Title: Quantum many-time physics: noise, complexity, and windows to new phenomena

Speakers: Gregory White

Series: Perimeter Institute Quantum Discussions

Date: November 30, 2022 - 5:15 PM

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Abstract: Quantum theory has a temporal composition, which is expressed under many different operational frameworks. Here, points in time are imbued with a Hilbert space structure, and quantum states are passed between times through a series of experimental interventions. A multi-time quantum process, therefore, carries the same complex properties as a many-body quantum state. This invites the question: to what extent can temporal correlations be as interesting as spatial ones, and how can we access them? One particular avenue through which this structure manifests is in open quantum systems. System-environment dynamics can precipitate non-Markovian processes by which correlations persist between different times. Recently, the advent of high-fidelity quantum devices has made it possible to probe coherent quantum systems. In this talk, I will discuss my recent work in which we show how this serves as a novel test bed to capture many-time physics. We build frameworks to extract generic spatiotemporal properties of quantum stochastic processes, show how process complexity may be manipulated, and elevate user-control into the theory to make it self-consistent. Remarkably, many of these complex features are already present in naturally occurring noise, and hence the results have direct application to the development of fault-tolerant quantum devices. I will also briefly discuss some of my future research goals: the existence of exotic temporal phenomena and how emergent spatiotemporal features can be captured through renormalisation group approaches; the learnability of spacetime quantum correlations and avenues here to quantum advantage; and the taming of correlated noise in quantum devices through bespoke error suppression and error correction.

IBM Quantum Network Hub
at the University of Melbourne

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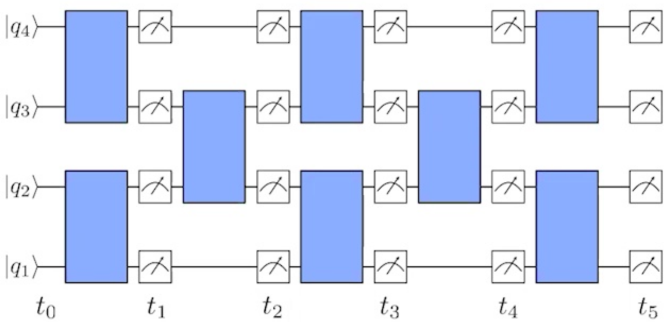
GREGORY WHITE

Quantum Many-Time Physics[redacted] Noise, Complexity, and Windows to New Phenomena


Background, Context, and
Motivation

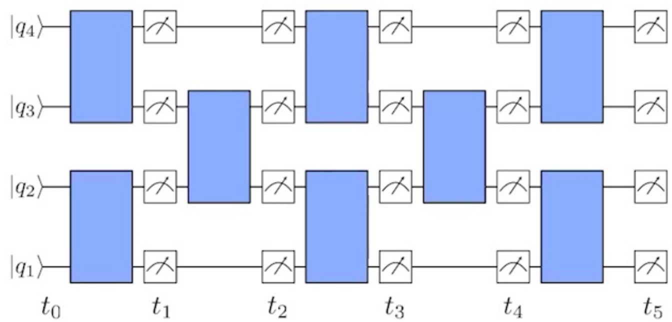
The Spacetime Structure of Quantum Mechanics

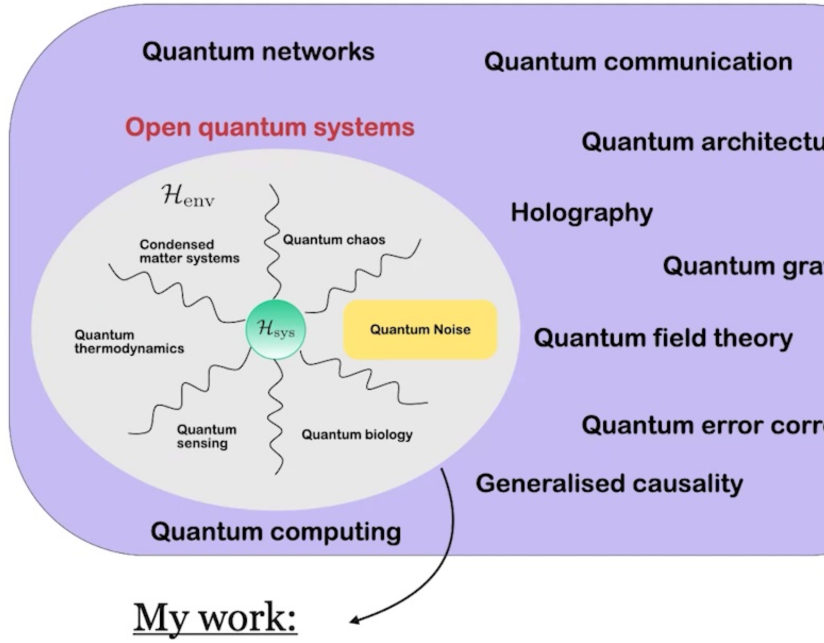


- Quantum theory has a spacetime structure with curious causal properties
- Particularly emerges in the context of open quantum systems

Chiribella et al. Phys. Rev. Letters **101**, 180501 (2008)
Hardy, Phil. Trans. R. Soc. A **370**, 3385 (2012)
Leifer & Spekkens Phys. Rev. A **88**, 052130 (2013)
Costa & Shrapnel, New Journal of Physics **18**, 063032 (2016)
Pollock et al. Phys. Rev. A **97**, 012127 (2018)
Cotler et al. J. High Energy Phys. **2018**, 93 (2018)

The Spacetime Structure of Quantum Mechanics





- Quantum theory has a spacetime structure with curious causal properties
- Particularly emerges in the context of open quantum systems

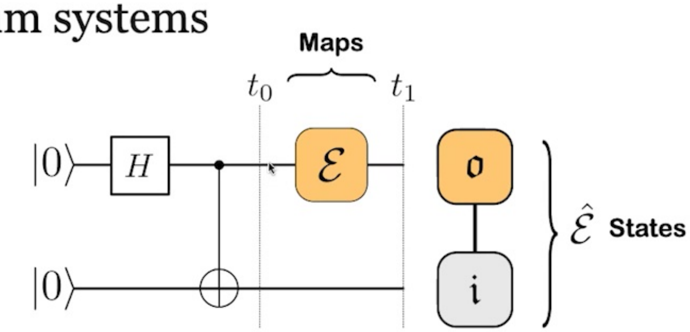
My work:

What generates spatiotemporal correlati[redacted]

What is their structure?

How can we access/measure/manipulate them?

Simple example, CJI:



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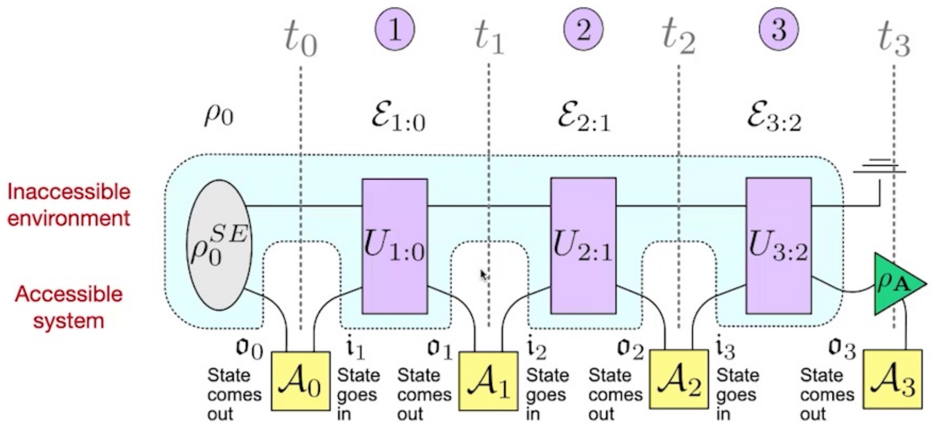
Process Tensors

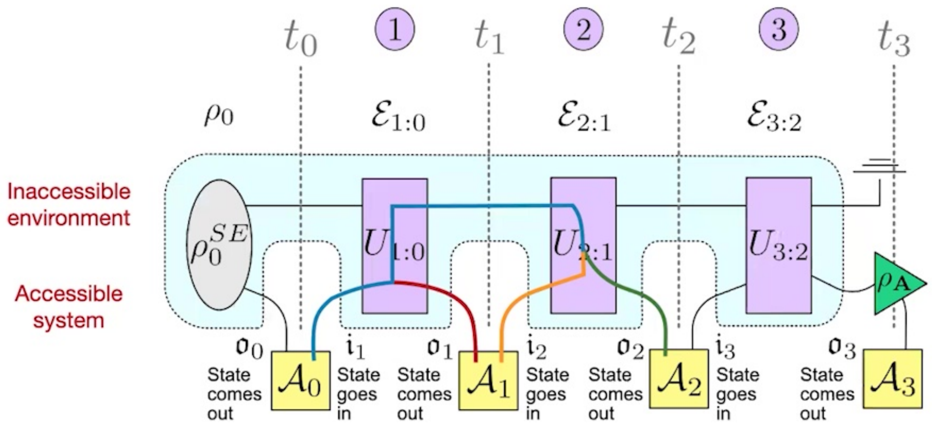


- Introduce the process tensor

$$\mathcal{T}_{k:0}[\mathbf{A}_{k-1:0}] = \rho(\mathbf{A}_{k-1:0})$$

Pollock [redacted]
97, 01[redacted]

Process Tensors



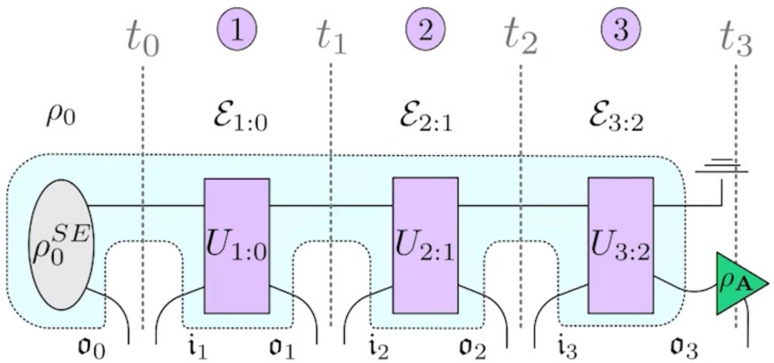
- Introduce the process tensor

$$\mathcal{T}_{k:0}[\mathbf{A}_{k-1:0}] = \rho(\mathbf{A}_{k-1:0})$$

Pollock [redacted]
97, 012 [redacted]

- Propagate a state along *and* account for con [redacted]
- Control can manipulate and allow you to le [redacted]
- Sequences of control operations are <u>observ</u> [redacted] process

Process Tensors



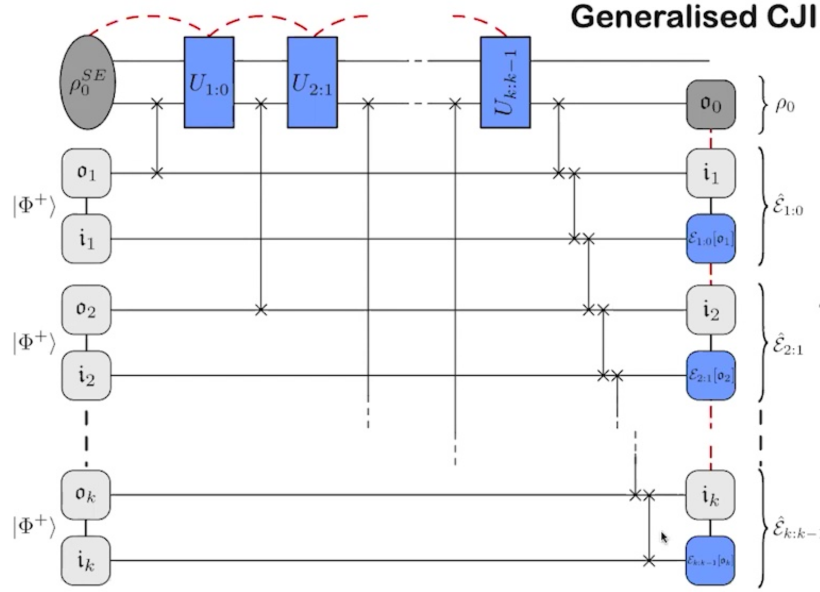
- Introduce the process tensor

$$\mathcal{T}_{k:0}[\mathbf{A}_{k-1:0}] = \rho(\mathbf{A}_{k-1:0})$$

Pollock[redacted]
97, 012[redacted]

- Propagate a state along *and* account for con[redacted]
- Control can manipulate and allow you to le[redacted]
- Sequences of control operations are observ[redacted] process

Generalised CJI



Υ_k[redacted]

[redacted] state are properties of the process!

Controls are events we can choose, process exists independently

Controls: deterministic, classical stochastic, quantum stochastic

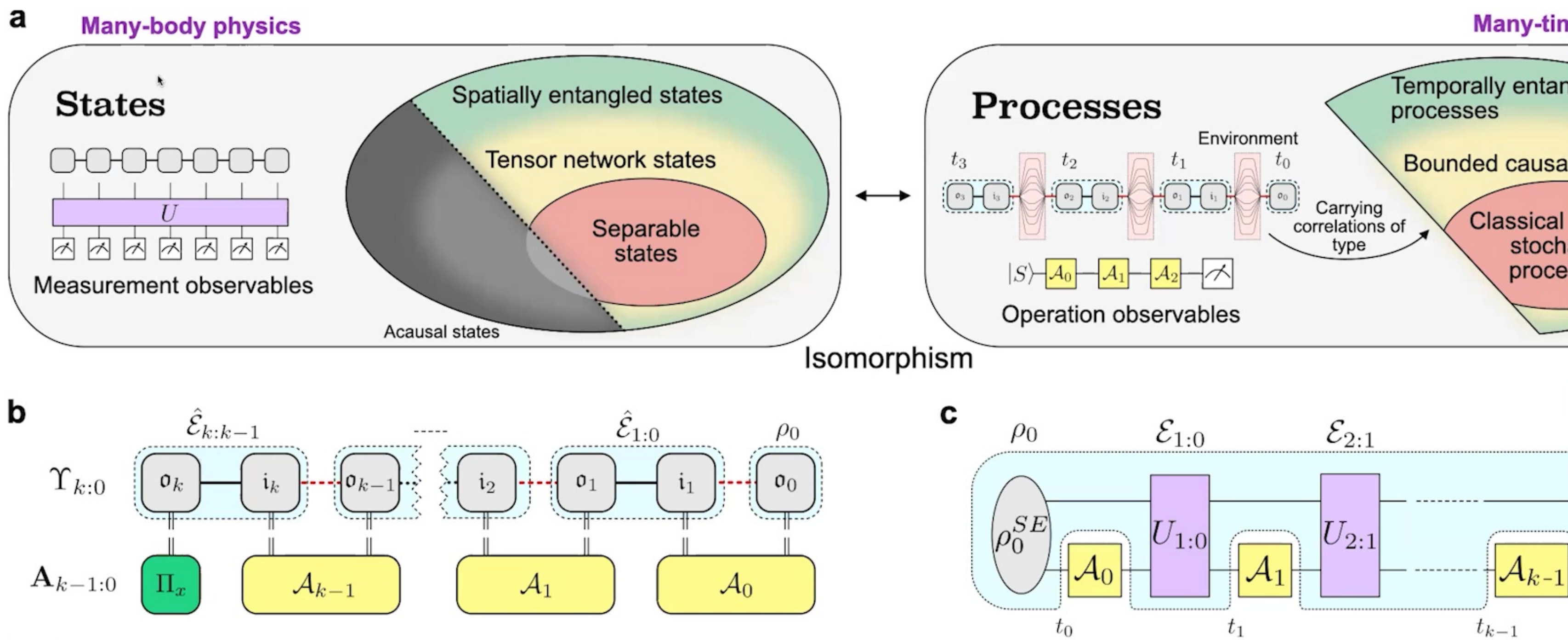
Instruments can click with outcome x_j at time t_j

$$\Pr(x_j, t_j; x_{j-1}, t_{j-1}; \cdots; x_0, t_0 | \mathbf{A}_{j:0}).$$

We now have a description of quantum stochastic processes

Milz et al. Quantum 4, 255 (2020)

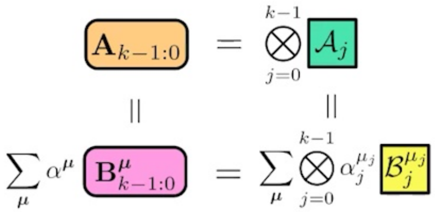
Many-Time Physics

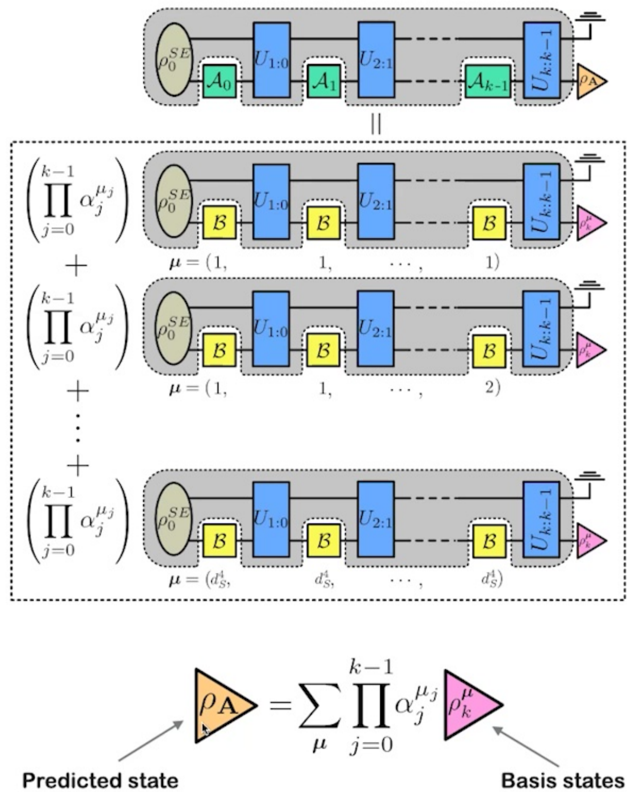


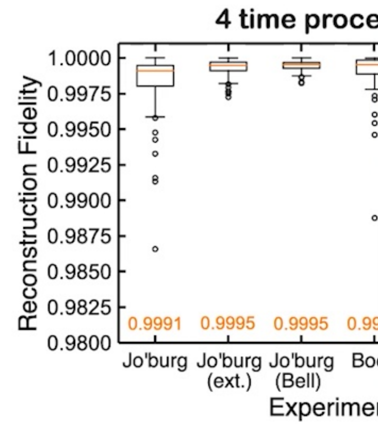
- Arbitrary correlations across time, mediated by an environment
- Formally structured in the same way as spatial many-body correlations
- What's missing is a way to study these correlations in a practical setting for arbitrary open dynamics

Aharonov et al. Phys. Rev. A **79**, 052110 (2009)
Costa et al. Phys. Rev. A 98, 012328 (2018)
Ried et al. Nature Physics **11**, 414-420 (2015)
Chiribella et al. Phys. Rev. A **80**, 022339 (2009)
Costa & Shrapnel, New Journal of Physics **18**, 063032 (2016)
Pollock et al. Phys. Rev. A **97**, 012127 (2018)
Milz et al. SciPost Phys. 10, 141 (2021)
White et al. arXiv:2107.13934 (2021)

Process Tensor Tomography







- Estimate non-Markovian dynamics
- Uniquely constrain on a complete basis
- Use the process tensor to predict random sequences
- Compare how close the two are: 'reconstruction fidelity'

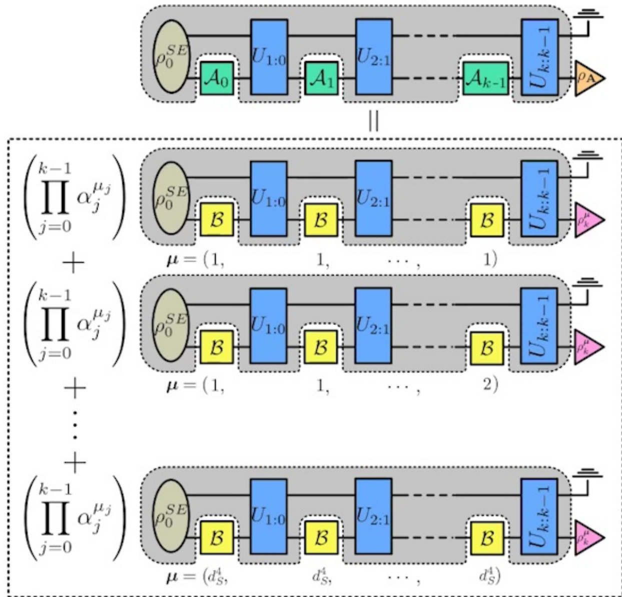
Nature Communications **11**, 6301 (2020)

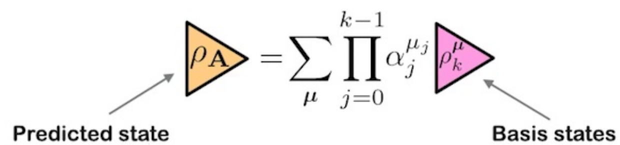
Process Tensor Tomography

$$\mathbf{A}_{k-1:0} = \bigotimes_{j=0}^{k-1} \mathcal{A}_j$$

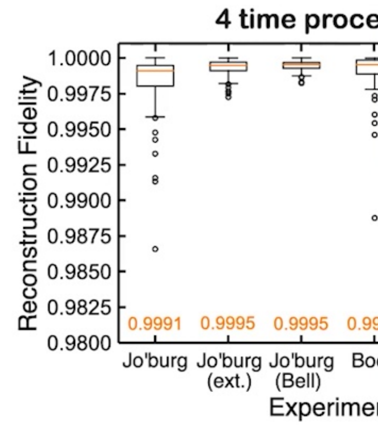
$$\sum_\mu \alpha^\mu \mathbf{B}^\mu_{k-1:0} = \sum_\mu \bigotimes_{j=0}^{k-1} \alpha_j^{\mu_j} \mathcal{B}_j^{\mu_j}$$

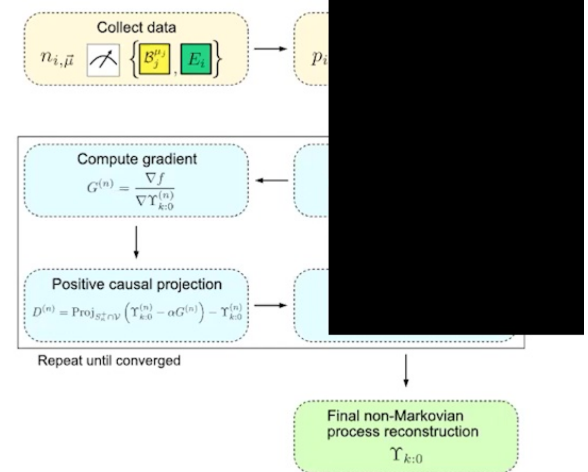
- Estimate non-Markovian dynamics
- Uniquely constrain on a complete basis
- Use the process tensor to predict random sequences
- Compare how close the two are: 'reconstruction fidelity'
- Generalised Born rule connects process tensor to reality
- Fit a physical, maximum likelihood model





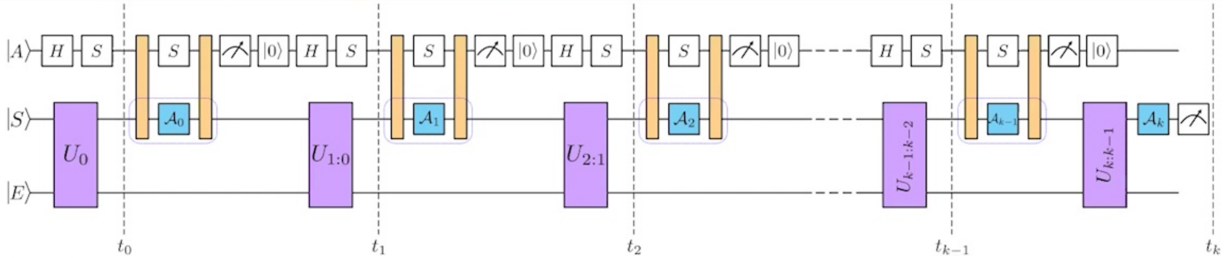
$$p_{i,\vec{\mu}} = \mathrm{Tr}\left[(\Pi_i \otimes \mathcal{B}_k^{\mu_{k-1}\mathrm{T}} \otimes \cdots \otimes \mathcal{B}_0^{\mu_0 \mathrm{T}})\Upsilon_{k:0}\right]$$



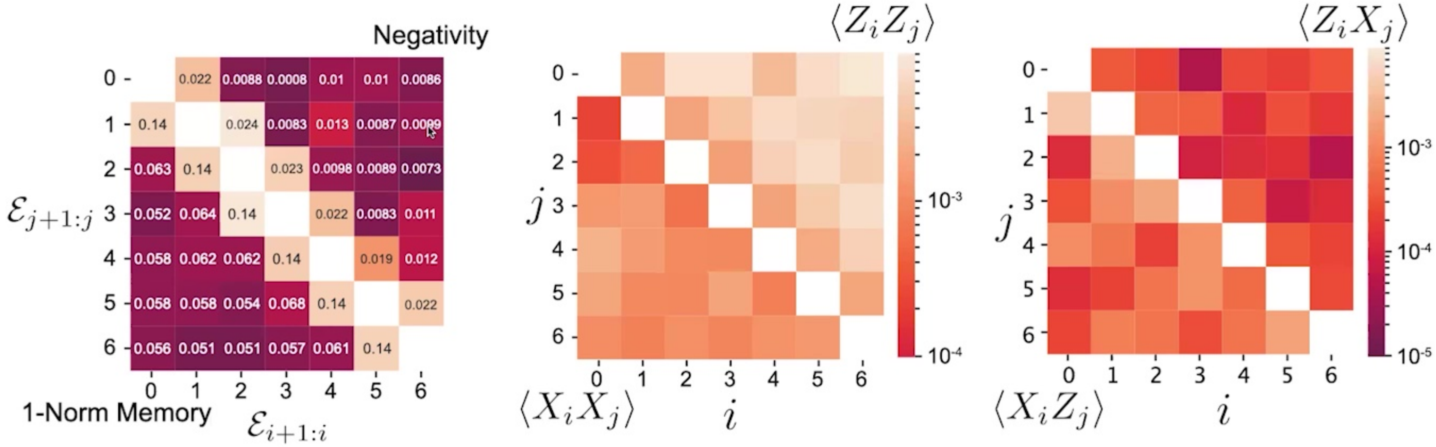


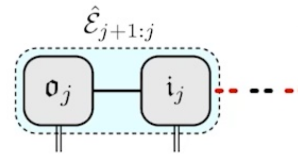
Nature Communications **11**, 6301 (2020)
PRX Quantum **3**, 020344 (2022)

Extracting Process Properties



- Obtain 2-map/4-body process marginals across seven steps





The noise itself [redacted]
complex across [redacted]

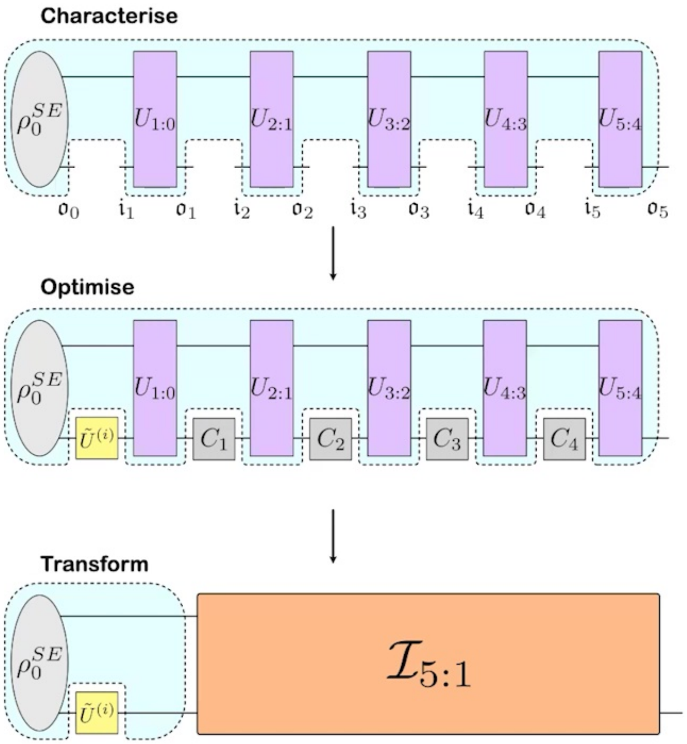
- Also look at 3-step/7-body processes with different backgrounds

Setup	QMI (min, max)	Negativity	Purity	Fidelity
#1. System Alone	(0.298, 0.304)	(0.0179, 0.0181)	(0.8900, 0.8904)	(0.9423, 0.9427)
#2. $\lvert + \rangle$ Nearest Neighbours (NN)	(0.363, 0.369)	(0.0255, 0.0259)	(0.7476, 0.7485)	(0.7239, 0.7244)
#3. Periodic CNOTs on NNs in $\lvert + \rangle$	(0.348, 0.358)	(0.0240, 0.0246)	(0.7796, 0.7811)	(0.7264, 0.7272)
#4. $\lvert 0 \rangle$ NNs with QDD	(0.358, 0.373)	(0.0205, 0.0210)	(0.8592, 0.8612)	(0.8034, 0.8045)
#5. $\lvert + \rangle$ Long-range Neighbours	(0.329, 0.339)	(0.0209, 0.0214)	(0.8594, 0.8608)	(0.9252, 0.9260)
#6. $\lvert + \rangle$ NN, delay, $\lvert + \rangle$ next-to-NN	(0.322, 0.329)	(0.0209, 0.0213)	(0.8534, 0.8549)	(0.9077, 0.9083)

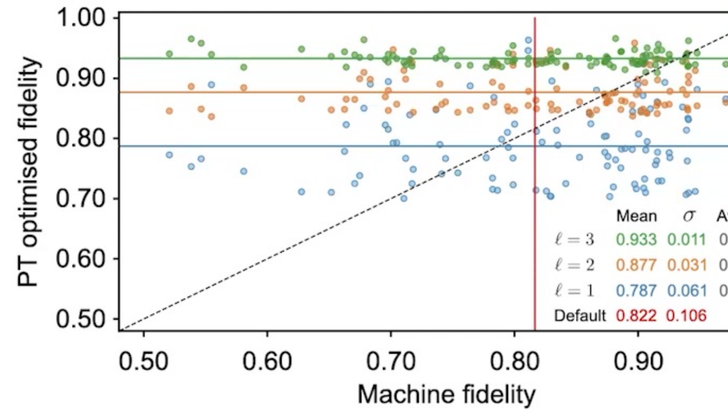
ibmq_casablanca

Manipulating Processes

- Knowing the process allows you to manipulate the structure
- Search for operations such that the conditional processes have desired properties

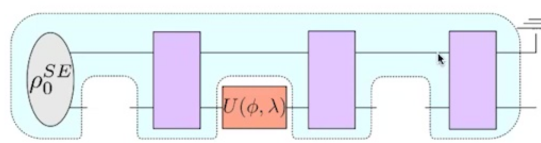


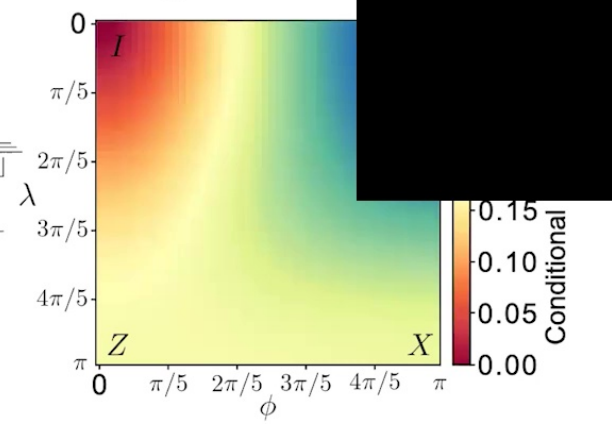
e.g. noise reduction



[redacted]

e.g. controlled entanglement

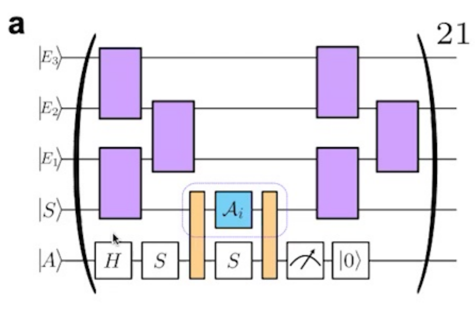




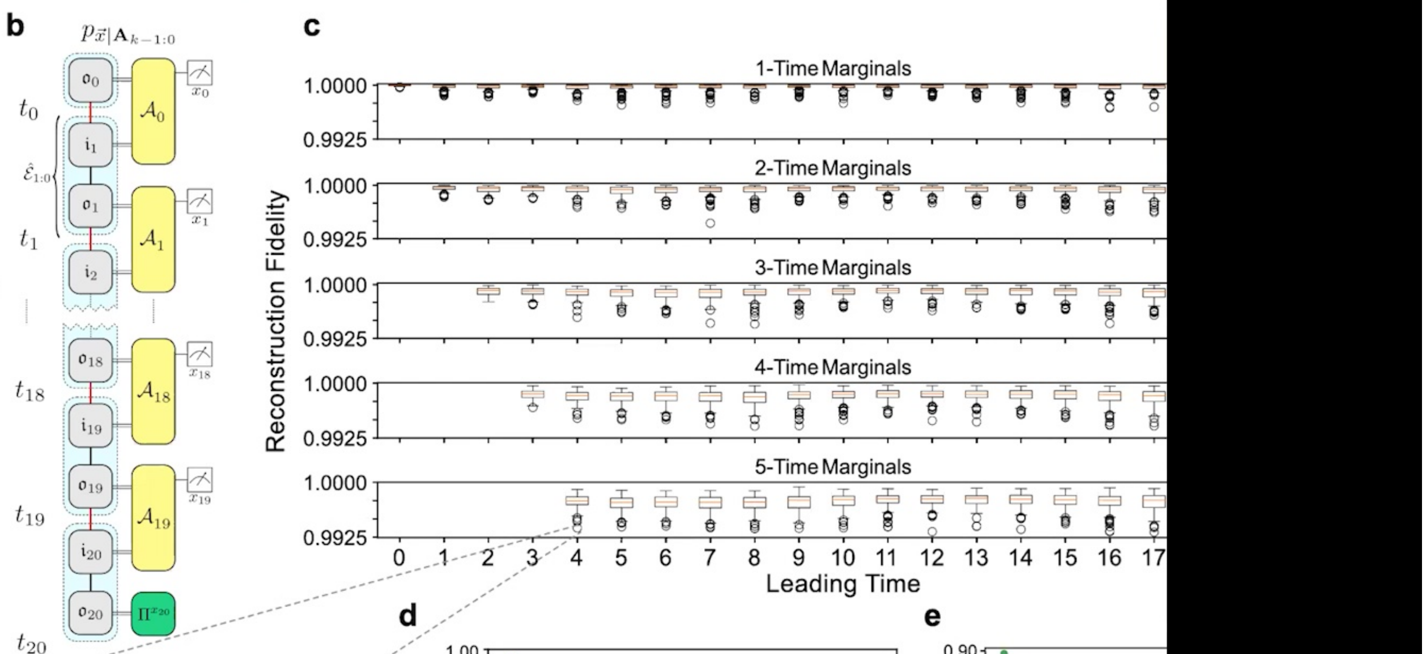
PRX Quantum **3**, 020344 (2022)
arXiv:2107.13934

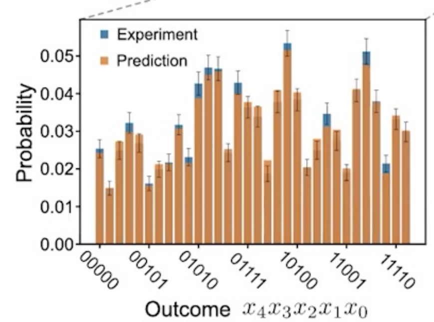
Open Simulation: Learning Large non-Markovian Process[redacted]

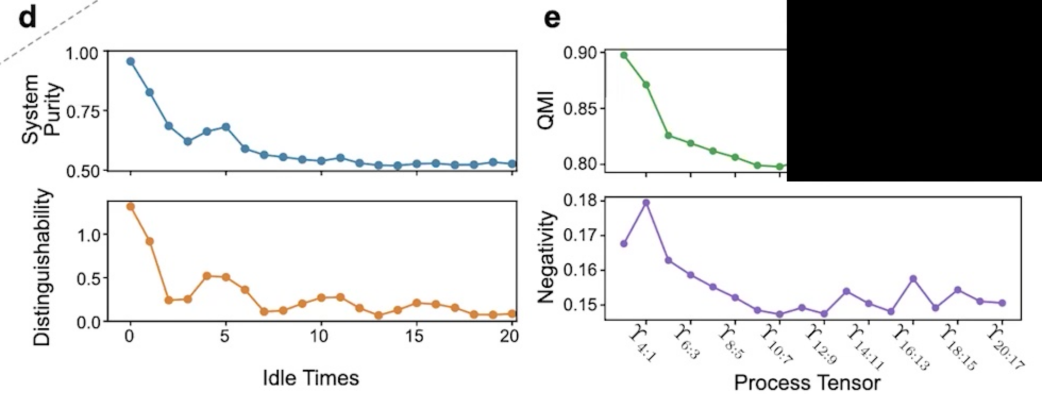
- Applied to simulating OQS, everything you can learn about a process
- Sampling complexity beyond classical simulability arXiv:2209.10870
- Using randomised control operations, we reconstructed the matrix product operator (MPO) representation of a 20-step process



arXiv:2107.13934

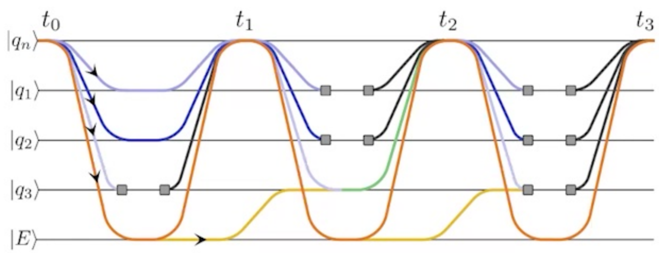


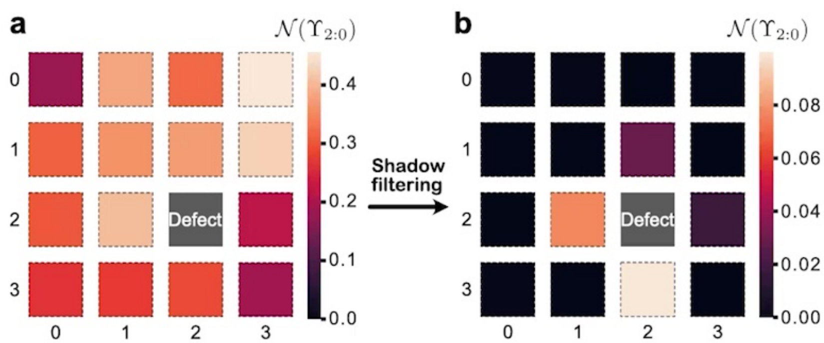


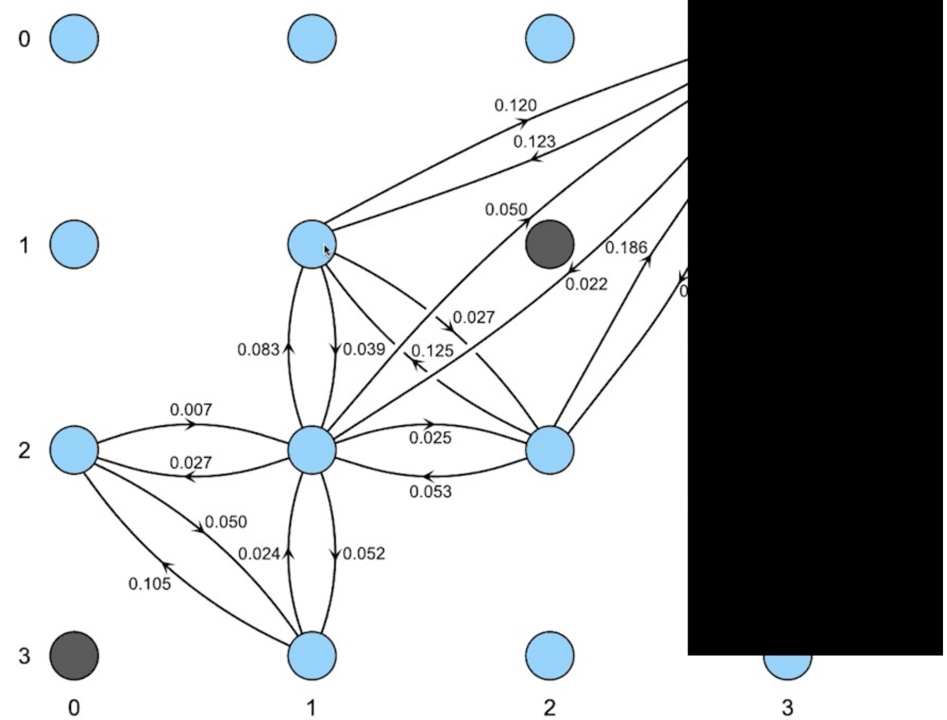


Filtering Crosstalk From Bath non-Markovianity

- How do you know whether NM came from a nearby qubit or an inaccessible bath?
- We use classical shadows to erase effects of neighbours and perform causal testing — reveals the bath
- Also can be used to check which qubits are commonly coupled to the same bath



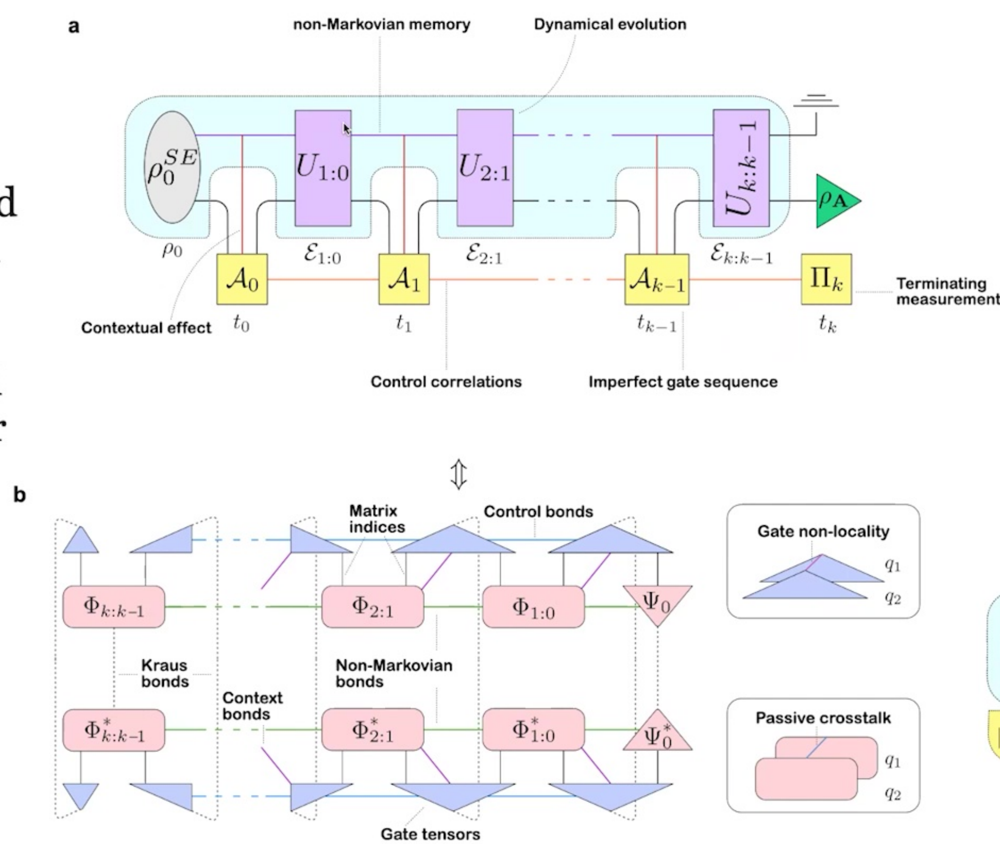


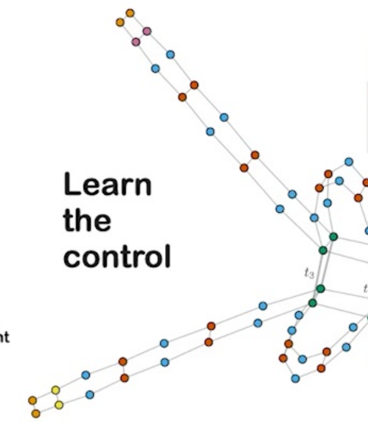


arXiv:2210.15333

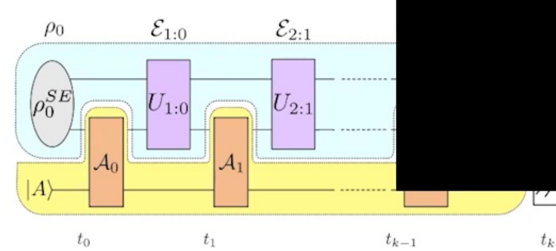
Scalability and Self-Consistency

- Universally model control process, and interplay of control and process
- Use locally purified tensor networks for scalability
- Fully determine sparse spacetime structures and the operational probes





Learn the control

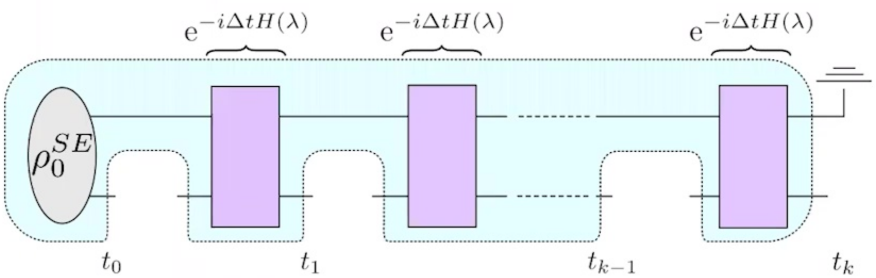


Use an ancilla as a probe — correlated instrument with no overhead

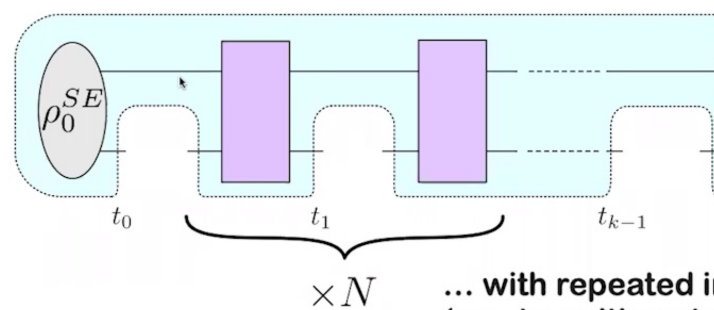

Future Directions

Exploring Classes of Exotic Quantum Processes

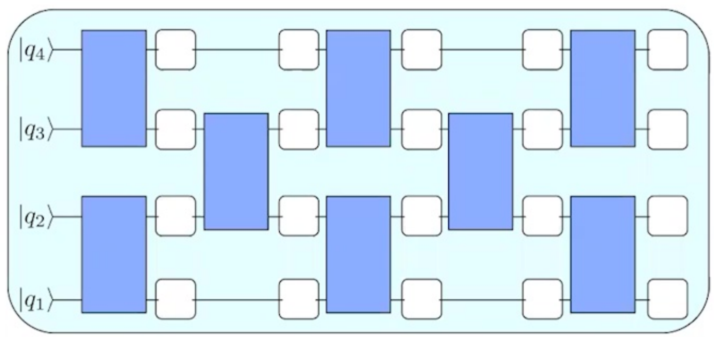
- Whole catalogues of many-body states to source inspiration from
- More general understanding of dynamics — e.g. temporal phase transition[redacted]



… with choice of order parameters (e.g. dynamical phase transition)

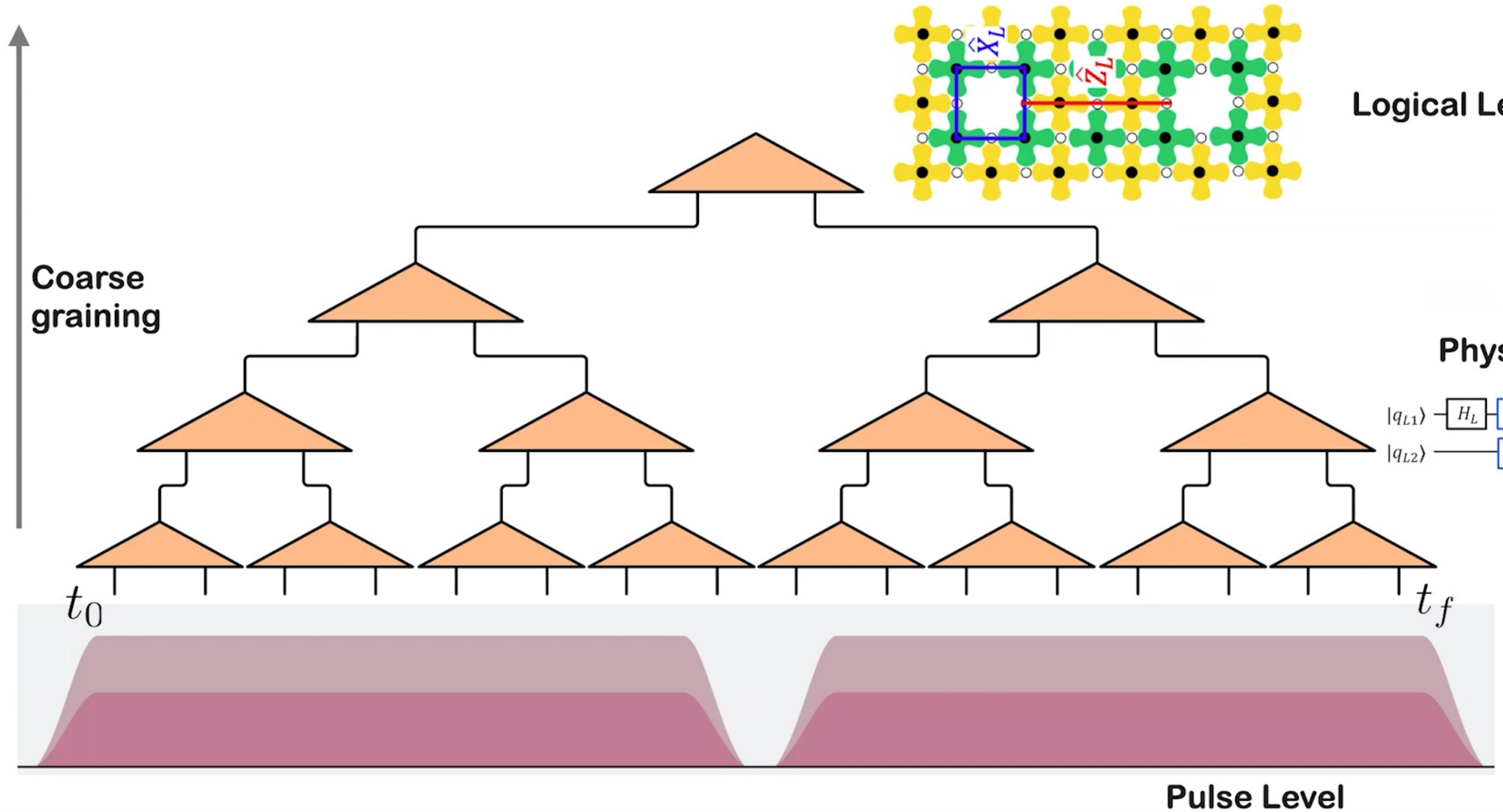


… with repeated i[redacted]
(e.g. transitions to[redacted]



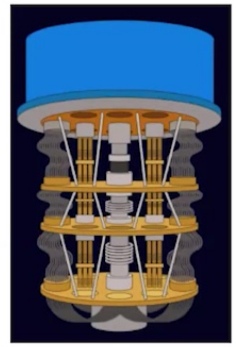
… with choice of control structure (e.g. measurement-induced phase transition)

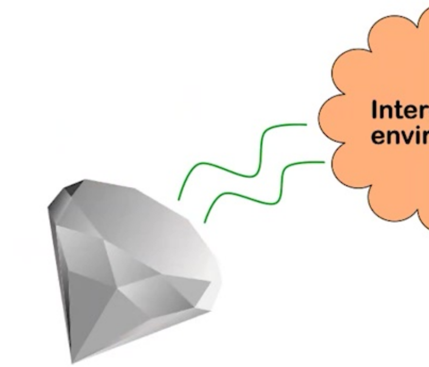
Renormalisation Group and Emergent Temporal Structur[redacted]

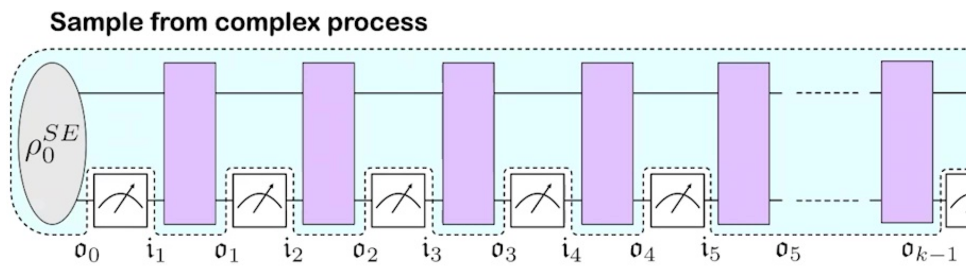


Quantum Advantage via Learning Properties of Quantum Stochastic Proce[redacted]

- We have recently shown the sampling complexity of open quantum systems to be above classical arXiv:2209.10870
- Quantum simulation or quantum sensing avenues towards advantage
- Two-time sampling not necessarily enough
- Exciting recent results in learning theory readily generalisable



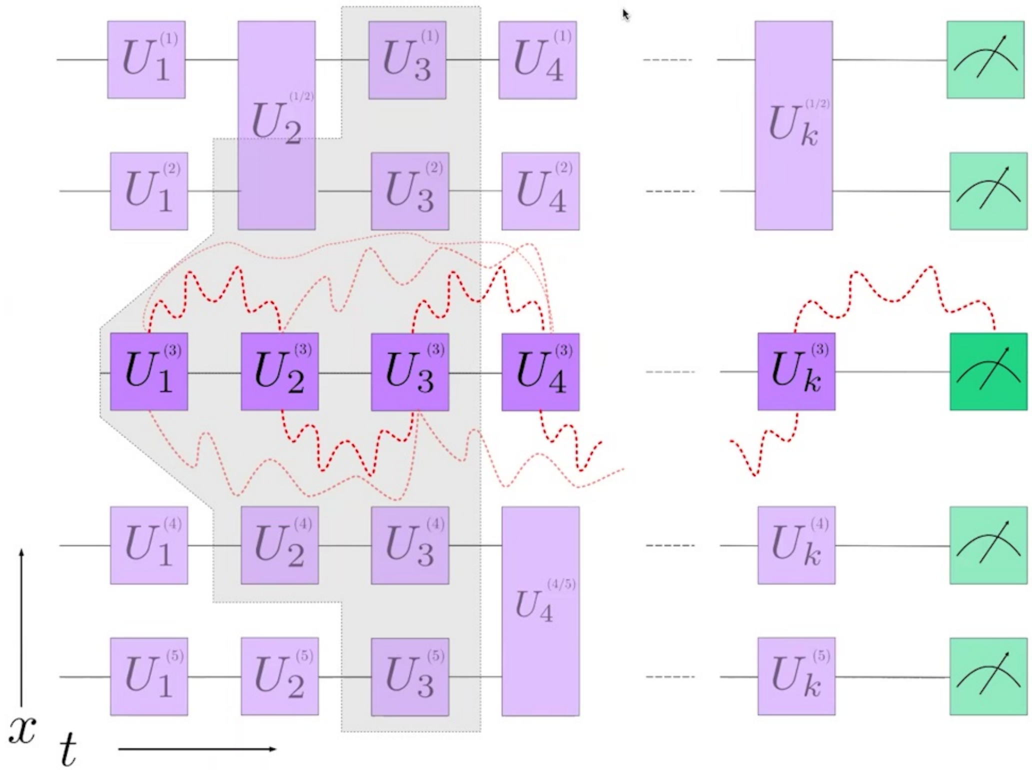




Process classically and predict

$$\mathrm{Tr}[\mathcal{O}\Upsilon_{k:0}]$$

Taming Correlated Noise



- Problematic: errors c[redacted]
exponentially hard t[redacted]
understand or chara[redacted]

- *Problematic*: more e[redacted]
circuit

- *__Problematic__*: correla[redacted]
can reduce or elimin[redacted]
effectiveness of QEC [redacted]

Clader et al. Phys. Rev. A **103**, 052428 (2021)
Nickerson, Brown Quantum **3**, 131 (2019)

- Scope for this info to be fed forward into all parts of the quantum computing stack: fabrication, error suppression, mitigation, correction

Summary

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- Quantum stochastic processes are the most general description of open quantu[redacted] dynamics
- Generalised CJI shows how many-time physics is as rich as many-body physics
- We develop ‘process tensor tomography’ and its variants to capture different aspects of the many-time physics
- Estimate contains operational meanings about dynamics
- Demonstrated tomography and applications on IBM Quantum devices
- Plenty of interesting followup problems

Thanks for Listening!
Any Questions?

Demonstration – Nature Communications 11 (1)[redacted]
Generalised QPT – PRX Quantum **3**, 020344 (2022)
Many-time physics – arXiv:2107.13934
Complexity of OQS – arXiv:2209.10870
Filtering crosstalk with shadows – arXiv:2210.15333