Characterizing resource states and efficient regimes of measurement-based quantum computation on NISQ devices

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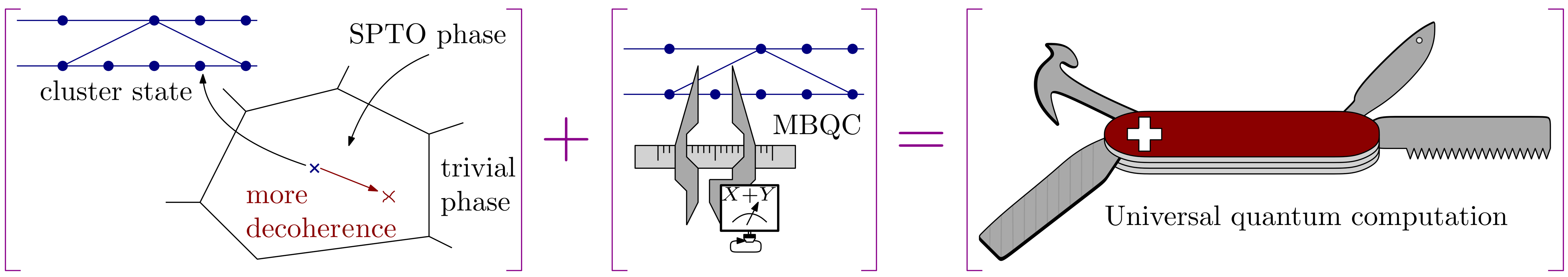
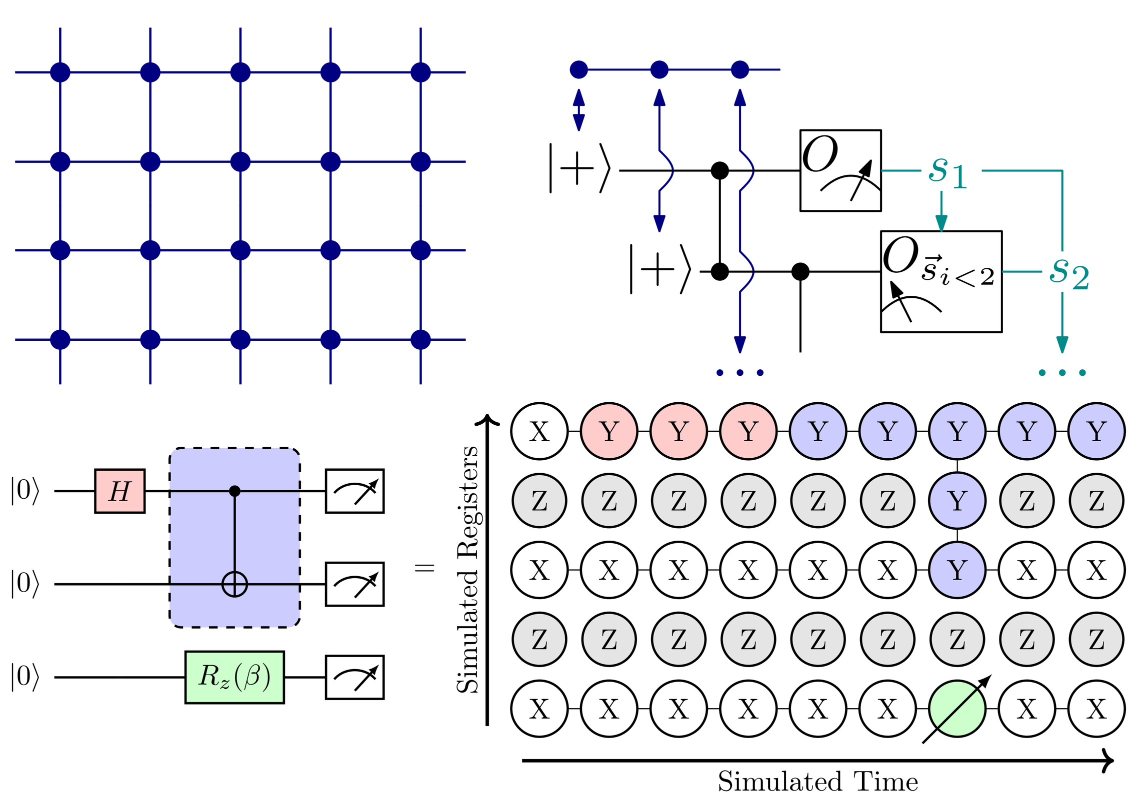
Computationally Universal Phases of Matter



- Motivating Question: Can we experimentally demonstrate computation throughout the cluster phase and optimal decoherence management techniques?

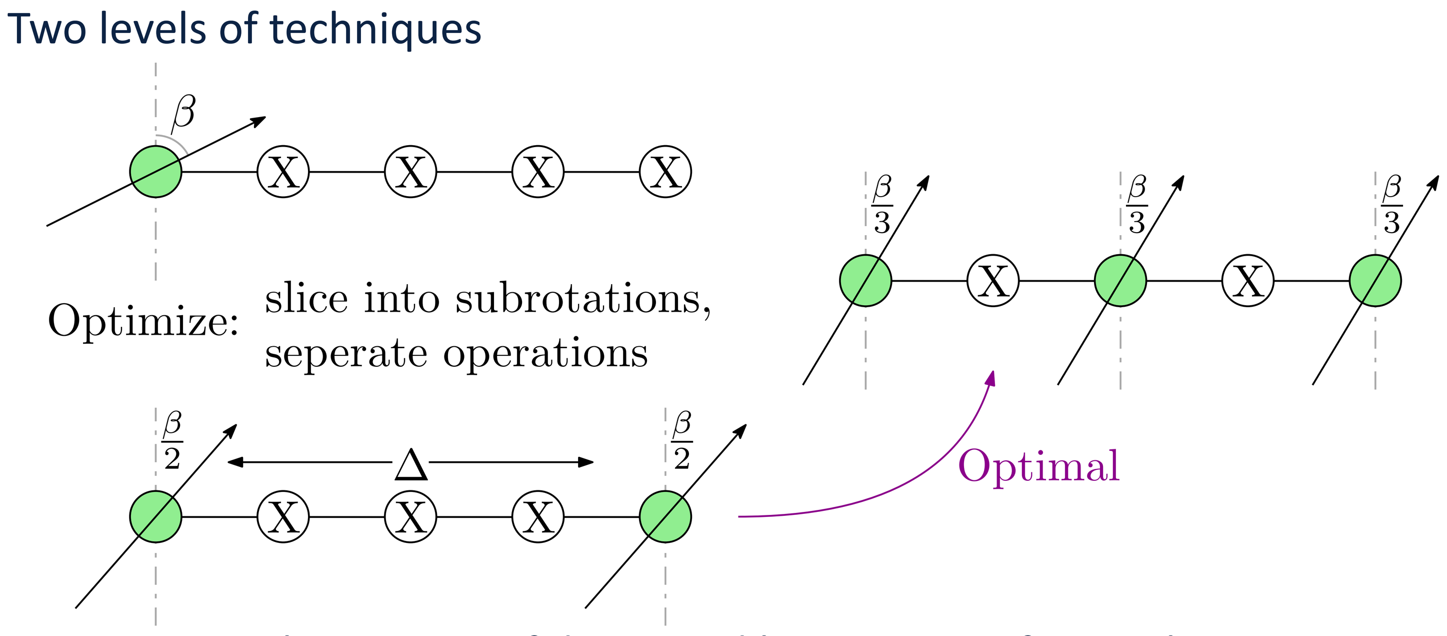
Measurement-based quantum computation

- Start: Robustly entangled state (cluster state): -1 eigenvalue state of $X_a \prod_{b\in N(a)} Z_b$ on $n \times m$ grid.
- Operations: Adaptive one-qubit measurements
- Result: Arbitrary m-qubit unitary.

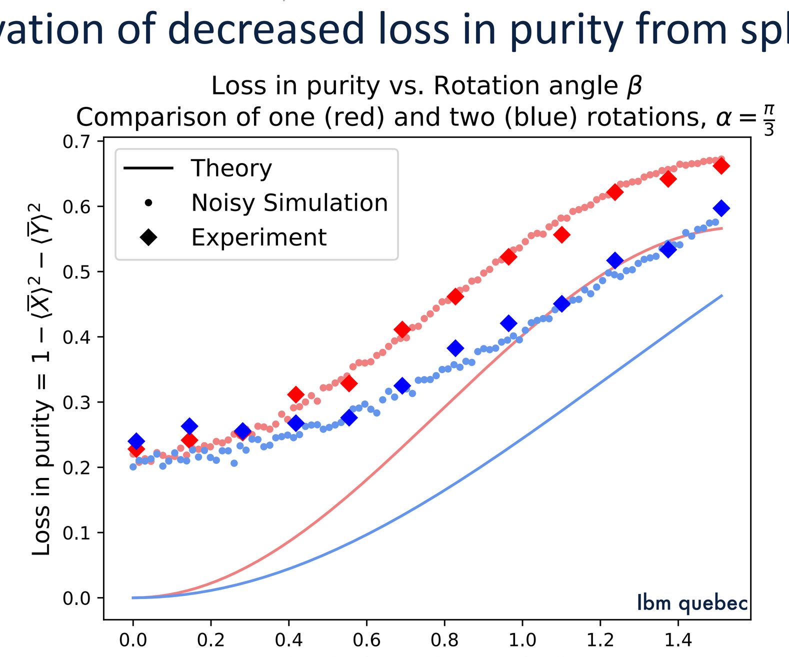


Managing Logical Decoherence

- Two levels of techniques

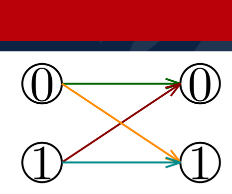


- Experiment: Observation of decreased loss in purity from splitting rotation



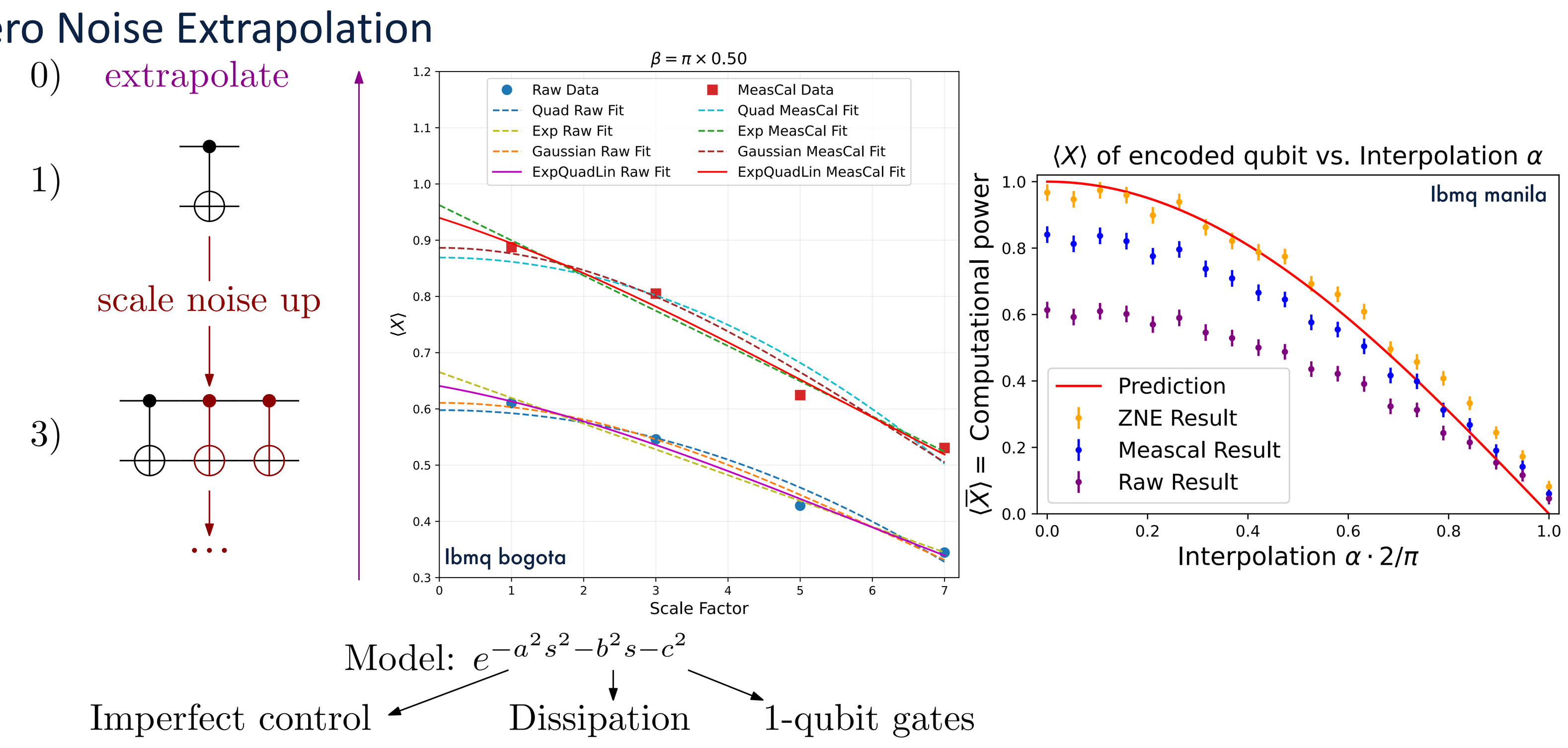
Error mitigation

- Measurement Noise



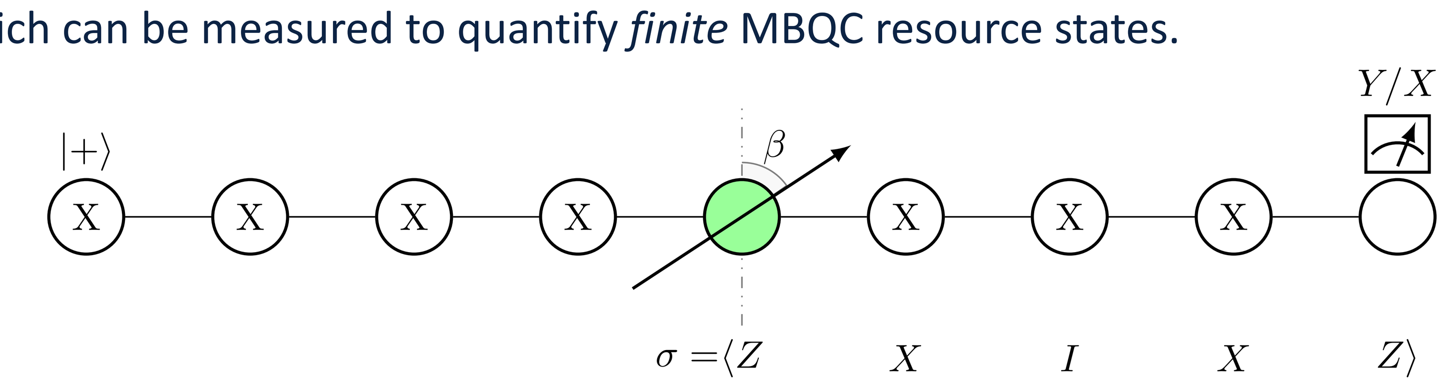
$$M = \begin{bmatrix} p & 1-q \\ 1-p & q \end{bmatrix} \quad [\text{noisy}] = M[\text{ideal}]$$

- Zero Noise Extrapolation

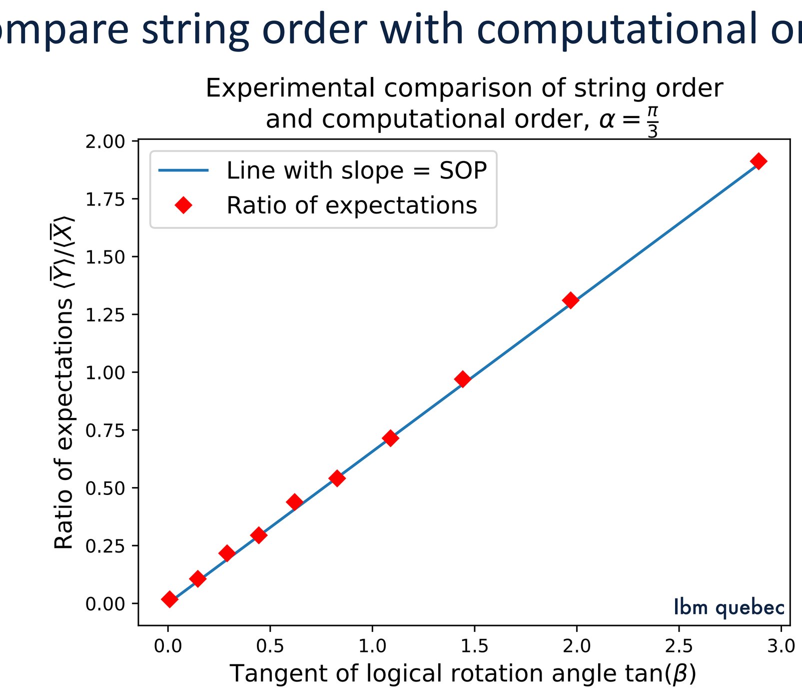


String Order = Computational Order

- Investigating ground states of:
$$H(\alpha) = -\cos(\alpha)\sum_i Z_{i-1}X_iZ_{i+1} - \sin(\alpha)\sum_i X_i$$
for infinite chains, ground states for $\alpha < \pi/4$ belong to the $\mathbb{Z}_2\times\mathbb{Z}_2$ cluster phase.
- Away from the cluster state, symmetry-breaking measurements induce logical decoherence. Action of Z-rotation at site j is given by:
$$\mathcal{V}_j[\beta] = \frac{1+\nu}{2}\exp\left(-i\frac{\beta}{2}Z_j\right) + \frac{1-\nu}{2}\exp\left(i\frac{\beta}{2}Z_j\right)$$
- ν is the computational order parameter. Characterizes the logical fidelity of the rotation, and analytically equivalent to the string order parameter:
$$\sigma_j = \langle Z_jX_{j+1}X_{j+3}\dots X_{n-3}X_{n-1}Z_n\rangle$$
which can be measured to quantify *finite* MBQC resource states.

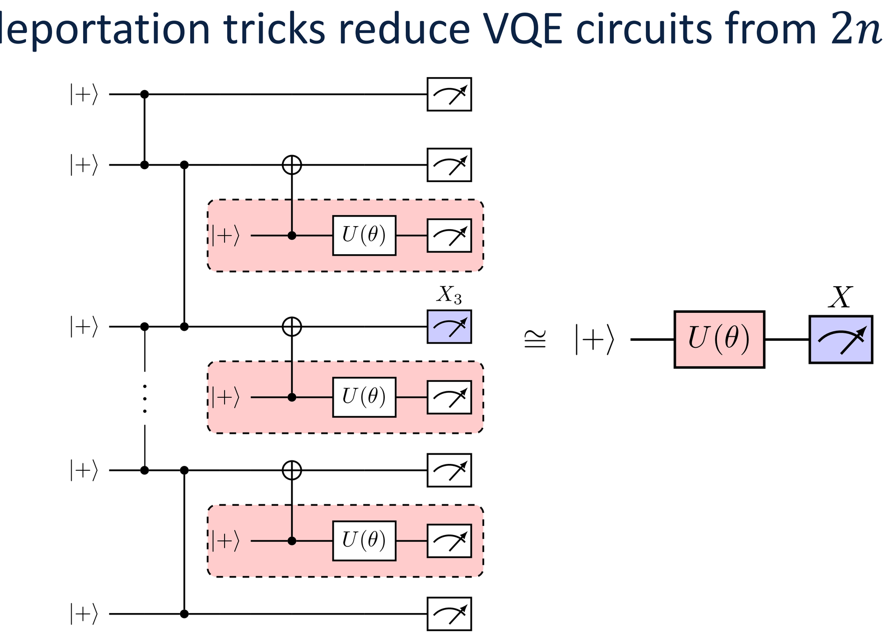


- Experiment: Prepare ground states, input logical state $|+\rangle$, perform symmetry-breaking rotation, and independently measure $\sigma = \langle ZXIXZ\rangle$ and $\frac{\langle Y\rangle_{log}}{\langle X\rangle_{log}} = \nu\tan(\beta)$ to experimentally compare string order with computational order.



State Preparation via VQE

- Variational ansatz for ground states of $H(\alpha)$; first-order perturbation theory gives:
$$|\Psi(\theta)\rangle = \otimes_i(\cos(\theta)I_i + \sin(\theta)X_i)|\mathcal{C}\rangle$$
- Respects $\mathbb{Z}_2\times\mathbb{Z}_2$ symmetry, reproduces (a form of) the phase transition, and exact for small system size. Minimizing $\langle\Psi(\theta)|H(\alpha)|\Psi(\theta)\rangle$ w.r.t. θ yields target state.
- Symmetry and teleportation tricks reduce VQE circuits from $2n-2 \to 1\&2$ qubits!



References

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[2] Adhikary, Arnab and Wang, Yang and Raussendorf, Robert Counter-intuitive yet efficient regimes for measurement based quantum computation on symmetry protected spin chains. arXiv preprint, arXiv:2307.08904, July 2023.
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