Generation of Large-Scale Entanglement on Physical Quantum Devices

Authors: Gary J Mooney, Gregory A L White, John Fidel Kam, Charles D Hill, and Lloyd C L Hollenberg

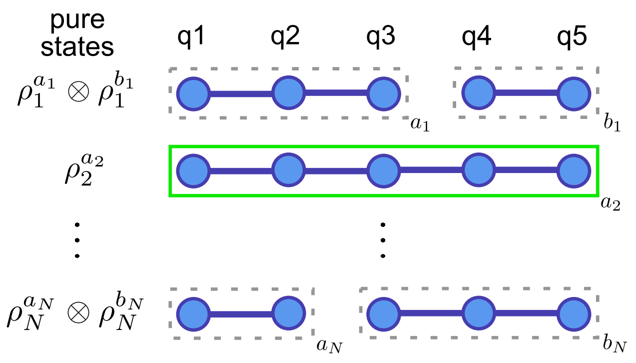
THE UNIVERSITY OF MELBOURNE

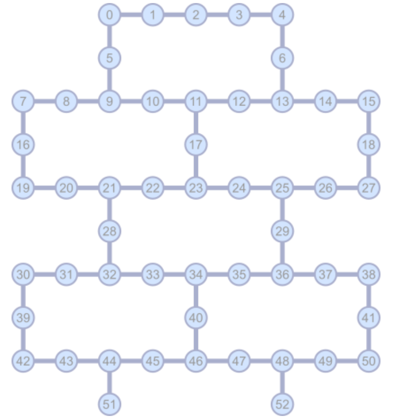
IBM Quantum Network Hub at the University of Melbourne

Overview

Forms of Multipartite Entanglement

- Bipartite and Genuine Multipartite entanglement





Detecting **Bipartite entanglement**

- By preparing Graph states on *IBM Quantum* devices

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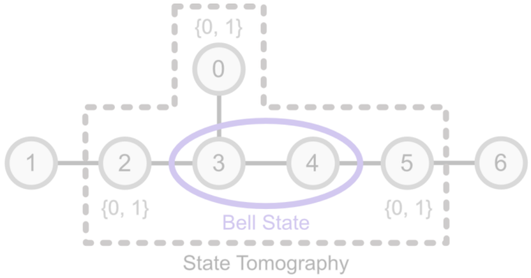
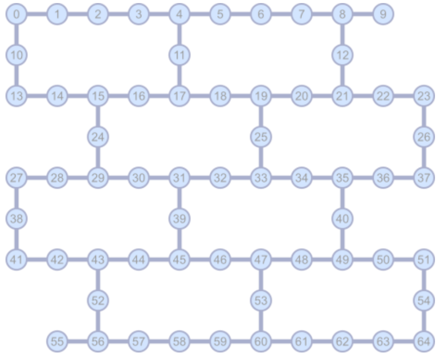
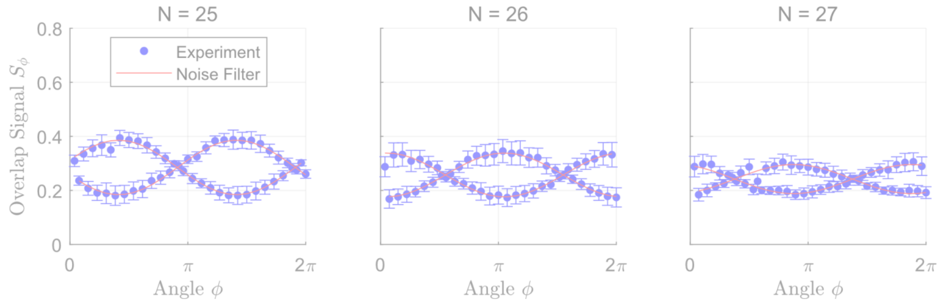




Detecting **Genuine multipartite entanglement**

- By preparing GHZ states
- Also apply parity checking error detection
  - Effects on fidelity

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



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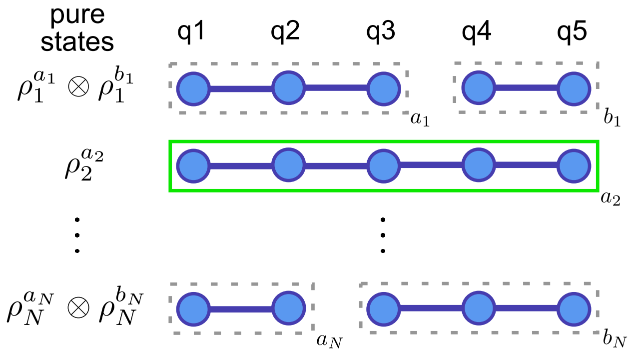

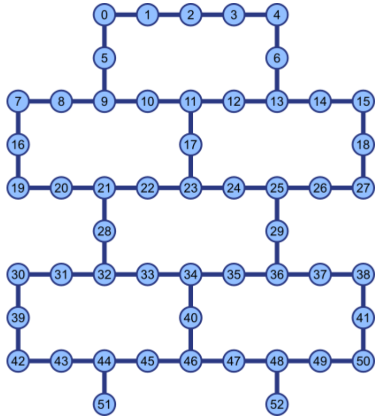

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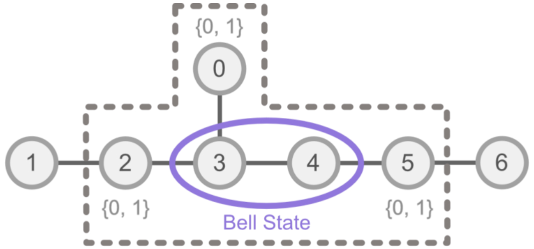

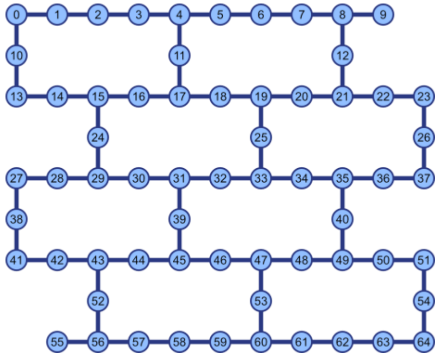

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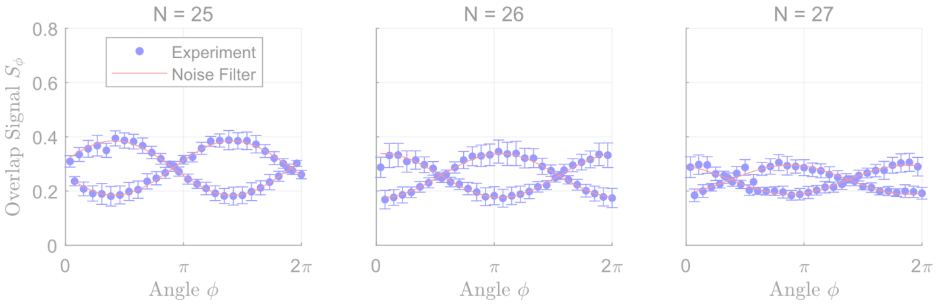

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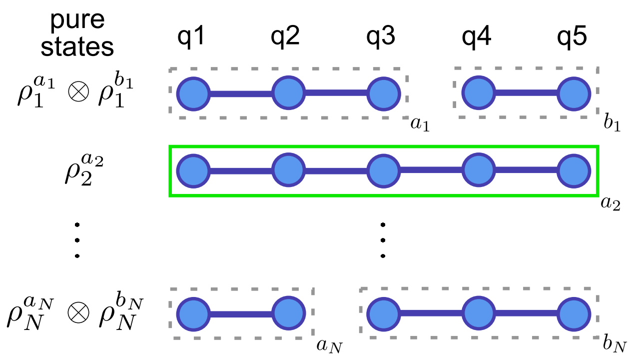

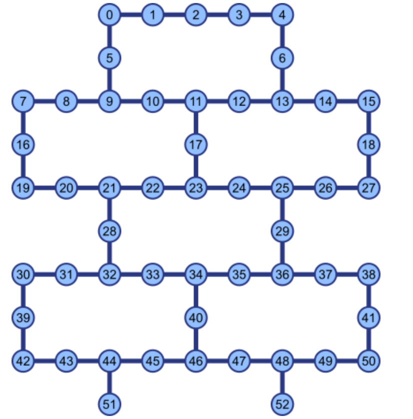

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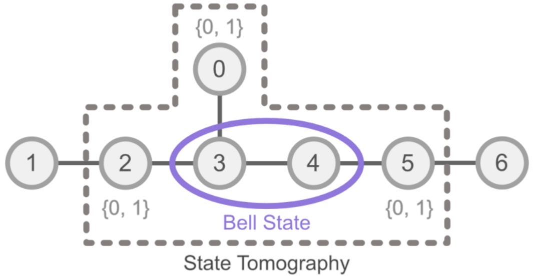

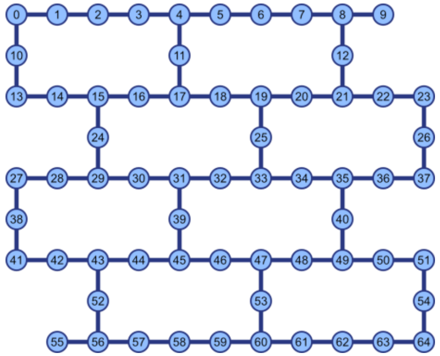

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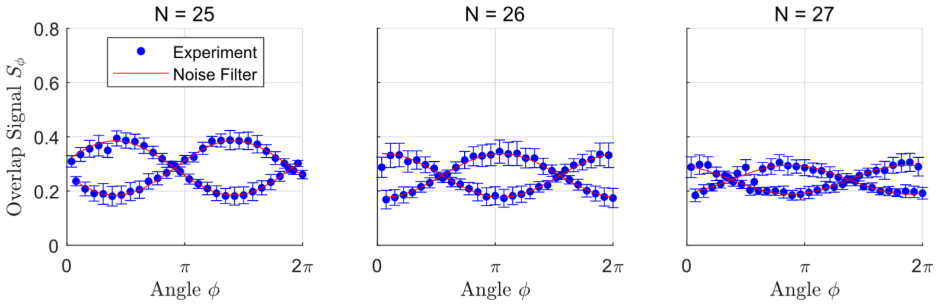

Forms of Multipartite Entanglement

Real quantum device → Noise

Quantum state is a **Mixed state**: probabilistic mixture of pure states

Mixed State

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

Density matrix ρ

Probabilities p_i

Pure states ρ_i

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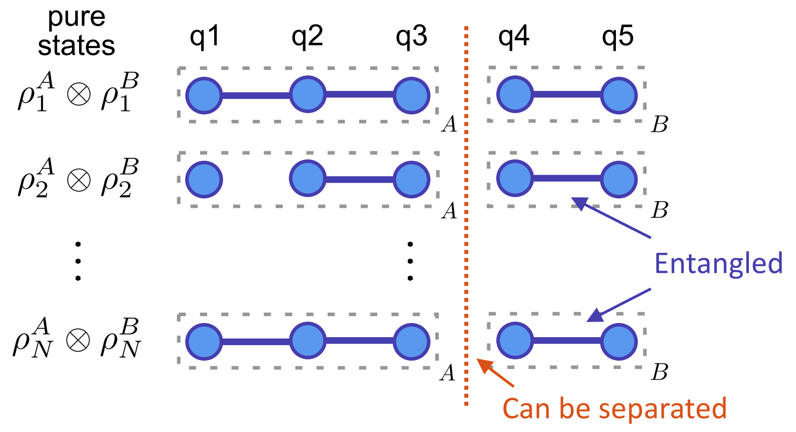

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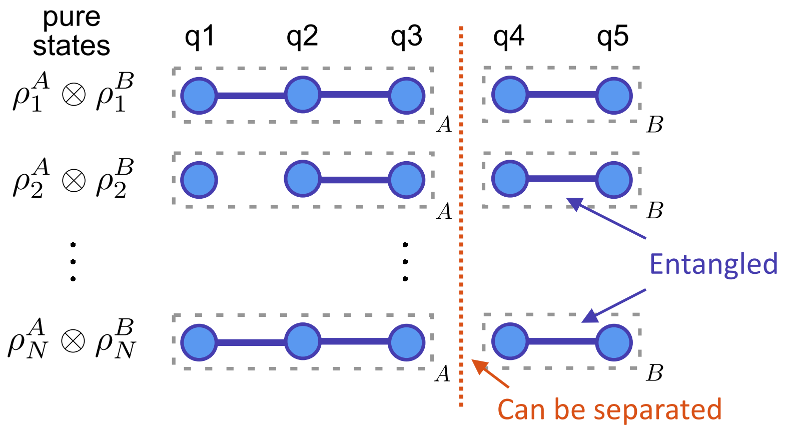
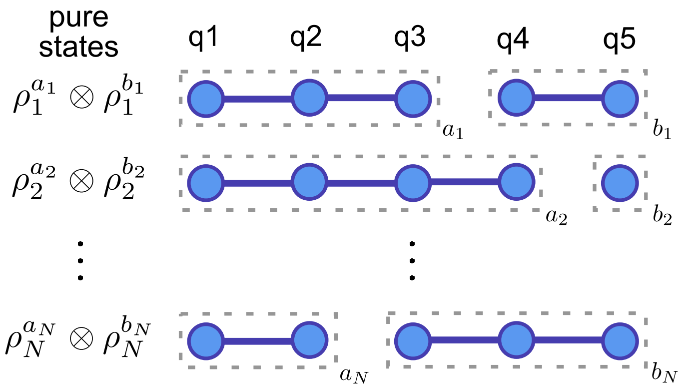


Bipartite Entanglement

- State is **not** separable
- Can't write the state as a tensor product of any bipartition



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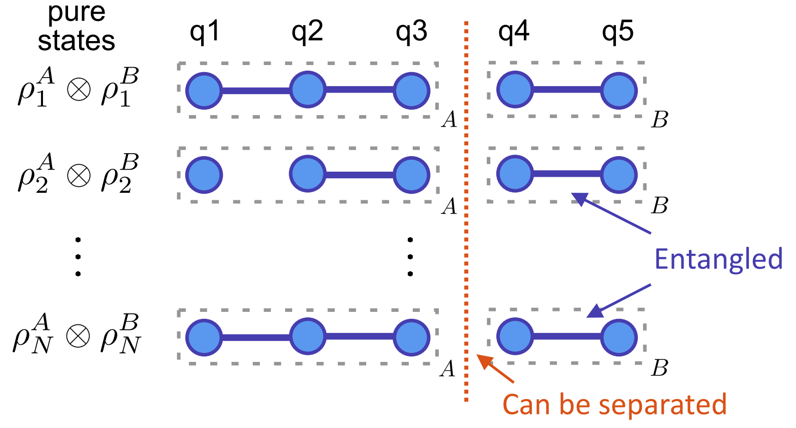

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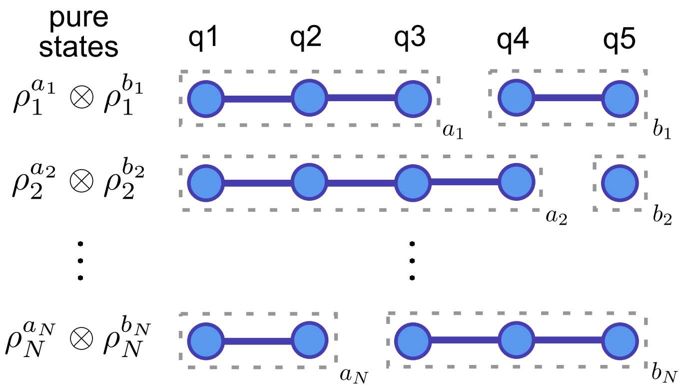
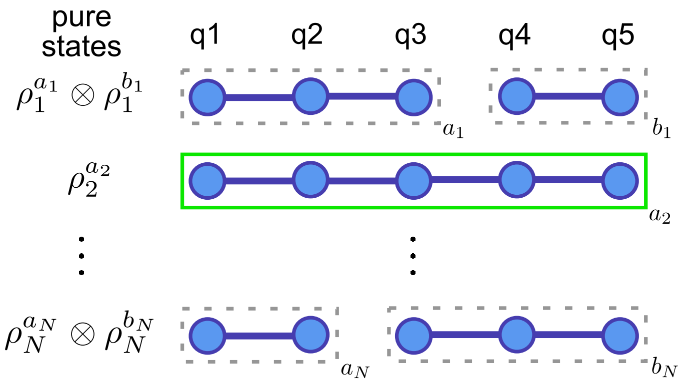


Genuine Multipartite Entanglement (GME)

- Stronger form of entanglement
- Contains pure states → entangled over all qubits



Bipartite Entanglement in Graph States

Graph State (Cluster State) → detect bipartite entanglement

- Robust to noise
  - Requires $n/2$ local measurements to disentangle

Briegel and Raussendorf, Phys. Rev. Lett. (2001)

- Low circuit depth

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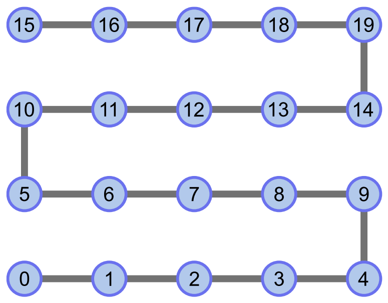
$$|G_n\rangle = \prod_{(\alpha,\beta)\in E} \mathrm{CZ}^{\alpha}_{\beta} |+\rangle^{\otimes \mathrm{n}}$$

Controlled-phase gate

$E :=$ (edge set)

Defined on a graph

20-qubit *ibmq_poughkeepsie* device



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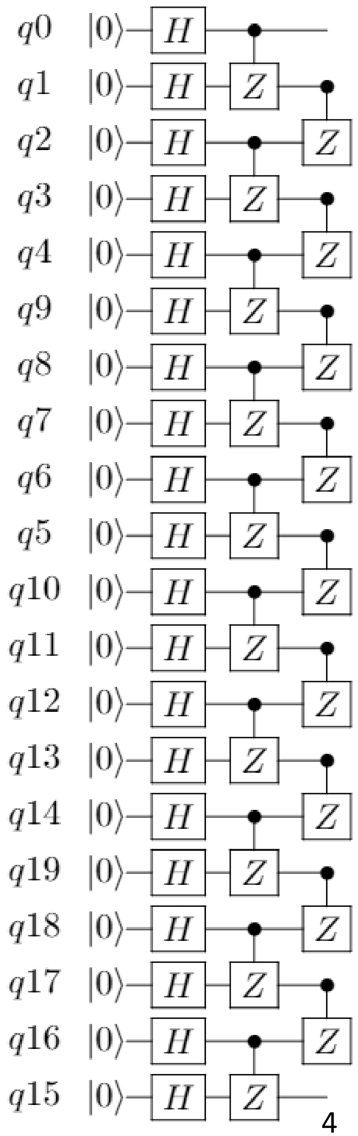

20-qubit line

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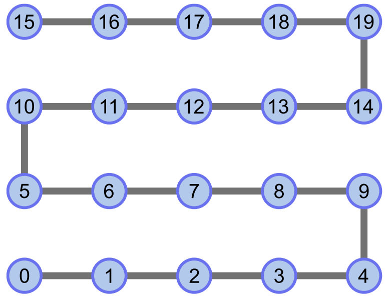

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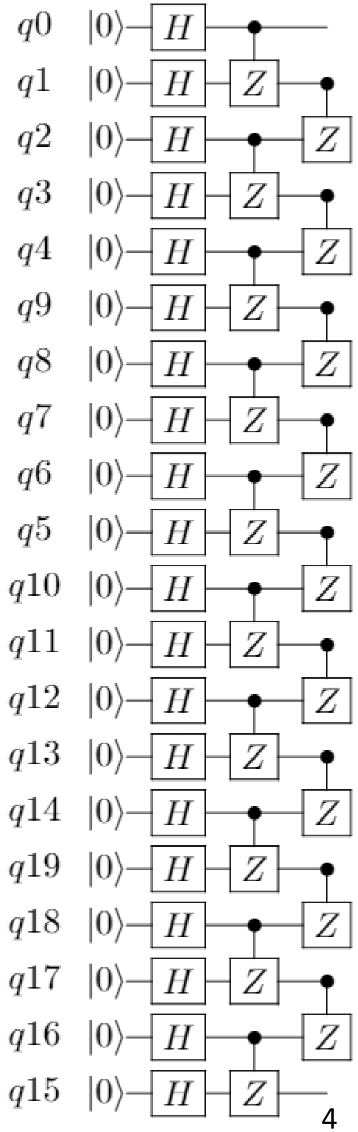

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Detection Strategy

Show state is **not separable**

⇒ At least **bipartite entangled**

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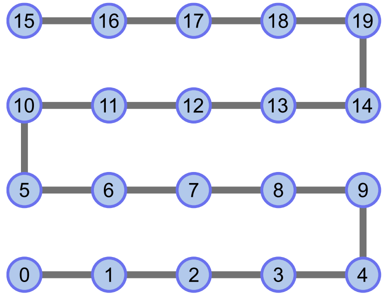

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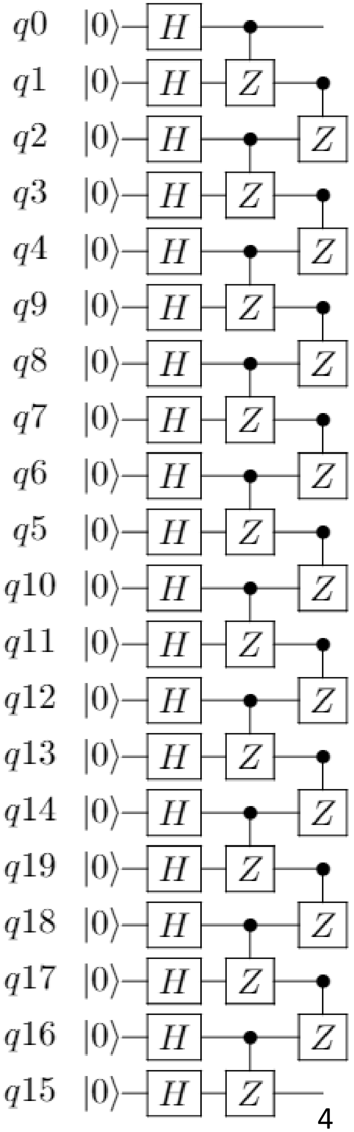

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Entanglement Graph

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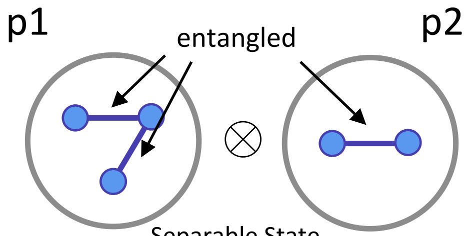

Separable State

Check each pair of connected qubits
→ Detect entanglement ⇒ Add edge

If entanglement graph is connected ⇒ State is entangled

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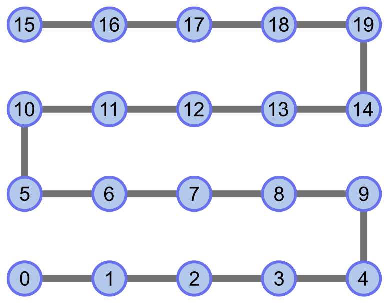

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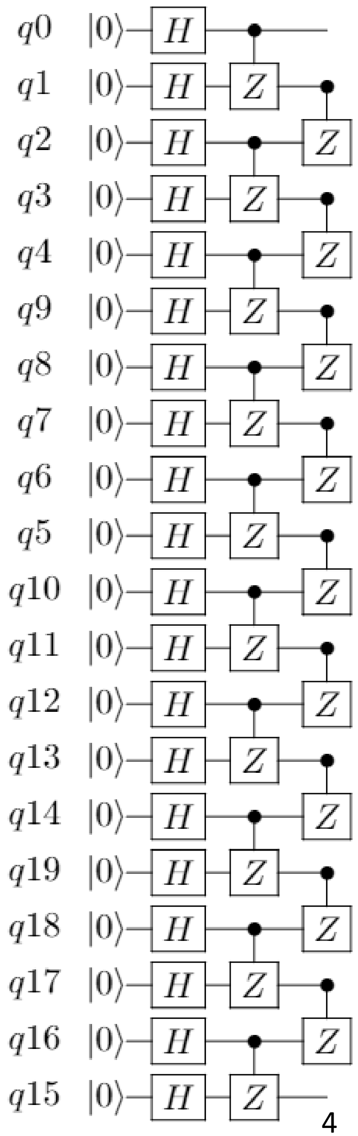

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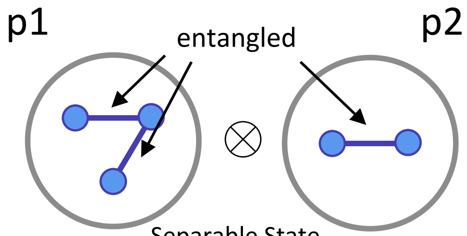

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<u>On Quantum Devices</u>

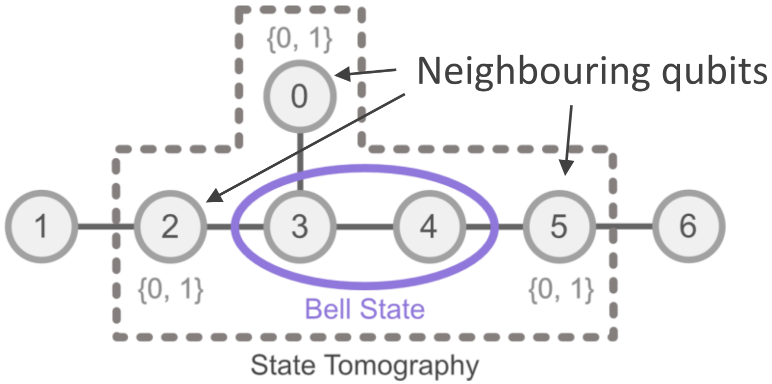
To show: entanglement graph is connected

How to Detect 2-Qubit Entanglement

Full state tomography on target pair of qubits and their neighbours

Example

Entanglement detection between qubits 3 and 4



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Turns out: project neighbour-qubits into Z-basis → **Bell state** (up to local operations)

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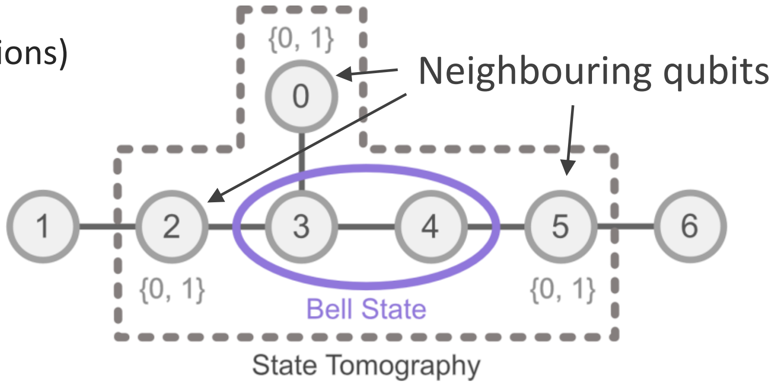

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- Calculate → Sum over magnitudes of negative eigenvalues of $\rho_{3,4}^{T_4}$

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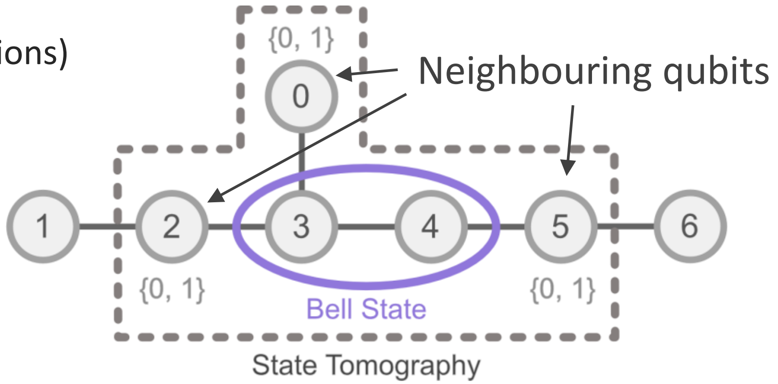

Negativity

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

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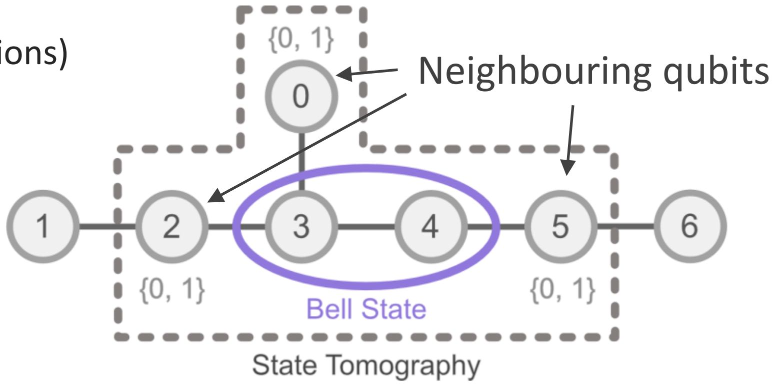

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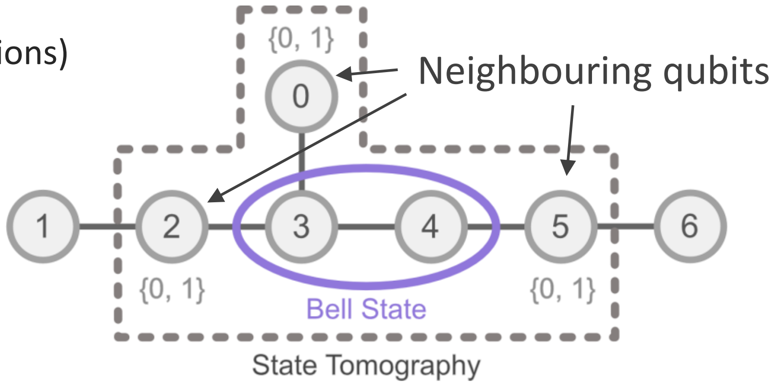

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→ Extent of entanglement is the largest negativity (among the combinations)

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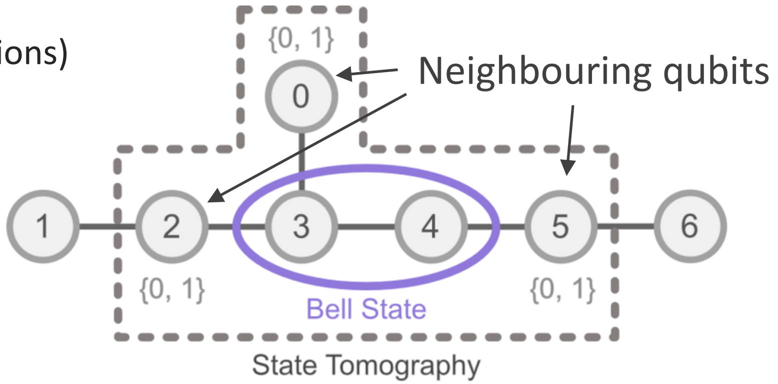

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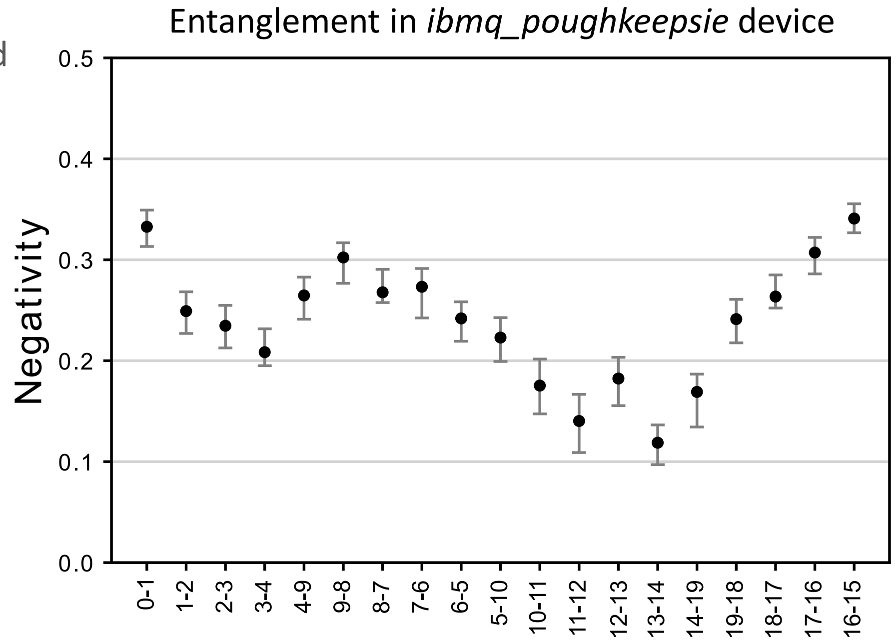
Results: Negativities on an *IBM Quantum* device

Apply these techniques to the **20-qubit** *ibmq_poughkeepsie* device
→ Generate entanglement graph

Maximally entangled

No entanglement



Higher Entanglement

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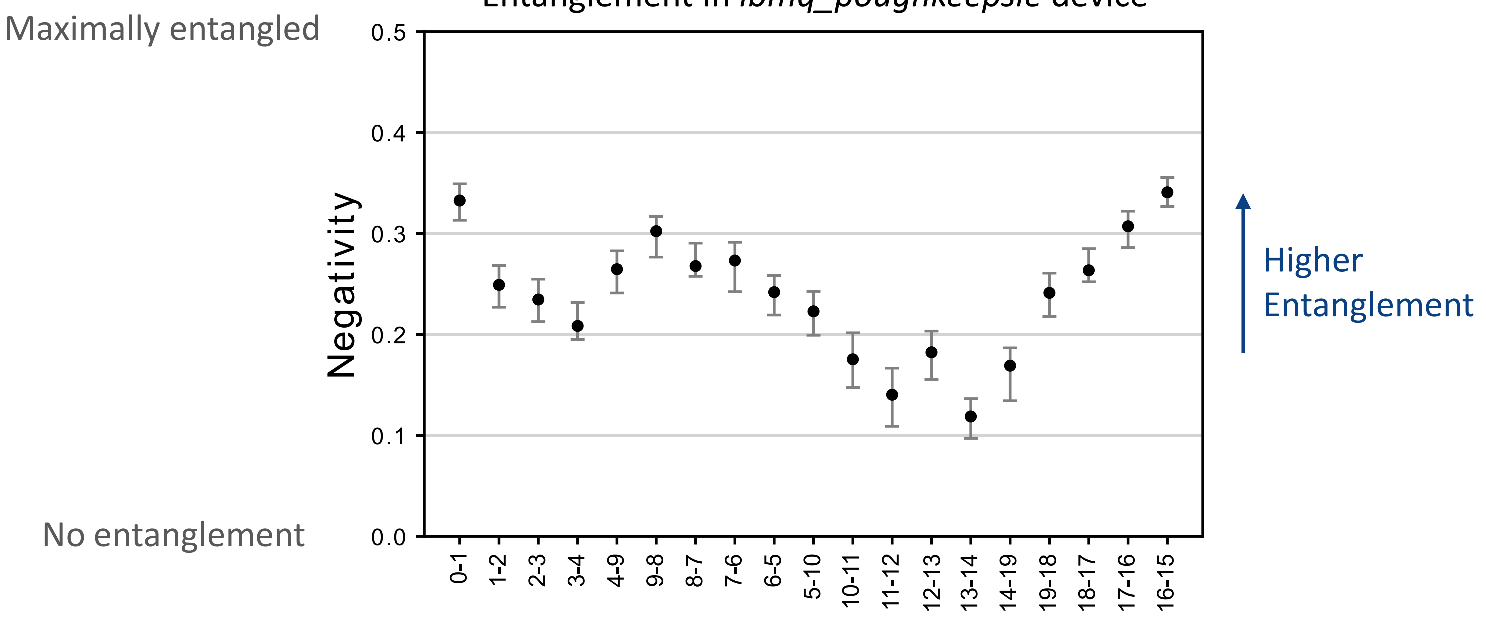

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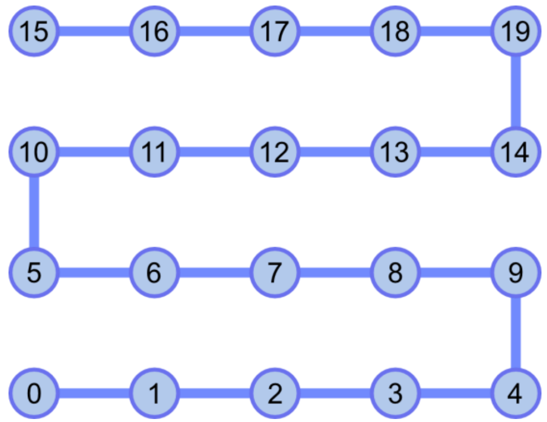
Entanglement Graph
(all qubits connected)



ibmq_poughkeepsie device

Entanglement graph is connected → Whole device is bipartite entangled

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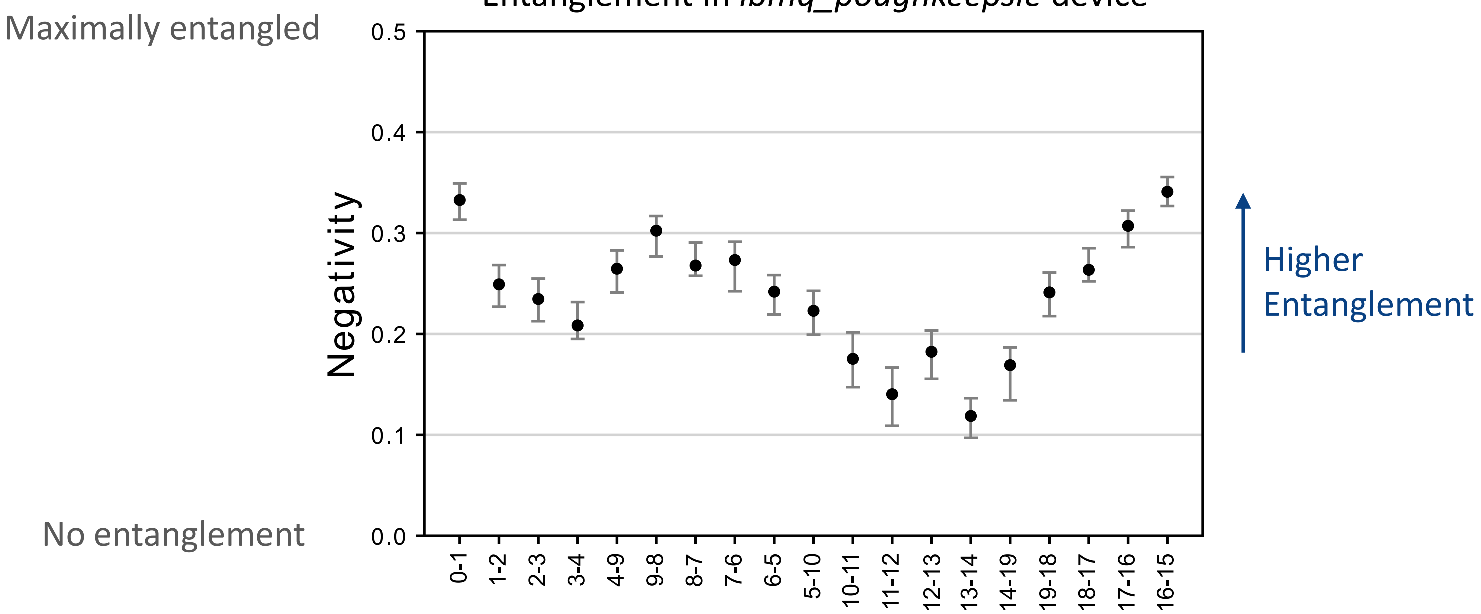

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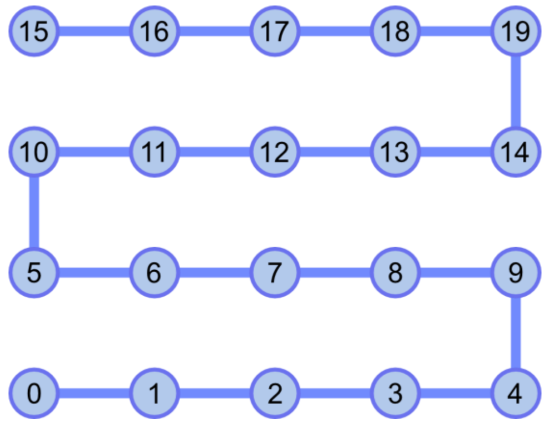

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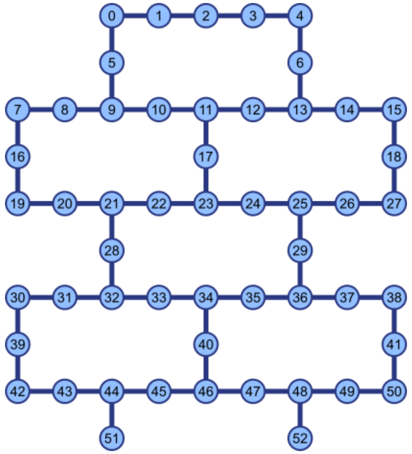
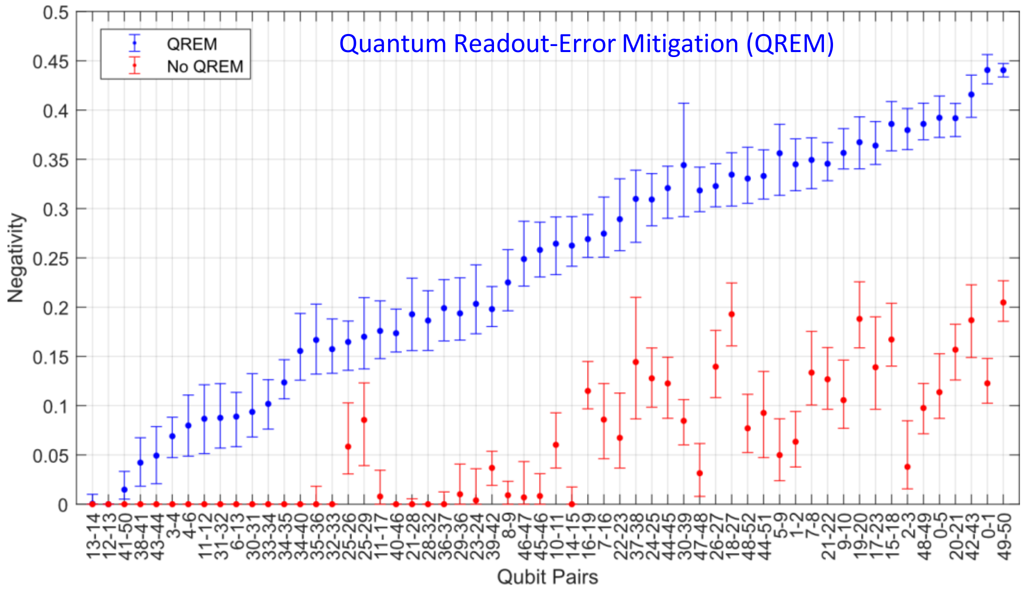
At the time → largest quantum entangled state (on a physical universal quantum computer)

Results: Newer IBM Quantum devices

53-qubit *ibmq_rochester* device





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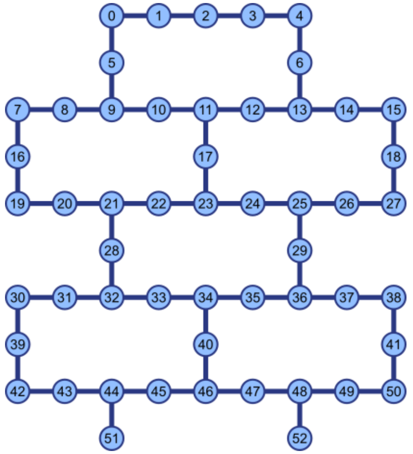
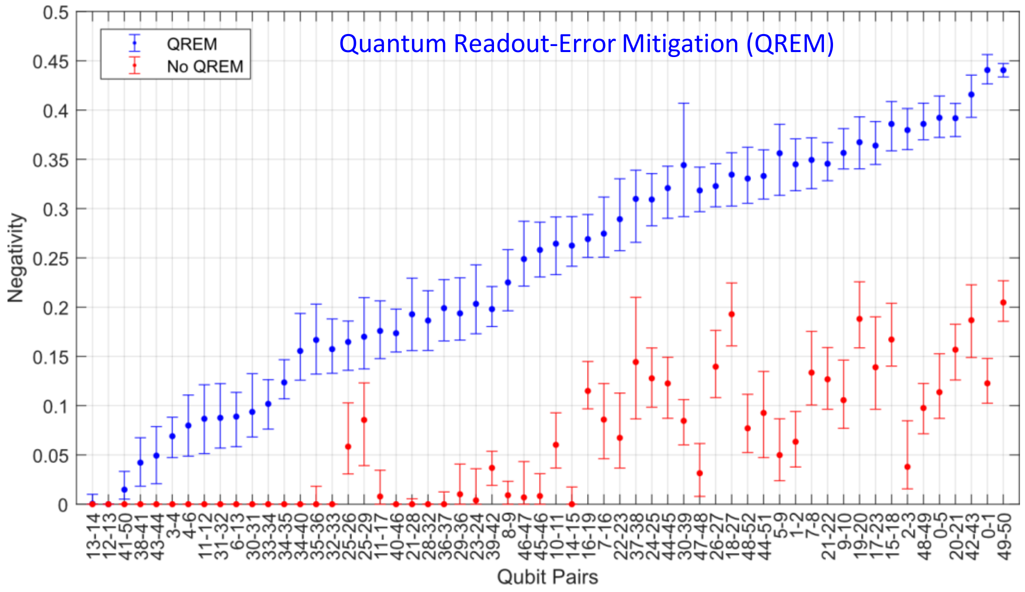
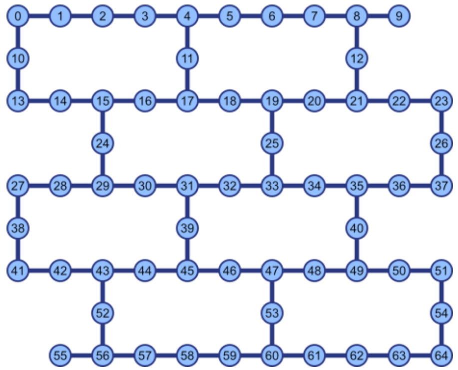
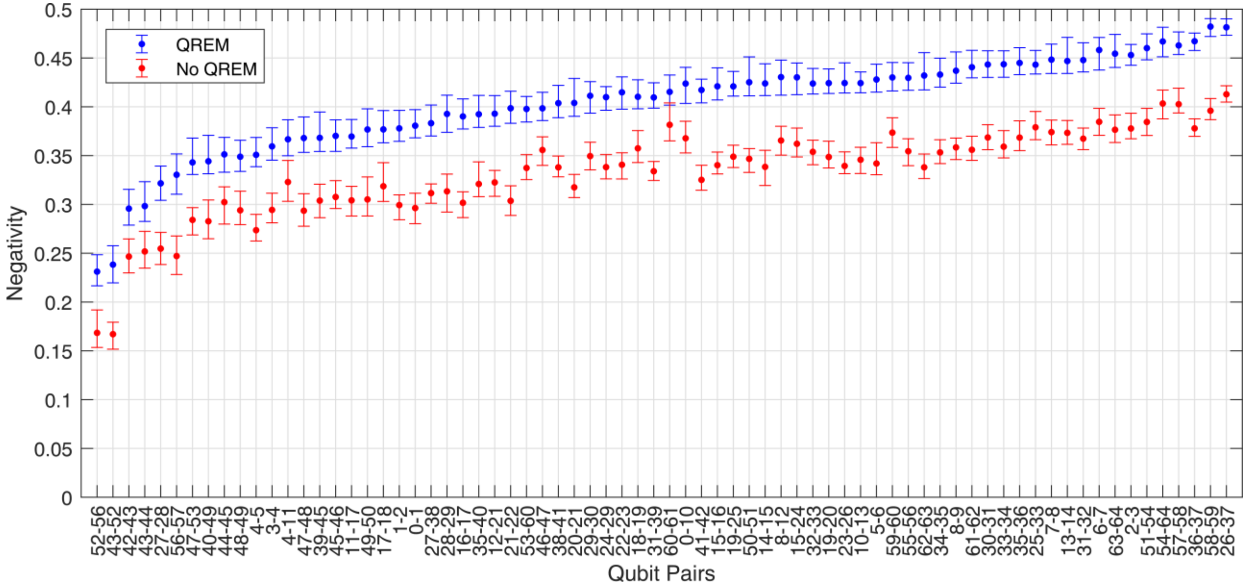




Higher Entanglement

65-qubit *ibmq_manhattan* device





Higher Entanglement

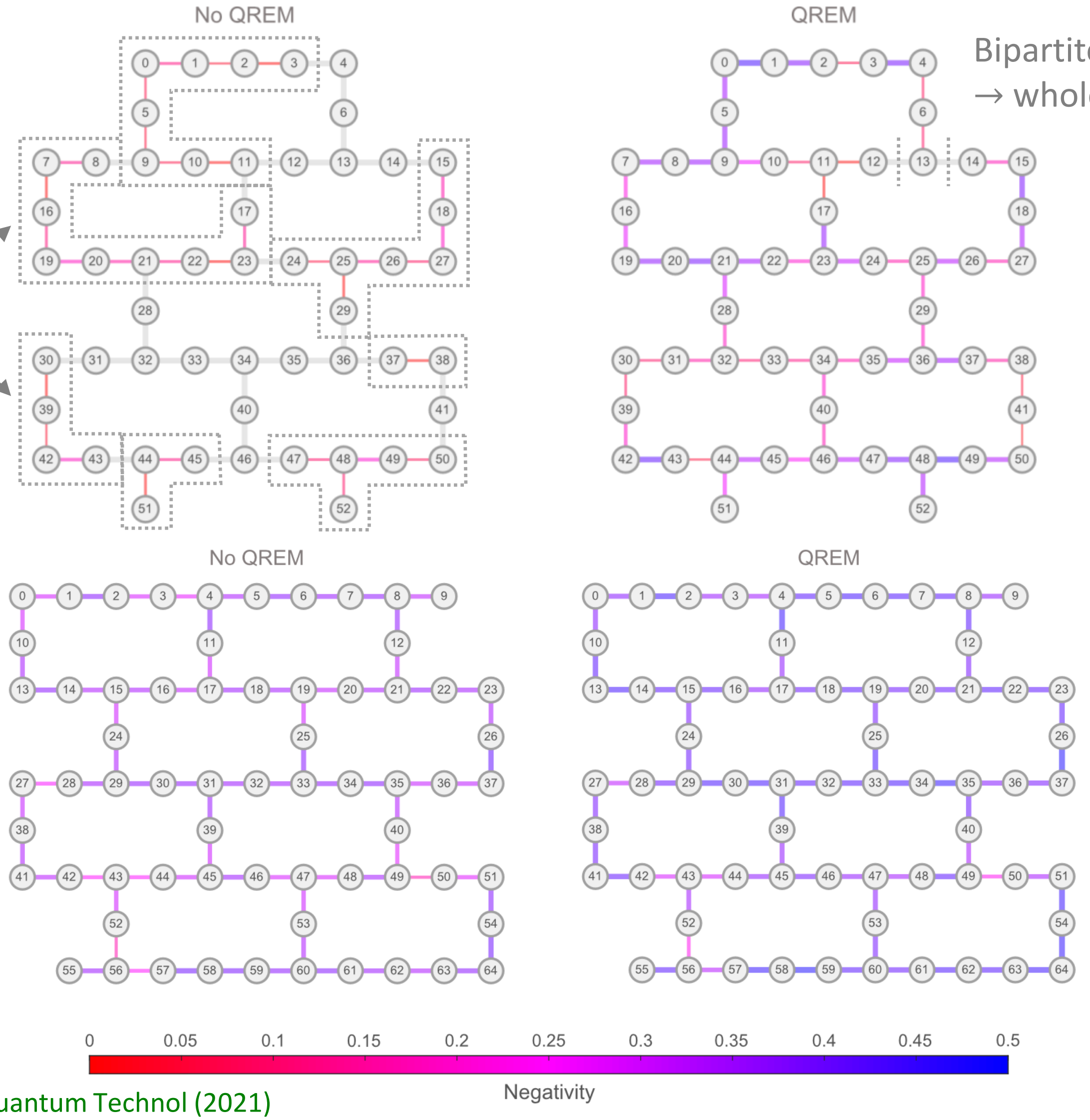
Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)

Results: Entanglement Graphs

53-qubit ibmq_*rochester* device

Bipartite entangled regions

65-qubit ibmq_*manhattan* device



Bipartite entangled region
→ whole device

<u>53 qubits</u>

→ Whole-device bipartite entanglement

<u>65 qubits</u>

→ Whole-device bipartite entanglement

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

Latest: 127-qubit *ibm_washington* Device

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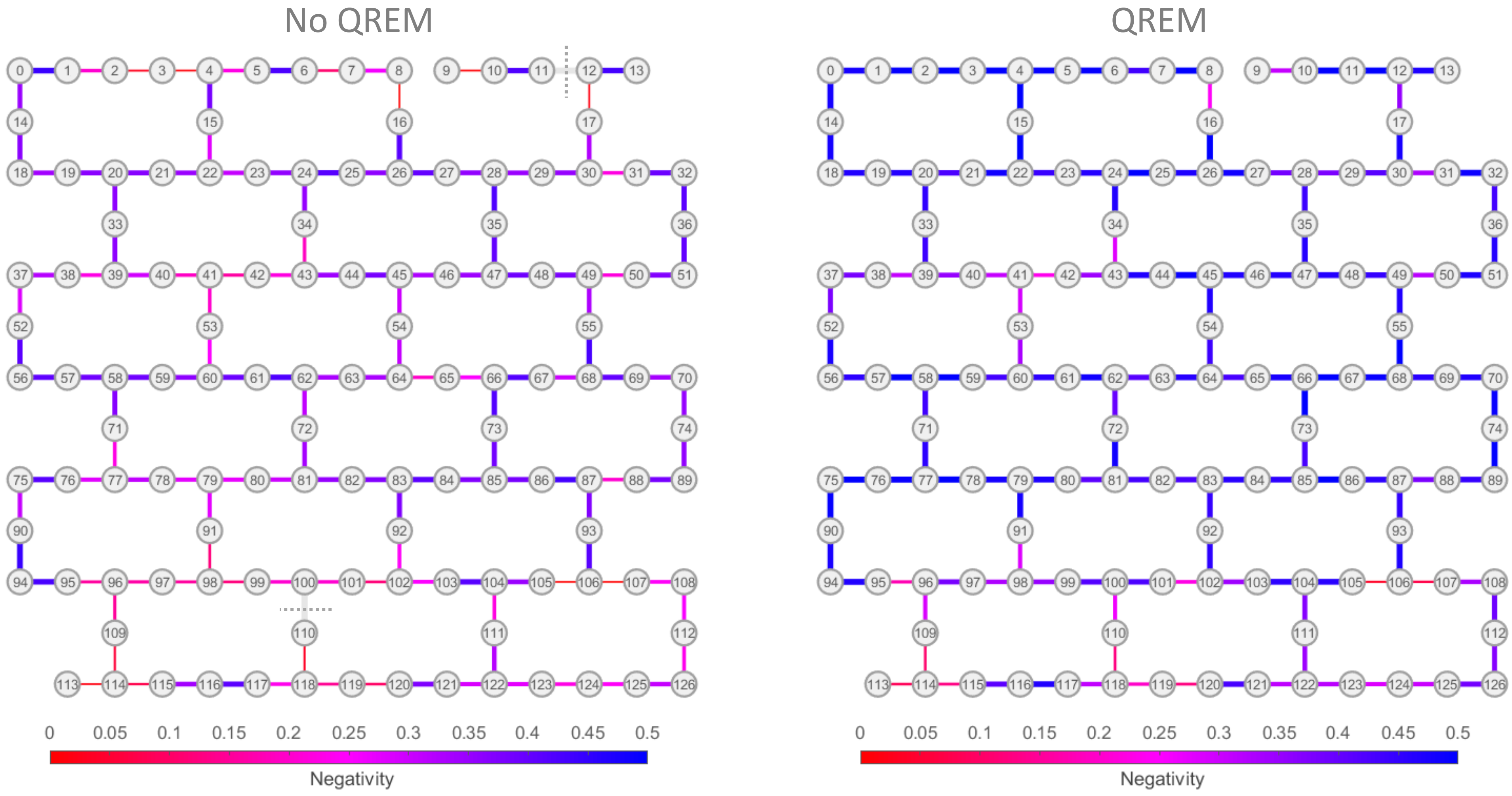
127-qubit *ibm_washington* device



<u>127 qubits</u>

→ Whole-device bipartite entanglement

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

Genuine Multipartite Entanglement (GME) in GHZ states

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

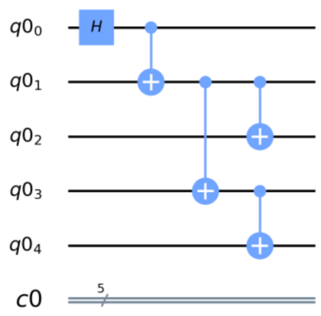
Preparation

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



Genuine Multipartite Entanglement (GME) in GHZ states

GHZ Fidelity (> 0.5) $\rightarrow$ 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)

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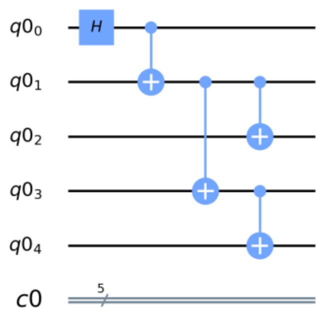

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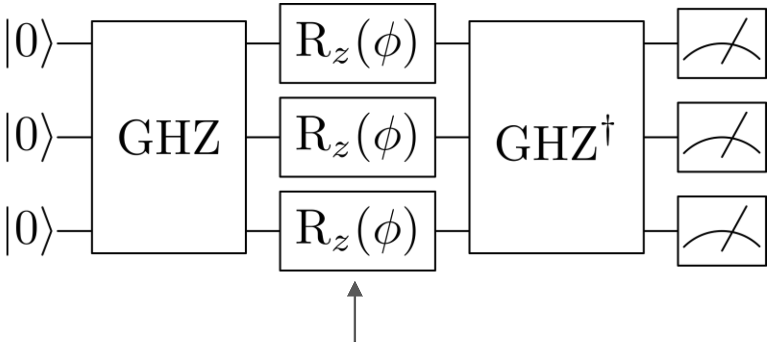
Multiple Quantum Coherences (MQC)



Ideal state: phase of $N\phi$

$$\frac{|00\ldots0\rangle + e^{iN\phi}|11\ldots1\rangle}{\sqrt{2}}$$

Ideal GHZ State

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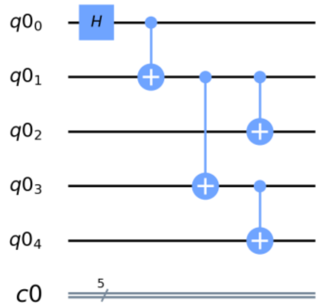

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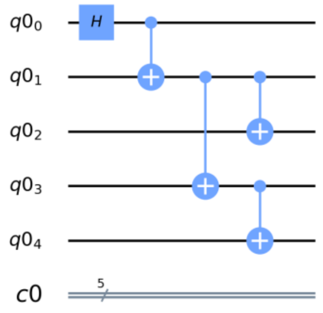
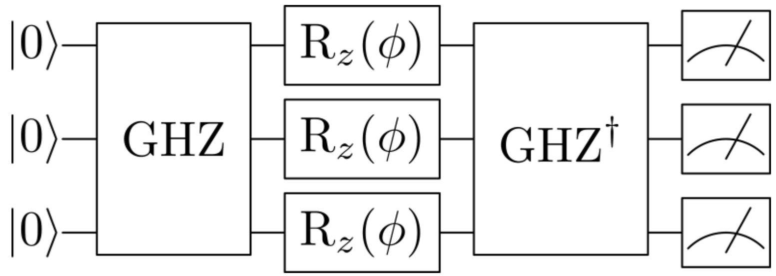


Multiple Quantum Coherences (MQC)



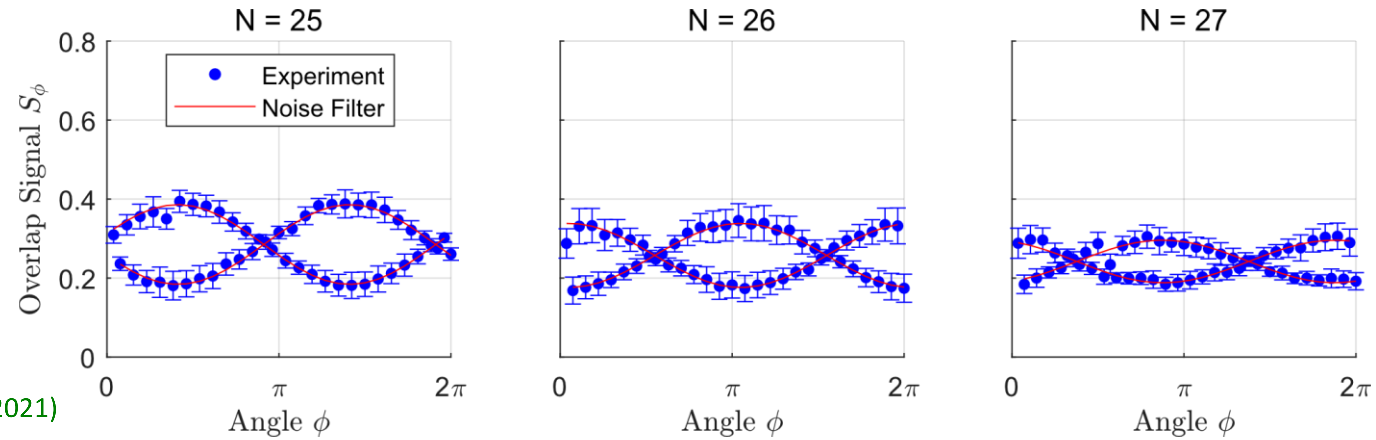
Overlap Signal:
Occupancy of $|00\ldots0\rangle$

Coherence $= 2\sqrt{I_N}$

I_N: Amplitude of overlap signals

Ideal state: phase of $N\phi$

$$\frac{|00\ldots0\rangle + e^{iN\phi}|11\ldots1\rangle}{\sqrt{2}}$$

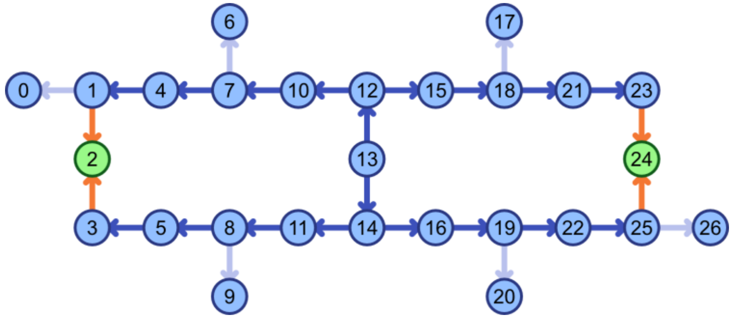


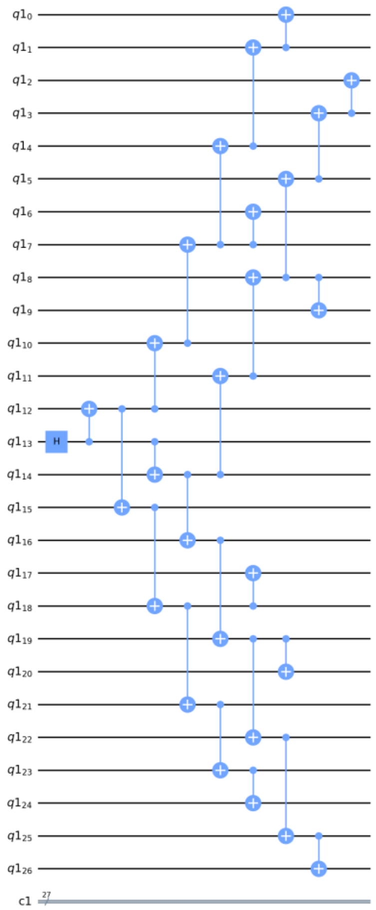
Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

Results: On the 27-qubit *ibmq_montreal device*

- Prepare GHZ States

27-qubit *ibmq_montreal* device



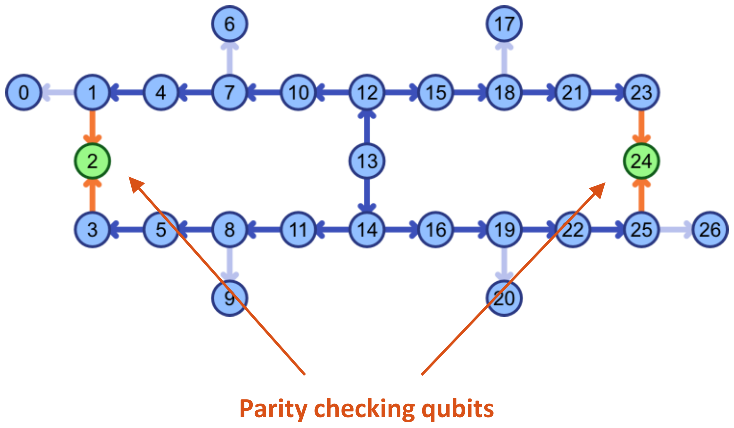


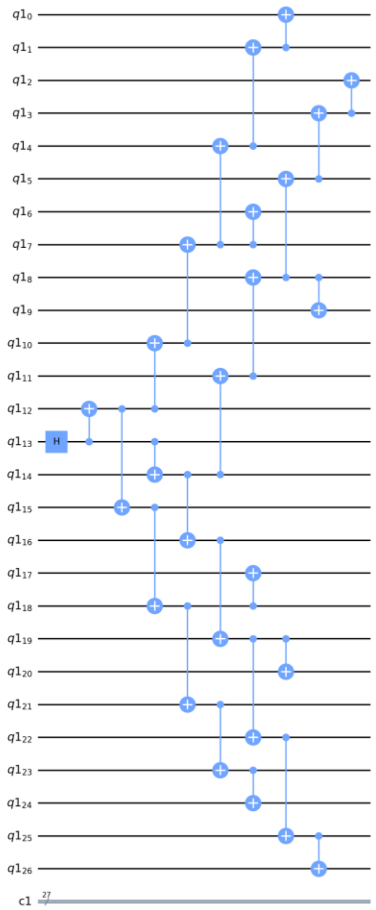
Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

Results: On the 27-qubit *ibmq_montreal device*

- Prepare GHZ States
- Add parity verification
  → effects on fidelity

27-qubit *ibmq_montreal* device





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

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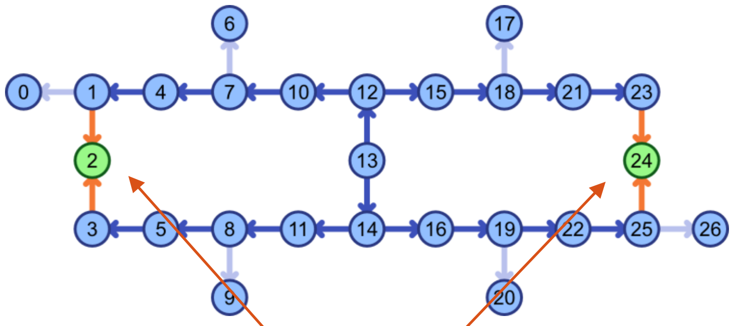

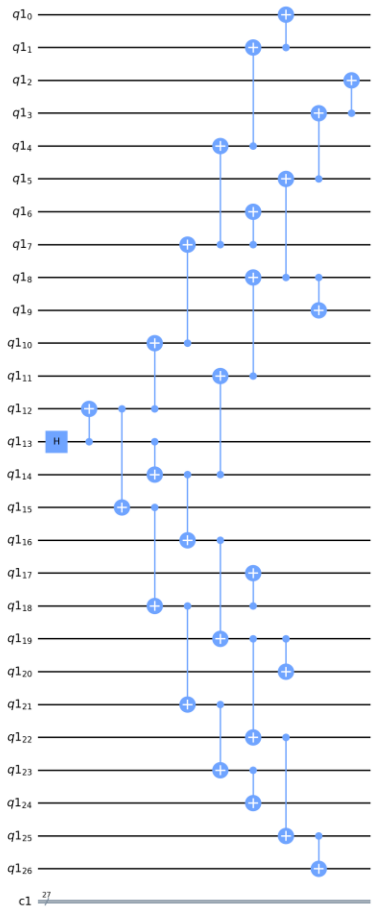

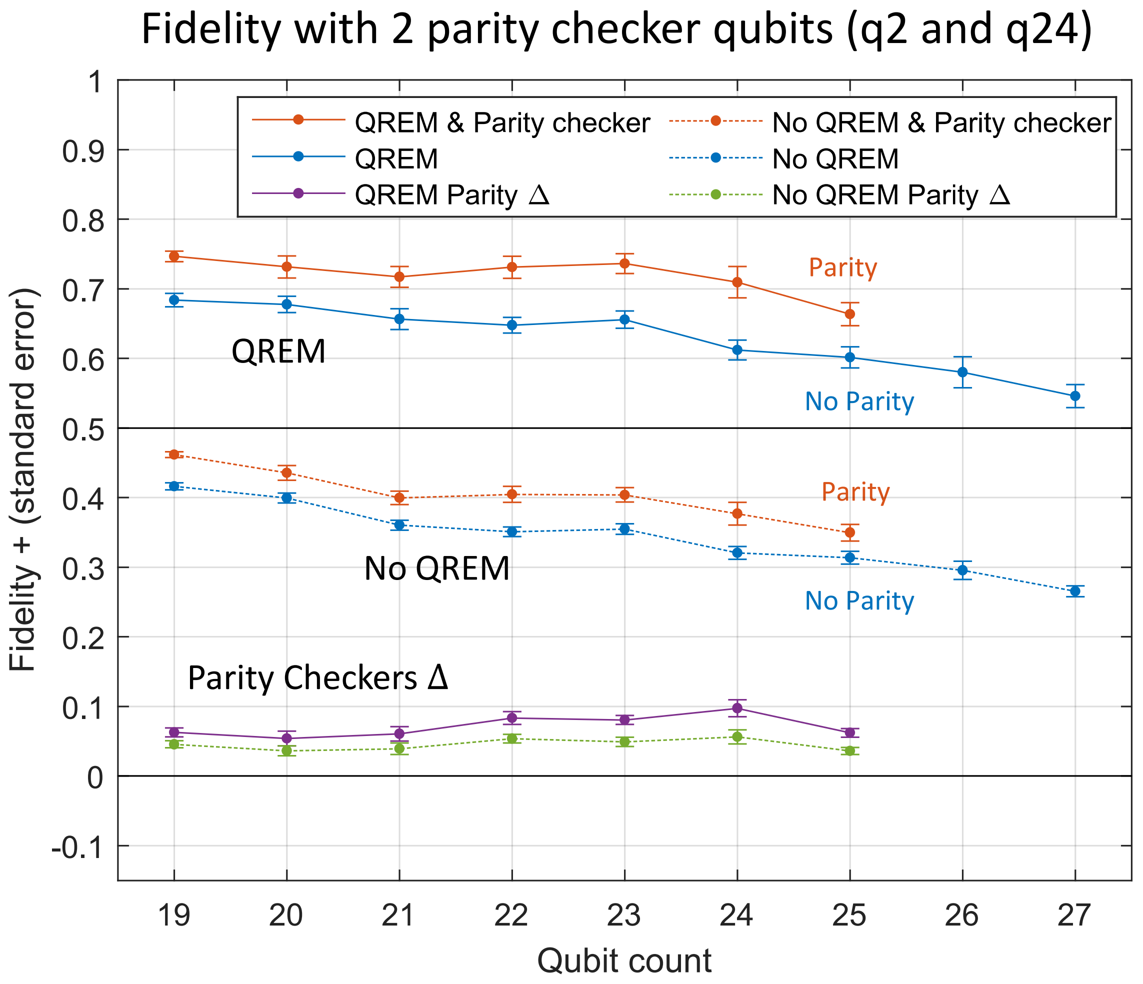

Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

QREM : Quantum Readout-Error Mitigation

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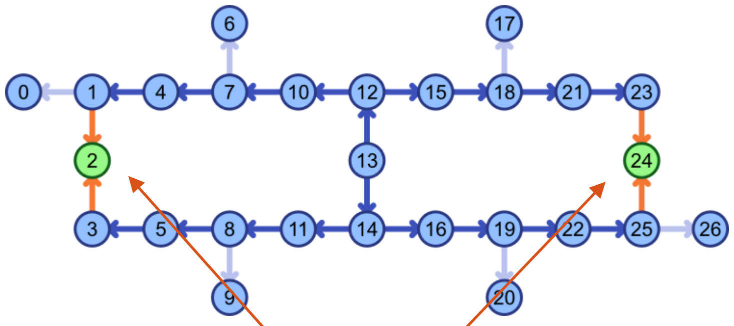
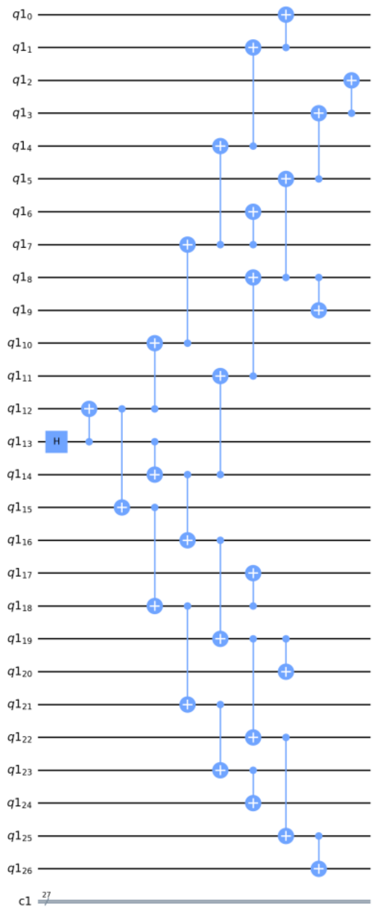
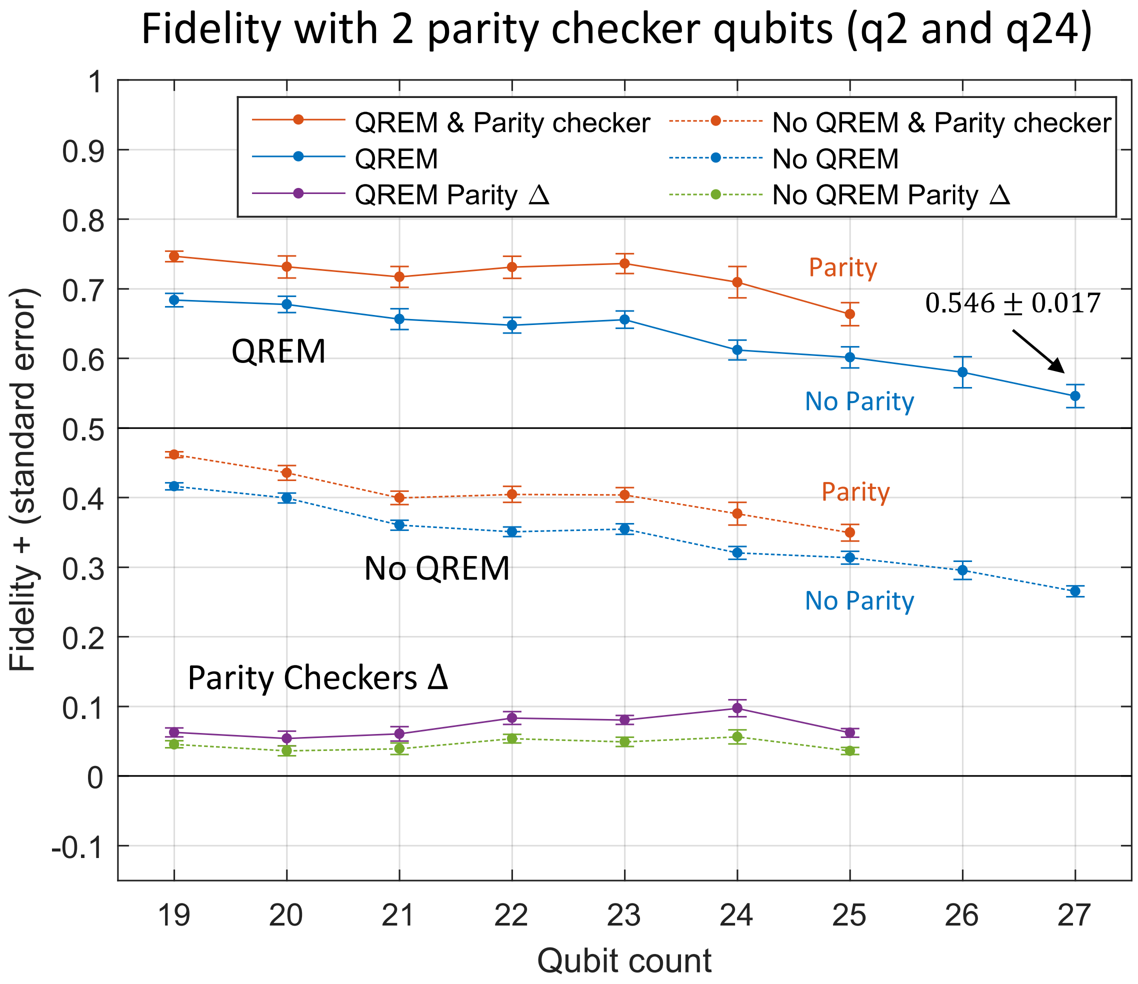
27-qubit *ibmq_montreal* device



Parity checking qubits





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

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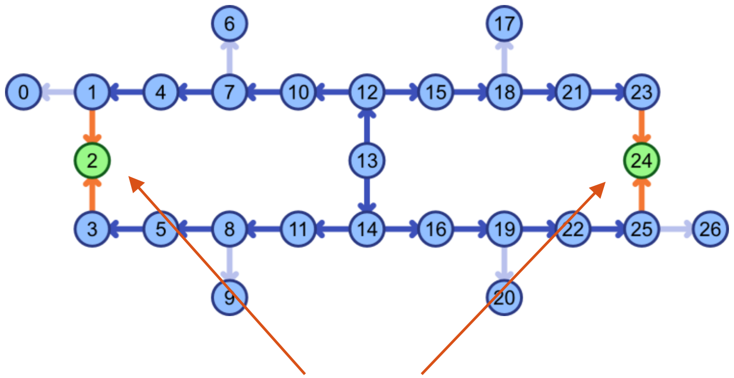

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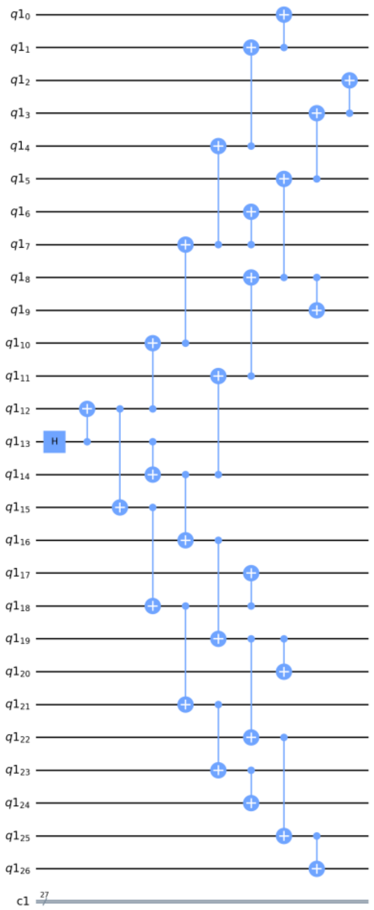
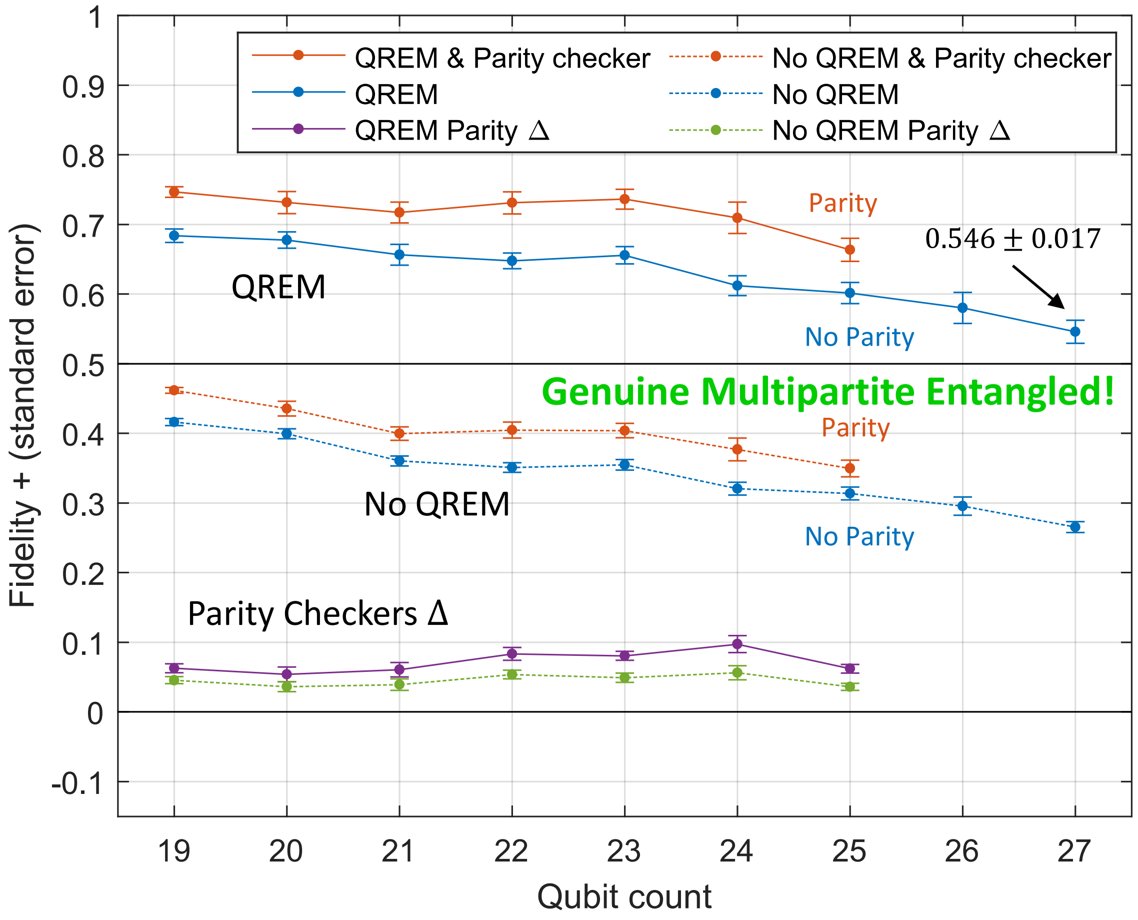


Fidelity with 2 parity checker qubits (q2 and q24)

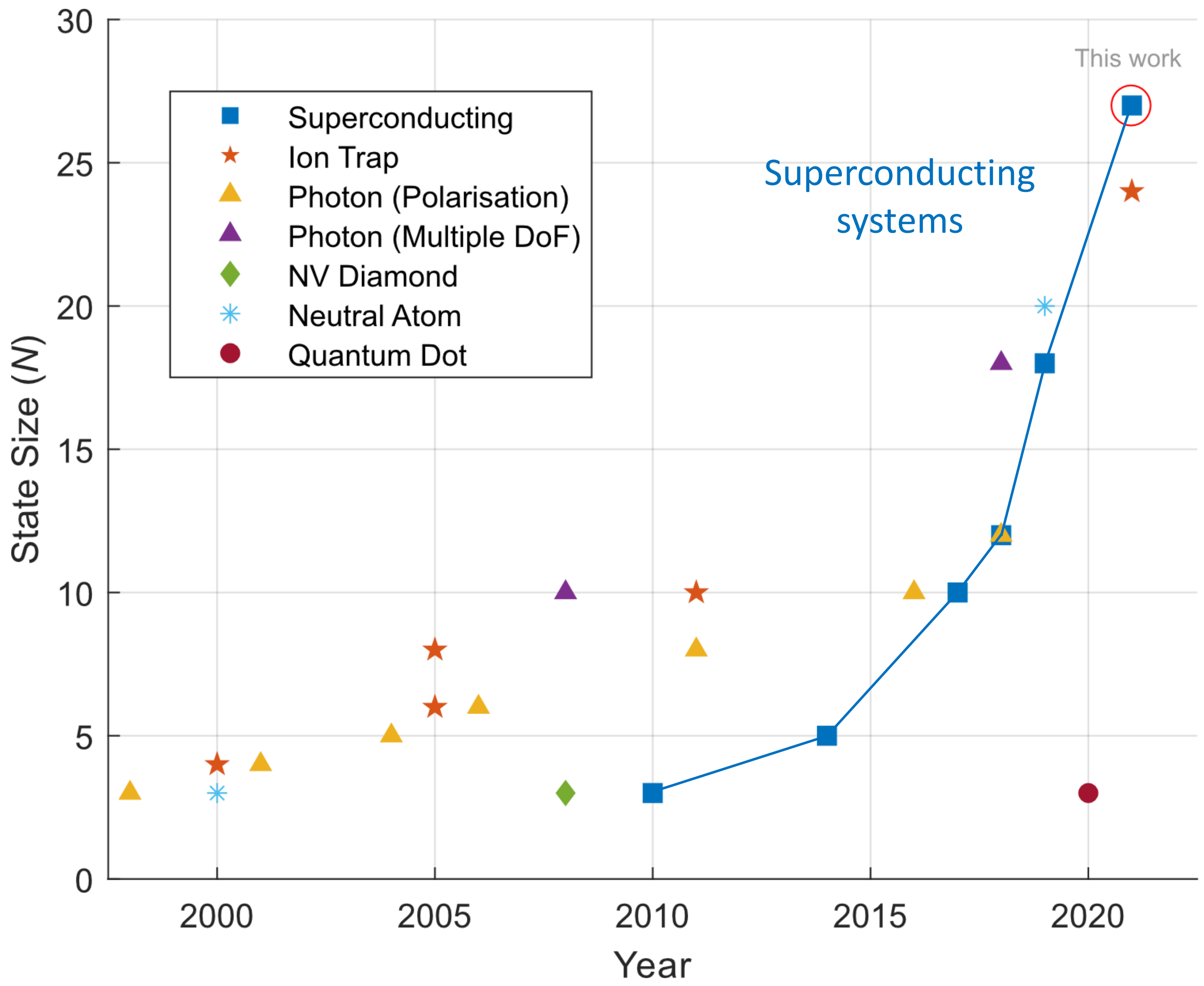


Mooney, White, Hill and Hollenberg, J. Phys. Commun (2021)

QREM : Quantum Readout-Error Mitigation

History of Genuine Multipartite Entanglement

Experimentally prepared states shown to exhibit GME

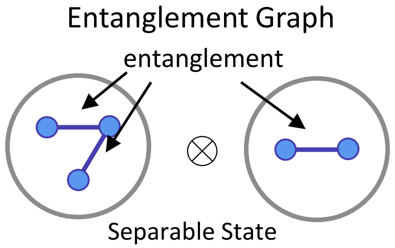


Summary

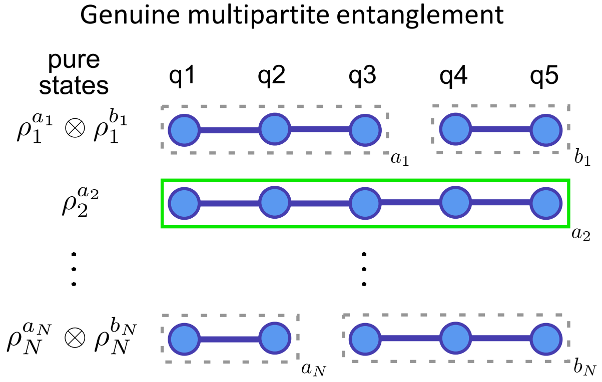
Pure states ρ_i

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

Probabilities p_i



IBM Quantum Network Hub
at the University of Melbourne



Forms of Multipartite Entanglement

- Bipartite entanglement
- Genuine multipartite entanglement

Summary

IBM Quantum Network Hub at the University of Melbourne

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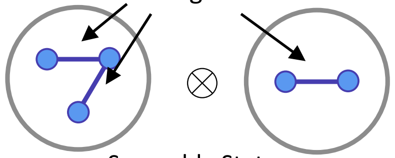
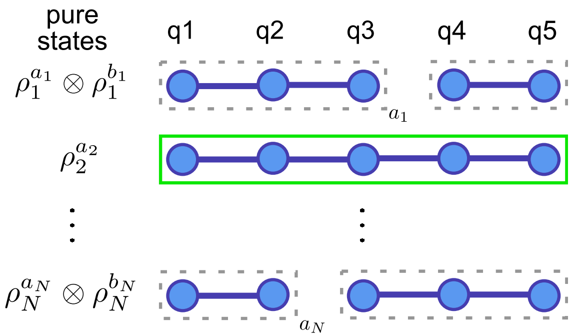
Entanglement Graph



Genuine multipartite entanglement

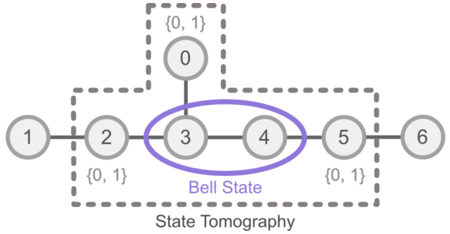


Bipartite entanglement in graph states

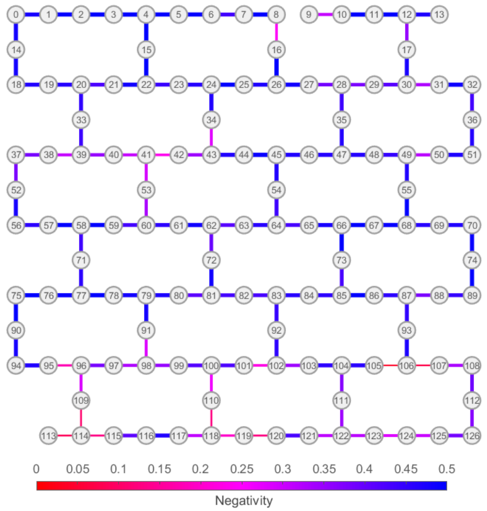
- Found whole-device entanglement on **20**, **53, 65,** and now **127-qubit** devices
- All pairs of the 127-qubit *ibmq_manhattan* entangled

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

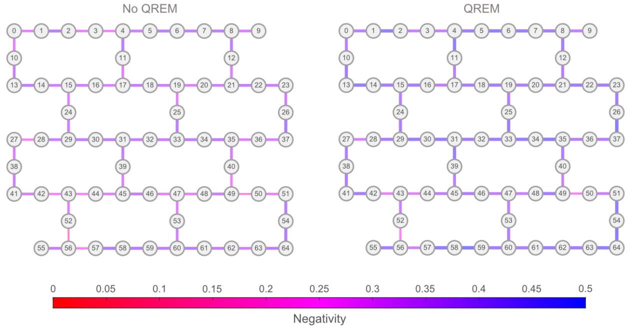
Mooney, White, Hill and Hollenberg, Adv. Quantum Technol (2021)



127-qubit *ibm_washington* device



65-qubit *ibmq_manhattan* device



THE UNIVERSITY OF MELBOURNE

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IBM Quantum Network Hub at the University of Melbourne

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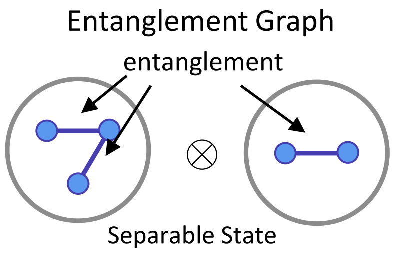

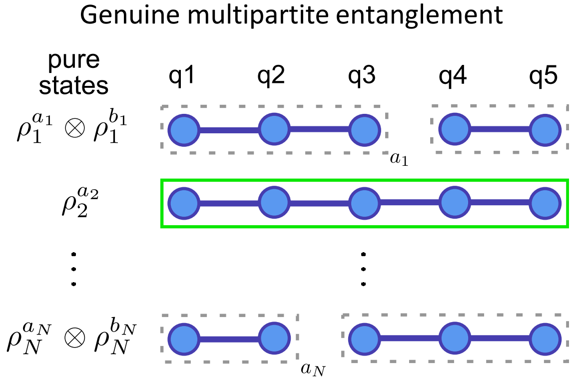

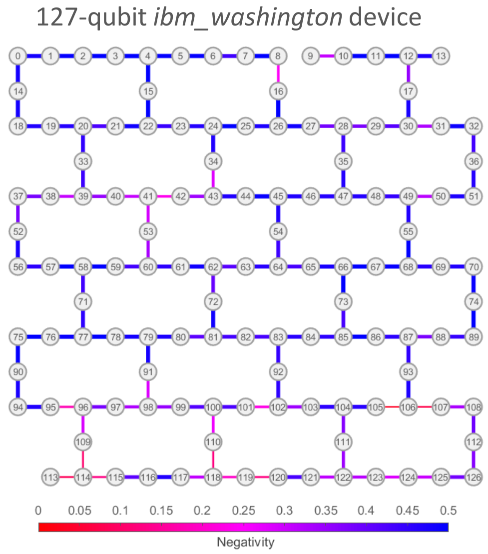

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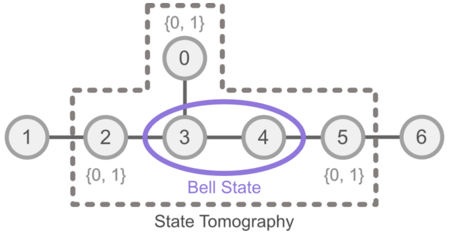
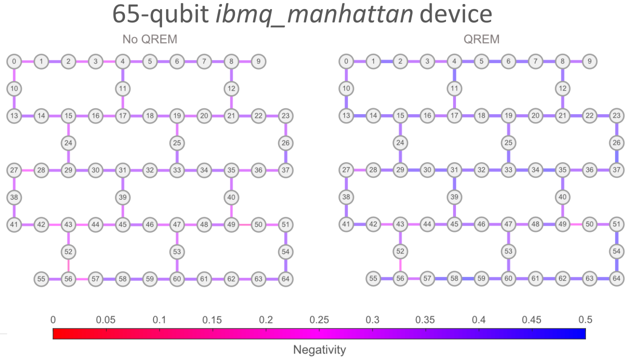
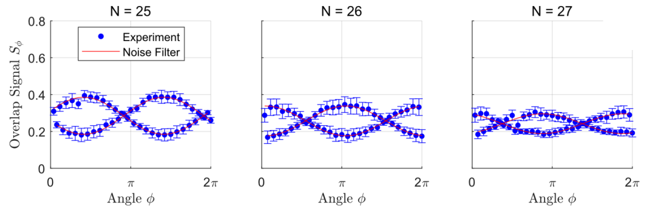


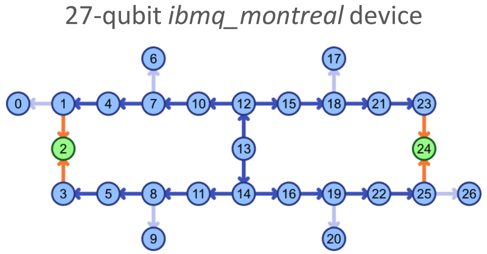


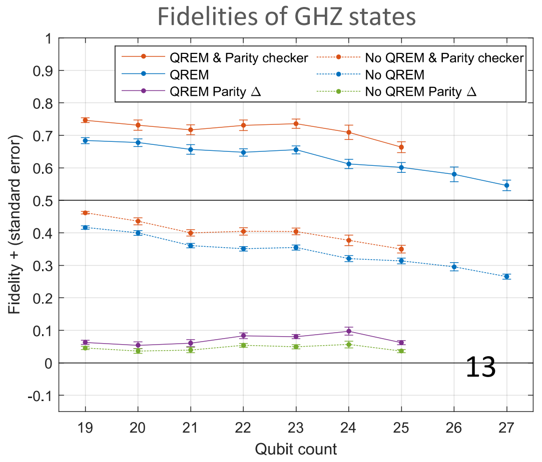


Genuine multipartite entanglement in GHZ state

- Found GME across all **27** qubits of *ibmq_montreal* device
- Applied parity checking error detection
  - Found detectable improvement in fidelity (relatively modest)

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





Thank you

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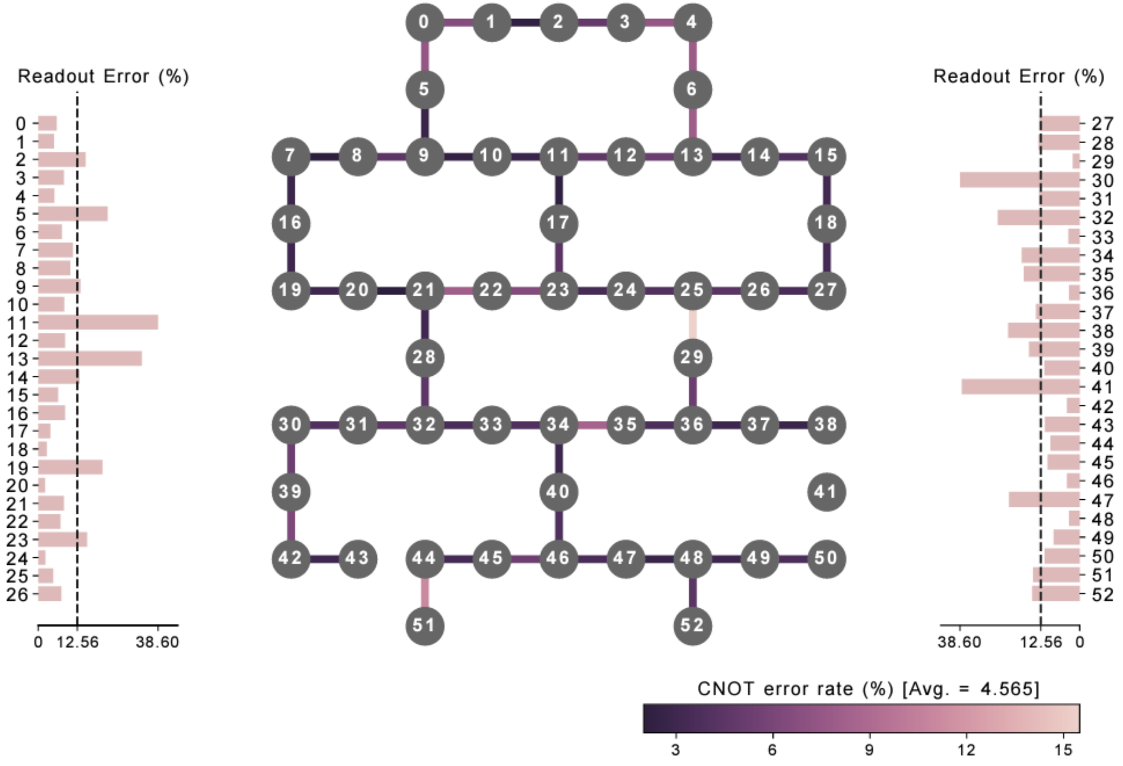
GHZ State Circuit Info

Table 1. CNOT circuit depths and counts required to perform the corresponding experiments.

	Population		Population (parity)		Coherence		Coherence (parity)	
State size (qubits)	Depth	Count	Depth	Count	Depth	Count	Depth	Count
Embedding 1—GHZ state sizes 11 to 19 (one parity-checker qubit)								
11	6	10	7	12	12	20	13	22
12	6	11	7	13	12	22	13	24
13	7	12	8	14	14	24	15	26
14	7	13	8	15	14	26	15	28
15	8	14	8	16	16	28	16	30
16	8	15	8	17	16	30	16	32
17	9	16	9	18	18	32	18	34
18	9	17	9	19	18	34	18	36
19	10	18	10	20	20	36	20	38
Embedding 2—GHZ state sizes 19 to 27 (two parity-checker qubits)								
19	7	18	8	22	14	36	15	40
20	7	19	8	23	14	38	15	42
21	7	20	8	24	14	40	15	44
22	7	21	8	25	14	42	15	46
23	7	22	8	26	14	44	15	48
24	7	23	9	27	14	46	16	50
25	7	24	9	28	14	48	16	52
26	7	25	⋯	⋯	14	50	⋯	⋯
27	7	26	⋯	⋯	14	52	⋯	⋯

Device calibration data

53-qubit *ibmq_rochester*



65-qubit *ibmq_manhattan*