THE UNIVERSITY OF MELBOURNE

Large-Scale Entanglement on Physical Quantum Computers

By Gary J Mooney

THE UNIVERSITY OF MELBOURNE

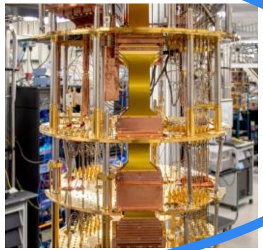
IBM Quantum Network Hub at the University of Melbourne

Noisy intermediate Scale Quantum (NISQ) Computing

Superconducting Qubits

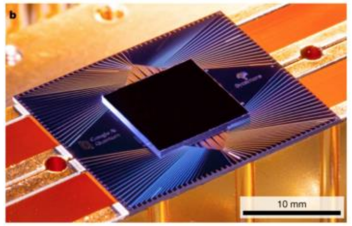
IBM

433q *Osprey* device



Google

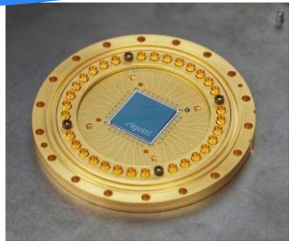
70q *Sycamore* processor



176q *Zuchongzhi-2* chip

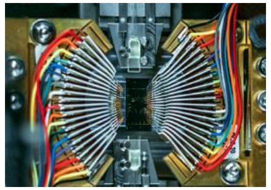
rigetti

84q *Ankaa-1* system



Photonic Qubits

XANADU



216q *Borealis* device

Neutral Atom

atom computing

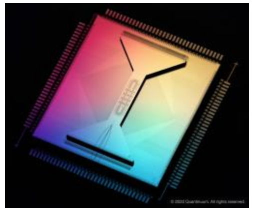
1,180q *Aquila* machine

Trapped Ion

IONQ

32q *Forte* device

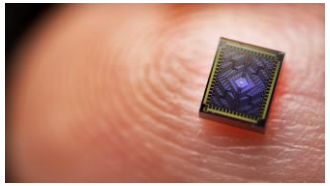
QUANTINUUM



32q *H2* device

Quantum Dot

intel



12q *Tunnel Falls* device

Benchmark devices: measure extent of quantumness

Overview

Benchmarking quantum devices

Forms of Multipartite Entanglement

- Bipartite and Genuine Multipartite entanglement

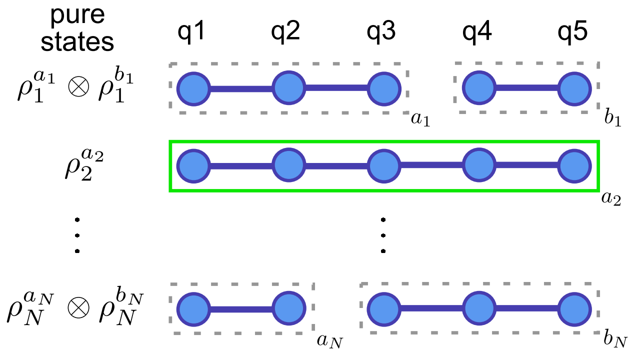
Detecting **Bipartite entanglement**

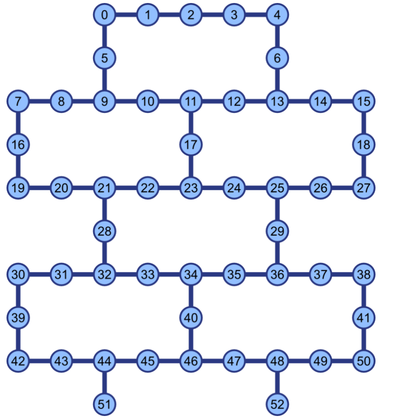
- By preparing Graph states on *IBM Quantum* devices

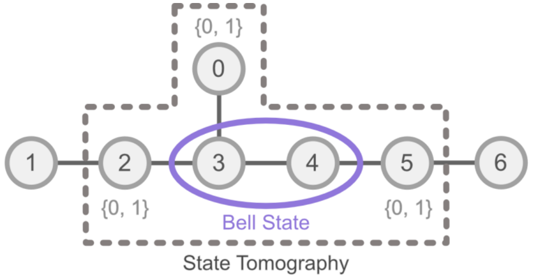
Detecting **Genuine multipartite entanglement**

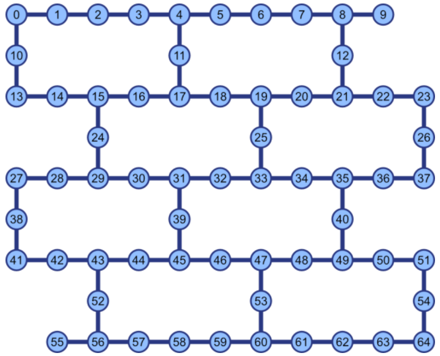
- By preparing GHZ states
- GHZ decoherence rates

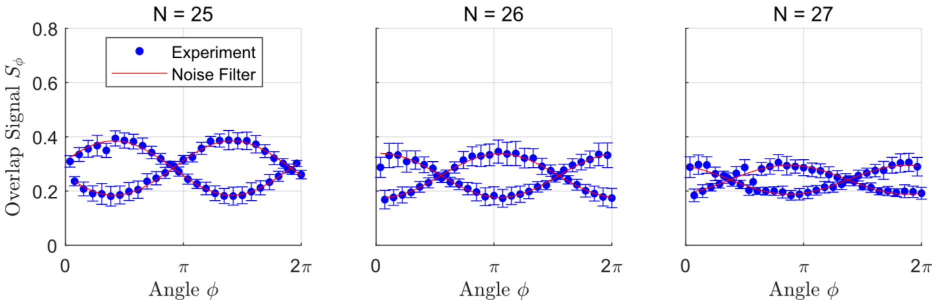
Bell state teleportation











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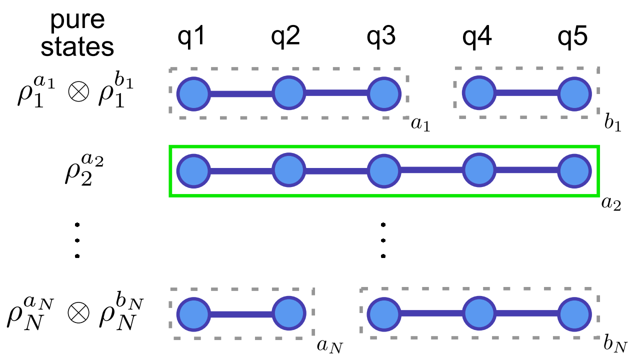
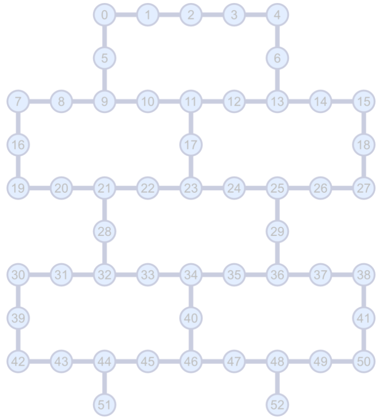
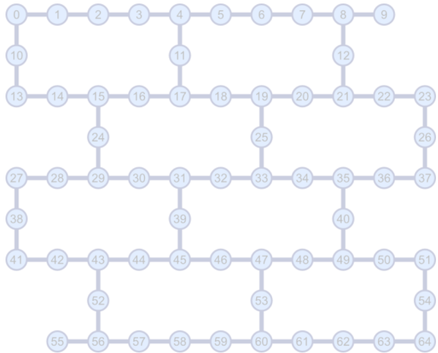
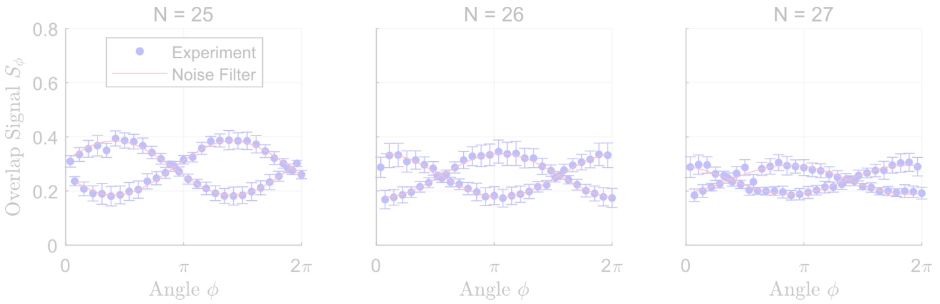








Pure State Entanglement - Definitions

- Entanglement
  - Non-classical correlations
  - State is not separable: $|\psi\rangle \neq |\phi_1\rangle \otimes |\phi_2\rangle$, for any $|\phi_1\rangle$ and $|\phi_2\rangle$
    - State is entangled

- Multiqubit Entanglement
  - A **multiqubit state** either:
    - “**is** fully bipartite entangled”
      - (aka “is entangled”)
    - “**contains** bipartite entanglement”

Qubit energy levels

$$|\mathrm{Bell}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Entanglement graph

$$|GHZ\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}$$

Fully Bipartite Entangled (aka entangled)

$$|\psi\rangle = \frac{(|00\rangle + |11\rangle)|0\rangle}{\sqrt{2}}$$

Contains Bipartite Entanglement

Bipartition {0} and {1,2}: Entangled
Bipartition {0,1} and {2}: Separable

What is Mixed State Entanglement?

Real quantum device → Noise

- Quantum state is a **Mixed state**: probabilistic mixture of pure states
- More complicated than pure states

Mixed State

$$\rho = \sum_{i=1}^{N} p_i \rho_i \qquad \rho = \begin{pmatrix} a_{1,1} & \cdots & a_{1,2^N} \\ \vdots & \ddots & \vdots \\ a_{2^N,1} & \cdots & a_{2^N 2^N} \end{pmatrix}$$

Pure states ρ_i

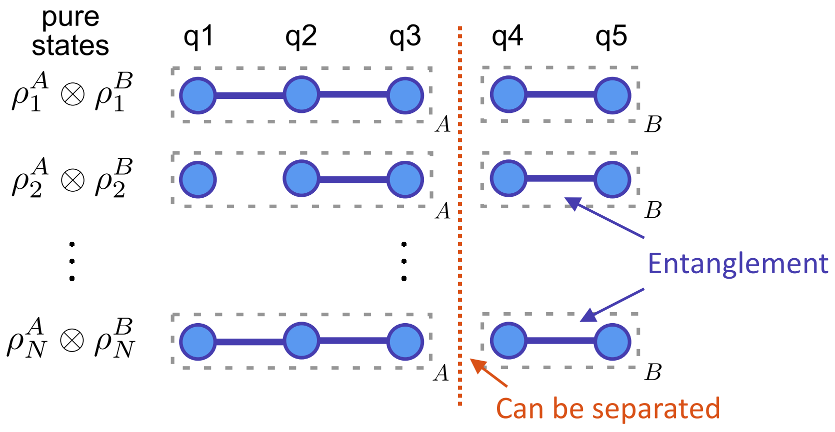
Density matrix ρ

Probabilities p_i

Quantum Theory: Concepts and Methods, (1993)

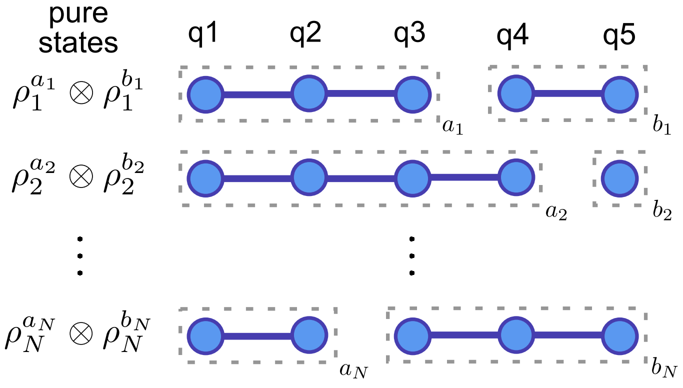
Separable

$\rho = \rho^A \otimes \rho^B$ (fixed bipartition A and B)



Bipartite Entangled (or just Entangled)

- State is **not separable**, i.e. $\rho \neq \rho^A \otimes \rho^B$, for all bipartitions A and B
- Although, individual pure states ρ_i might be separable



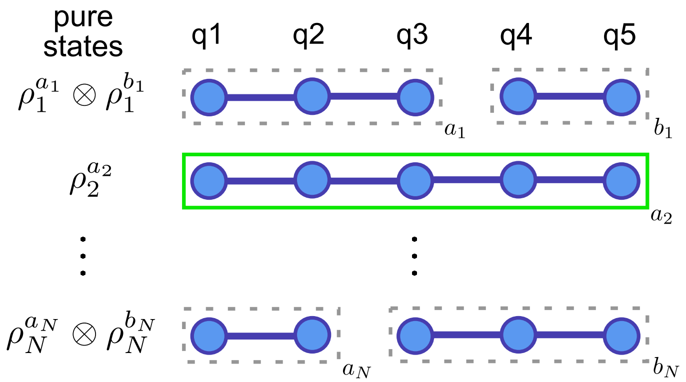
Overlapping regions of entanglement.

Entanglement across all qubits

Mooney, Hill and Hollenberg, Sci. Rep. (2019)

Genuine Multipartite Entangled (GME)

- Stronger form of entanglement
- There is always a fully entangled pure state



GME states are always fully bipartite entangled

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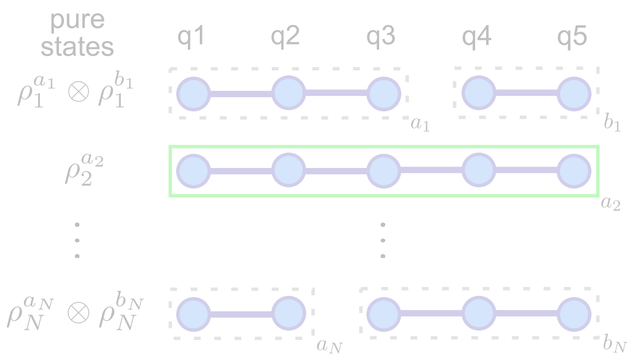
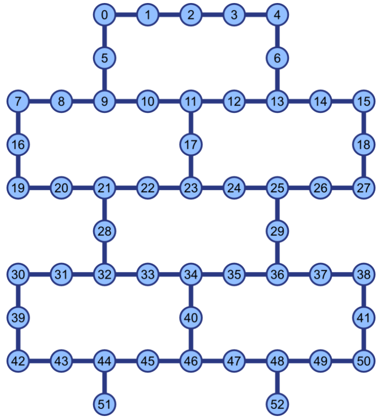
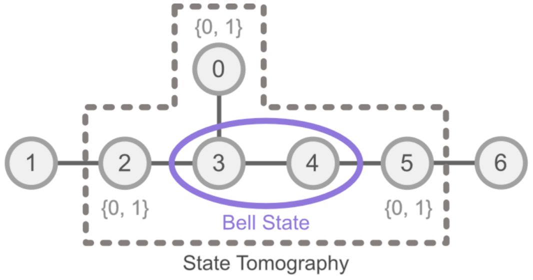
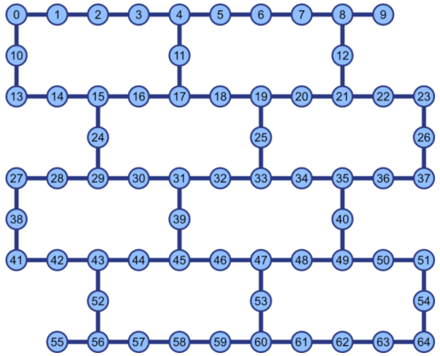
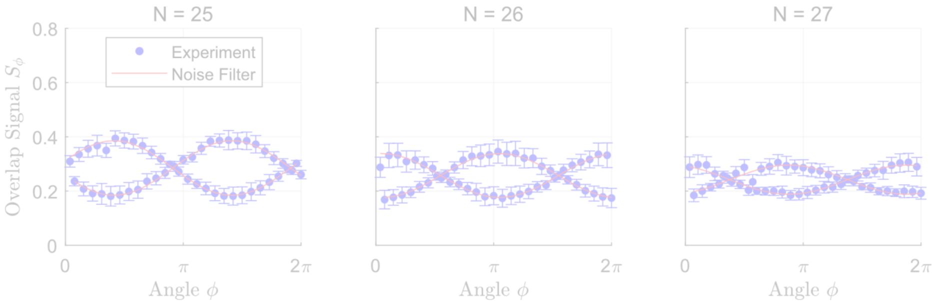










Graph States

➢ Choose a quantum state to prepare

$$|G_n\rangle = \prod_{(\alpha,\beta)\in E} \mathrm{CZ}^{\alpha}_{\beta} |+\rangle^{\otimes \mathrm{n}}$$

$E :=$ (edge set)

Controlled-phase gate

Graph State (Cluster State)

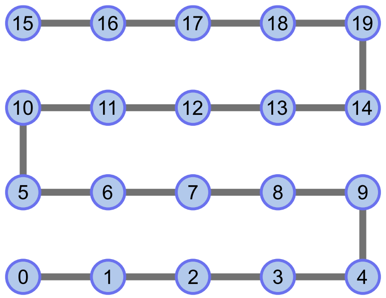
- Robust to noise — Briegel and Raussendorf, Phys. Rev. Lett. (2001)
  - Requires $n/2$ local measurements to disentangle
- Low circuit depth
- Convenient for detecting bipartite entanglement

- Applications
  - One-way quantum computing — Raussendorf and Briegel, Phys. Rev. Lett. (2001); Kitaev, arXiv. (1997)
  - Fault-tolerant error correction — Raussendorf, Harrington, Goyal, New Journal of Physics. (2007)
  - Measurement-Based variational quantum eigensolver — Ferguson, Phys. Rev. Lett. (2021)

How do we detect entanglement?

Defined on a graph

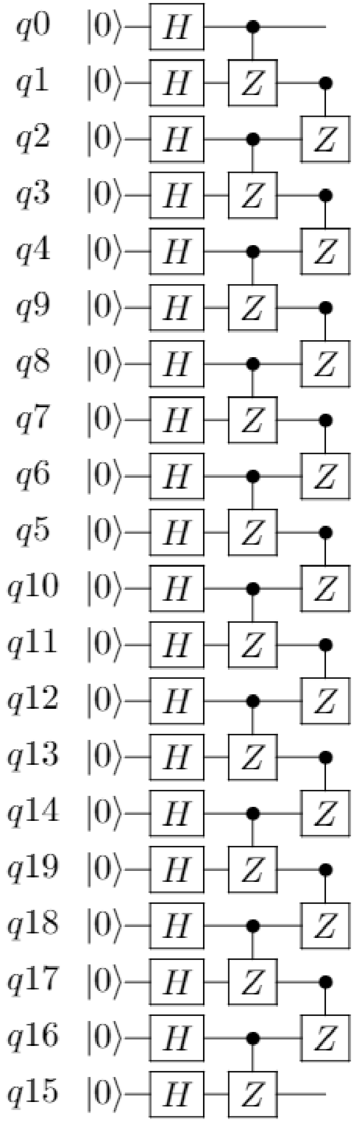
Graph representation



20-qubit line graph state

Preparation

Circuit representation

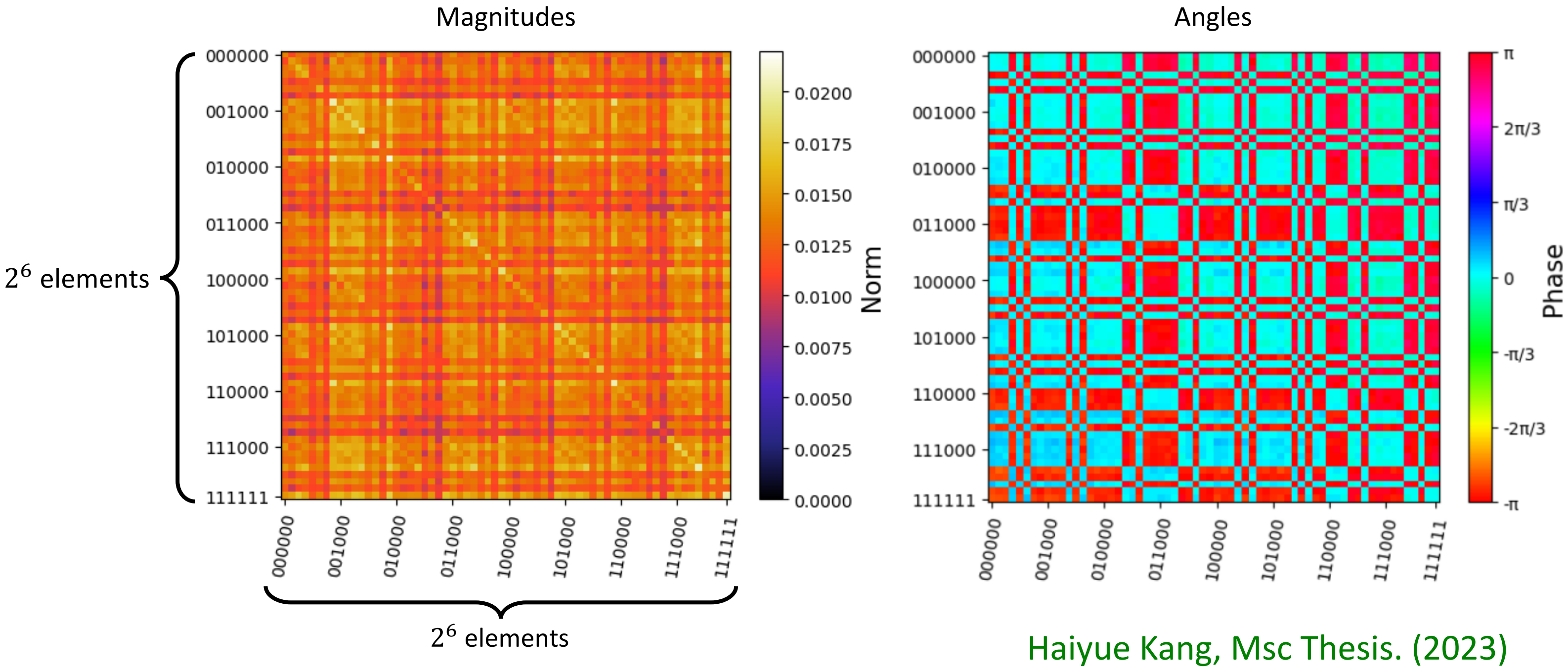


Full Quantum State Tomography

Quantum State Tomography (QST)

- Get a **density matrix**, encapsulating noise
  - $2^N \times 2^N$ complex matrix
- Analyse entanglement properties

6-qubit density matrix



Haiyue Kang, Msc Thesis. (2023)

Full quantum state information

- ➢ Can be overkill for measuring a particular property
- ➢ Use a detection strategy

<u>Requires 3^N circuits</u>
6 qubits: 729 circuits
10 qubits: ~59,000 circuits
20 qubits: ~3.5 Billion circuits!

Requires 3^N basis measurements

1 day ≈ 15-30k circuits (approx)

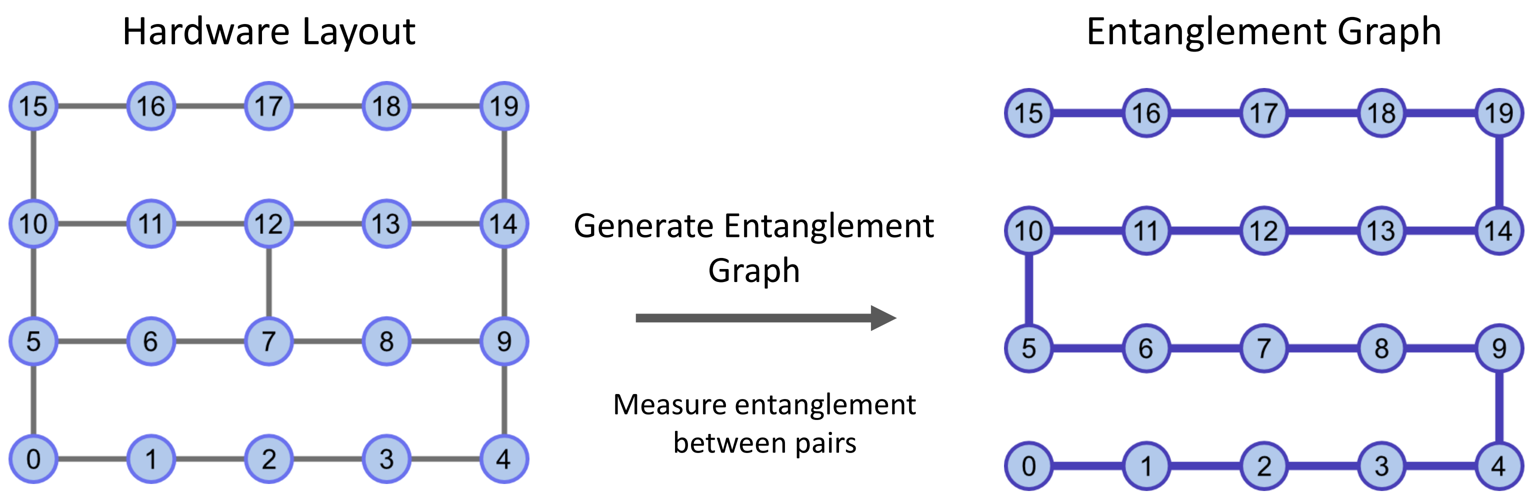
Detection Strategy – Show Non-Separability

Focus on bipartite entanglement

<u>Detection Strategy</u>

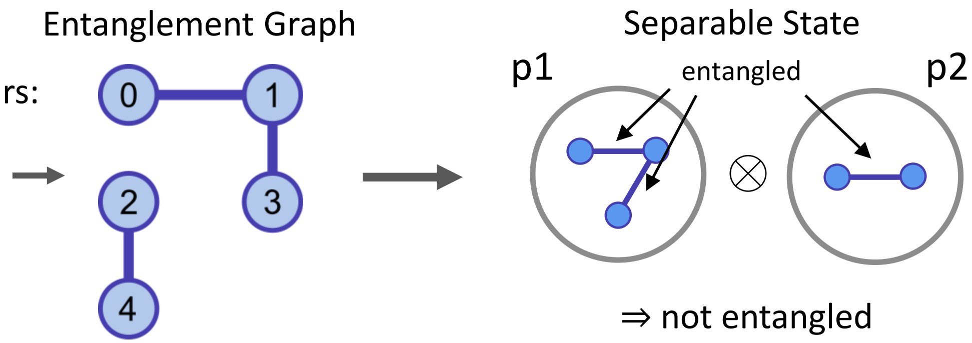
- State is **not separable**
  ⇒ State is at least **bipartite entangled**

1. Generate **entanglement graph**
   – Measure entanglement between qubit pairs
2. Is entanglement graph **connected**?



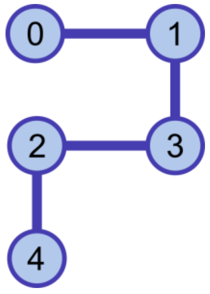
Example: Separable State

Entangled pairs:
(0, 1)
(1, 3)
(2, 4)



⇒ not entangled

So if **connected**, then **entangled**



⇒ entangled

<u>On Quantum Devices</u>
To show:
entanglement graph is connected

Detecting 2-Qubit Entanglement

Perform state tomography on qubit pair and their neighbours

Graph State Property:

Project neighbouring qubits to Z-basis states → Bell state (up to local operations)

- Bell states produced from combinations of states $\{0,1\}^{\#(neighbours)}$:

$$
\begin{aligned}
H \otimes I|\Phi^+\rangle &= (|00\rangle + |01\rangle + |10\rangle - |11\rangle) \,/\, 2 \\
H \otimes X|\Phi^+\rangle &= (|00\rangle + |01\rangle - |10\rangle + |11\rangle) \,/\, 2 \\
XH \otimes I|\Phi^+\rangle &= (|00\rangle - |01\rangle + |10\rangle + |11\rangle) \,/\, 2 \\
XH \otimes X|\Phi^+\rangle &= (|00\rangle - |01\rangle - |10\rangle - |11\rangle) \,/\, 2
\end{aligned}
$$

One of 4 Bell states (up to local operations)

Calculate entanglement for each set of states $\{0,1\}^{\#(neighbours)}$

Negativity of partial transpose

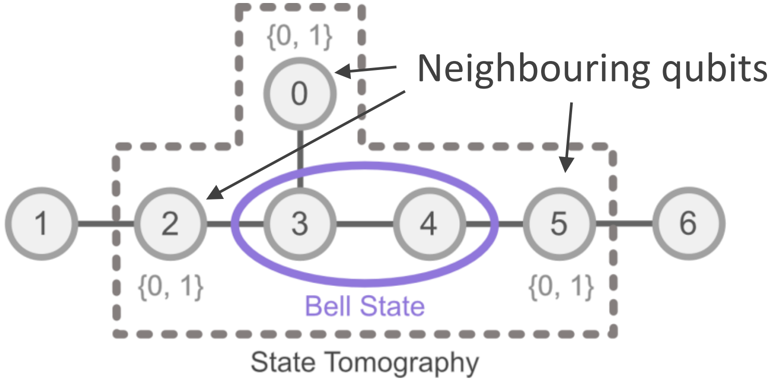
- Calculate → Sum over magnitudes of negative eigenvalues of $\rho_{3,4}^{T_4}$
- For **Two Qubits**: Non-zero negativity is **necessary** and **sufficient**
  - **Negativity is non-zero ↔ Entanglement** Horodecki, Horodecki and Horodecki, Phys. Lett. A. (1996)

Measure negativity for all neighbour states: $\{0,1\}^{\#(neighbours)}$

→ Extent of entanglement is the largest negativity (among the combinations)

<u>Example</u>

Entanglement detection between qubits 3 and 4



Make physical

Michelot, J. Opim. Theory Appl. (1986)

Negativity

$$\mathcal{N}(\rho_{3,4}^{T_4}) = \sum_{\lambda_i < 0} |\lambda_i|$$

Negative eigenvalues of $\rho_{3,4}^{T_4}$

Wang et. al. npj Quantum Information (2018)

Results: Negativities on an *IBM Quantum* device

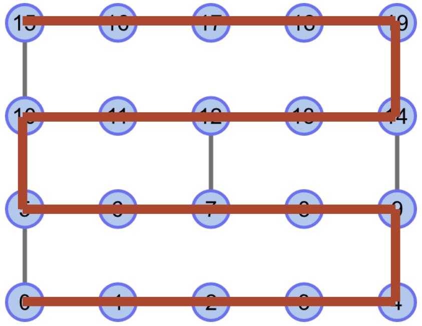
Apply these techniques on an IBM Quantum computer: the **20-qubit** *ibmq_poughkeepsie* device

→ Embed a line graph state

→ Generate entanglement graph

Hardware Layout

20-qubit *ibmq_poughkeepsie* device



Error rates:

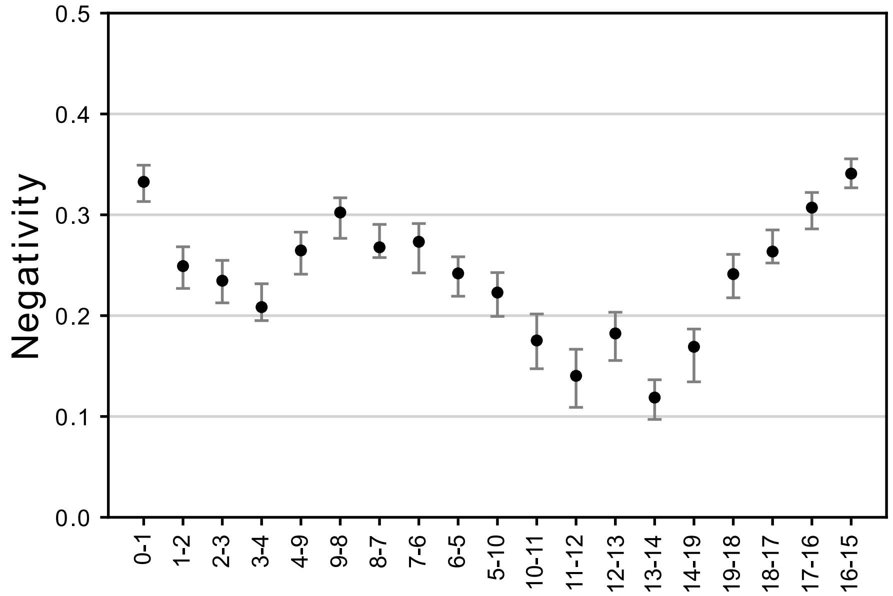
Readout: 3.8%, $\sigma = 1.6\%$

CNOT: 2.3%, $\sigma = 0.8\%$

Decoherence times:

- $T_1 = \sim 100\ \mu s$ (relaxation)
- $T_2 = \sim 100\ \mu s$ (dephasing)

Entanglement in *ibmq_poughkeepsie* device



Maximally entangled

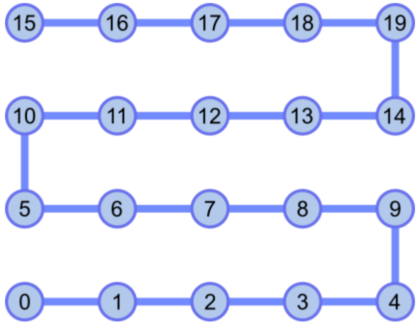
Higher Entanglement

No entanglement

Mooney, Hill and Hollenberg, Sci. Rep. (2019)

Entanglement Graph

(all qubits connected)



State is bipartite entangled

Scale up to larger devices

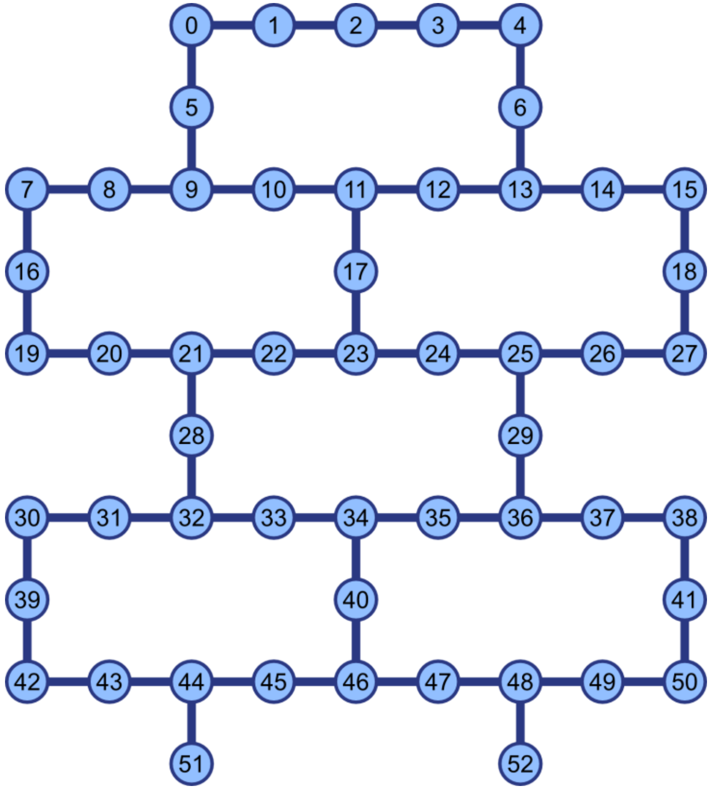
- Whole device is bipartite entangled
- At the time → largest quantum entangled state (on a universal quantum computer)
- Previous record was 16 qubits Wang et. al. npj Quantum Information (2018)

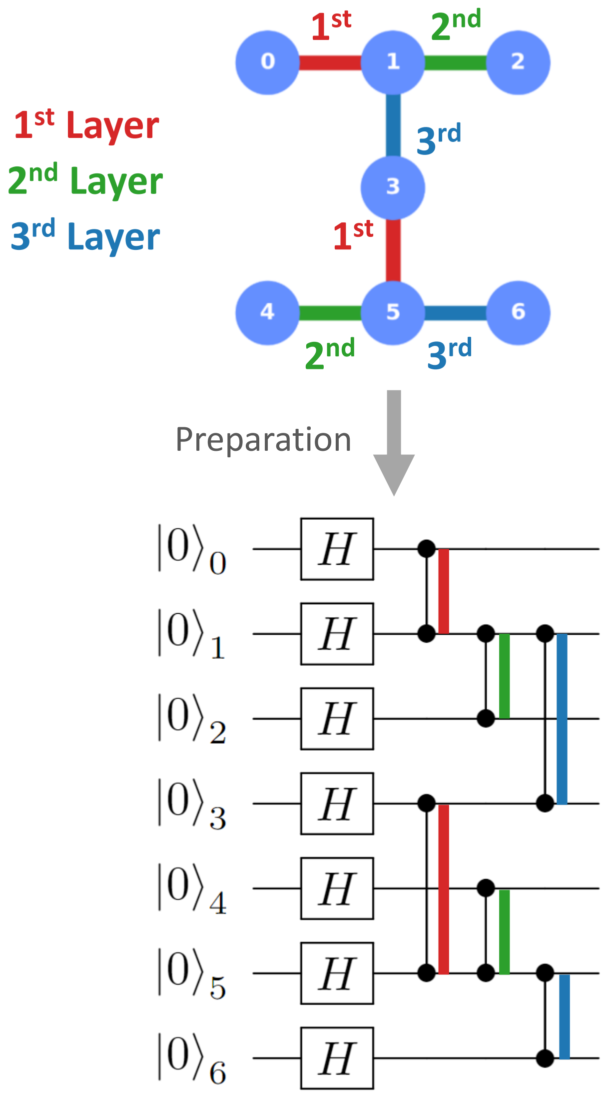
Native Graph State

Native graph state: match the hardware layout

- Benchmark qubit pairs
- More connected cycles
  - ➢ Requires more separable pairs to break connectedness
- Still constant circuit depth
  - ➢ Depth = largest neighbour count of qubits

Hardware Layout
53-qubits





3 Layers of 2-qubit gates

Constant depth → largest neighbour count of qubits

Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)

Quantum Readout-Error Mitigation (QREM)

- Readout assignment errors:
  - Obfuscates quantum data
  - State **appears less entangled** than it is

Calibrate readout-errors with stochastic matrix A:

$$A\vec{p} = \vec{p}_{\text{noisy}}$$

$$\rightarrow \vec{p} = A^{-1}\vec{p}_{\text{noisy}}$$

$$A = \bigotimes_{i=1}^{N} A_i \qquad A_i = \begin{pmatrix} p_i(0|0) & p_i(0|1) \\ p_i(1|0) & p_i(1|1) \end{pmatrix}$$

Calibration matrix for qubit i

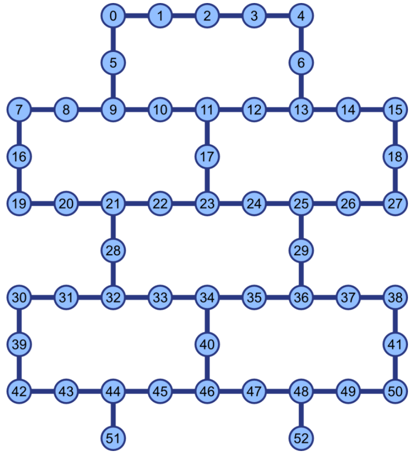
Requires only 2 measurements $\{|00\ldots0\rangle,\ |11\ldots1\rangle\}$

$$A^{-1} = \bigotimes_{i=1}^{N} A_i^{-1}$$

- Efficient application
  - Apply each qubit calibration matrix separately, zeroing small probabilities Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)
  - M3 python package Nation et al. PRX Quantum (2021)
- Make physical Smolin et al. Phys. Rev. Lett. (2012)

Results: Newer IBM Quantum devices

53-qubit *ibmq_rochester* device

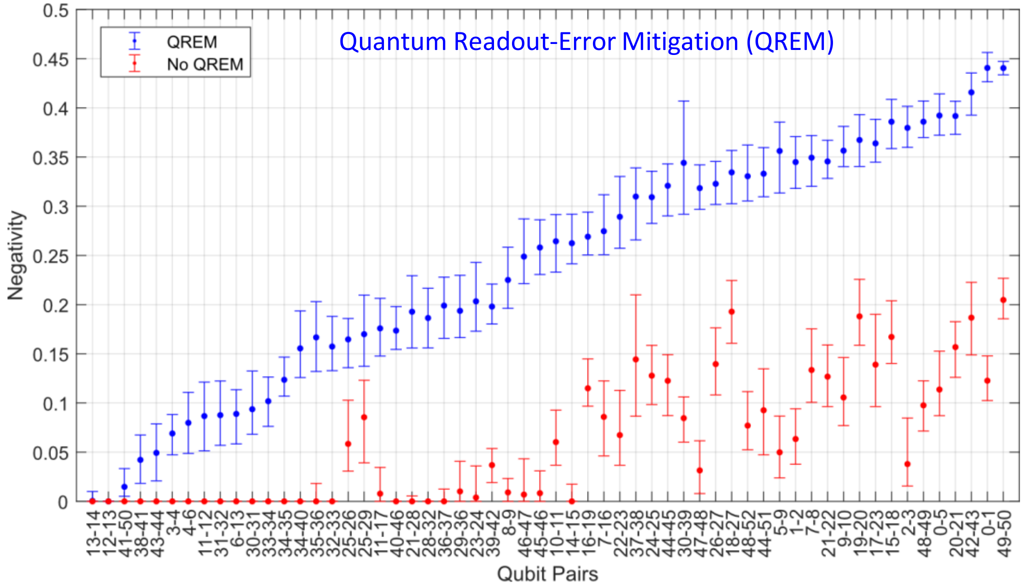


Error Rates:

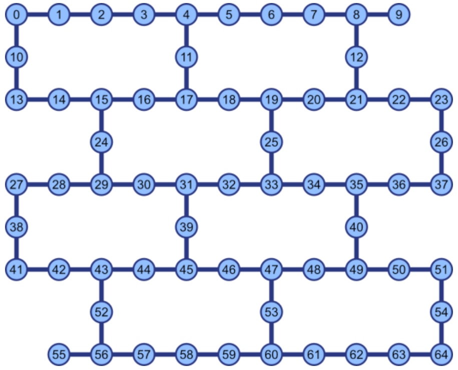
- Readout: 12.6%, $\sigma = 9.3\%$
- CNOT: 4.6%, $\sigma = 2.4\%$

Decoherence Times:

- $T_1 = \sim 53\ \mu s$ (relaxation)
- $T_2 = \sim 53\ \mu s$ (dephasing)



65-qubit *ibmq_manhattan* device

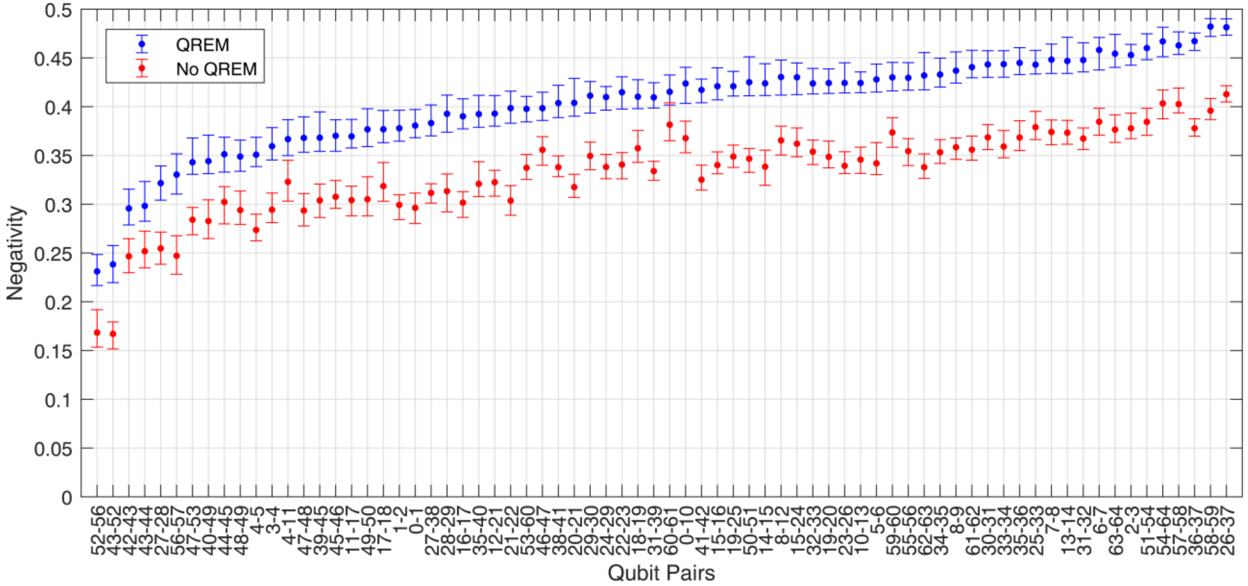


Error Rates:

- Readout: 2.1%, $\sigma = 1.5\%$
- CNOT: 1.5%, $\sigma = 0.6\%$

Decoherence Times:

- $T_1 = \sim 60\ \mu s$ (relaxation)
- $T_2 = \sim 78\ \mu s$ (dephasing)



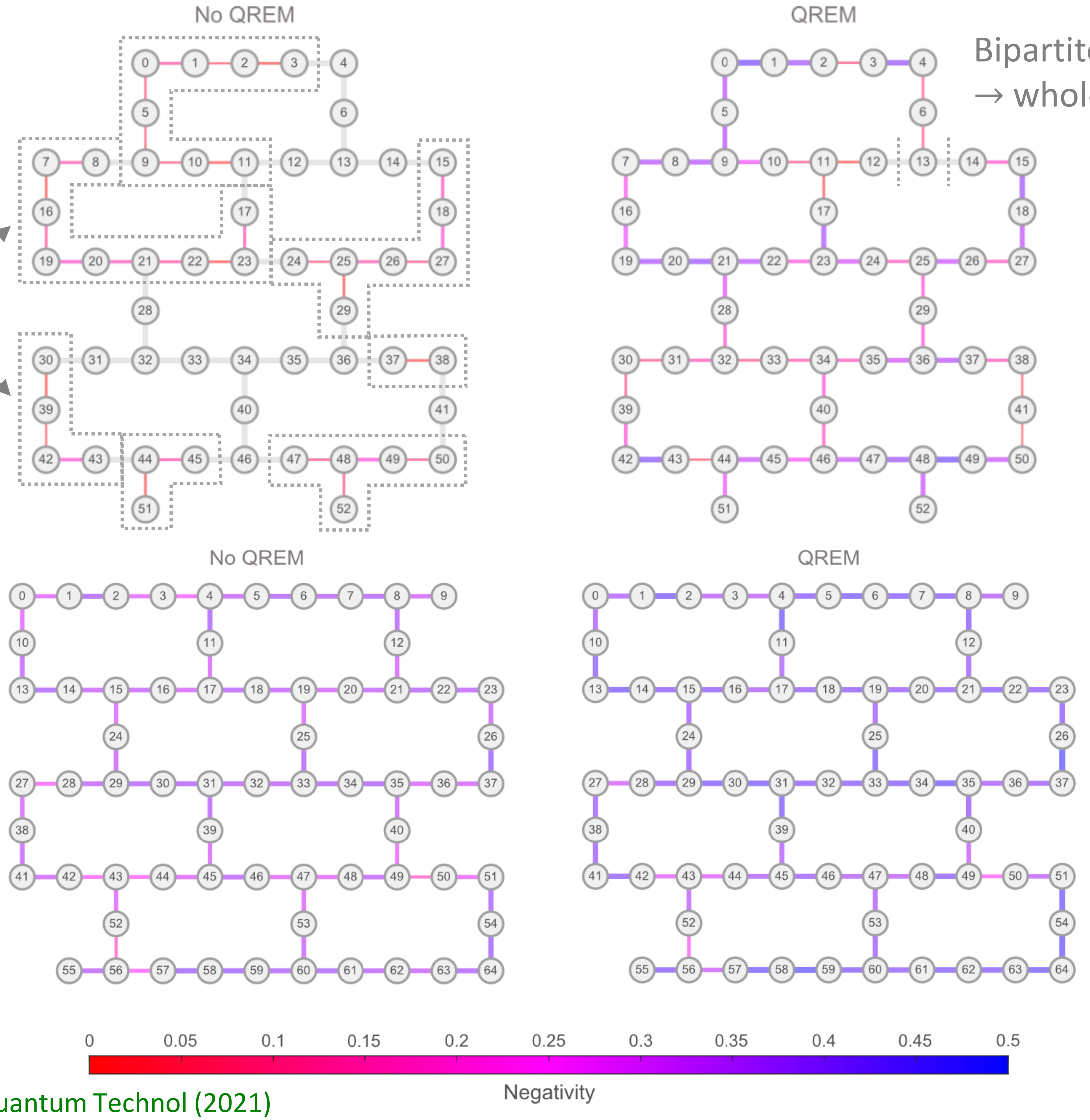
Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)

Results: Entanglement Graphs

53-qubit ibmq_*rochester* device

Bipartite entangled regions

Bipartite entangled region
→ whole device



<u>53 qubits</u>

→ Whole-device
bipartite entanglement

65-qubit ibmq_m*anhattan* device

<u>65 qubits</u>

→ Whole-device
bipartite entanglement

Scale up to larger devices

Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)

Let’s Look at the Required Resources

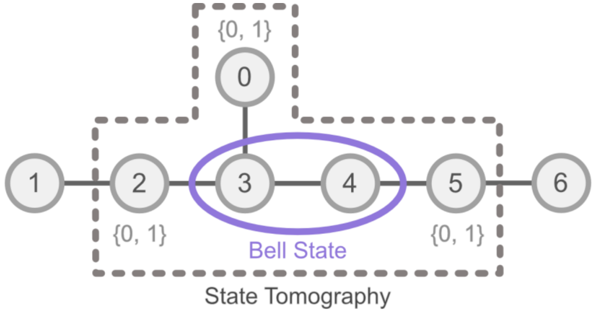
Quantum State Tomography on Each Pair

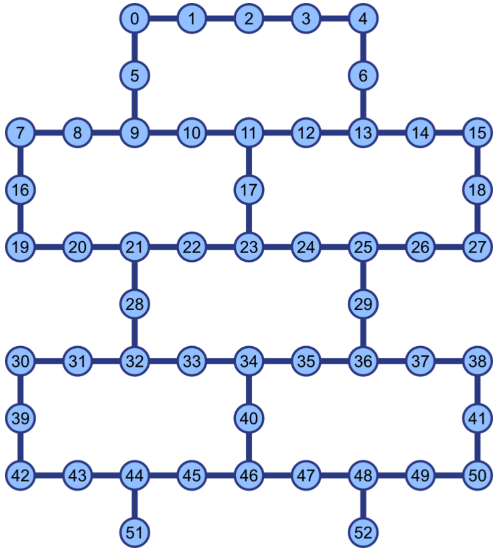
Requires 3^N

$N = 4$ qubits $\rightarrow 3^4 = 81$ circuits (~350k shots*)

$N = 5$ qubits $\rightarrow 3^5 = 243$ circuits (~1 Million shots*)

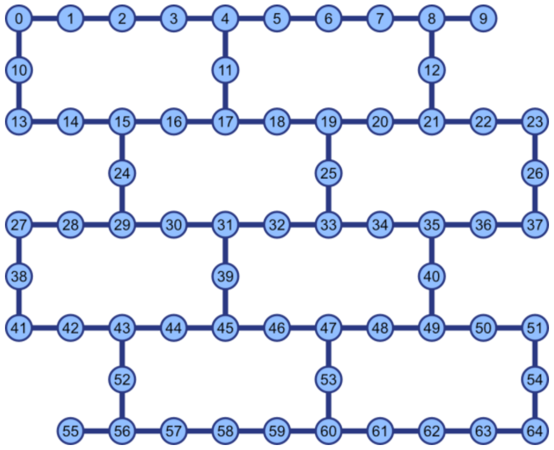
* at ~4000 shots each





53-qubit Rochester:

- 58 qubit pairs
  - ➢ **~11,000 circuits**
  - ➢ Or ~44 Million shots



65-qubit Manhattan:

- 72 qubit pairs
  - ➢ **~14,000 circuits!**
  - ➢ Or ~56 Million shots!

Could take a **whole day** to complete

- Was barely executing within device calibration cycles

We need to go higher

Target: 127-qubit *ibm_washington* device

127-qubit Washington:

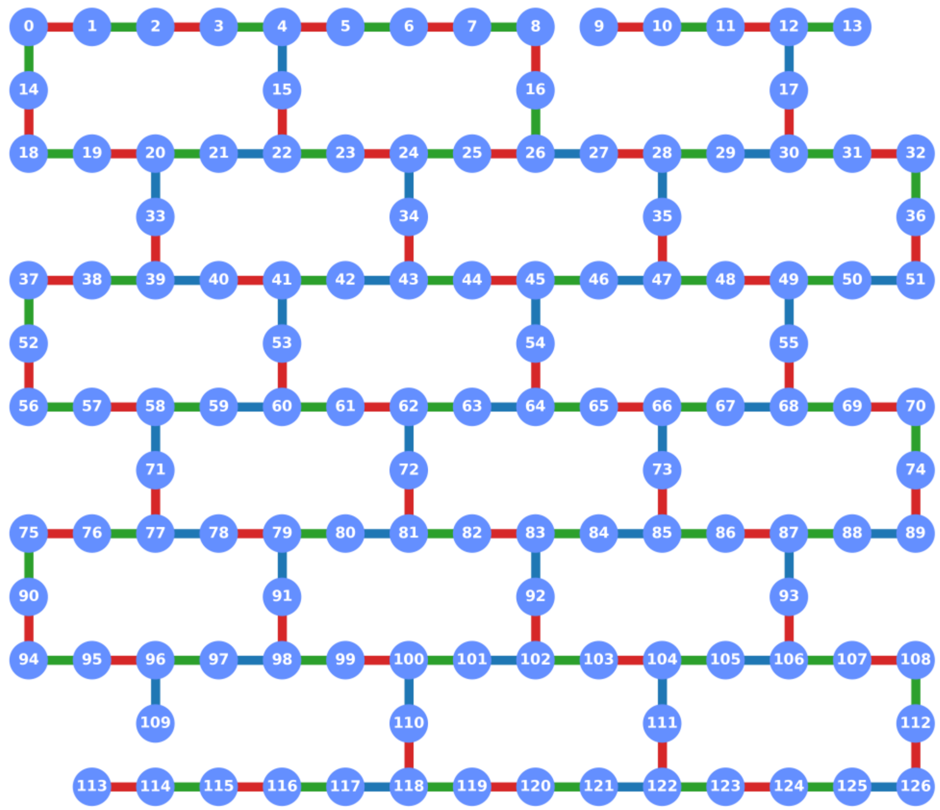
- 142 pairs of qubits
  - **$\sim 28,000$ circuits**
  - Or $\sim$112 Million shots!
  - Error bars: x8 more

How to reduce this?

Two Optimisation Techniques

1. Neighbour-state bucketing
2. Parallel Quantum State Tomography

127-qubit *ibm_washington* device



Error Rates:

- Readout: 2.3%, $\sigma = 2.8\%$
- CNOT: 0.8%

Decoherence Times:

- $T_1 = \sim 240\ \mu s$ (relaxation)
- $T_2 = \sim 142\ \mu s$ (dephasing)

Optimisation 1: Neighbour-State Bucketing

Currently

- Tomography on qubit pair and neighbours (4 or 5 qubits)

➢ 5 qubits → requires 3^5 = **243 circuits per pair**

However

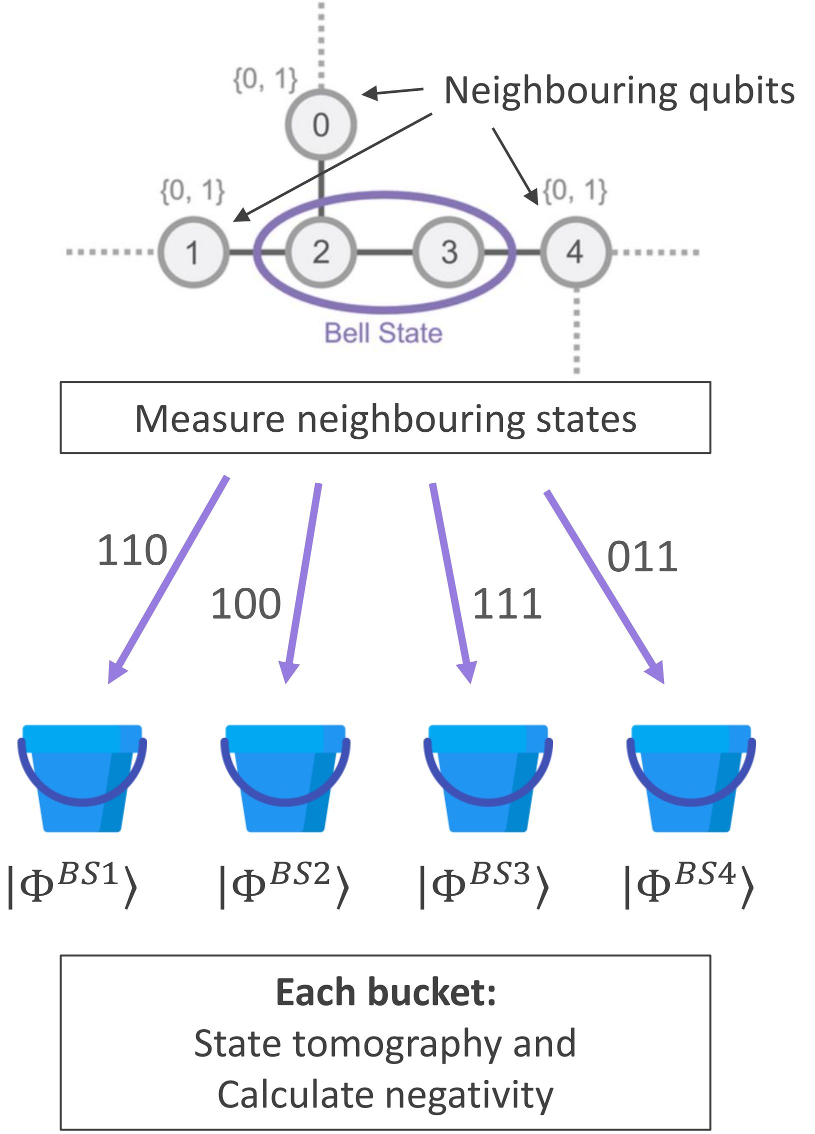
- Projecting neighbours only ever results in 1 of 4 Bell state variations

1. $|\Phi^{BS1}\rangle \equiv H \otimes I|\Phi^+\rangle = (|00\rangle + |01\rangle + |10\rangle - |11\rangle) / 2$
2. $|\Phi^{BS2}\rangle \equiv H \otimes X|\Phi^+\rangle = (|00\rangle + |01\rangle - |10\rangle + |11\rangle) / 2$
3. $|\Phi^{BS3}\rangle \equiv XH \otimes I|\Phi^+\rangle = (|00\rangle - |01\rangle + |10\rangle + |11\rangle) / 2$
4. $|\Phi^{BS4}\rangle \equiv XH \otimes X|\Phi^+\rangle = (|00\rangle - |01\rangle - |10\rangle - |11\rangle) / 2$

- Bucket based on obtained Bell state
- Perform 2-qubit tomography

- Requires only 3^2 = **9 circuits per pair**

- **127-qubit Washington:**
  - From ~28,000 circuits
    - ➢ down to **1,278 circuits!**
    - ➢ A factor of 22 saving



John F. Kam, et. al., paper in preparation

Optimisation 2: Parallel Quantum State Tomography

Currently
- Tomography on each qubit pair separately

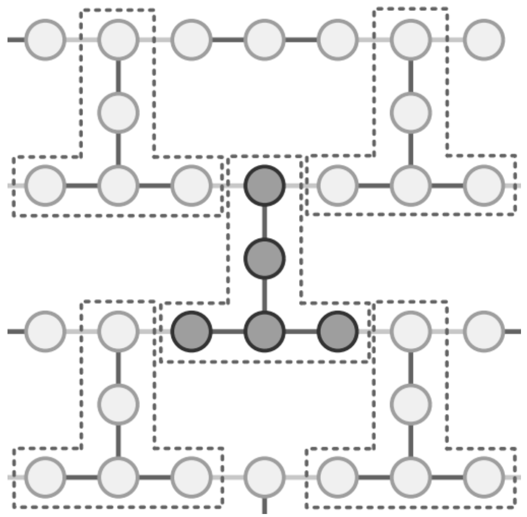
Instead
- Perform in parallel on non-overlapping sets of qubit-pairs and their neighbours

- Only need up to **8 rounds** for IBM Quantum heavy-hexagonal layouts
  - Using layout-agnostic greedy algorithm
- Can reduce to **4 rounds** when sharing neighbours

- **127-qubit Washington:**
  - Originally ~28,000 circuits
  - Then 1,278 circuits (neighbour-state bucketing)
    - ➢ down to **constant 36 circuits!** (Parallel-QST)

- 36 circuits for all heavy hex layouts

Hardware Layout

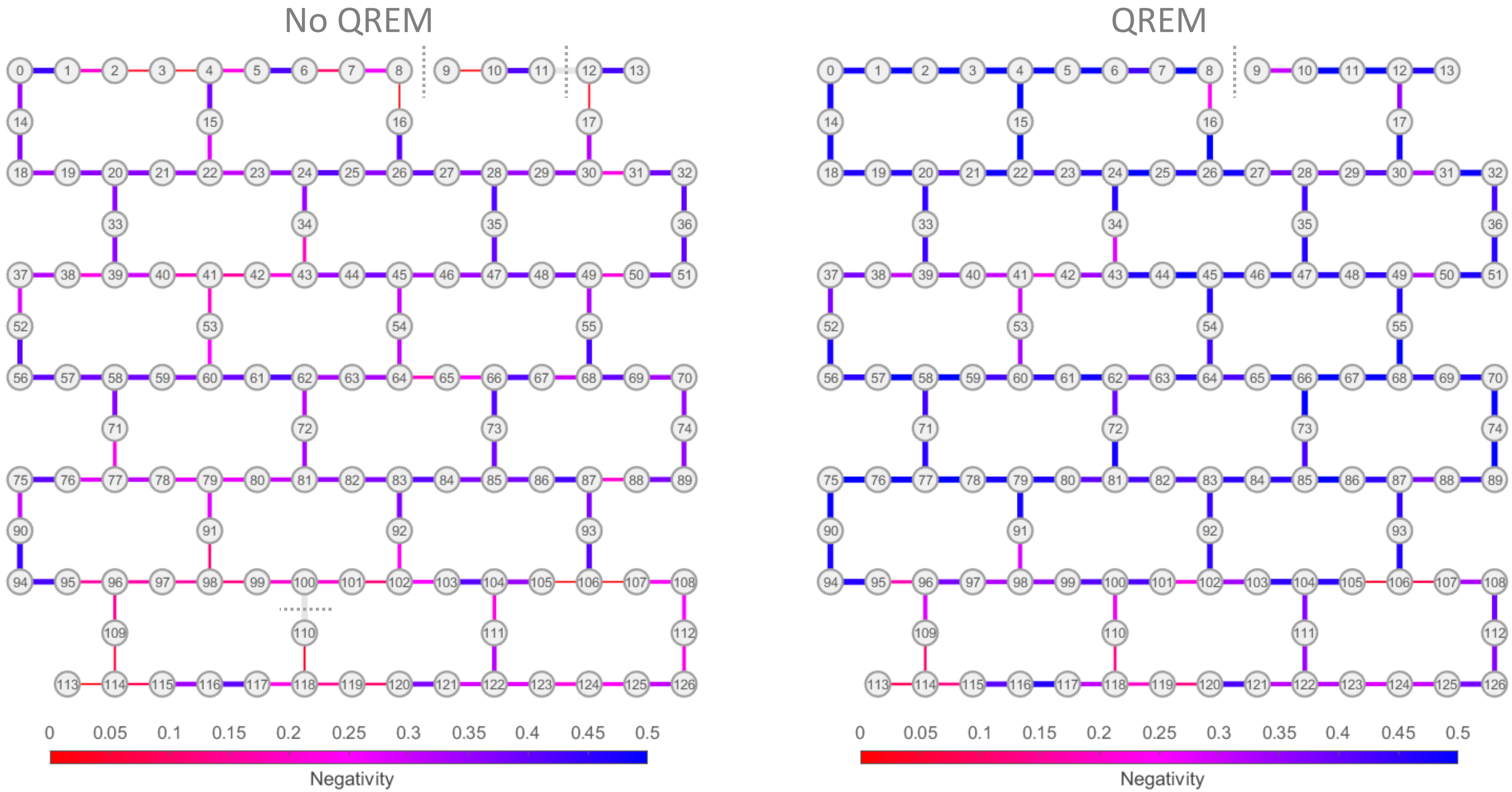


non-overlapping regions performed in parallel

John F. Kam, et. al., paper in preparation

Results: 127-qubit ***ibm_washington*** Device

127-qubit *ibm_washington* device



<u>127 qubits</u>

→ Whole-device bipartite entanglement

John Fidel Kam *et al.*,
(paper in production)

Latest: 433-qubit *ibm_seattle* Device

Device (*ibm_seattle*):

- 19 inactive qubits
- 433 → 414 active qubits

Error rates (mean):

- Readout: 7.6%, $\sigma = 7.4\%$
- CNOT: 2.9%, $\sigma = 3.4\%$

Decoherence times:

- $T_1 = \sim 90\ \mu s$ (relaxation)
- $T_2 = \sim 60\ \mu s$ (dephasing)

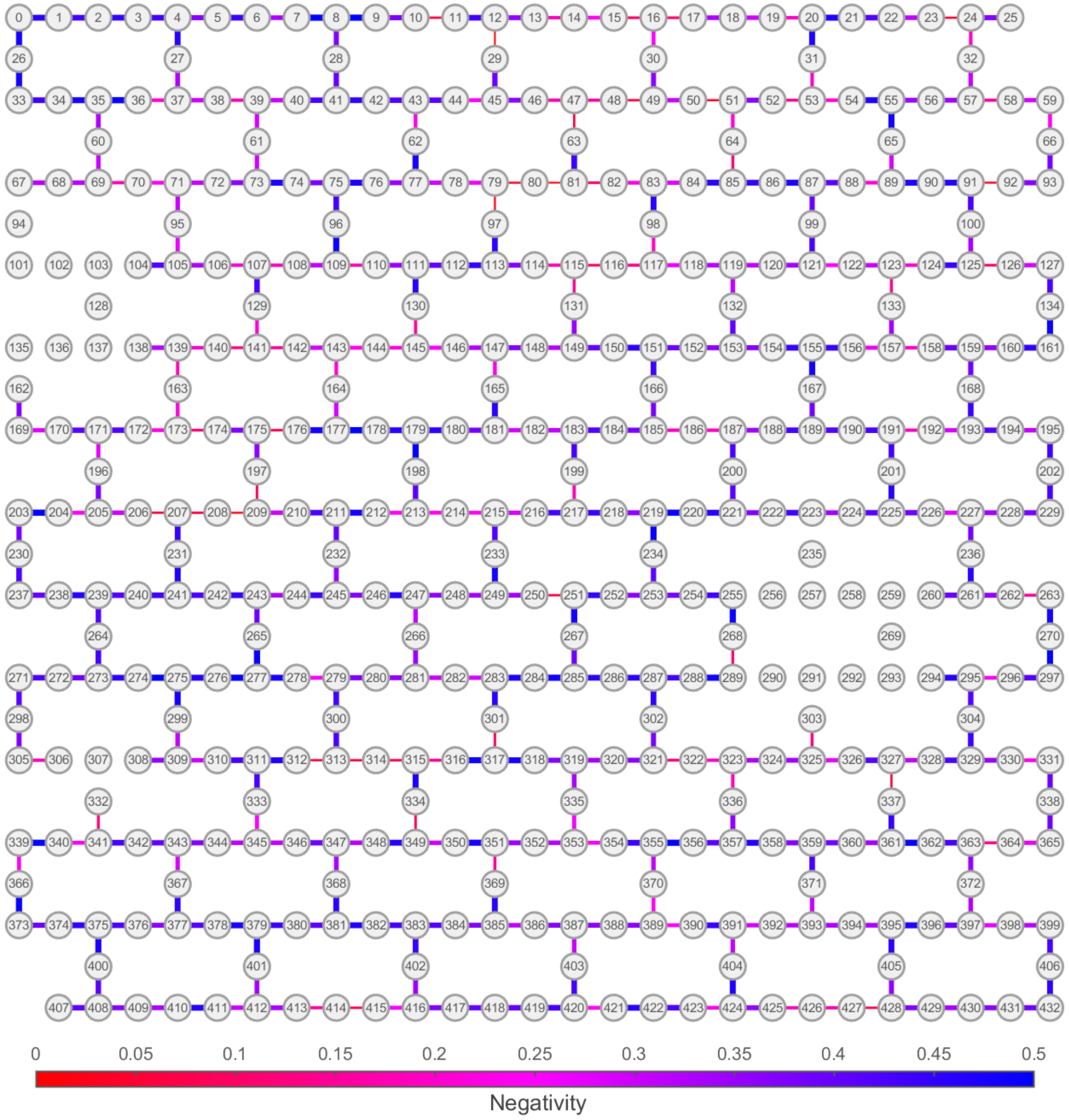
Experiment:

Originally $\sim 100{,}000$ circuits

➢ down to **36 circuits!**

Result:

- Graph state is bipartite entangled
- All active qubits

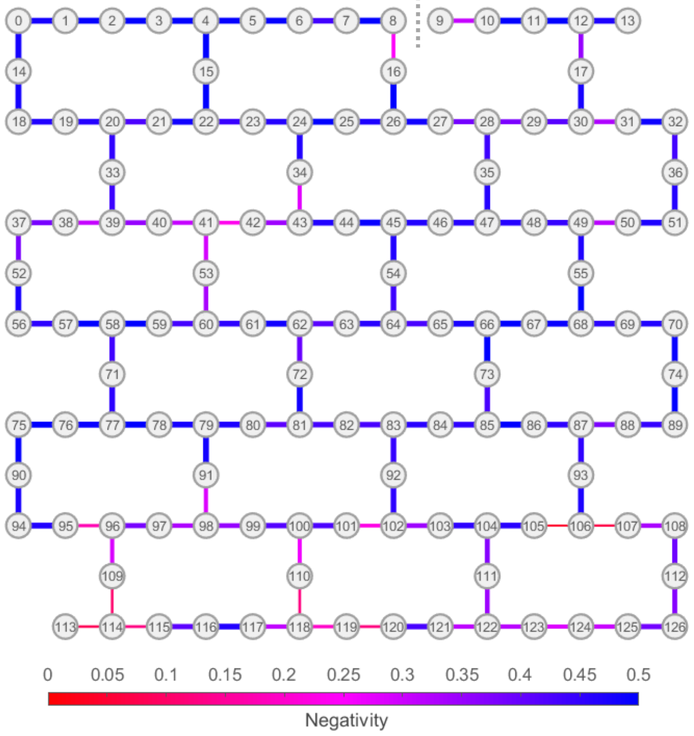


John Fidel Kam *et al.*,
(paper in production)

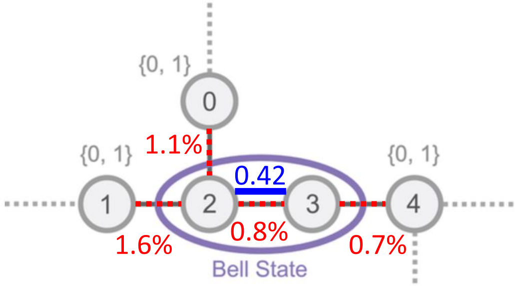
Relation to physical device

Benchmark: how does it relate to device?

127-qubit *ibm_washington*



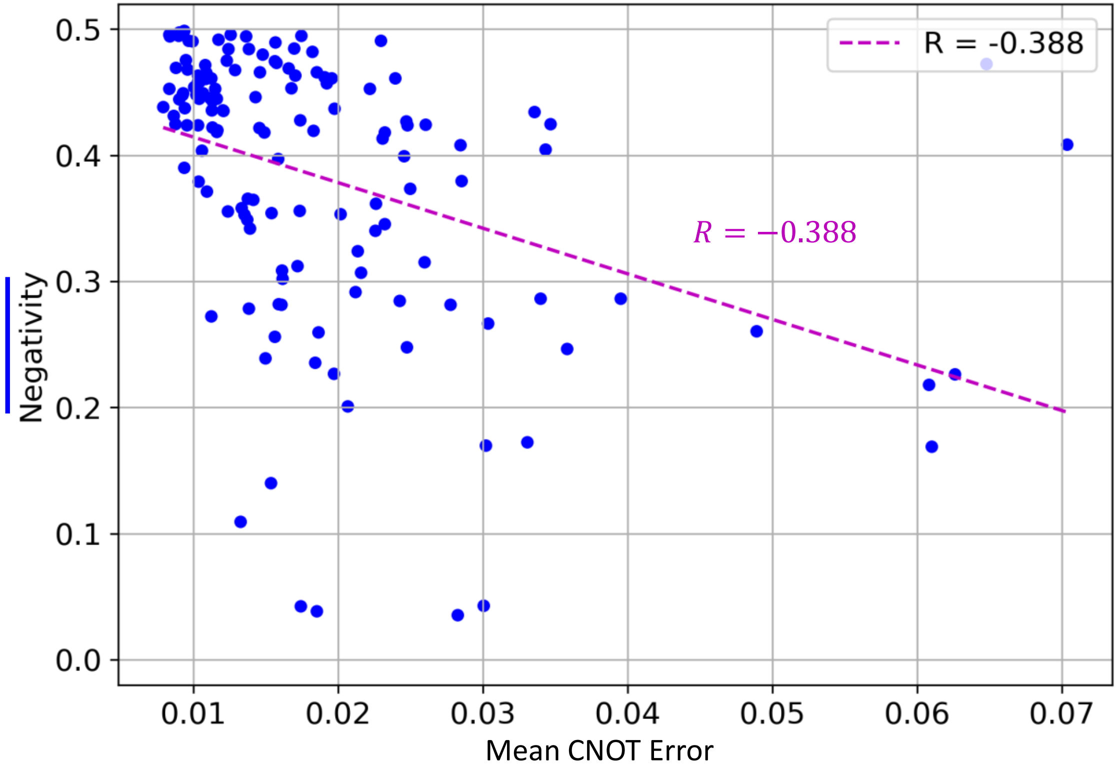
Errors of all CNOTs directly involved



Compare with

Negativity of qubit pair

Individual couplings for 127-qubit *ibm_washington*



(directly involved CNOTs)

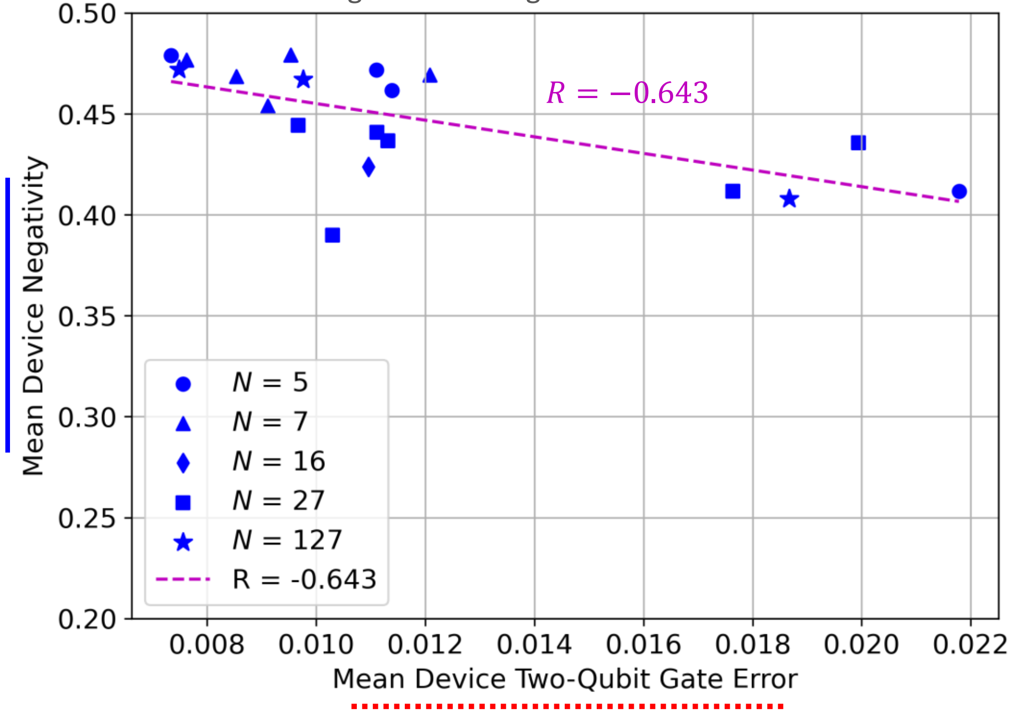
All Device Errors vs. Entanglement

Device Negativities (readout-error mitigated)

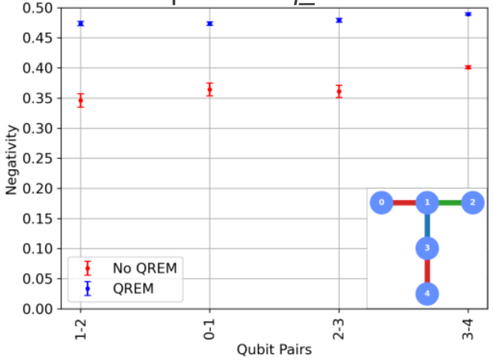
Device	Qubits	QV	Mean $\mathcal{N}$	Whole-Device
lima	5	8	0.470 ± 0.011	✓
belem	5	16	0.427 ± 0.010	✓
quito	5	16	0.486 ± 0.010	✓
manila	5	32	0.487 ± 0.003	✓
jakarta	7	16	0.482 ± 0.007	✓
oslo	7	32	0.488 ± 0.010	✓
nairobi	7	32	0.488 ± 0.004	✓
lagos	7	32	0.466 ± 0.008	✓
perth	7	32	0.482 ± 0.011	✓
guadalupe	16	32	0.447 ± 0.032	✓
toronto	27	32	0.403 ± 0.075	✓
geneva	27	32	0.461 ± 0.089	✓
hanoi	27	64	0.467 ± 0.026	✓
auckland	27	64	0.437 ± 0.060	✓
cairo	27	64	0.455 ± 0.026	✓
mumbai	27	128	0.460 ± 0.078	✓
montreal	27	128	0.424 ± 0.055	✓
kolkata	27	128	0.407 ± 0.134	✓
washington	127	64	0.403 ± 0.125	✓
Seattle	433	-	0.340	✓ (active)

Quantum Volume

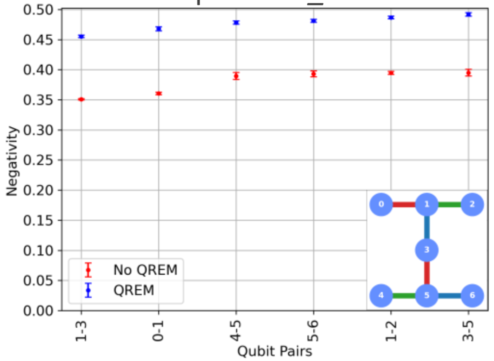
Averaged device negativities vs CNOT errors



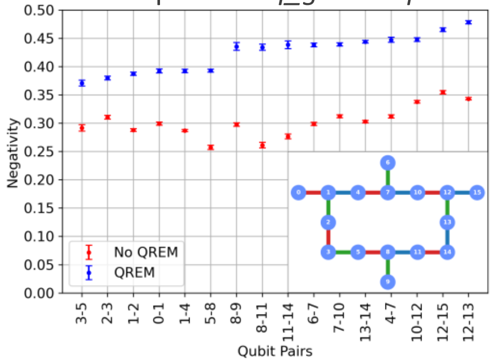
4-qubit *ibmq_manila*



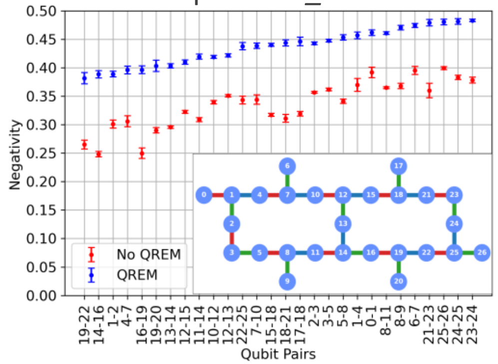
7-qubit *ibm_oslo*



16-qubit *ibmq_guadalupe*



27-qubit *ibm_cairo*



Overview

Benchmarking quantum devices

Forms of Multipartite Entanglement

- Bipartite and Genuine Multipartite entanglement

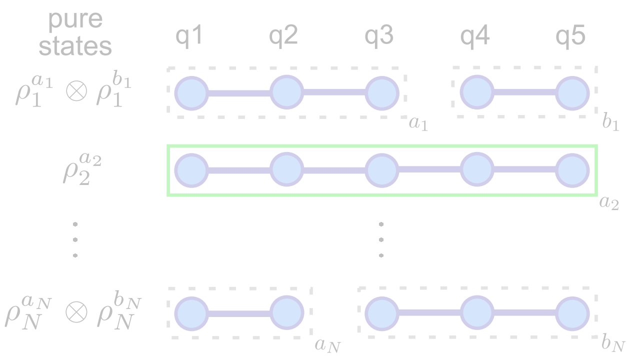
Detecting **Bipartite entanglement**

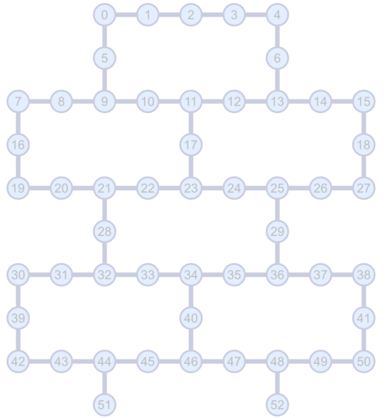
- By preparing Graph states on *IBM Quantum* devices

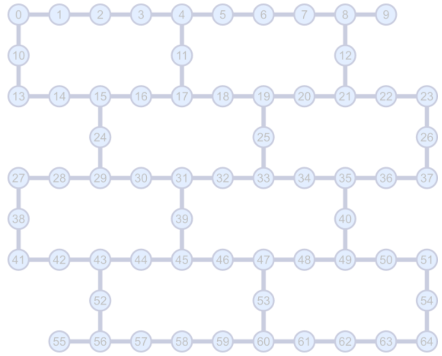
Detecting **Genuine multipartite entanglement**

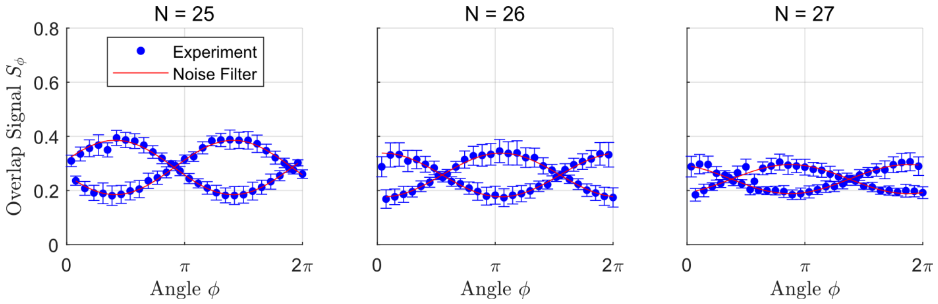
- By preparing GHZ states
- GHZ decoherence rates

Bell state teleportation









GHZ States

- GHZ State → generalisation of Bell state to more qubits

$$|Bell\rangle = \frac{|0\rangle^{\otimes 2} + |1\rangle^{\otimes 2}}{\sqrt{2}} \quad \rightarrow \quad |\mathrm{GHZ}\rangle_N = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}}$$

- Conveniently sparse density matrix
- Sensitive to noise
  - Disentangled after only 1 local measurement

$$\frac{|000\rangle + |111\rangle}{\sqrt{2}} \rightarrow \{|000\rangle, |111\rangle\}$$

Density matrix (2 qubits)

$$\begin{pmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & \frac{1}{2} \end{pmatrix}$$

Coherence

Population

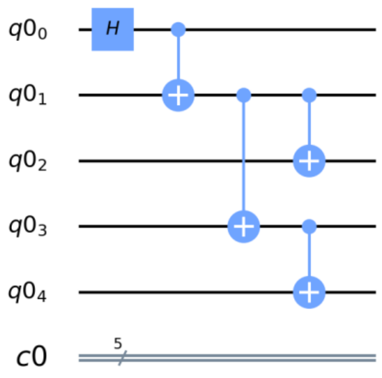
GHZ State density matrix (4-qubit)

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} /2$$

Graph State density matrix (4-qubit)

$$\begin{pmatrix} 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \end{pmatrix} /8$$

Preparation



Hadamard $\rightarrow \frac{(|0\rangle+|1\rangle)|00\ldots0\rangle}{\sqrt{2}}$

Grow the state with CNOTs

CNOT $\rightarrow \frac{(|00\rangle+|11\rangle)|0\ldots0\rangle}{\sqrt{2}}$

CNOT $\rightarrow \frac{(|000\rangle+|111\rangle)|\ldots0\rangle}{\sqrt{2}}$

All-to-all connectivity:
(CNOT Depth) $\approx \log_2 N$

Cruz et al., Adv. Quantum Technol (2019)

IBM Quantum Heavy Hex Layout:
(CNOT Depth) $\approx \sqrt{2N}$

Yang et al., IEEE J. Emerg. Sel. Topics in Circuits and Systems (2022)

Genuine Multipartite Entanglement (GME) in GHZ states

GHZ Fidelity (> 0.5) → GME

Fidelity = (Population)/2 + (Coherence)/2

- Population: Occupancies of $|00 \dots 0\rangle$ and $|11 \dots 1\rangle$
- Coherence: Multiple Quantum Coherences (MQC) Wei *et al.*, Phys. Rev. A (2020)

Ideal GHZ State

State Vector

$$\frac{|00 \dots 0\rangle + |11 \dots 1\rangle}{\sqrt{2}}$$

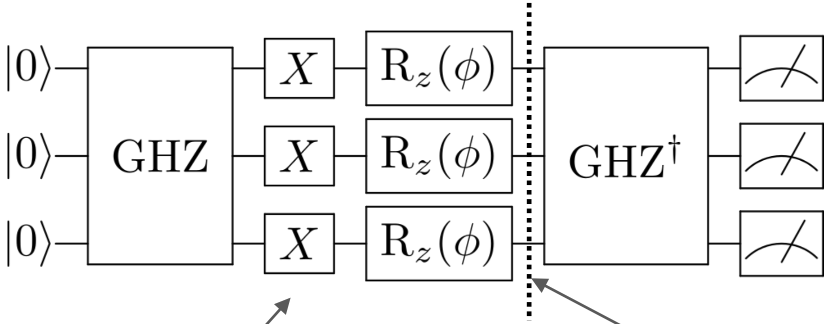
Density Matrix

$$\begin{pmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & \frac{1}{2} \end{pmatrix}$$

Coherence

Population

Multiple Quantum Coherences (MQC)



Hahn Echo: Refocussing π-pulse (Reduce qubit phase errors)

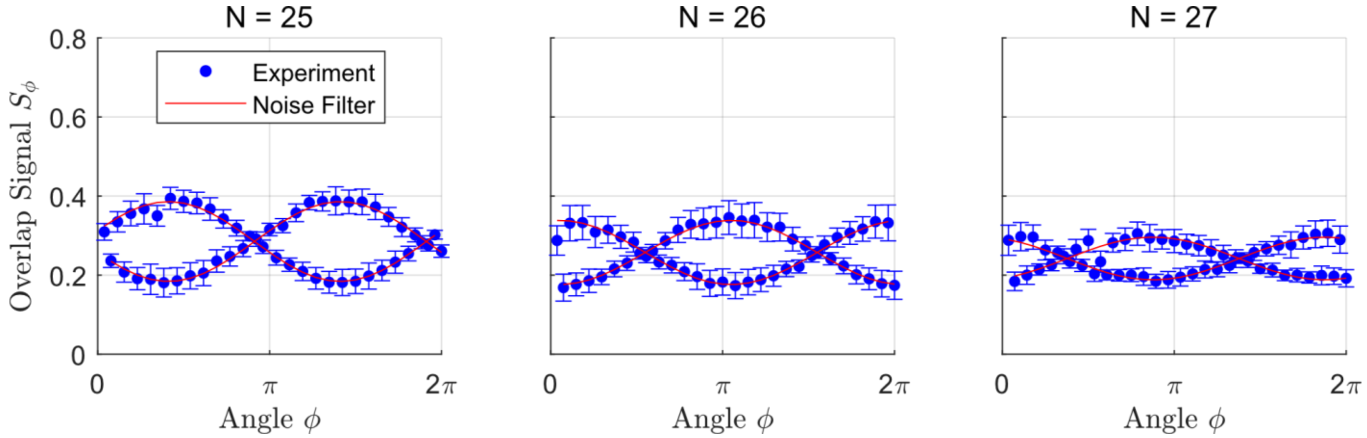
Ideal state: phase of $N\phi$

$$\frac{|00 \dots 0\rangle + e^{iN\phi}|11 \dots 1\rangle}{\sqrt{2}}$$

→ **Overlap Signal:** Occupancy of $|00 \dots 0\rangle$ →

$$\text{Coherence} = 2\sqrt{I_N}$$

I_N: Amplitude of overlap signals

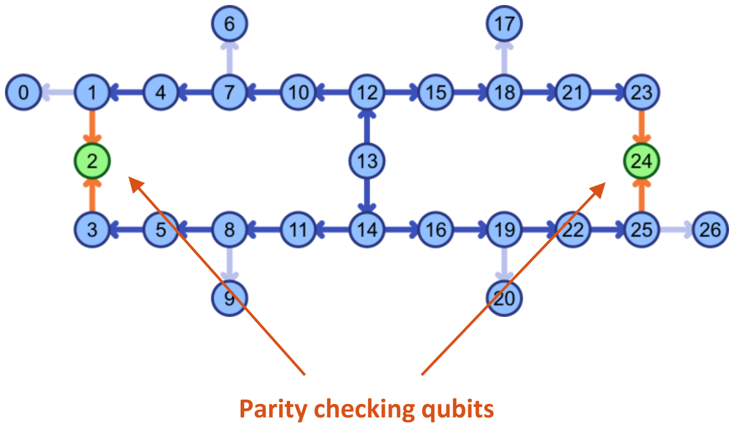


Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

Results: On the 27-qubit *ibmq_montreal device*

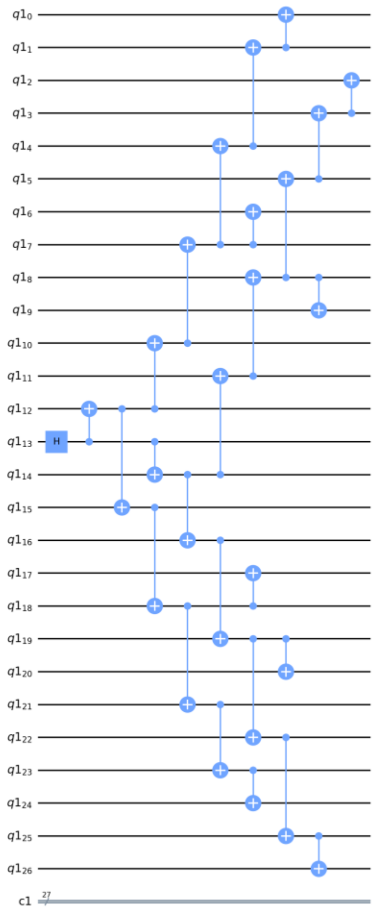
- Prepare on device
- Add parity verification
  → effects on fidelity
  → discard when measure 1

27-qubit *ibmq_montreal* device

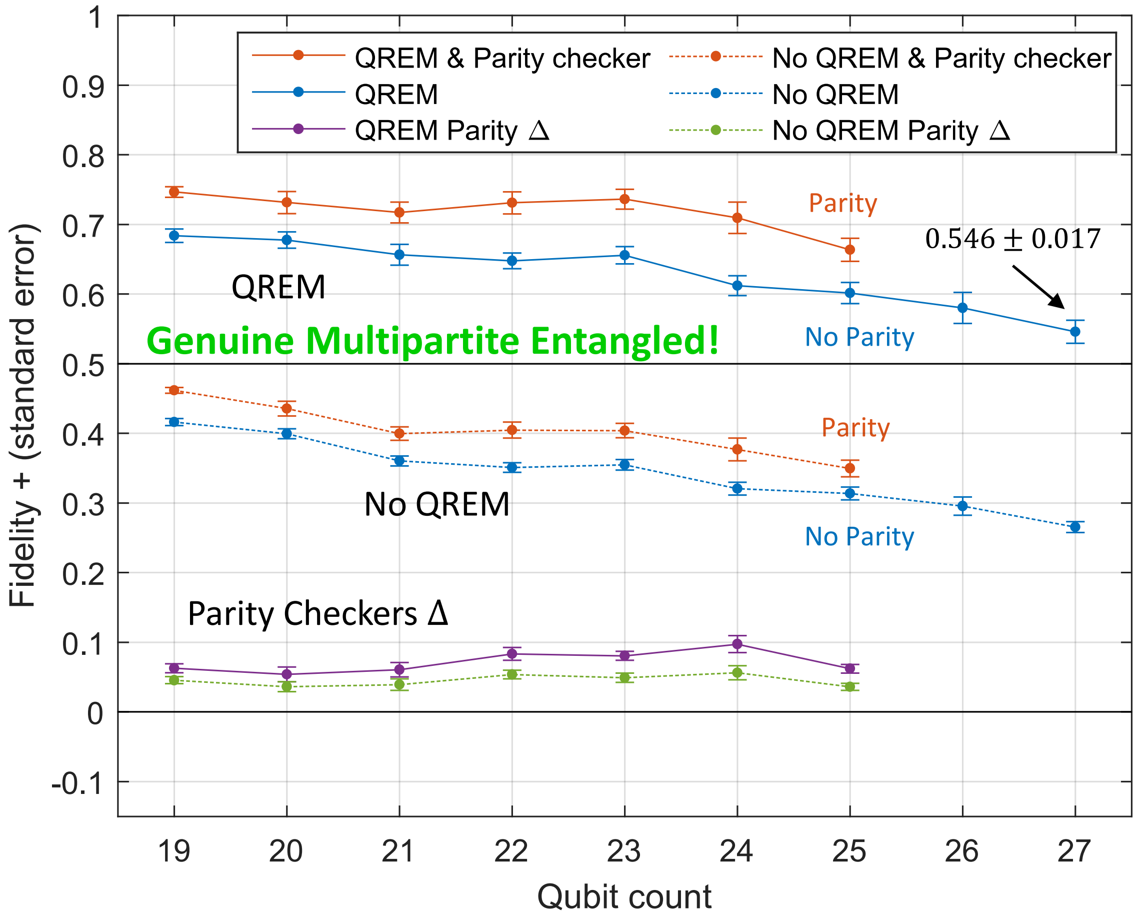


- 27-qubit GME, whole device!
- Next: Scale to larger devices

GHZ state circuit



Fidelity with 2 parity checker qubits (q2 and q24)



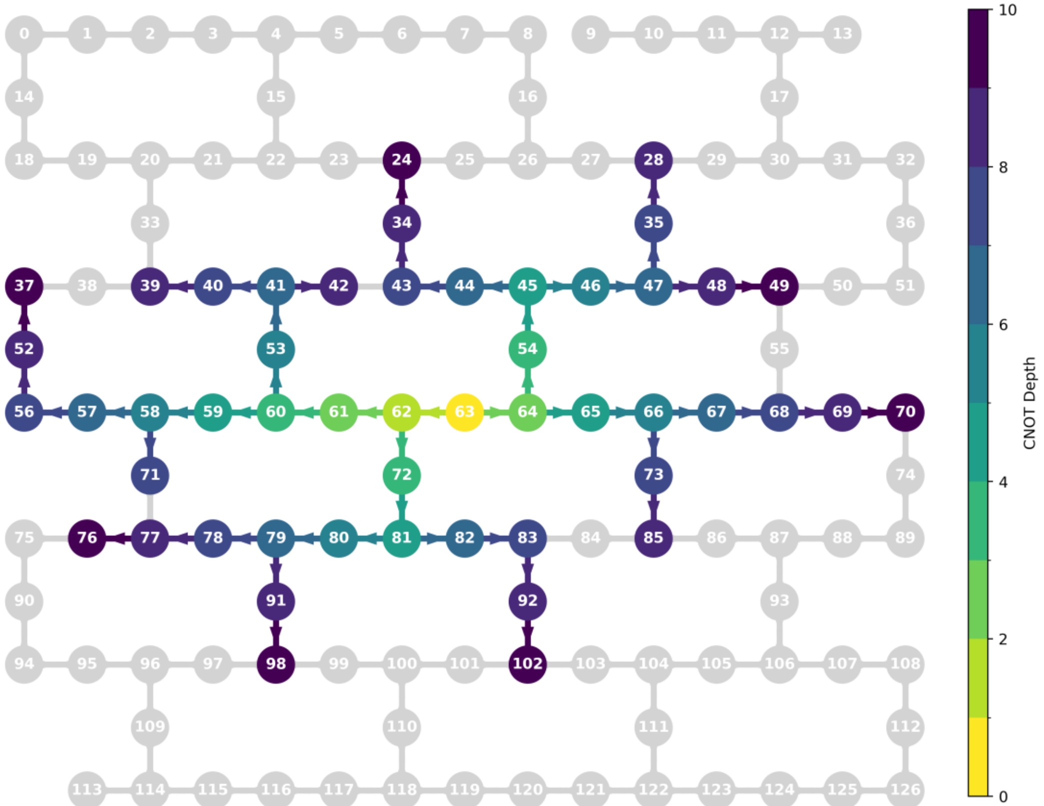
Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

QREM : Quantum Readout-Error Mitigation

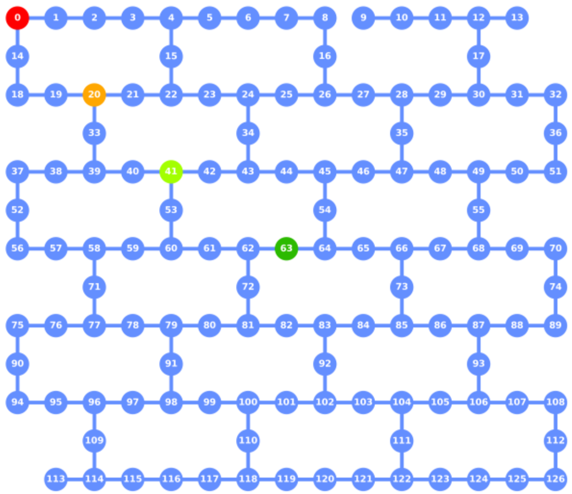
GHZ Embedding Algorithm

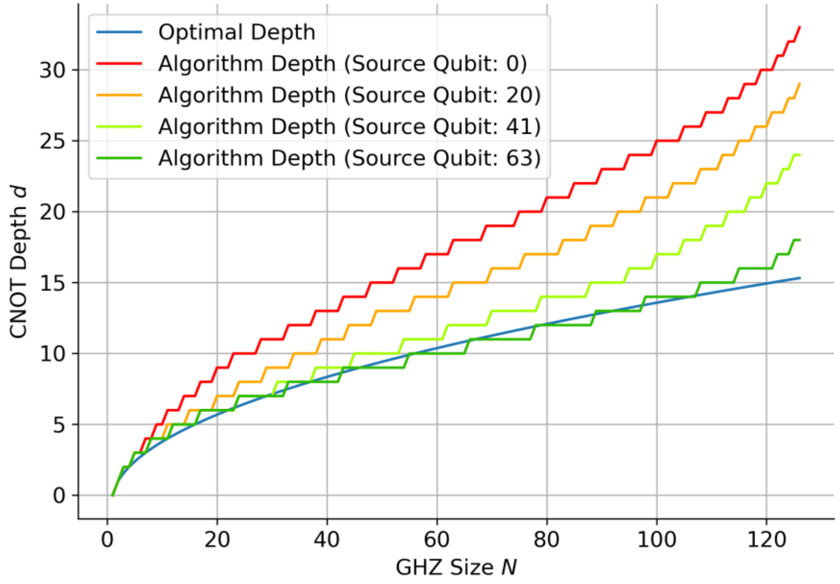
GHZ State embedding algorithm

1. Select a qubit
   a) Breadth first search
   b) Preference CNOTs with low error
2. Repeat 1. for each qubit and choose the best embedding



127-qubit *Ibm_Washington device*



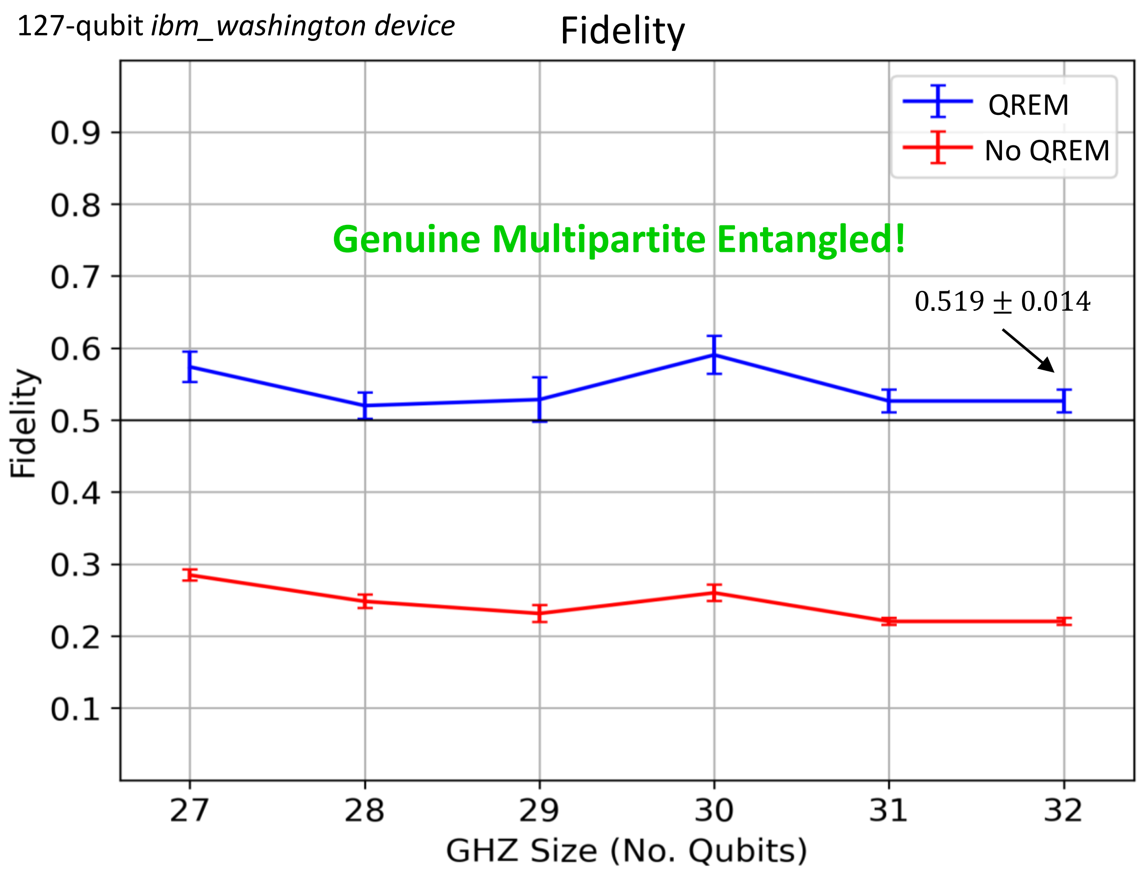


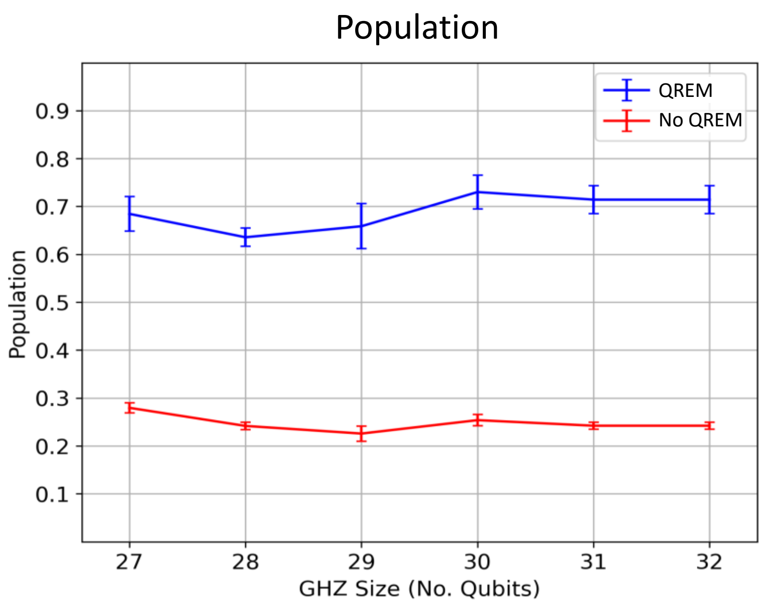
John F. Kam, et. al., paper in preparation

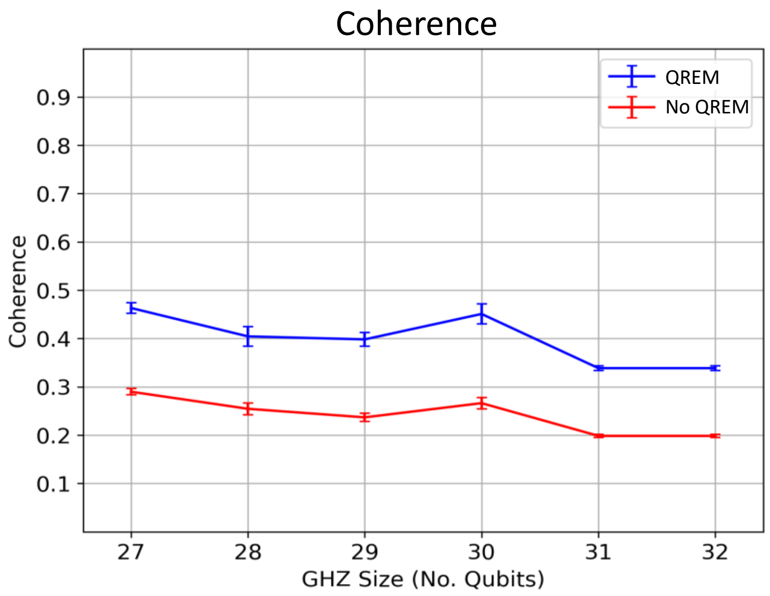
Results: *ibm_washington*

The 32-qubit GHZ is genuine multipartite entangled!

127-qubit *ibm_washington device*



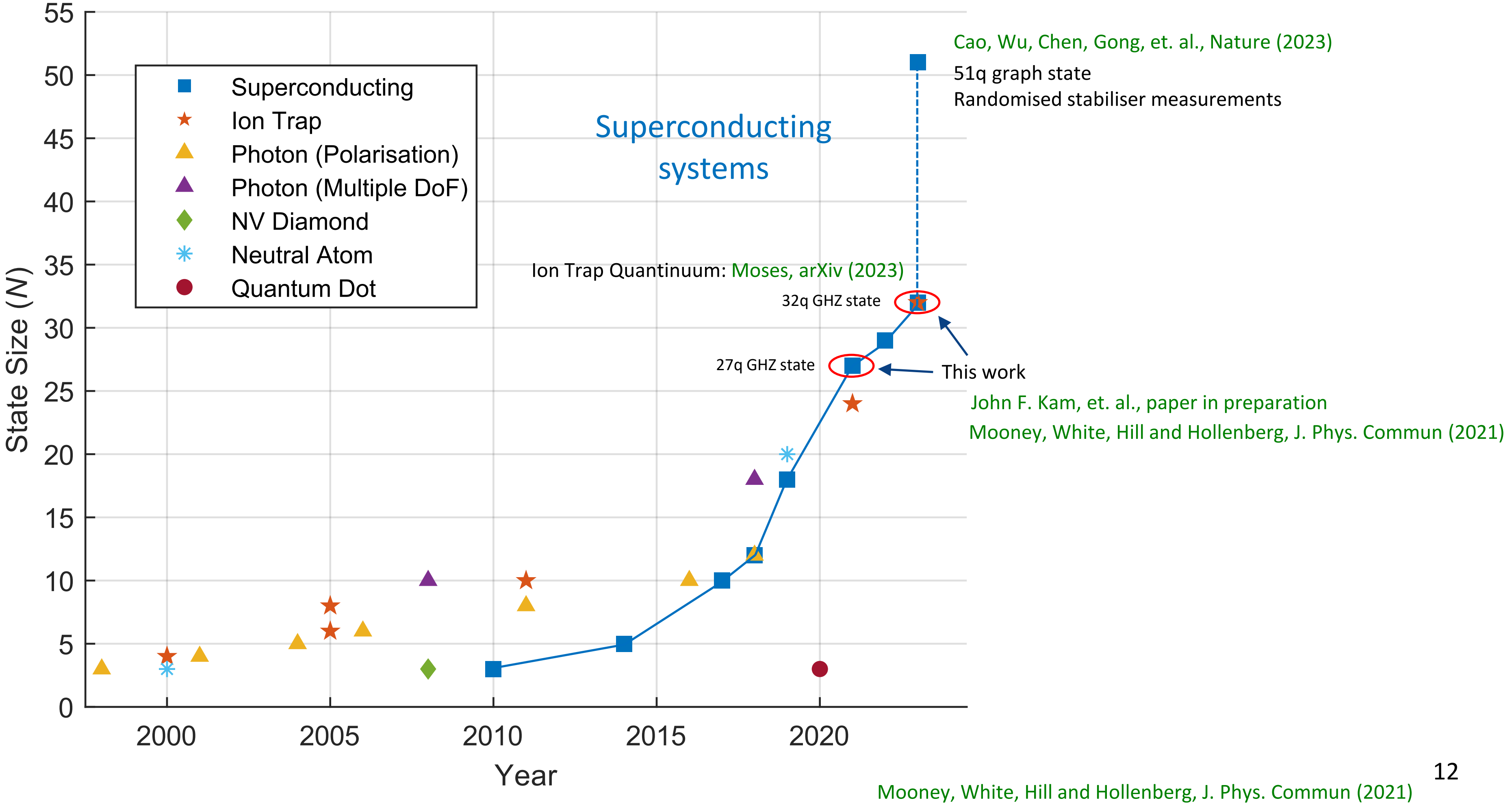




John F. Kam, et. al., paper in preparation

History of Genuine Multipartite Entanglement

Experimentally prepared states shown to exhibit GME



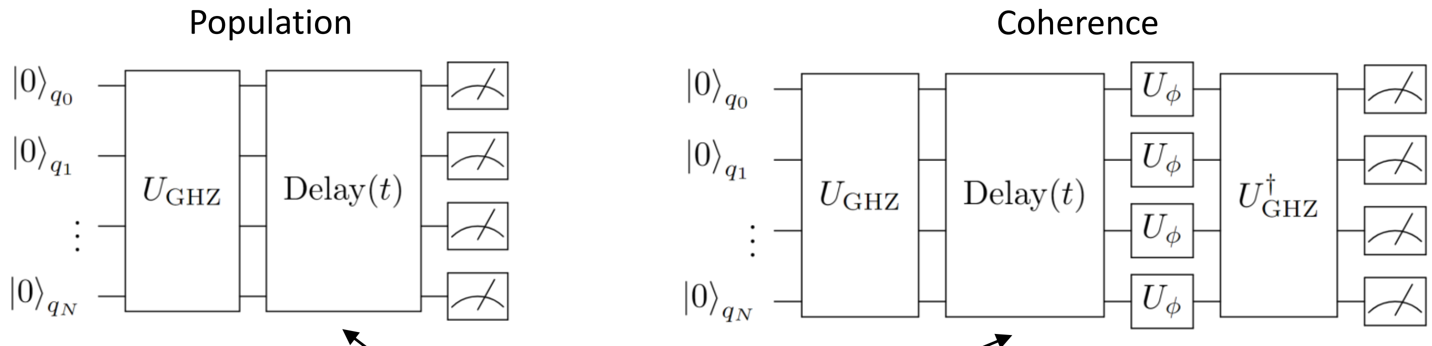
Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)
Mario Krenn, mariokrenn.wordpress.com

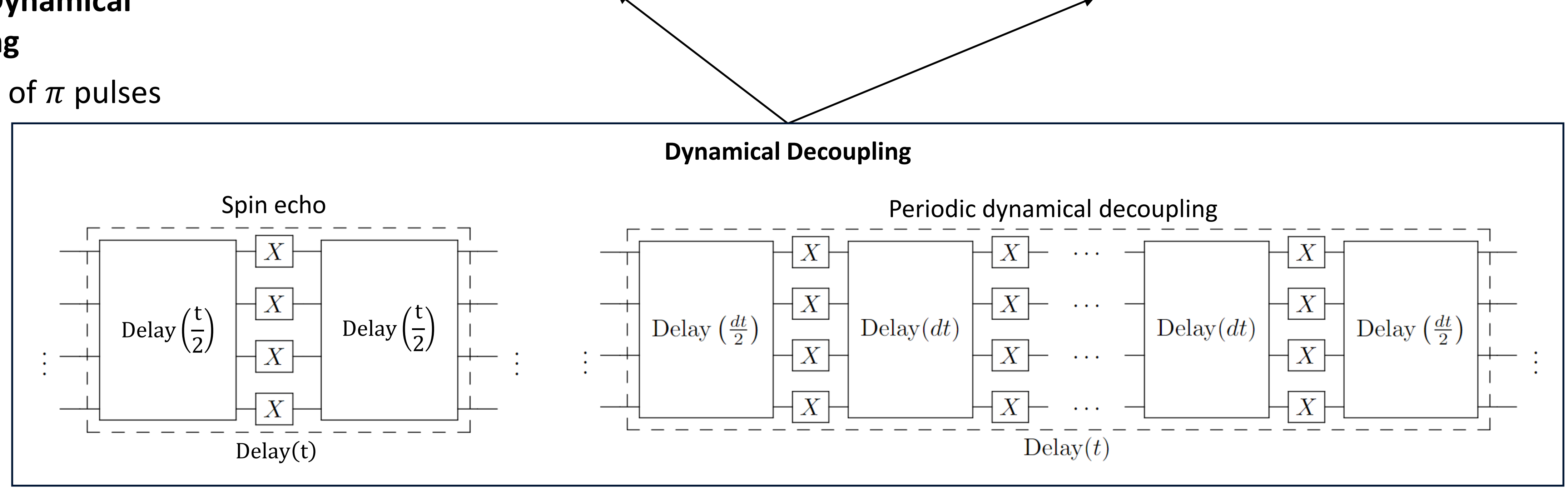
Preserving the GHZ State Fidelity

Wait after preparation

- **Spin Echo**
  - One π pulses
- **Dynamical Decoupling**
  - A series of pulses
- **Periodic Dynamical Decoupling**
  - A series of π pulses

Free Delay Circuits

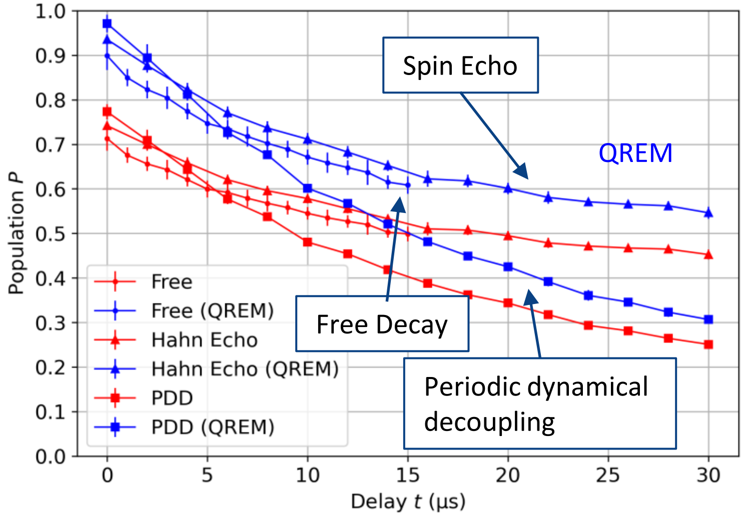


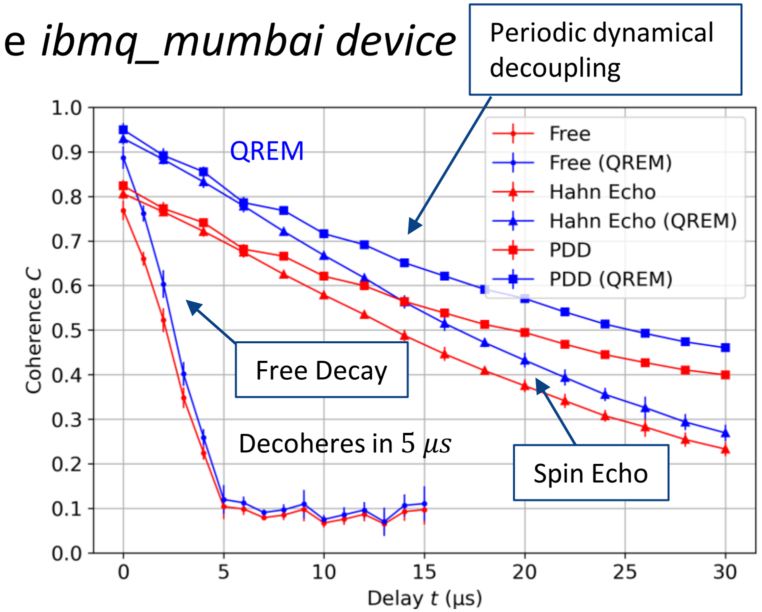


Results: GHZ State Decay Curves

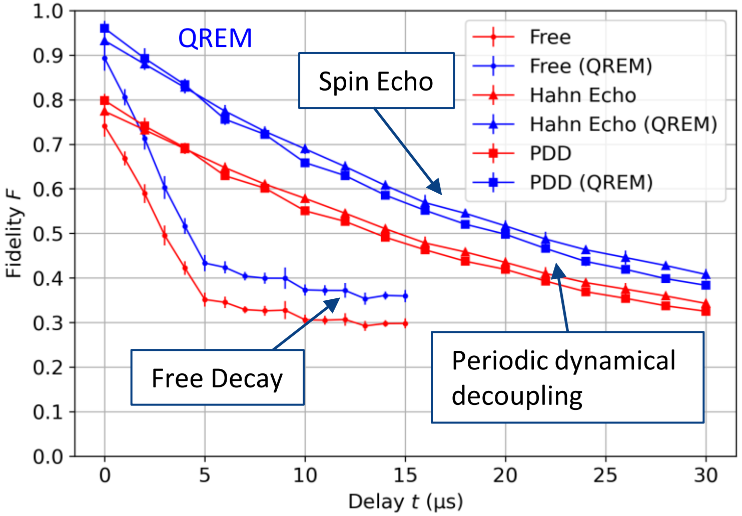
- Decay curves for 7-qubit state
- Measured **Population**
  - No real improvement
  - PDD gates introduce errors
- Measured **Coherence**
  - Big improvement
  - Idle phase are being cancelled
- Measured **Fidelity**
  - **Big Improvement**

7-qubit GHZ state on the *ibmq_mumbai device*





Point of reference:
(CNOT gate time) ≈ 400 ns



John F. Kam, et. al., paper in preparation

Superdecoherence?

- Plot GHZ decoherence vs qubit count
- **Superdecoherence**
  - Qubit decoherence rates scale with system size
    - When qubits are coupled to the same reservoir

$$C^{(N)}(t) = C_0^{(N)} e^{-\alpha^{(N)} t}$$

α: GHZ decoherence rate

- **Previous work**
  - An Ion trap system → N^2 GHZ decoherence rate scaling
    - **Superdecoherence**
    - Up to 6-qubit GHZ states

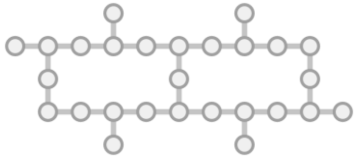
Monz, et. al., Phys Rev Lett (2011)

  - IBM Quantum device → N GHZ decoherence rate scaling
    - **No Superdecoherence**
    - Up to 8-qubit GHZ states

Ozaeta and McMahon, Quantum Sci. Technol. (2019)

16-qubit *ibmq_melbourne*

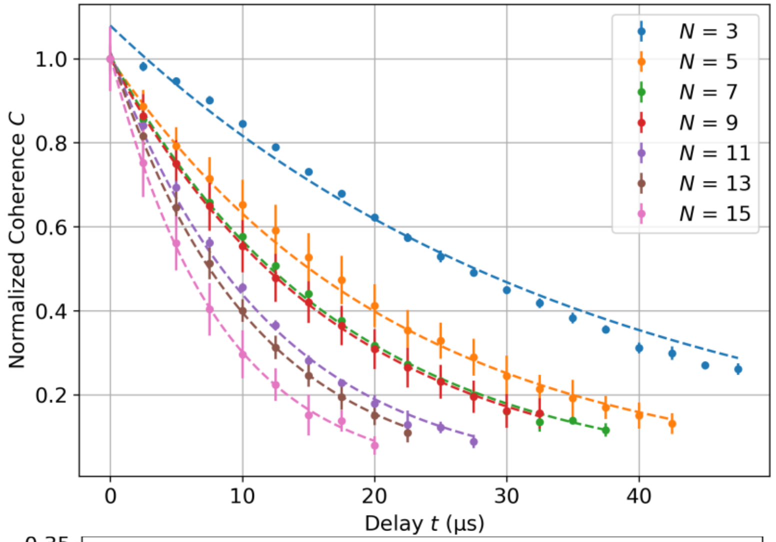
27-qubit *ibm_hanoi*

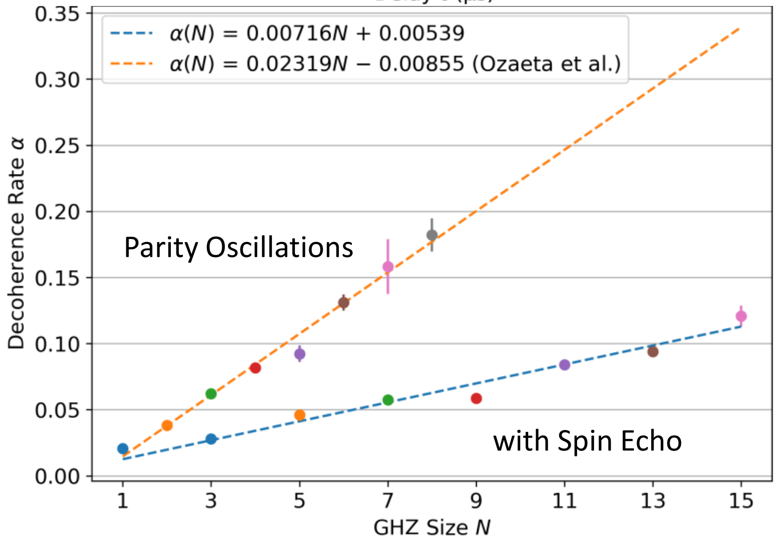


- Test on current IBM Quantum device

(CNOT gate time) $\approx$ 400 ns

27-qubit *ibm_hanoi device*





John F. Kam, et. al., paper in preparation

Overview

Benchmarking quantum devices

Forms of Multipartite Entanglement

- Bipartite and Genuine Multipartite entanglement

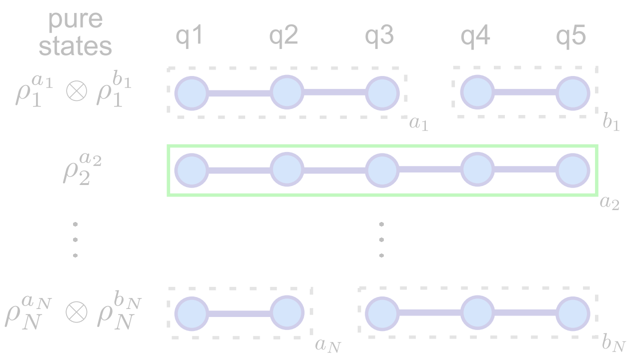
Detecting **Bipartite entanglement**

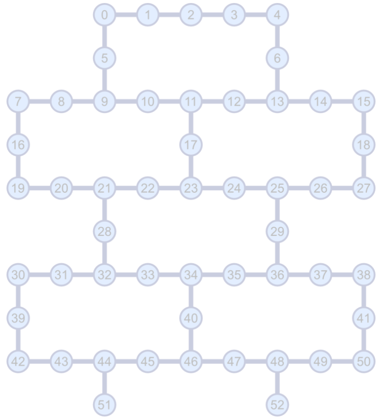
- By preparing Graph states on *IBM Quantum* devices

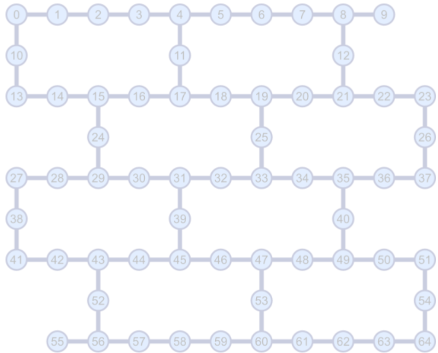
Detecting **Genuine multipartite entanglement**

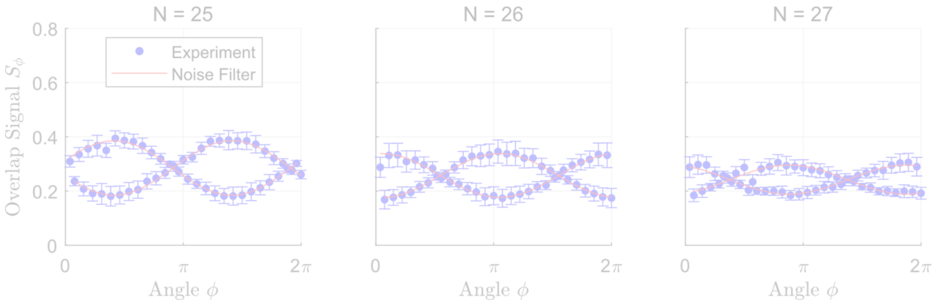
- By preparing GHZ states
- GHZ decoherence rates

Bell state teleportation



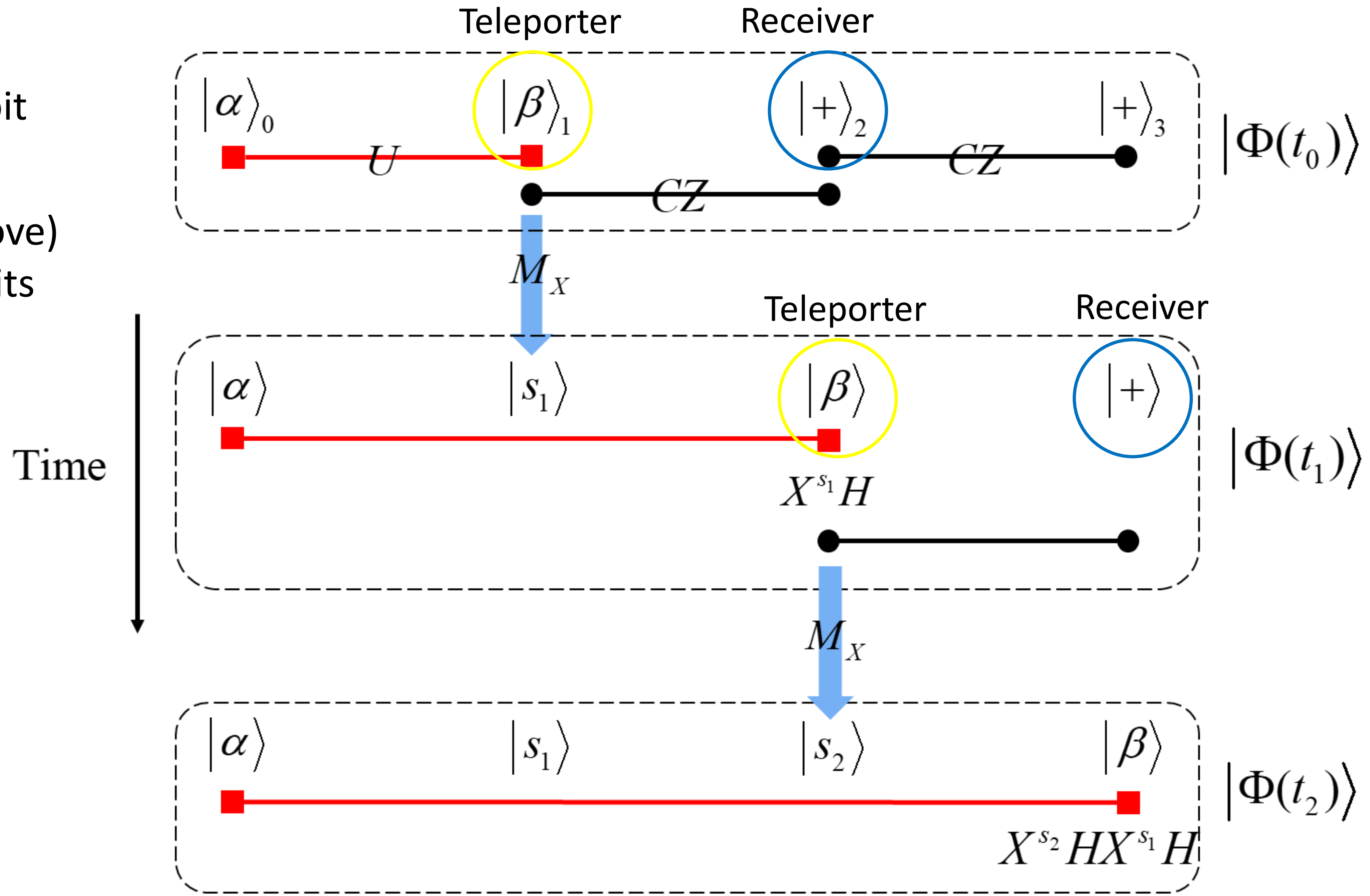






One-Way Quantum Computation

- Start with 2 entangled qubit states $|\boldsymbol{\alpha}\rangle_0$ and $|\boldsymbol{\beta}\rangle_1$
- Challenge: **Teleport** (or move) $|\boldsymbol{\beta}\rangle_1$ across a chain of qubits
  - Keeping $|\alpha\rangle_0$ and $|\beta\rangle_1$ entangled
- Compare **3 approaches**
  - Swap gates
  - Teleportation: Dynamic circuits
  - Teleportation: Post-selection



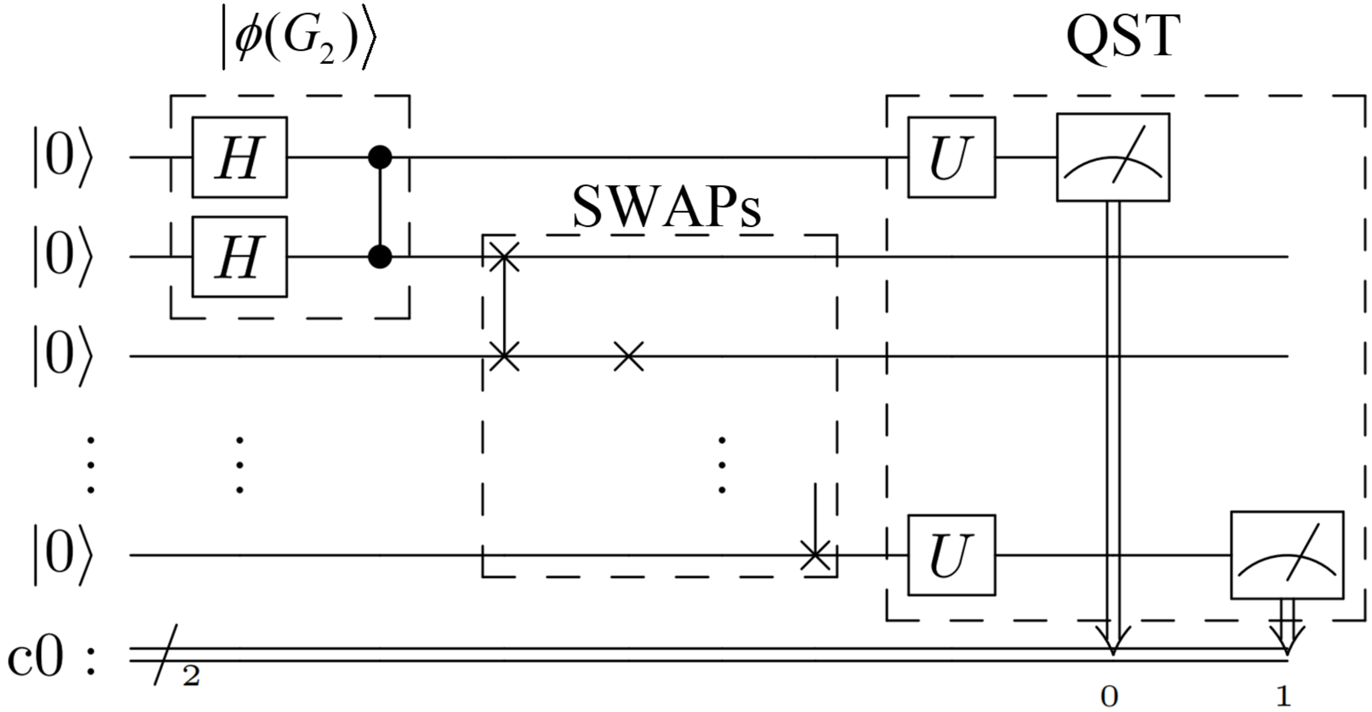
Raussendorf, et al. Phys. Rev. A (2003)

Bennet, Phys. Rev. Lett. (1993)

Using SWAP gates

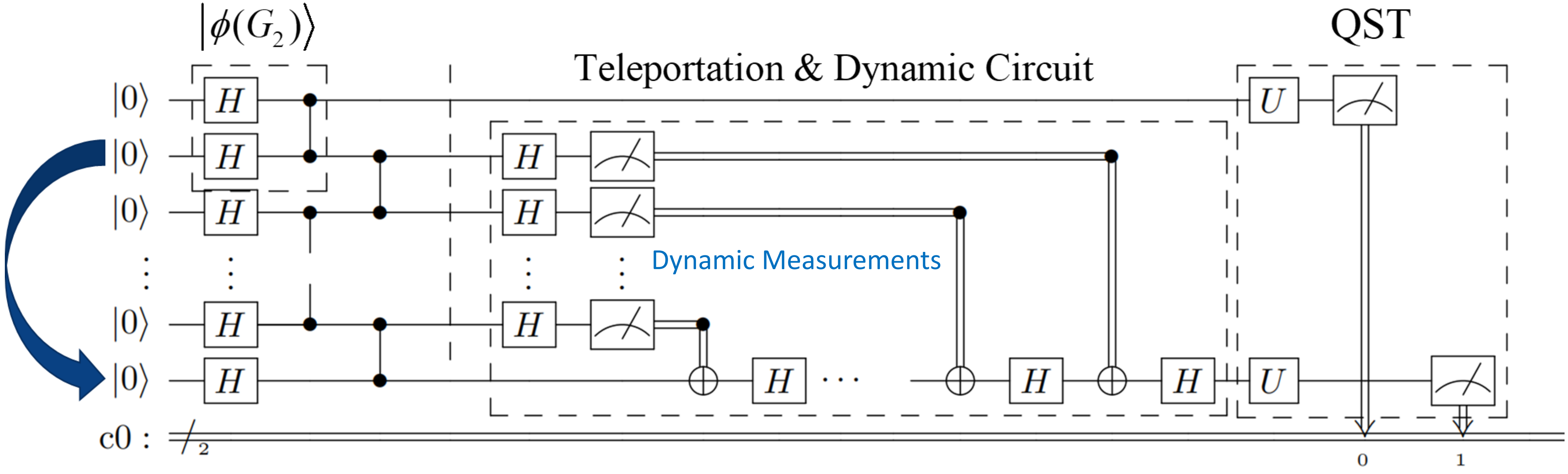
- Start with 2-qubit Bell state
- Use SWAP gates to transport the state along a chain
- Circuit depth scales with chain length

$$SWAP_{12}\,|q_1 q_2\rangle = |q_2 q_1\rangle$$



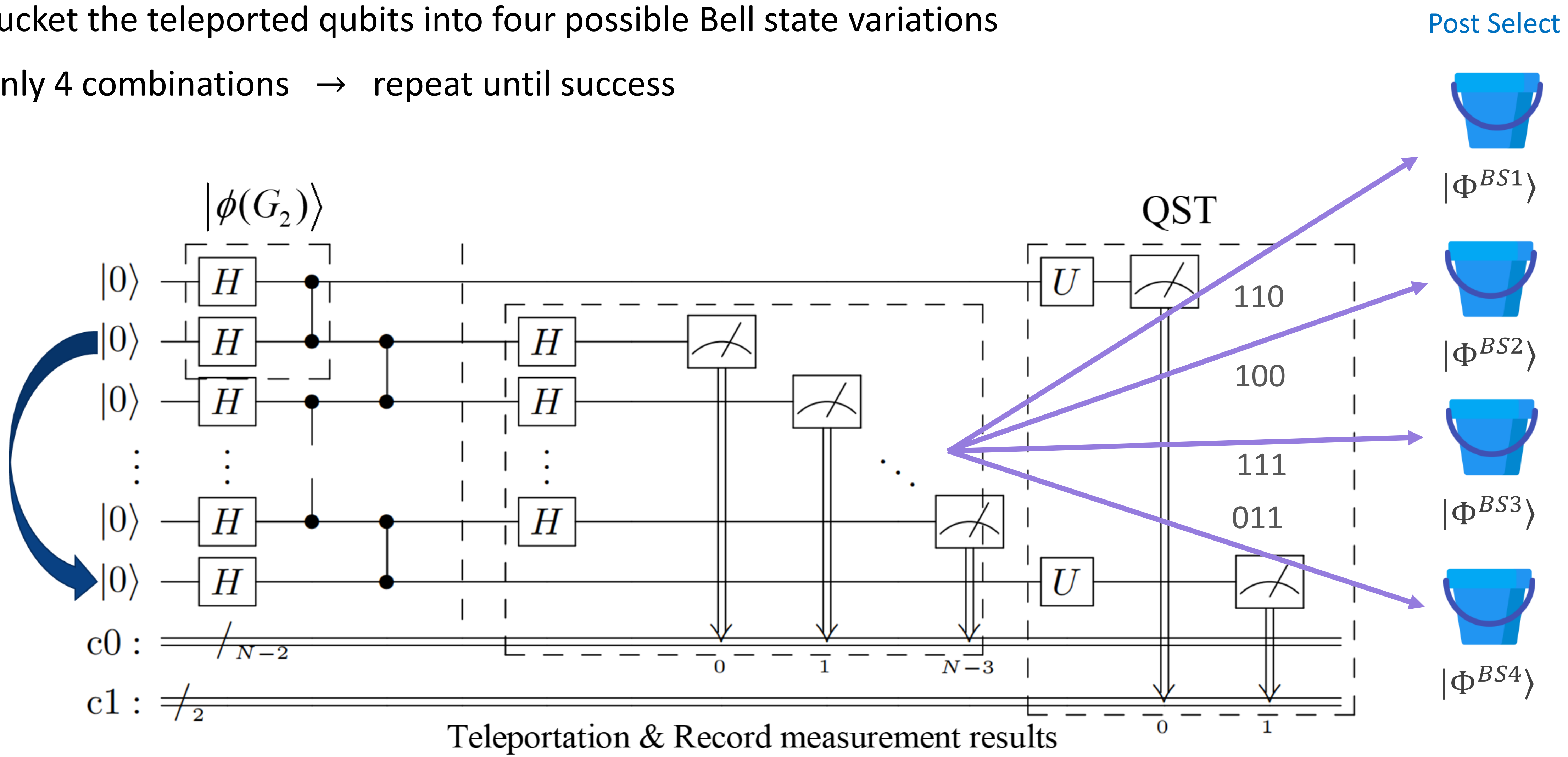
Teleportation: Dynamic Circuit

- Corrections are applied after each measurement
- Depth grows with qubit-measurement count

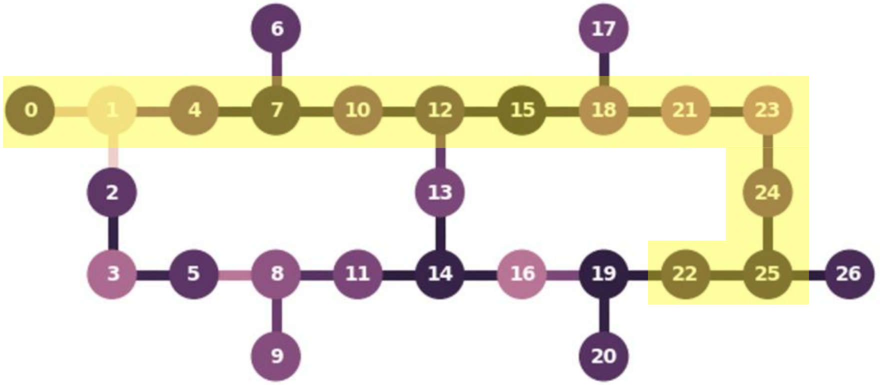


Teleportation: Post-Selection Circuit

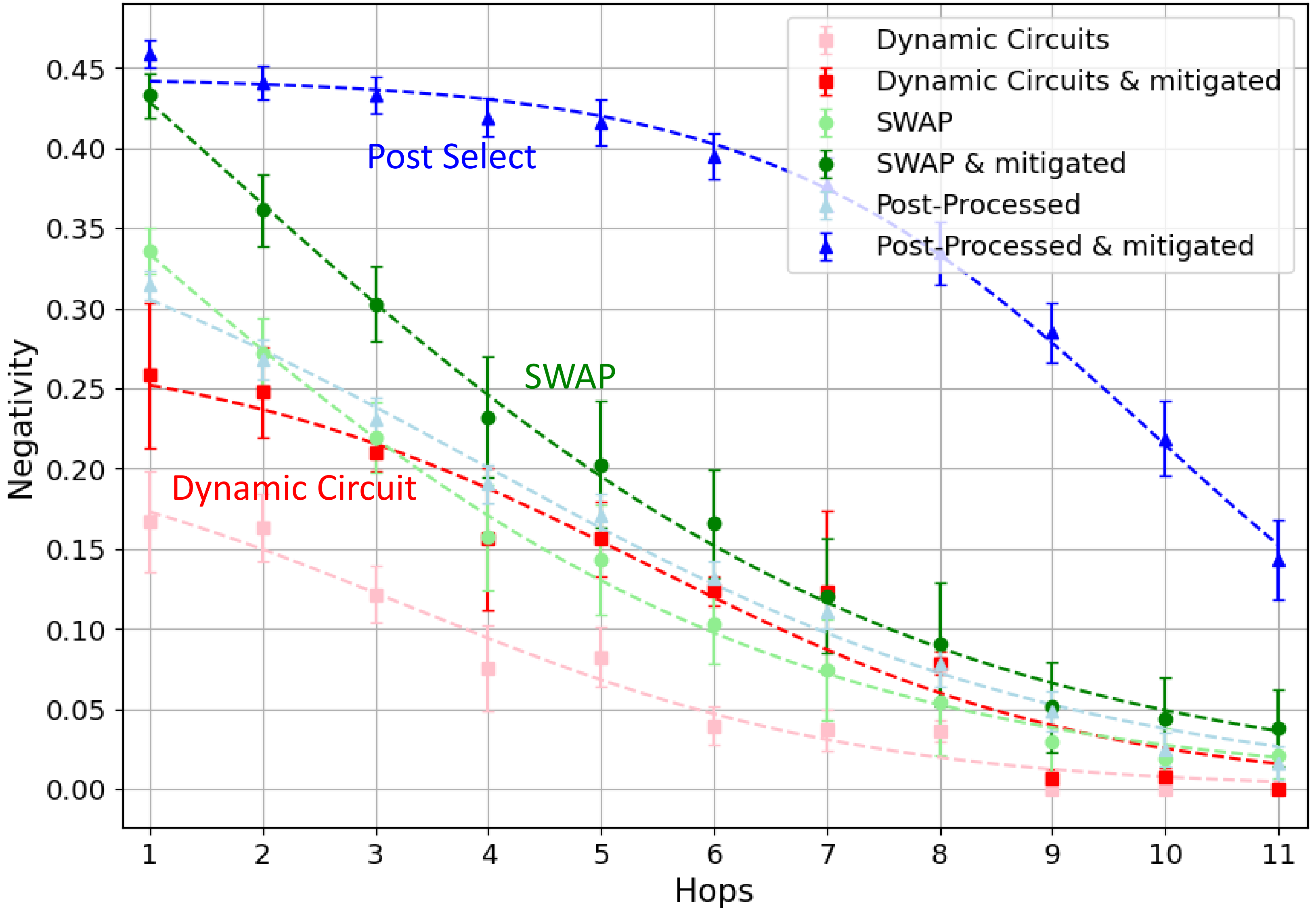
- Bucket the teleported qubits into four possible Bell state variations
- Only 4 combinations → repeat until success



Comparisons



27-qubit ibmq_Mumbai device



Summary

IBM Quantum Network Hub at the University of Melbourne

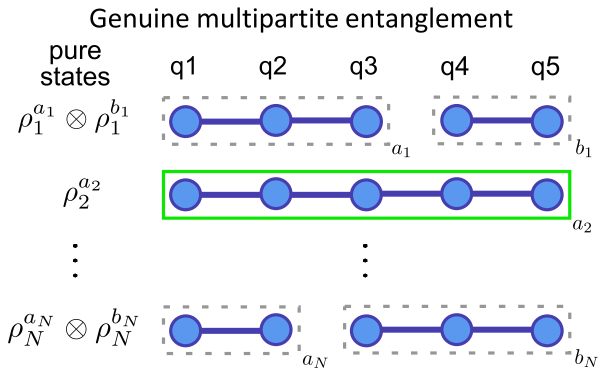
Forms of Multipartite Entanglement

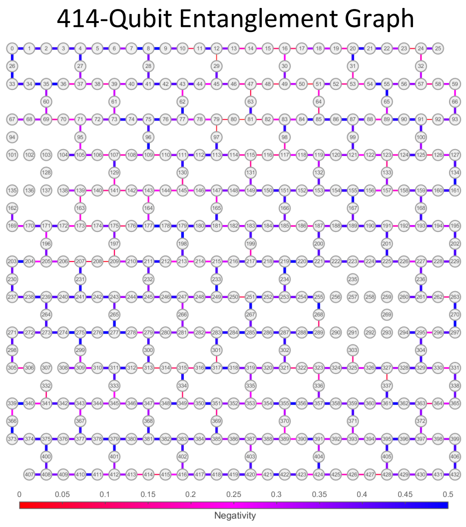
- Bipartite entanglement
- Genuine multipartite entanglement

$$\rho = \sum_{i=1}^{N} p_i \rho_i$$

Pure states ρ_i

Probabilities p_i

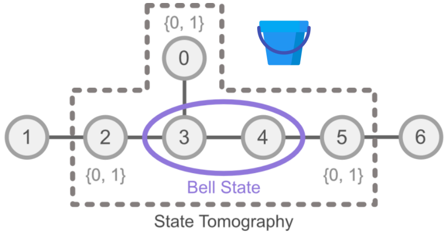


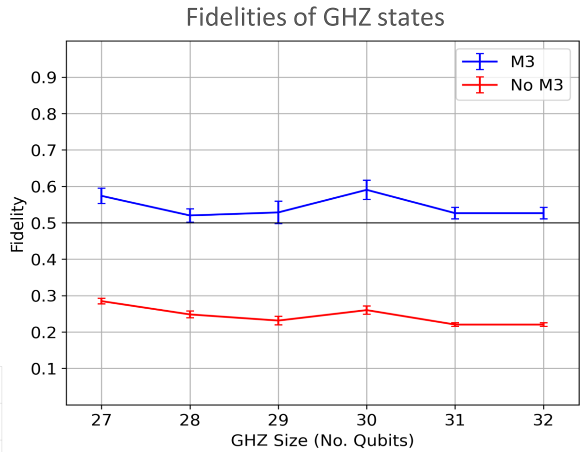


Bipartite entanglement in graph states

- Constant 36-circuit algorithm
- Whole-device entanglement on up to **414-qubits**
- Negativity correlated with CNOT fidelities

Mooney, Hill and Hollenberg, Sci. Rep. (2019)
Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)
John F Kam et. al. paper in preparation

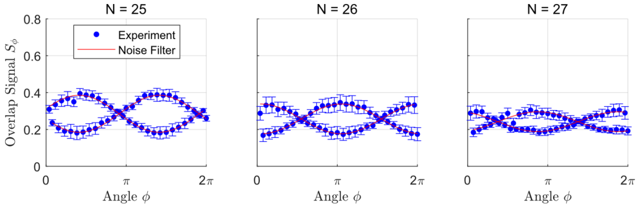




Genuine multipartite entanglement in GHZ state

- GME across **32** qubits on *ibm_washington* device
- Looked at GHZ decoherence times
  - No superdecoherence

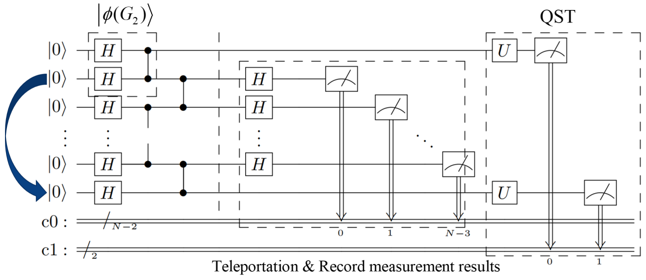
John F Kam et. al. paper in preparation

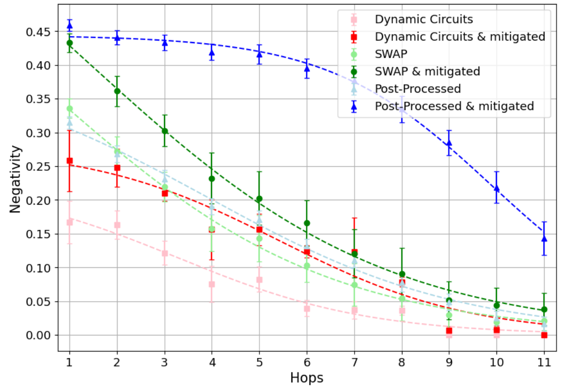


Bell state **teleportation**

- Post-selected teleportation easily hopped over 11 qubits

Haiyue Kang, et. al. paper in preparation





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Thank you

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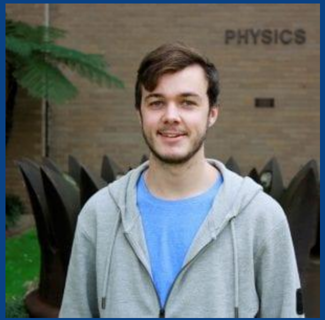

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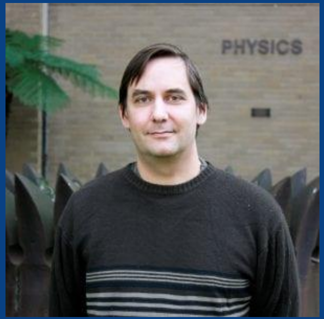
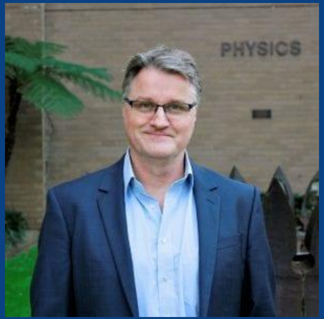


A/Prof Charles D Hill



Prof Lloyd C L Hollenberg

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