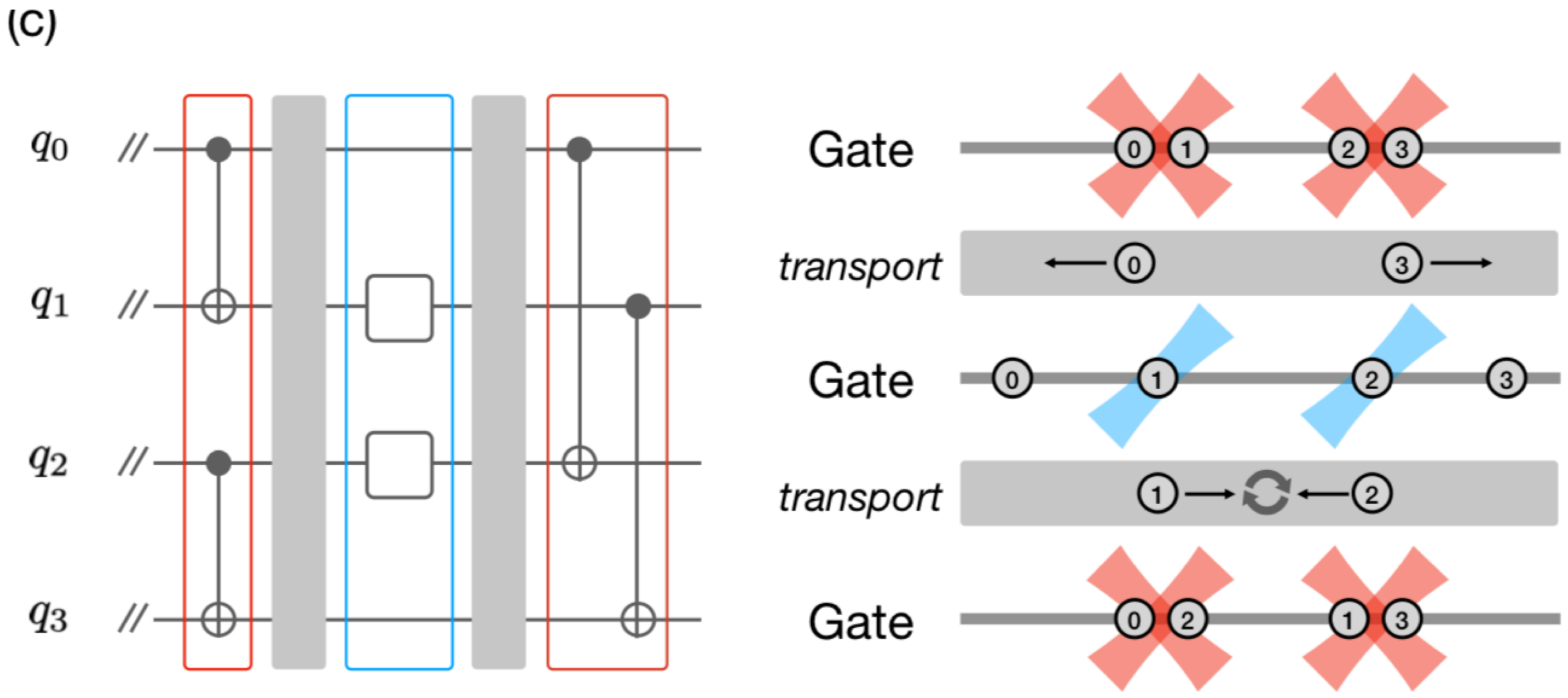
Trapped Ion Architectures

QCCD

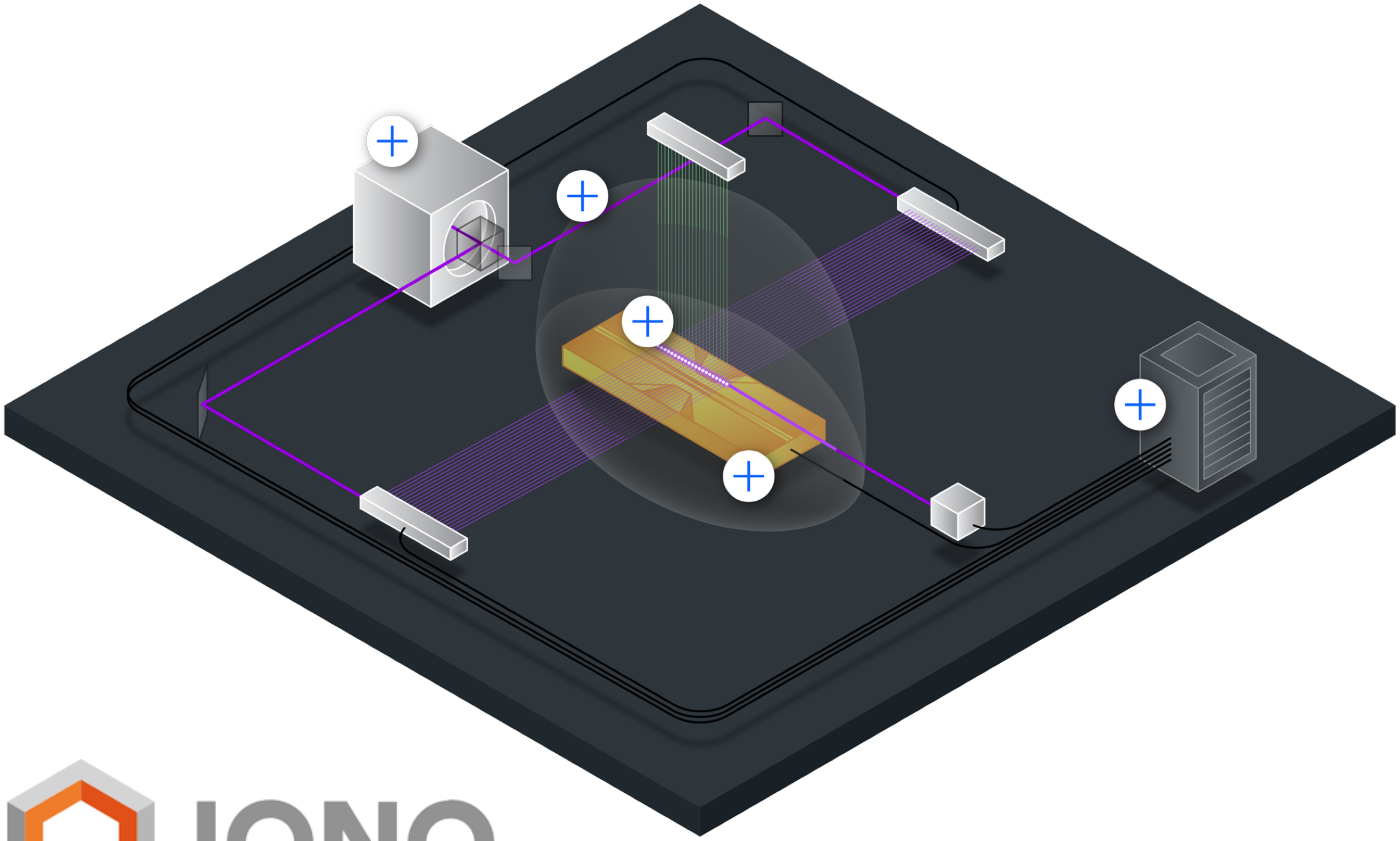


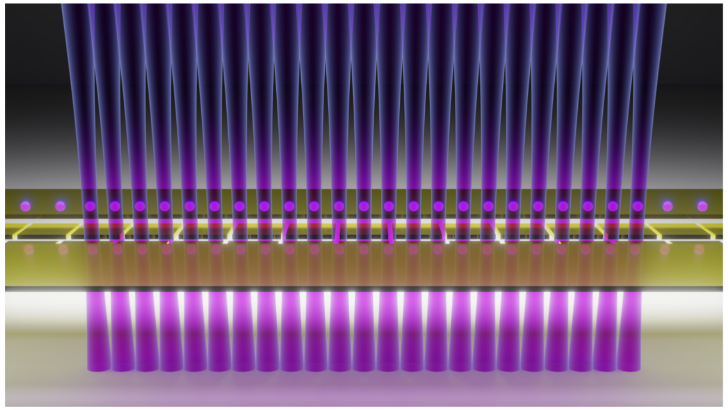
ArXiv: 2003.01293

QCCD


2020
2030+
H1
POWERED BY HONEYWELL
LINEAR
H2
POWERED BY HONEYWELL
RACETRACK
H3
POWERED BY HONEYWELL
GRID
H4
POWERED BY HONEYWELL
INTEGRATED OPTICS
H5
POWERED BY HONEYWELL
LARGE SCALE

Long Chain

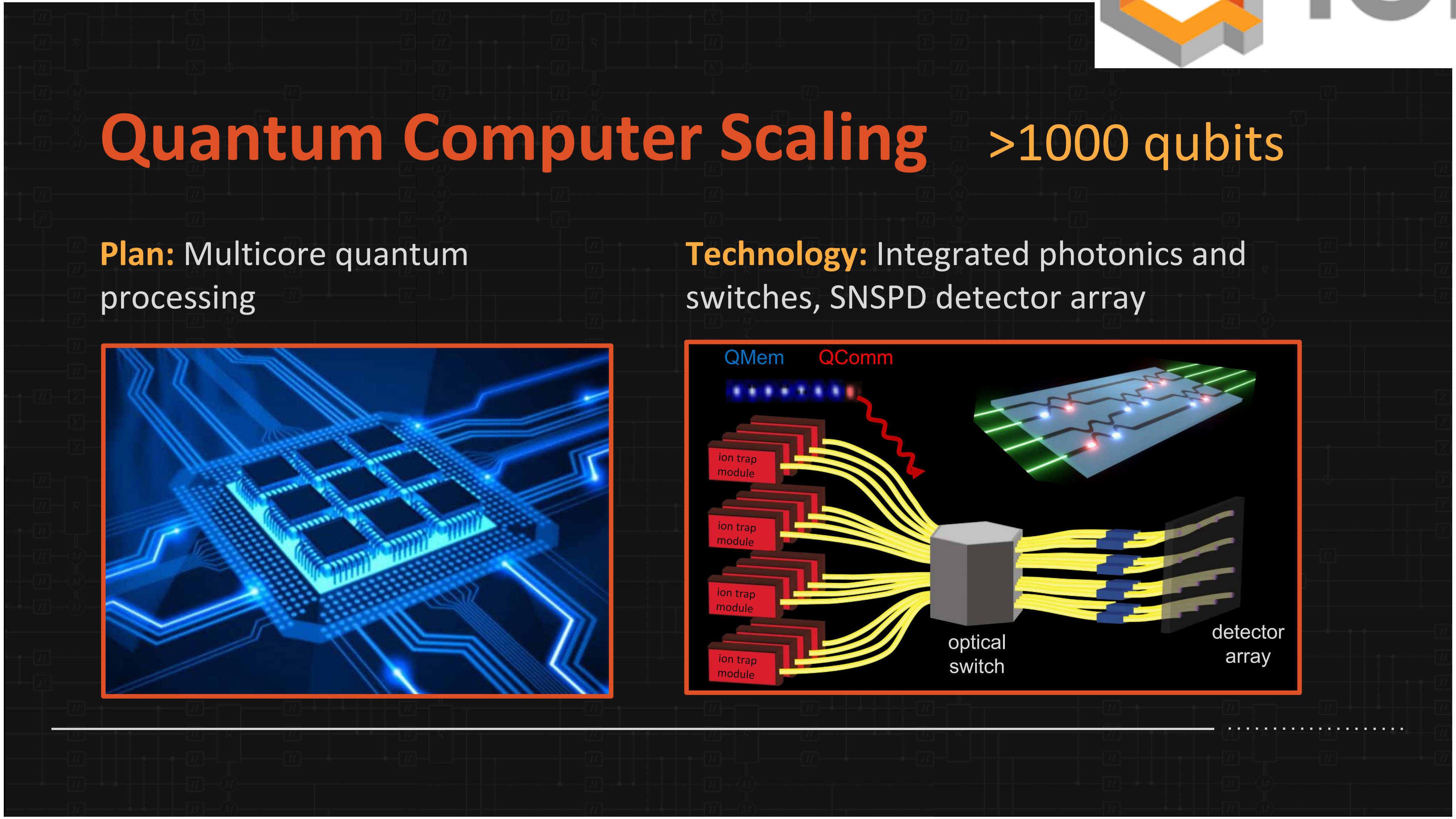




IONQ

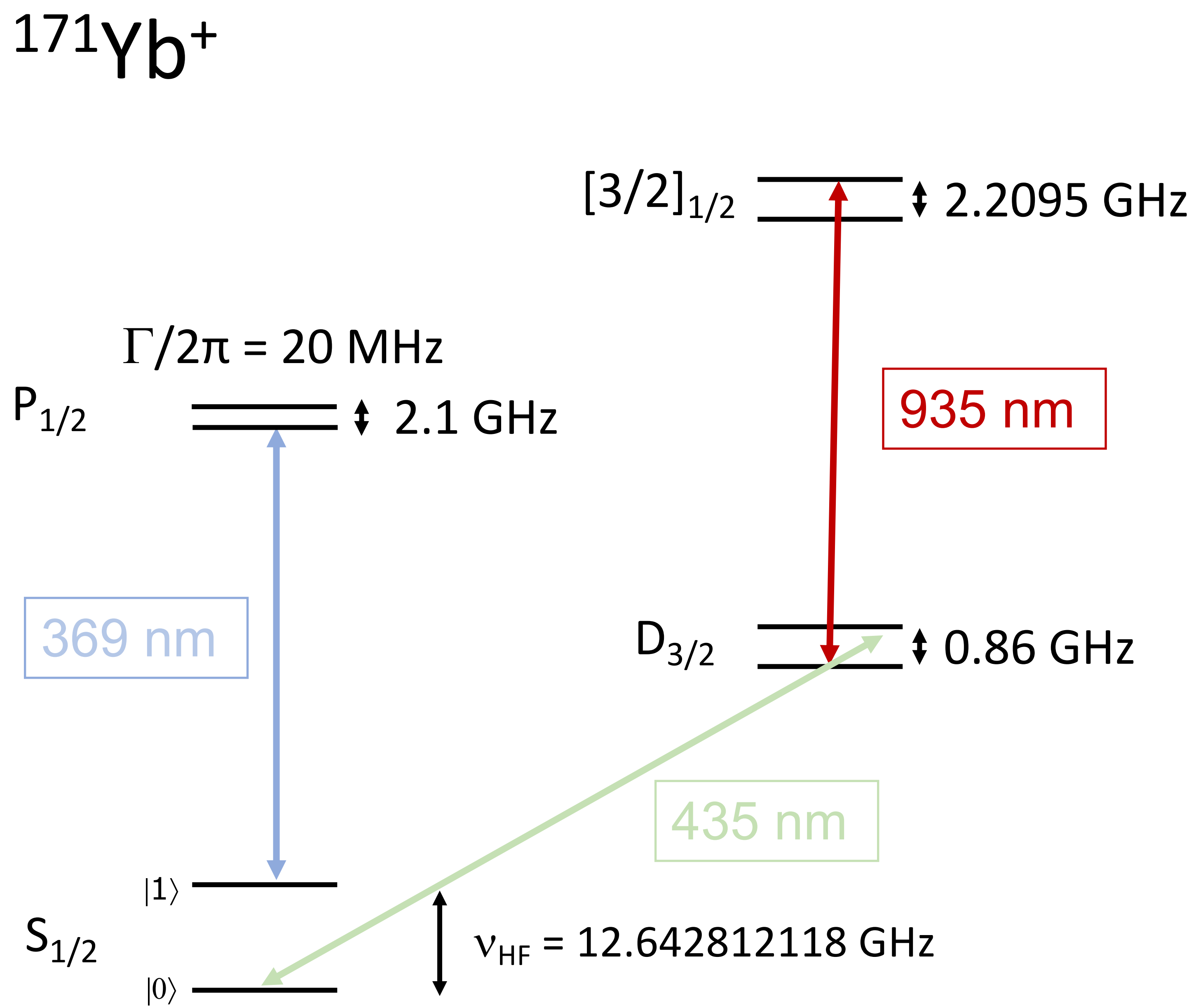
Duke
UNIVERSITY

Photonic Interconnects

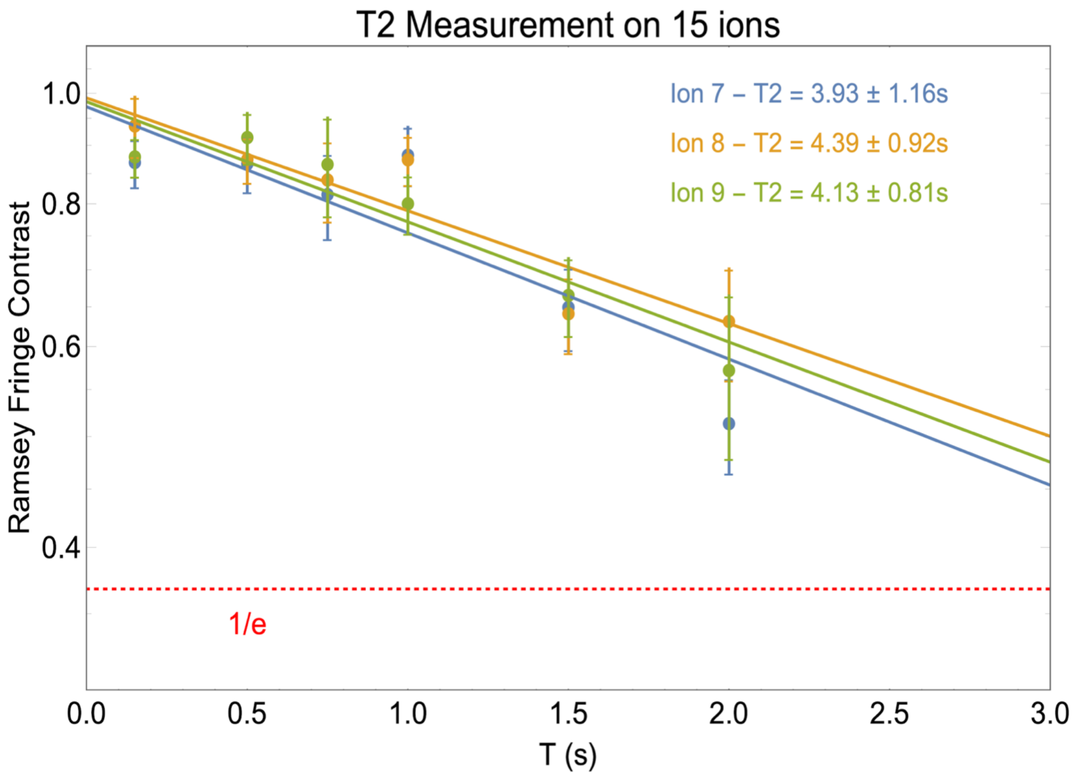


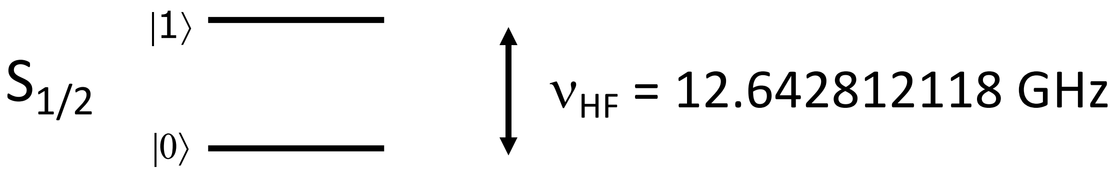
Systems at Duke

Atomic Ion Qubit

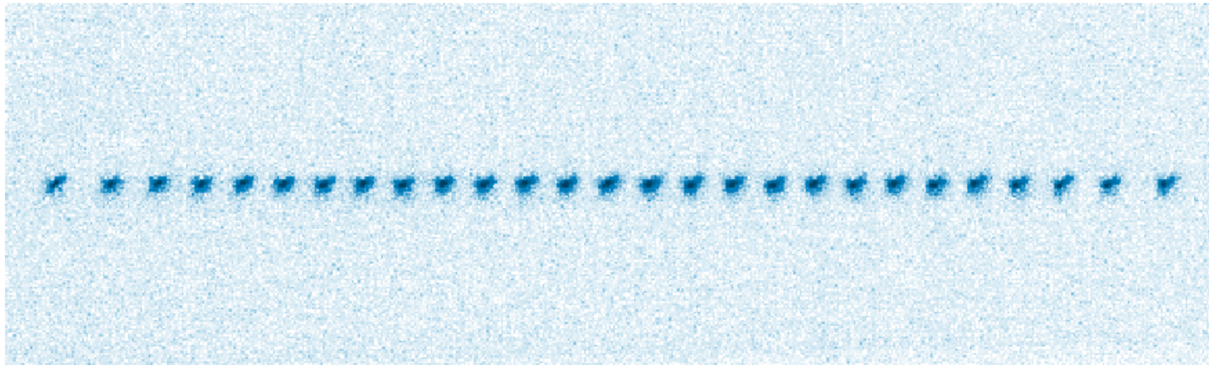


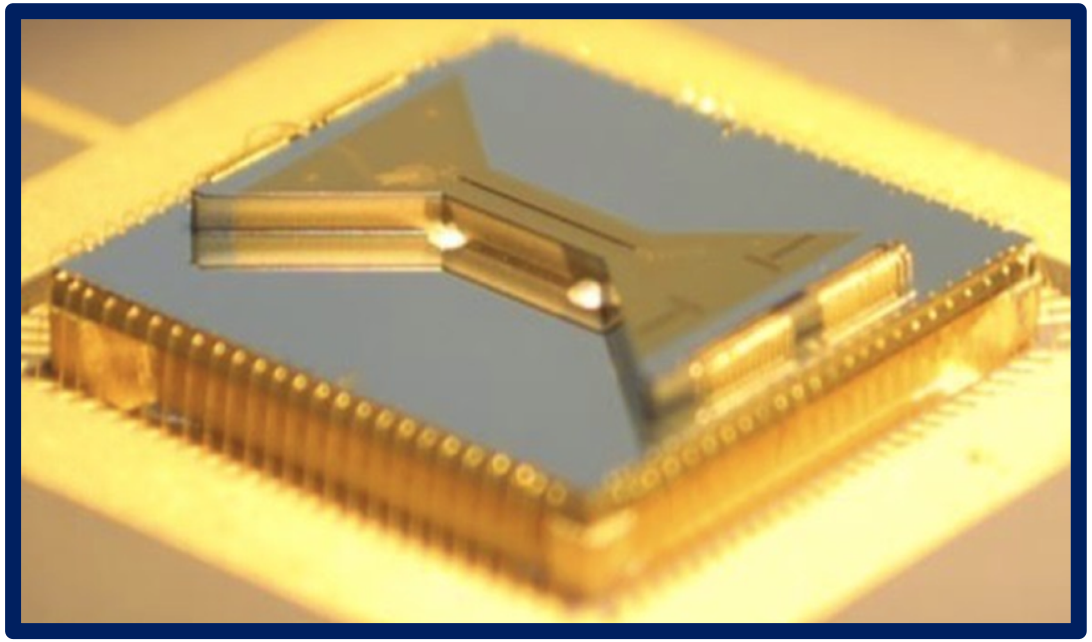
Atomic Ion Qubit





Single Long Chain

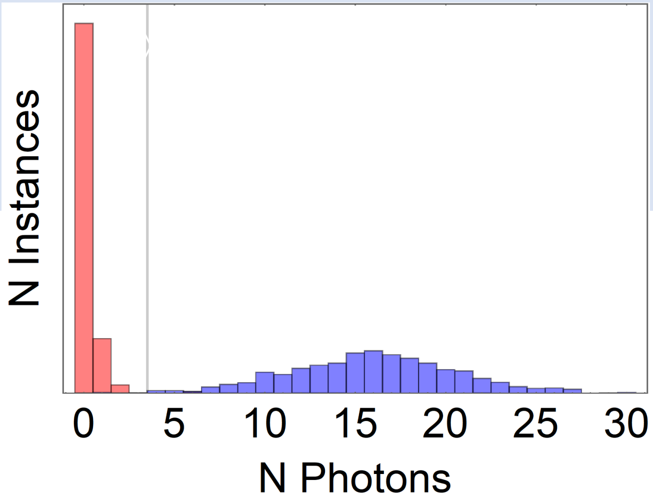


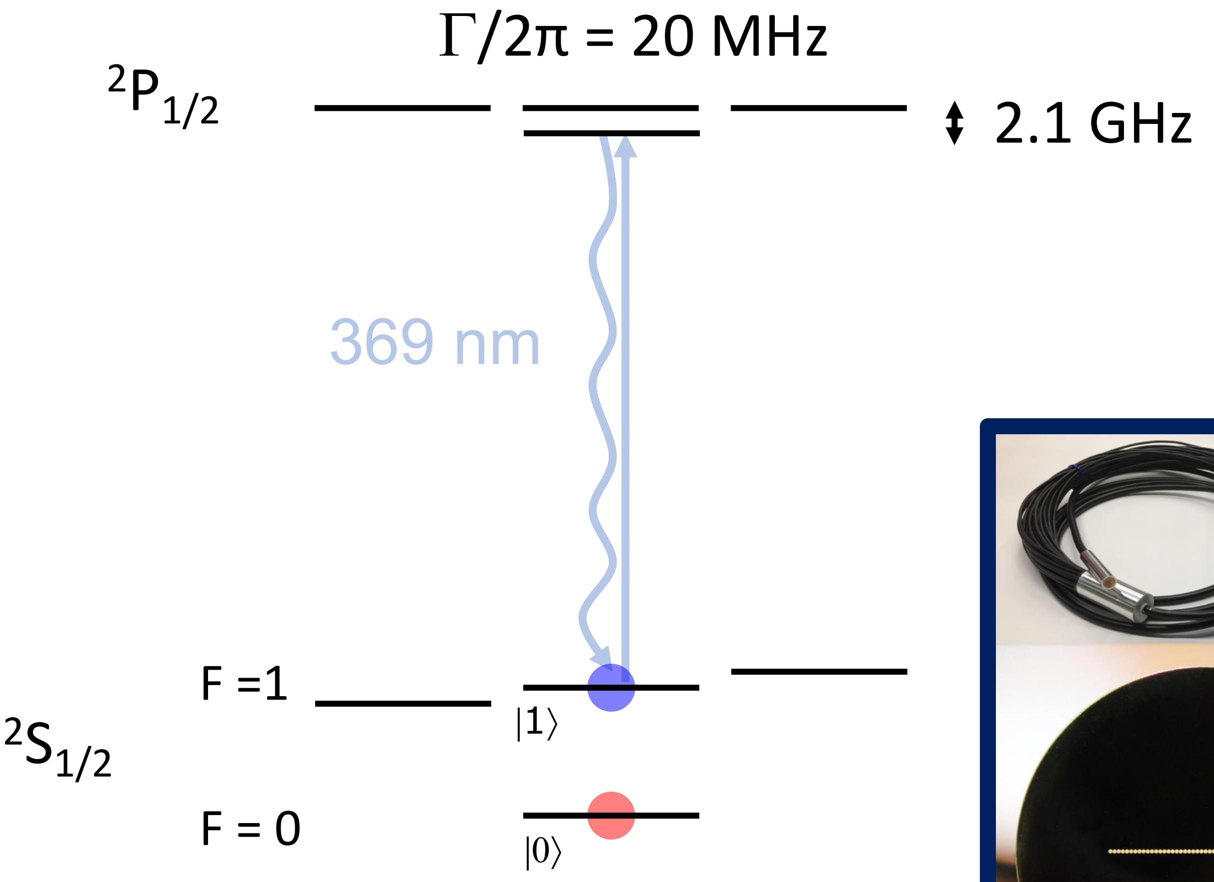


Sandia National Laboratories HOA

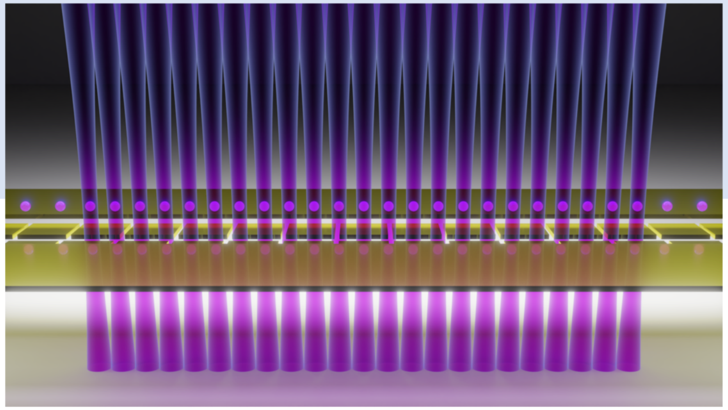
$^{171}Yb^{+}$

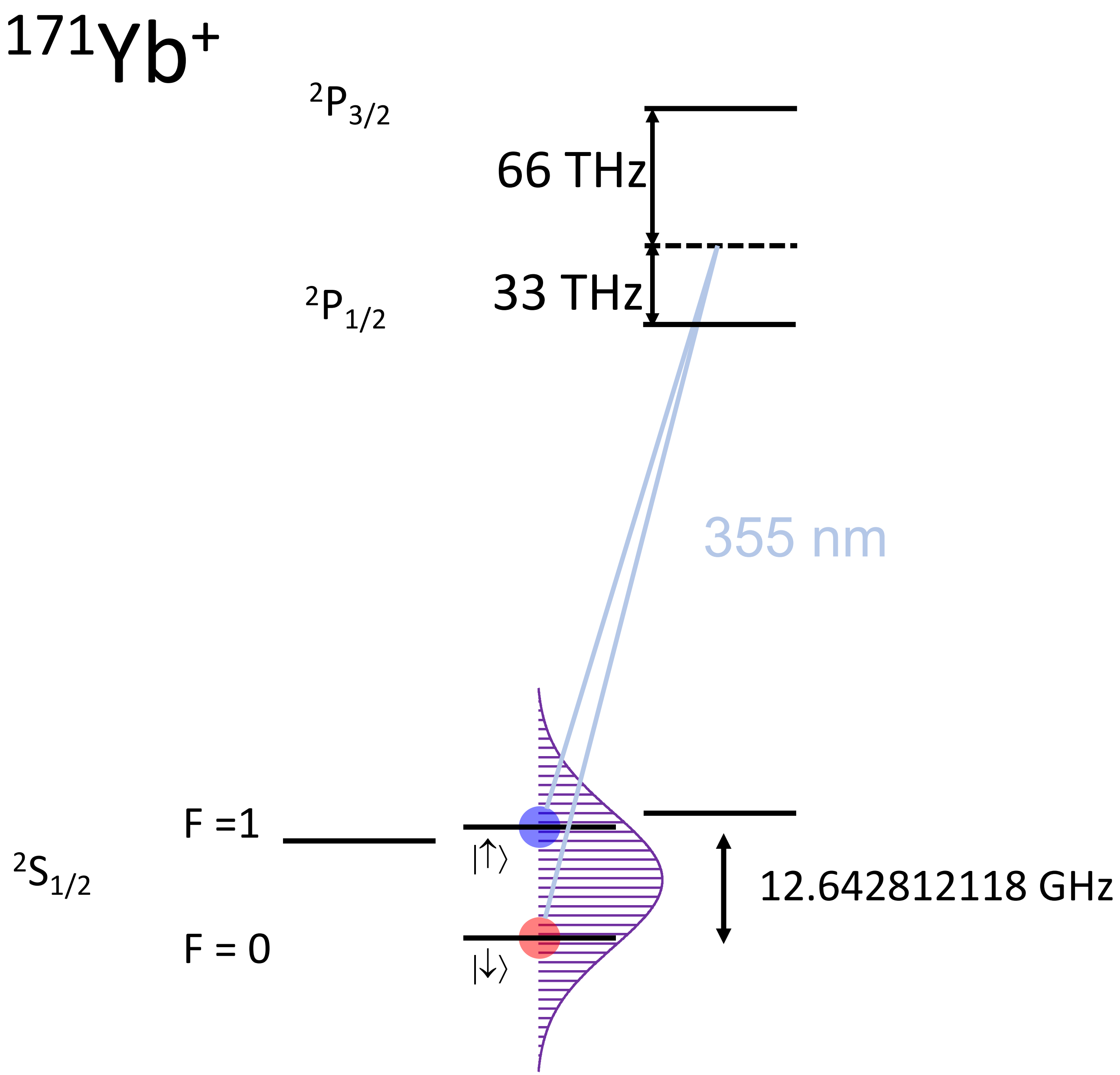
Laser cooling and detection





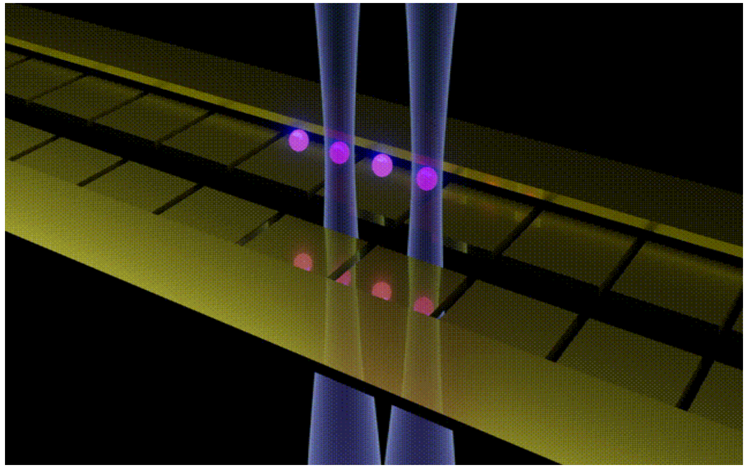
Laser qubit operations

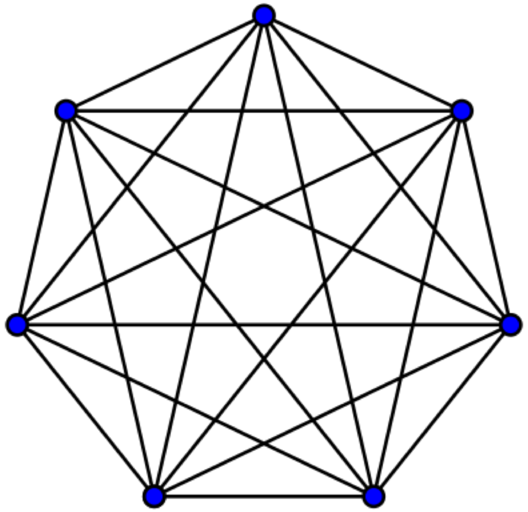


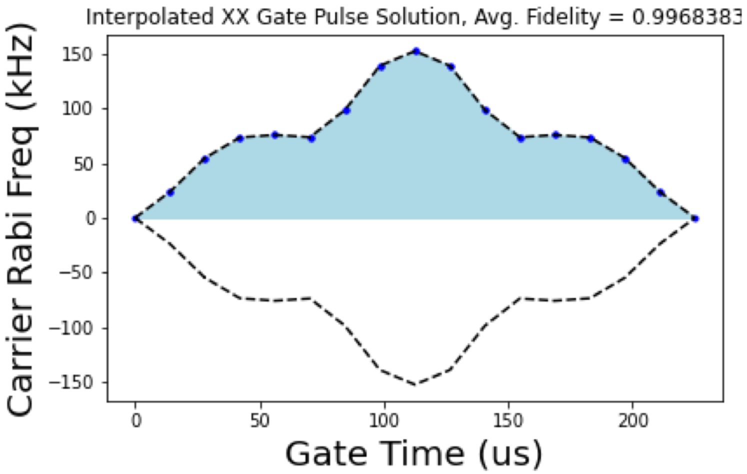


Coupled through motion

- High connectivity
- Engineered motional modes
- Optimized gate pulses







Native Ion Trap Operation: "Ising" gate

$$XX[\varphi] = e^{-i\sigma_x^{(1)}\sigma_x^{(2)}\varphi}$$

Blue System Snapshot

Metric	Typical Performance
# qubits	13
Connectivity	All-to-all
2-qubit gate fidelity	98.5-99.3% (Parity fringe)
1-qubit gate fidelity	>99.96% (RB)
SPAM	<0.5%

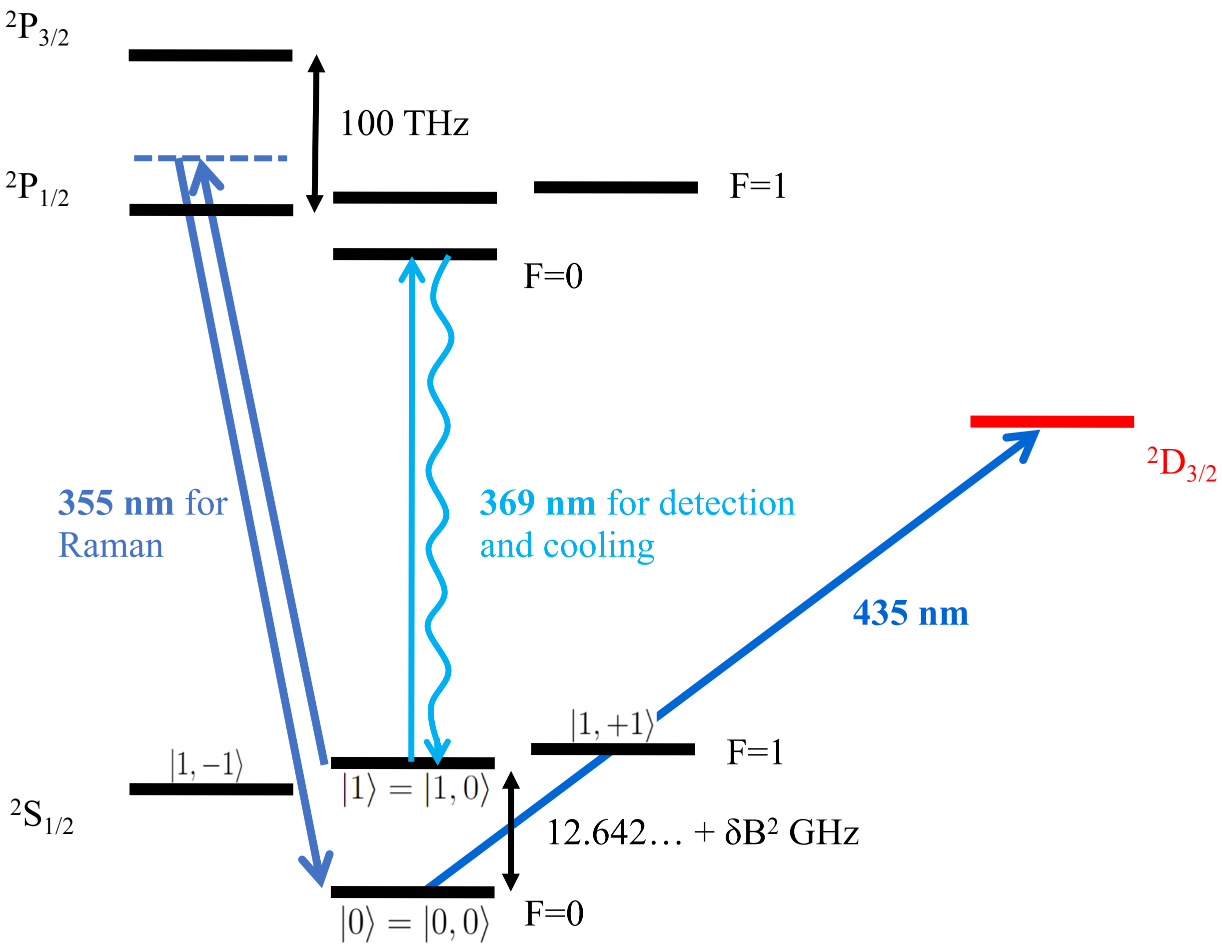
Blue System

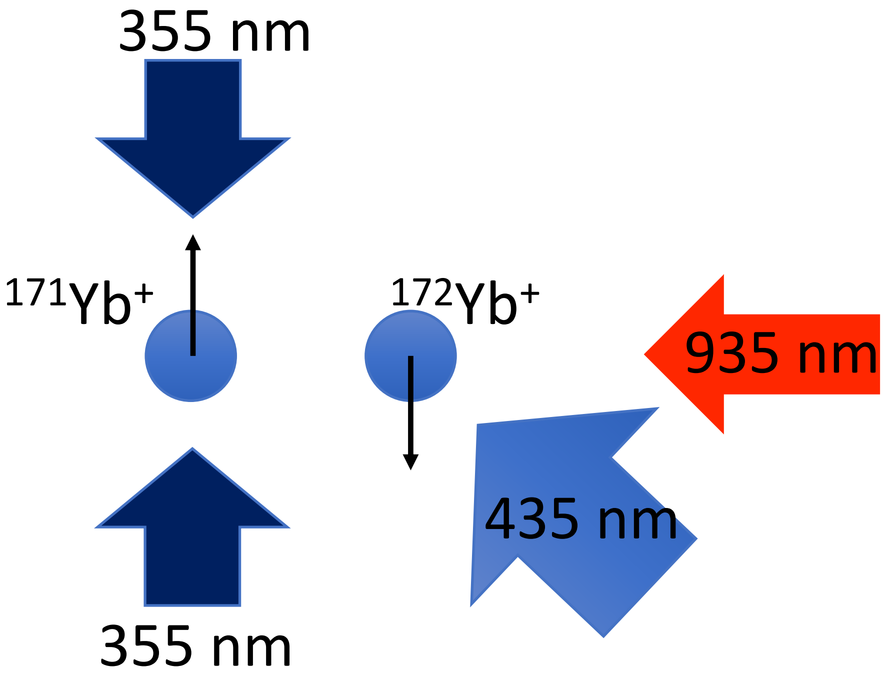
Chris Monroe

Marko Cetina

*circa 2021

^{172}Yb Sympathetic Cooling

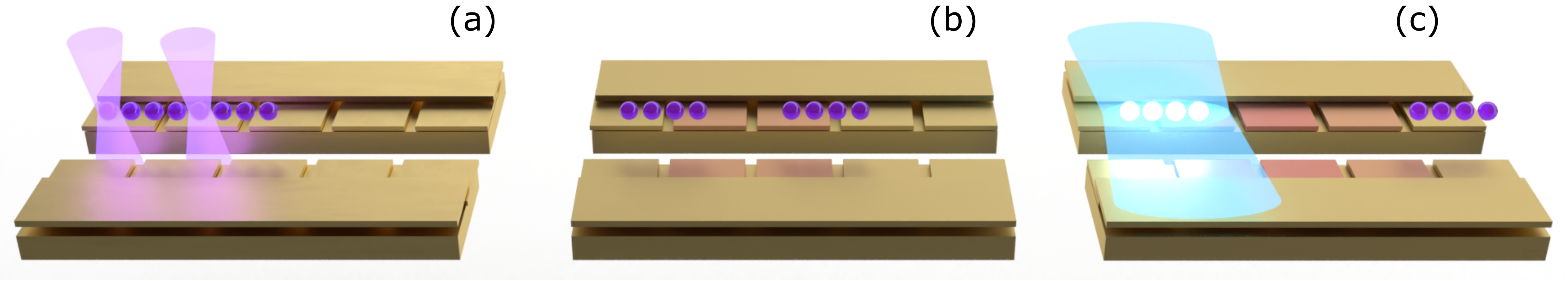


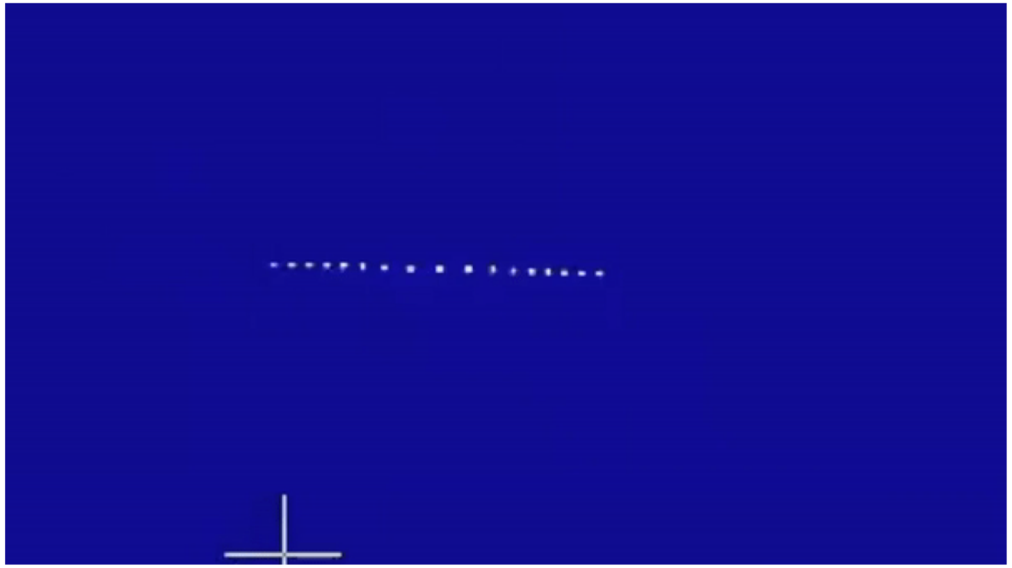


Duke Quantum Center

Cetina et al. PRX Quantum 2022

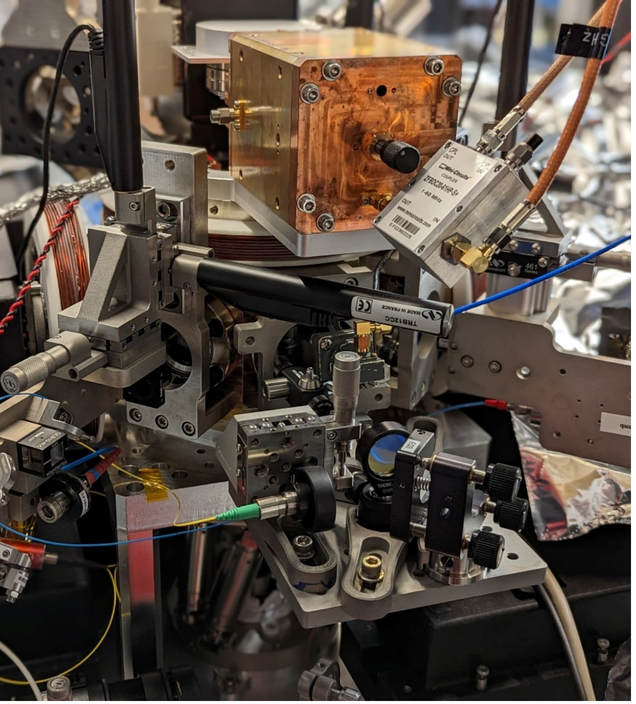
Mid-circuit measurement via shuttling

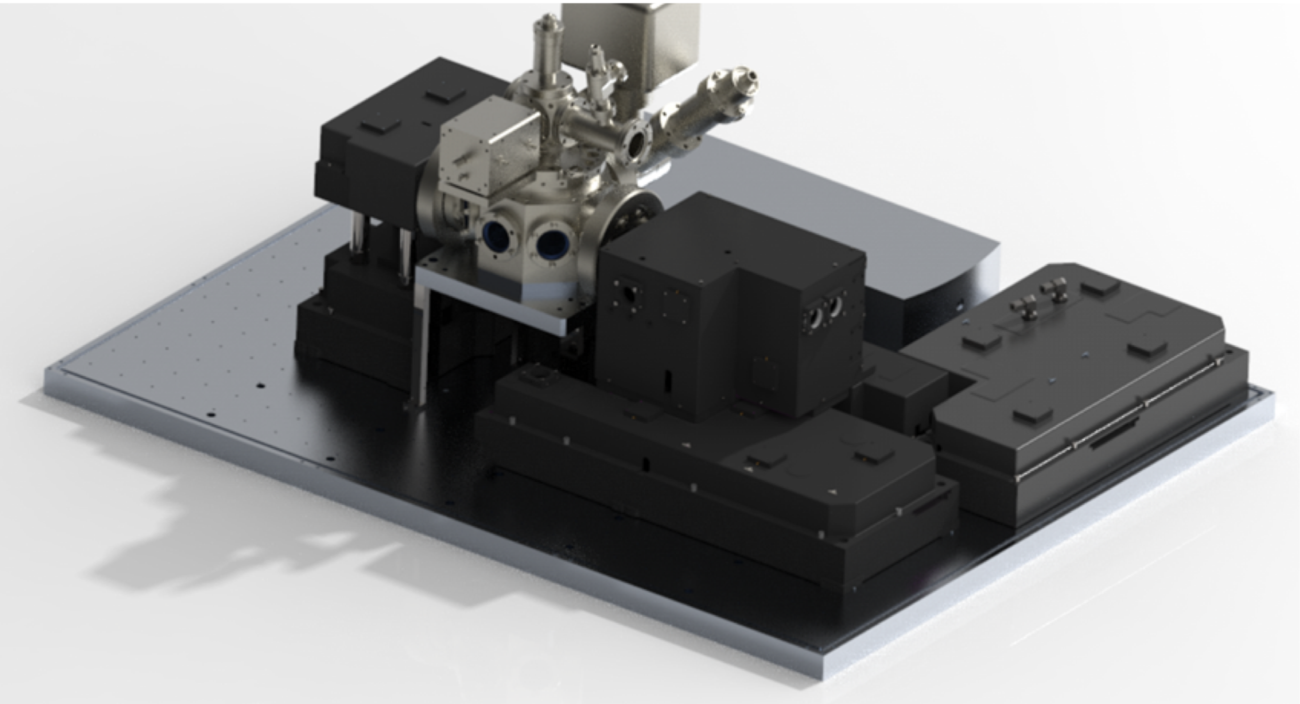




Duke Quantum Center

arXiv:2112.05156





New Gold System

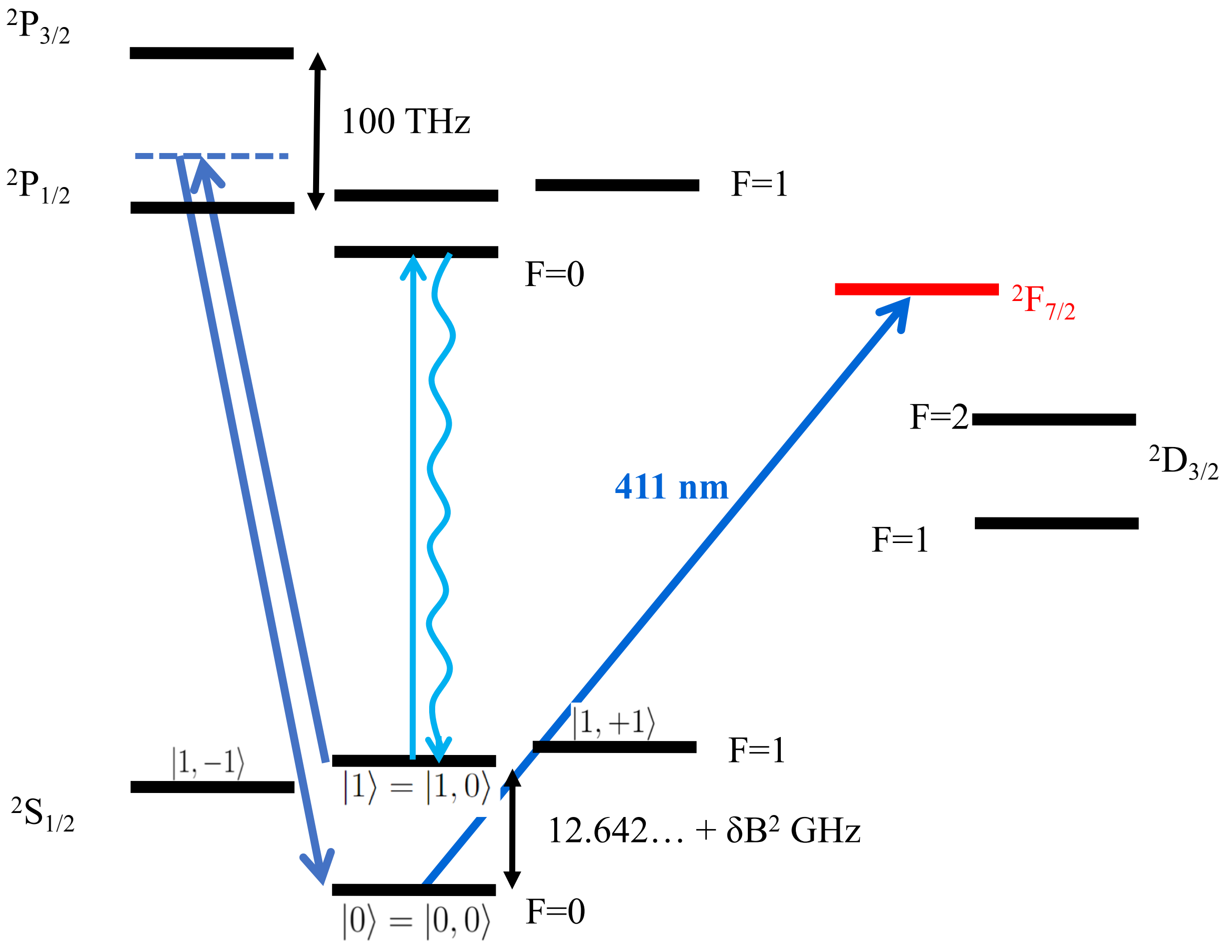
- Individual Addressing
- Fully-connected long chain
- Up to 32 qubits
- Improved stability and control

Alexander Kozhanov

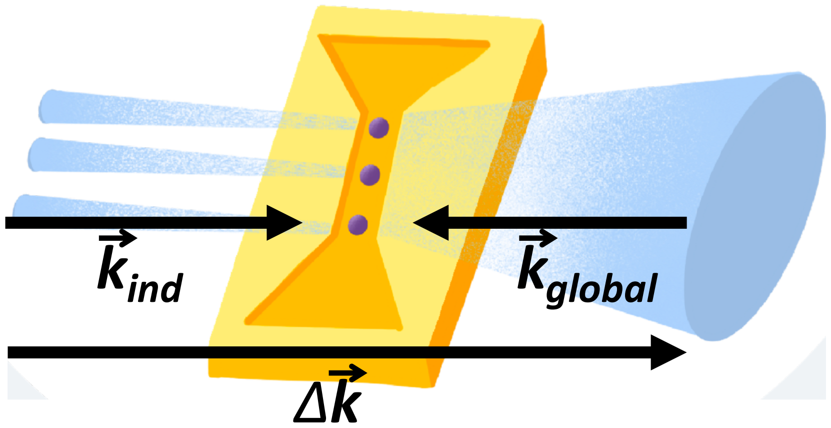
Chris Monroe

Crystal Noel

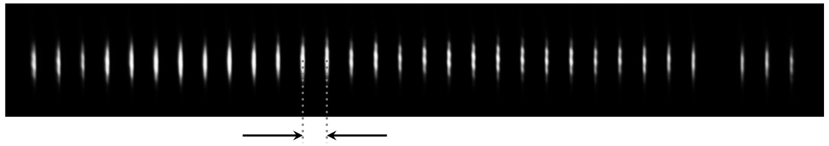
^{171}Yb Shelving



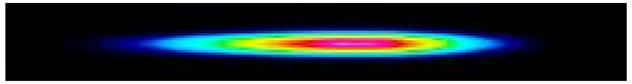
- Hide information during readout
- Reduce shuttling needed
- Possible F-state qubit operation



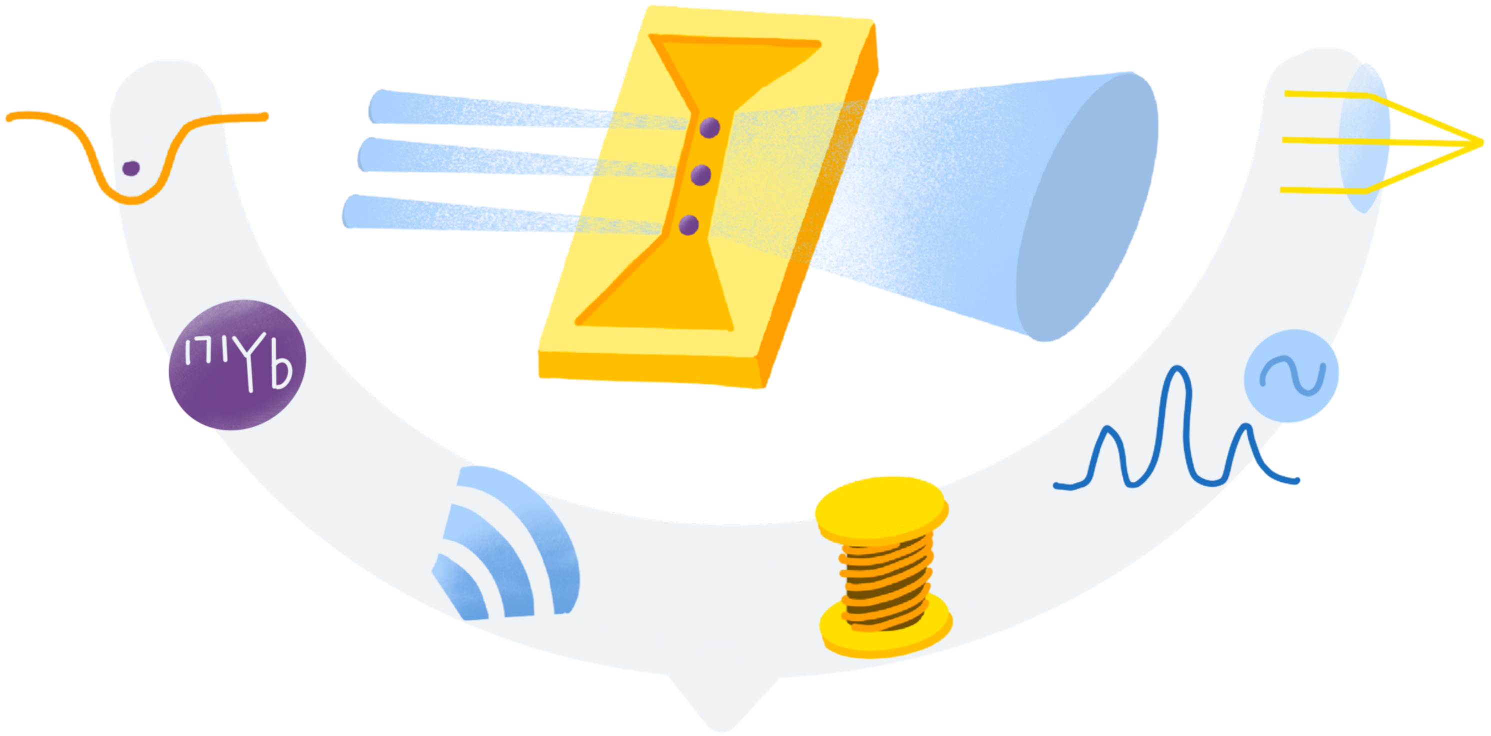
Raman system



Individual Raman Beams



Global Raman Beam



Systems level control

Duke Quantum Center

Systems-level control

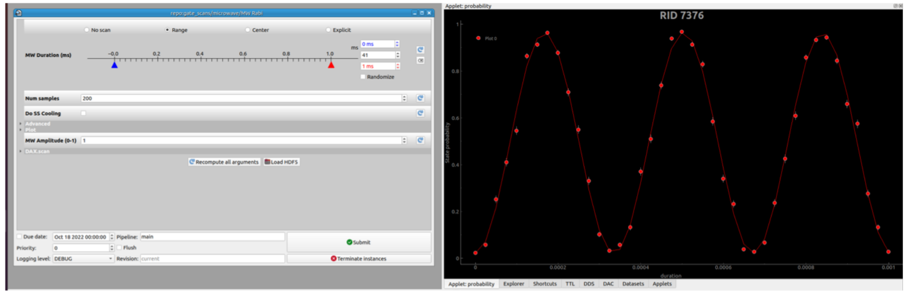
ARTIQ

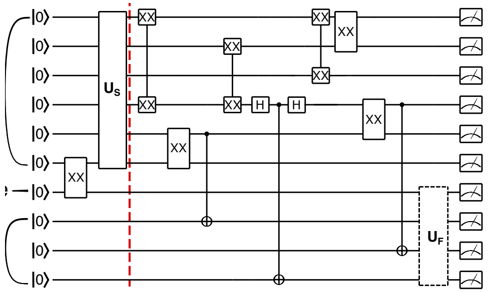
M-Labs

PENTEK

Duke ARTIQ Extensions

Qiskit





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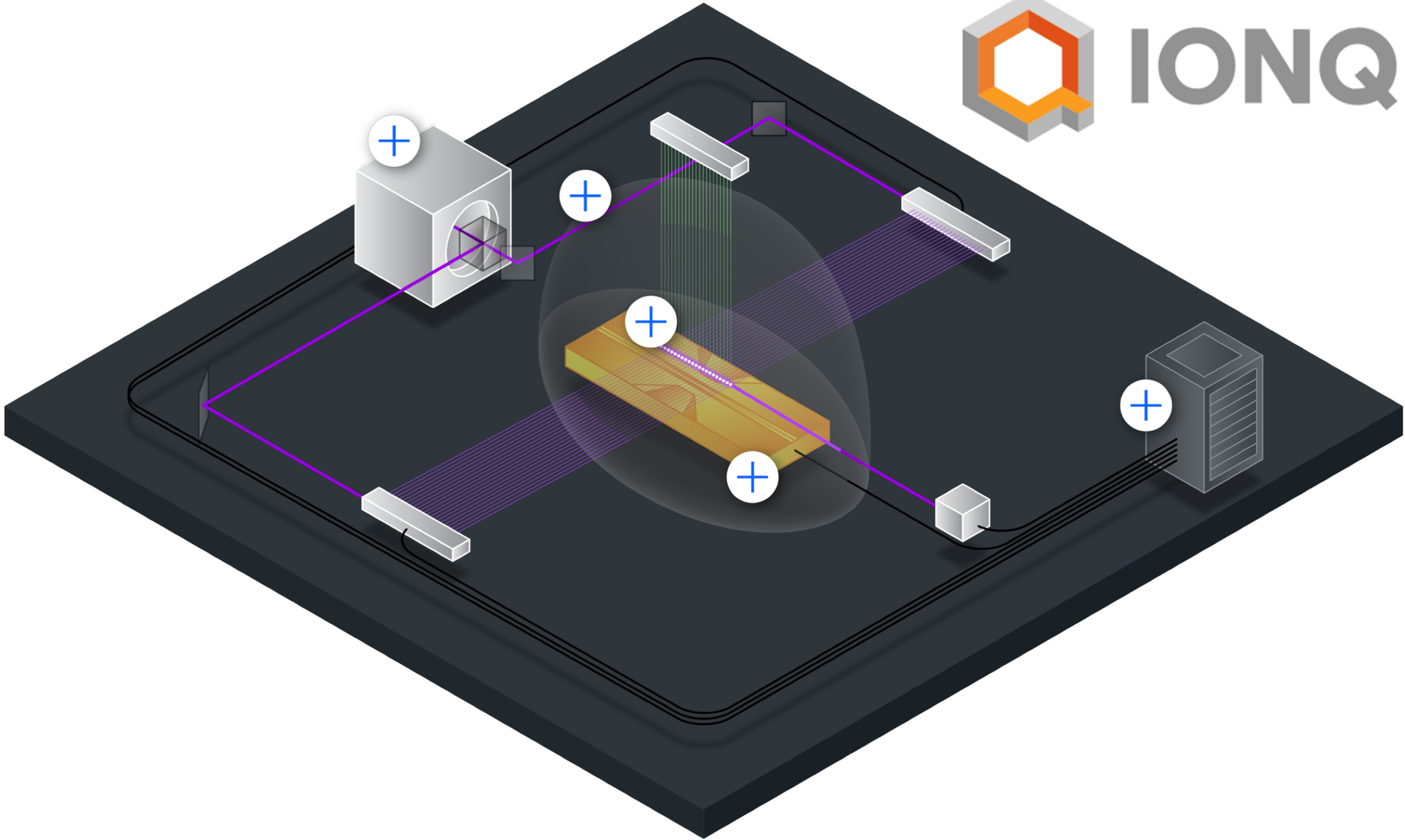
An MIPT in *Magic*

Niroula et al. arXiv: 2304.10481

This work: Q-Lab at UMD



<u>Magic Team:</u>
Pradeep Niroula (UMD)
Christopher David White (UMD)
Qingfeng Wang (UMD)
Sonika Johri (IonQ)
Daiwei Zhu (IonQ)
Christopher Monroe (Duke/UMD/IonQ)
Michael Gullans (NIST/UMD)

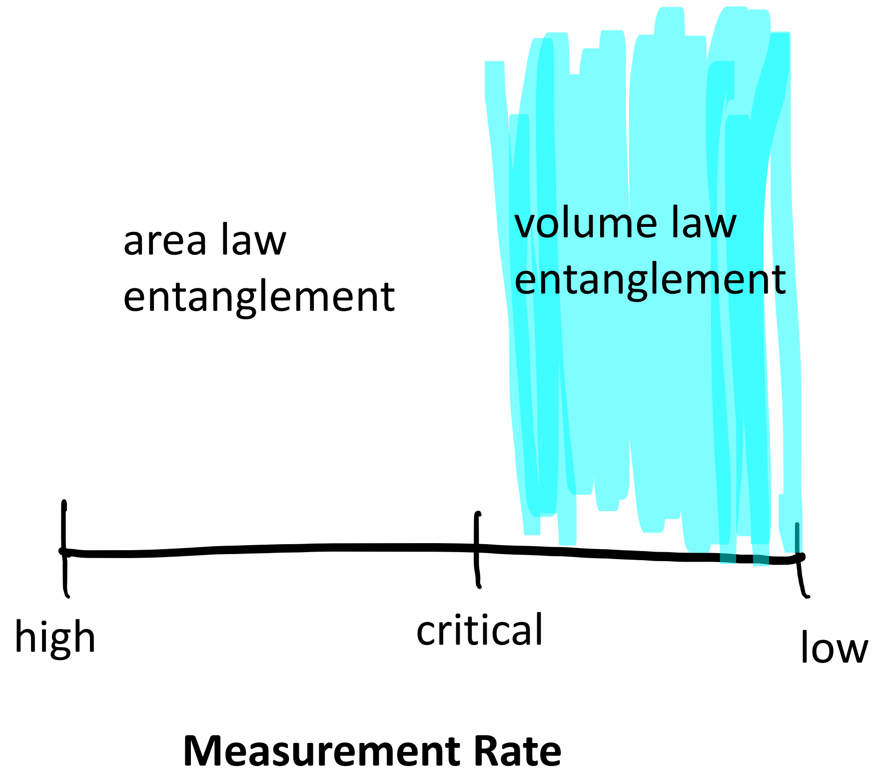
The power of quantum computing?

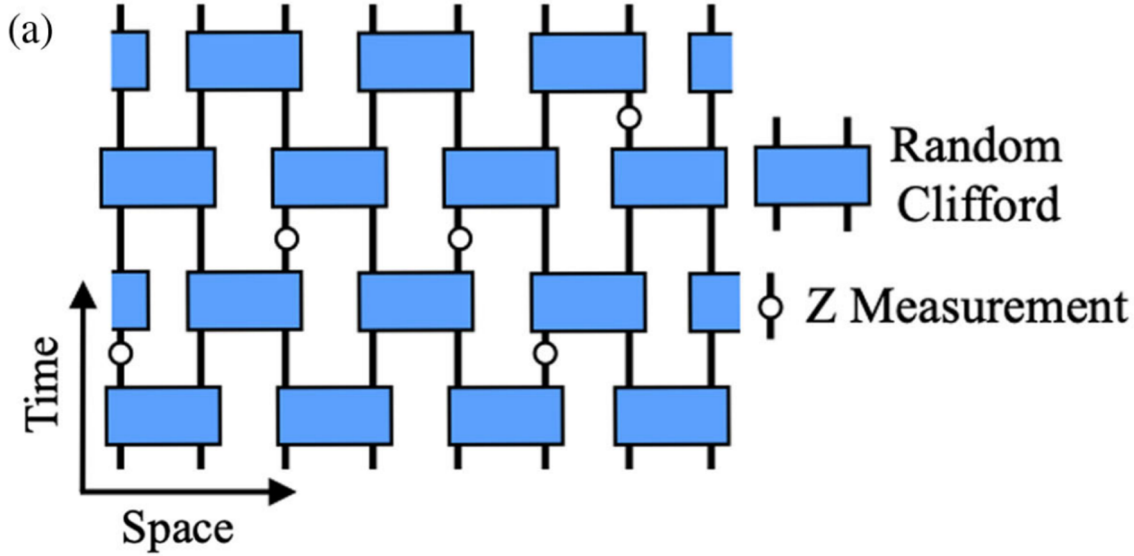
- Superposition (coherence)
  - ~~Parallel computing!~~ → Measurement problem
- Entanglement
  - ~~GHZ states~~ → Easily simulated

What is missing?
Magic (nonstabilizerness)

1. *Resource*: V. Veitch, S. A. H. Mousavian, D. Gottesman, J. Emerson, New Journal of Physics 16, 013009 (2014). ArXiv: 1307.7171.
2. *Complexity*: K. Bu, R. J. Garcia, A. Jaffe, D. E. Koh, L. Li, arXiv:2204.12051 [math-ph, physics:quant-ph] (2022).
3. *AdS-CFT*: C. D. White, C. Cao, B. Swingle, Physical Review B 103, 075145 (2021).
4. *Chaos*: L. Leone, S. F. Oliviero, Y. Zhou, A. Hamma, Quantum 5, 453 (2021).

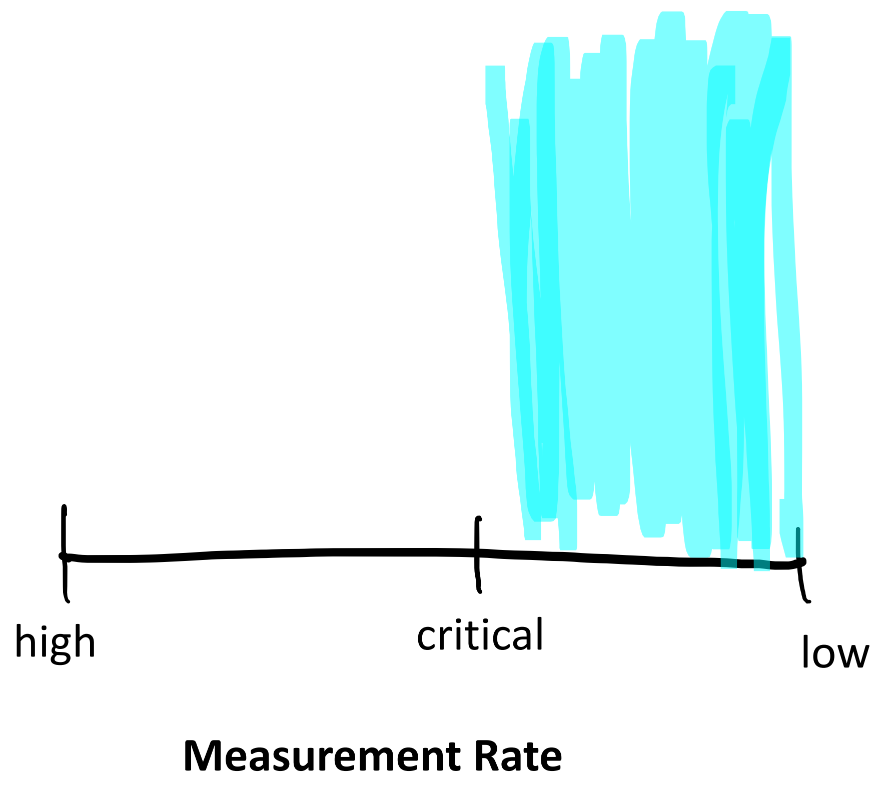
Measurement induced phase transition

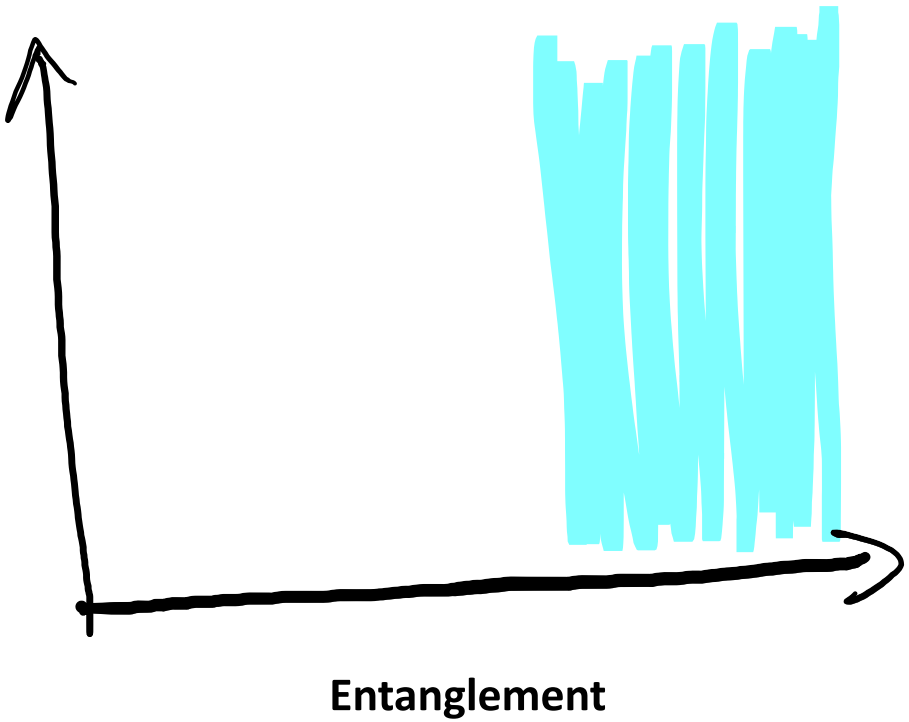




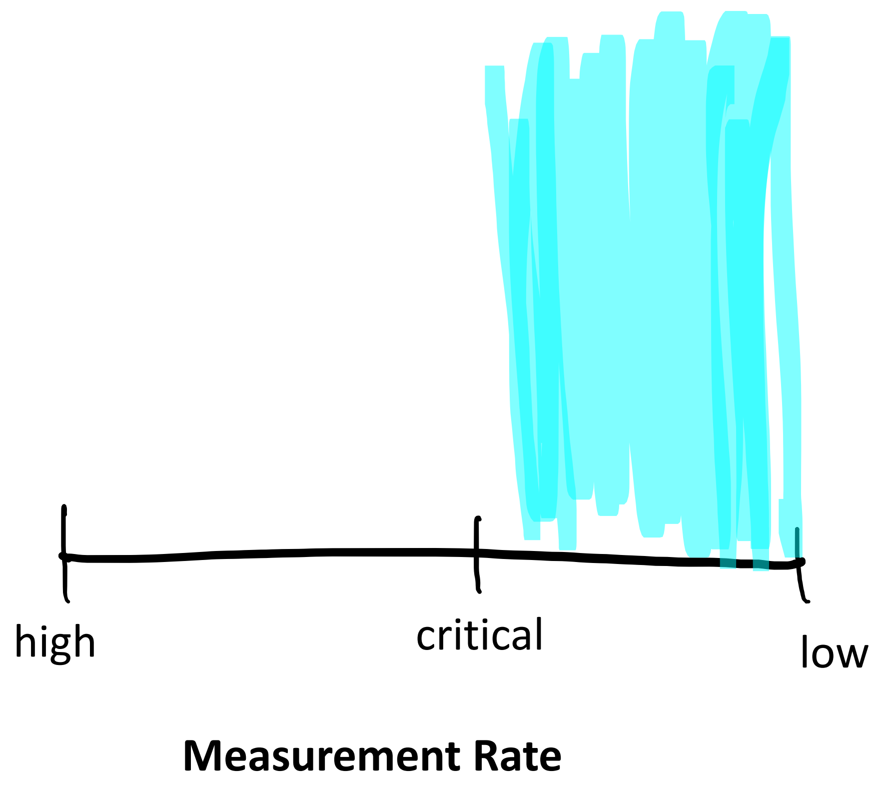
Gullans and Huse PRX 2020
Many more…

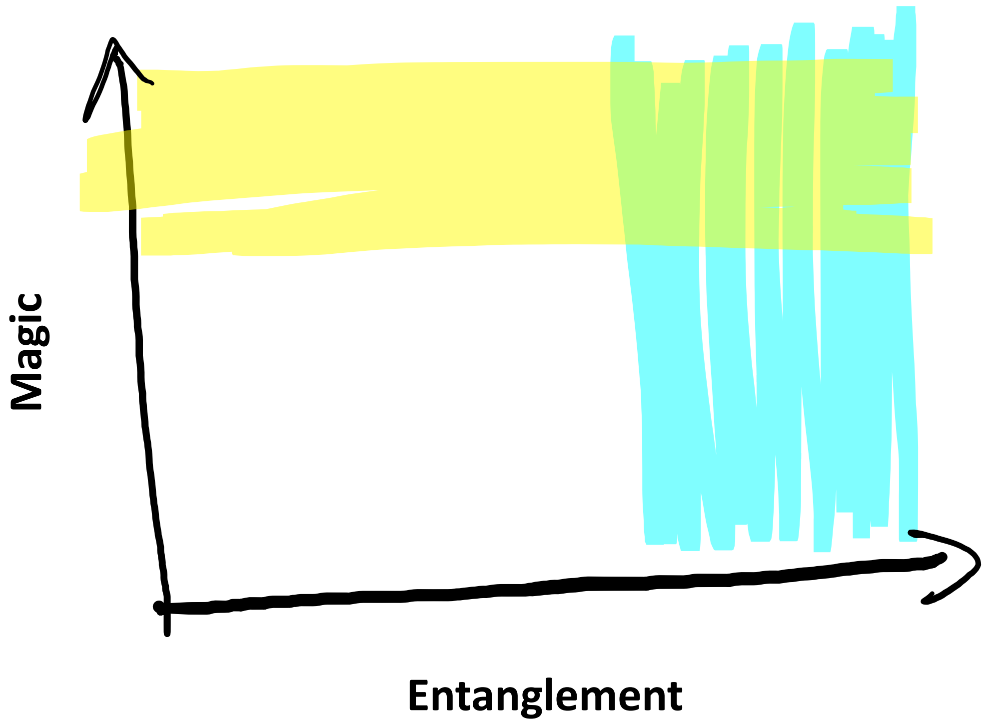
Understanding quantum advantage



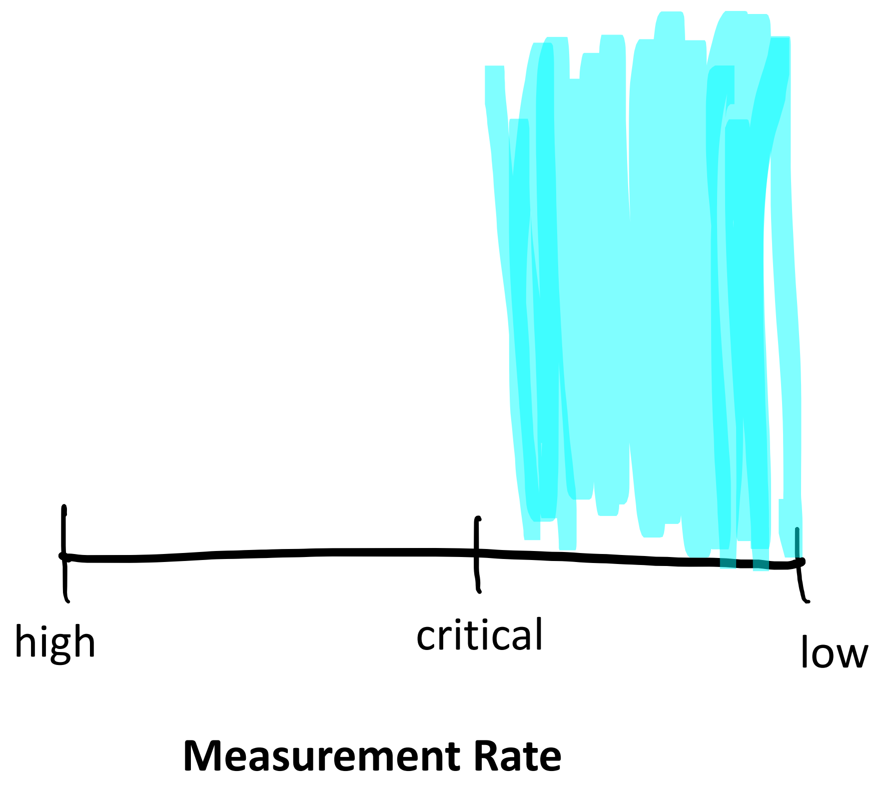


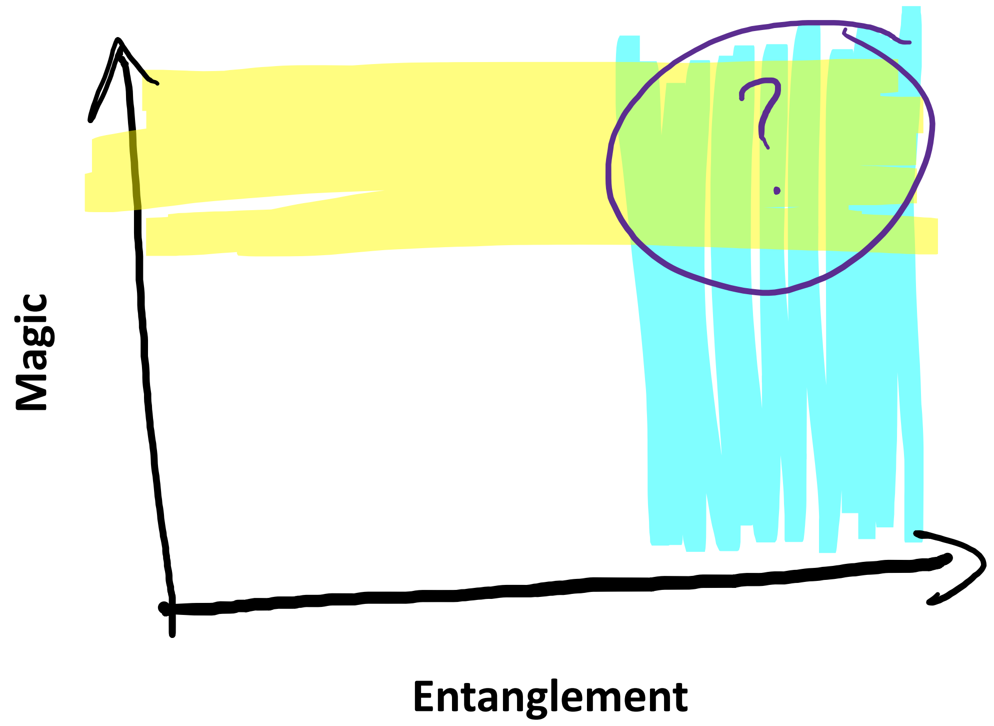
Understanding quantum advantage





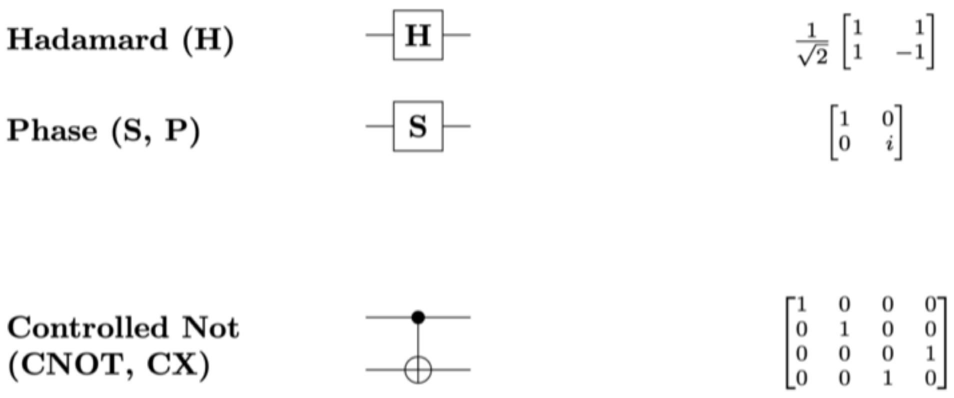
Understanding quantum advantage

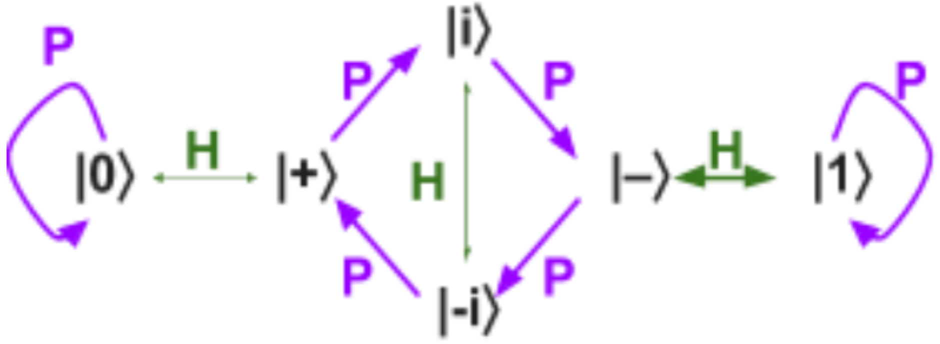




Stabilizer states have no magic

- Generated from a stabilizer circuit starting from 00000…
- Stabilizer circuits are made of stabilizer gates (Clifford)
- Cliffords: CNOT, H, P(S)





Aaronson Notes; https://earltcampbell.com/research/magic-states/

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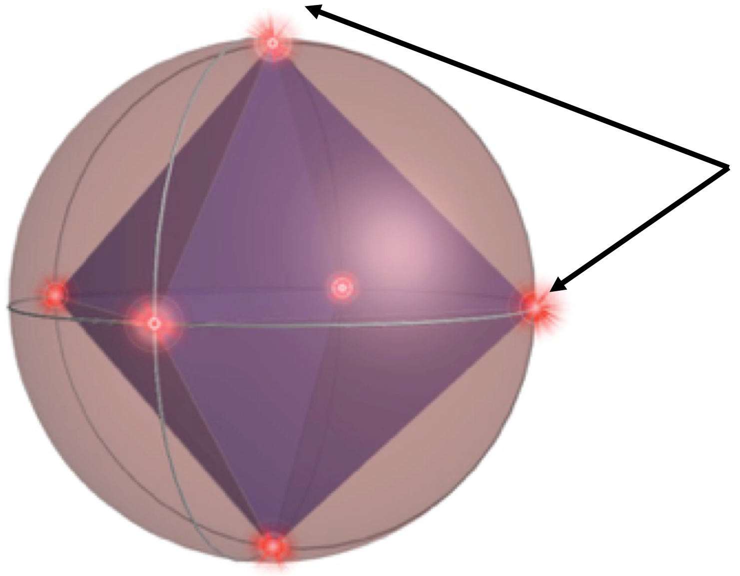
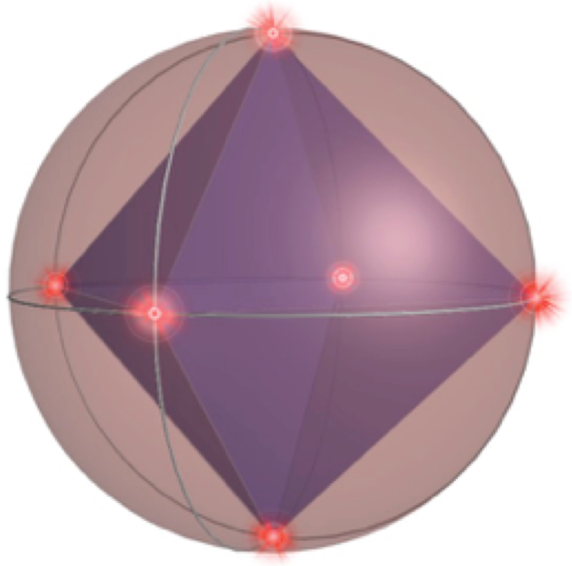


Aaronson Notes, https://earltcampbell.com/research/magic-states/

Stabilizer circuits

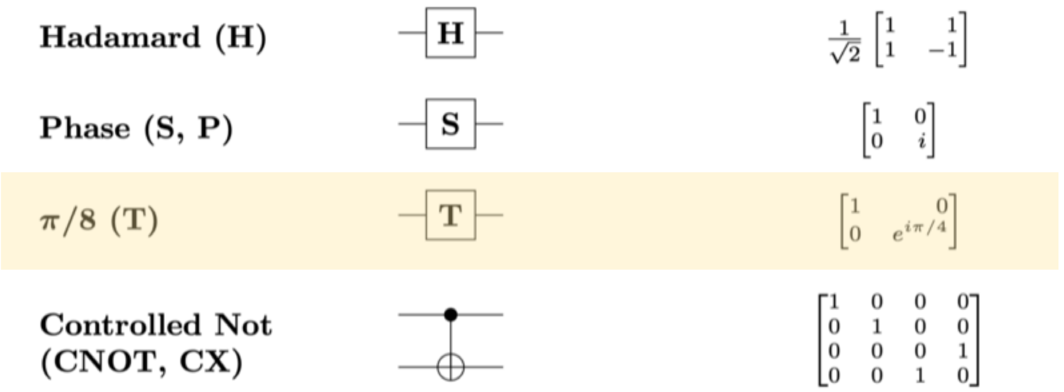
- Gottesman-Knill Theorem: stabilizer circuits are efficiently simulatable classically[1,2]
- Quantum advantage related to nonstabilizerness (magic)?



1. D. Gottesman, arXiv preprint quant-ph/9807006 (1998).
2. S. Aaronson, D. Gottesman, Physical Review A 70, 052328 (2004)

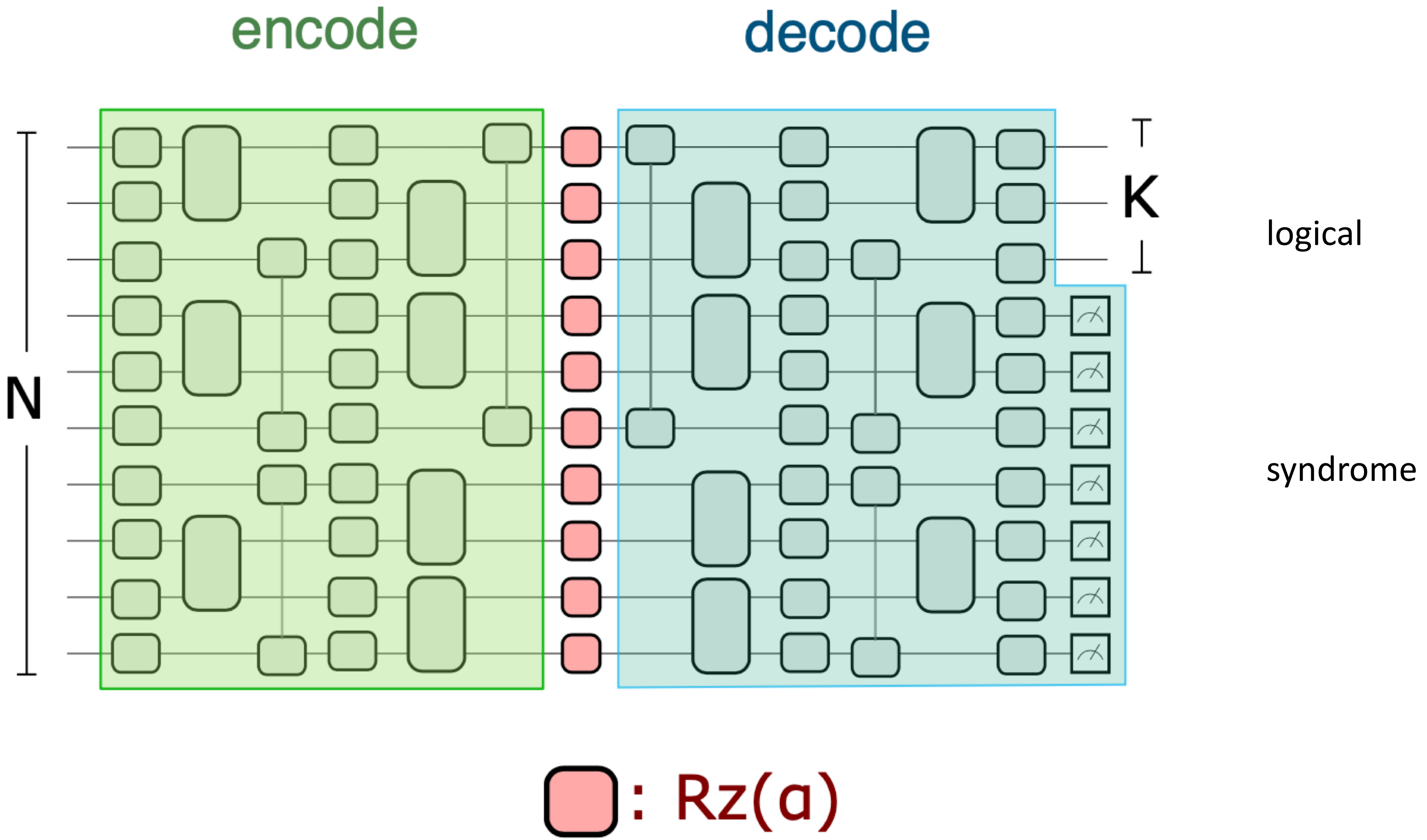
From stabilizer to magical…

- Add T gate for magic
- Magic state distillation[1-4]
  - Required for stabilizer code FTQC
  - Resource intensive
- Magic can be used to measure noise[5]



1. S. Bravyi, A. Kitaev, Physical Review A 71, 022316 (2005). ArXiv: quant-ph/0403025.
2. A. G. Fowler, M. Mariantoni, J. M. Martinis, A. N. Cleland, Physical Review A 86, 032324 (2012).
3. J. O’Gorman, E. T. Campbell, Physical Review A 95, 032338 (2017).
4. E. T. Campbell, B. M. Terhal, C. Vuillot, Nature 549, 172 (2017).
5. S.F.E. Oliviero, L. Leone, A. Hamma, S. Lloyd NPJ Quantum Information 8, 148 (2022).

Random circuit model



arXiv: 2304.10481

What makes a good measure of magic?

- Zero for a stabilizer state
- Non-increasing under stabilizer circuits (Clifford gates)
- Sub-additive for product states $f(\sigma \otimes \rho) \leq f(\sigma) + f(\rho)$

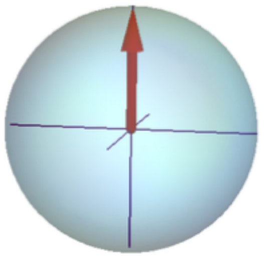
Expansion into Pauli basis

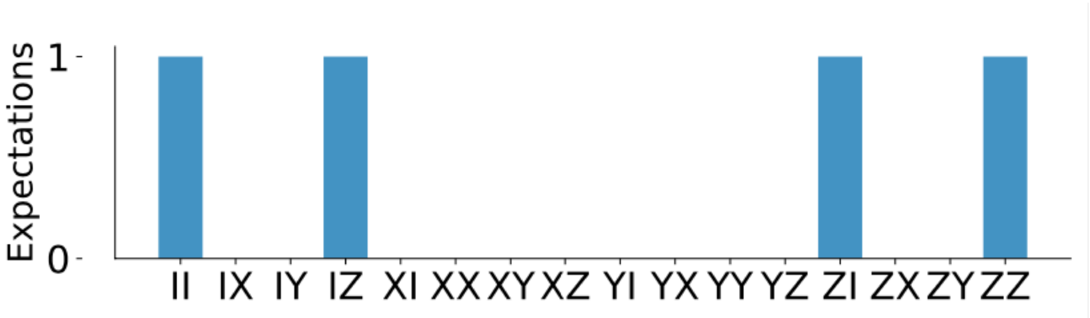
$$\rho = |0\rangle\langle 0| = \mathbf{1} + \mathbf{Z}$$

ρ is stabilized by **1** and **Z**

$$\rho = |00\rangle\langle 00|$$

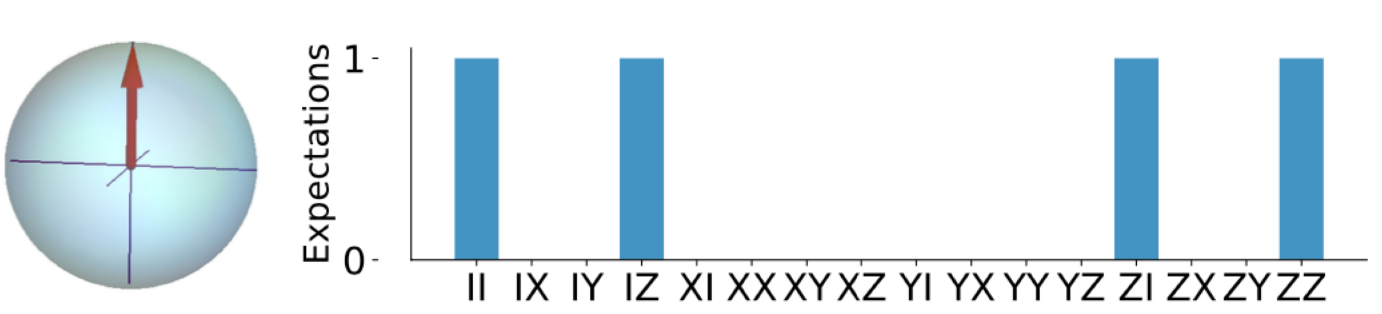
is stabilized by **II, IZ, ZI, ZZ**



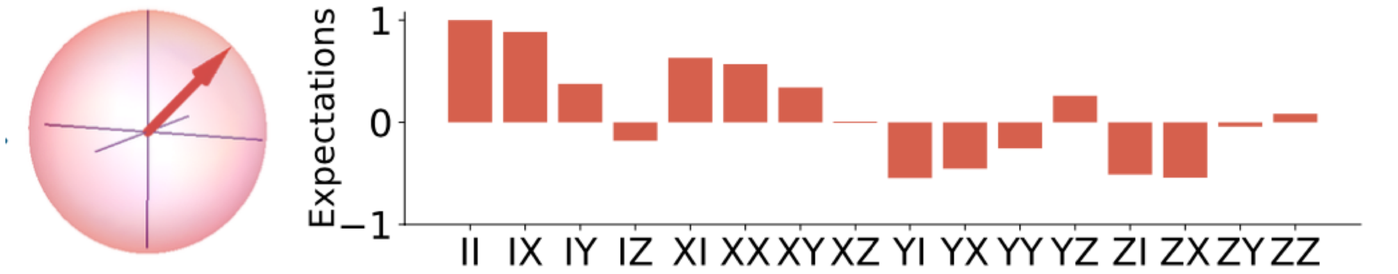


Expansion into Pauli basis

Stabilizer state



Haar random state



Second Stabilizer Renyi Entropy

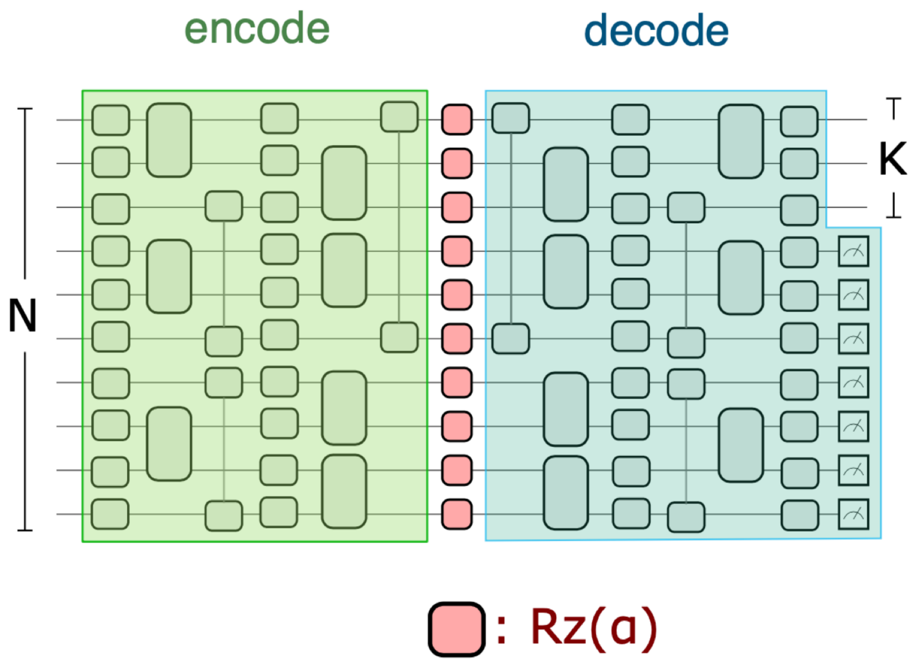
- Spread of ρ when expanded in basis of Pauli operators[1]

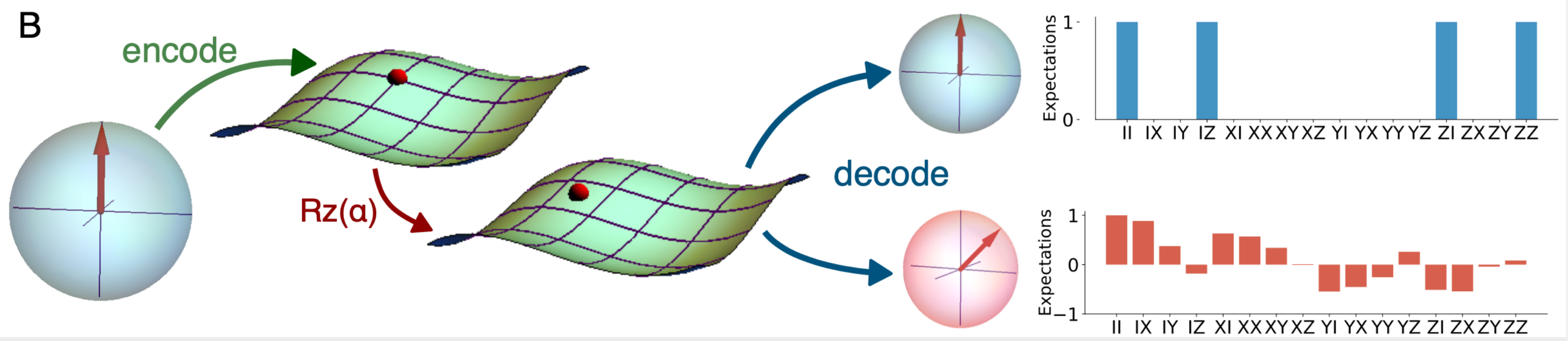
$$M_2(\rho) = -\log \frac{1}{2^N} \sum_{P \in \mathcal{P}} \mathrm{Tr}(\rho P)^4$$

- Requires full (or partial[2]) knowledge of ρ

1. L. Leone, S. FE Oliviero, and A. Hamma. *Physical Review Letters* 128.5 (2022): 050402.
2. S.F.E. Oliviero, L. Leone, A. Hamma, S. Lloyd NPJ Quantum Information 8, 148 (2022).

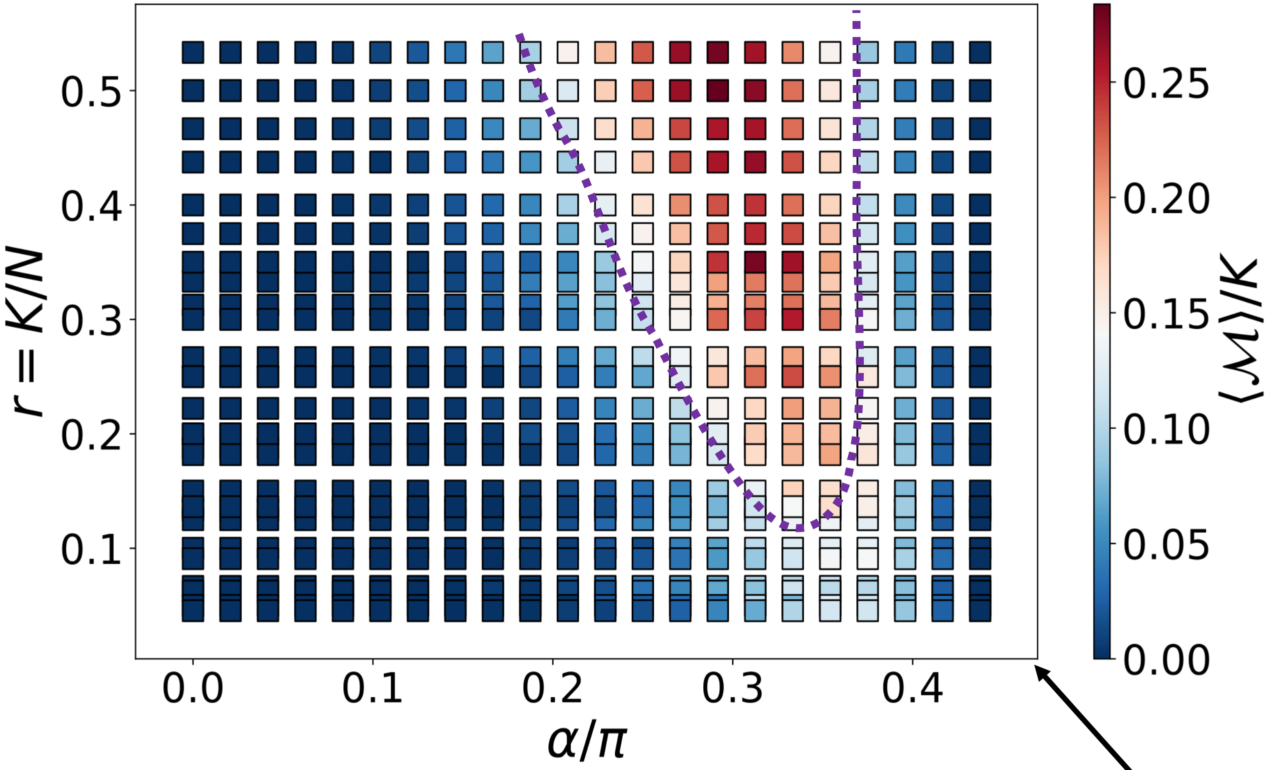
Random circuit model





arXiv: 2304.10481

Phase transition in magic



Code rate

Error parameter

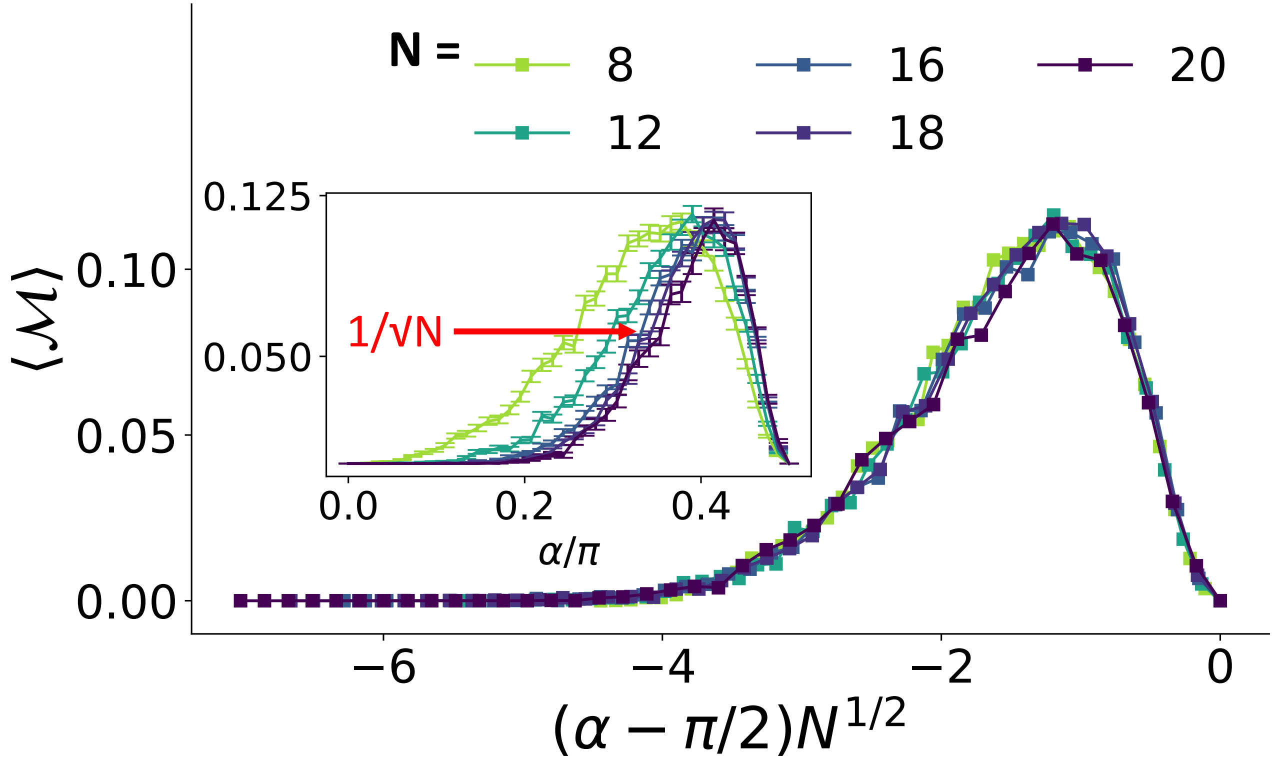
Magic (SSRE)

$\alpha = \pi/2$ is a Clifford gate

arXiv: 2304.10481

Vanishing Rate Code

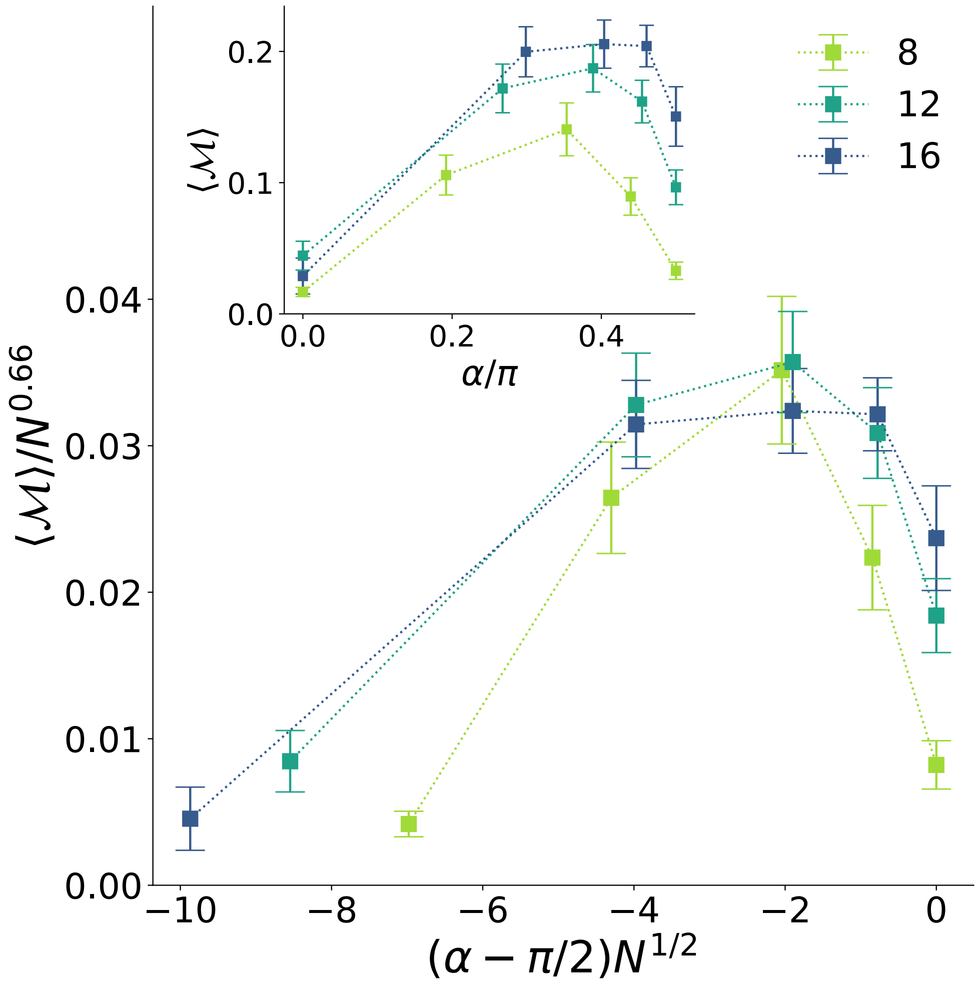
- Magic of the logical state when K=1 (code rate r=1/N)



arXiv: 2304.10481

Error mitigation strategies

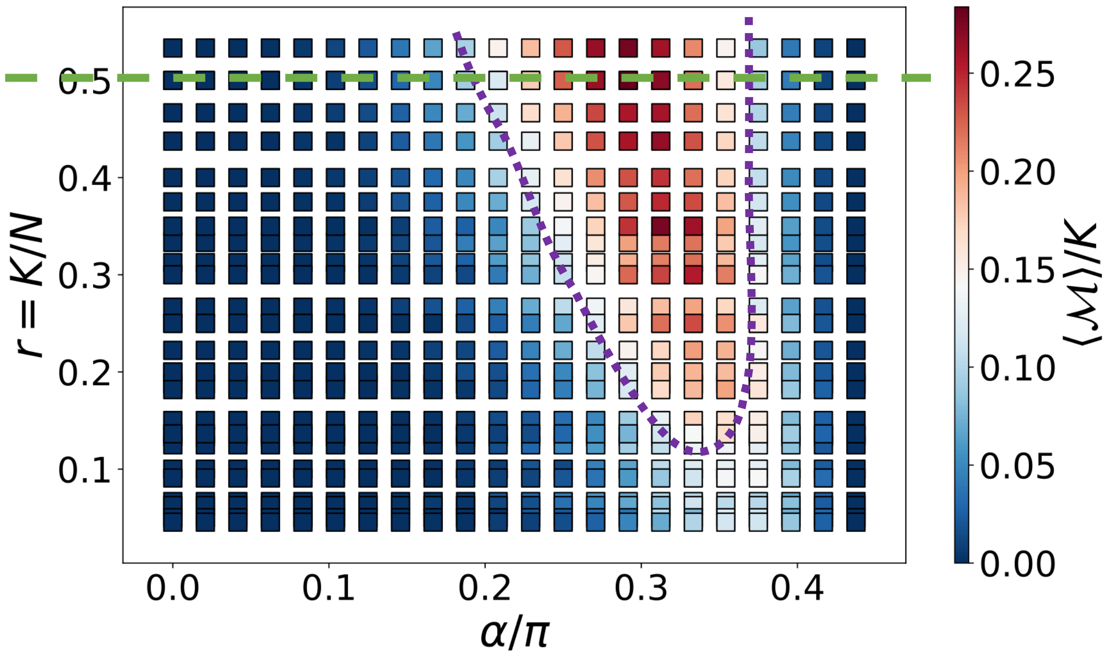
- Post-selection: Syndromes grouped into classes with equivalent logical qubit actions using classical simulations
- Decoherence: Project to nearest pure state in post processing



Experiment

Finite rate code

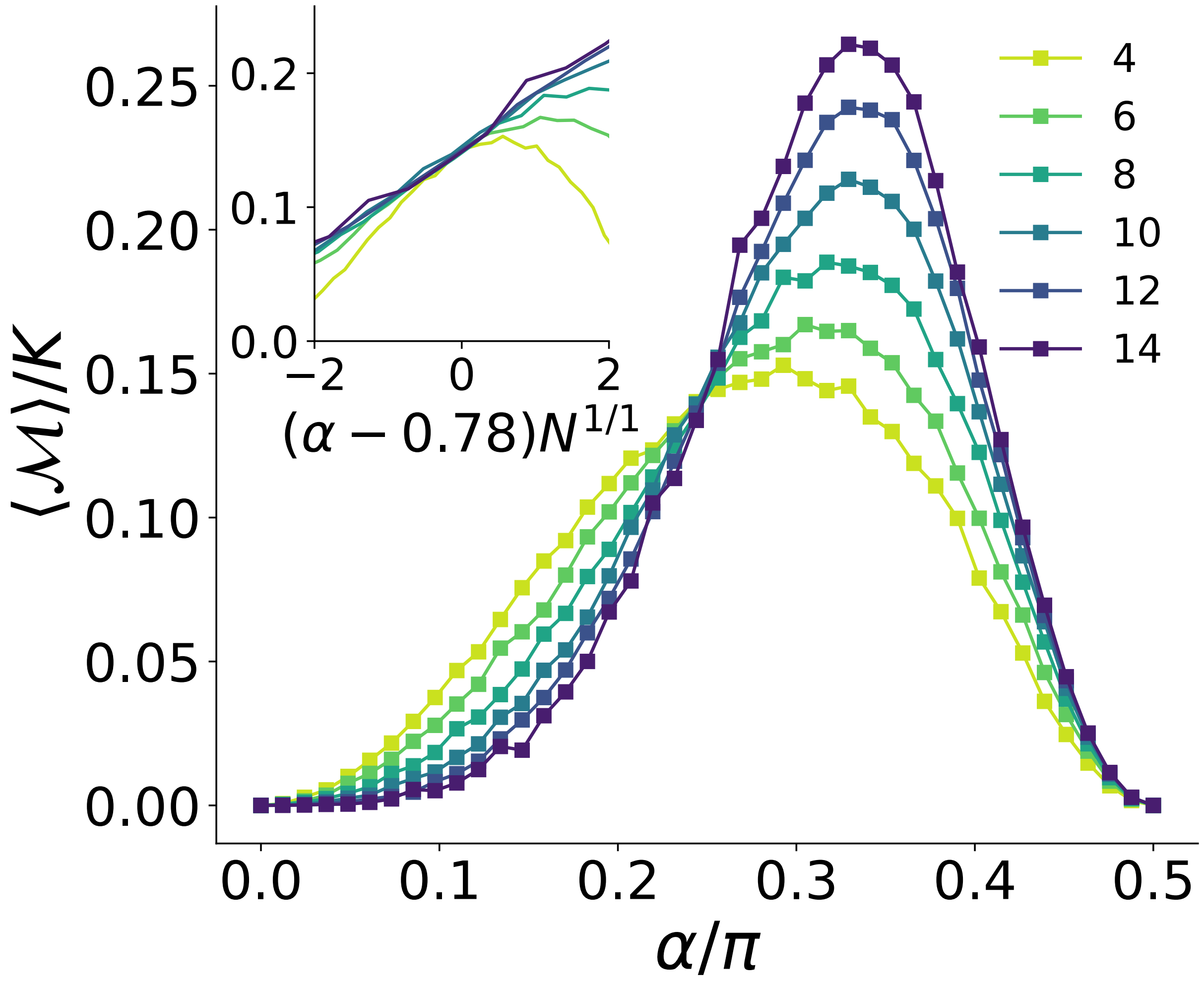
- K = rN for fixed r



arXiv: 2304.10481

Finite rate code

- K = rN for fixed r = ½
- SSRE takes full tomography



arXiv: 2304.10481

Basis minimized measurement entropy

- The entropy of the Born probability distribution of measurement outcomes, minimized over the finite set of possible stabilizer measurement bases

Example:

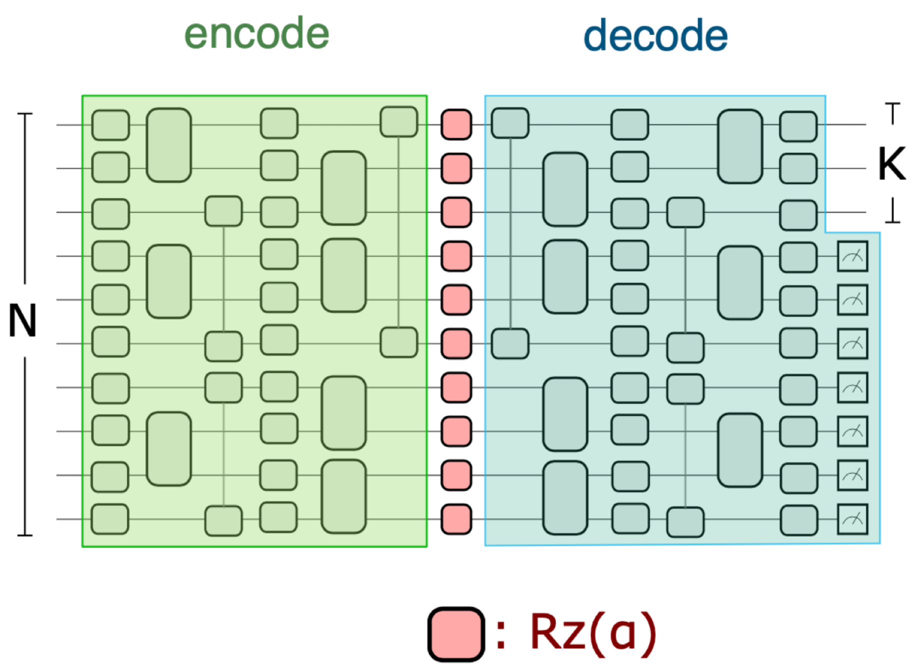
Measure $|00\rangle$ in the x-basis, four equally probable measurement outcomes $|\pm\pm\rangle$ with S=2

Measure $|00\rangle$ in the z-basis, only one outcome $|00\rangle$ with S=0

BMME = 0

arXiv: 2304.10481

Experimental magic measure



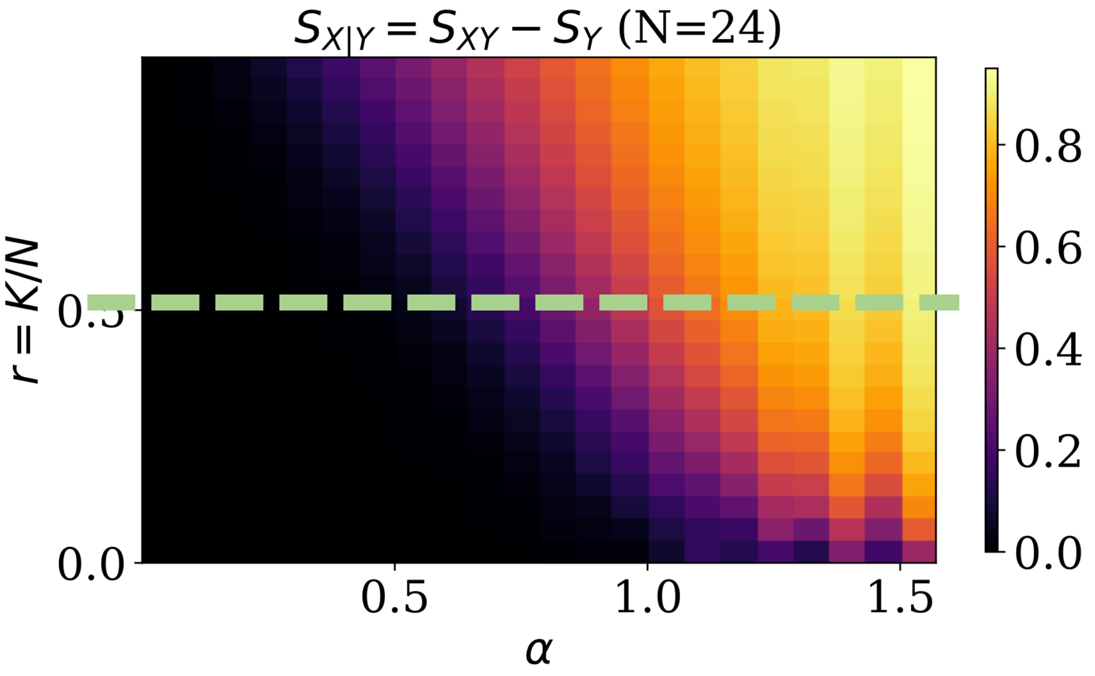
- Avoid full state tomography
- Conditional entropy : $S_{X(B)|Y} = S_{X(B)Y} - S_Y$
  - Uncertainty about logical space, given syndrome.
- Basis minimized conditional entropy $\min_B S_{X(B)|Y}$
- Error mitigation using classical simulation

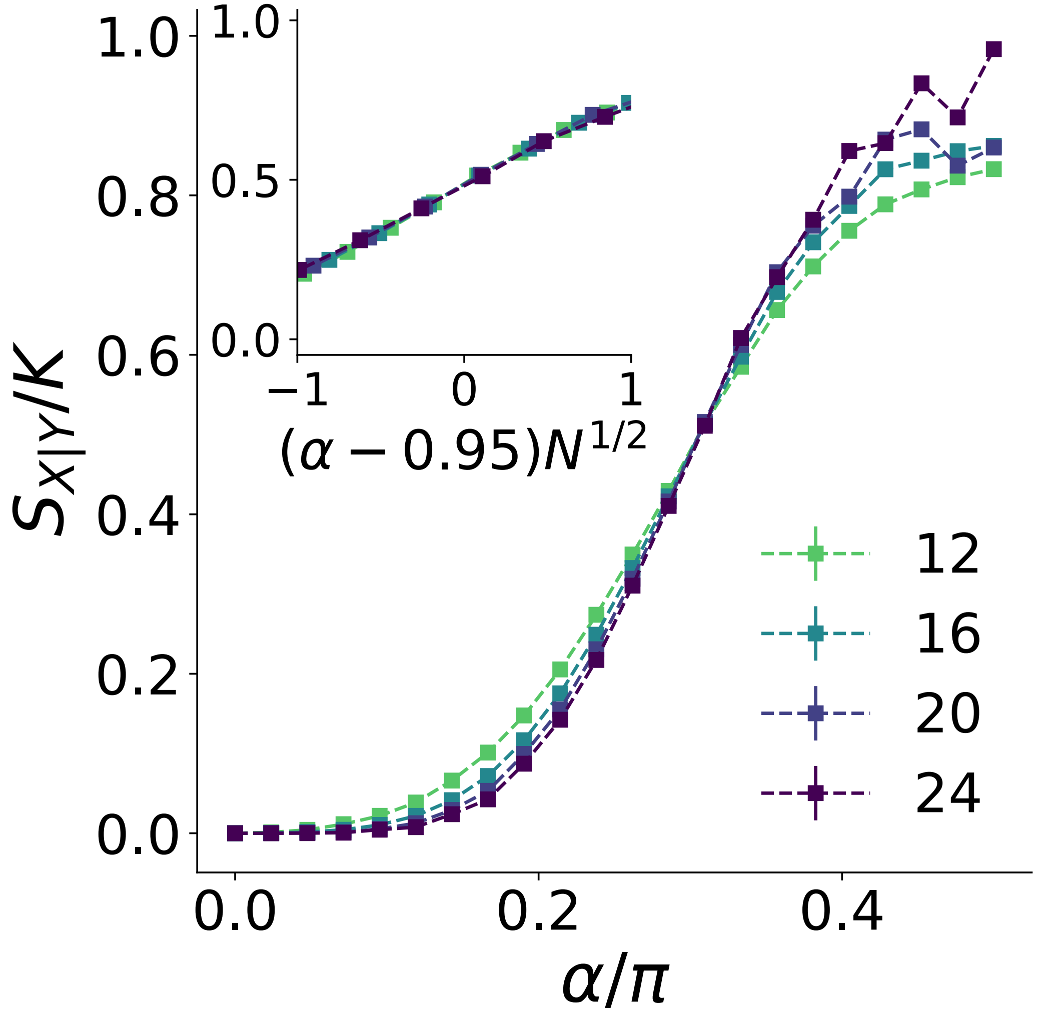
$$S_X = -\sum_x p(x) \log \tilde{p}(x)$$

arXiv: 2304.10481

Finite Rate Code: Conditional Entropy

- The conditional entropy is a good measure for the phase where magic is suppressed.

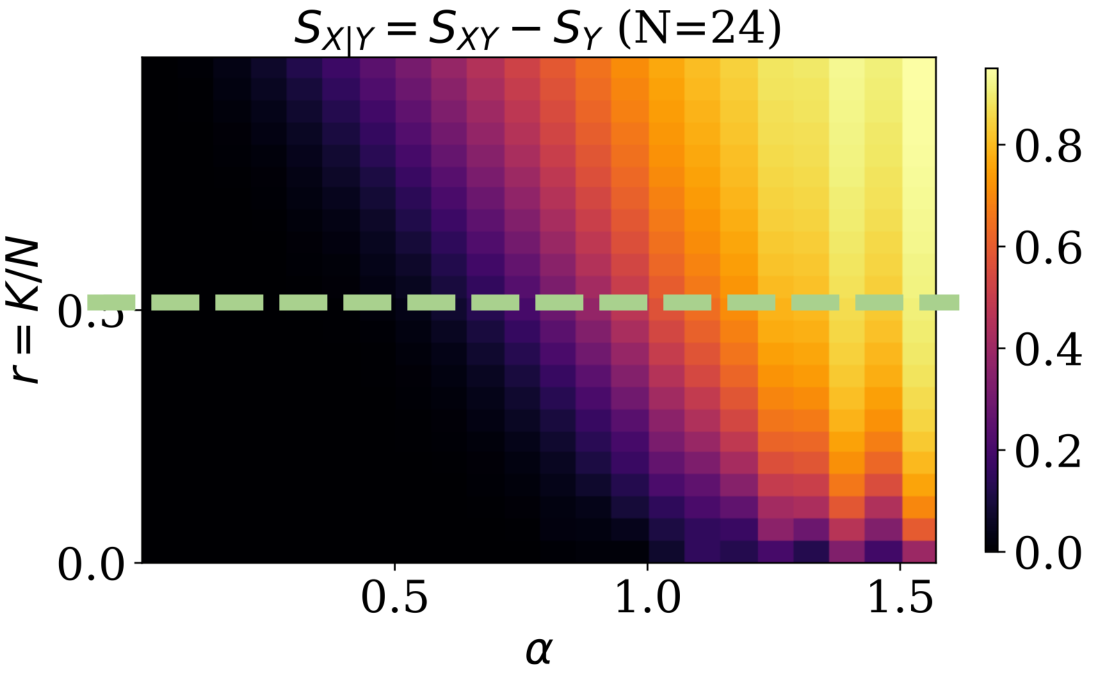


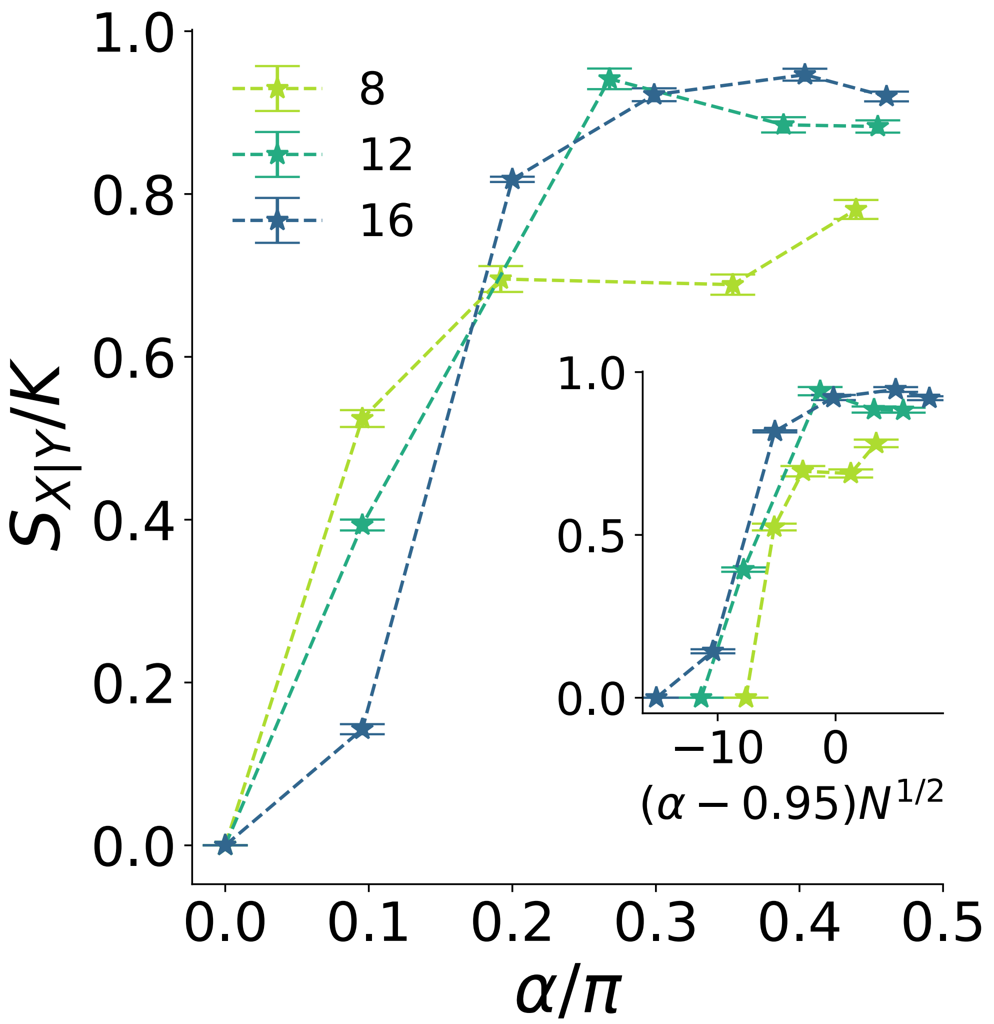


arXiv: 2304.10481

Finite Rate Code: Conditional Entropy

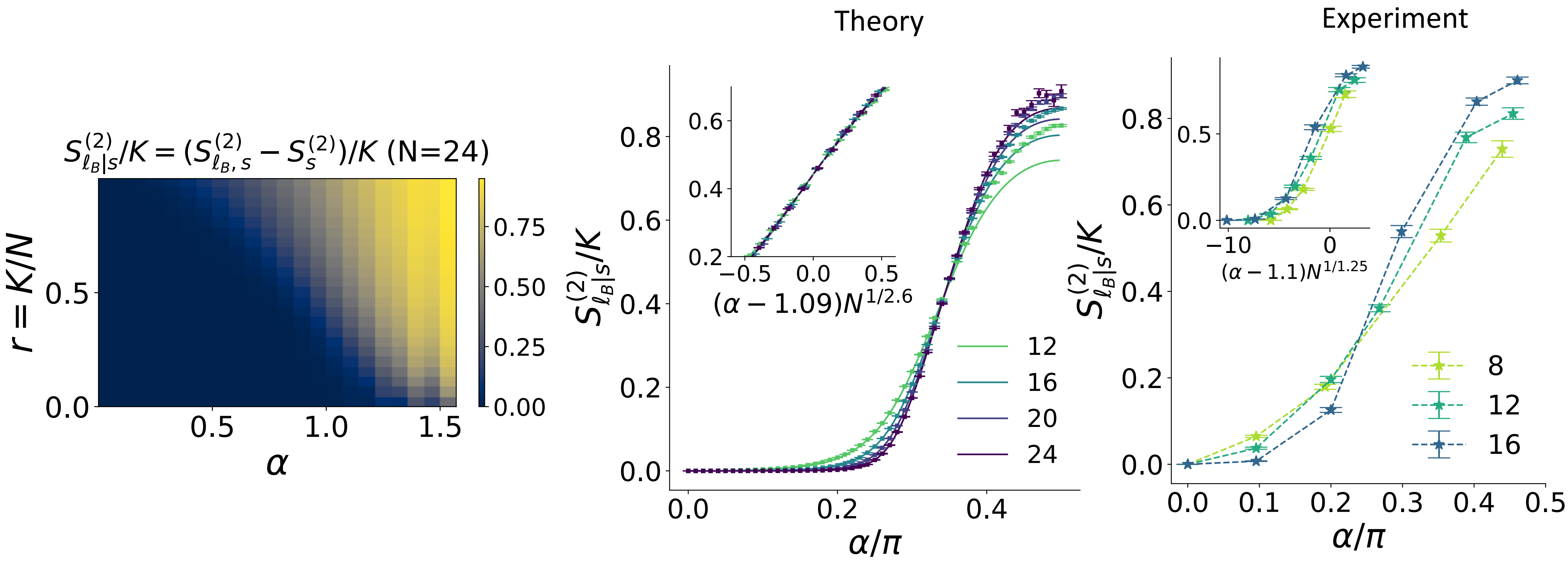
- Can also observe this in experiment.





arXiv: 2304.10481

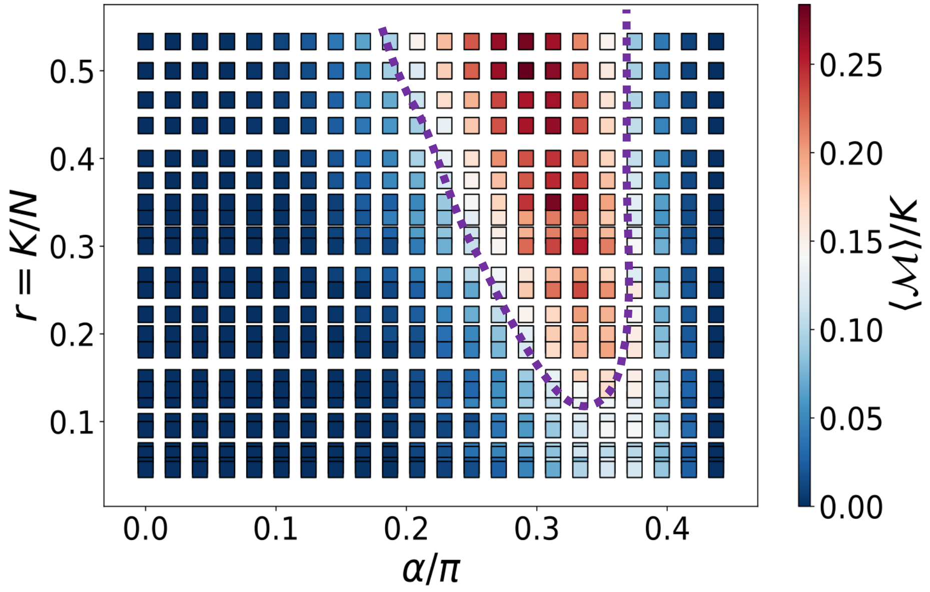
Finite rate code: Renyi approximation of conditional entropy



arXiv: 2304.10481

Outlook

- Efficient magic measures
- Expansion of MIPT beyond entanglement
  - Resource generation
  - Correlation generation
  - Resource destruction
- Magic state distillation from noise?



L. Leone, S. F. Oliviero, G. Esposito, A. Hamma, *arXiv preprint arXiv:2302.07895* (2023).

M. Ippoliti, M. J. Gullans, S. Gopalakrishnan, D. A. Huse, V. Khemani, *Physical Review X* 11, 011030 (2021).

Thank you!

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IARPA

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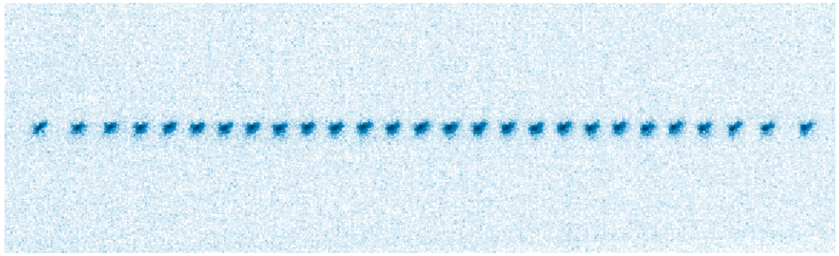
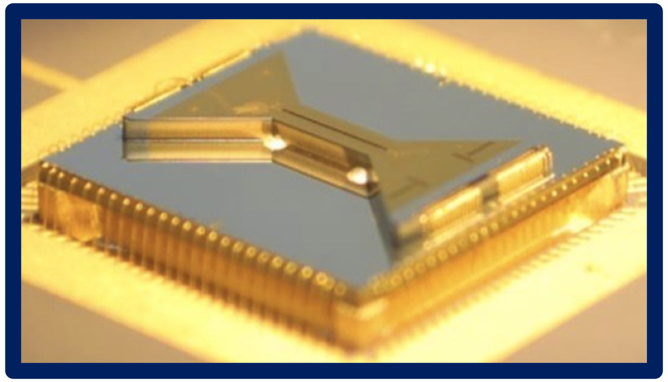
STAQ SOFTWARE-TAILORED ARCHITECTURES *for* QUANTUM CODESIGN

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem



Several quantum computers and simulators at Duke!
- 23-27 qubit Blue system
- 25 qubit Gold System
- upcoming Green system
- and more!



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