Real-time dynamics of SYK model on a noisy quantum computer

Based on arXiv:2311.17991 with M. Asaduzzaman & B. Sambasivam + upcoming work (~April/May 2024)

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Jefferson Lab Exploring the Nature of Matter JSA

C²QA Co-design Center for Quantum Advantage

Talk available online at rgjha.github.io

Today's agenda

- Holography from super Yang-Mills (SYM) to Sachdev-Ye-Kitaev (SYK)
- Effectiveness of tensor networks for local Hamiltonians
- Approaches to universal computing: Gates and real-time evolution using quantum circuits
- SYK model with $N \leq 8$ on IBM quantum computers with error mitigation
- Brief comment on upcoming tVQ solver, summary, and future directions

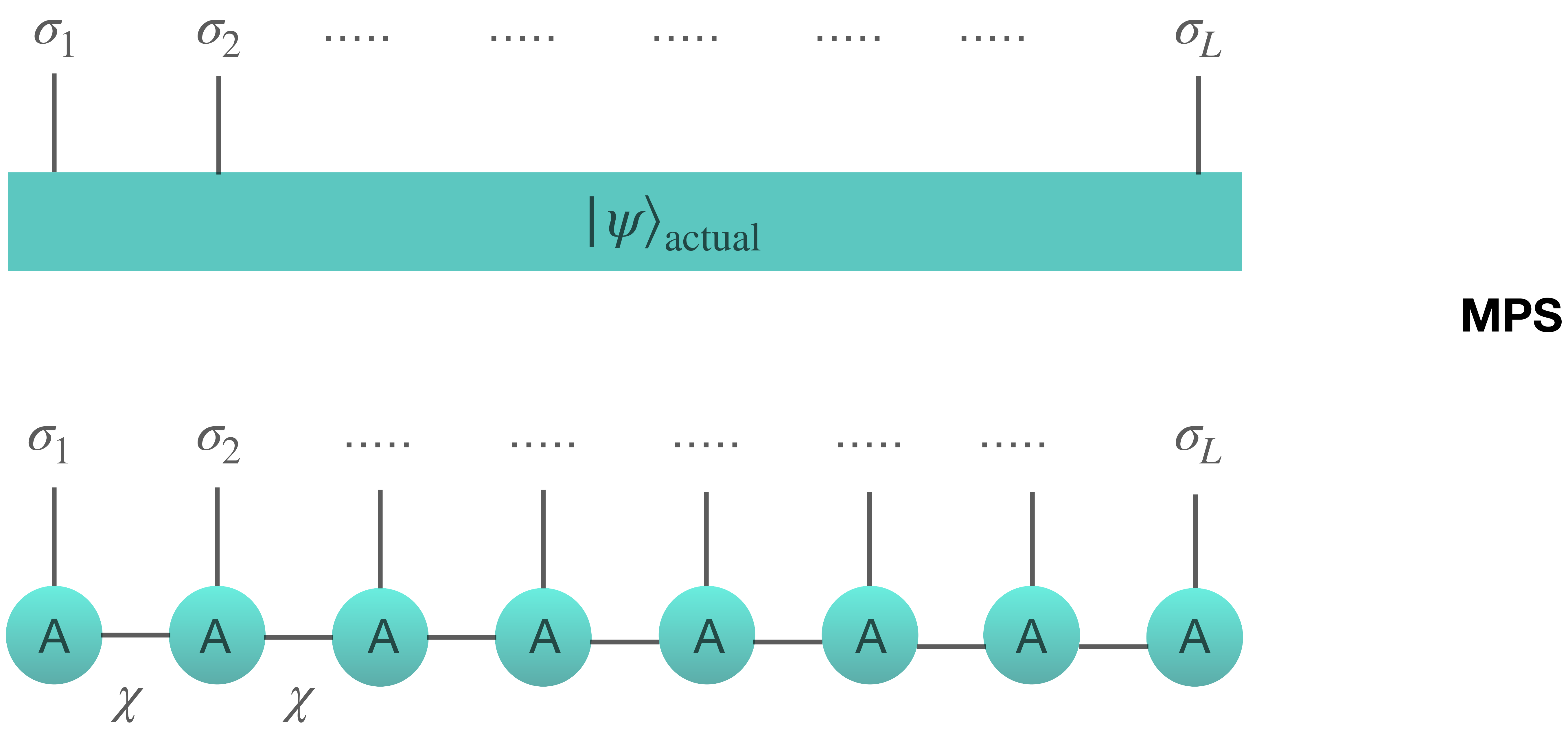
Holographic duality

- Certain supersymmetric (maximal) gauge theories are dual to Type IIA/B supergravity at strong couplings in the large N (planar) limit.
- Insights into quantum gravity from quantum field theory and quantum many-body systems.
- Famous example: AdS/CFT, a version of it was soon also extended to super Yang-Mills (SYM) in $p+1$ dimensions for $p<3$ [Maldacena et al., PRD **58** 046004(1998)]
- Due to strong/weak nature, solving both sides simultaneously is difficult (possible due to integrability for some cases) even for 0+1-dimensional models such as BFSS. Reduce the field content to a point where we just have interacting fermions (all-to-all). This model proposed by SY and K is a potential toy model where certain limit can be evaluated on both sides and therefore interesting.
- We have limited tools to study real-time dynamics of such strongly coupled models. One leading candidate is tensor networks (which also have holographic interpretation such as AdS/MERA etc.)

Tensor Networks

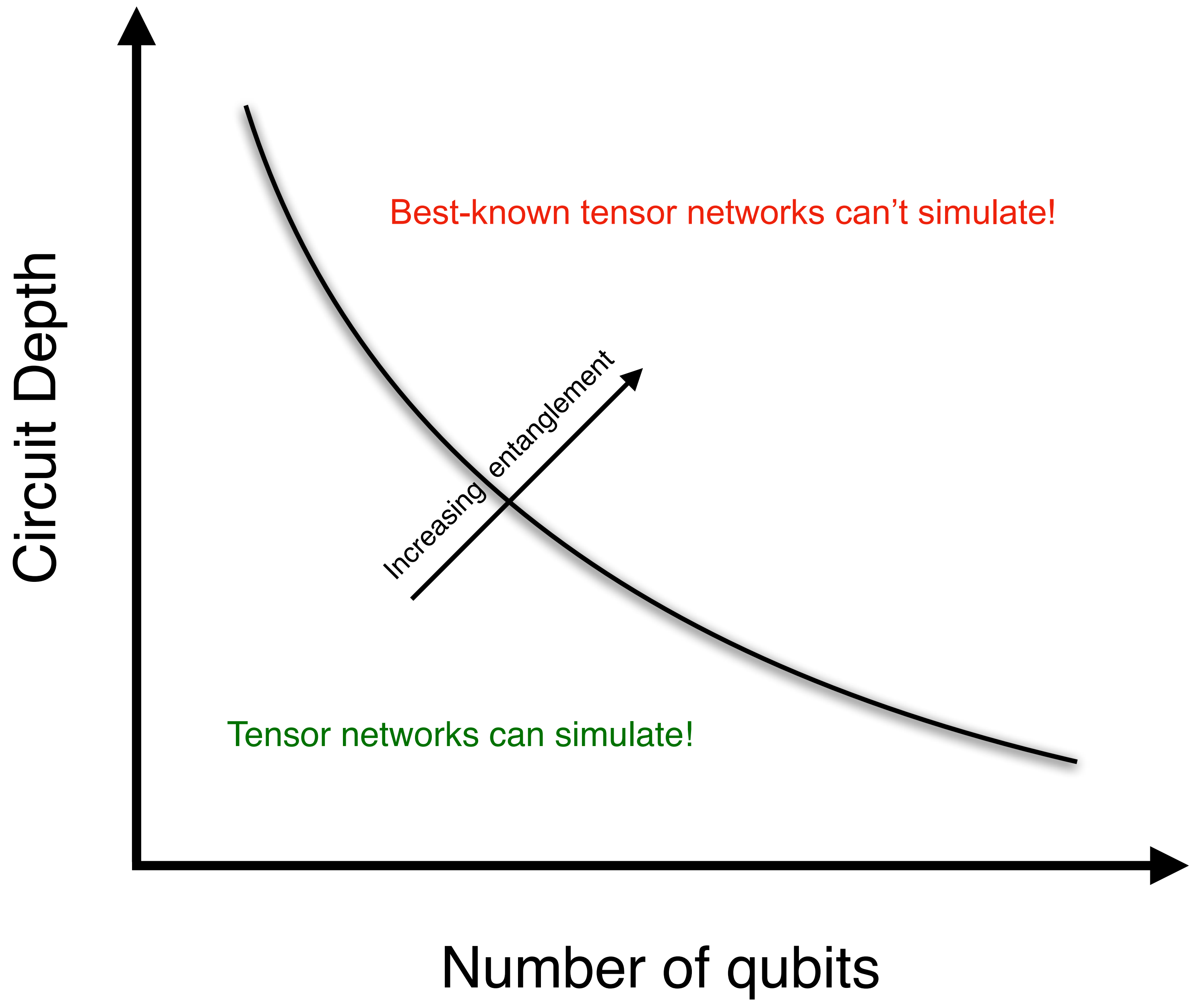
- The most efficient classical method of studying the properties of lower-dimensional systems is tensor networks. The idea is based on the fact that if the Hamiltonian is sufficiently local and gapped, then the relevant sector of the entire Hilbert space is a tiny region which satisfies area-law entanglement i.e., they are less entangled.

- In that case, the vector space of dimensions d^N can be described by $\mathcal{O}(d\chi^2)$ where χ is the bond dimension of the MPS. Though has well-understood limitations. Extensions to gapless systems exist such as MERA networks.



Classical to Quantum

- An important ingredient of numerical lattice Monte Carlo work is Wick rotation. Can't use well-established sampling methods otherwise.
- Tensor networks can help sometimes but they have their own limitations. Do not scale well in higher dimensions.
- It is *now clear* that we need new tools to understand real-time dynamics of interacting field theories or quantum many-body systems.
- We require fundamentally *new* idea of computing [Manin, Feynman et al., circa 1978] such that we can compute $\exp(-iHt)$ for a given H in terms of circuits exploiting features of QM more efficiently than classical computers. They are now known as quantum computers (QC).



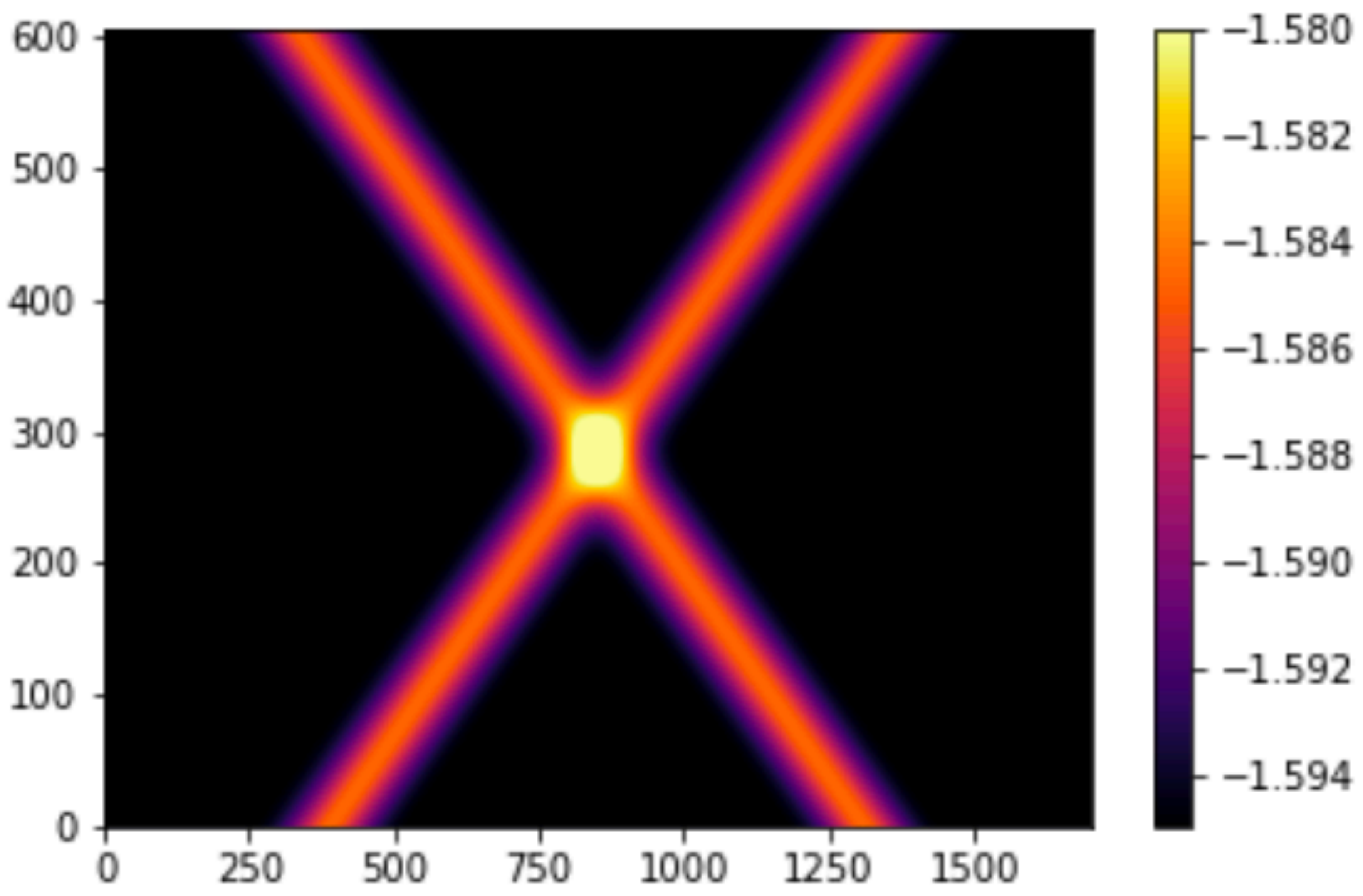
MPS for real-time dynamics

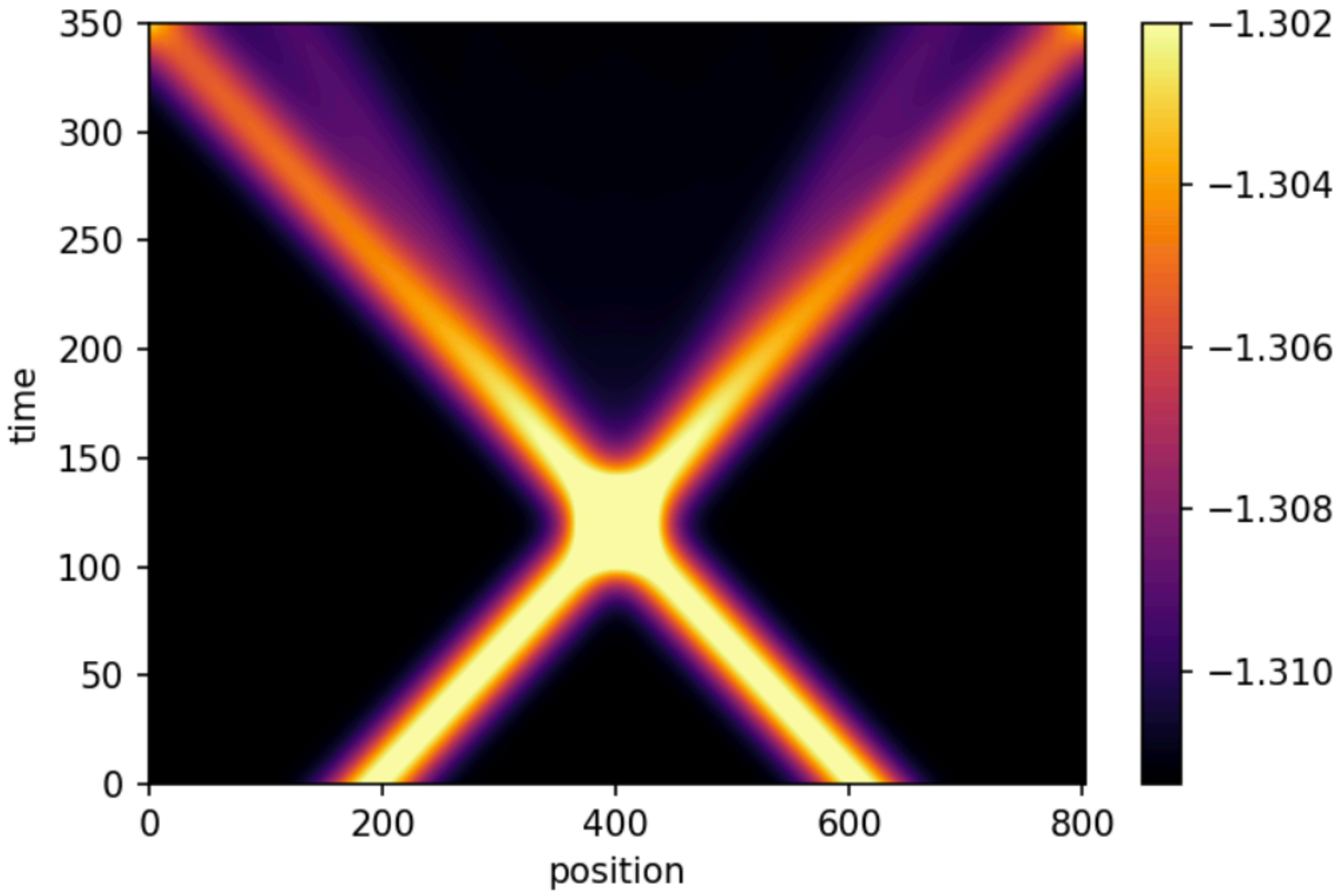
(in progress with Milsted, Neuenfeld, Preskill, Vieira)

- MPS methods are powerful for understanding real-time scattering in interacting, strongly-coupled 1+1-dimensional (gapped) field theories .

- We are exploring the $2 \to 2$ scattering in *Ising Field theory (IFT)* using well-known time evolution methods. Very complicated spin model integrable in some limits.

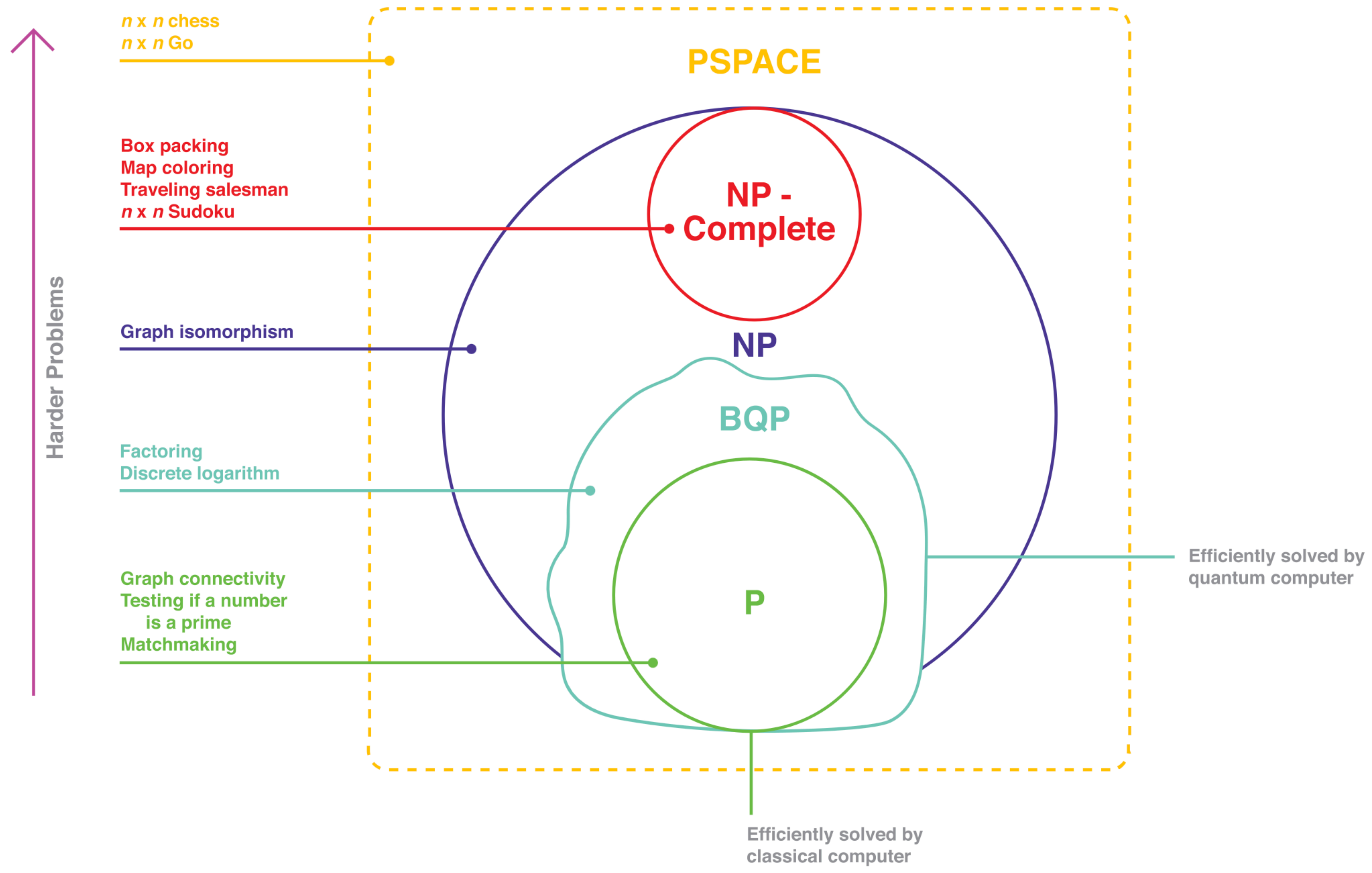
- See signs of particle production away from the integrable points of the model. What about high E glueball-glueball scattering? No tools available. Can quantum computers help?





Misconception: QC *can* solve all problems

- It turns out that for majority of problems, quantum computers would do no better than classical computers. A major research direction is to understand which problems can be solved efficiently by QCs.
- For example, we know that scattering in ϕ^4 in 1+1-dimensions can be solved efficiently by quantum computers, it might be that glueball-glueball scattering in "real" QCD cannot be solved (we don't know).
- Class of problems which are best suited for quantum advantage belong to complexity class BQP. For ex: Shor's algorithm.



Approaches to 'universal' Quantum computing

- Qubit approach — Manipulate and utilise the two-state quantum system. More than dozen approaches. Two most popular — Superconducting and Trapped Ion.

- Qumodes approach — Use photons (quantum harmonic oscillators), infinite-dimensional Hilbert space. Not as popular as qubit approach (for general audience!).

- This talk will utilise the qubit approach, however, other approach might be better suited for bosonic d.o.f as we explored for sigma model (see 2310.12512). Now extending this approach to $SU(2)$ gauge theory.

arXiv > quant-ph > arXiv:2310.12512

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Quantum Physics

[Submitted on 19 Oct 2023]

Continuous variable quantum computation of the $O(3)$ model in 1+1 dimensions

Raghav G. Jha, Felix Ringer, George Siopsis, Shane Thompson

We formulate the $O(3)$ non-linear sigma model in 1+1 dimensions as a limit of a three-component scalar field theory restricted to the unit sphere in the large squeezing limit. This allows us to describe the model in terms of the continuous variable (CV) approach to quantum computing. We construct the ground state and excited states using the coupled-cluster Ansatz and find excellent agreement with the exact diagonalization results for a small number of lattice sites. We then present the simulation protocol for the time evolution of the model using CV gates and obtain numerical results using a photonic quantum simulator. We expect that the methods developed in this work will be useful for exploring interesting dynamics for a wide class of sigma models and gauge theories, as well as for simulating scattering events on quantum hardware in the coming decades.

Comments: 28 pages, 16 figures
Subjects: **Quantum Physics (quant-ph)**; High Energy Physics - Lattice (hep-lat)
Cite as: arXiv:2310.12512 **[quant-ph]**
(or arXiv:2310.12512v1 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2310.12512

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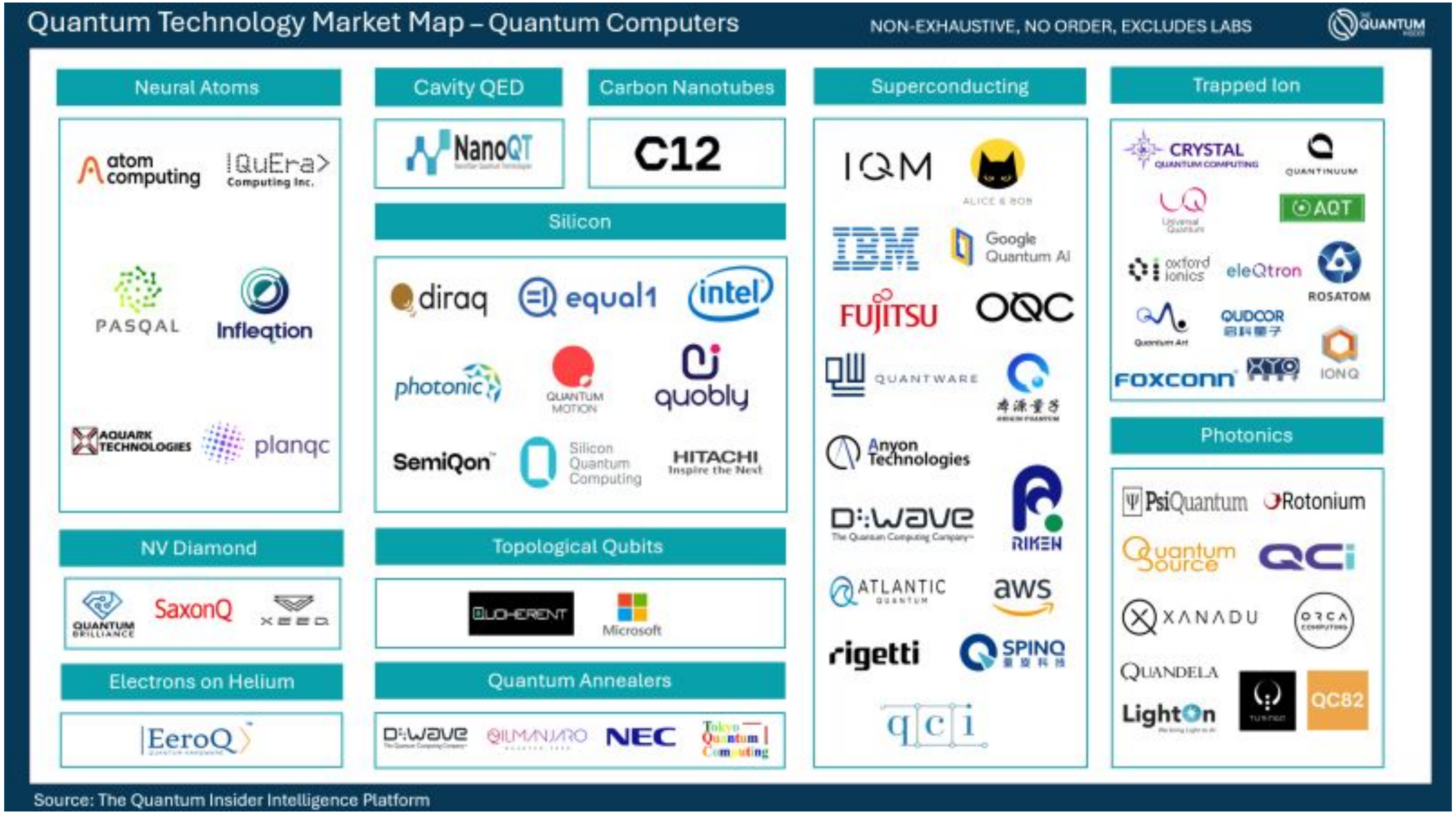
Qubits vs. Qumodes

	CV	Qubit
Basic element	Qumodes	Qubits
Relevant operators	Quadrature operators $\hat{x}, \hat{p}$ Mode operators $\hat{a}, \hat{a}^\dagger$	Pauli operators $\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z$
Common states	Coherent states $\|\alpha\rangle$ Squeezed states $\|z\rangle$ Number states $\|n\rangle$	Pauli eigenstates $\|0/1\rangle, \|\pm\rangle, \|\pm i\rangle$
Common gates	Rotation, Displacement, Squeezing, Beamsplitter, Cubic Phase	Phase Shift, Hadamard, CNOT, T Gate

Approaches to ‘universal’ Quantum computing



Quick recap: Quantum Gates

$$-\boxed{H}- = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}, \quad |0\rangle -\boxed{H}- |+\rangle$$

$$-\boxed{X}- = \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}, \quad |0\rangle -\boxed{X}- |1\rangle$$

$$-\boxed{Z}- = \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}, \quad |1\rangle -\boxed{Z}- \; -|1\rangle$$

$$-\boxed{Y}- = \begin{bmatrix}0 & -i\\ i & 0\end{bmatrix}$$

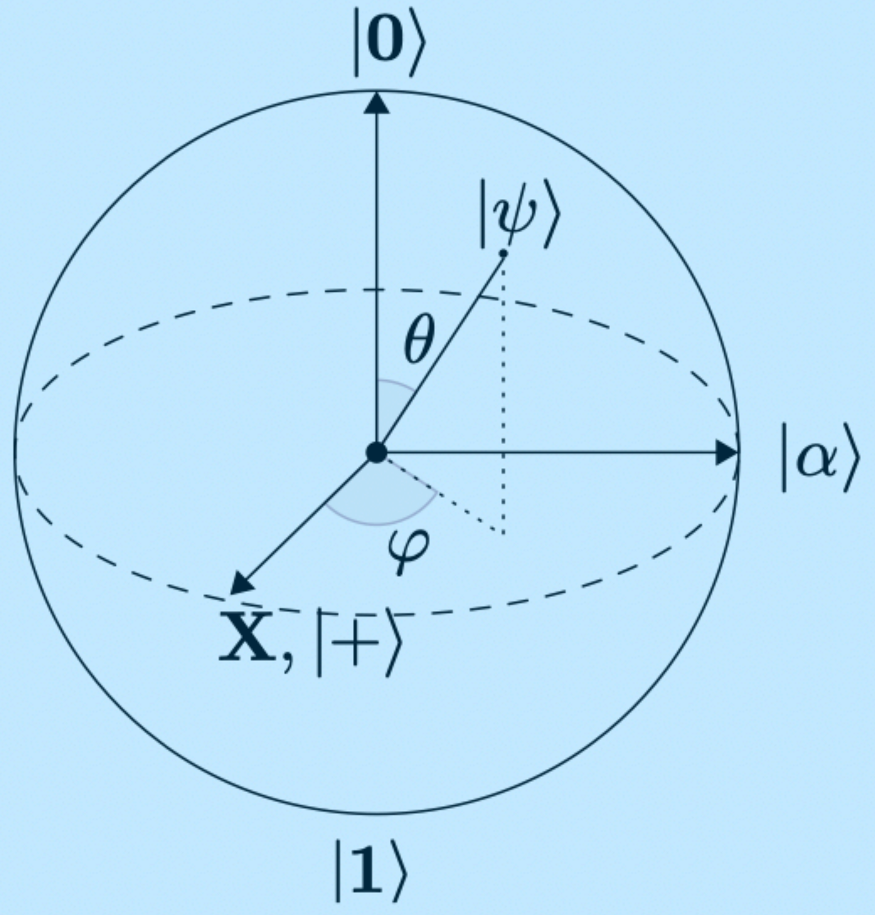
$$-\boxed{P}- = \begin{bmatrix}1 & 0\\ 0 & e^{i\phi}\end{bmatrix}$$

$$-\boxed{R_z(\theta)}- = \begin{bmatrix}e^{-i\theta/2} & 0\\ 0 & e^{i\theta/2}\end{bmatrix}$$

$$-\boxed{S}- = \begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$$

$$-\boxed{T}- = \begin{bmatrix}1 & 0\\ 0 & e^{\frac{i\pi}{4}}\end{bmatrix} = e^{\frac{i\pi}{8}}\begin{bmatrix}e^{\frac{-i\pi}{8}} & 0\\ 0 & e^{\frac{i\pi}{8}}\end{bmatrix}$$

$$|+\rangle = \frac{1}{\sqrt{2}}\Big(|0\rangle + |1\rangle\Big)$$



Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix}0 & -i\\ i & 0\end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP			$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$

Questions?

SYK model

$$H = \frac{(i)^{q/2}}{q\,!} \sum_{i,j,k,\cdots,q=1}^{N} J_{ijk\cdots q} \;\; \chi_i \chi_j \chi_k \cdots \chi_q,$$

- Model of N Majorana fermions with q-interaction terms with random coupling taken from a Gaussian distribution with $\overline{J_{\dots}} = 0, \;\; \overline{J^2_{\dots}} = \frac{q\,!J^2}{N^{q-1}}$.

- The fermions χ satisfy, $\chi_i \chi_j + \chi_j \chi_i = \delta_{ij}$. We will set $J = 1$. Note that it has units of energy and inverse time.

- In the limit of large N and $\beta J \gg 1$, the model has several interesting features and is related to the black holes (in JT gravity) that develop near-AdS2 geometry.

Mapping fermions to qubits

$$\chi_{2k-1} = \frac{1}{\sqrt{2}}\left(\prod_{j=1}^{k-1} Z_j\right) X_k \mathbb{I}^{\otimes (N-2k)/2} \quad , \quad \chi_{2k} = \frac{1}{\sqrt{2}}\left(\prod_{j=1}^{k-1} Z_j\right) Y_k \mathbb{I}^{\otimes (N-2k)/2}$$

- N fermions requires $N/2$ qubits. We use the standard Jordan-Wigner mapping to write χ in terms of Pauli matrices X, Y, Z and Identity.
- Now, the SYK Hamiltonian is written as sum of Pauli strings. The number of strings is $\binom{N}{q}$ and grows like $\sim N^q$. Simplest non-trivial case for is $N = q$ with one term. We restrict to $q = 4$.

Simplest case of $N = 4$

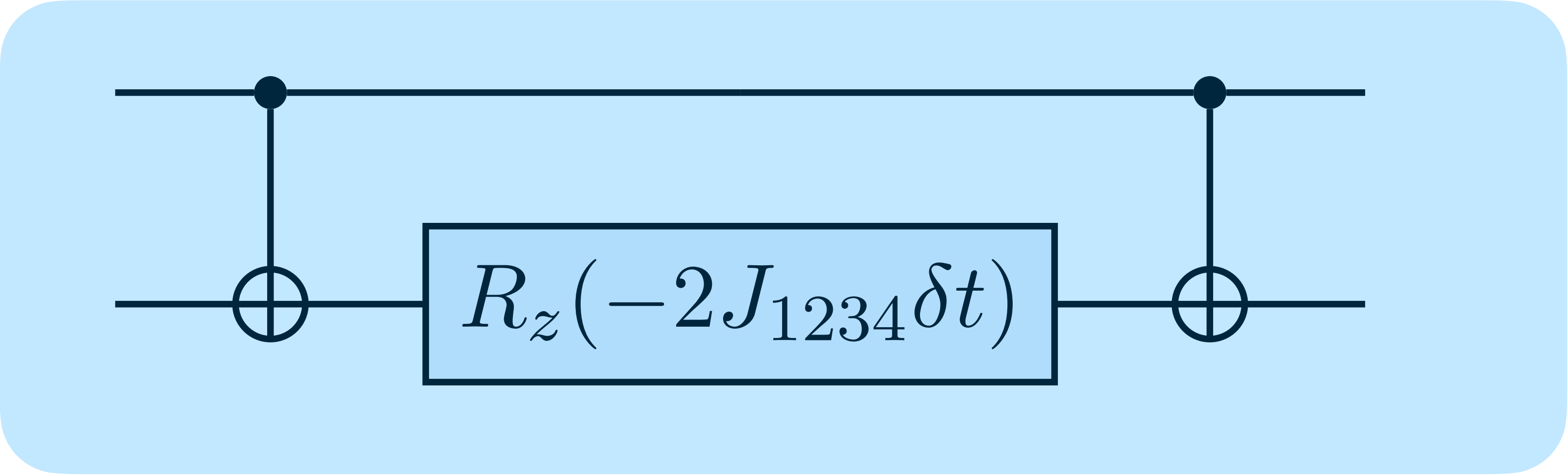
$$H = J_{1234}\chi_1\chi_2\chi_3\chi_4$$

$$\chi_1 = X\mathbb{I},\ \chi_2 = Y\mathbb{I},\ \chi_3 = ZX,\ \chi_4 = ZY$$

$$H = J_{1234}(X\mathbb{I})\cdot(Y\mathbb{I})\cdot(ZX)\cdot(ZY) = -J_{1234}ZZ$$

- The goal of quantum computation is to construct a unitary operator corresponding to this Hamiltonian. So, for this case we have $\exp(-iHt) = \exp(iJ_{1234}ZZt)$.

- This circuit is simple to construct and just needs 2 CNOTs and 1 rotation gate. The circuit is :



Circuit complexity ($\mathscr{C}$)

Definition: How many 2q-gates do we need to simulate SYK model?

- Different approaches can be used to do the Hamiltonian simulation (aka time evolution). A popular method is Trotter method. It is based on Lie-Suzuki-Trotter product formula* (writing $H = \sum_{j=1}^{m} H_j$, $m \sim N^4$)

$$e^{-iHt} = \Big(\prod_{j=1}^{m} e^{-iH_j t/r}\Big)^r + \mathcal{O}\Big(\sum_{j<k} \Big|\Big|[H_j, H_k]\Big|\Big| \frac{t^2}{r}\Big),$$

- Depending on what error (ϵ) we desire in the time-evolution from the second term, we can compute the number of slices (r) we need to take. So, the complexity reduces to finding number of 2q-gates for each Trotter step. Recall that $N = 4$ needed just 2 2q-gates for each Trotter step.

* *Corollary of Zassenhaus formula i.e., exp(t(X+Y)) = exp(tX) exp(tY) + O(t^2) (also known as dual of BCH formula).*

Old work(s)

$\mathscr{C} = \mathscr{O}(N^{10}t^2/\epsilon)$	L. García-Álvarez et al., PRL 119, 040501 (2017)
$\mathscr{C} = \mathscr{O}(N^8 t^2/\epsilon)$	Susskind, Swingle et al., arXiv: 2008.02303 (2020)
$\mathscr{C} = \tilde{\mathscr{O}}(N^{7/2}t)$	Babbush et al., Phys. Rev. A 99, 040301 (2019)

- The last one clearly is the most efficient, however, in the noisy-era implementing this is not feasible. It requires fault-tolerant quantum resources + ancillas since it is based on the basic idea of embedding H in a bigger vector space.

- Using the Trotter methods, the best seems to be $\sim N^8$. In our paper, we improved the complexity to $\mathscr{C} = \mathscr{O}(N^5 t^2/\epsilon)$ which we now discuss. It is possible to improve to $\mathscr{C} = \mathscr{O}(N^4 \log(N) t^{3/2}/\sqrt{\epsilon})$. In fact, sparse versions have better complexity [RGJ, work in progress]

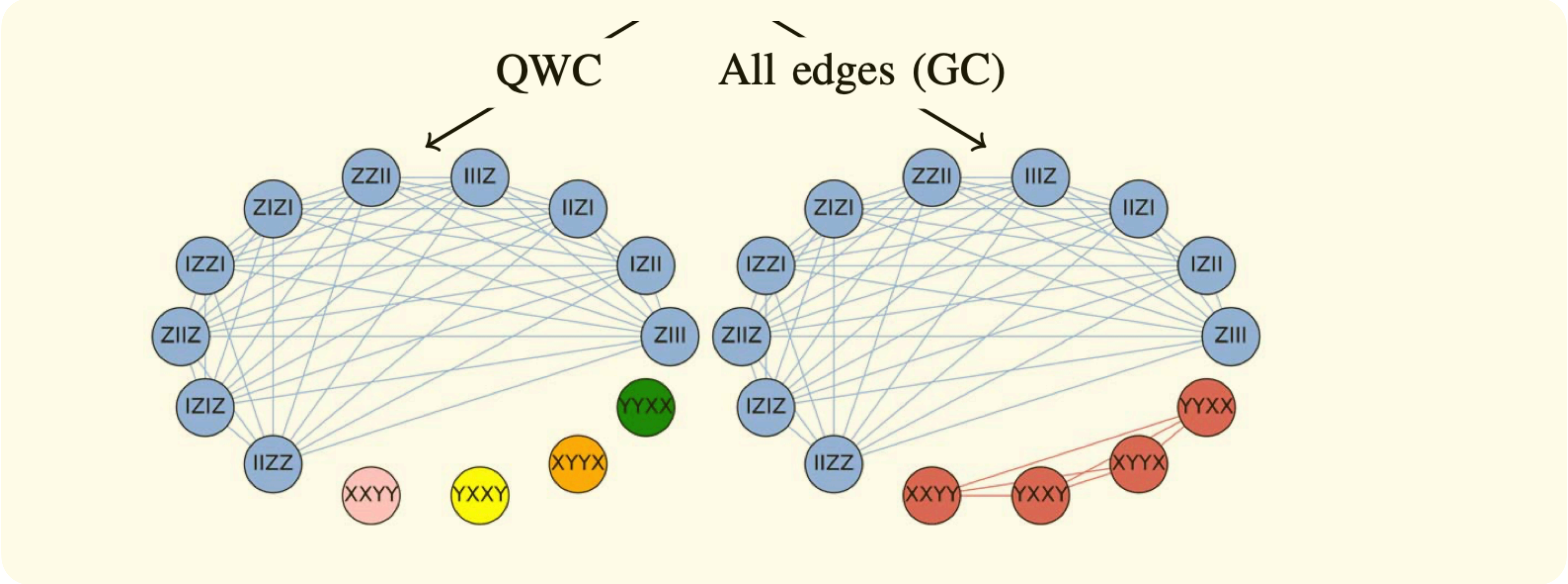
Commuting terms

- The costs can be simplified if we are little careful in splitting the SYK Hamiltonian.

- The number of terms grows like $\sim N^4$, however, a large fraction of them commute with one another and can be collected together and then time-evolved more efficiently. We can find diagonalising circuit for each cluster and then apply time-evolution operator.

- Finding *optimal* number of such clusters is a well-studied computer science problem. We use a graph-colouring algorithm to achieve this. Figure from Gokhale et al., IEEE 379,(2020)

Qubit-wise commutivity **General commutivity**



Trivia: Do $XYZZXY$ and $YX\mathbb{I}\mathbb{I}XY$ commute?

Estimate based on general commutivity

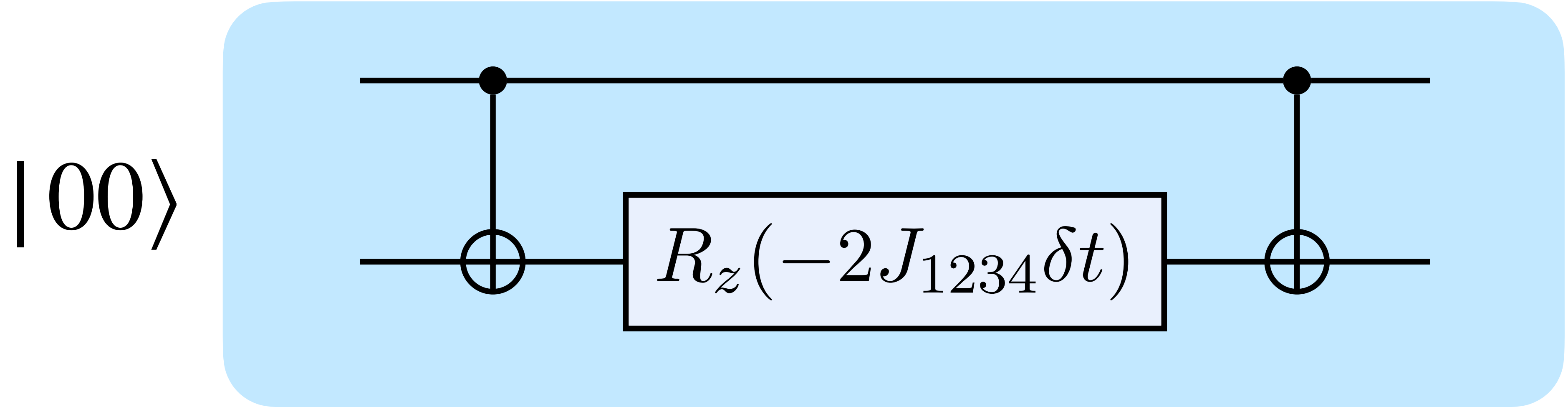
N	Pauli strings	Clusters	Two-qubit gates
4	1	1	2
6	15	5	30
8	70	6	110
10	210	23	498
12	495	57	1504
14	1001	92	3560
16	1820	116	6812
18	3060	175	11962
20	4845	246	19984

Return probability

- A simple observable we can compute is the probability that we return to the same initial state after some evolution time t i.e., $\mathscr{P}_0 = |\langle\psi_0|e^{-iHt}|\psi_0\rangle|^2$. For initial state, we take $|0\rangle^{\otimes N/2}$.

- For approximating the unitary, we use the first-order product formula and construct the corresponding quantum circuit.

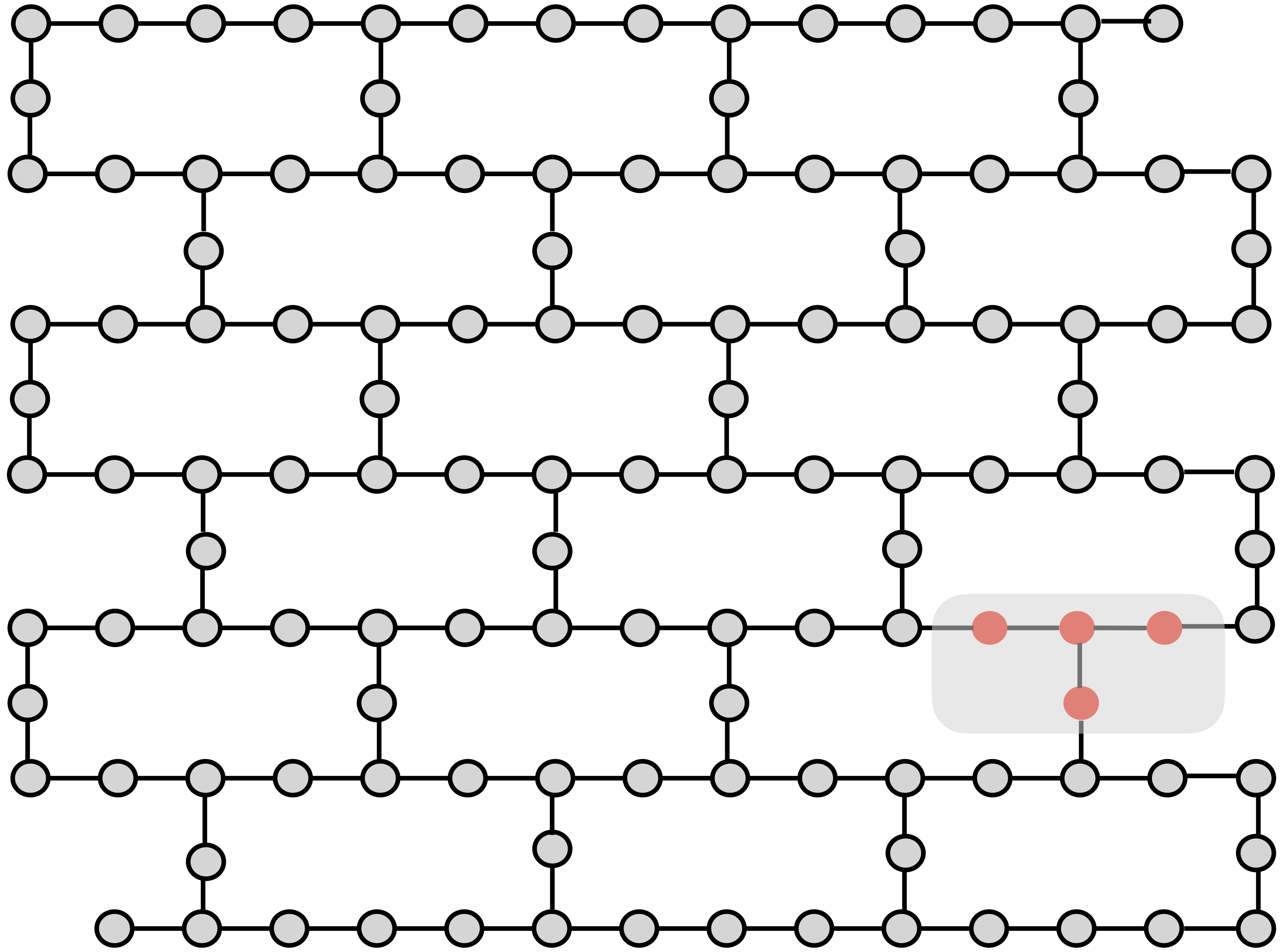
- For $N = 4$, we have a simple circuit of only two 2Q gates, so the entire circuit for return prob. is straightforward. For $N = 6$, there are 30 2Q gates per step which we cannot show here.



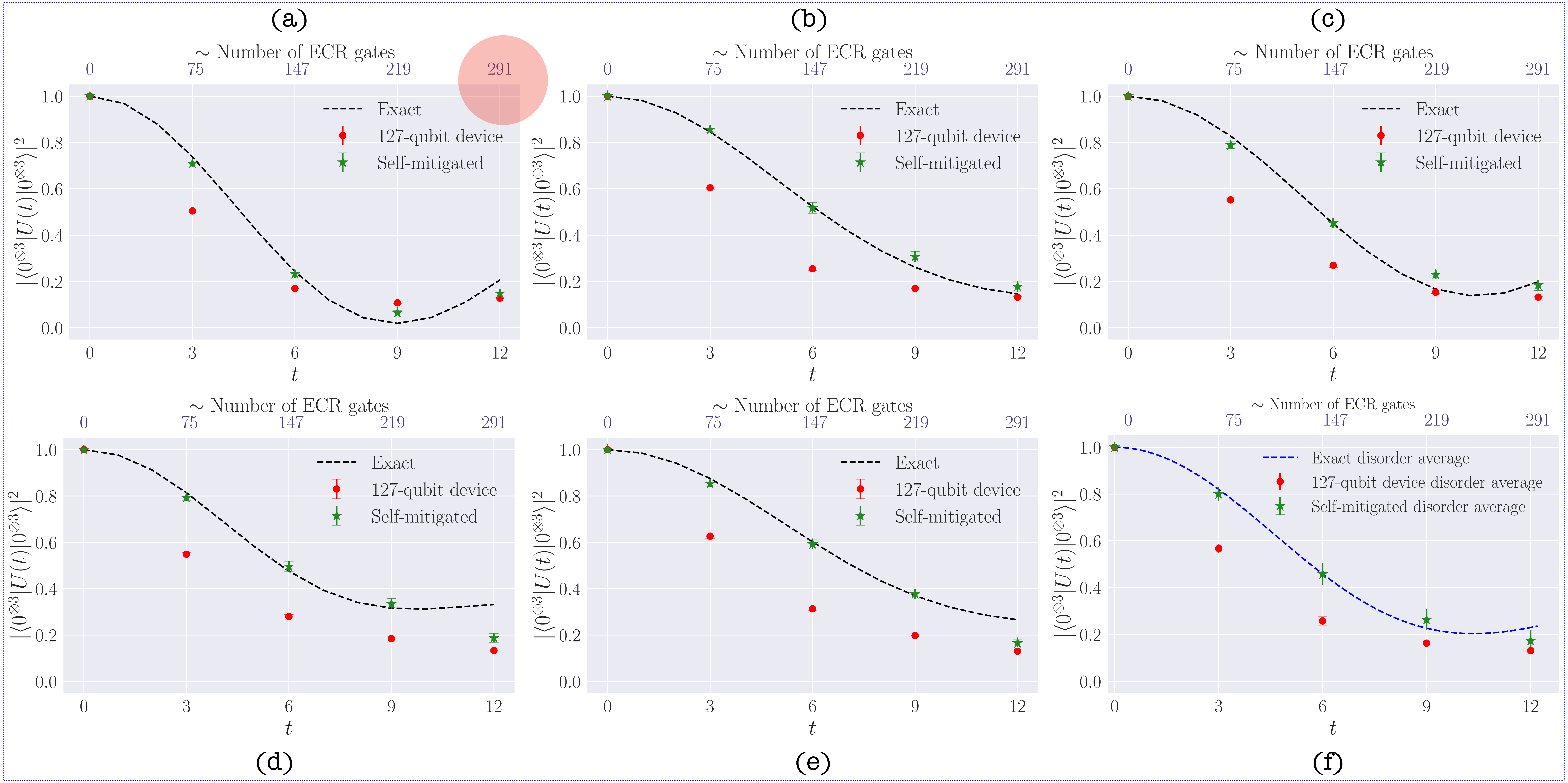
$Z \otimes Z =$ **CNOT** $\cdot (\mathbb{I} \otimes Z) \cdot$ **CNOT**

Return probability

- We used the quantum computers available through IBM to simulate the SYK model. The topology of the processor is shown below. In practice, we need more gates than necessary. For example, we show a combination of qubits we used for $N = 8$.



Return probability - Results



Error Mitigation

- The results from the 127-qubit device (red) agrees slightly less than those with self-mitigation (green). The red points have been read from some fixed number of measurements/shots and post-processed with mild mitigation including M3 to correct read-out errors and DD to increase coherence time of qubits. This is not enough for complicated models like SYK!

- To get closer to the exact results, we found that an idea similar to CNOT only mitigation (known as self-mitigation) seems to help drastically. Basic idea introduced in Urbanek et al. `arXiv:2103.08591` and extended to $SU(2)$ work of Rahman et al. `arXiv:2205.09247`

M3 is a matrix measurement mitigation (MMM or M3) technique that solves for corrected measurement probabilities using a dimensionality reduction step followed by either direct LU factorization or a preconditioned iterative method

DD (dynamical decoupling) which implements a series of strong fast pulses are applied on the system which on average increases the lifetime of qubits and delays decoherence (or effect of interactions with environment)

CNOT-only and self-mitigation

- We saw previously that if the input state is $|0\rangle^{\otimes n}$, then applying any of CNOT will still result in the same input state. However, in practice, the errors of 2q gates (CNOT) is the dominant source of gate error in current devices.

- This can be used to quantify the errors occurring in the time-evolution circuit. Remove all the single-qubit gates from $\exp(-iHt)$ and apply it on the $|0\rangle^{\otimes n}$ state. Measure the output. The deviation from $|0\rangle^{\otimes n}$ is a measure of the probability of error and used to correct the expectation value of the observable. This is CNOT-only mitigation.

- However, this underestimates the error since "many 1-qubit gates" when added $\sim \mathcal{O}(1000)$ times can also contribute to error. Self-mitigation argues to not remove any gates from $\exp(-iHt)$. One constructs two circuits: Physics (P) and Self-Mitigated (SM) circuits and then run the P circuits for N Trotter steps and the SM mitigation circuit for $N/2$ Trotter steps with dt and the other $N/2$ with -dt. Note the error from SM circuits, use it to correct exp. value of P circuits.

Quantum depolarizing channel

- An efficient way to model *decoherence of qubit* is to use a depolarising quantum channel which is a CPTP (completely-positive trace preserving, (Tr $\mathscr{E}(\rho) =$ Tr $\rho = 1$ and $\mathscr{E}(\rho) > 0$) map:

$$\mathscr{E}(\rho) = (1-p)\rho + p\mathbb{I}/2^n,$$

- If the quantum channel is free of noise, then the depolarizing parameter (error rate) is p = 0.

- Once the error rate is determined from self-mitigation, we use it to correct the expectation value of the observable using $\langle O_n \rangle = (1-p)\langle O_c \rangle + (p/2^n)\mathrm{Tr}(\mathbb{I})$ where n and c are noisy and corrected value.

SYK model - Bound on chaos

- SYK model famously saturated the Lyapunov exponent i.e., $\lambda = 2\pi T$ for $J/T \gg 1$ when N is large.

- One considers $C(t) = -\langle [W(t), V(0)]\,[W(t), V(0)] \rangle$ and the expansion of the commutator gives OTOC := $\langle W(t)V(0)W(t)V(0) \rangle_\beta$ = Tr$(\rho W(t)V(0)W(t)V(0))$ which characterizes quantum chaos.

- Suppose one starts at $t = 0$, and computes also the two-pt correlator given by $\langle W(t)W(0) \rangle$, the time scales at which the lower order correlators decay is called 'dissipation time'. After this time, the OTOC grows as $\exp(\lambda t)$ and saturates beyond $t_\star$ known as scrambling time. Black holes are fastest scramblers!

- These correlators have been computed up to $N = 60$ numerically i.e., H has ~million terms and matrix has size ~billion. *Hard for classical computers but doable.* $N = 70$ probably not doable, around limit where quantum advantage sets in. At least 10-15 years away (optimistic estimate).

Out-of-time correlators (OTOC)

- So the goal is to compute $\langle W(t)V(0)W(t)V(0)\rangle_\beta$ on a quantum computer. Thermal correlators are currently not easy to compute due to limited resources. One simplification we can make is consider the $\beta \to 0$ limit of OTOC. This is not at all interesting for holography, but this is where we must start. Hence, the density matrix is just $\rho \propto \mathbb{I}$.

- The unusual time-ordering of OTOC is also hard for quantum computers which often mean carrying out forward and backward evolution. We use a protocol (next slide) which uses only forward evolution to compute OTOC on quantum hardware.

Randomised Protocol

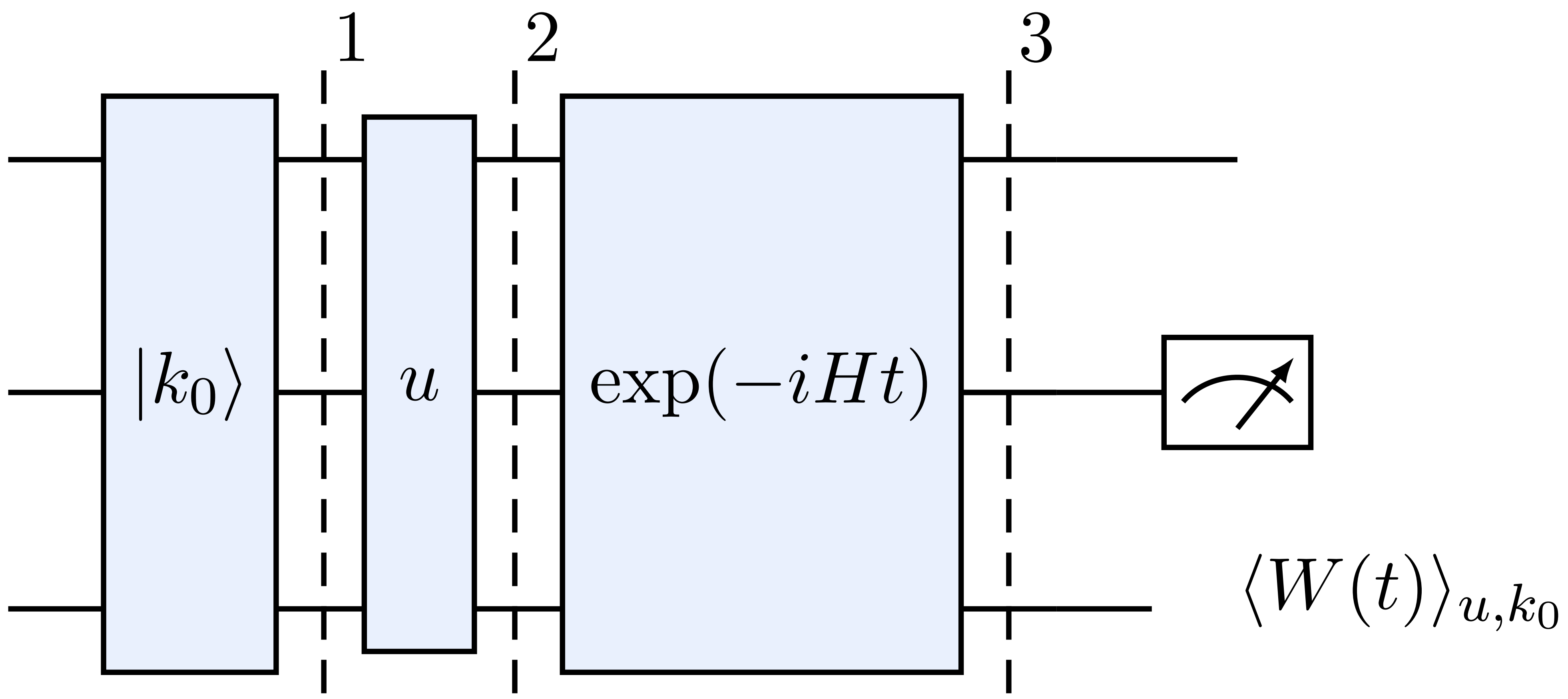
- There are various protocols to measure OTOC on quantum computers, see Swingle 2202.07060 for review.

- We use the one proposed in 1807.09087 now known as ‘randomised protocol’ since it computes OTOC through statistical correlations of observables measured on random states generated from a given matrix ensemble (CUE).

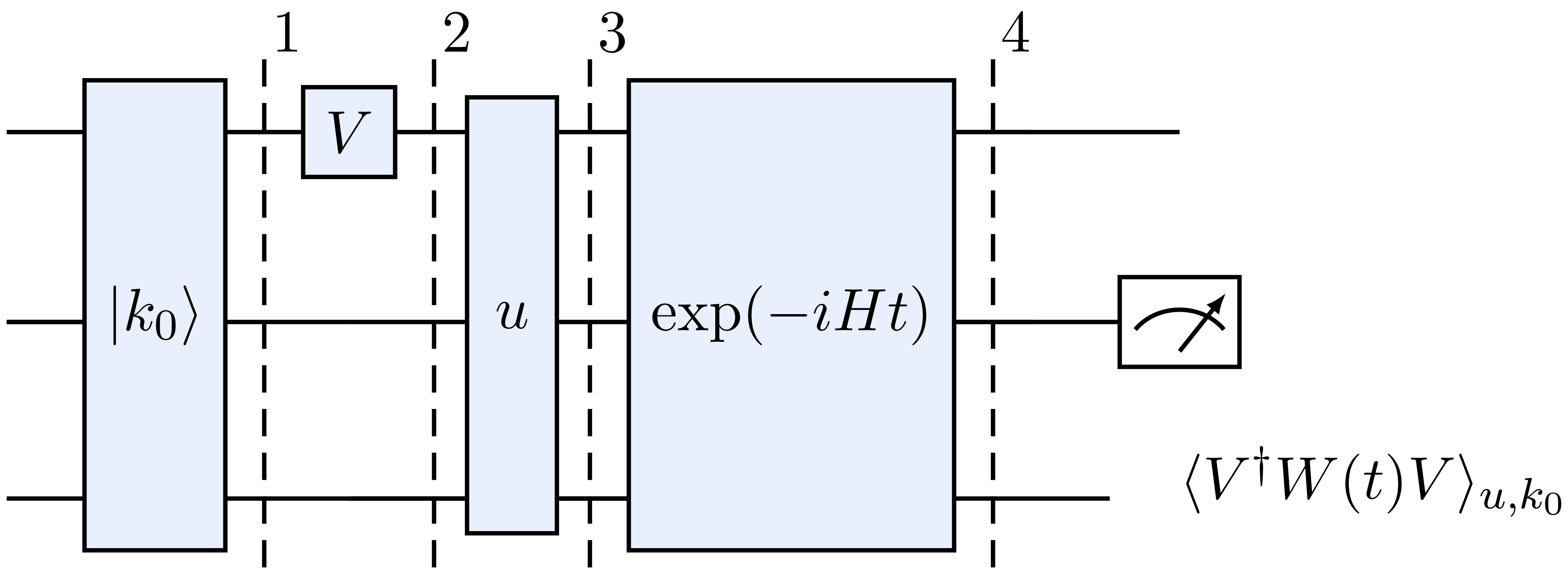
- Infinite-temp OTOC is given by Tr$(W(t)V^\dagger W(t)V) \propto \overline{\langle W(t)\rangle_u \langle V^\dagger W(t) V\rangle_u}$ where the average is over different random states $|\psi_u\rangle$ prepared by acting with random unitary on arbitrary state say $|0\rangle^{\otimes n}$. Note that this protocol works when W is traceless operator.

Randomised Protocol

- We need two measurements (between which we compute the statistical correlation) and it is shown below. This is the global version of the protocol (since u has support over all qubits). There is also a local version of the protocol. Note that cost of decomposing arbitrary u increases exponentially, one can instead use unitary from a subset of Haar measure. We are currently exploring this direction. They are called *unitary t-designs** in literature.



(a)

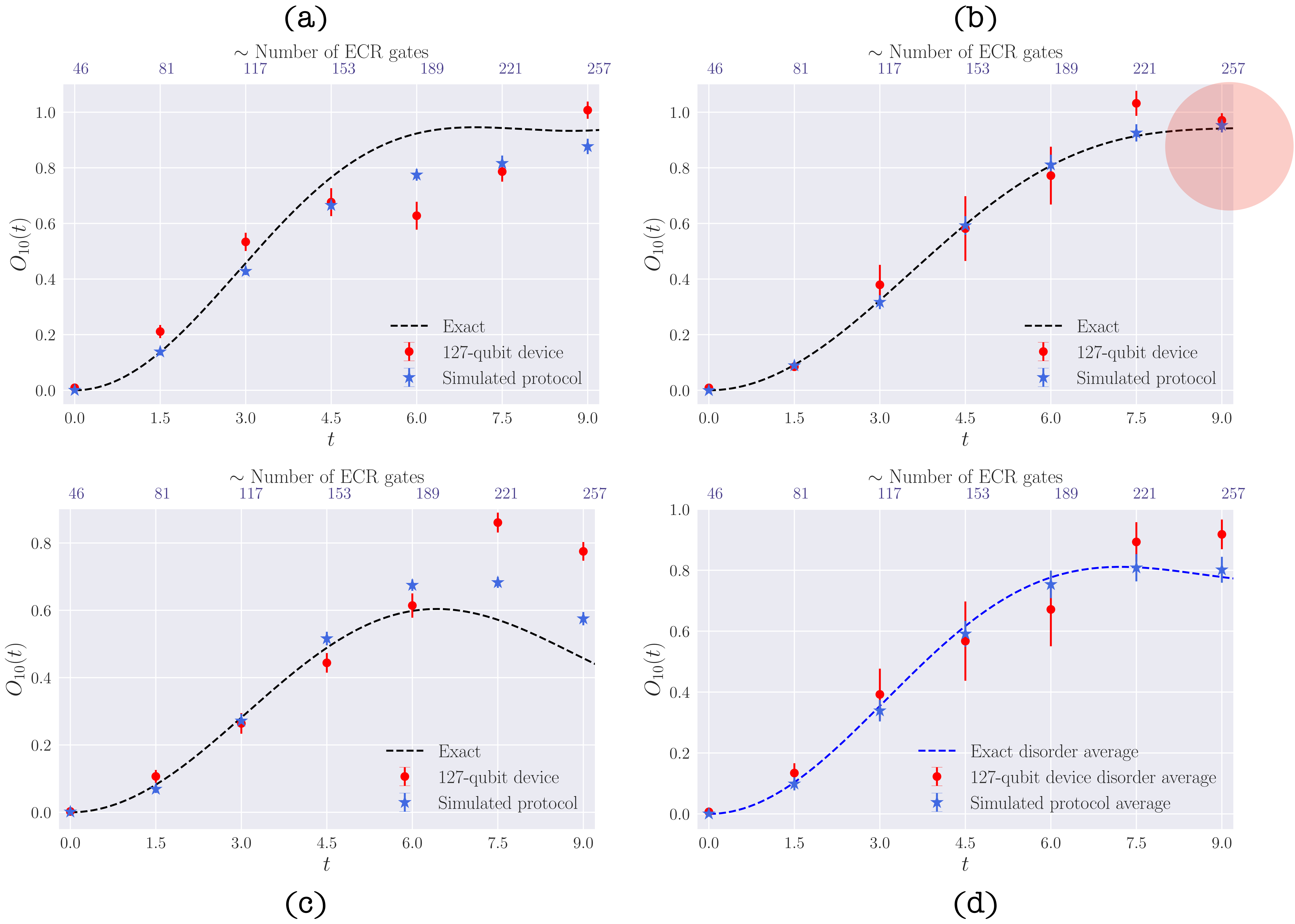


(b)

t-designs equivalent to first t moments of Haar group

OTOC Results

- We used ibm_cusco and ibm_nazca to obtain the results show for $N = 6$. We took simplest operators where both W and V were taken to be single Pauli. We see good agreement without need to do self-mitigation like we did for return probability.



Finite-temperature SYK model

- We considered OTOC measured over random states (maximally mixed) generated i.e., $\beta = 1/T = 0$. However, much of interesting Physics of the SYK happens in the region $\beta \gg 1$ and classical computations have argued that you need $\beta \sim 70$ to extract Lyapunov exponents close to the chaos bound.

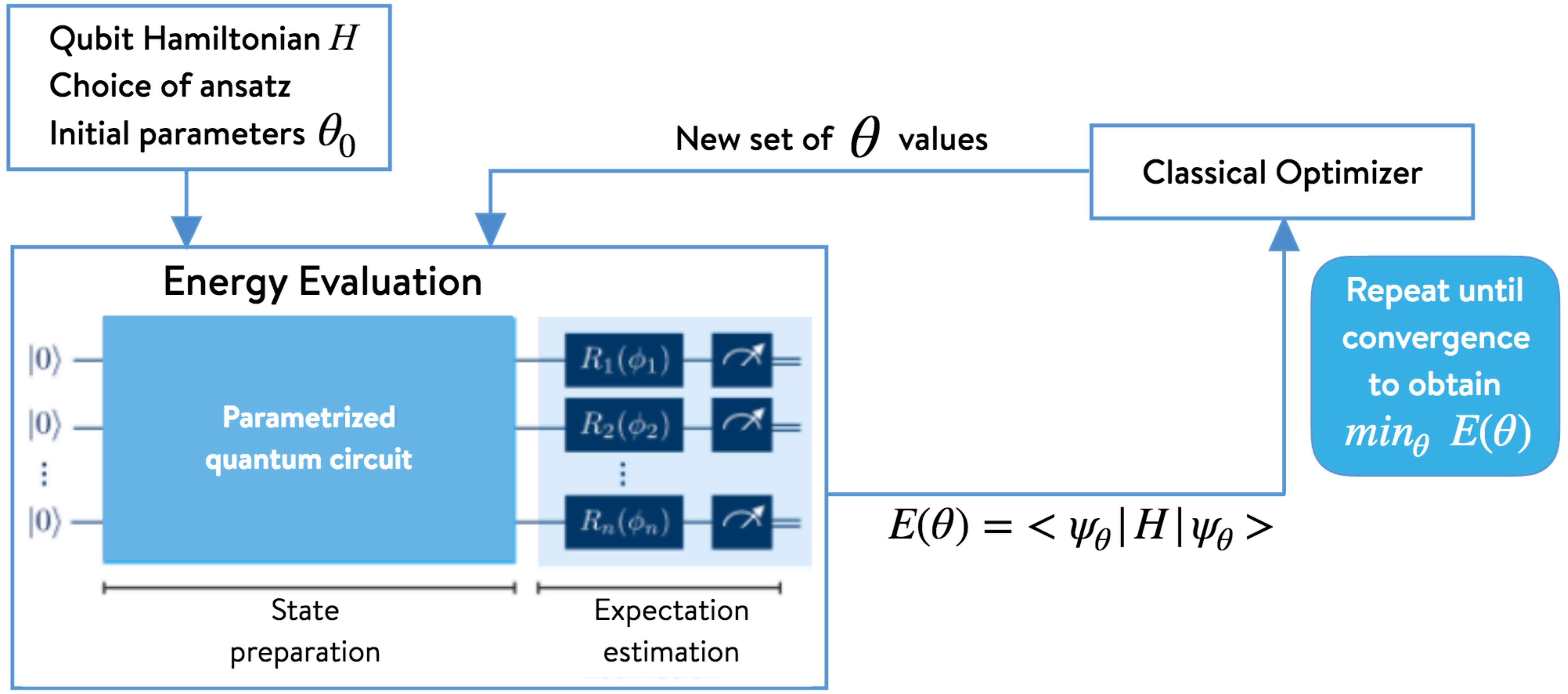
- Finite-temperature OTOCs are difficult for quantum computers in general. No simple/general cost-effective protocol exists. To move towards this goal, we are studying the preparation of Gibbs (thermal) states on quantum computer for the SYK model.

- In addition to the thermal state (mixed) of the SYK model, one can also consider a purification of this known as thermo-field double state (TFD). TFD state is a pure state (up to unitary trans.) of some other system (coupled SYK) and when we perform partial trace over either system, we recover thermal state the other one.

- However, even if we can do this, going beyond $N = 60$ Majorana seems far away. We are no where close to *quantum supremacy* in this model which needs about $\sim 10^9$ 2Q gates and several orders of better gate error (fidelity).

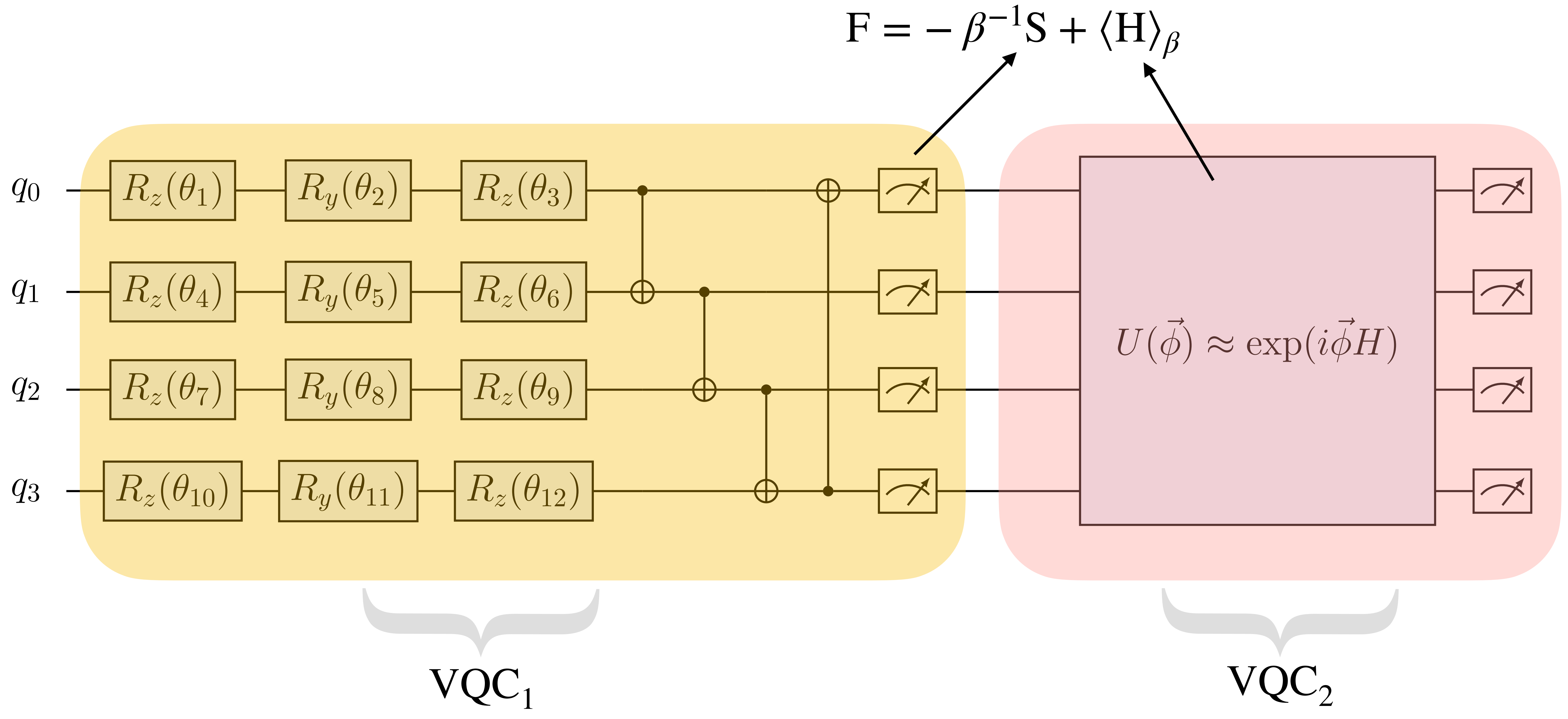
VQE algorithm

- Before we move to preparation of Gibbs state, let's us look at popular algorithm for preparing (approximate) ground states on QC.
- Hybrid classical/quantum algorithm to find the ground state problem of a given Hamiltonian by finding the parameters of a quantum circuit ansatz that minimizes the Hamiltonian expectation value.
- It primarily consists of three steps: 1) Prepare initial ansatz on QC i.e., $|\psi(\vec{\Theta})\rangle$, 2) Measure energy on QC and optimise the parameters Θ using classical optimisers and 3) Repeat until desired convergence is achieved.



VQE for finite temperatures

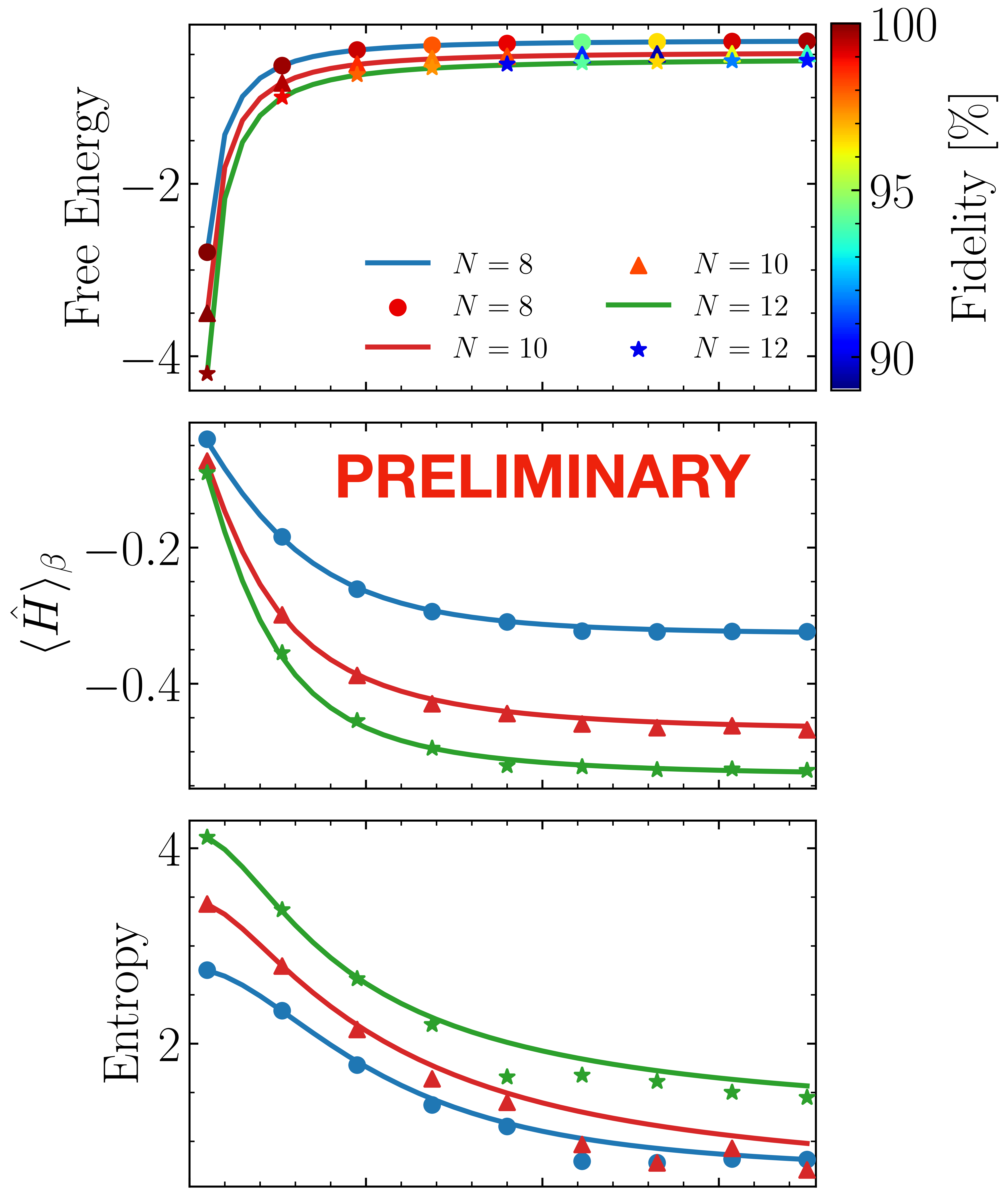
- Finite-temperature VQE methods are still an active area of research. Many proposals exist. The cost function is no longer E but rather $E - TS$ (free energy) which can be hard to compute on QC.



Selisko et al., 2208.07621

Finite-temperature SYK model

[upcoming work with Araz, Sambasivam, and Ringer]



Results from PennyLane simulator

Summary & other directions

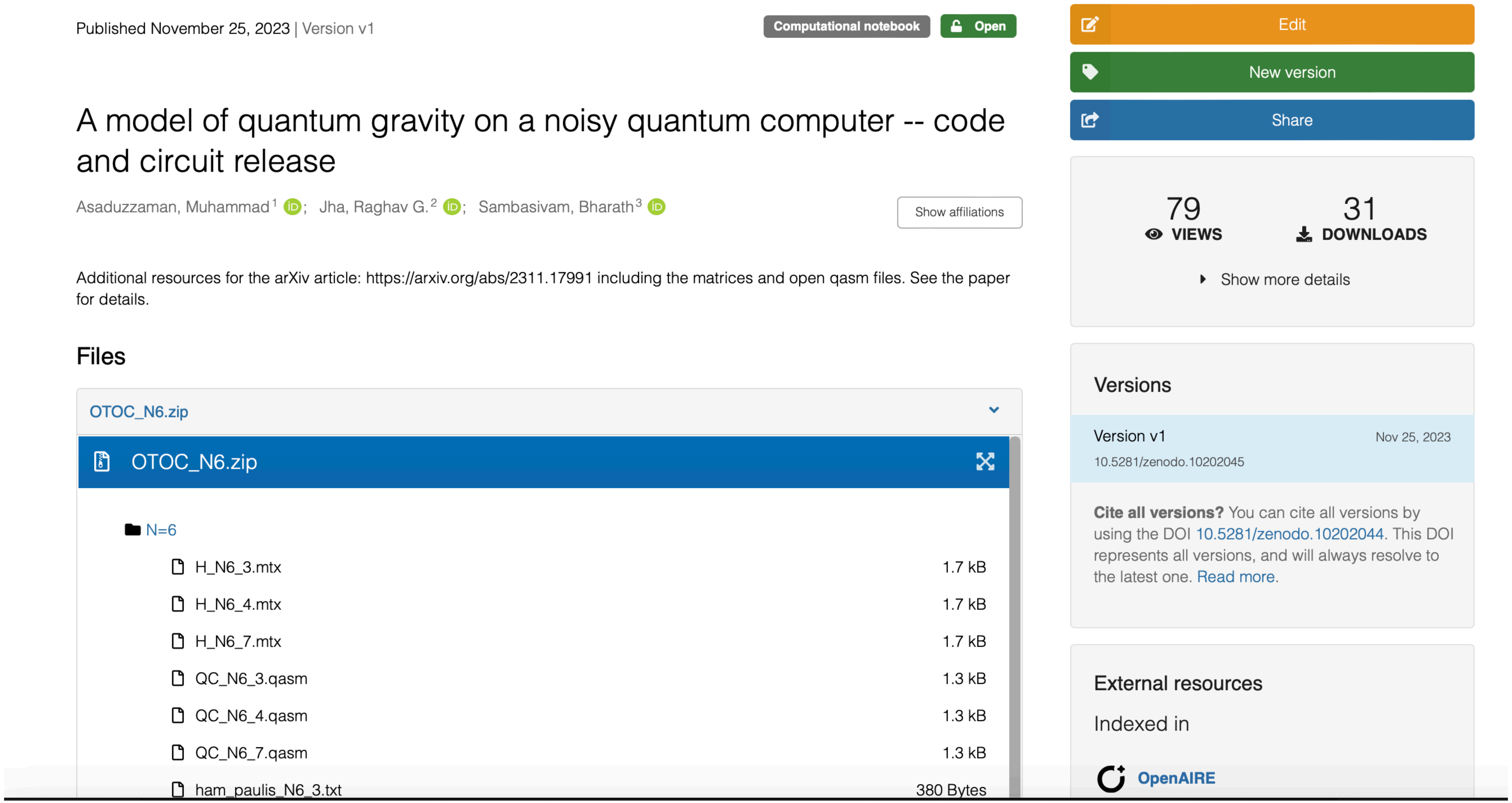
- We are entering an era where we can compute few things (even if they can be done quickly) using our laptops. Exploring these toy models will hopefully teach us new things.

- It is instructive to see that if we can characterise the noise in these quantum devices, we can mitigate and get reasonable results! In coming decades with improved technology, the capability will increase and hopefully one day we can simulate $N \gg 60$ SYK or do dynamics of 4d SYM at finite-temperatures and compare to black hole Physics through gauge/gravity.

- In addition, one should consider modifications of SYK model which have similar properties and are easier to study on quantum computers. Several such proposals exist but there might be room to improve.

- Unfortunately, if quantum computers also cannot help (we know they cannot help in certain problems), then it might always be impossible to study real-time properties of interactions QFTs in 4d.

Resources and Data Statement



Both classical and quantum code available at: `https://github.com/rgjha/SYKquantumcomp`

Thank you