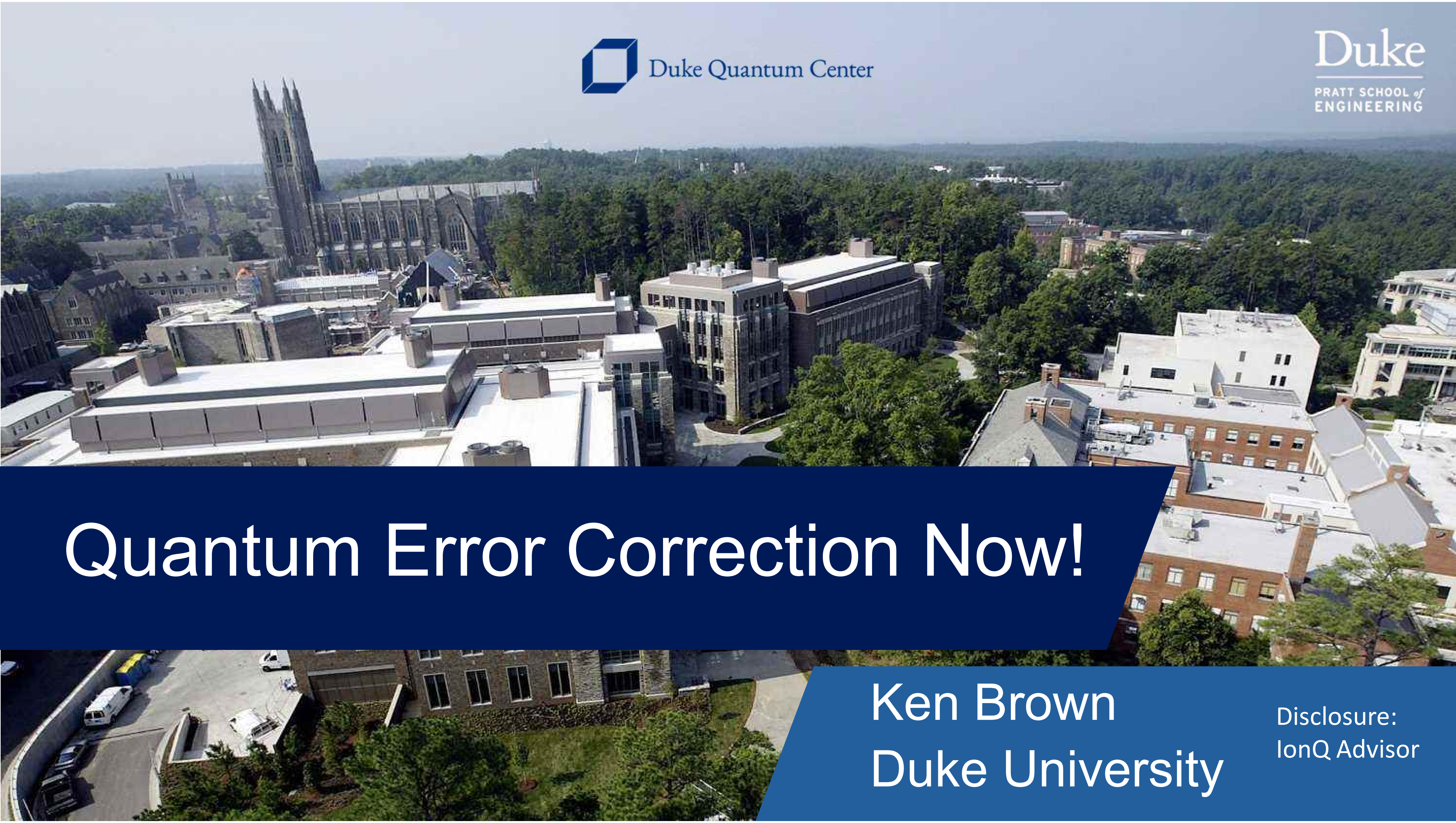


Duke Quantum Center

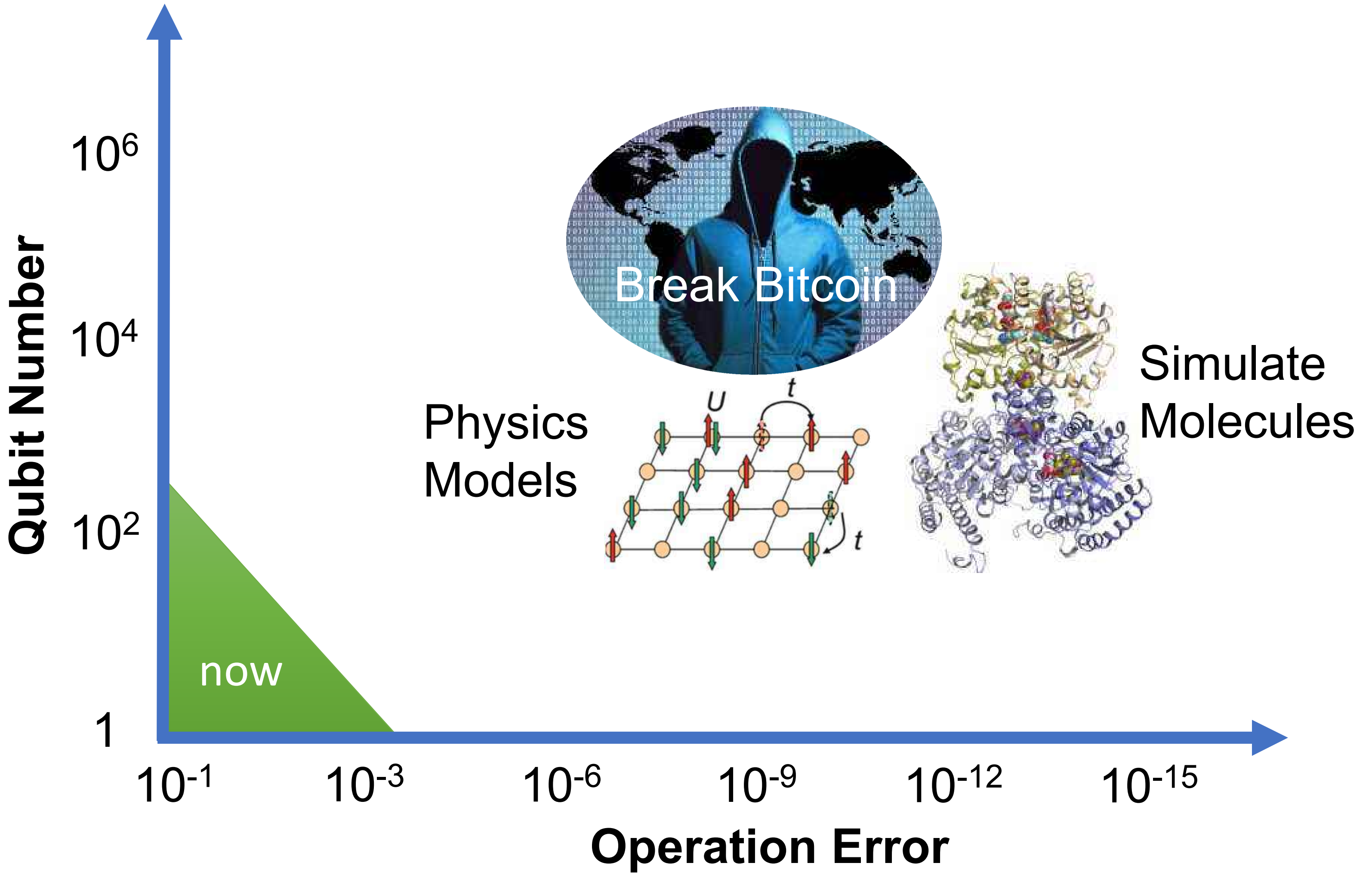
Duke PRATT SCHOOL of ENGINEERING

Quantum Error Correction Now!

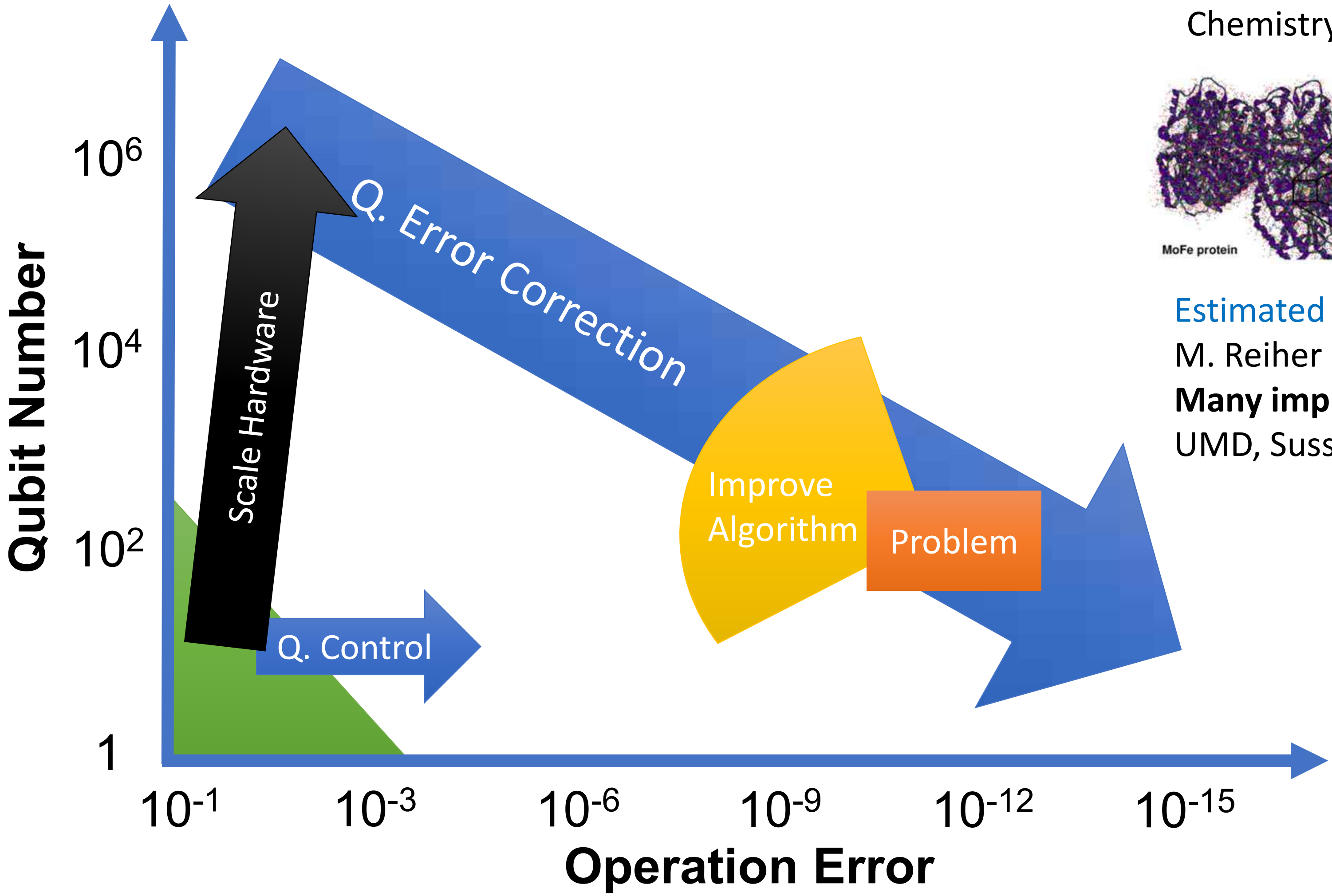
Ken Brown
Duke University

Disclosure:
IonQ Advisor

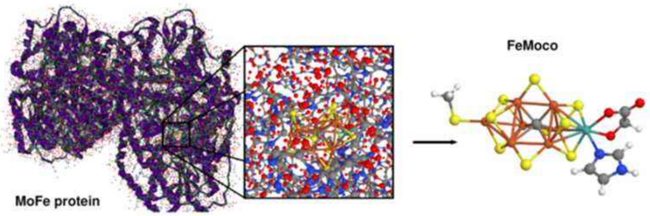
Wanted: More qubits and less error



Wanted: More qubits and less error



Chemistry algorithm



Estimated needed logical gates: 10^{15}

M. Reiher et al. PNAS **114**, 7555 (2017)

Many improvements since 2017

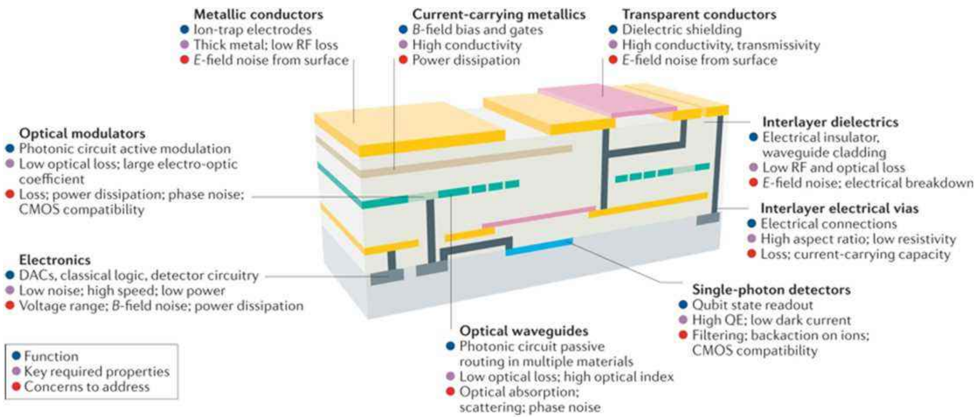
UMD, Sussex, Macquarie, Google, Microsoft, ..

Institute for **Robust Quantum Simulation**

Scaling Hardware

Nature provided (AMO)

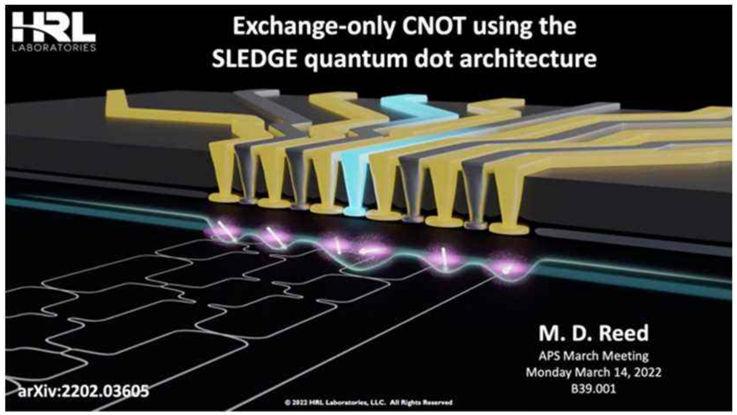
- Every qubit is the same by nature
- Weak coupling to environment
- Challenges in control and confinement of large numbers



K.R. Brown, J. Chiaverini, J. M. Sage, and H. Haeffner
Nat Rev Mater **6,** 892–905 (2021).

Human crafted (CM)

- Every qubit is the same up to manufacturing defects
- Stronger coupling to environment
- Able to "print" as many as can fit on a chip

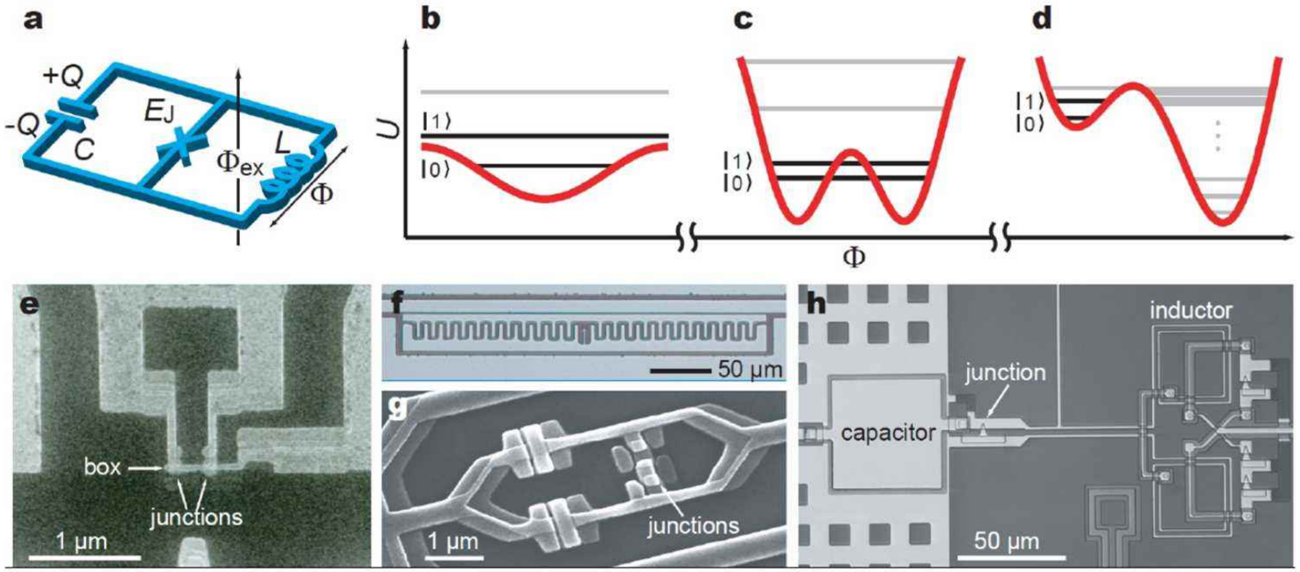


arXiv:2202.03605

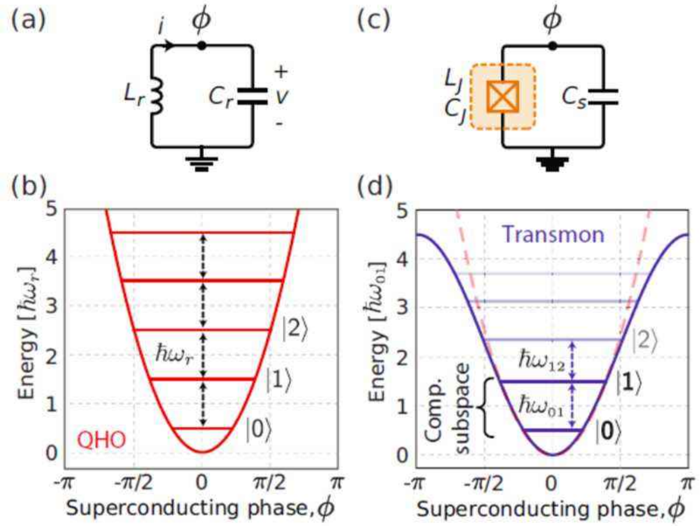
Hilbert space is a vast expanse

Anselm Kiefer, Dragon, 2001

Superconducting qubits



T.D. Ladd et al. *Nature* **464**, 45 (2010)



Krantz et al. Appl. Phys. Rev. **6**, 021318 (2019)
MIT Oliver group

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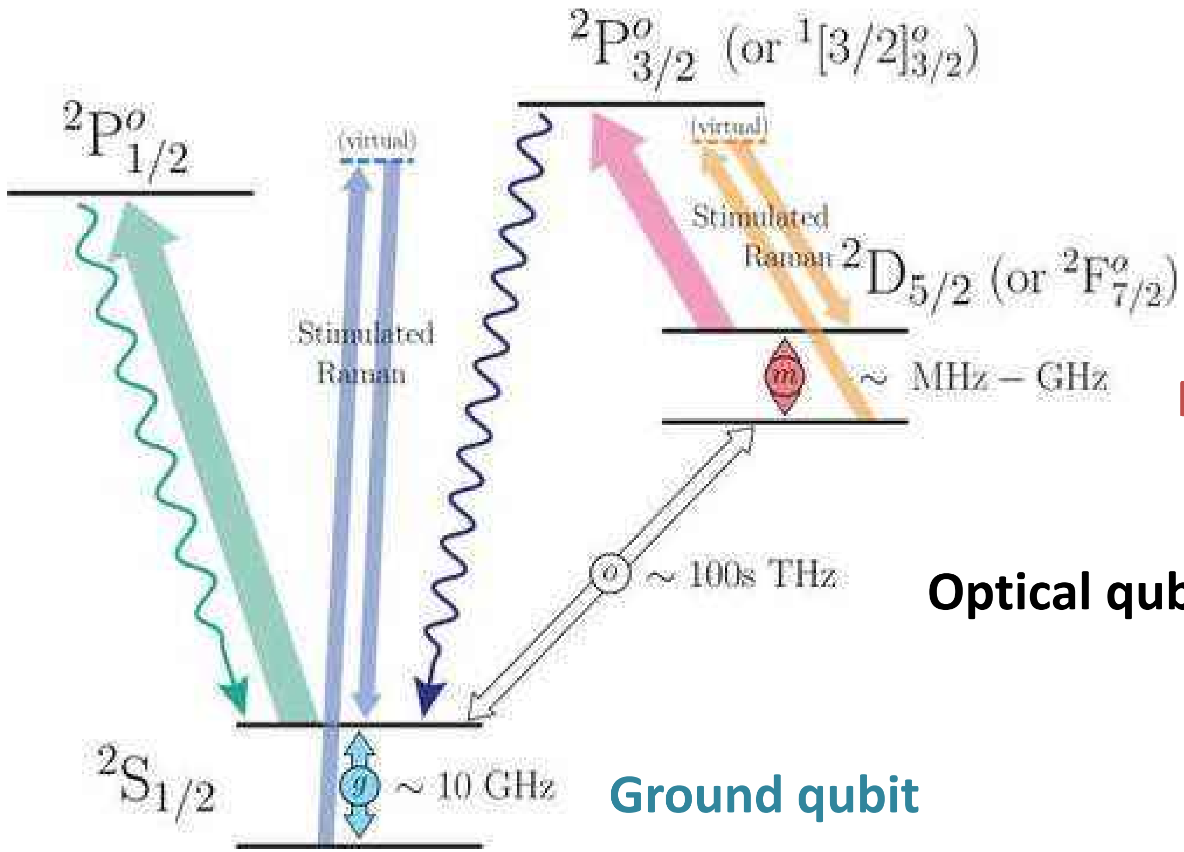
Ion Qubits



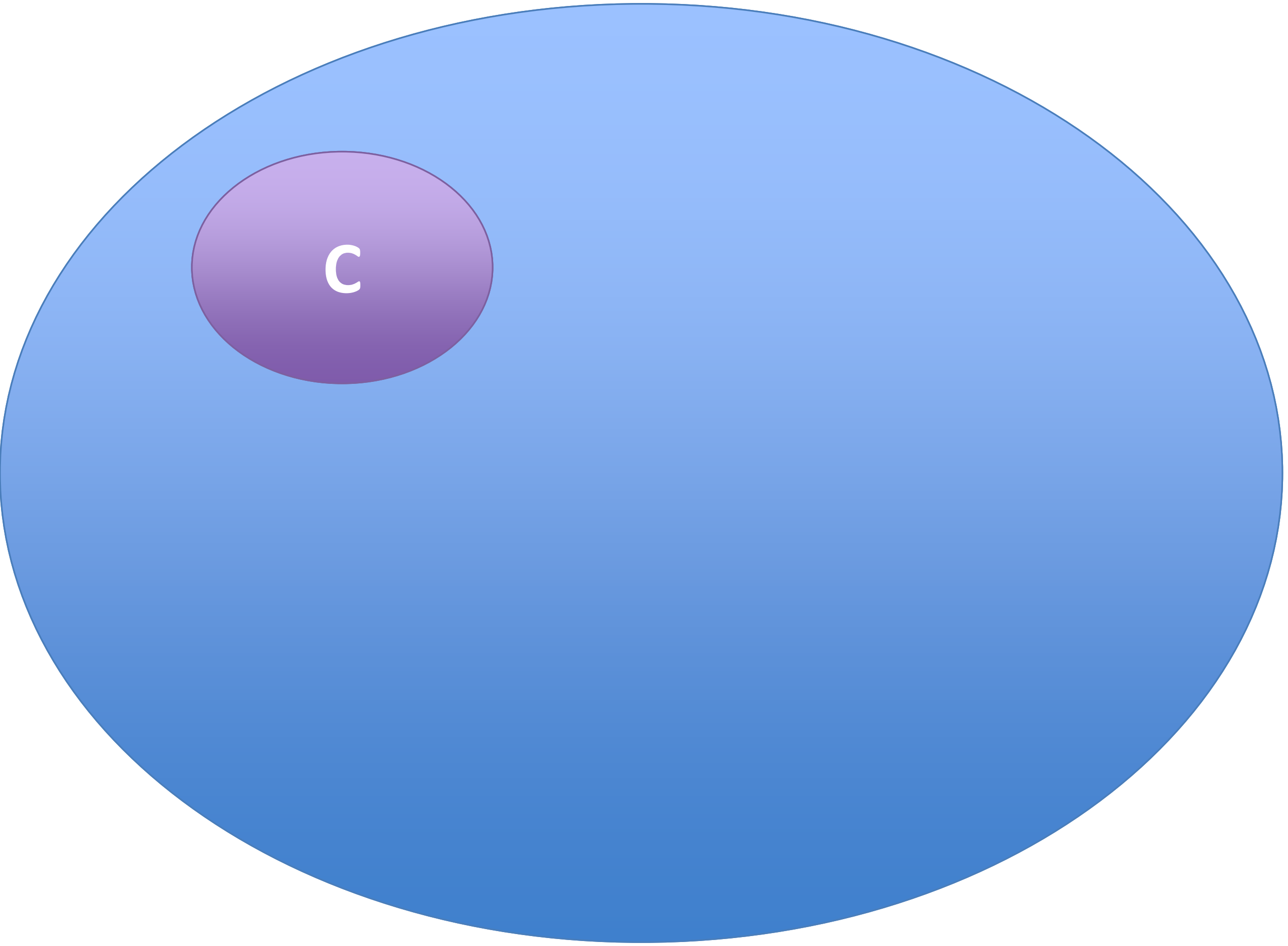
Metastable qubit

Optical qubit

Ground qubit

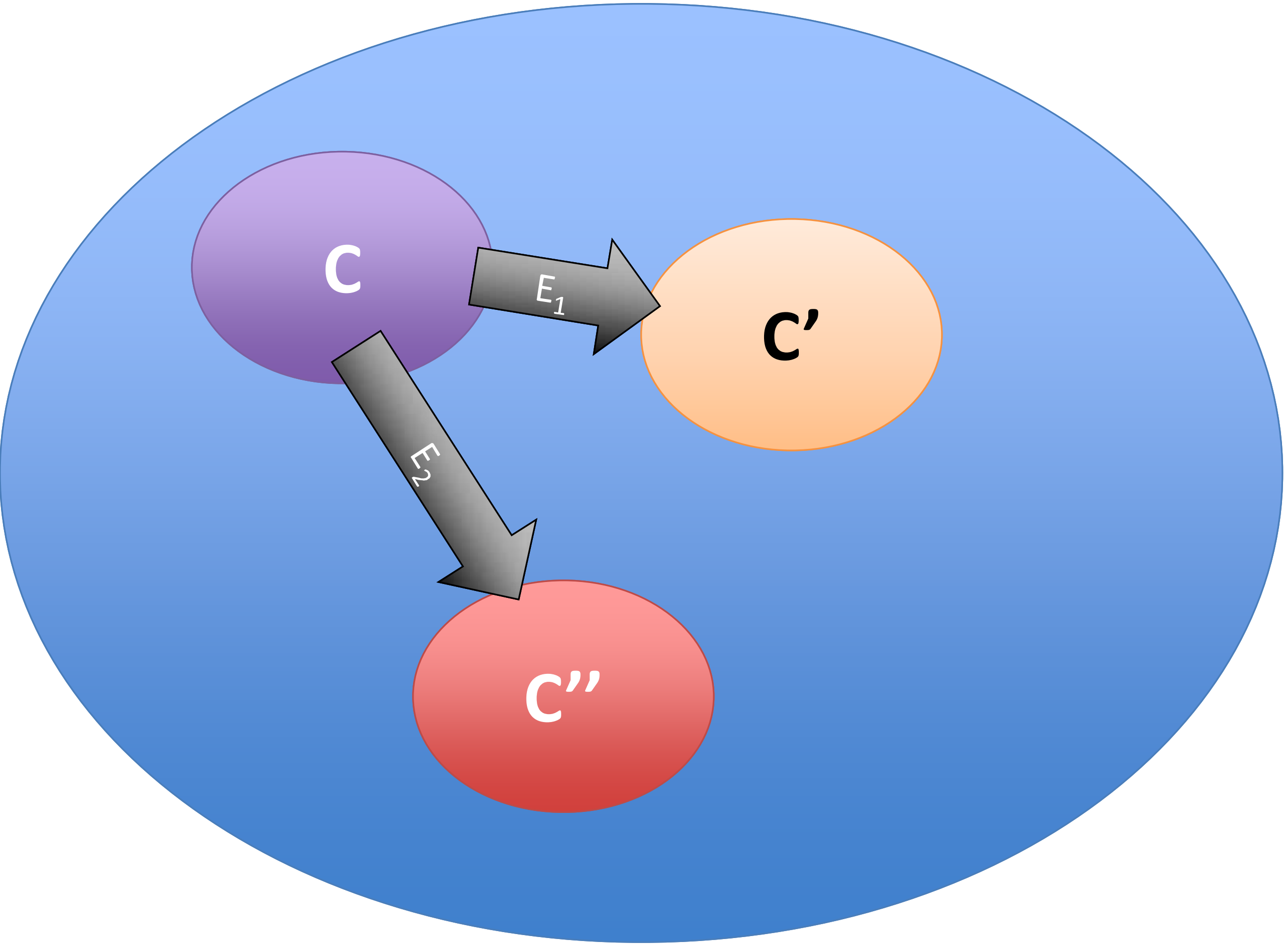
OMG qubits. Allcock et al. Appl. Phys. Lett. **119**, 214002 (2021)

Quantum Error Correction



A quantum code defines
a subspace of Hilbert space

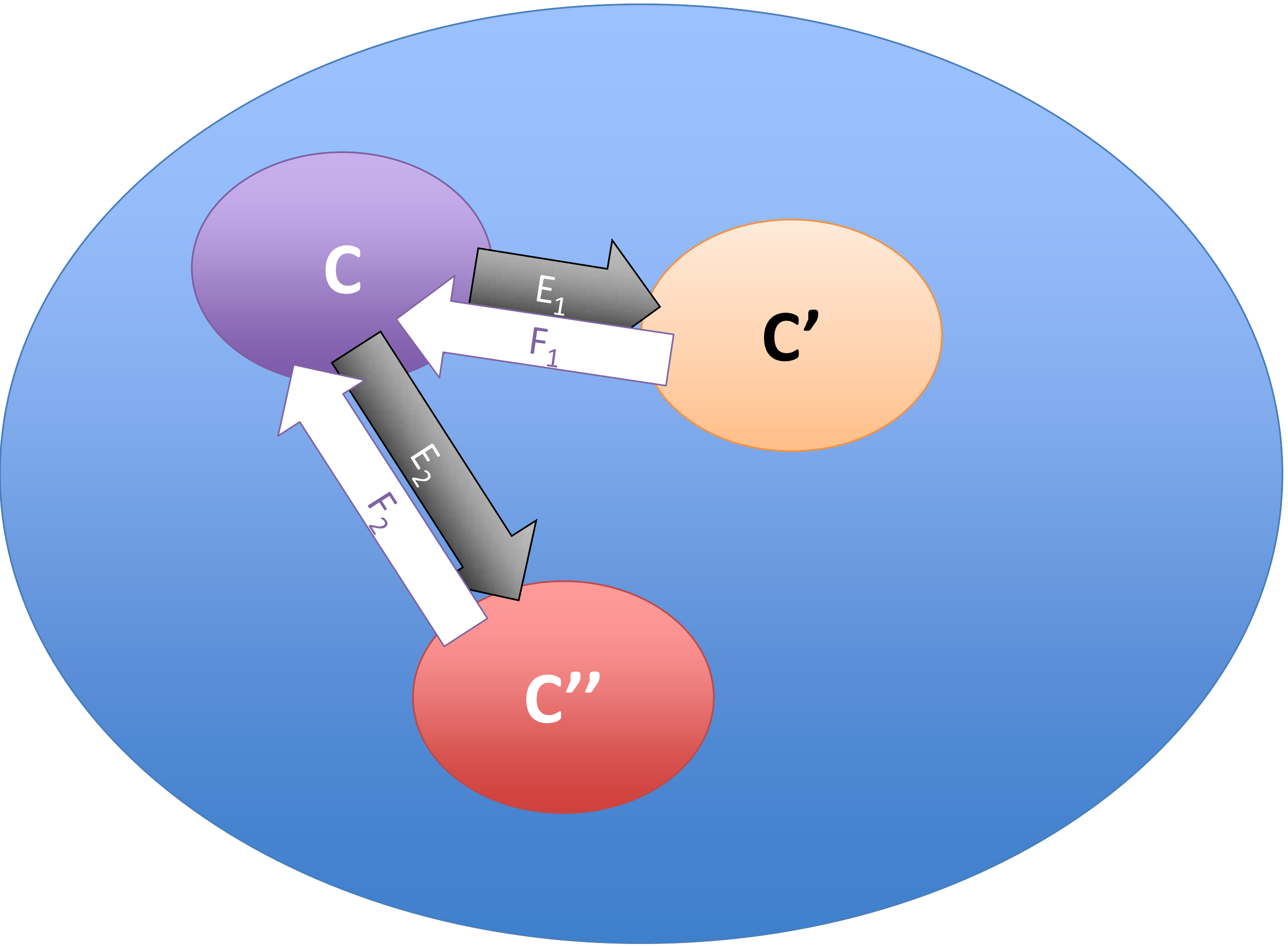
Quantum Error Correction



A quantum code defines a subspace of Hilbert space

A detectable error maps to an orthogonal subspace

Quantum Error Correction

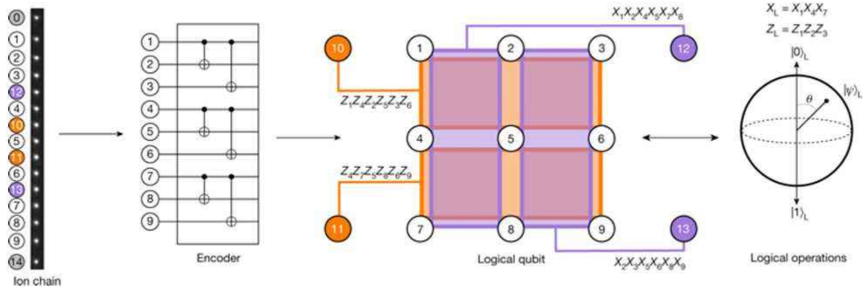


A quantum code defines a subspace of Hilbert space

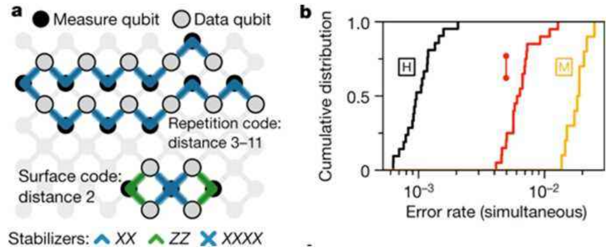
A detectable error maps to an orthogonal subspace

A correctable error can be mapped back

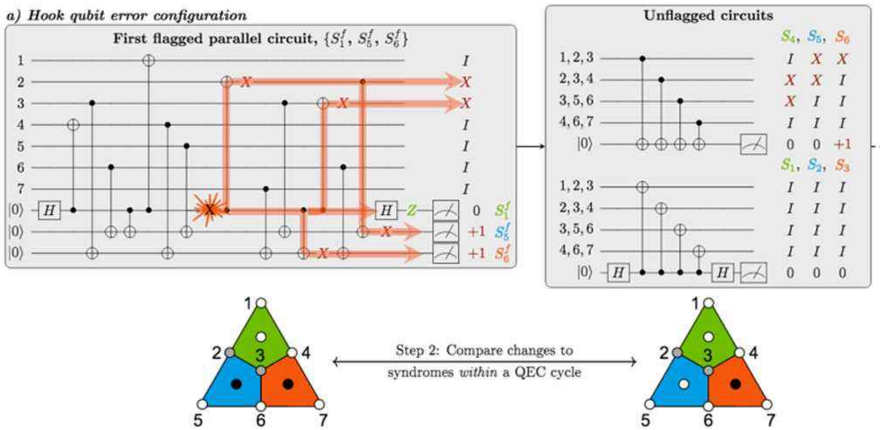
Quantum Error Correction Now

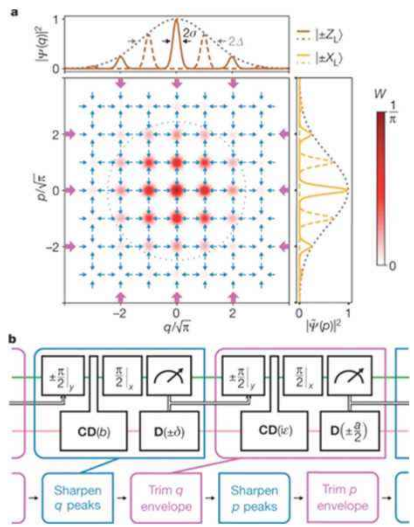


L. Egan et al. Nature (2021)



Google Quantum AI Nature (2021)



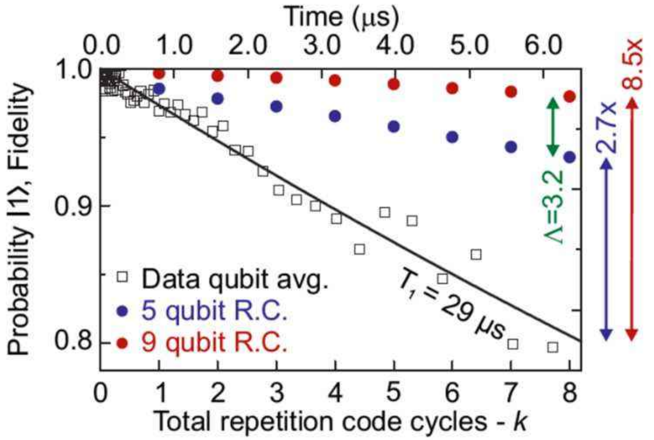


Honeywell/Quantinuum C. Ryan-Anderson et al. Phys. Rev. X (2021)

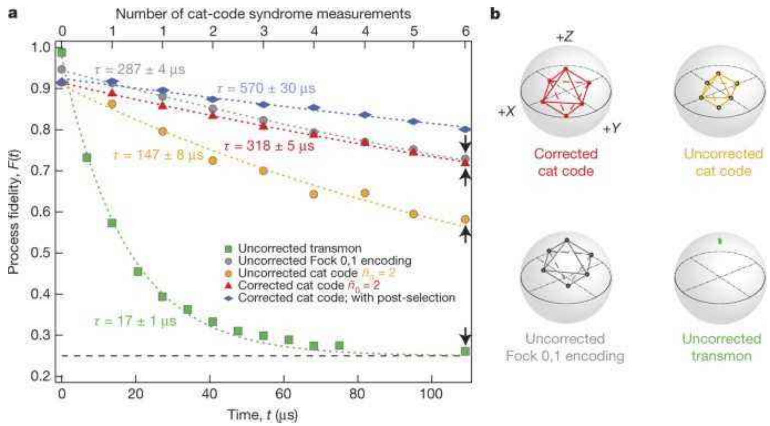
Yale P. Campagne-Ibarcq et al., Nature (2021)

Quantum Error Correction Tasks

Improved Memory

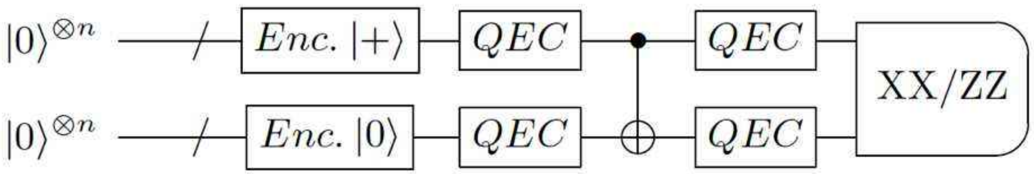


Kelly et al. Nature (2015) (Martinis UCSB)



Ofek et al. Nature (2016) (Yale)

Improved Circuits



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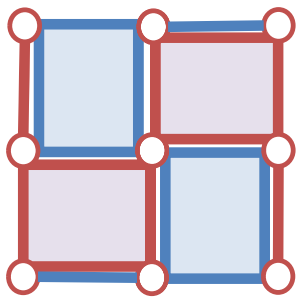
Stabilizer Code

- Stabilizer code [[*n*, *k*, *d*]]
  - Codes defined as +1 subspace of (n-k) commuting Pauli operators
  - *n* unencoded qubits
  - *k* encoded qubits
  - *d* minimal weight of Pauli operator on unencoded qubits that generates a Pauli operator on the logical qubit



$Z_i Z_j$

$X_i X_j$

$Z_i Z_j Z_k Z_l$

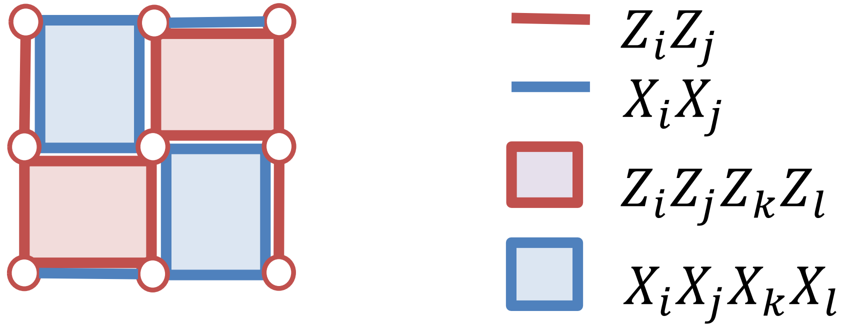
$X_i X_j X_k X_l$

$$Z_L = Z_0 Z_1 Z_2$$

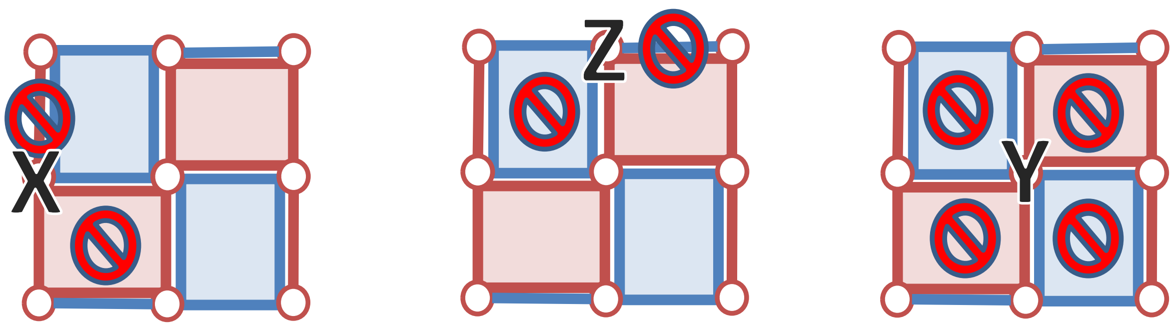
$$X_L = X_0 X_3 X_6$$

Bravyi and Kitaev, arXiv (1998)
Bombin and Delgado, PRA (2007)

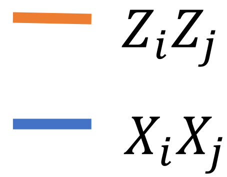
Surface [9,1,3]

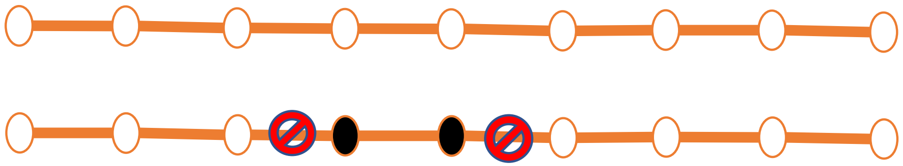


Surface



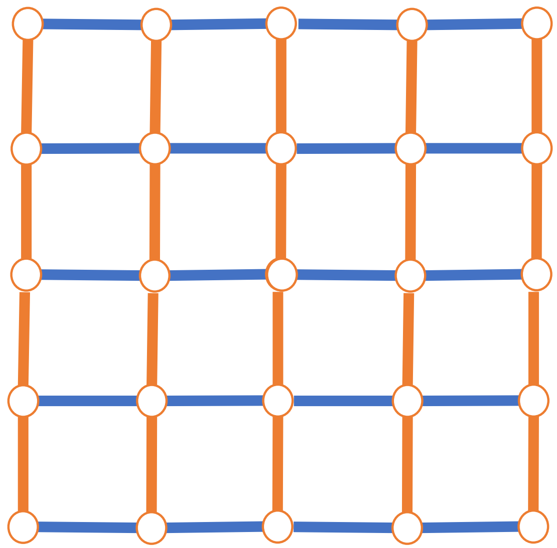
Codes from spin models





Ising model

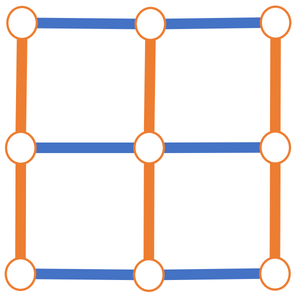
repetition code



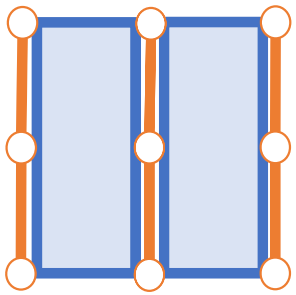
compass model

compass codes

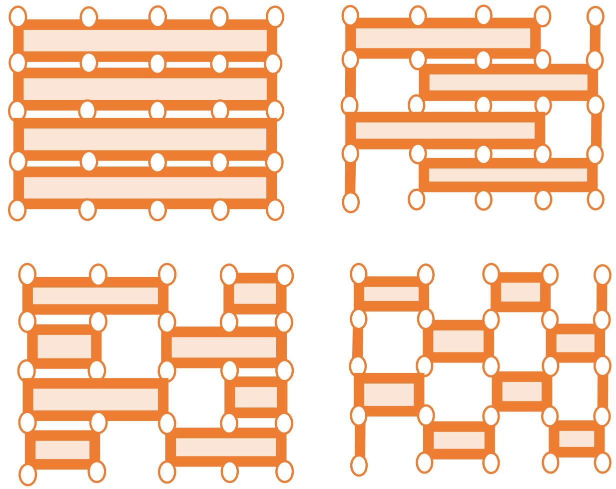
Codes Derivable from Compass Model



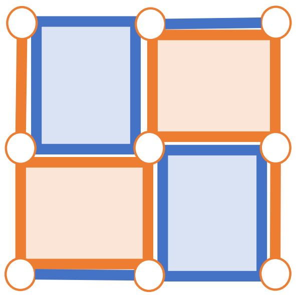
Compass



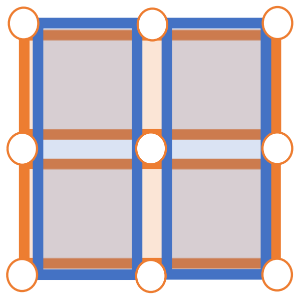
Shor
Shor. PRA (1995)



Many other codes
Li, Miller, Newman, Wu, KRB PRX (2019)



Surface
Bravyi and Kitaev, arXiv (1998)
Bombin and Delgado, PRA (2007)

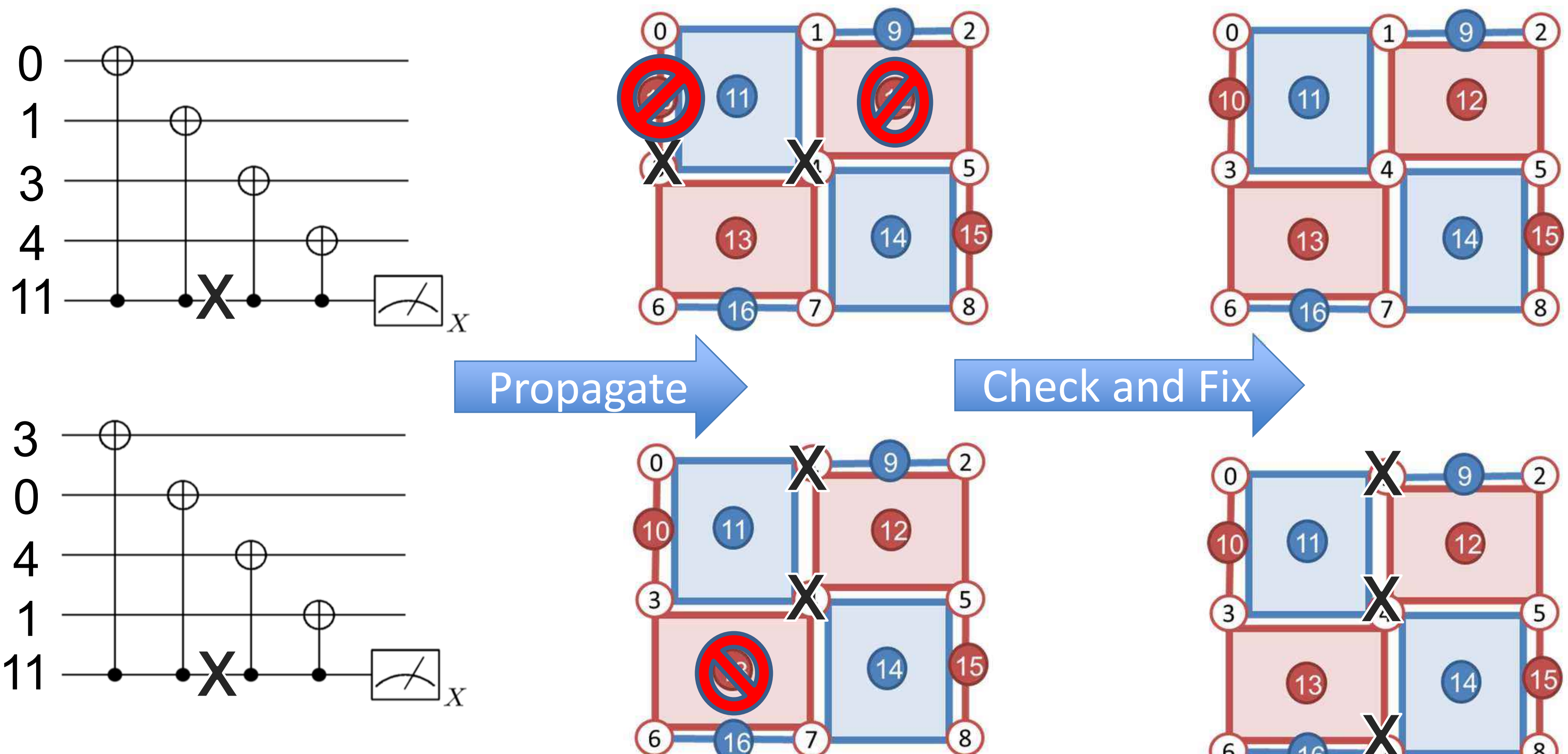


Bacon-Shor
Bacon, PRA (2006)
Aliferis and Cross, PRL (2007)

Fault-Tolerance

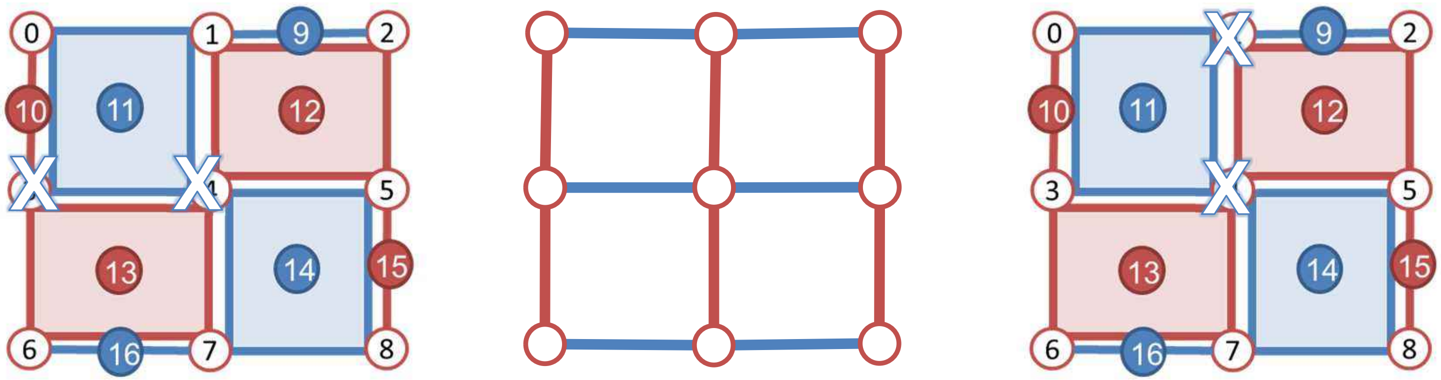
- *Principle for designing processes where the correct answer is guaranteed if there are k or less faults.*
- Design code, circuit, and decoder for specific fault set (Pauli errors)
- Limits operations (transversal + magic state)
- If error corrected circuit improves performance, you are below a threshold

Fault-Tolerance and Small Codes



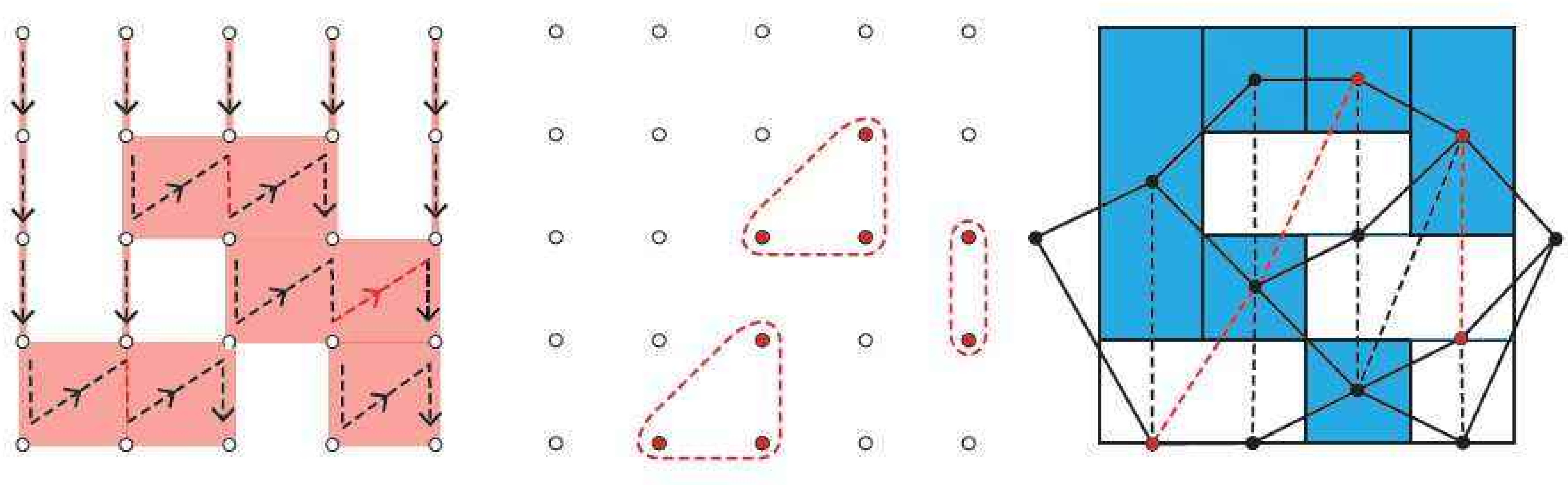
Tomita and Svore, Phys. Rev. A (2014)

Pattern Determined by Compass Model



Correct order: For X stabilizers, group CNOTs by XX compass model bonds.
For Z stabilizers, group CNOTs by ZZ compass model bonds.

Single qubit syndrome checks are FT



Gauges determine the circuit construction.

LI, Miller, KRB PRA (2018)
Li, Miller, Newman, Wu, KRB PRX (2019) all compass codes, no algorithm
Huang and KRB PRA (2020) algorithm (+ weighted union-find decoder)
Huang, Newman, and Brown PRA (2020) application to surface code

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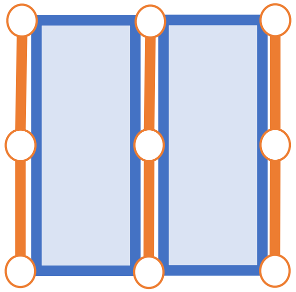
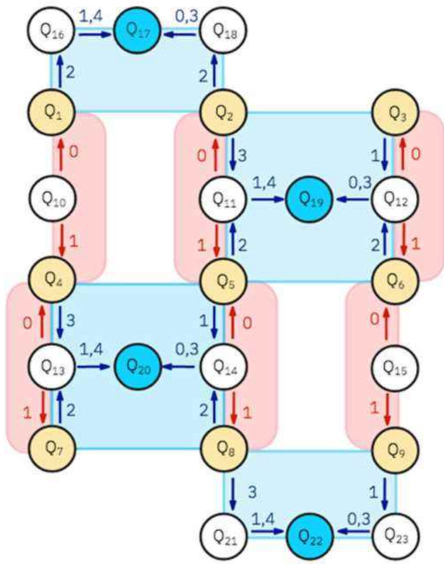
Compass Codes Now!

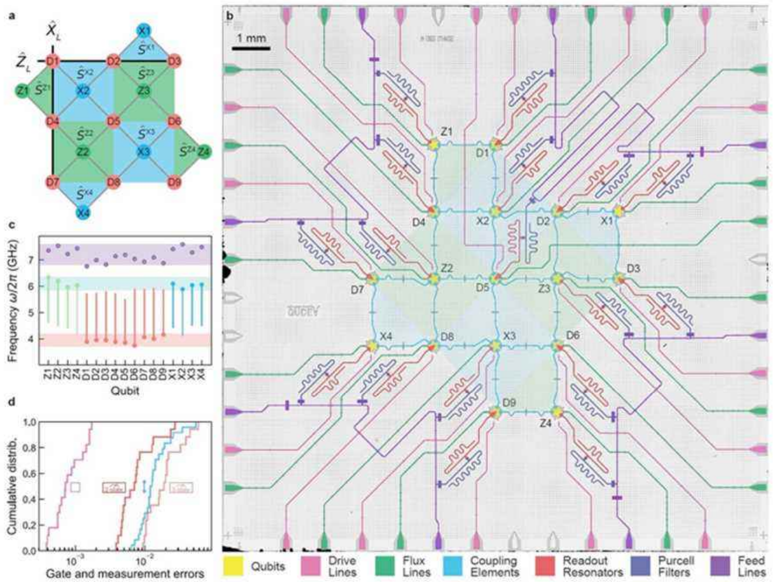


m	Prep.	Z Meas. $\mathcal{F}_z$	X Meas. $\mathcal{F}_x^+$	X Meas. $\mathcal{F}_x^-$	Majority vote $\mathcal{F}_L^+$	Majority vote $\mathcal{F}_L^-$
3	+	0.951(1)	0.965(1)	0.035(1)	0.9963(4)	0.0037(1)
	−		0.033(1)	0.967(1)	0.0032(1)	0.9968(4)
4	+	0.917(2)	0.947(2)	0.053(1)	0.9919(6)	0.0081(1)
	−		0.051(1)	0.949(2)	0.0076(1)	0.9924(6)
5	+	0.882(2)	0.936(2)	0.064(1)	0.9976(3)	0.0024(1)
	−		0.072(1)	0.928(2)	0.0033(1)	0.9967(4)
6	+	0.806(2)	0.917(2)	0.083(1)	0.9949(5)	0.0051(1)
	−		0.086(1)	0.914(2)	0.0056(1)	0.9944(5)
7	+	0.723(2)	0.869(2)	0.131(1)	0.9925(6)	0.0075(1)
	−		0.132(1)	0.868(2)	0.0076(1)	0.9924(6)

[m^2,1,m] Shor code
N Nguyen et al. (Linke group Duke)
Phys. Rev. Applied 16, 024057 (2021)



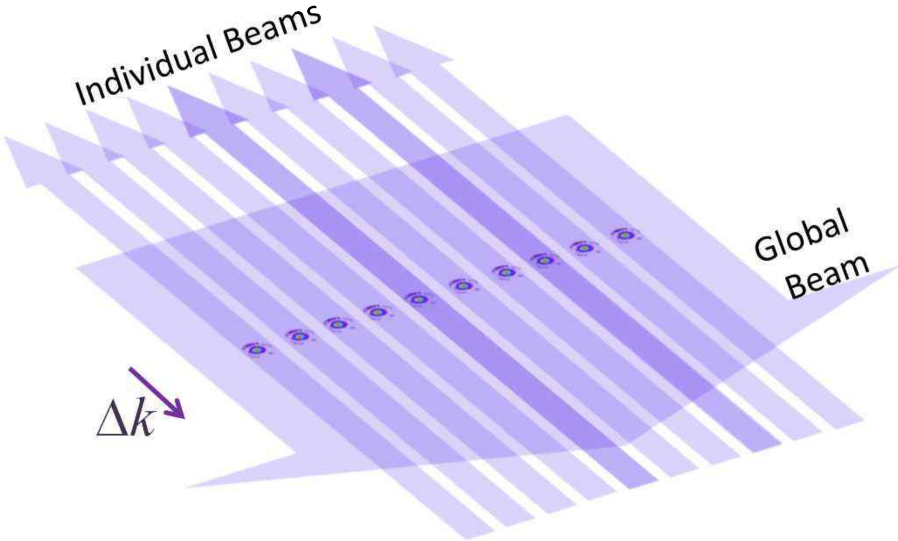
[9,1,3] Heavy Hex
N. Sundaresan et al. (IBM)
arXiv:2203.07205

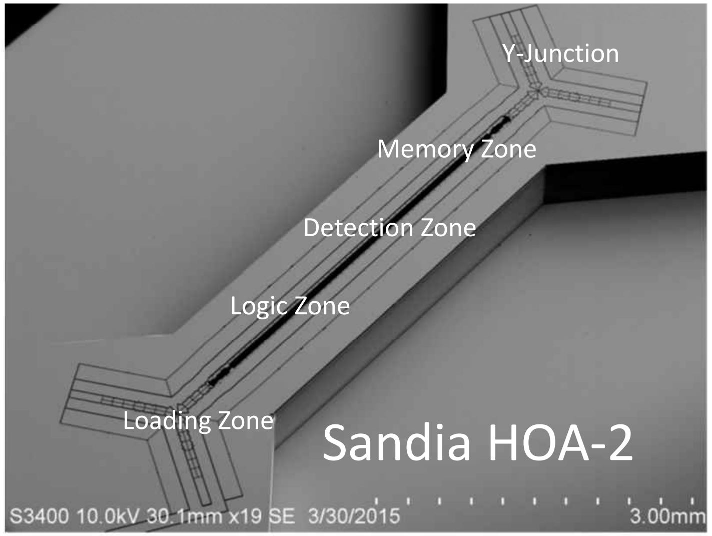


[9,1,3] Surface Code
S. Krinner, N. Lacroix et al. (Wallraff group ETH)
Nature 605, 669 (2022)
Y. Zhao et al. (USTC), PRL (2022)
Google [25,1,5] Nature (2023)

[4,1,2] or [4,2,2] UMD, ETH-Zurich, IBM, Sydney, Aachen 2017-2020

Ion chain quantum computer





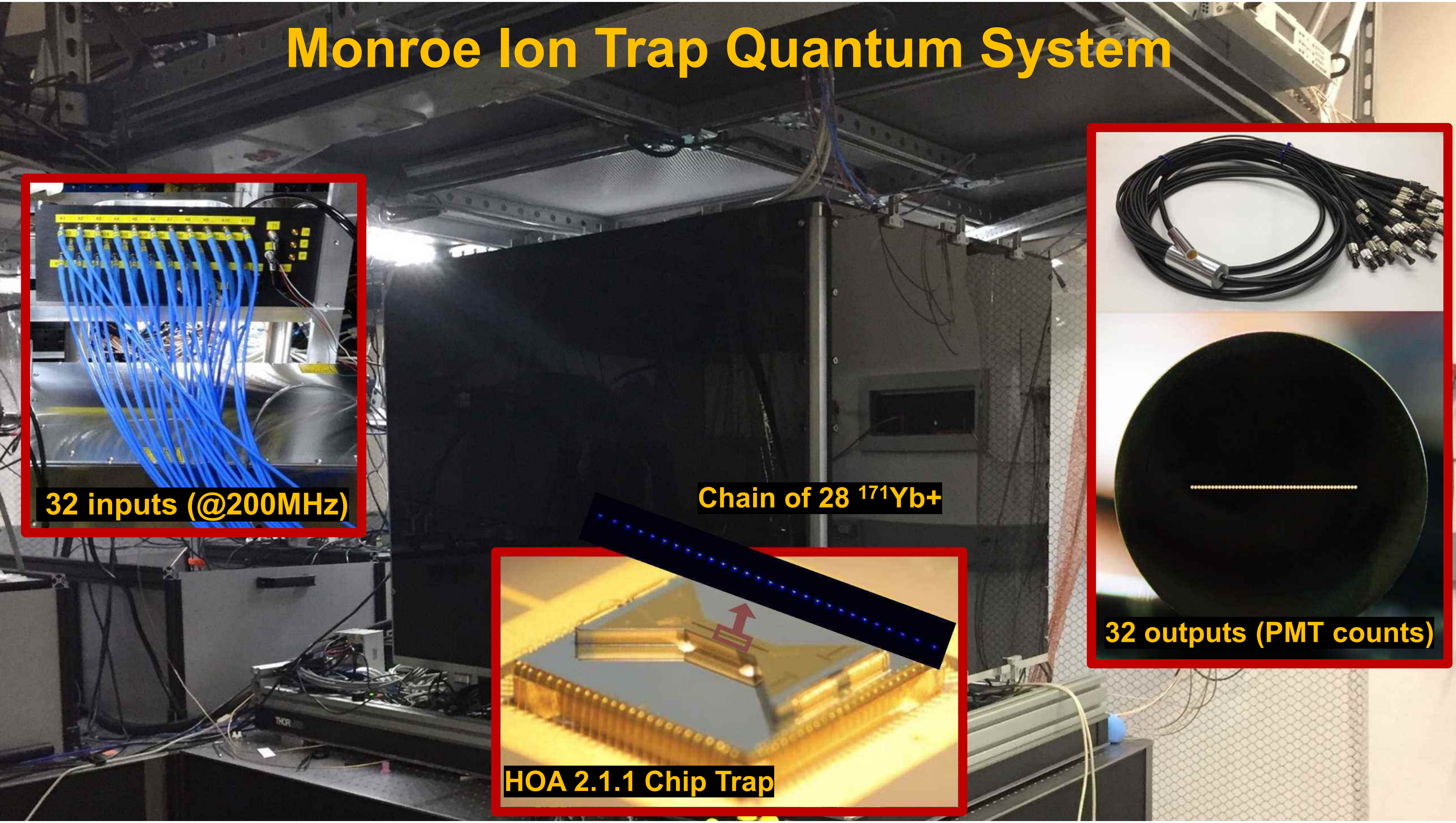
Quantum gates: Laser pulses on multiple ions
amplitude, frequency, phase, pulse shape

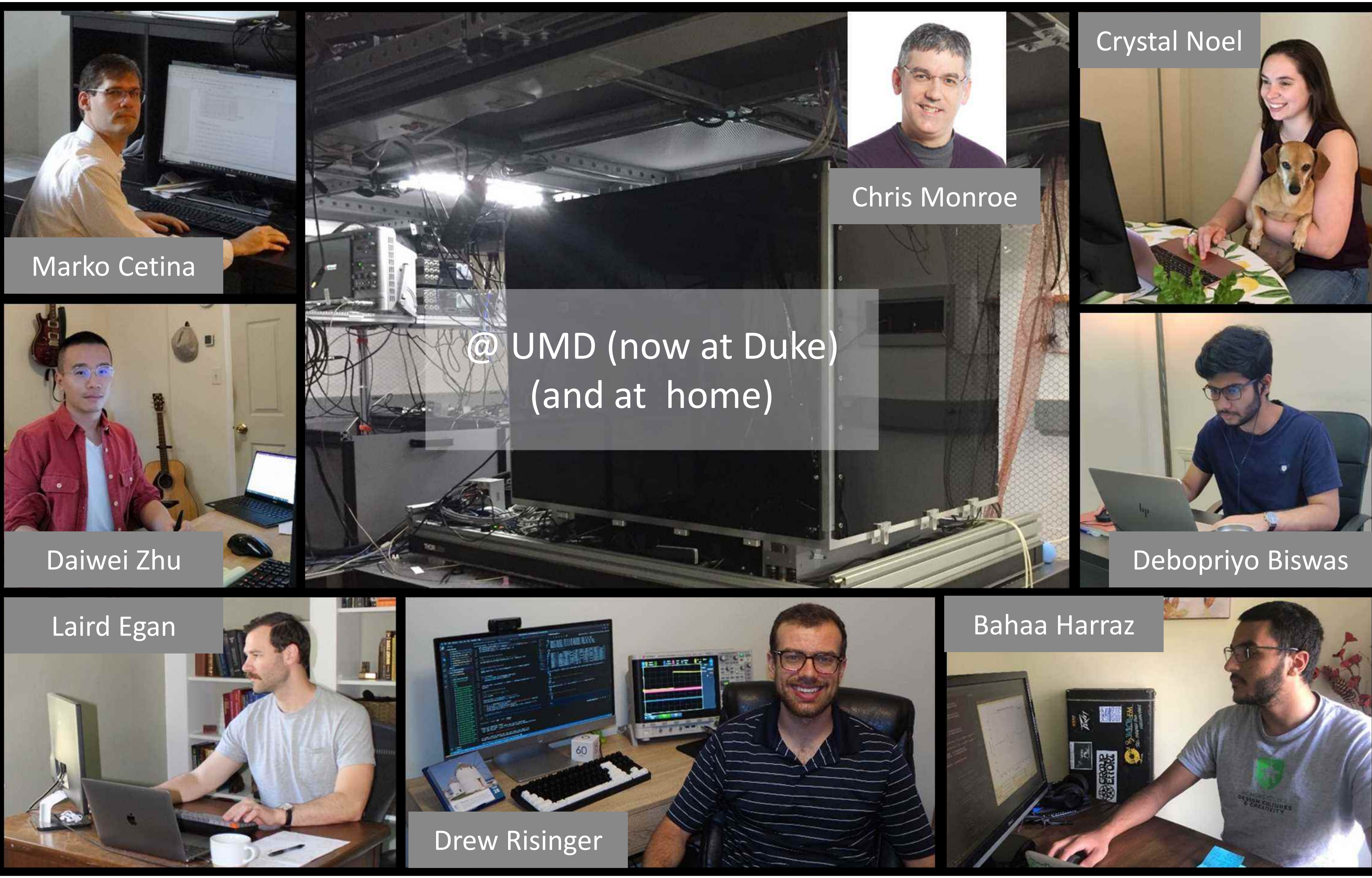
Measurement: photon detection
ion separation by trap electrodes

IARPA EURIQA collaboration: Duke, Harris, ColdQuanta, AOSense

NSF STAQ collaboration: Duke, U Maryland, Tufts, UC Berkeley, Chicago, U New Mexico

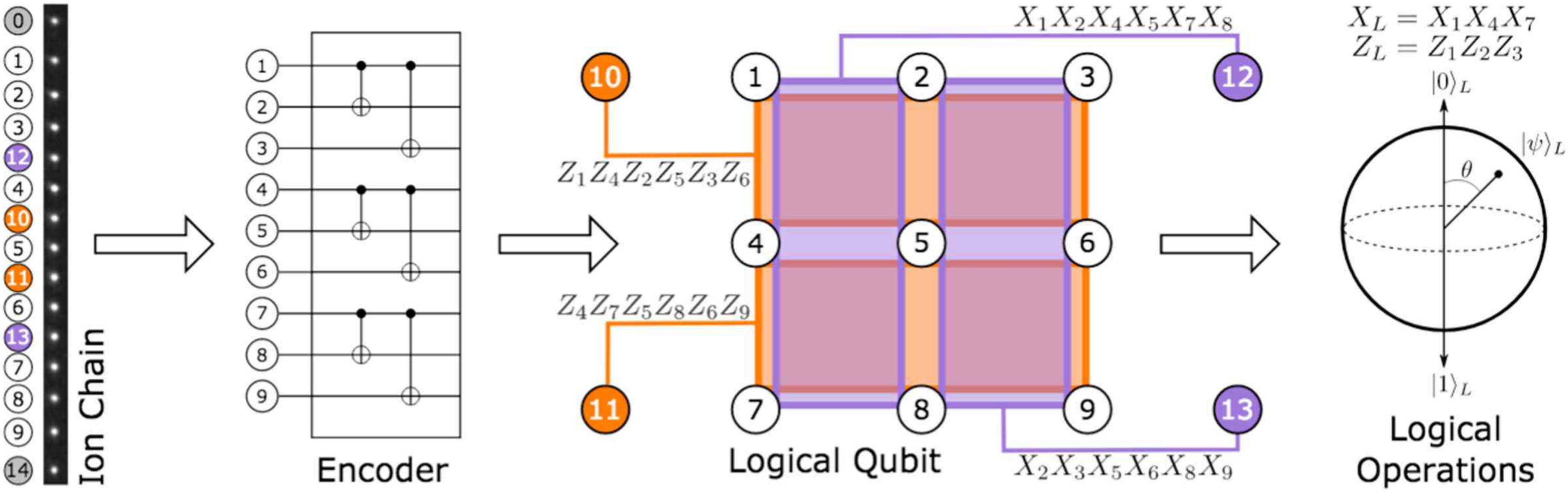
DOE QSCOUT collaboration: Sandia, Duke, Tufts


Monroe Ion Trap Quantum System
32 inputs (@200MHz)
Chain of 28 171Yb+
HOA 2.1.1 Chip Trap
32 outputs (PMT counts)



Marko Cetina
Chris Monroe
Crystal Noel
@ UMD (now at Duke)
(and at home)
Daiwei Zhu
Debopriyo Biswas
Laird Egan
Drew Risinger
Bahaa Harraz

Bacon-Shor Experiment



Egan, Debroy, Noel, Risinger, Zhu, Biswas, Newman, Li, Brown, Cetina, Monroe
Nature (2021), arXiv:2009.11482. UMD/Duke

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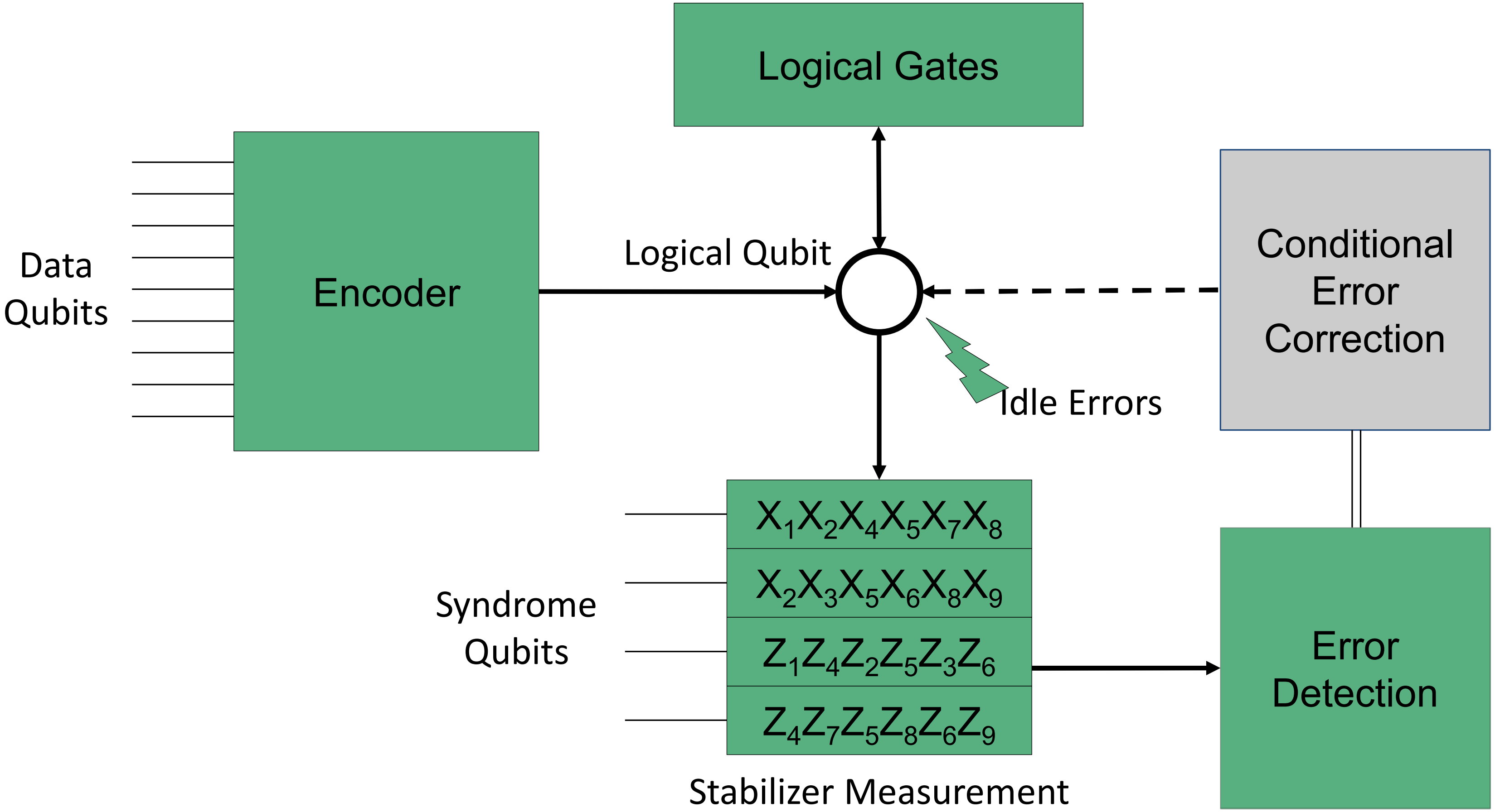
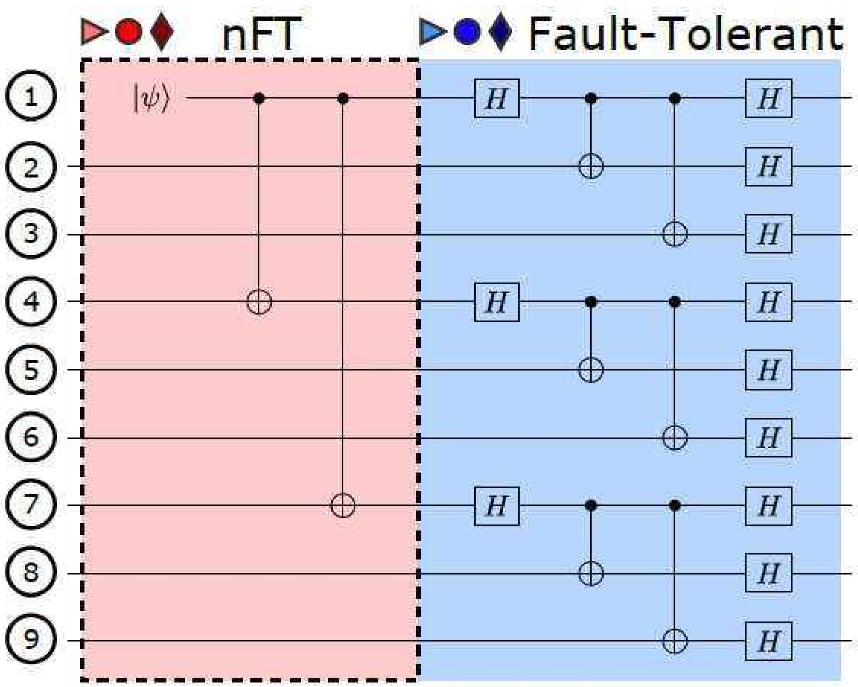
Bacon-Shor Experiment



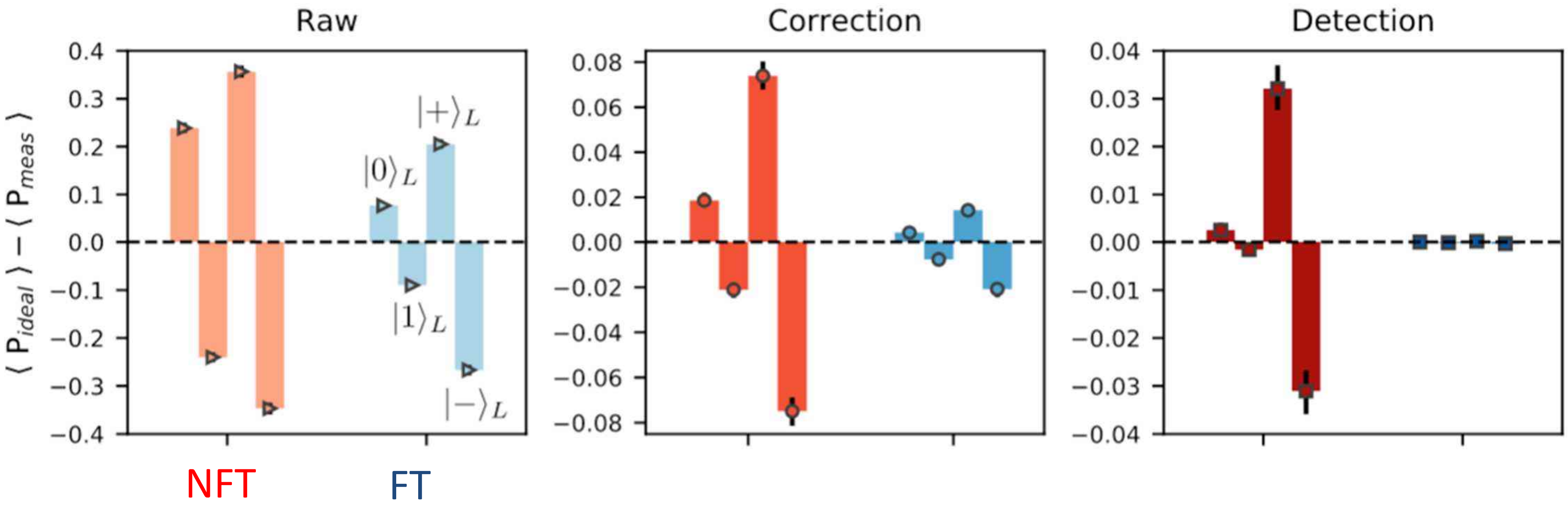
Preparation & Measurement



Bacon-Shor allows for fault-tolerant preparation of X and Z eigenstates without measurement due to Shor code structure.

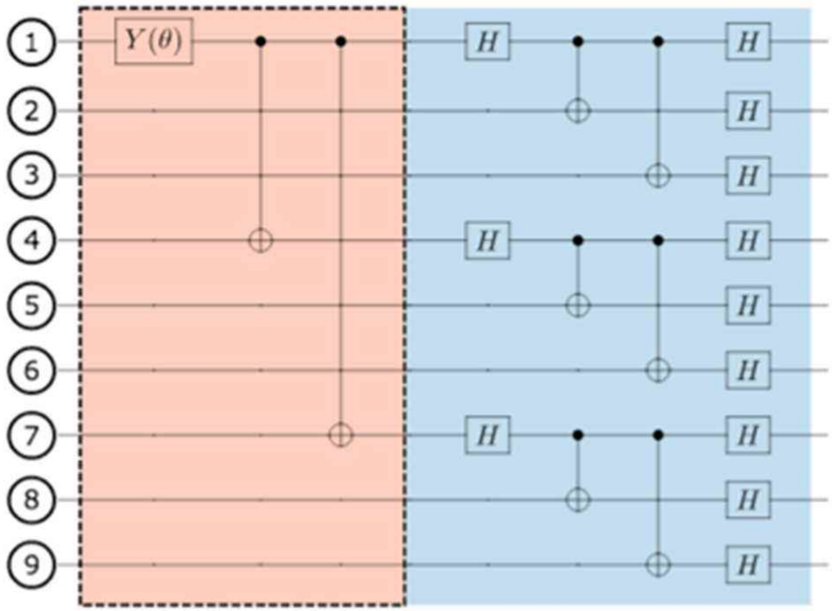
We can generate logical magic states creating a 9 qubit entangled states. The process is not fault-tolerant but necessary for universal computation.

FT Preparation & Measurement

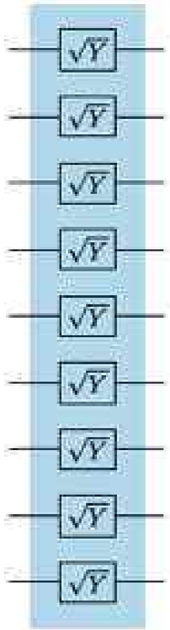


|+> and |-> prepared by applying FT gate to |0> and |1>

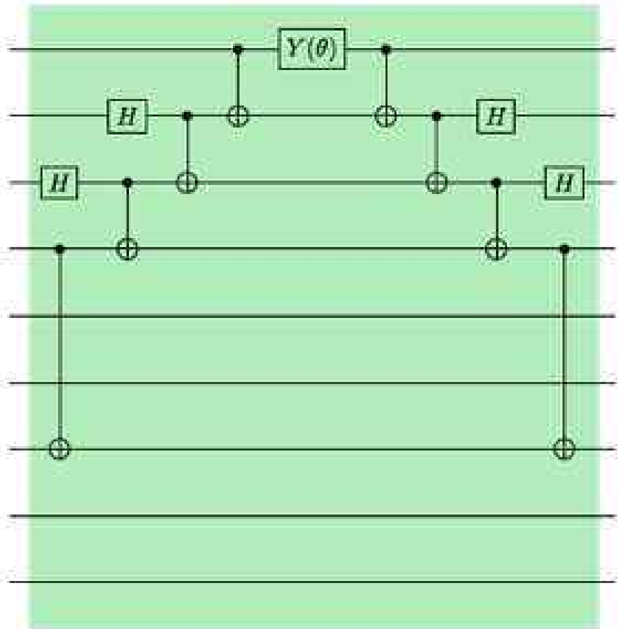
Preparing other states



direct



FT



continuous

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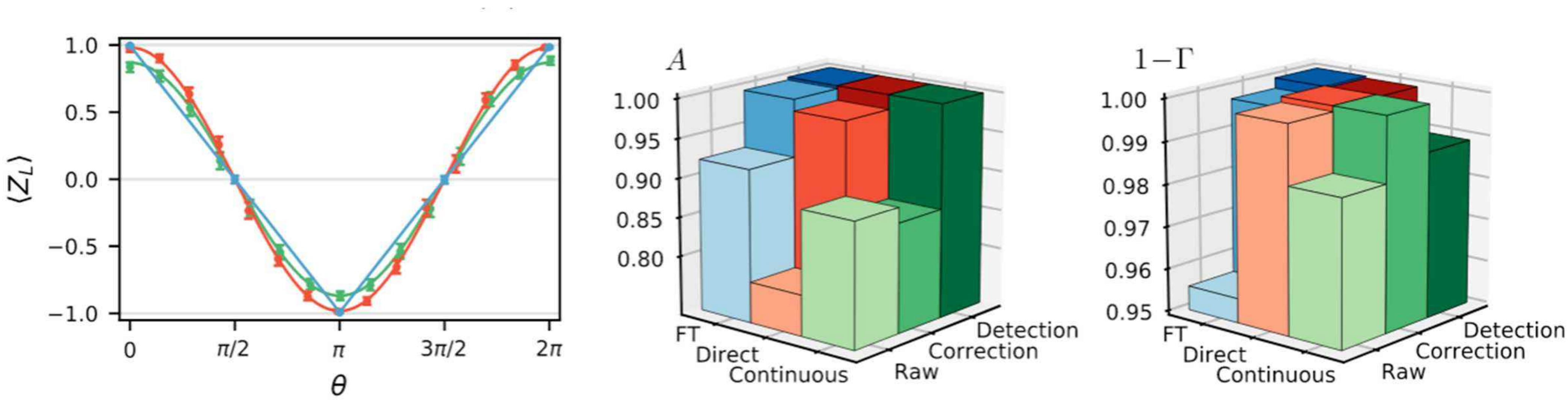
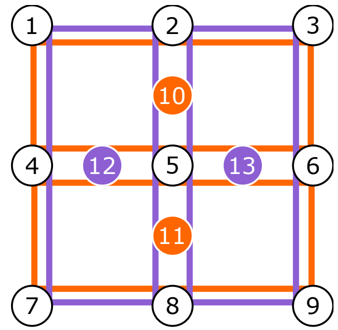
Comparison of preparations/gates

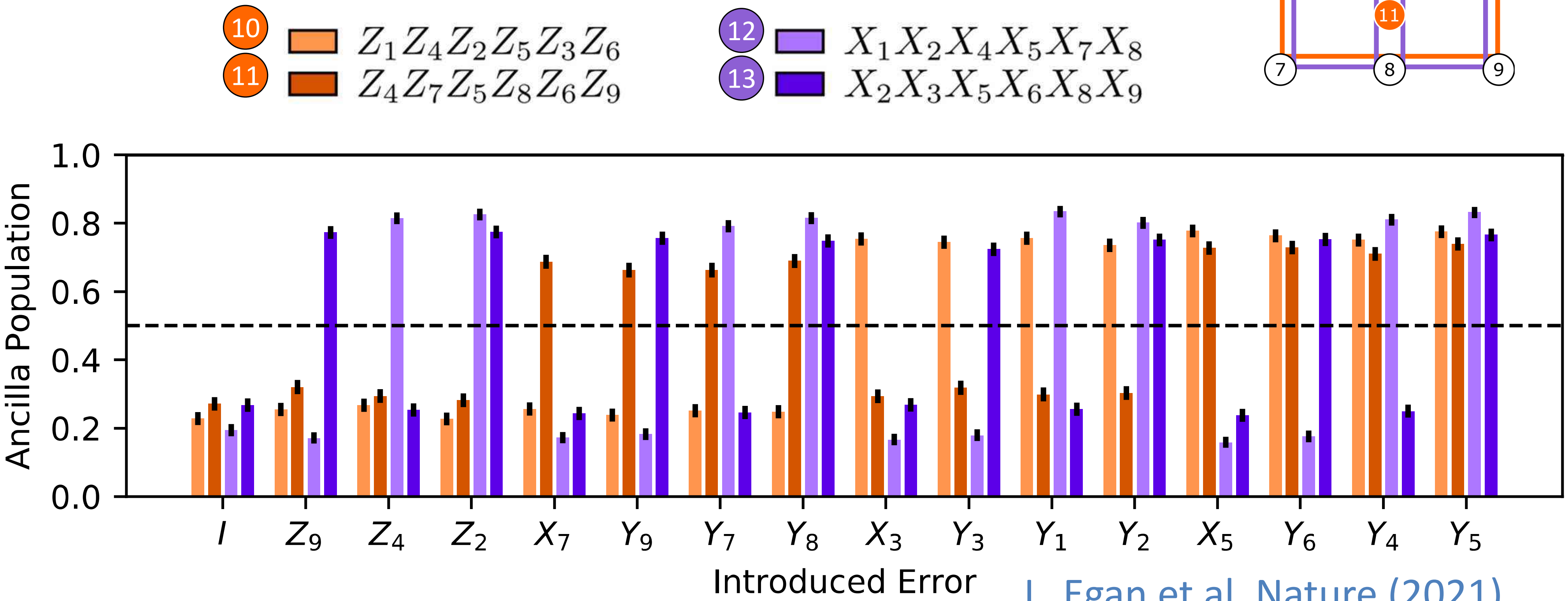


π/2 fault-tolerant gate error: 0.3%
encoded magic state prep error: 2%*

Stabilizer checks

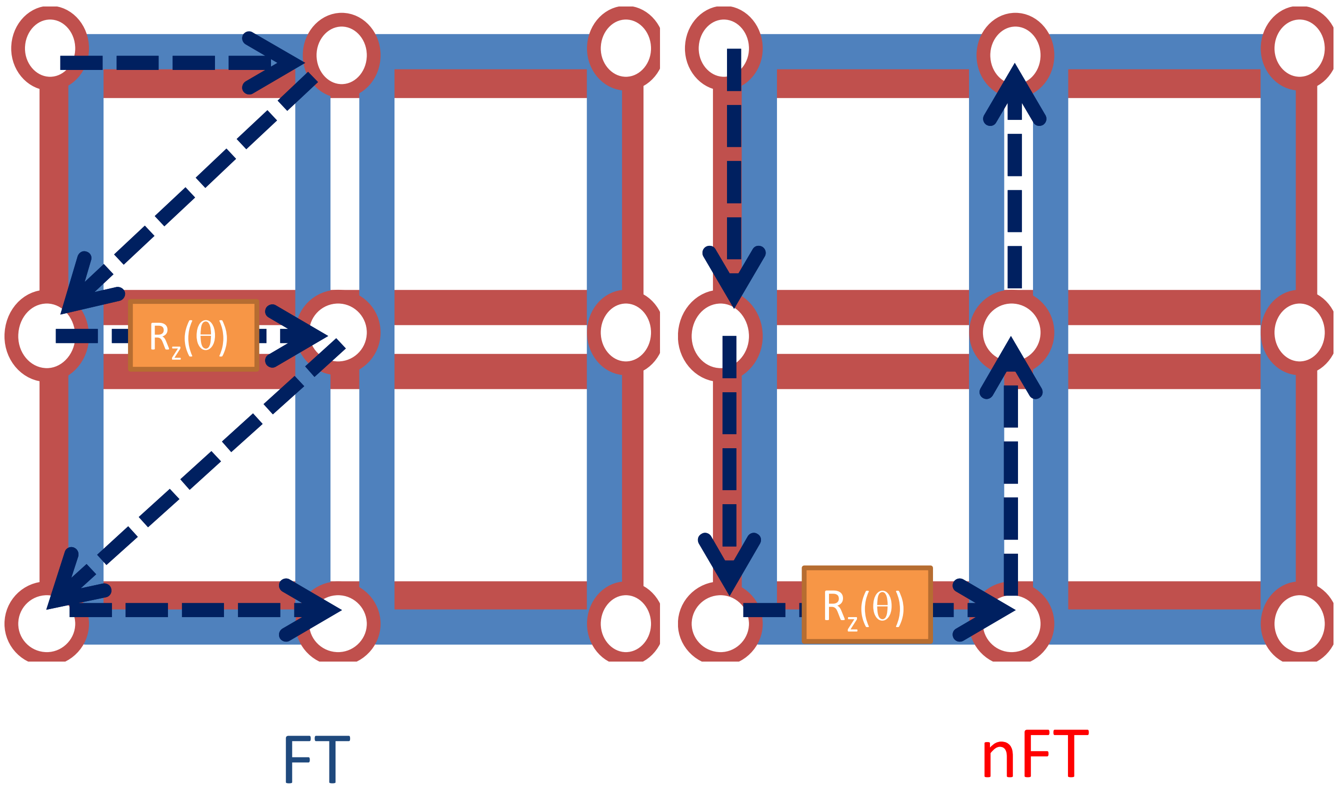
<u>Experiment</u>: Encode $|0\rangle_L$, introduce an error, map all 4 stabilizers onto syndrome qubits, measure globally

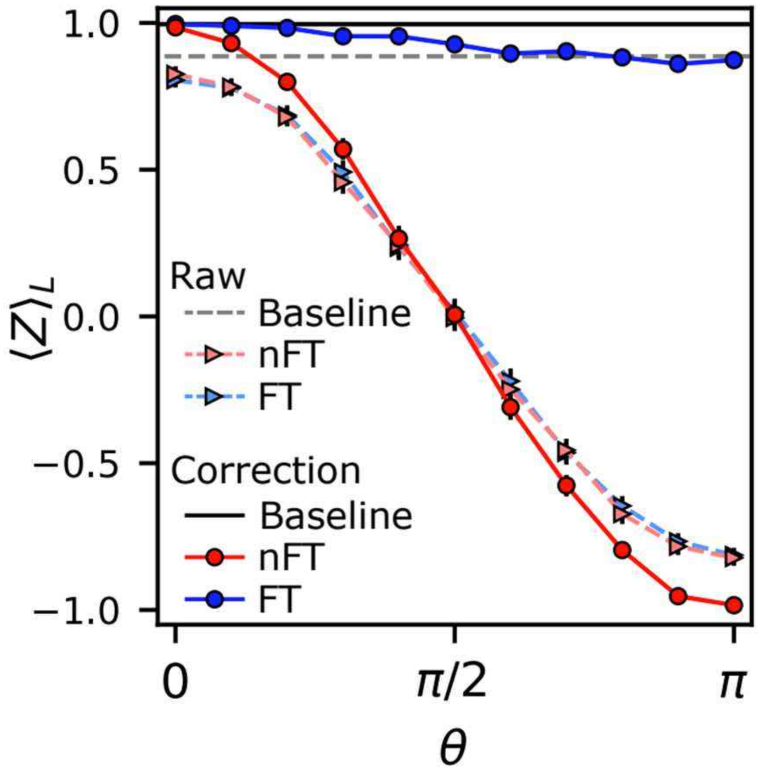




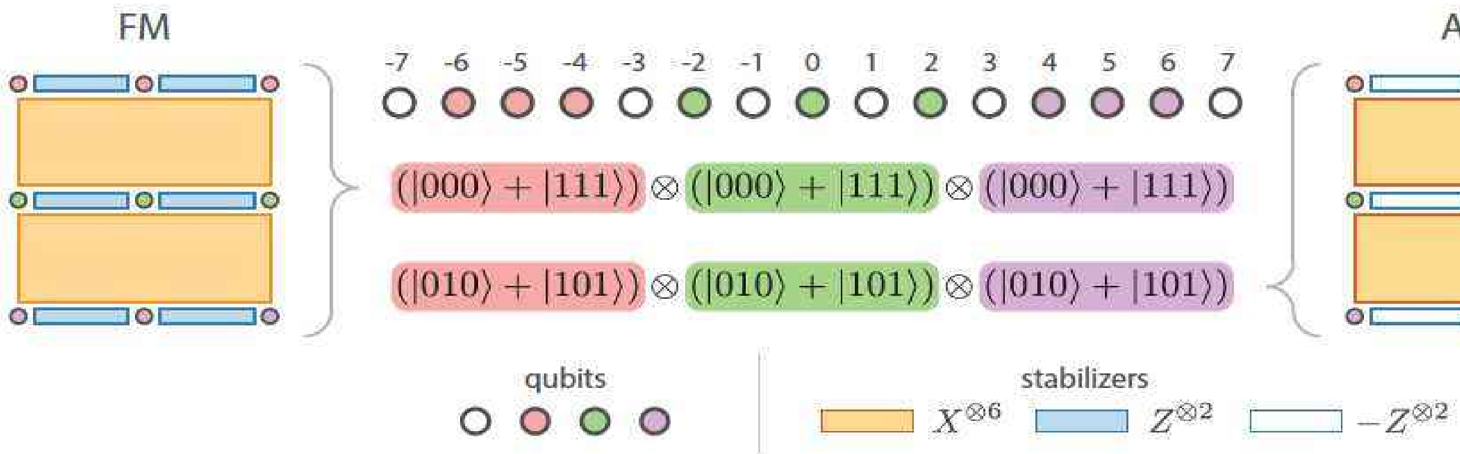
L. Egan et al. Nature (2021)

Fault-tolerant gadgets

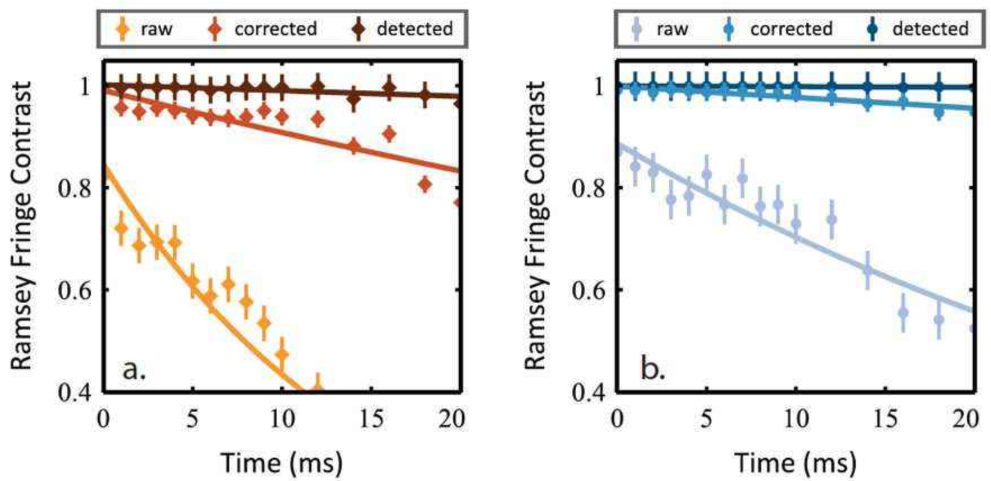




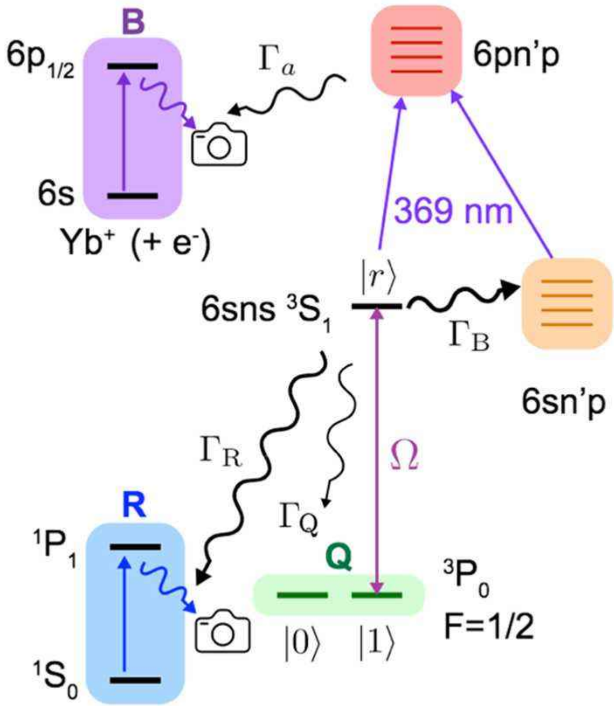
Reducing Correlated Errors



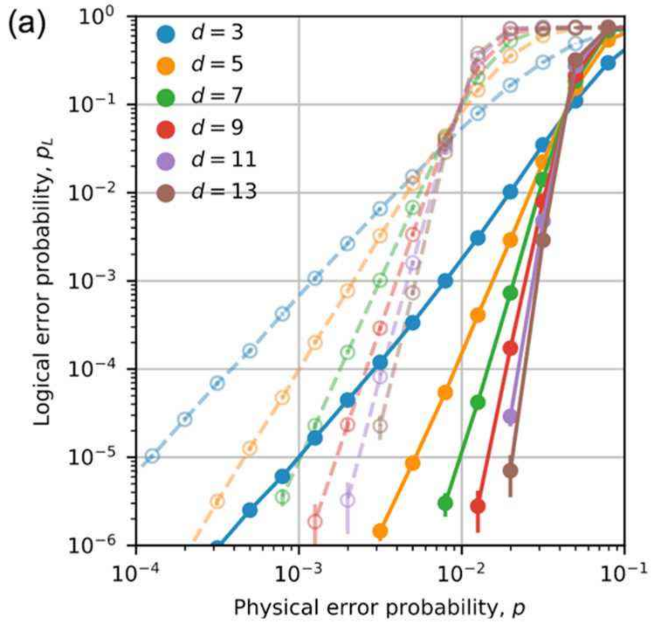
Increase of encoded corrected lifetime by a factor of 4.
Comparable to our single qubit life time.
In standard independent Pauli error model these codes should have the exact same behavior.
D. Debroy et al. Phys. Rev. Lett. (2021) arXiv:2105.05068
See also Hu, Liang, Rengaswamy, Calderbank, arXiv:2011.00197



Matching codes and decoders to physical errors



Wu, Kolkowitz, Puri, Thompson
arXiv:2201.03540



Conversion to erasure greatly improves threshold

Other ideas: XZZX codes, bias preserving cat codes, designer cluster states

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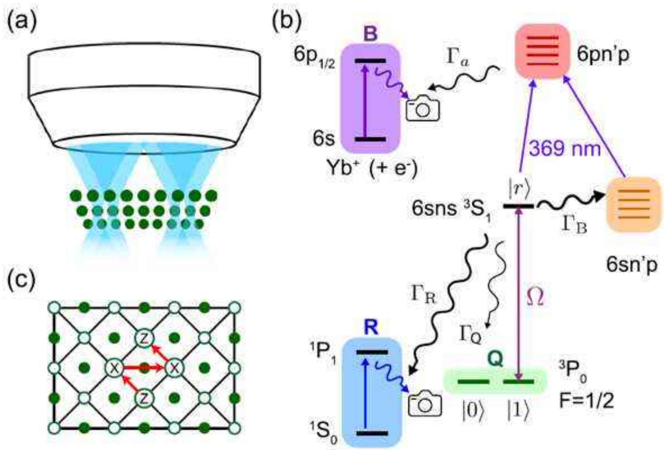
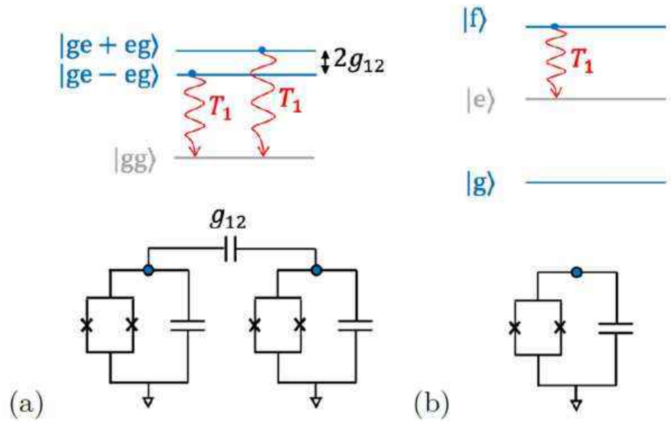
Erasure Conversion Trilogy

Rydberg atoms



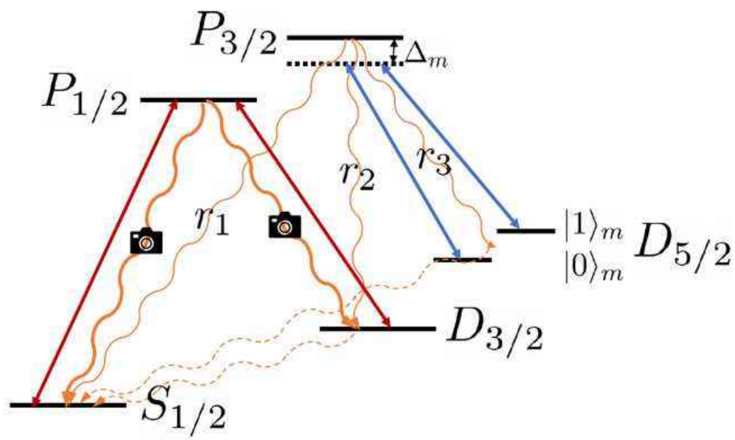
Y. Wu et al., Nat. Comm. 13, 4657 (2022)

Superconducting qubits



A. Kubica et al., arXiv:2208.05461

Trapped ions



M. Kang, W.C. Campbell, KRB, arXiv:2210.15024

- Design qubits s.t. physical noise causes **leakage** outside the qubit in a **detectible** way
- Additional operations turn leaked state to $\hat{I}/2$ in qubit subspace → **erasure**!

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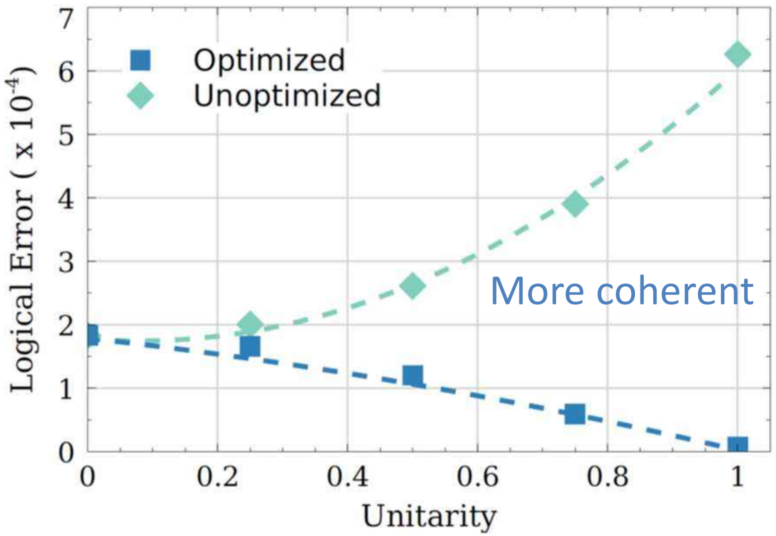
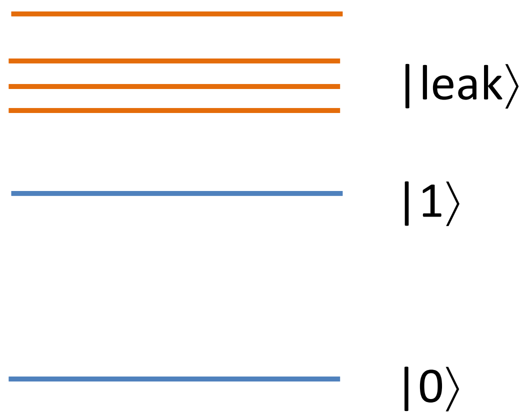
QEC Beyond Pauli Errors

Coherent Errors



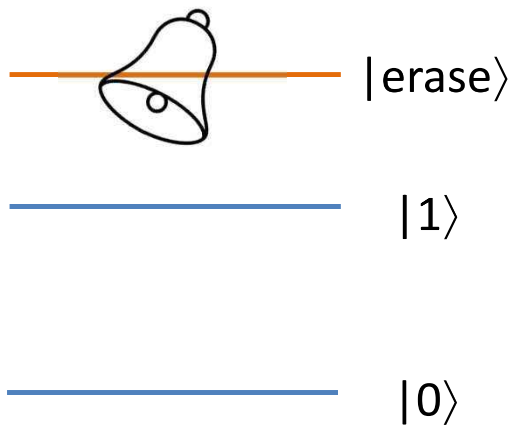
Not a problem for larger codes
Beale et al., PRL 2018
Not a problem if you try to fix it
Debroy, Li, Newman, Brown PRL 2019
Minimize with codespace
Debroy, Egan, et al. PRL 2021

Leakage Errors



Leakage vs memory errors
Brown and KRB, PRA 2018, PRA 2019
Subsystem codes for leakage
Brown, Newman, KRB NJP 2019

Erasure Errors



Erasure errors
Kang, Campbell and KRB
arXiv:2210.15024

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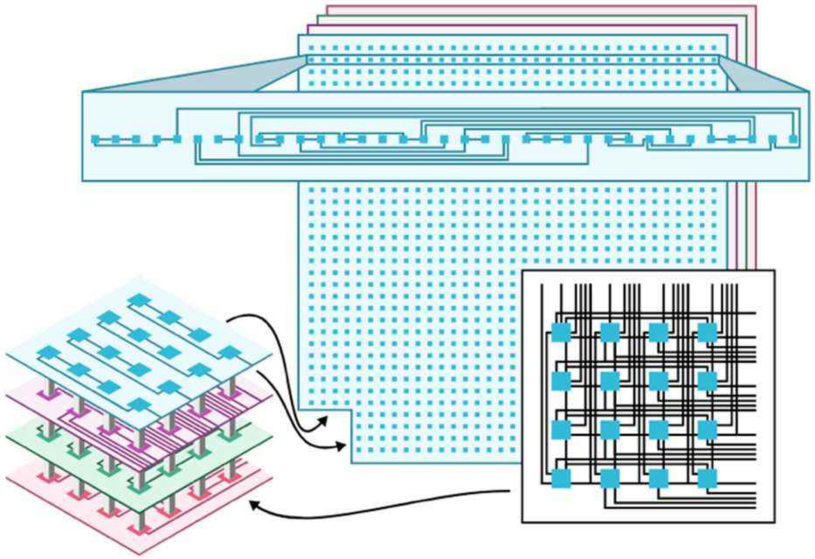
QEC Now!

- Experiments have reached a point where QEC is possible
- Designing hardware that enables finite rate codes remains challenging
- QEC procedures tailored to physical errors can reduce the overhead
- Fault-tolerant gate design for finite rate codes remains an open question
- Theory of fault tolerance is also transforming



Tremblay, Delfosse, Beverland
arXiv:2109.14609
1000 qubits/logical qubit to
50 qubits/logical qubit

Low overhead constructive codes
Panteleev and Kalachev, arXiv:2111.03654
Leverrier and Zemor, arXiv:2202.13641
Yamasaki and Koashi, arXiv:2207.08826
and more..... dynamic research area

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Wes Campbell
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