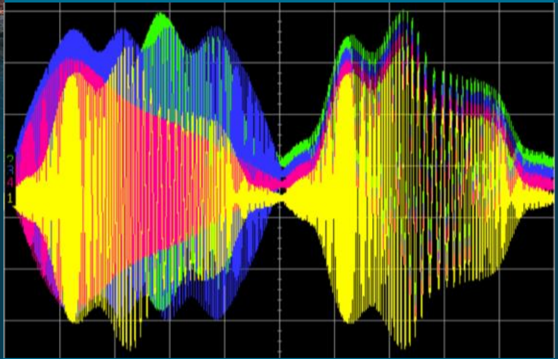
SAND2023-00230C

QSCOUT: Continuously parameterized Mølmer-Sørensen gates for quantum computing circuits (Part II)



QSCOUT

PRESENTED BY

Christopher G. Yale

QSCOUT @ Sandia National Laboratories
Christopher G. Yale, Ashlyn D. Burch, Matthew N. H. Chow, Megan Ivory, Daniel S. Lobser, Melissa C. Revelle, Susan M. Clark

Oak Ridge National Laboratory / Duke University Team
Swarnadeep Majumder, Titus Morris, Raphael C. Pooser

University of California, Berkeley Team
Ryan Shaffer, Hang Ren, Emiliia Dyrenkova, Hartmut Häffner

Oak Ridge National Laboratory

Duke Quantum Center

Berkeley UNIVERSITY OF CALIFORNIA

U.S. DEPARTMENT OF ENERGY Office of Science

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Continuously Parameterized Mølmer-Sørensen Gates

- The MS gate has an entangling interaction of the form:

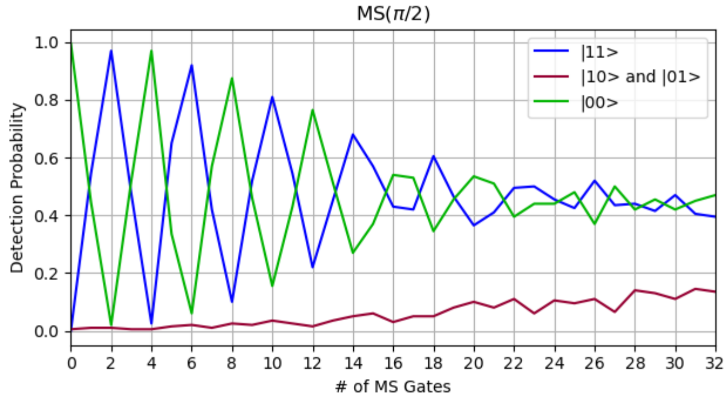
$$MS(\theta,\phi) = \exp\left[-i\frac{\theta}{2}(\cos(\phi)\sigma^x + \sin(\phi)\,\sigma^y)^{\otimes 2}\right]$$

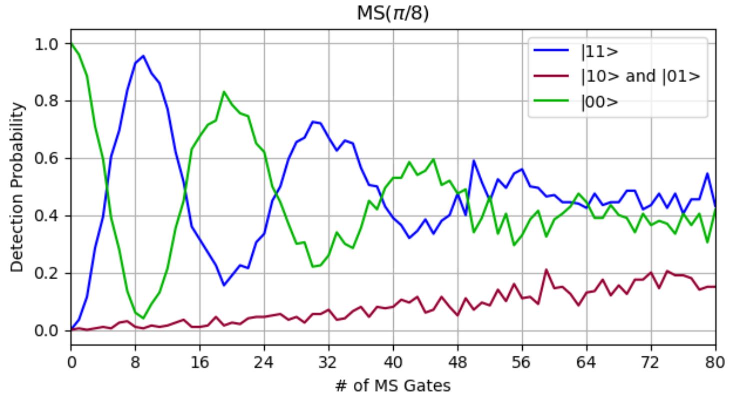
- θ is related to the amount of entanglement from the gate

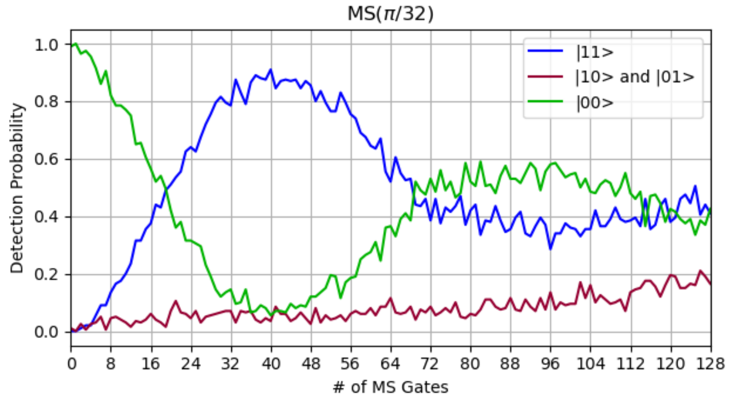
Enables:

- **Reduction in quantum circuit depth**
- **Less error / more coherence per gate for smaller θ**

- Most quantum computers have not previously offered arbitrary θ for the two-qubit gate (IonQ only offers $MS(\frac{\pi}{2})$, Quantinuum recently announced $MS(\theta)$)







Key Elements of $MS(\theta)$

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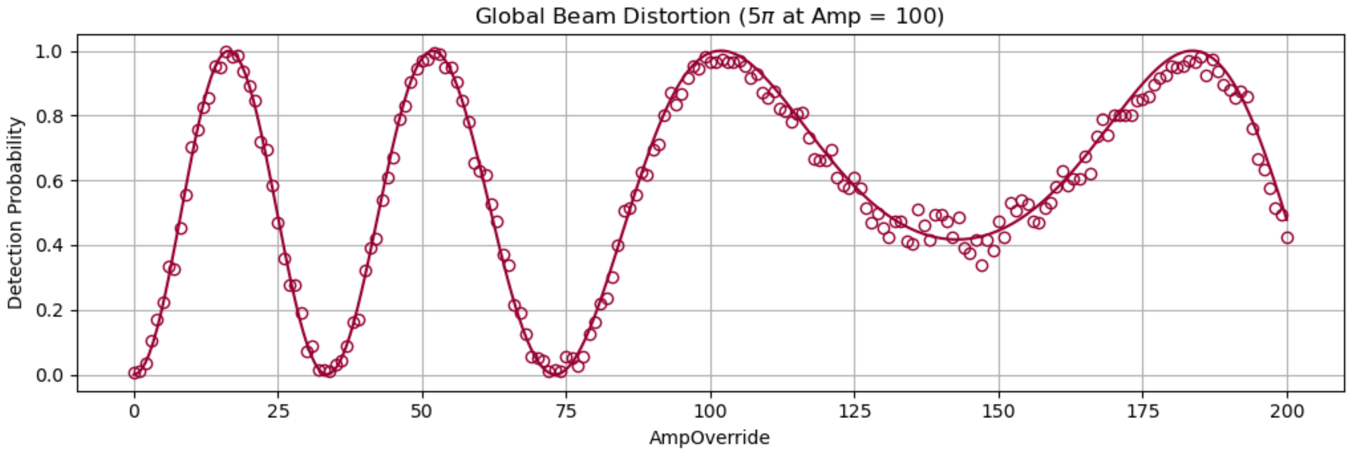
- **How do we realize an arbitrary-angle $MS(\theta)$ gate?**
  - Global tone and two individual tones to form the needed red- and blue-detuned Raman transition
  - All tones have a Gaussian pulse envelope to limit displacement errors [see B. Ruzic B67.00012 (this session)]
  - To set the angular enclosure, we adjust the global beam power

Sources of Error:

- **$\delta\theta$ (coherent rotation errors)** → distortion/saturation in global beam control electronics
- **$\delta\phi$ (coherent phase errors)** → resulting AC Stark shifts

Distortion correction



Residual Coherent Rotation Error on Arbitrary-Angle MS Gates

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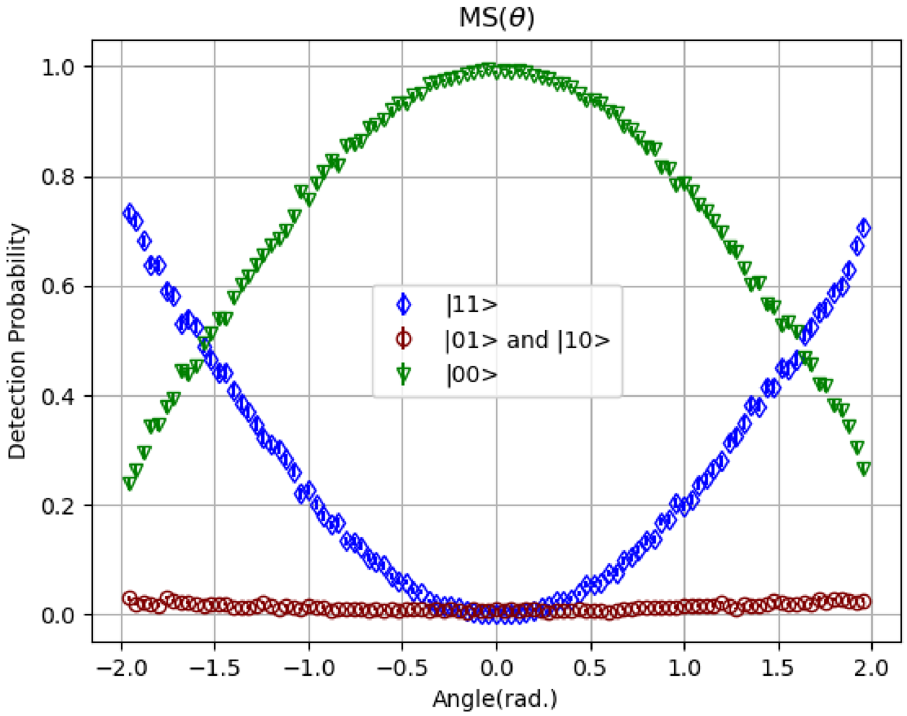
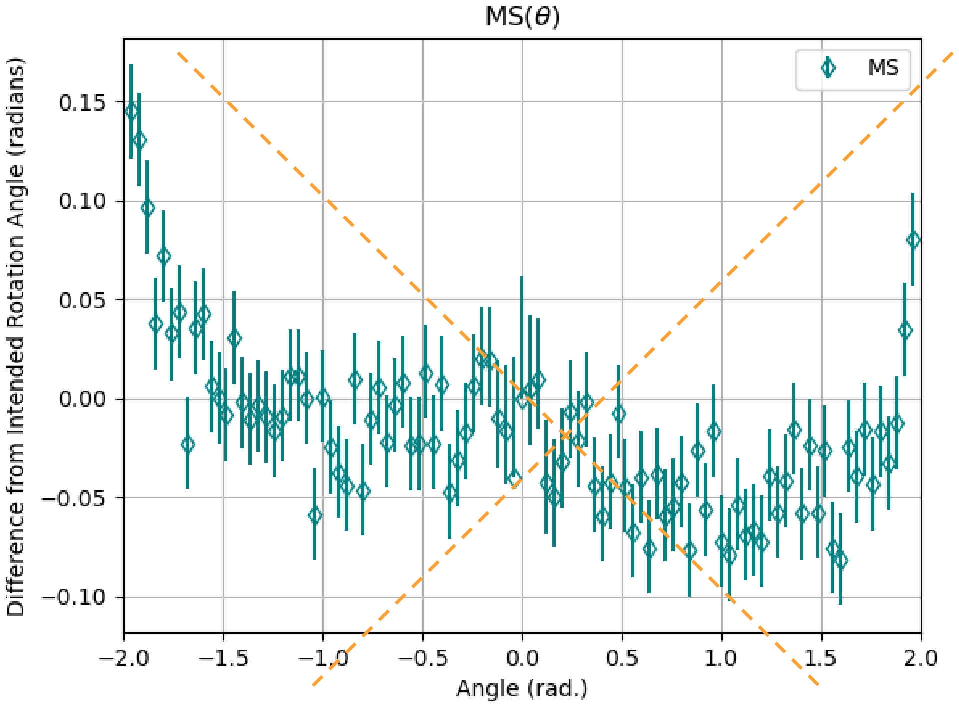
- Compensating for distortion and saturation effects, we can now scan the MS gate angle
- When we scan both negative and positive angles we find discrepancies across the deviation from expected rotation angle, and it appears negative gates rotate a little bit more.





- This apparent discrepancy between positive and negative angles is related to the relative phase between the waveforms that make up the gate
- Coherent rotation error per gate, $\frac{\delta\theta}{\theta} \lesssim 0.10$

Possible solution?
Use phase-agnostic ZZ basis for MS gates

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AC Stark Shift Cancellation for Arbitrary-Angle MS Gates

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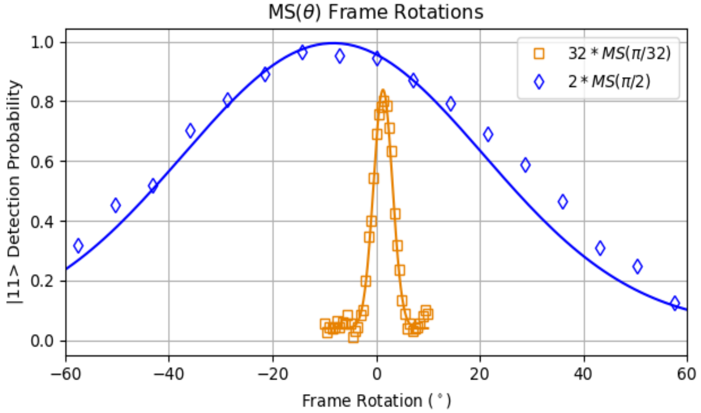
All lasers induce a power-dependent AC Stark shift, shifting energy splittings generating phase accumulation

Inherent AC Stark Cancellation

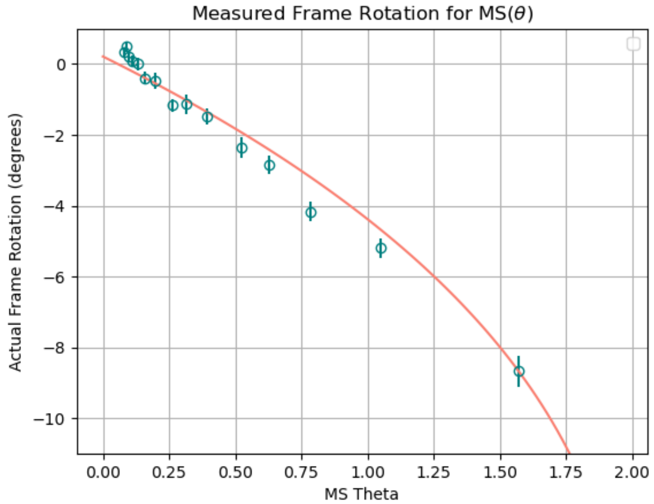
- Red- and blue- detuned Raman transitions from carrier dominate the Stark shift
- Differing signs allow for cancellation when magnitudes are matched for red/blue and across qubits

Residual AC Stark Correction

- Use a virtual Z rotation, or "frame rotation," applied during the gate to effectively cancel residual phase accumulation



- To calibrate:
  - Stack $n * MS(\frac{\pi}{n})$ gates
  - Scan frame rotation
  - Find maximum $|11\rangle$ population



- We find the frame rotation for a variety of angles, and then use a simple relation (quadratic or cubic) to approximately deduce the needed rotation for any given gate
  - Coherent phase error: $\delta\phi \lesssim 1°$ per gate

Characterizing and Mitigating Coherent Errors via Hidden Inverses

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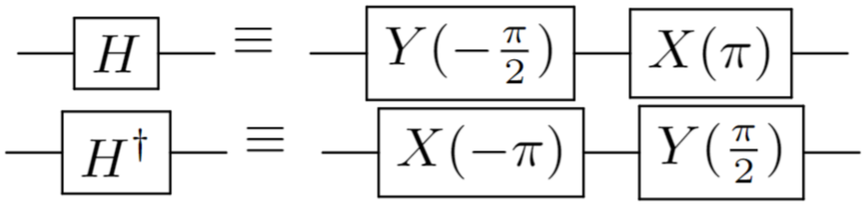
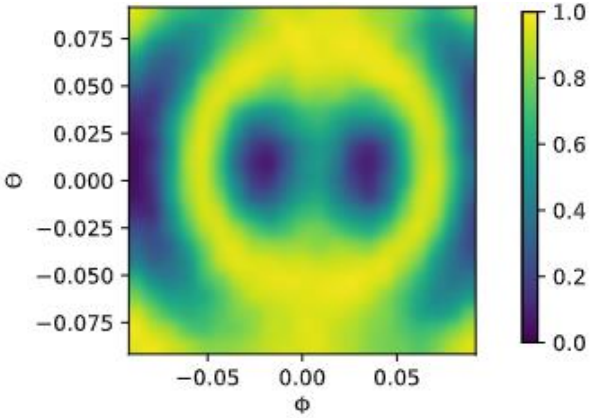
Hidden inverses → unitary operators that are self-adjoints i.e. $G = G^\dagger$, but component gates are not self-adjoint

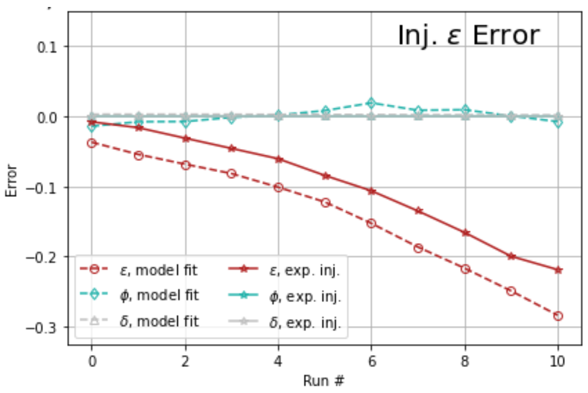
$$G = ABC \qquad G^\dagger = C^\dagger B^\dagger A^\dagger$$

Hadamard

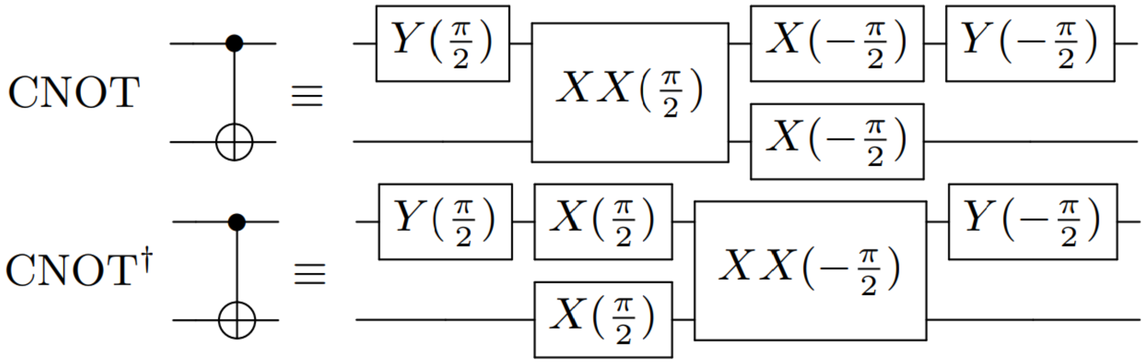


- We'll use the Hadamard and its inverse to **probe errors in the system**





Controlled-NOT

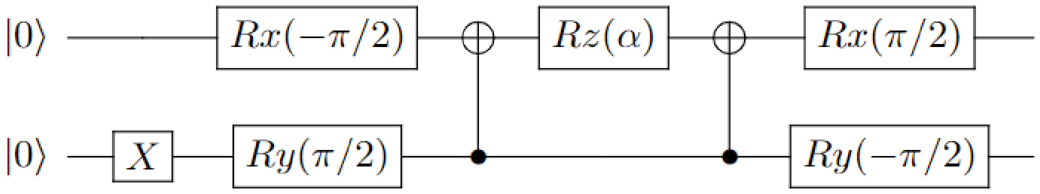


- We'll use the CNOT and its inverse in a simple variational quantum eigensolver (VQE) to **demonstrate its robustness to coherent errors**

S. Majumder, C. G. Yale, T. Morris, D. S. Lobser, A. D. Burch, M. N. H. Chow, M. C. Revelle, S. M. Clark, and R. C. Pooser, "Characterizing and mitigating coherent errors in a trapped ion quantum processor using hidden inverses," *arXiv:2205.14225* (2022)

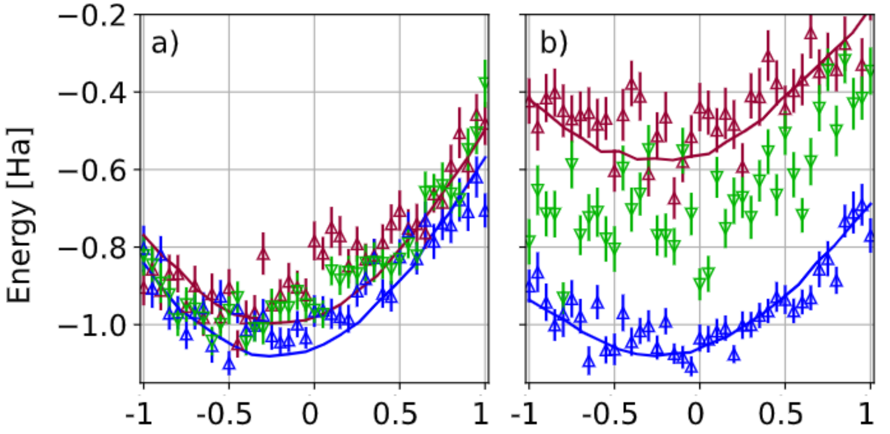
Error Mitigation in VQE with HI

- Construct VQE with BK Ansatz under the following conditions:
  - Natural construction
  - Hidden inverse (second CNOT is CNOT†)
  - Randomized compiling (Pauli twirl around each CNOT)
- Compare robustness of approaches in the presence of injected error



Coherent Error Injection

Calibrated -0.5 rad. MS under-rotation

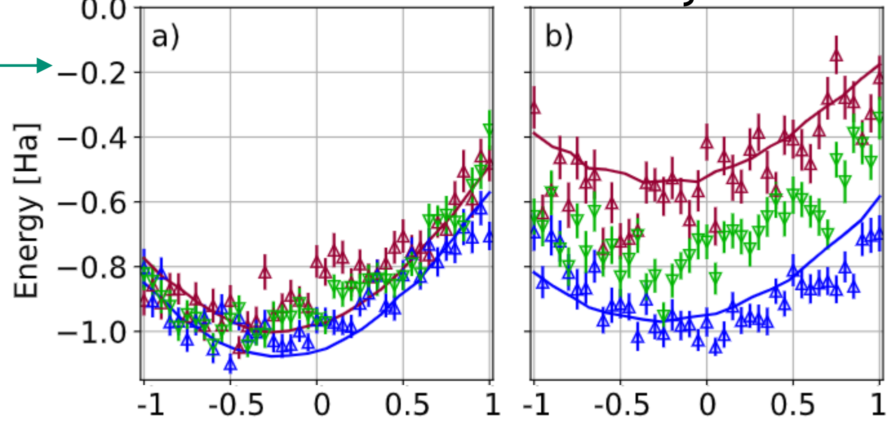


← Resultant Energy →

- HI outperforms RC in both contexts: coherent and stochastic errors

Stochastic (& Coherent) Error Injection

Cooled Partially cooled



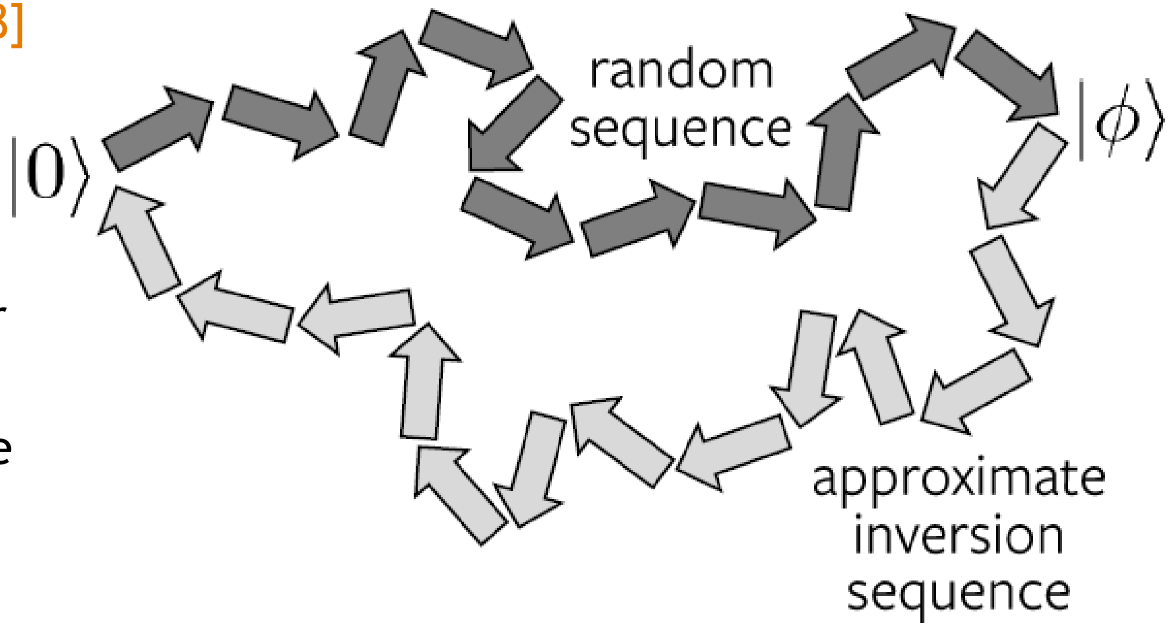
Constructing circuits with hidden inverses can be a powerful tool not only for mitigating coherent errors, but also for understanding them

S. Majumder, *et al.*, *arXiv:2205.14225* (2022)

Efficient Verification of Continuously Parameterized Gates

Randomized Analog Verification [see R. Shaffer B72.00008]

- Related approach is cross-entropy benchmarking (XEB)
  - XEB: $|0\rangle \rightarrow |\phi\rangle$
  - RAV: $|0\rangle \rightarrow |\phi\rangle \rightarrow |0\rangle$
- Inversion sequence generated via stochastic protocol for approximate quantum unitary compilation (STOQ)
- Each layer consists of continuously parameterized native gates:
  - 3 $R(\theta,\varphi)$
  - 3 $R_Z(\theta)$
  - 1 $MS(\theta,\varphi)$



Depolarization Fidelity

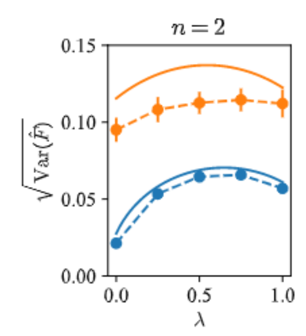
- Simulations suggest variance of $\hat{F}_{RAV}$ is lower than variance of $\hat{F}_{XEB}$
  - → fewer shots required

$$\hat{F}_{\mathrm{RAV}} = \frac{Q(x_0) - \frac{1}{N}}{P(x_0) - \frac{1}{N}}.$$

vs.

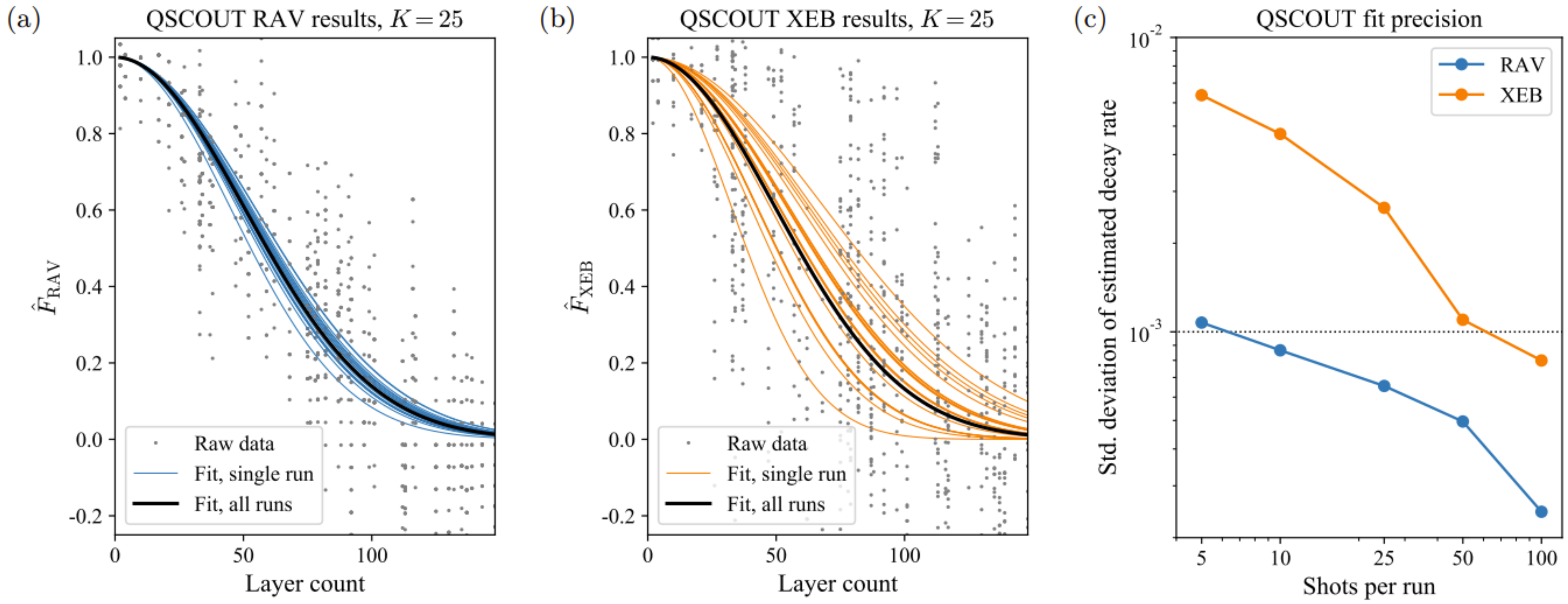
$$\hat{F}_{\mathrm{XEB}} = \frac{\sum_x P(x)Q(x) - \frac{1}{N}}{\sum_x P(x)^2 - \frac{1}{N}}$$

- Fidelity loss estimates are depolarization fidelity per layer



R. Shaffer, H. Ren, E. Dyrenkova, C. G. Yale, D. S. Lobser, A. D. Burch, M. N. H. Chow, M. C. Revelle, S. M. Clark, H. Häffner, "Efficient verification of continuously-parameterized quantum gates," *arXiv:2205.13074* (2022)

Experimental Demonstrations (QSCOUT)



- 500 total shots per sequence, with full shot-to-shot information
- Subdividing those into 20 groups of K = 25, fidelity loss estimate is:
  - RAV: $1.403 \times 10^{-2} \pm 0.065 \times 10^{-2}$
  - XEB: $1.399 \times 10^{-2} \pm 0.264 \times 10^{-2}$
- Subdividing shots yields RAV error rates 2.3-5.5x more precise than XEB

(
- Also run on IBM Q's *ibmq_manila*
- Non-native gateset for IBM Q → composite gates form MS(θ) gate
- Similar error rates to QSCOUT and precision improvements
)

RAV is a method to characterize QSCOUT's native continuously parameterized gateset with less benchmarking time to achieve the same level of precision as compared to XEB

R. Shaffer *et al.*, *arXiv:2205.13074* (2022)

Summary and Conclusions

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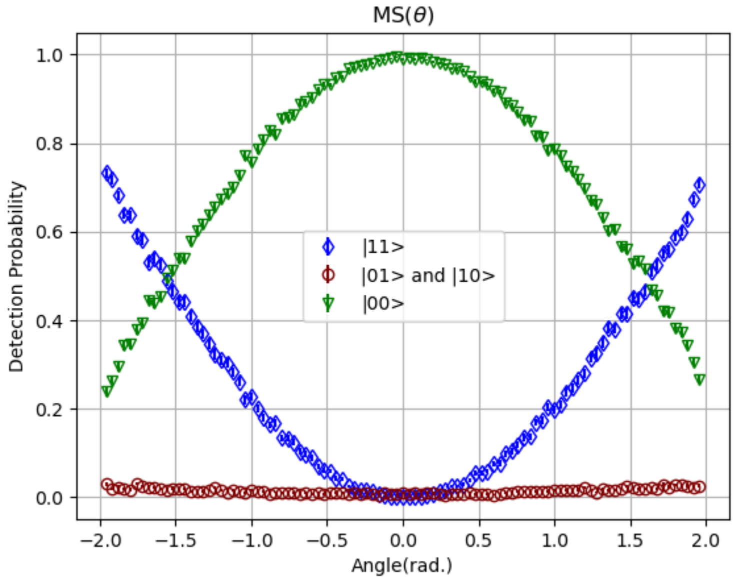
- **Continuously parameterized two-qubit gates** provide a richer and more versatile gateset with smaller angle gates appearing to provide more coherence per gate

$$MS(\theta,\phi) = \exp\left[-i\frac{\theta}{2}(\cos(\phi)\sigma^x + \sin(\phi)\,\sigma^y)^{\otimes 2}\right]$$



- **Amplitude and phase errors** across the parameterized spectrum are mitigated in a variety of ways:
  - Amplitude: distortion correction
  - Phase: Red/blue Stark shift cancellation, frame rotation

- **Applications**
  - Hidden inverses → used for injection two-qubit rotation errors

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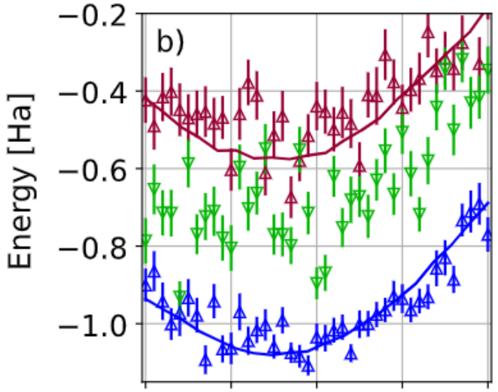
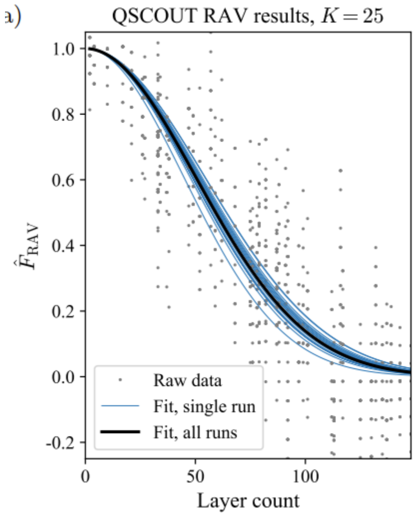
    S. Majumder, *et al.*, *arXiv:2205.14225* (2022)
  - Randomized analog verification → designed to explore continuously parameterized native gatesets

    Berkeley UNIVERSITY OF CALIFORNIA

    R. Shaffer *et al.*, *arXiv:2205.13074* (2022)





QSCOUT Team

Email: qscout@sandia.gov (mailing list) **Web:** https://qscout.sandia.gov **Jaqal:** https://gitlab.com/jaqal/jaqalpaq

User and Collaborator Teams

Experimental
Susan Clark, PI
Christopher Yale
Dan Lobser
Melissa Revelle
Matt Chow
Ashlyn Burch
Megan Ivory
Theala Redhouse
Craig Hogle
Dan Stick

Mech. & Opt. Engineering
Brad Salzbrenner
Madelyn Kosednar
Ted Winrow
Josh Lane

Theory & Software
Andrew Landahl
Ben Morrison
Kenny Rudinger
Antonio Russo
Brandon Ruzic
Jay Van Der Wall
Josh Goldberg
Tim Proctor
Kevin Young

Trap Fabrication and Packaging
Matt Delaney
Ed Heller
Chris Nordquist
Ray Haltli
Tipp Jennings
Ben Thurston
Eric Ou
Zach Meinelt
Nick Jimenez

Collaborators
Ken Brown, Duke
Peter Love, Tufts
Oliver Maupin, Tufts
William Simon, Tufts

QSCOUT @ March Meeting 2023

Mon: B67.00003, *A. Burch* (QSCOUT intro)
Mon: B67.00004, *C. Yale* (MS(θ) gates)
Mon: B67.00012, *B. Ruzic* (Freq-robust MS)
Mon: B72.00008, *R. Shaffer* (RAV protocol)
Thu: W64.00007, *O. Maupin* (0-noise extrap.)
Thu: W64.00012, *D. Saha* (chemical dynamics)