



Design of a Superconducting Quantum Computer: Surface Code & Fidelity

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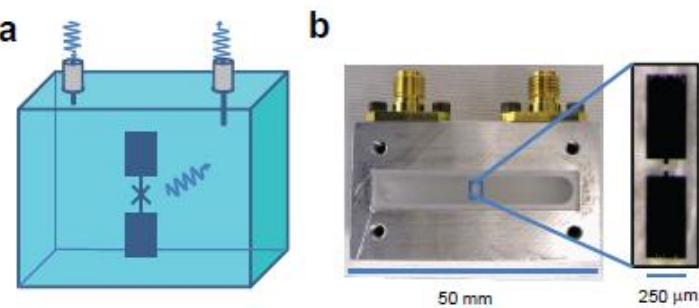


1. Why surface code design?
2. Surface code review
3. Cell design methodology
4. χ matrix
5. Design comments

Superconducting Qubits and Surface Code

3D transmons:

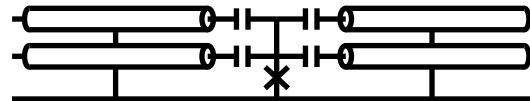
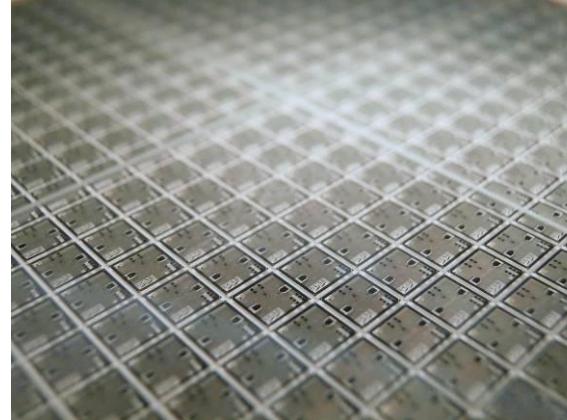
- $T_1, T_2 \sim 60 \mu\text{s}$
- $t_{\text{gate}1} = 15 \text{ ns}$:
 fidelity = 99.8%
- $t_{\text{gate}2} = 200 \text{ ns}$:
 fidelity = 99%
- $P_{\text{meas}} = 99.4\%$;
 1000's meas./ T_1
- Scalable?



qIQC's, UCSB strategy:

- Interconnectivity
- Theory: $t_{\text{CZ}} = 25 \text{ ns}$,
 intrinsic fidelity = 99.99%
- UCSB Xmon: $T_1 \sim 42 \mu\text{s}$

$t_{\text{th}} \sim 2.5 \mu\text{s}$
↑
 $\times 100$
 $t_{\text{gate}} \sim 25 \text{ ns}$

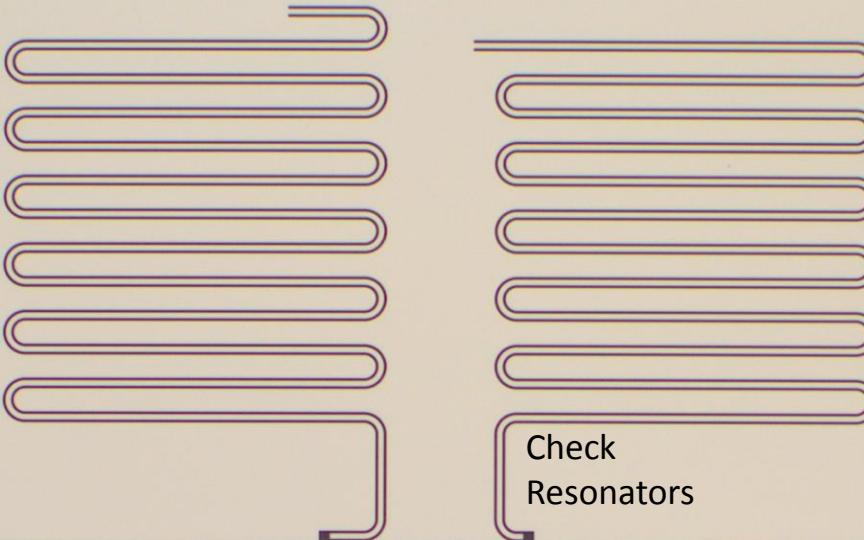


UCSB

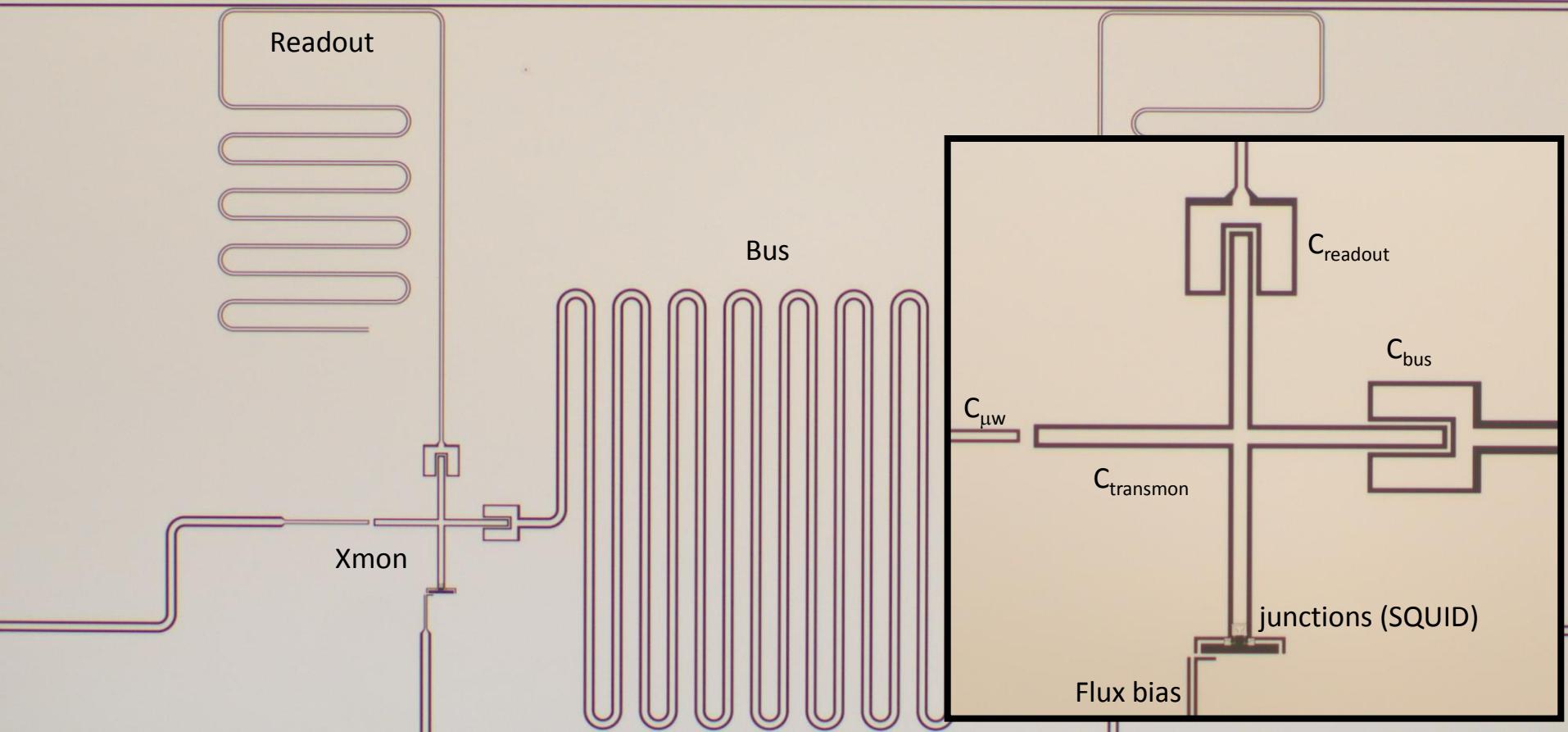
Xmons

200 μ m

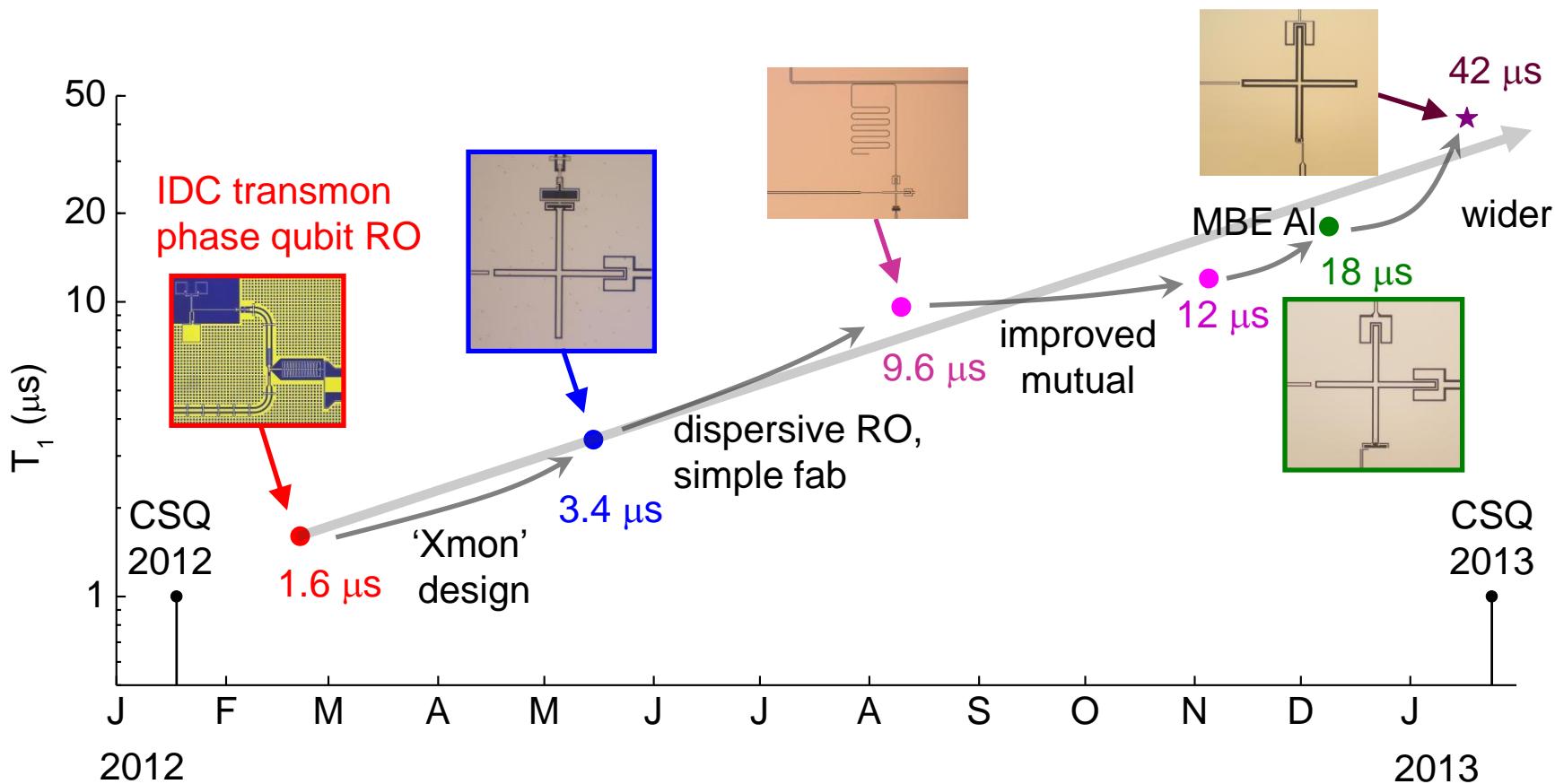
Multiplexed Measurement



- Broken “design rules”:
- Transmon outside of resonator
 - Direct μ wave drive
 - Single ended:
galvanically connected
(SQUID with high M)
(No IDC, 3um gap)
(C not double-evap.)



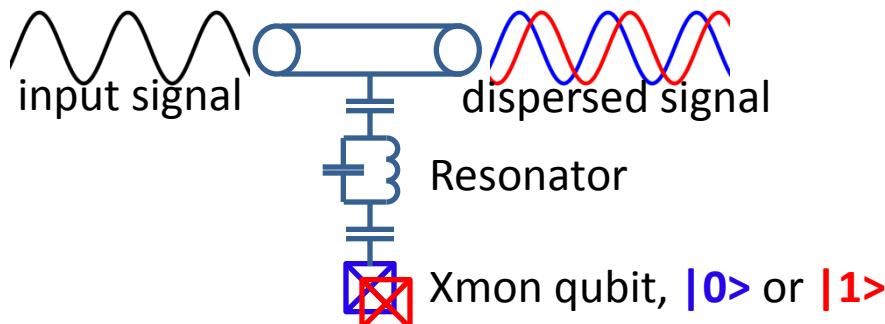
Timeline of T1 coherence



Xmon yield: 26/26
Qubit freq. to 100 MHz

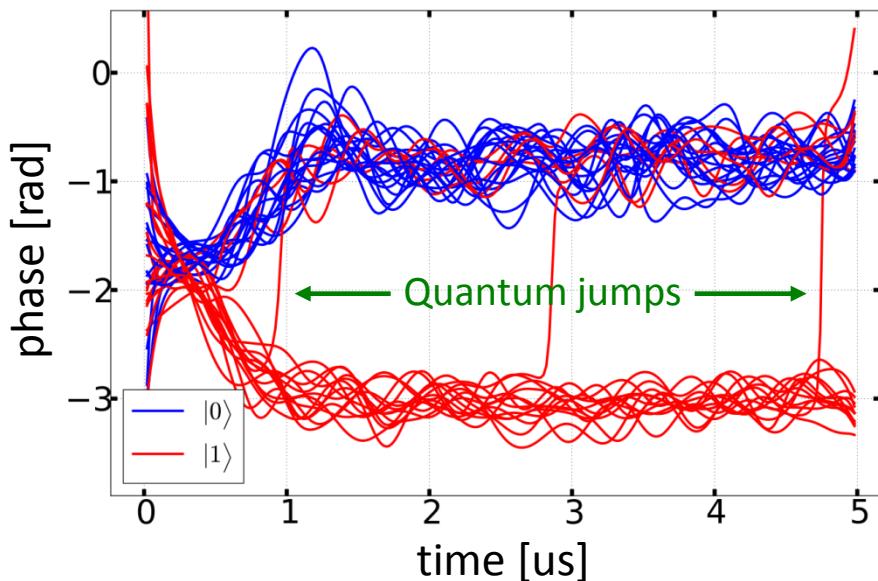
For next run, expect:
70 μs best, 40 μs avg.

UCSB single shot readout with in-house paramp



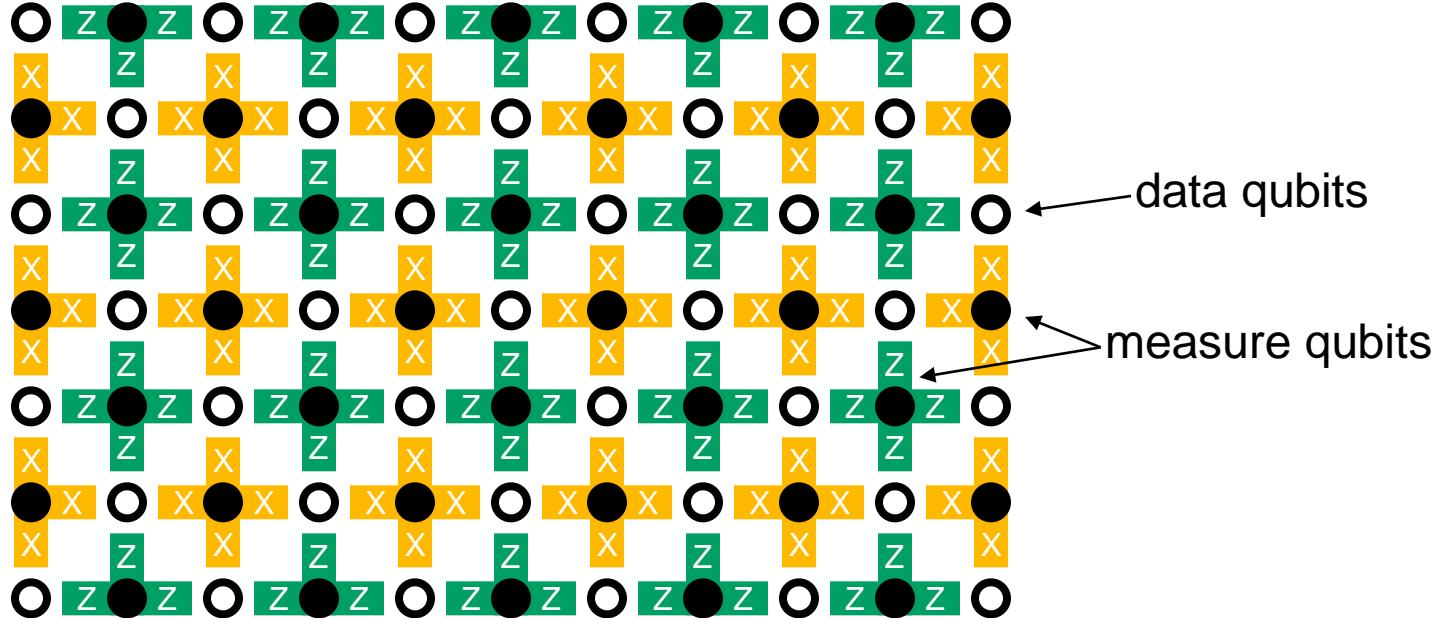
Parameter	Value
$g/2\pi$	30 MHz
K	$1/500$ ns
$\Delta/2\pi$	1 GHz
$\langle n \rangle$	160

Phase of single-shot time traces



- Measurement time: $T_{\text{meas}} = 800$ ns
- High separation gives 100% intrinsic fidelity
- Errors from T_1 only: $T_{\text{meas}}/T_1 = 0.05$
- Surface code: $\kappa=1/50$ ns possible

Surface Code Hardware



Measurement Symbol

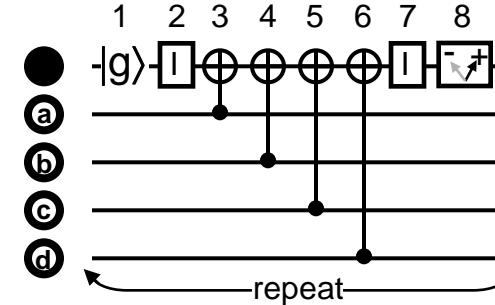
Physical Logic Sequence

4-bit parity

$$Z_{abcd} = Z_a Z_b Z_c Z_d$$

(a)

(b)

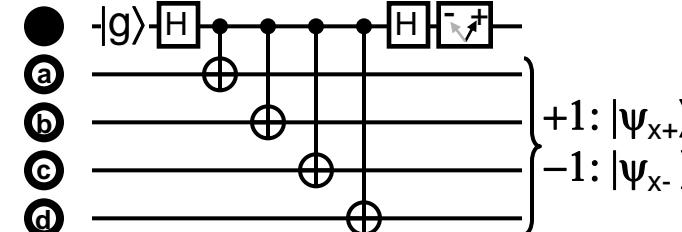


4-phase parity

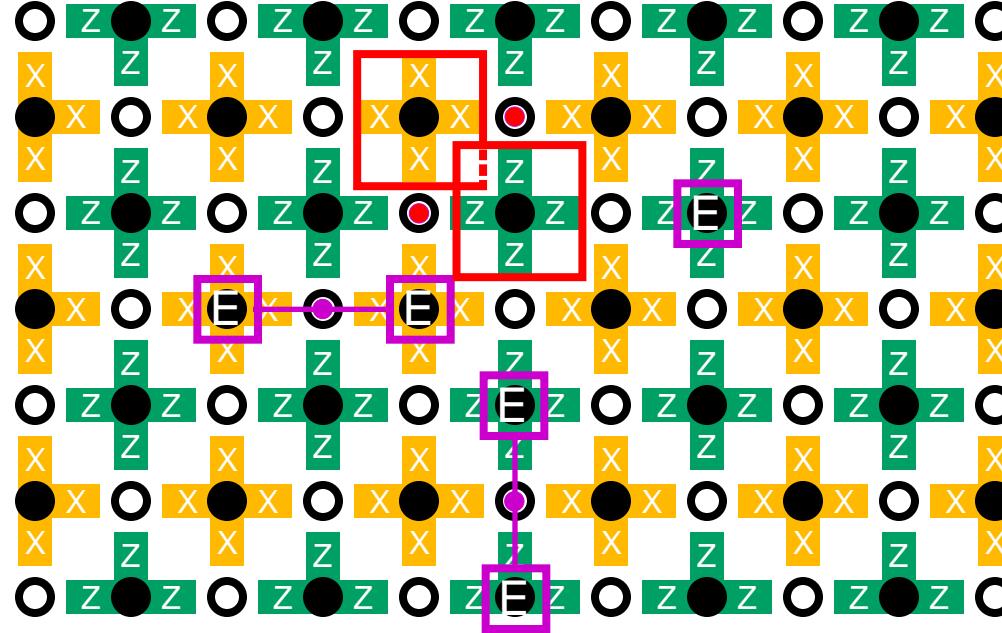
$$X_{abcd} = X_a X_b X_c X_d$$

(a)

(b)



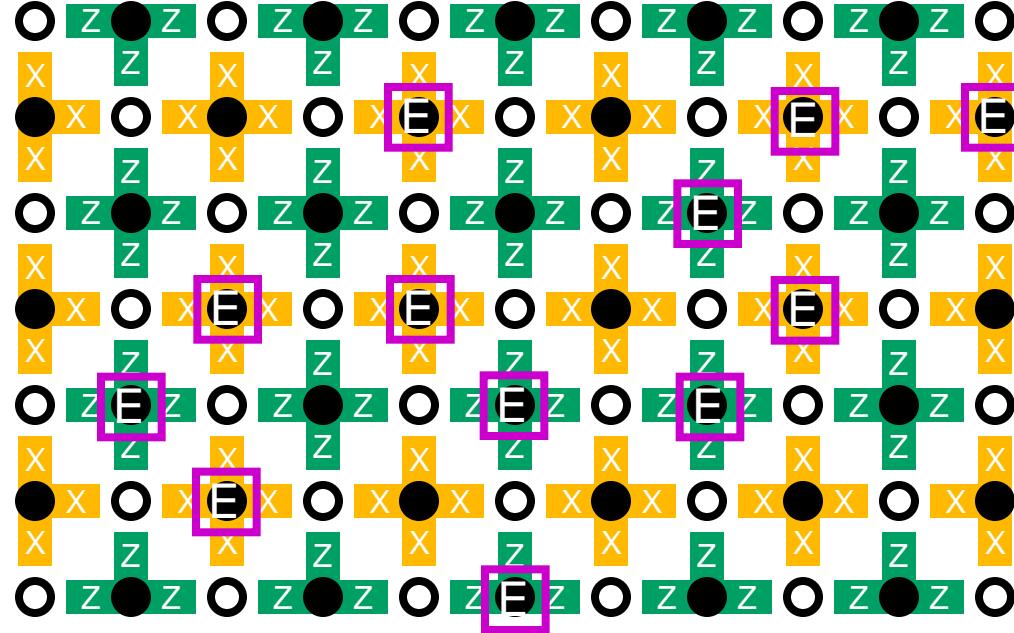
Stabilized State and Identifying Qubit Errors



All measurements **X** and **Z** commute:
Measurement outcomes unchanging

When errors:
Data qubit errors – pairs in space
Measure errors – pairs in time

Stabilized State and Identifying Qubit Errors

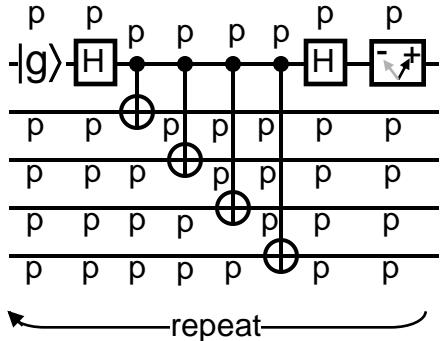


When large density -
Backing out errors not unique

Logical Error Probability

Model: total error p each step & qubit

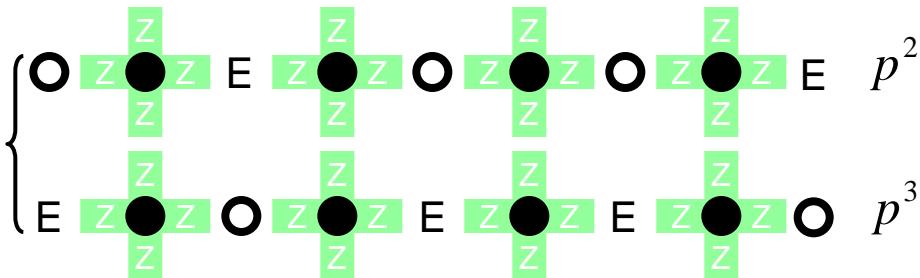
- 1: $p/3$ for X, Y, Z
- 2: $p/15$ for XX, YY, IX, ZI ...



measured error chain:

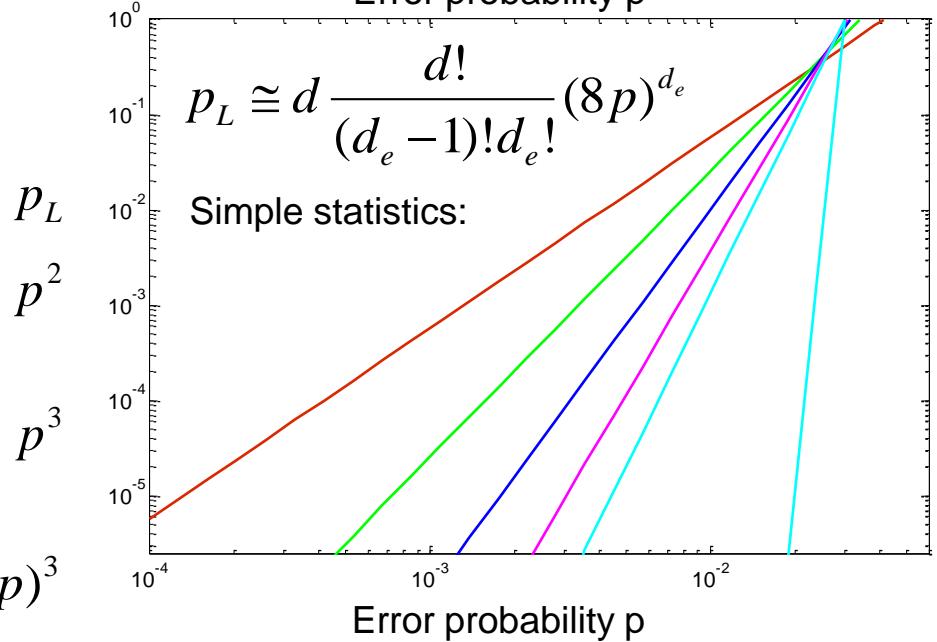
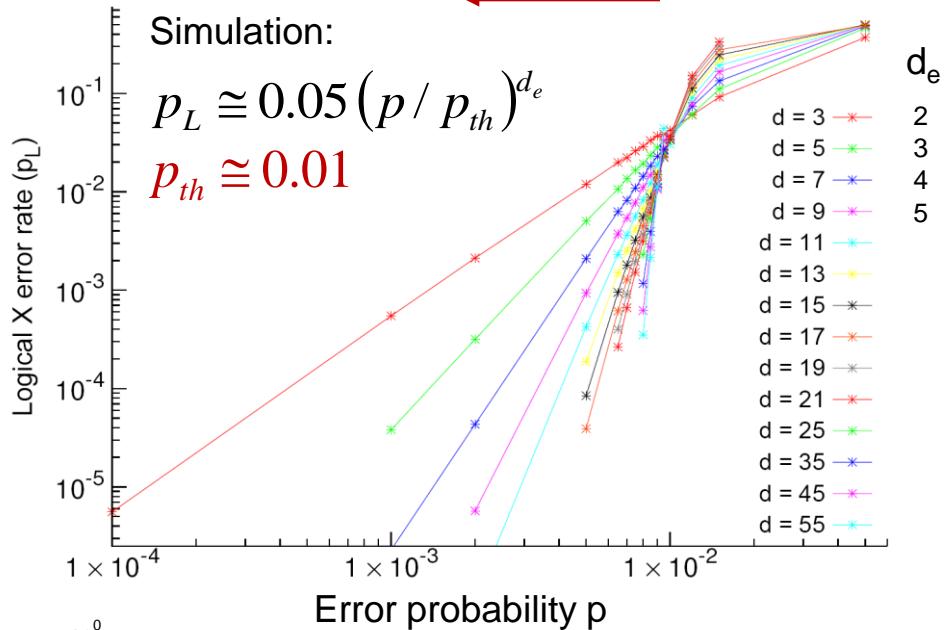


computed error of data qubits:



$$P_L \approx \frac{5 \cdot 4 \cdot 3}{3 \cdot 2 \cdot 1} (8p)^3$$

logical error improves with size



The Problem: Characterizing Errors

Quantum
Process Tomography

Complex
Not scalable
Sensitive to calibration
 χ matrix is overly complex

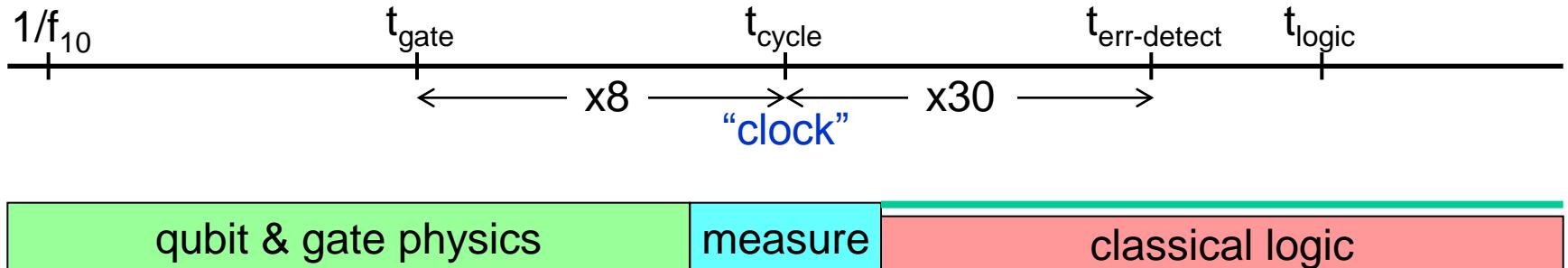
Pauli Gate Errors

Pauli error after every gate
One & two qubit errors
Need 3 to 15 probabilities
How to measure?

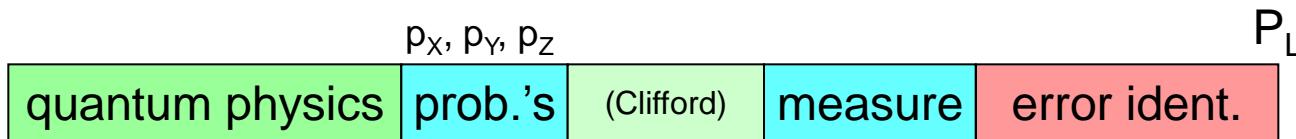
Randomized Benchmark

Scalable
One average fidelity
Overly simple

Designing for the Surface Code



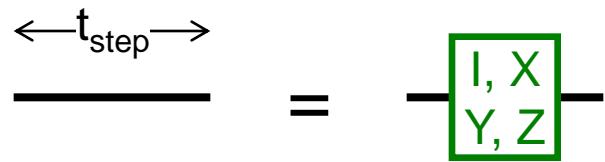
surface code design:



p 's are diagonal matrix elements of
computed or measured QPT

Theory Example: T_1, T_2 errors

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

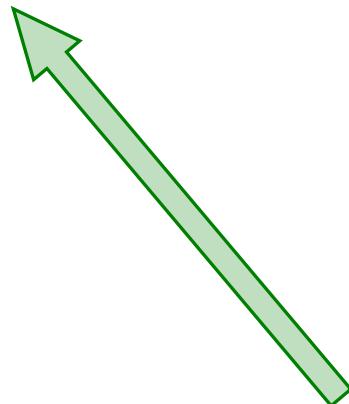


$$\rho = \begin{pmatrix} 1 - \rho_{11} e^{-t/T_1} & \rho_{01} e^{-t/2T_1} e^{-(t/T_\phi)^{1+\alpha}} \\ \rho_{01}^* e^{-t/2T_1} e^{-(t/T_\phi)^{1+\alpha}} & \rho_{11} e^{-t/T_1} \end{pmatrix}$$

3 possible probability errors: p_X, p_Y, p_Z

$$= (1 - p_X - p_Y - p_Z) \rho$$

$$+ p_X X \rho X + p_Y Y \rho Y + p_Z Z \rho Z$$

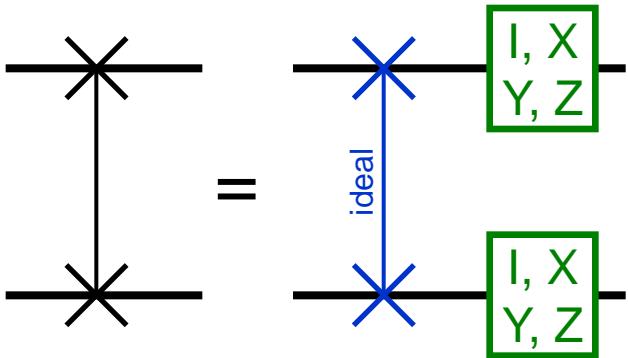


$$p_X = p_Y = \frac{t_{step}}{4T_1}$$

$$p_Z = \frac{1}{2} \left(\frac{t_{step}}{T_\phi} \right)^{1+\alpha}$$

$\alpha \neq 0$ is for correlated phase errors

Experiment Example: χ_{err} of $\text{iswap}^{1/2}$ gate

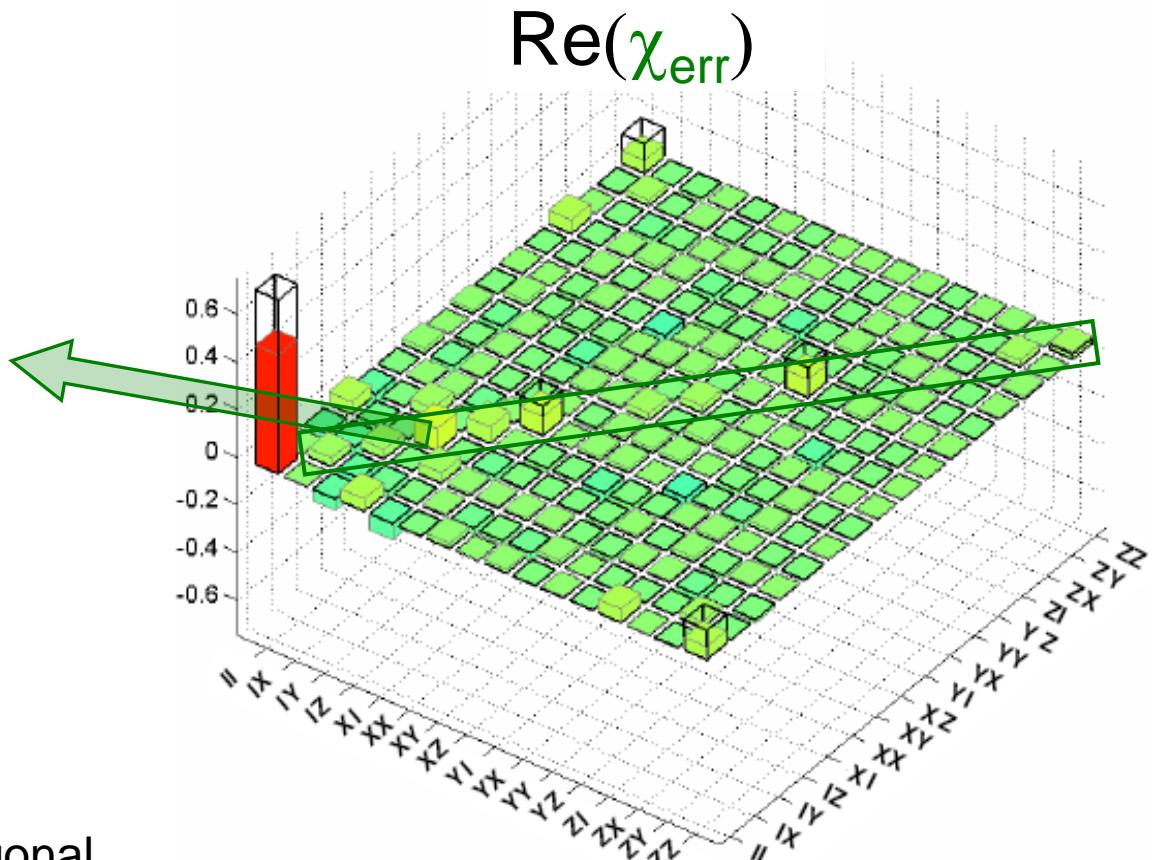


$$\chi_{\text{meas}} = \chi^+_{\text{ideal}} \chi_{\text{err}} \chi_{\text{ideal}}$$

15 possible probability errors:

p_{XI}, p_{YI}, p_{ZI}
 p_{IX}, p_{IY}, p_{IZ}
 p_{XX}, p_{XY}, p_{XZ}
 p_{YX}, p_{YY}, p_{YZ}
 p_{ZX}, p_{ZY}, p_{ZZ}

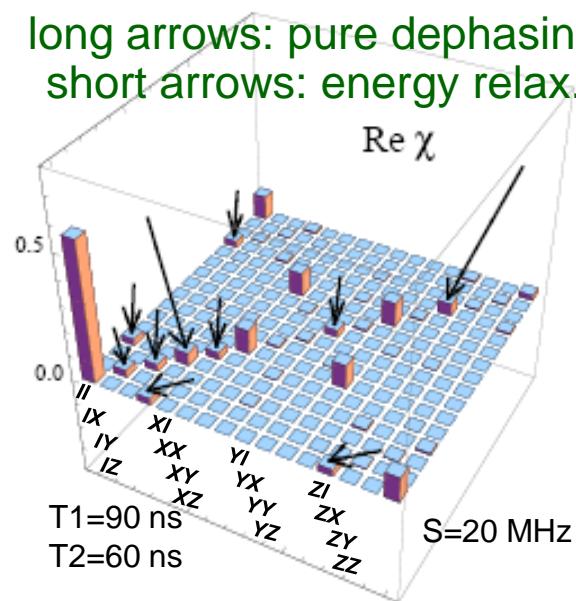
Simple: Fidelity = $\chi_{II,II}$
Modeling: Pauli errors = diagonal



Using χ_{err} Matrix to Test for Errors

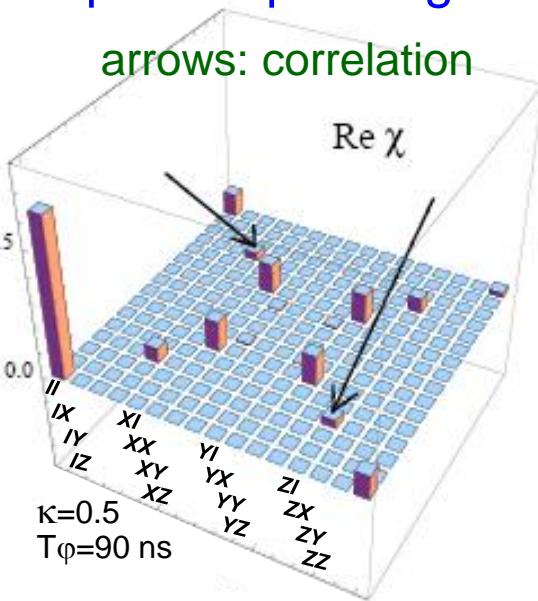
Local T_1 & T_2

long arrows: pure dephasing
short arrows: energy relax.

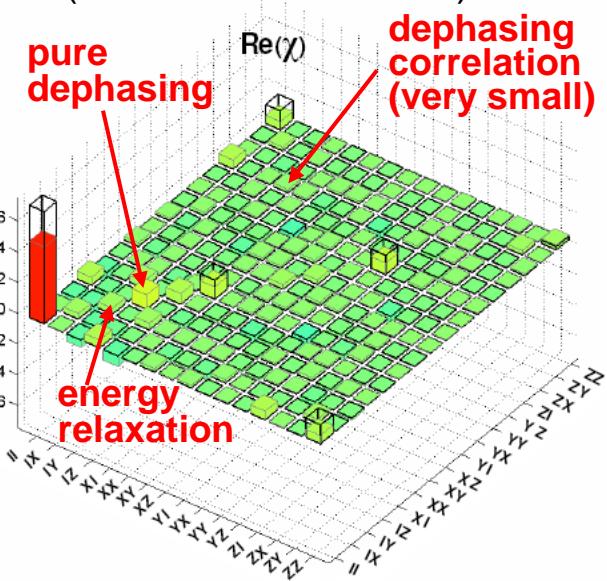


Correlated ($\kappa=0.5$)
pure dephasing

arrows: correlation



Actual experiment
(modified Pauli basis)

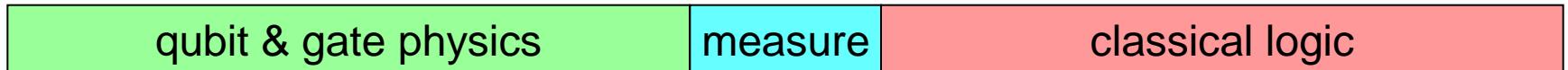
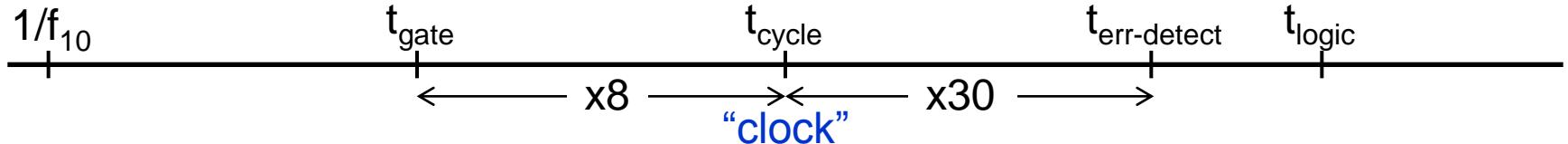


Kofman & Korotkov, arXiv:0903.0671

Bialczak et al.

T_ϕ extracted from QPT is close
to independently measured value

Designing for the Surface Code

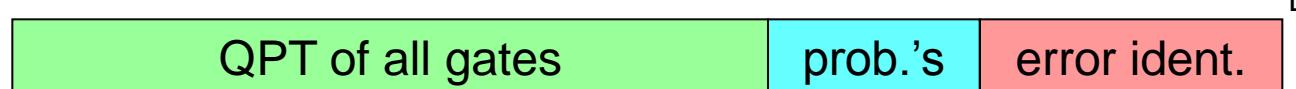


surface code design:



P 's are diagonal matrix elements of
computed or measured QPT

full model:



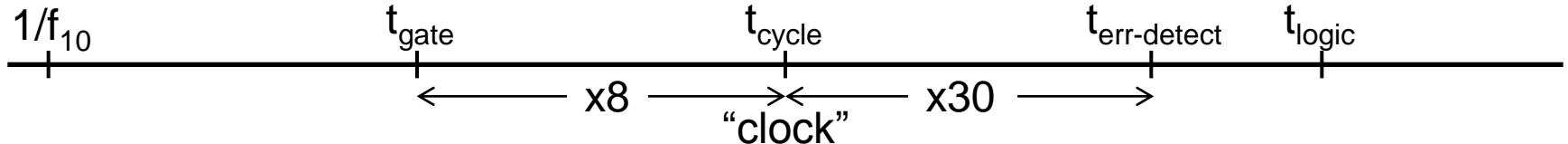
incoherent avg.
(twirling approx.)

$$\begin{aligned} P_{\text{err}} &= p_{x_1} + p_{x_1 y_2} + \dots && (\text{order } 10^{-3}) \\ &+ a p_{x_1} p_{x_2} + \dots && (\text{order } 10^{-6}) \end{aligned}$$

need χ to compute interferences, $\langle a \rangle = 1$

χ_{err} expansion:

Surface Code Output

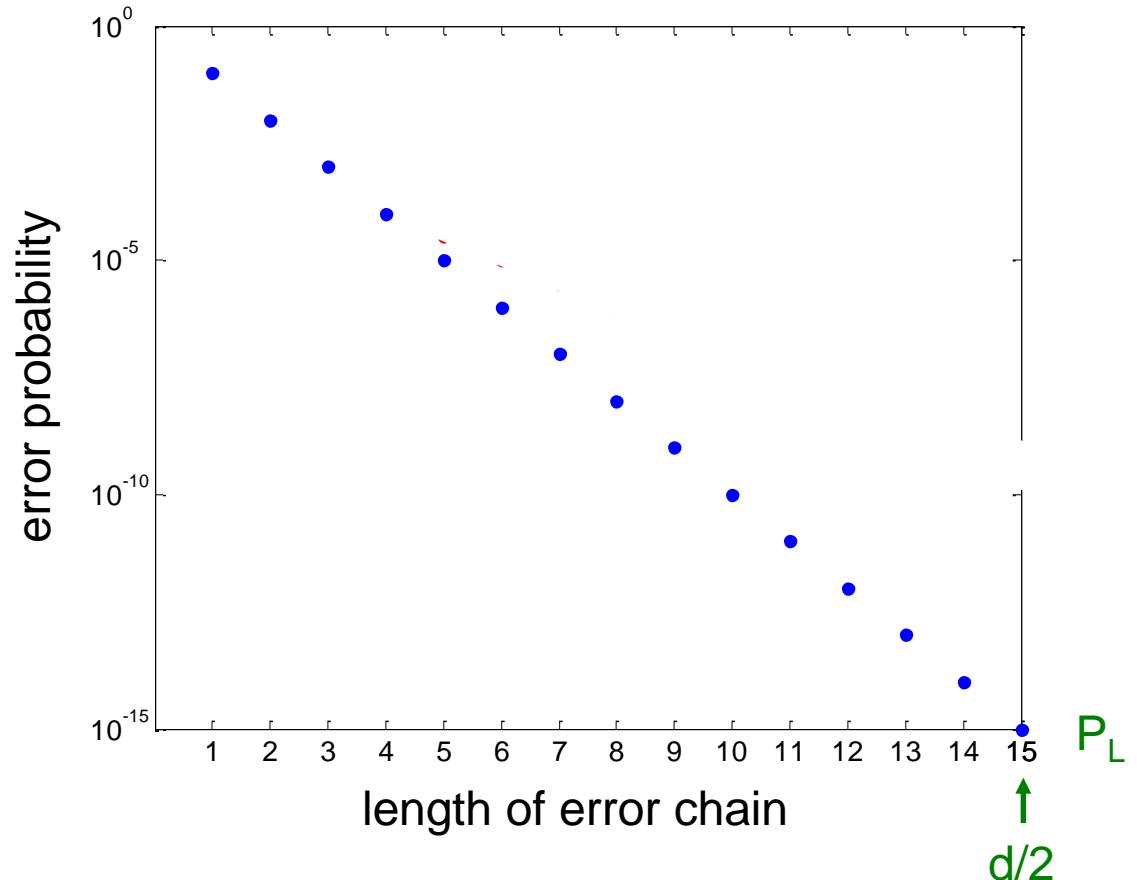


(1) Statistics of errors
indicates where and
type of errors

p_x, p_{xy}, \dots

(2) Higher probability
from correlated errors

How identify
correlated errors?



Example: CZ gate

Natural, fast, easy to characterize

$$CZ = \begin{pmatrix} |00\rangle & & & & |00\rangle \\ & 1 & & & \\ |01\rangle & \cdot & \cdot & \cdot & |01\rangle \\ & 1 & & & \\ |10\rangle & \cdot & \cdot & \cdot & |10\rangle \\ & & 1 & & \\ |11\rangle & \cdot & \cdot & \cdot & -1 \\ & & & & |11\rangle \end{pmatrix}$$

Do not care about phases
of **single** and **2-qubit** errors:

Just measure (small) prob's
to put in SC errors, e.g.
 $p_{IX}, p_{YI}, p_{XY}, p_{YY} \dots$

Measure accurately phases &
coherences of diagonal elements

For accuracy & get around single qubit fidelity errors,
is it possible to measure reduced process tomography?

(Still do full QPT to ensure huge error not obscured)

Architecture Design: Surface Code Cells

1) Figure of merit: size $\sim t_{\text{cycle}} (t_{\text{cycle}}/t_{\text{coh}})$ fast is important

Quantum Hardware: Shor Algorithm

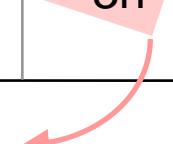
Limited by modular exponentiation

Need $\sim 40N^3$ Toffoli (qu-AND) gates

2048 bit number, for 0.1 of threshold:

2048	factoring size N
x3600	logical overhead
x30	A states for Toffoli
220M	physical qubits (1day)

Number of computational logical qubits	Sequential Toffoli gates	Total Toffoli gates	physical qubits		run time			
			algor.	A gener.	10ns	1us	100us	gate 1ms cycle
serial	$2N$	$40N^3$	$40N^3$	15M	200M	1d	100d	30y
	$5N$	$600N^2$	$\mathcal{O}(N^3 \log N)$	37M	20B	10m	20h	70d
	$2N^2$	$15N(\log_2 N)^2$	$\mathcal{O}(N^3 \log^2 N)$	31B	20T	1s	2m	3h
parallel	$\mathcal{O}(N^3)$	$\mathcal{O}(\log^3 N)$	$\mathcal{O}(N^3 \log^3 N)$	~ constant				

$$\begin{aligned} \text{Size} &\sim (p/p_{th}) t_{cycle} \\ &\sim t_{cycle}^2 / t_{coh} \end{aligned}$$


Interesting example – quantum memory :

100x coherence time, 10x cycle time

Relative size = 1

Error detection: once below threshold, want to extract information quickly

Architecture Design: Surface Code Cells

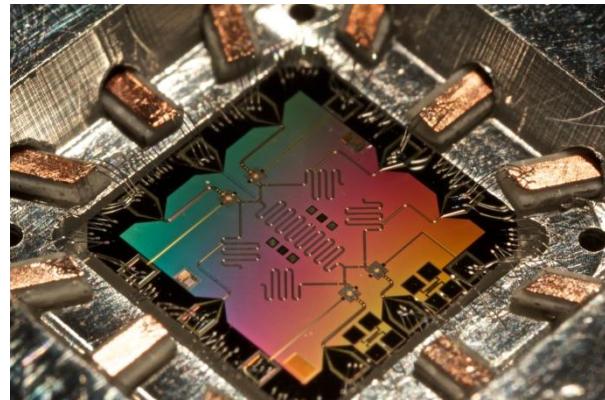
- 1) Figure of merit: size $\sim t_{\text{cycle}}$ ($t_{\text{cycle}}/t_{\text{coh}}$) fast is important
- 2) Global optimization: data qubit with NO decoherence, $p_{\text{th}} = 99\% \rightarrow 97\%$
- 3) Performance does not add trivially: 1 qubit exp. + 2 qubit exp. NOT scalable
Need interconnectivity
- 4) Quantum bus:



The quantum bus is
the smart car



- 5) Use ideas from the RezQu architecture



Conclusions

- 1) Compute χ_{err}
- 2) Need error probabilities, diagonal elements of χ_{err}
- 3) Full χ_{err} matrix not very useful; maybe for diagnostics
- 4) Are there alternative forms to quantify useful fidelity
based on direct measure of error probabilities?
- 5) Ready to test good qubits

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Aaron O'Connell
Matthew Neeley

Peter O'Malley
James Wenner
Jian Zhang
Michael Lenander
Erik Lucero

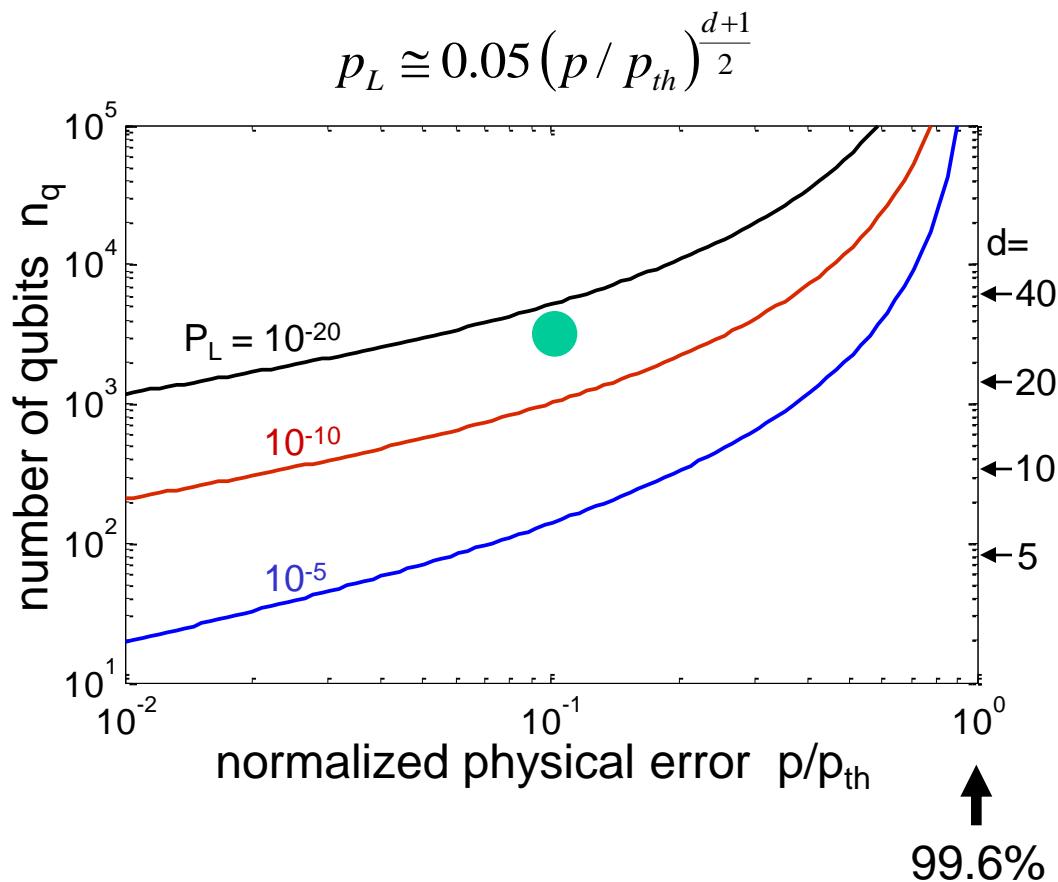
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(Yu Chen) (Josh Mutus) (Shunobu Ohya) (Andrew Dunsworth)
(Rami Barends) (Evan Jeffrey) (Jimmy Chen) (Ben Chiaro)
(Charles Neill) (Anthony Megrant)

Size of Logical Qubits



$p=99.9\%, n_q \sim 3000$
 $p=99.99\%, n_q \sim 600$

physical qubits per logical qubit