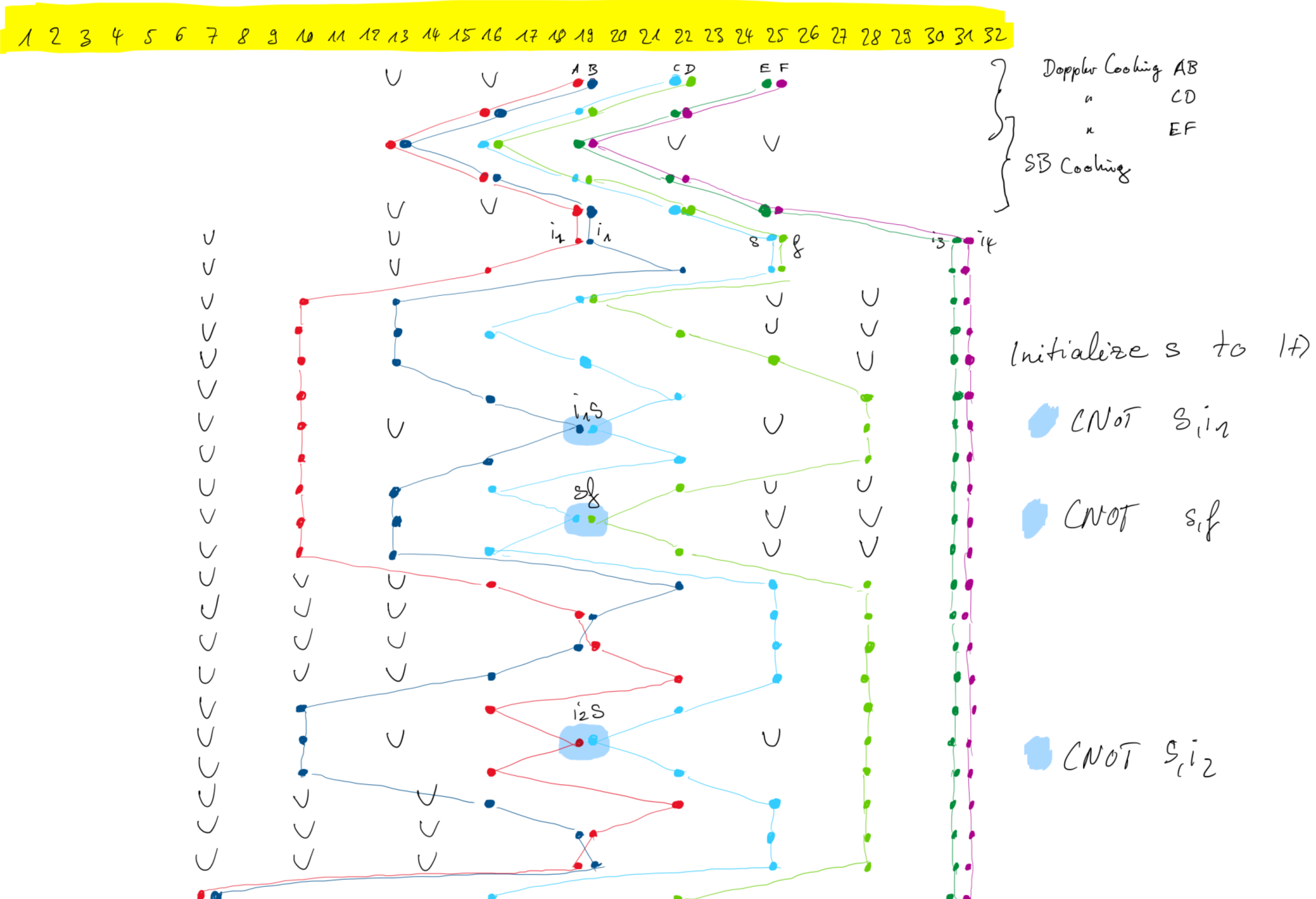
w/ Markus Müller
FZJ



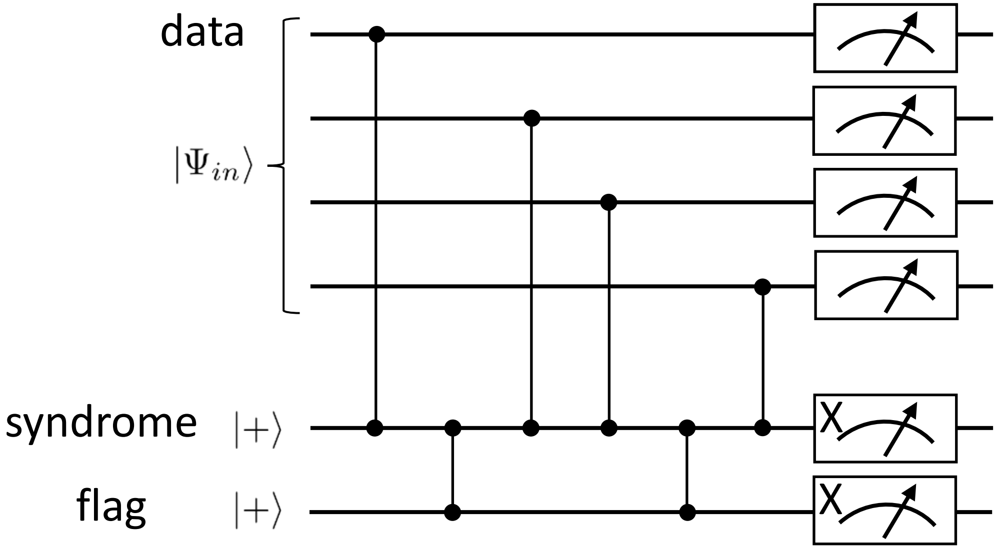


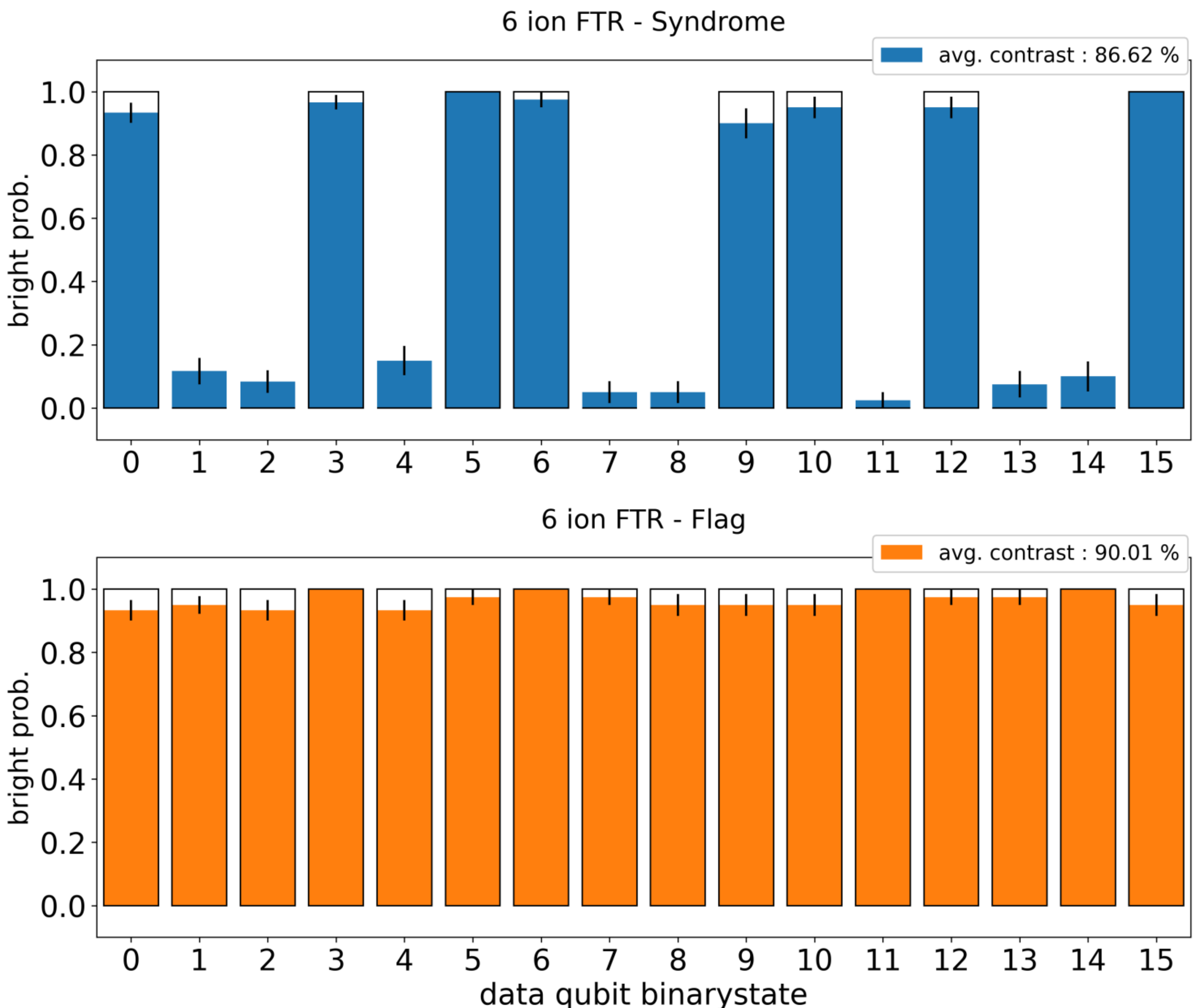
A. Bermudez et al., Phys. Rev. X **7**, 041061 (2017)
A. Rodriguez-Blanco, PRX Quantum **2**, 020304 (2021)

4QB Topological Error Correction

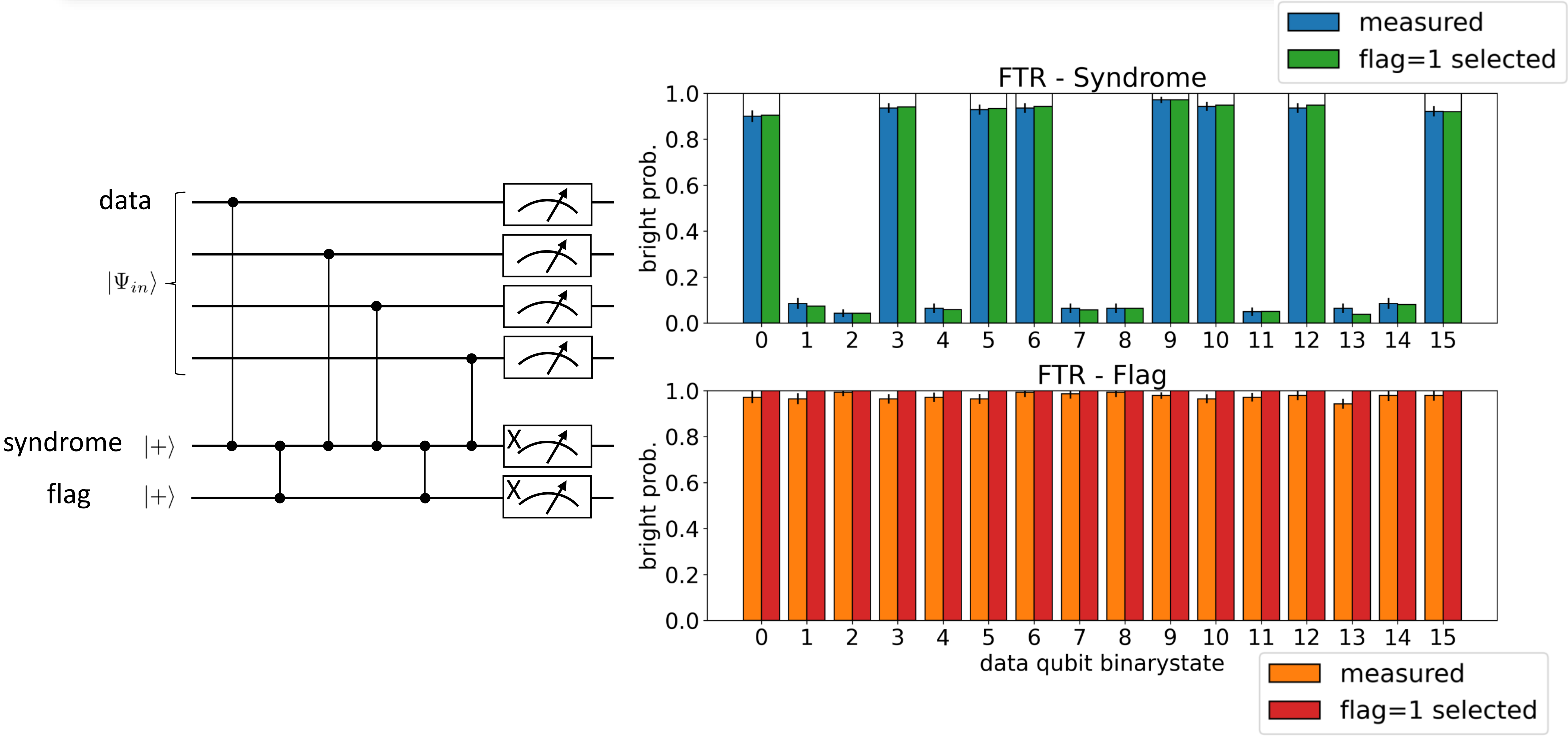


Results


data
$|\Psi_{in}\rangle$
syndrome $|+\rangle$
flag $|+\rangle$
X
X

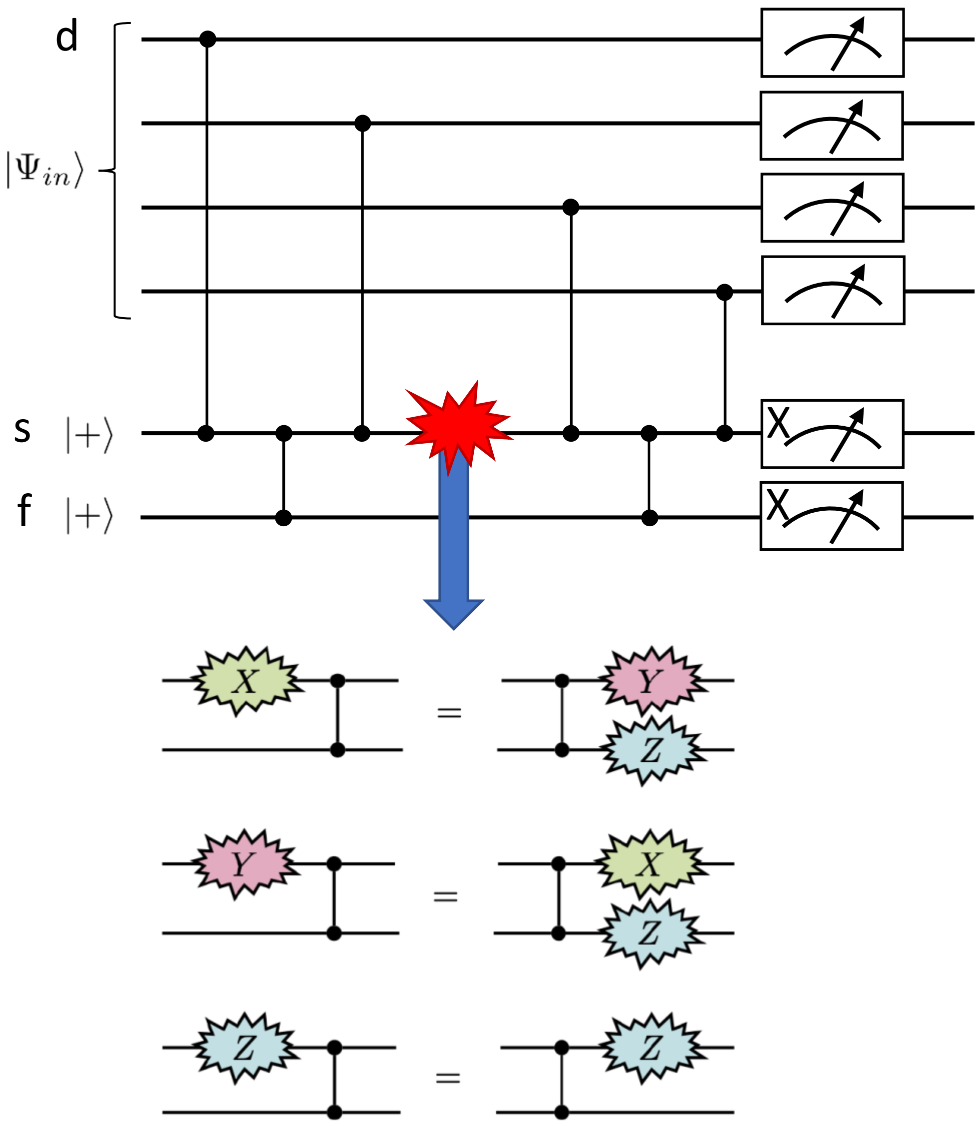

6 ion FTR - Syndrome
avg. contrast : 86.62 %
bright prob.
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
6 ion FTR - Flag
avg. contrast : 90.01 %
bright prob.
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
data qubit binarystate

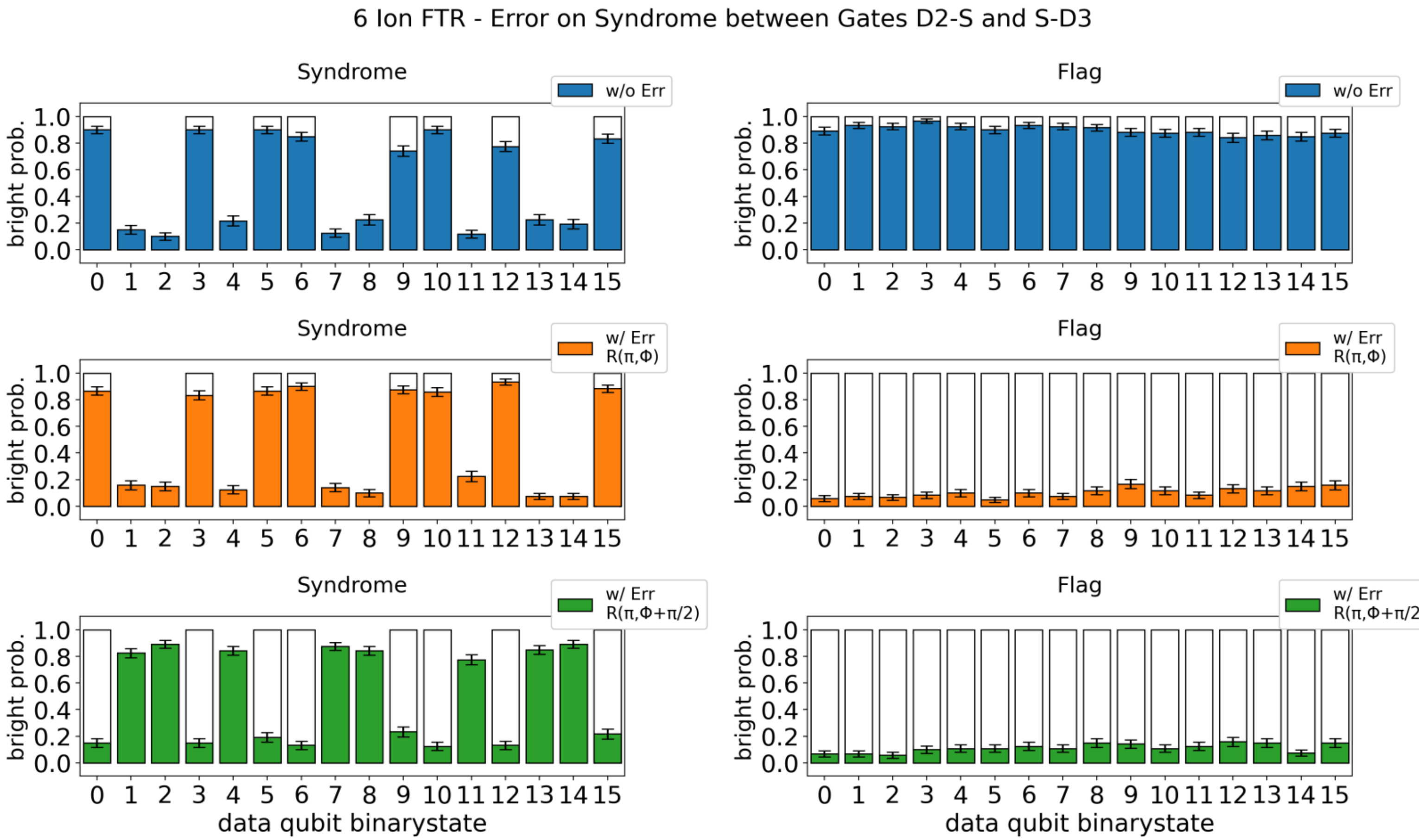
Results



data
$|\Psi_{in}\rangle$
syndrome $|+\rangle$
flag $|+\rangle$
X
X
FTR - Syndrome
bright prob.
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
measured
flag=1 selected
FTR - Flag
bright prob.
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
data qubit binarystate
measured
flag=1 selected

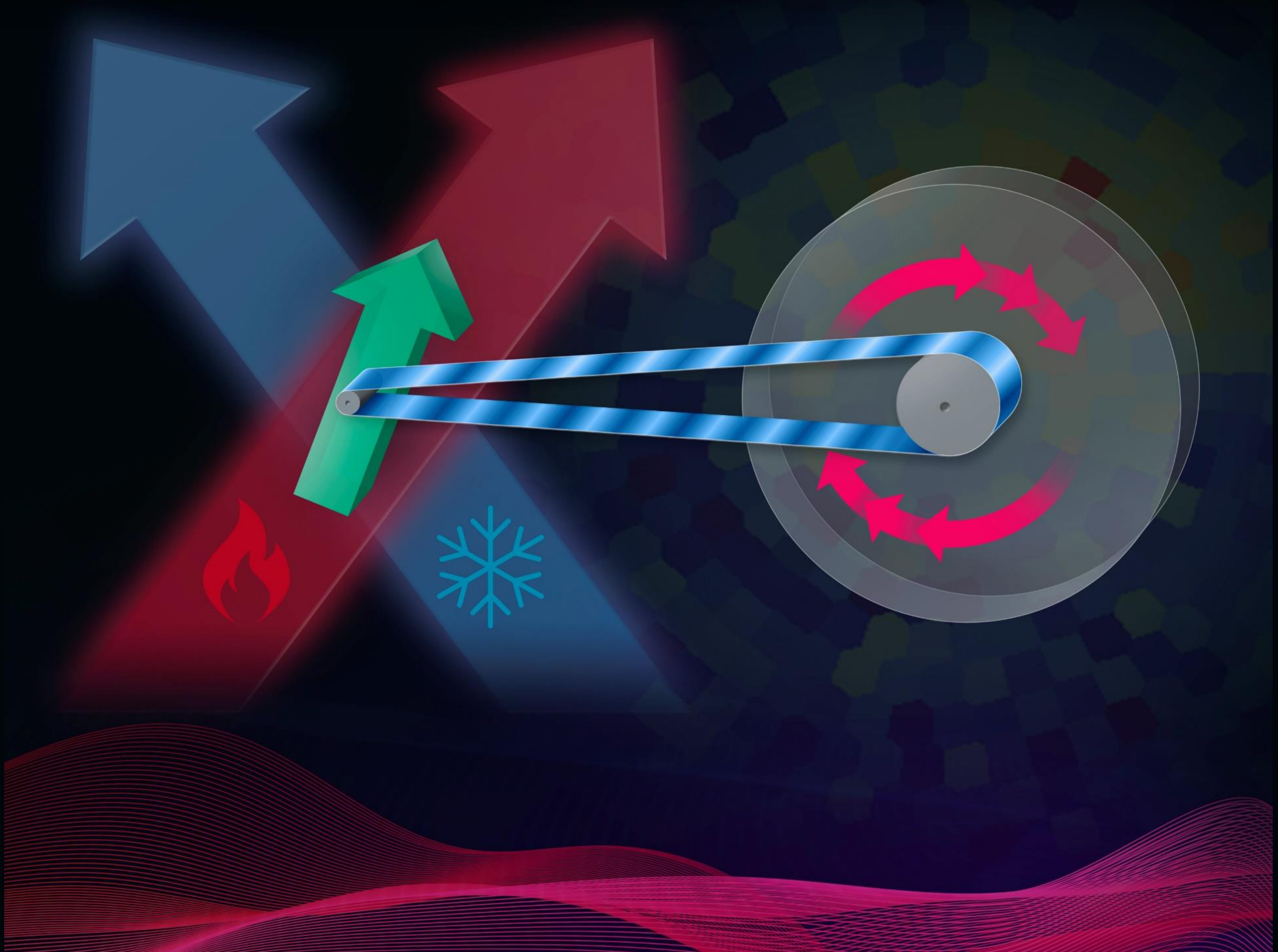
Results



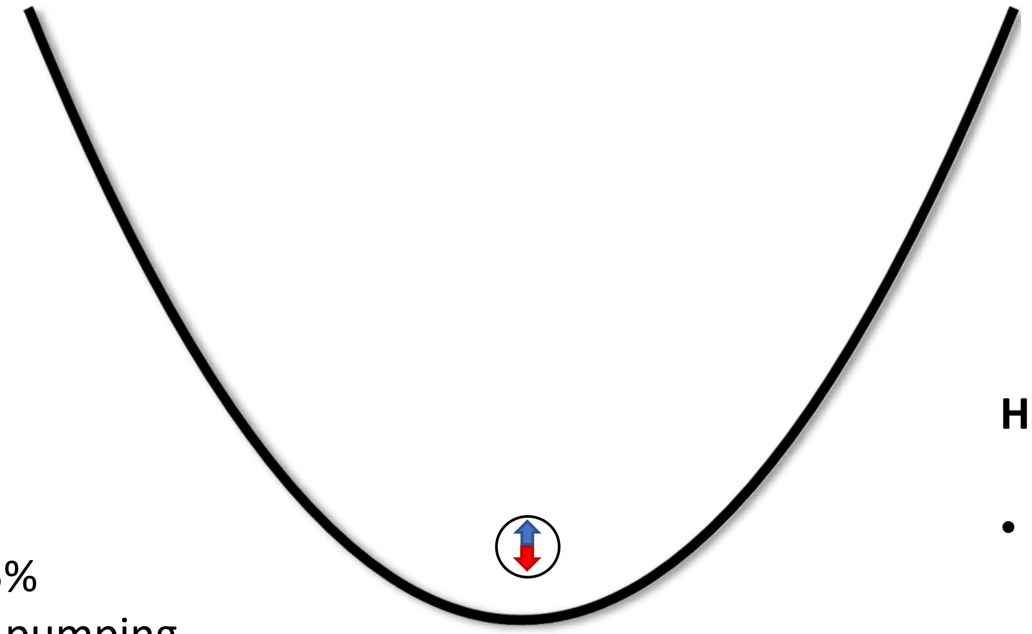


J. Hilder et al., to be published

Thermodynamics of single-ion machines



Engineered dissipation



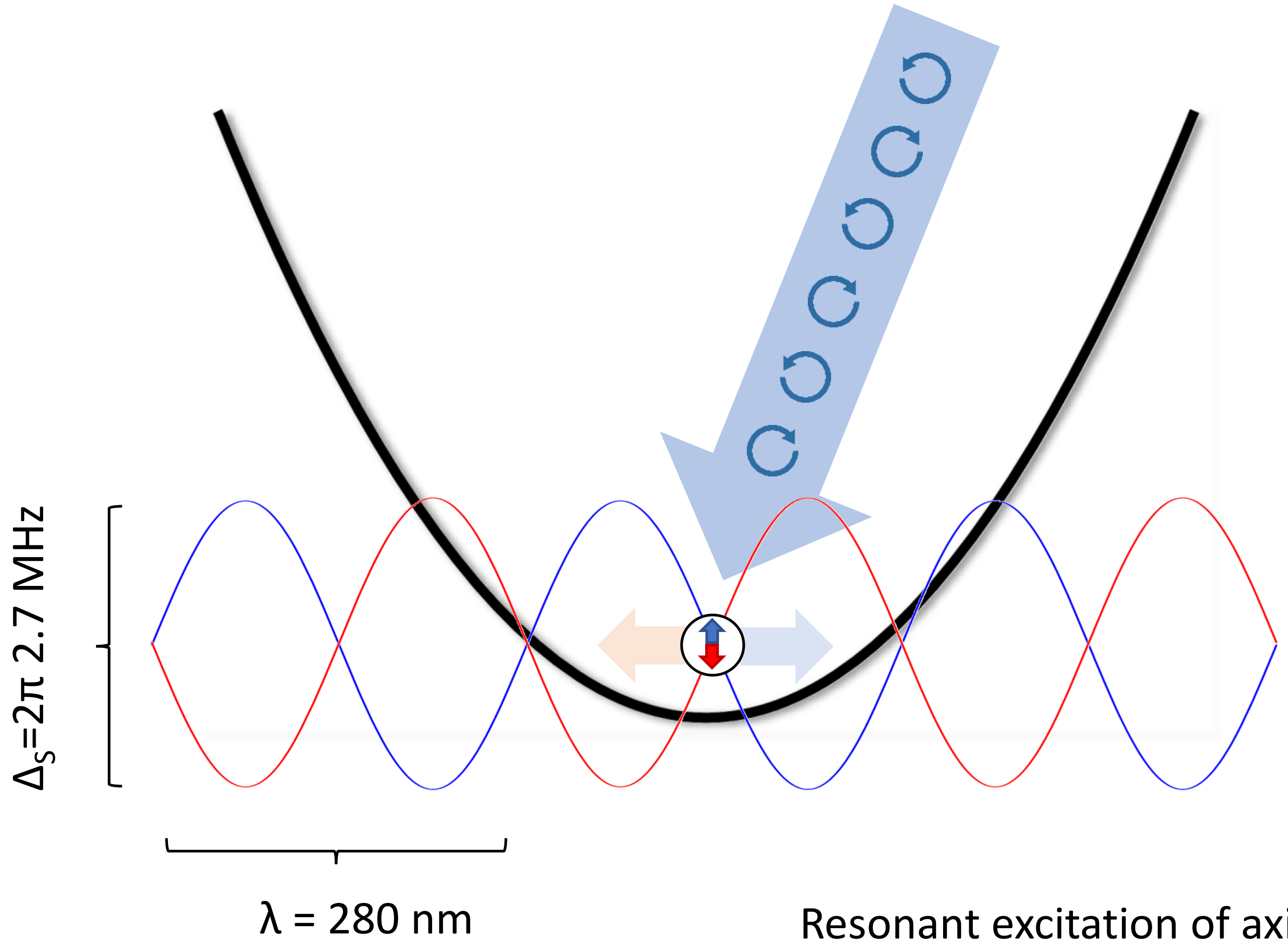
Spin degree of freedom

- Full quantum control
- Operation fidelities > 99.5%
- Thermal states via optical pumping
- Ideal quantum measurement
- Long coherence time ~2s

Harmonic oscillator degree of freedom

- Control via electric fields, optical forces or coherent spin-motion couping
- Ground state intialization
- State reconstruction

Spin heat engine



Lin perp lin optical lattice: Alternating, spin dependent ac Stark shift

Resonant excitation of axial oscillation, but:

- Equivalent to Otto cycle
- **Fluctuations**

Otto cycle

Working principle of four-stroke spin heat engine:

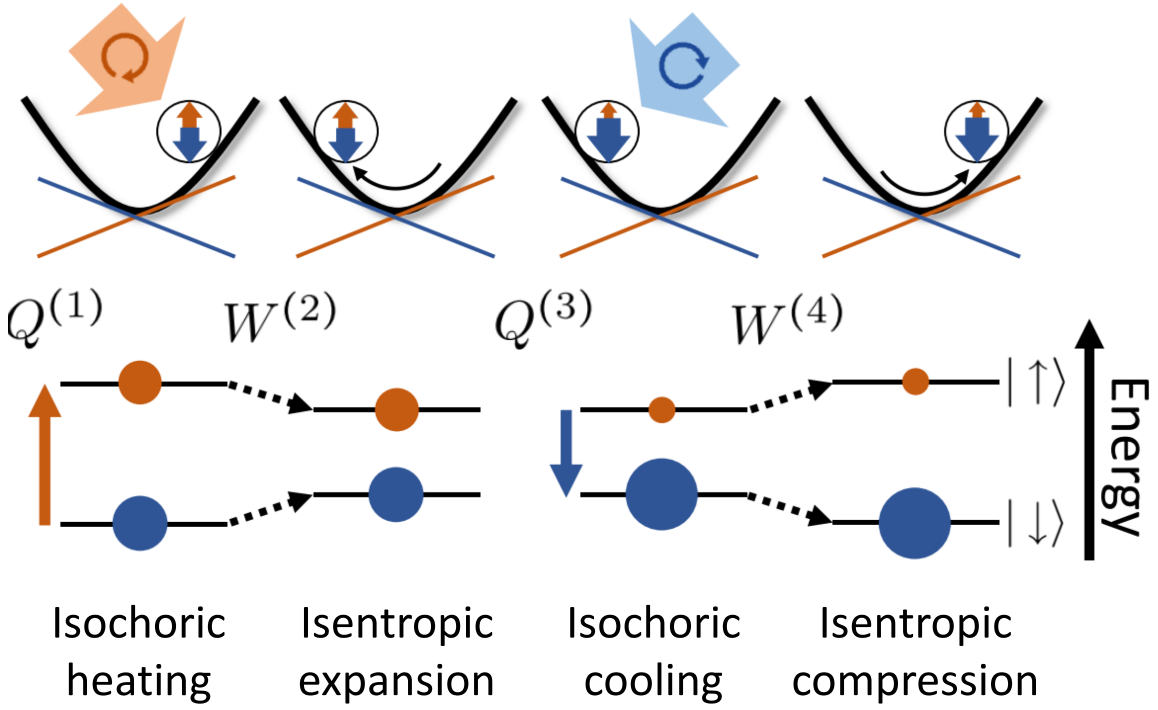
Spin ½ working agent:

Effective Zeeman energy corresponds to inverse „Volume“

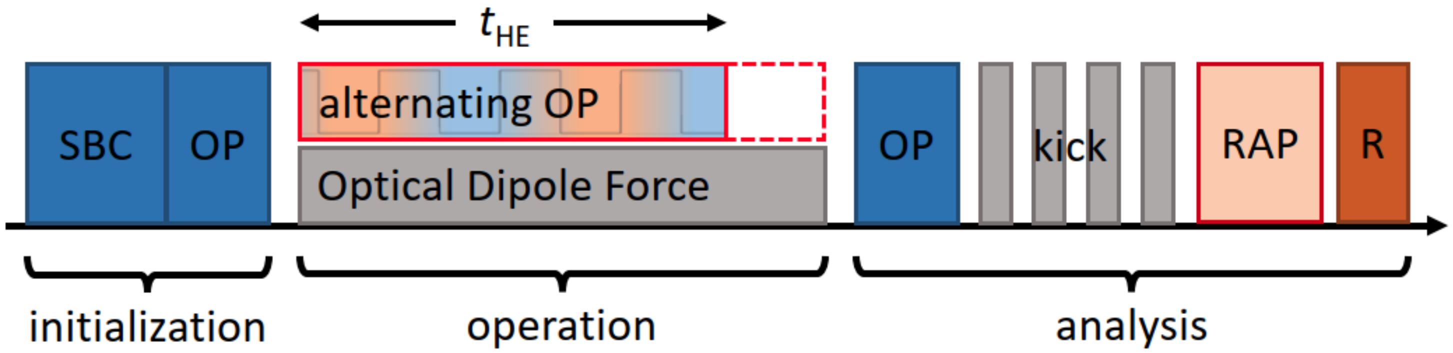
$$(\omega_Z + \Delta_S(\hat{x}))\,\langle\hat{\sigma}_z\rangle \propto 1/V$$

Spin temperature:

$$\langle\hat{\sigma}_z\rangle = -\tanh(\hbar\omega_z'/2k_BT)$$



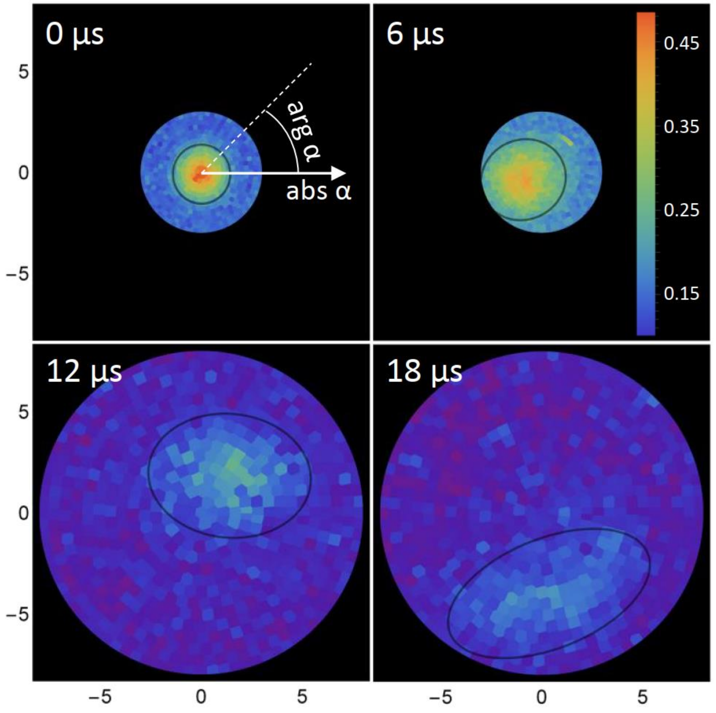
Probing the flywheel



$$Q_{\hat{\rho}}(\alpha, \alpha^*) = \frac{1}{\pi} \langle 0 | \hat{D}^\dagger(\alpha) \hat{\rho} \hat{D}(\alpha) | 0 \rangle$$

Scan phase space by varying:

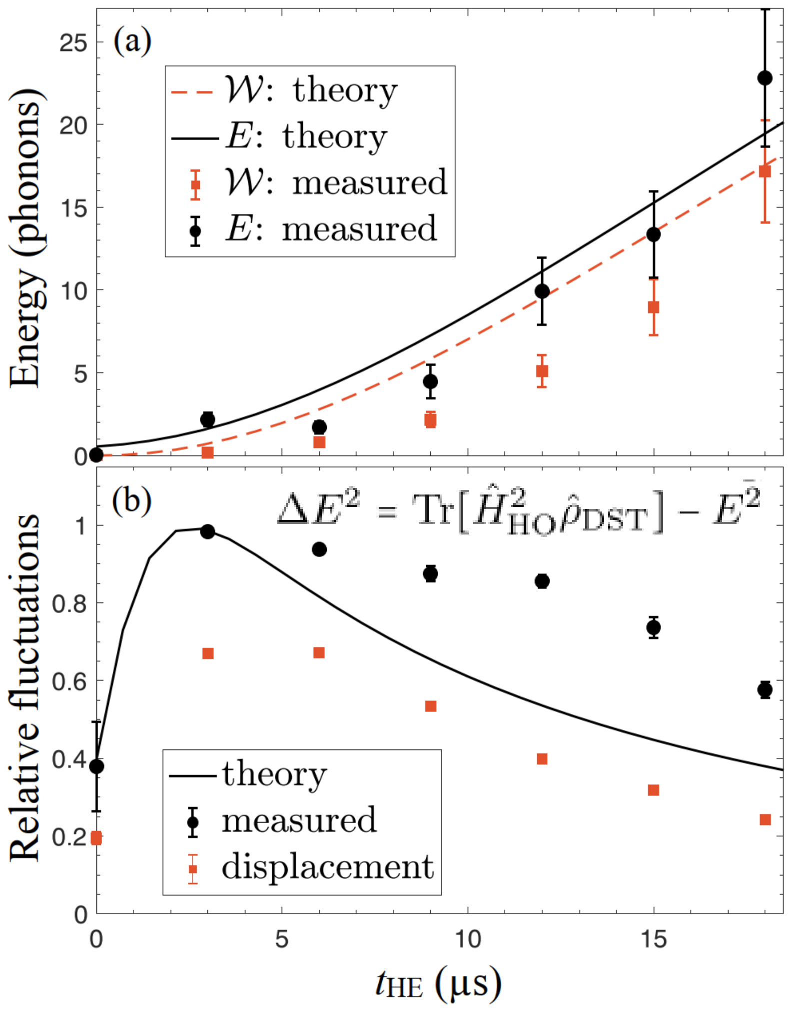
- Delay of 1st kick w.r.t. HE operation
  → arg α
- Kick amplitude
  → abs α



Fit to model Q function including:

- Displacement
- Squeezing
- Thermal excitation

Work fluctuations

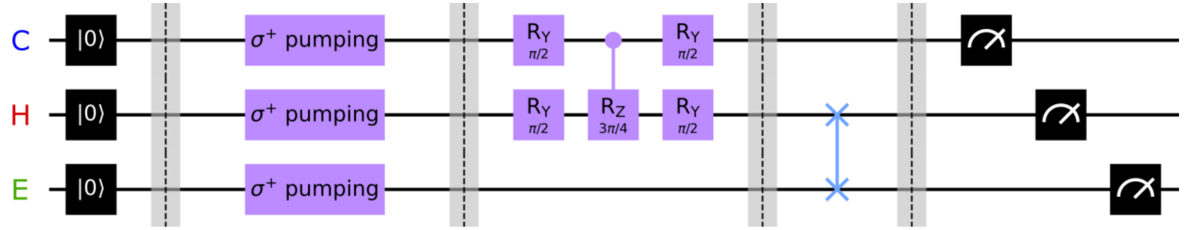


- Start from oscillator ground state
- Deposited energy and **ergotropy** increase
- Ergotropy falls short of energy because of fluctuations
- Rough agreement with simulations, ergotropy falls short because of technical imperfections
- Work fluctuations exceed unitary limit

D. v. Lindenfels et al., PRL **123**, 080602 (2019)

Ongoing / future work

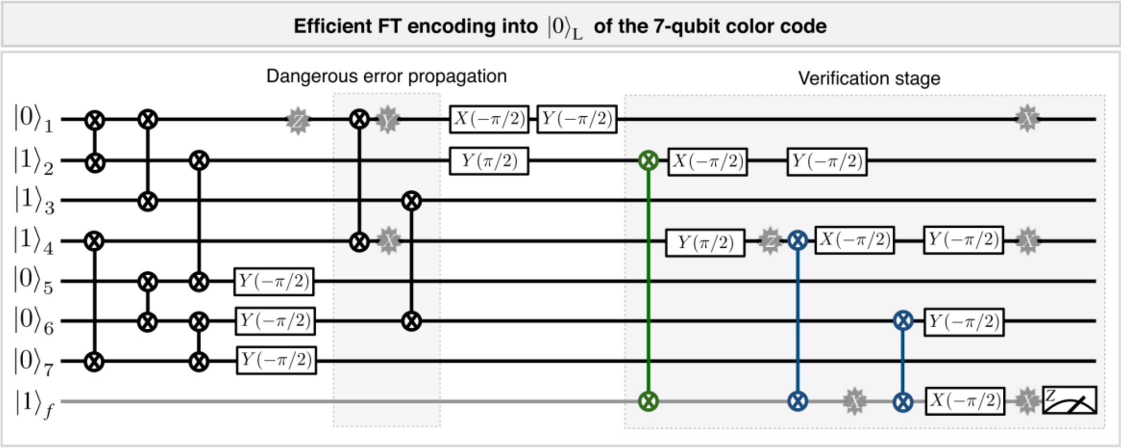
Heat leak detection beyond 2nd law:



I Henao, R Uzdin, N Katz, arXiv:1908.08968

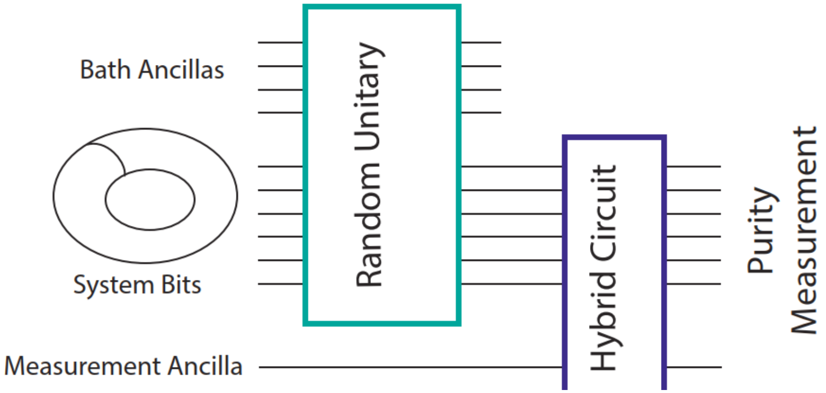
w/ Raam Uzdin, HUJI

Fault tolerant QEC:



- Improve hardware capabilities
- Full Stack QC
- FT-QEC building blocks
- Full QEC cycles

Minimal instance purifcation transition:



w/ Jamir Marino
& Shane Kelly
UMZ

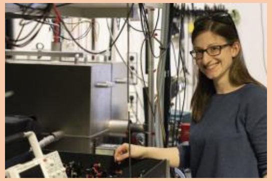
A. Bermudez et al.,
PRA **100**, 062307 (2019)

w/ Markus Müller
FZJ

People & funding

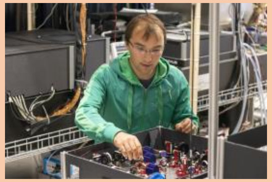
Red trap

Oleksiy Onishenko
PostDoc



Janine Hilder
phd

Daniel Pijn
phd

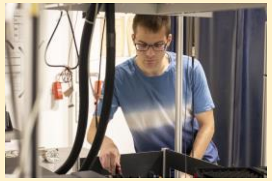


Ram-Janik Petzold
phd

Yellow trap

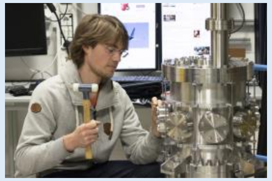
Alex Müller
phd

Daniel Wessel
phd



Can Patrick Leichtweiß
bac

Cryo trap



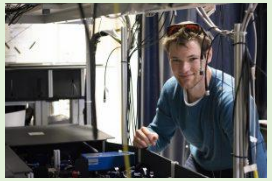
Jonas Schulz
phd

Max Werner
phd

HW/SW/
Methods

Alex Stahl
phd

Max Orth
master



Andreas Conta
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FSK

UGP

BL

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Quantum Flagship
aQtion

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