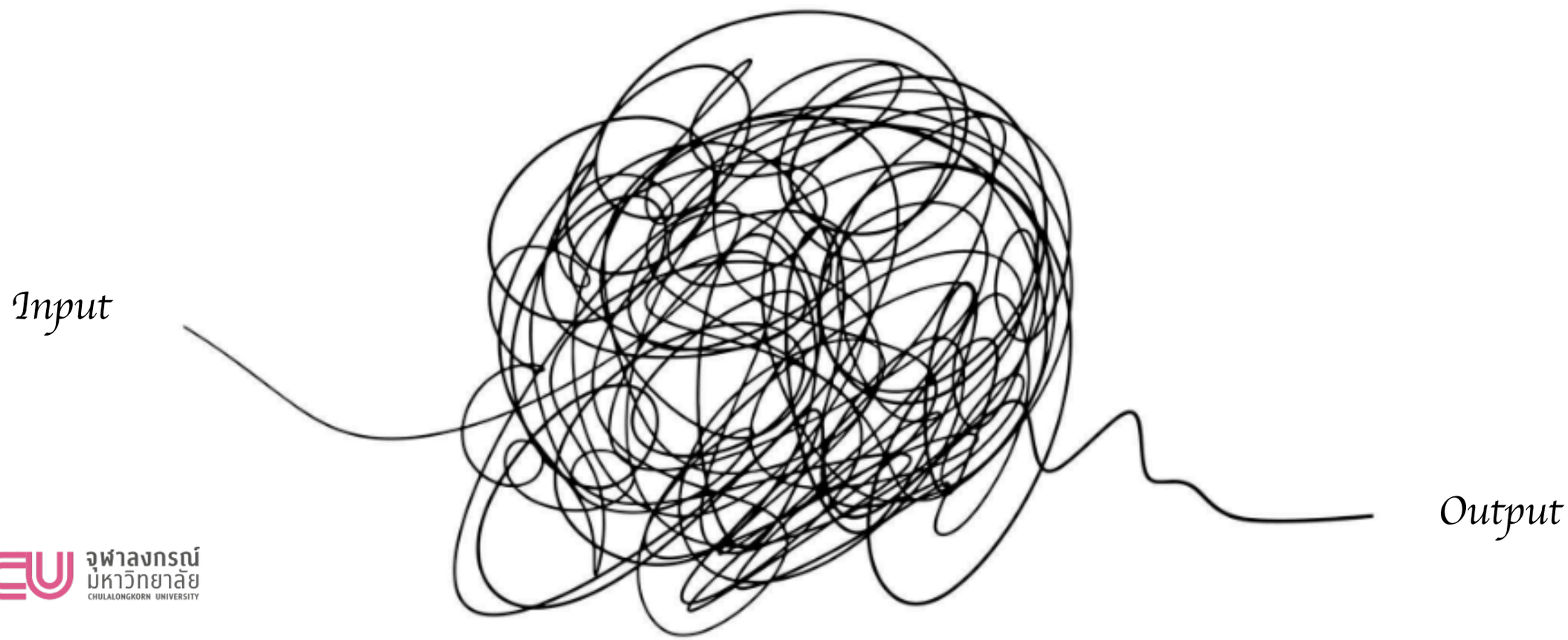
Roles of Scrambling and Noise in Information Processing with Quantum Systems

Thiparat Chotibut (Thip)
Chula Intelligent and Complex Systems Research Unit,
Department of Physics,
Chulalongkorn University, Bangkok, Thailand

October 8, 2025

100 Years of Quantum Physics
Recontres du Vietnam
ICISE, Quy Nhon



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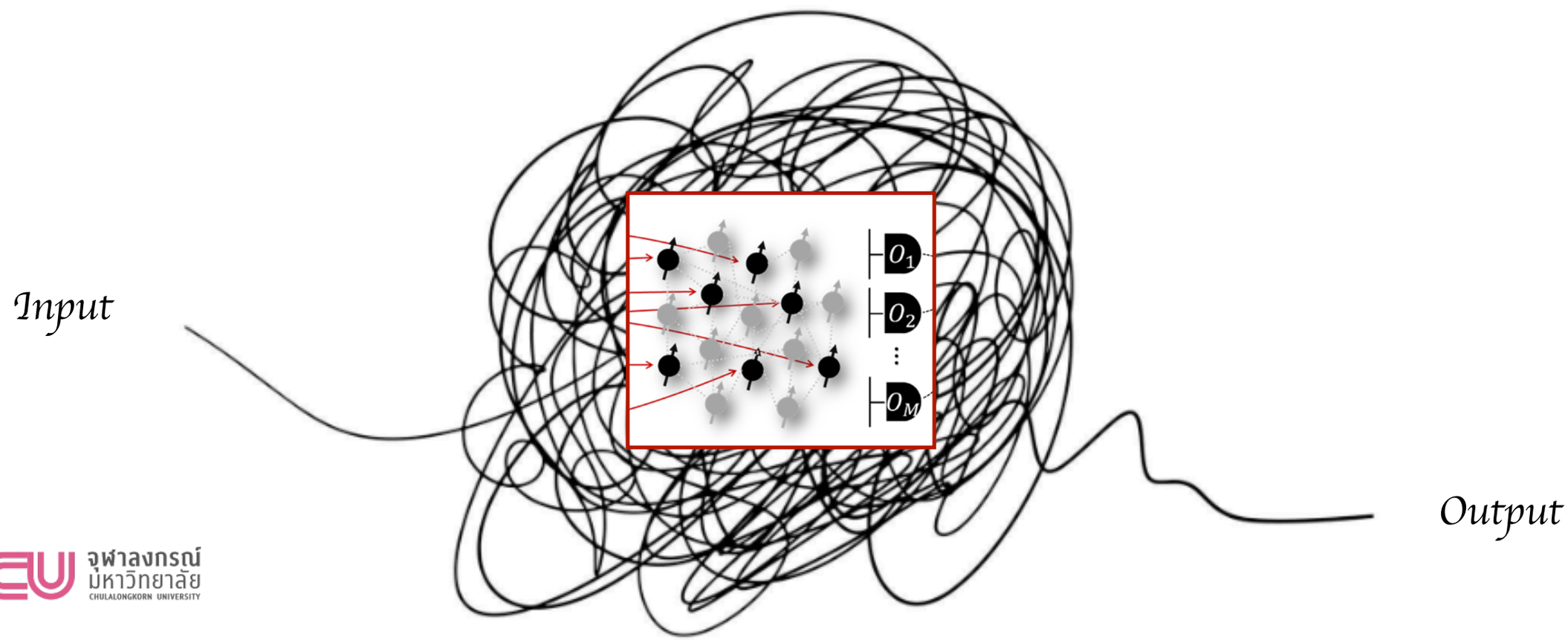
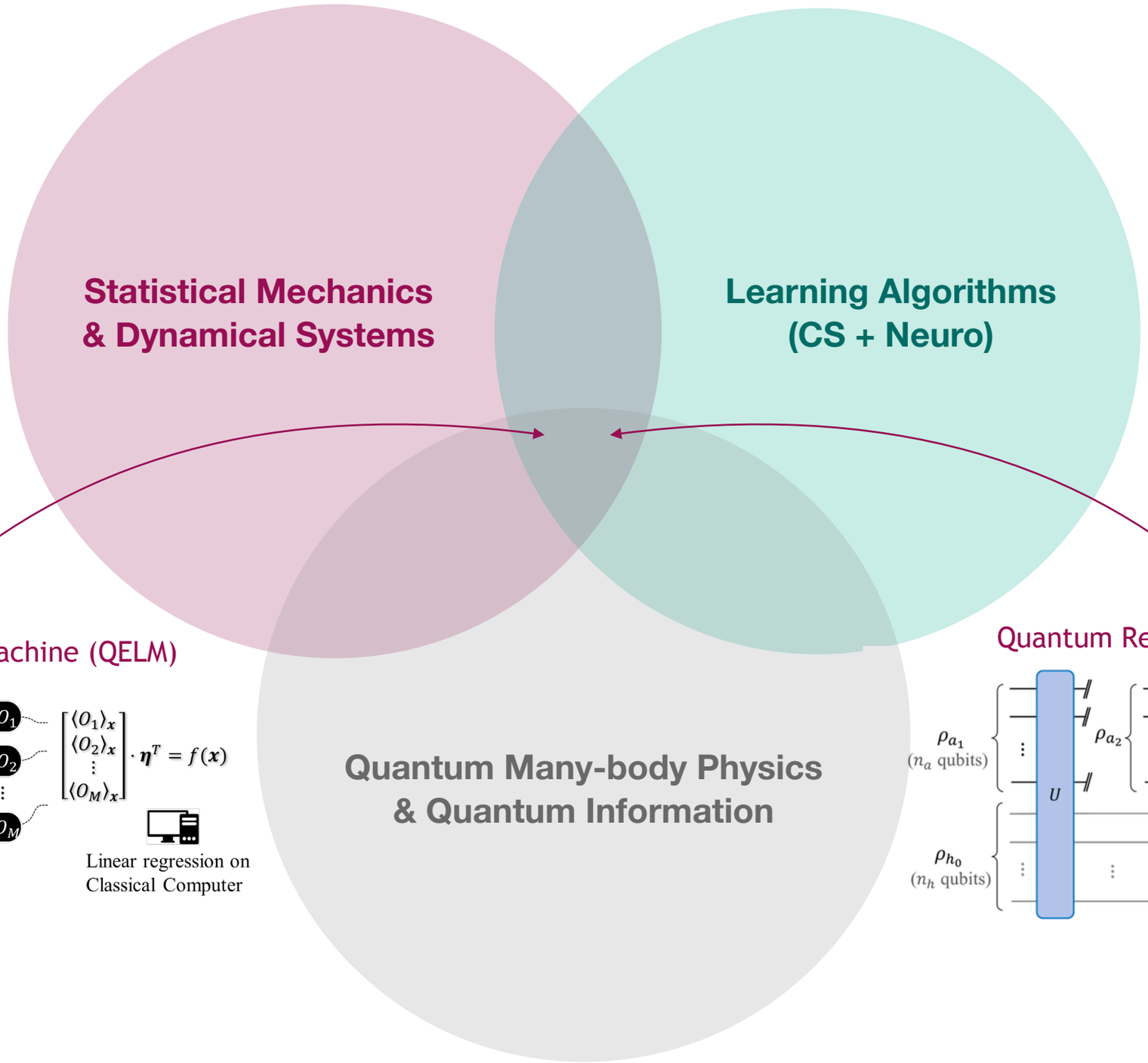
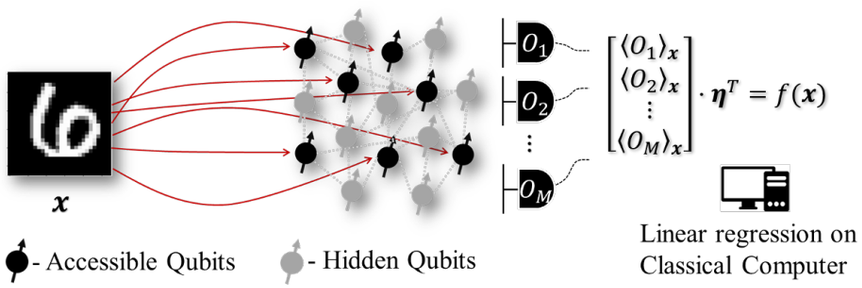


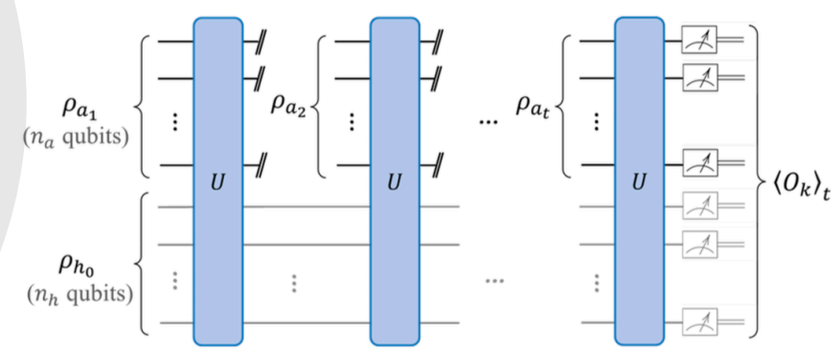
Statistical mechanics/dynamics of learning algorithms on quantum substrate



Quantum Extreme Learning Machine (QELM)



Quantum Reservoir Computing (QRC)

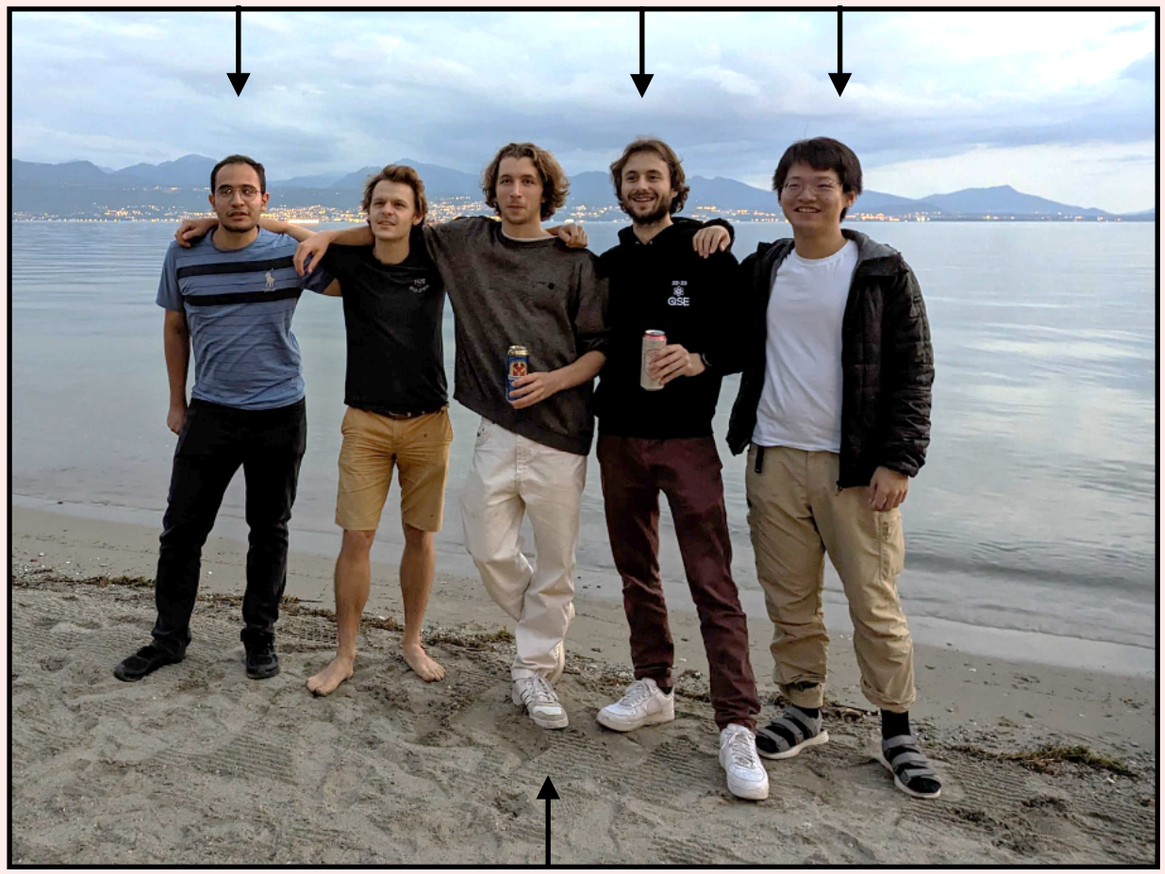


W. Xiong, … **TC**, Z. Holmes, *Quantum Machine Intelligence* 2025

W. Xiong, … **TC**, S. Thanasilp, *under review in npj QI*

Acknowledgement

Mehrad Sahebi Giorgio Facelli Weijie Xiong (EPFL)



Owen Agnel (Oxford)

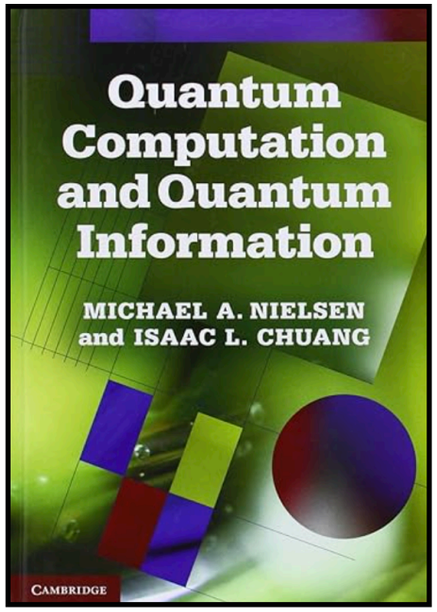
Supanut Thanasilp
(Chulalongkorn)

Zoe Holmes
(EPFL)

Why QELM and QRC? A Brief Detour: The Quest for Quantum Advantages

Ideal (Fault-tolerant) quantum computational advantages

Textbook algorithms: Shor's, Grovers's, HHL, etc.



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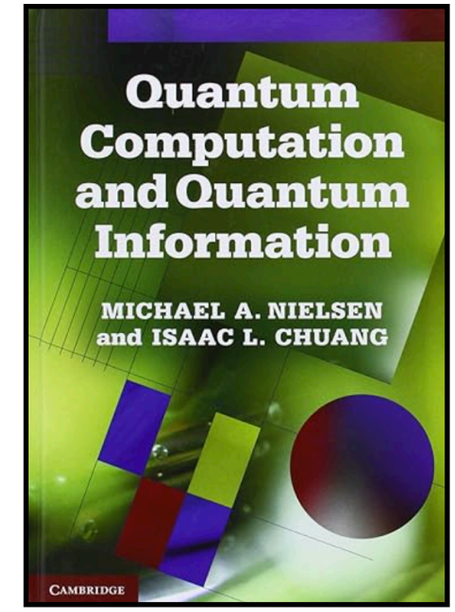
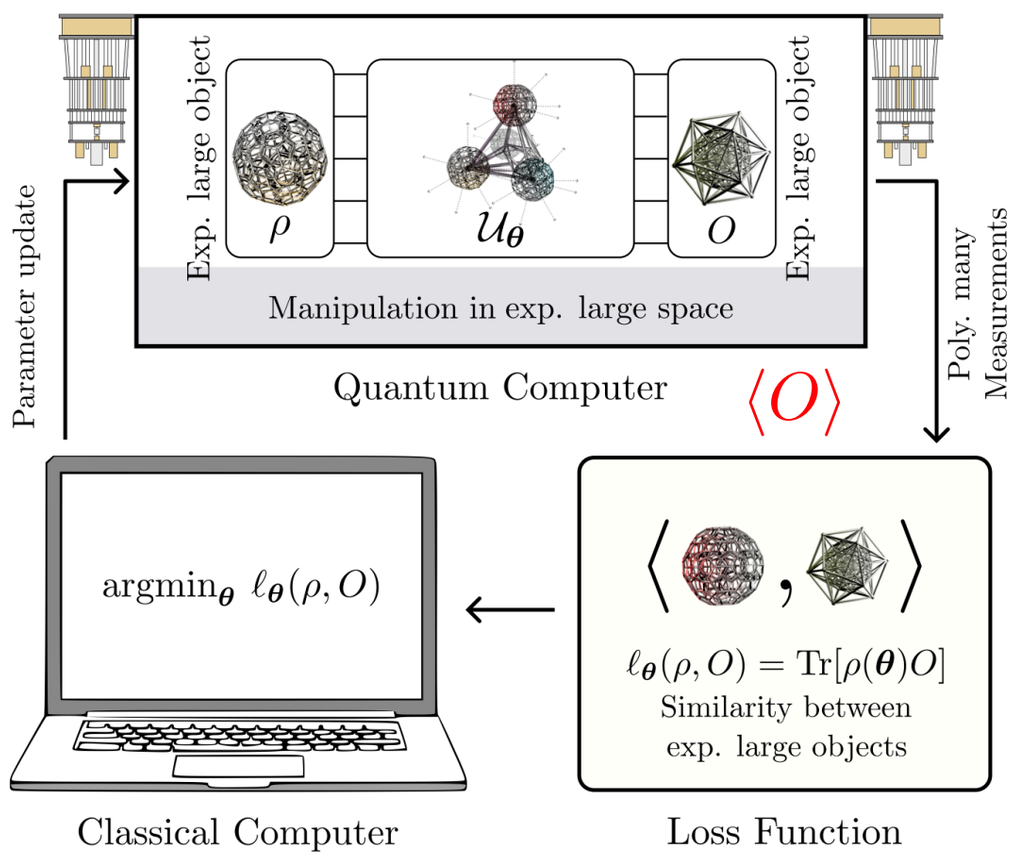
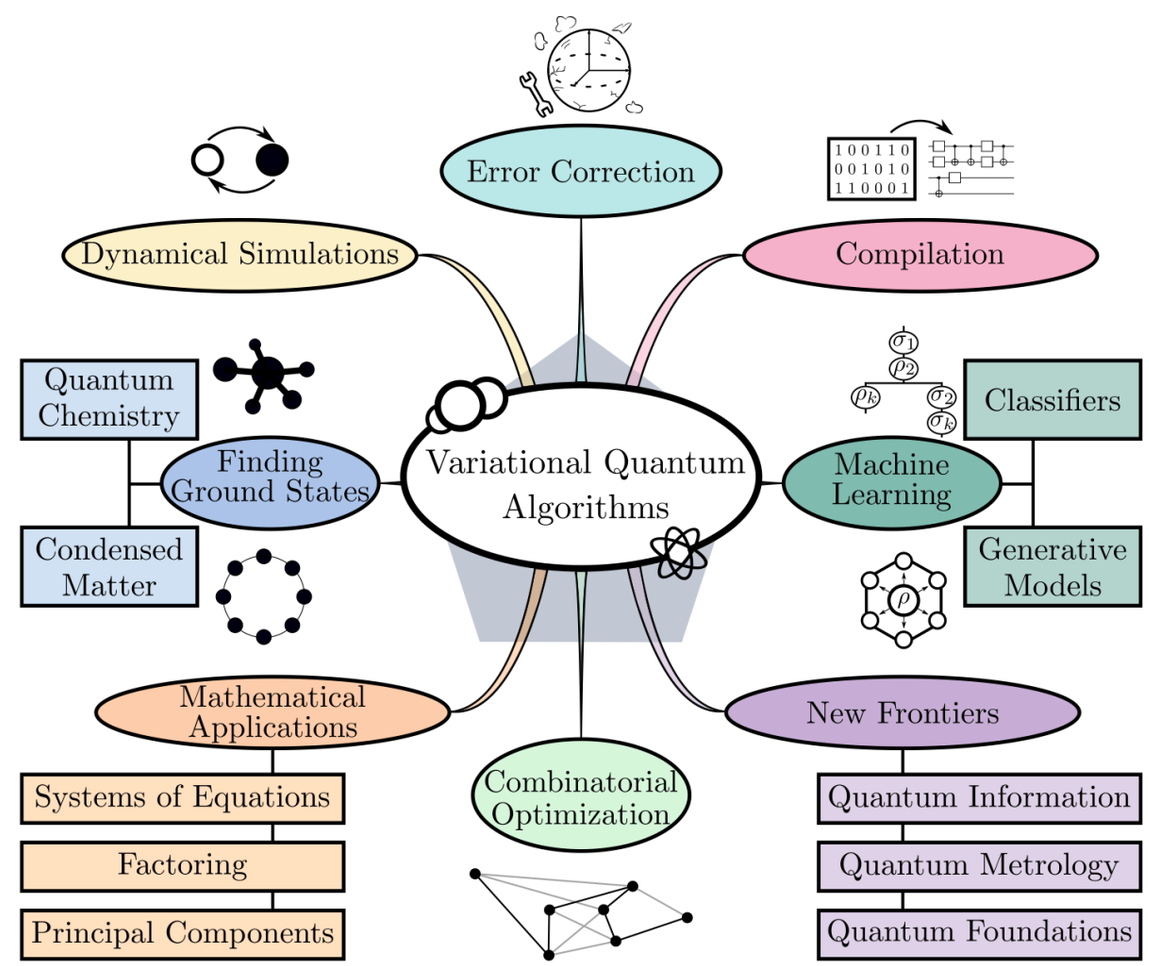
✅ Noisy Intermediate-Scale Quantum (NISQ) Era

Variational Quantum Algorithms (VQAs)





M. Larocca, et. al., A Review of Barren Plateaus in Variational Quantum Computing, *Nature Review Physics* 2025



M. Cerezo, et. al., *Nature Review Physics* 2021

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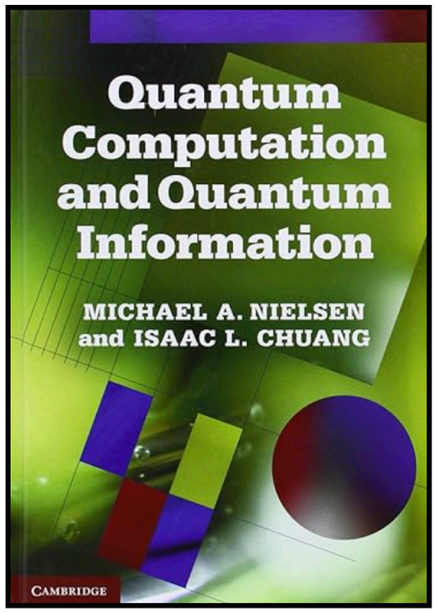

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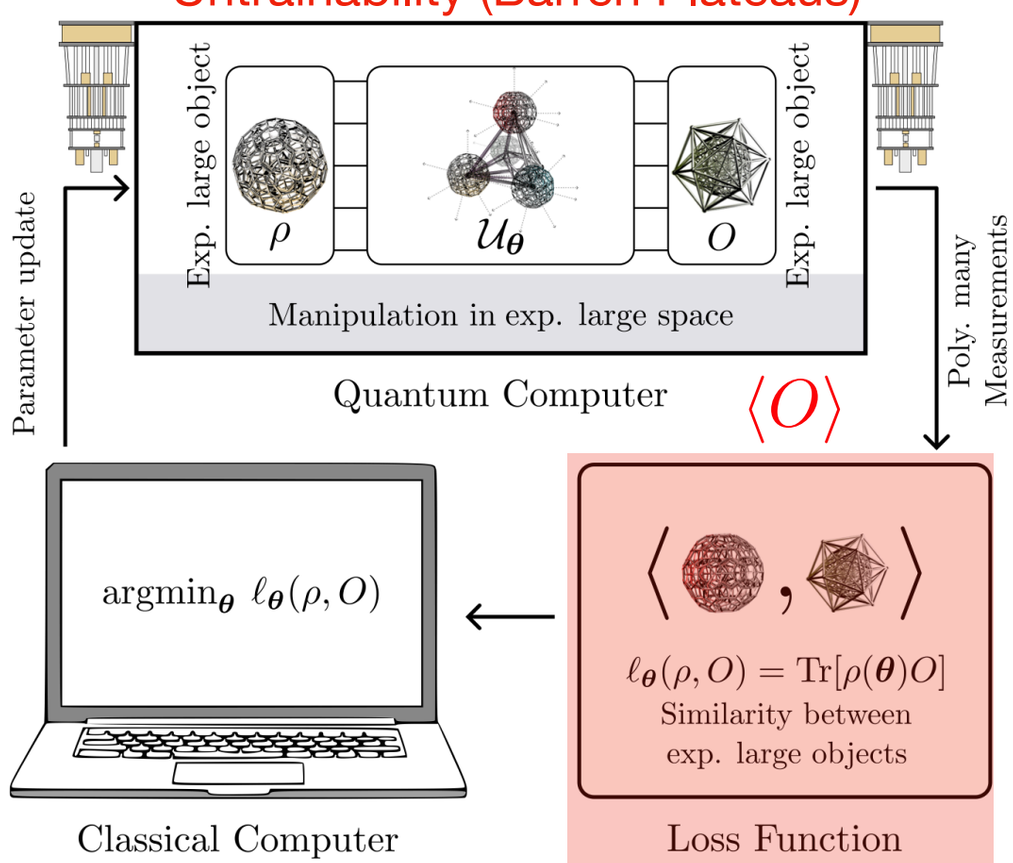
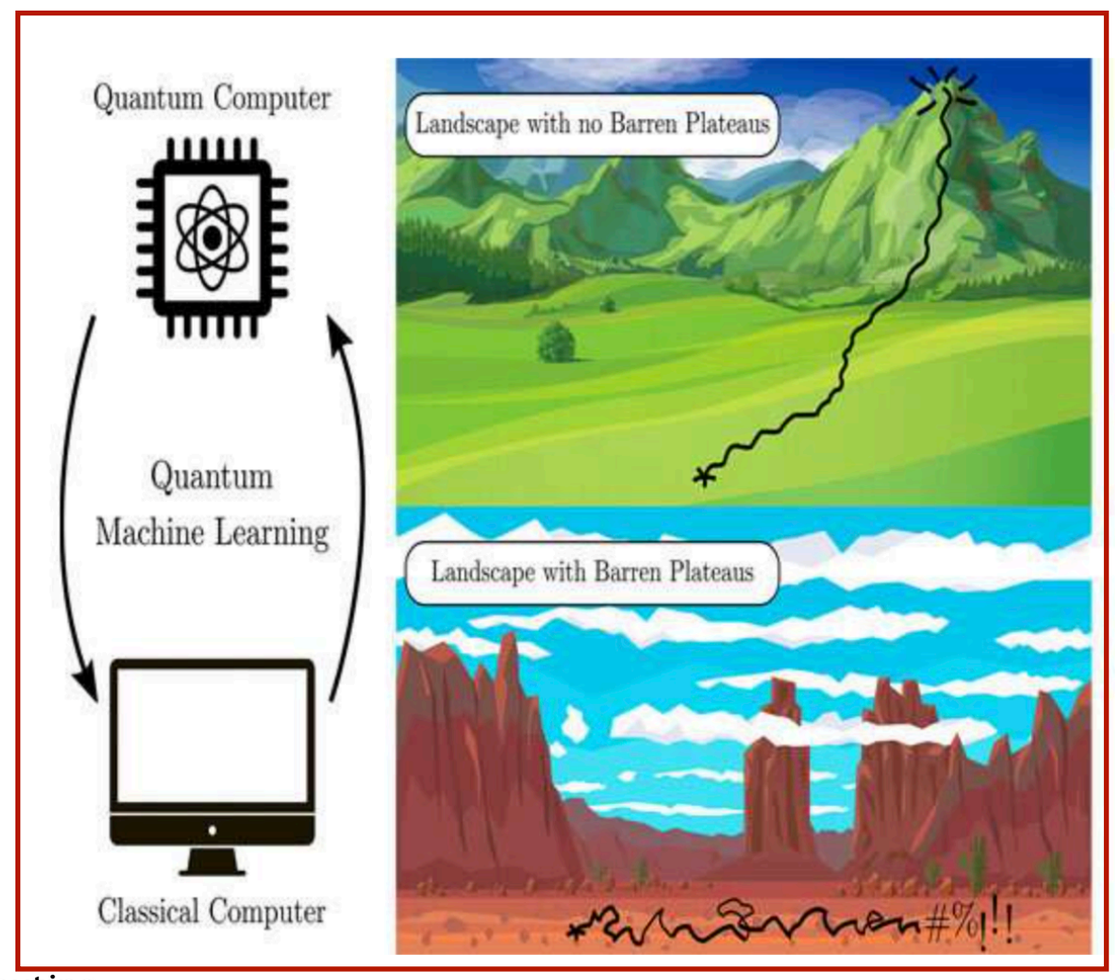
Variational Quantum Algorithms (VQAs)

❌ **Curse of Dimensionality**

Untrainability (Barren Plateaus)





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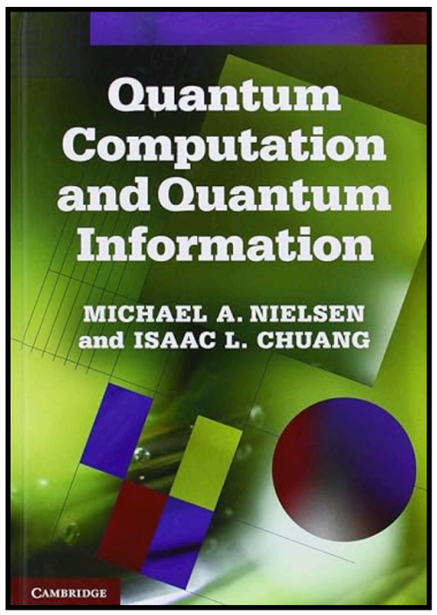

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Textbook algorithms: Shor's, Grovers's, HHL, etc.

✓ Noisy Intermediate-Scale Quantum (NISQ) Era

Variational Quantum Algorithms (VQAs)

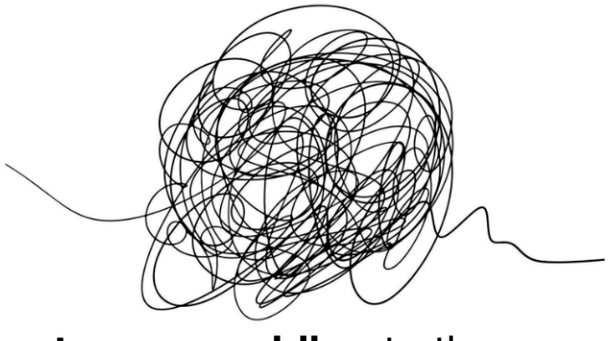
✗ Barren plateaus are ubiquitous

No variational parameters. Use NISQ devices to generate **high dimensional feature** maps for **Quantum Machine Learning**

Quantum Kernel Methods

? Quantum Extreme Learning Machines (QELMs)

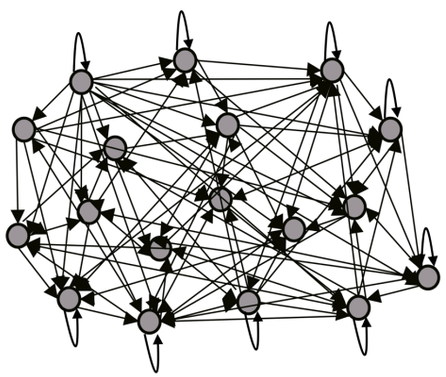
? Quantum Reservoir Computing (QRC)



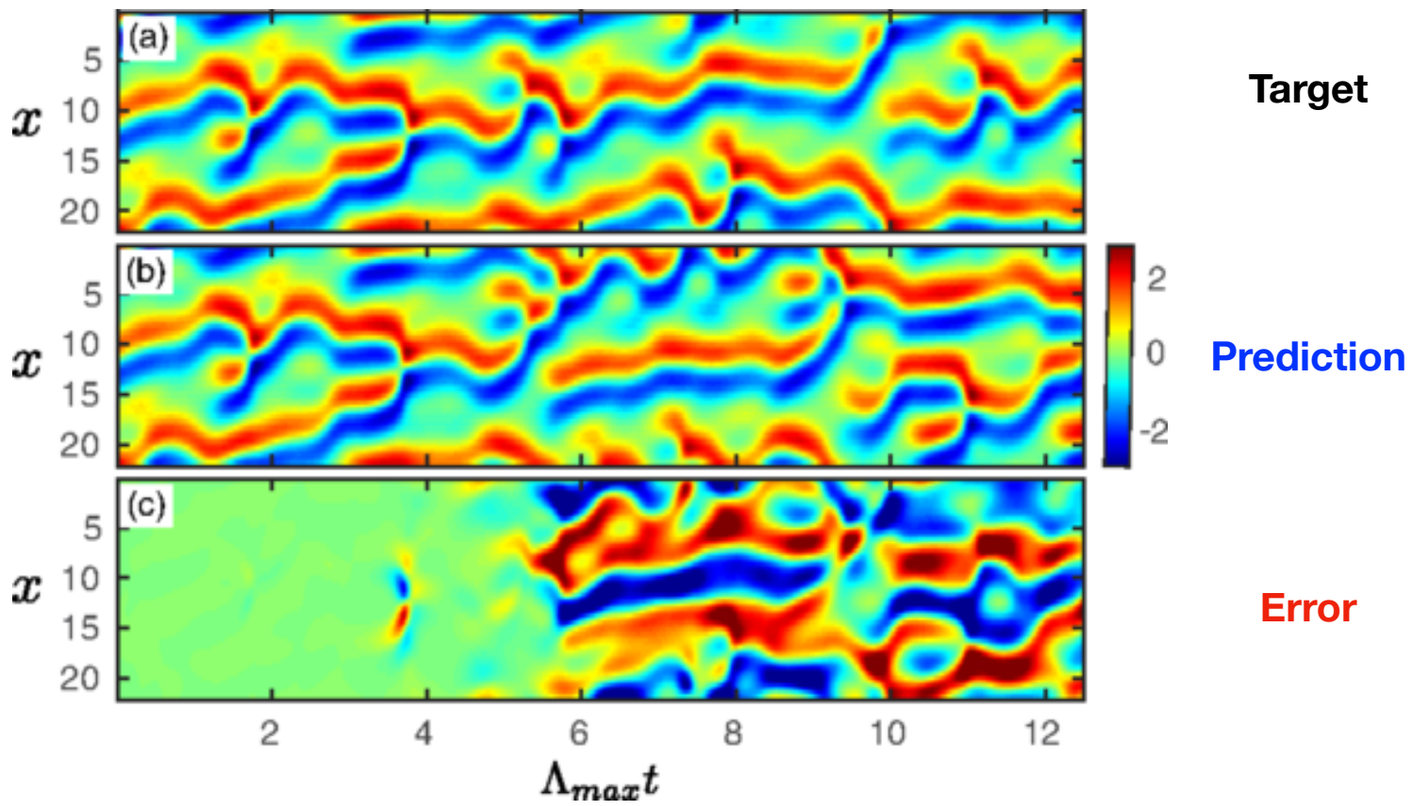
quantum scrambling to the rescue?

Examples of Non-Variational Algorithm: Reservoir Computing

Edge-of-chaos recurrent network reservoir



kuramoto-sivashinsky spatiotemporal chaos



J. Pathak et. al. *Phys. Rev. Lett.* **120**, 024102, 2018

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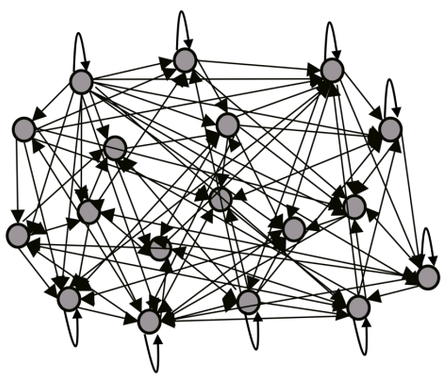

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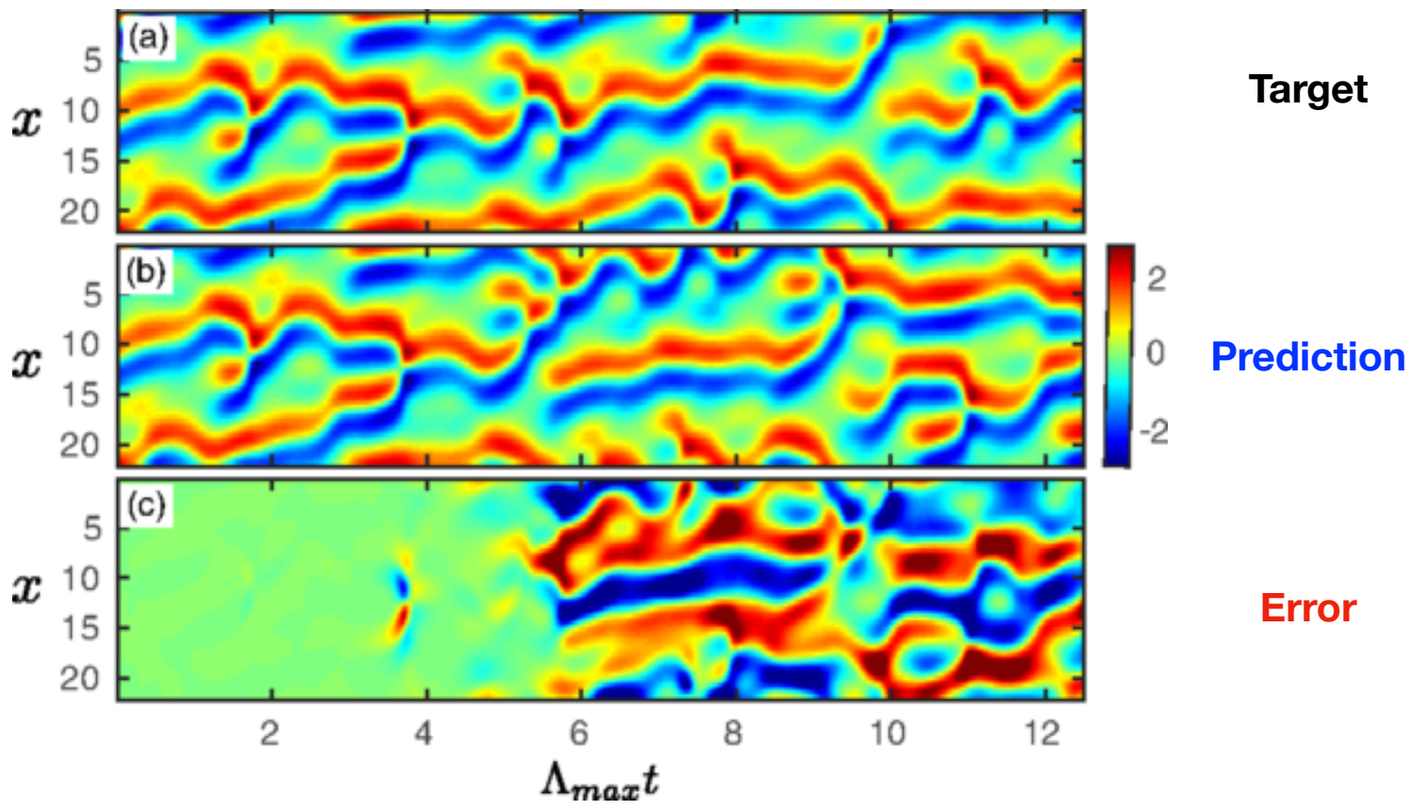
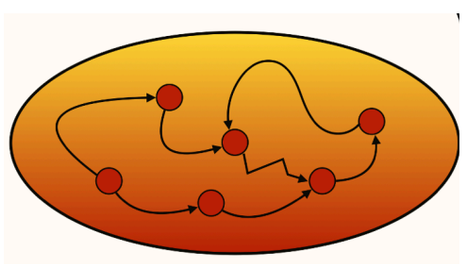
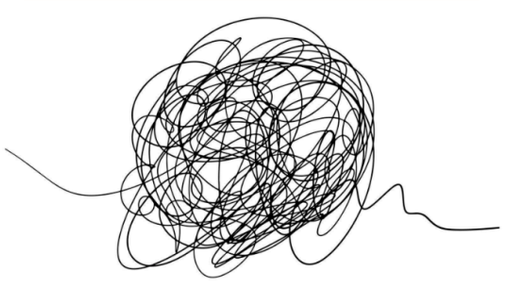
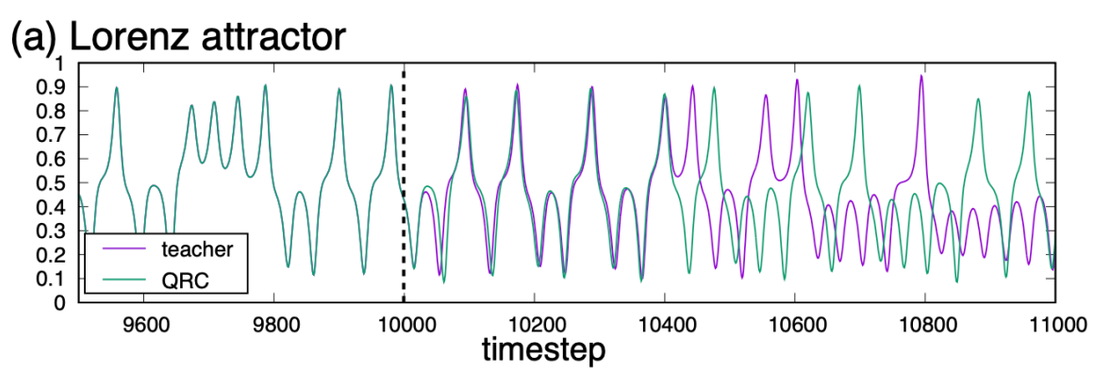


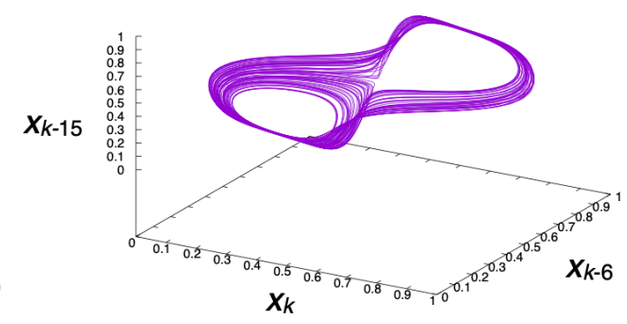
J. Pathak et. al. *Phys. Rev. Lett.* **120**, 024102, 2018

Quantum scrambling reservoir (Chaotic Ising)





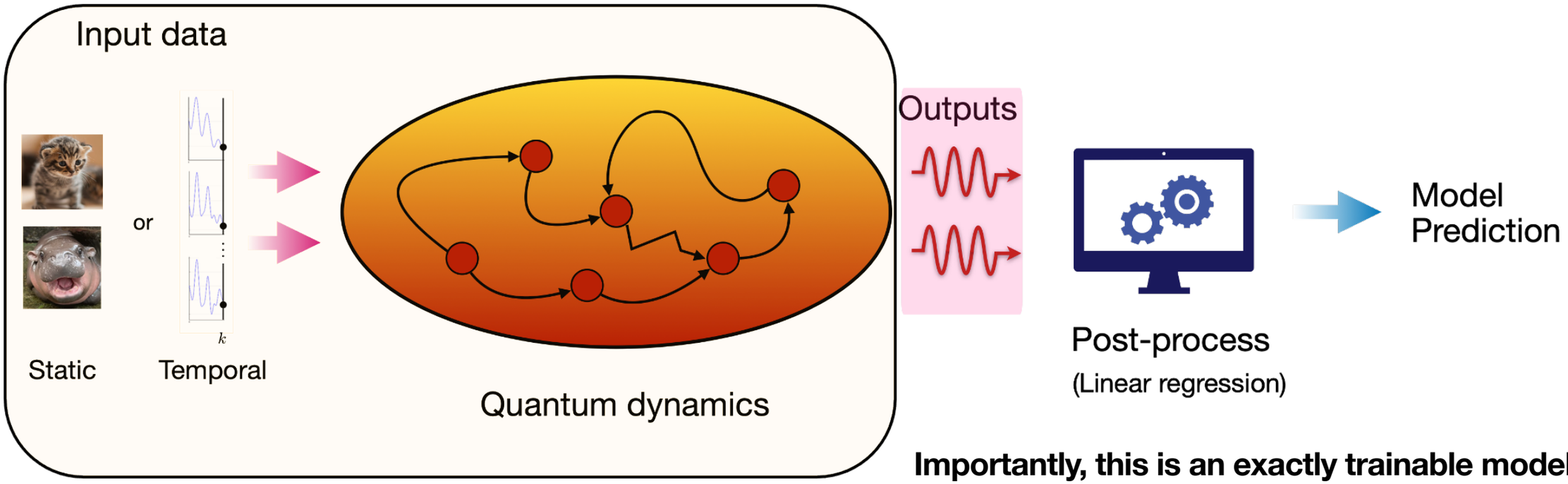




Seems promising for 10+ qubits, but will this scale?

K. Fujii, K. Nakajima, *Reservoir Computing* 423-450, 2021

Quantum Reservoir Computing in a Nutshell



Importantly, this is an exactly trainable model!

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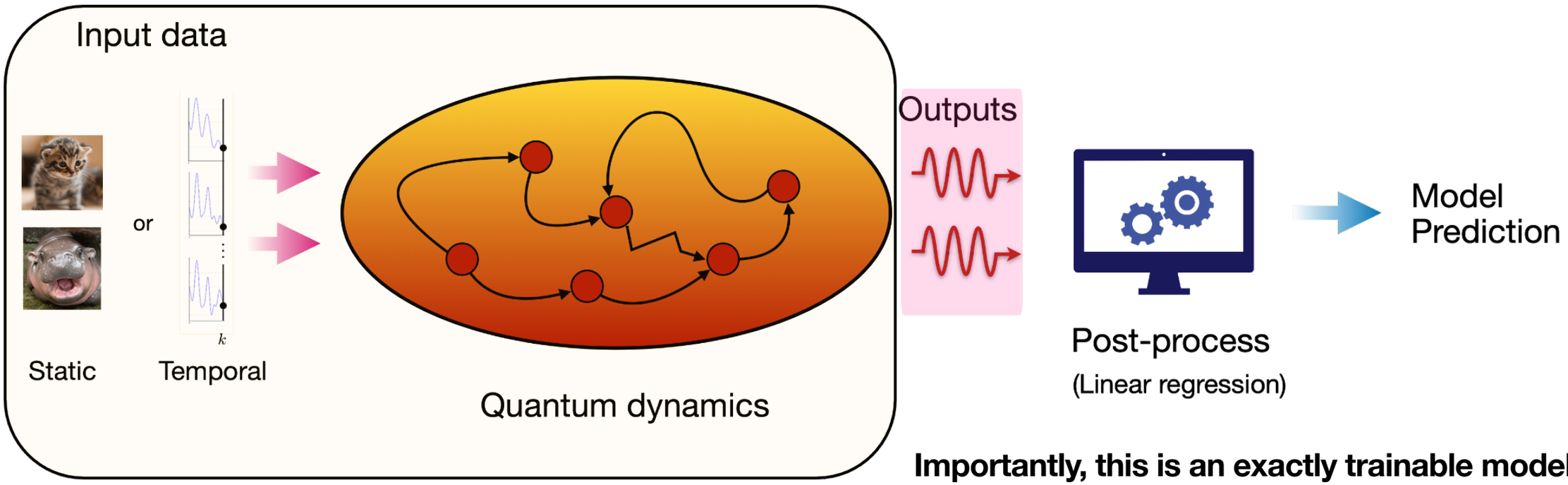

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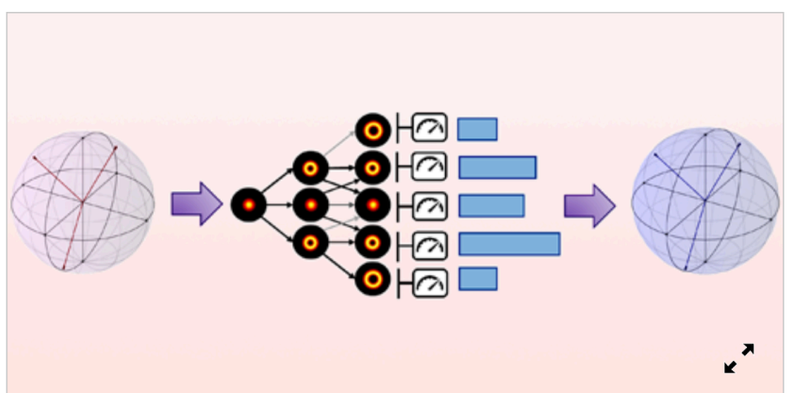
SYNOPSIS

Quantum Machine Learning Goes Photonic

April 16, 2024 • *Physics* 17, s41

Measuring a photon's angular momentum after it passes through optical devices teaches an algorithm to reconstruct the properties of the photon's initial quantum state.



A. Suprano *et al.* [1]

FEATURED IN PHYSICS | EDITORS' SUGGESTION

Experimental Property Reconstruction in a Photonic Quantum Extreme Learning Machine

Alessia Suprano[1,*], Danilo Zia[1,*], Luca Innocenti[2,*], Salvatore Lorenzo[2,*], Valeria Cimini[1], Taira Giordani[1], Ivan Palmisano[3], Emanuele Polino[1,4], Nicolò Spagnolo[1] *et al.*

Phys. Rev. Lett. **132**, 160802 – **Published 16 April, 2024**
DOI: https://doi.org/10.1103/PhysRevLett.132.160802

nature communications

Article https://doi.org/10.1038/s41467-024-51161-8

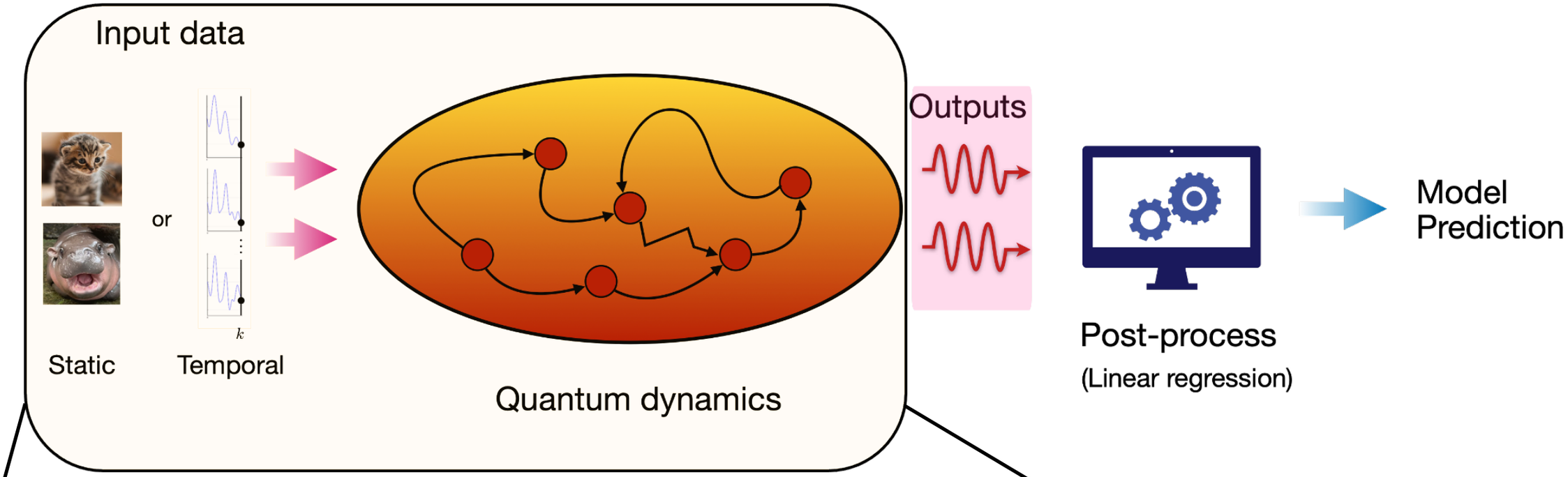
Microwave signal processing using an analog quantum reservoir computer

Received: 12 February 2024
Accepted: 31 July 2024
Published online: 30 August 2024

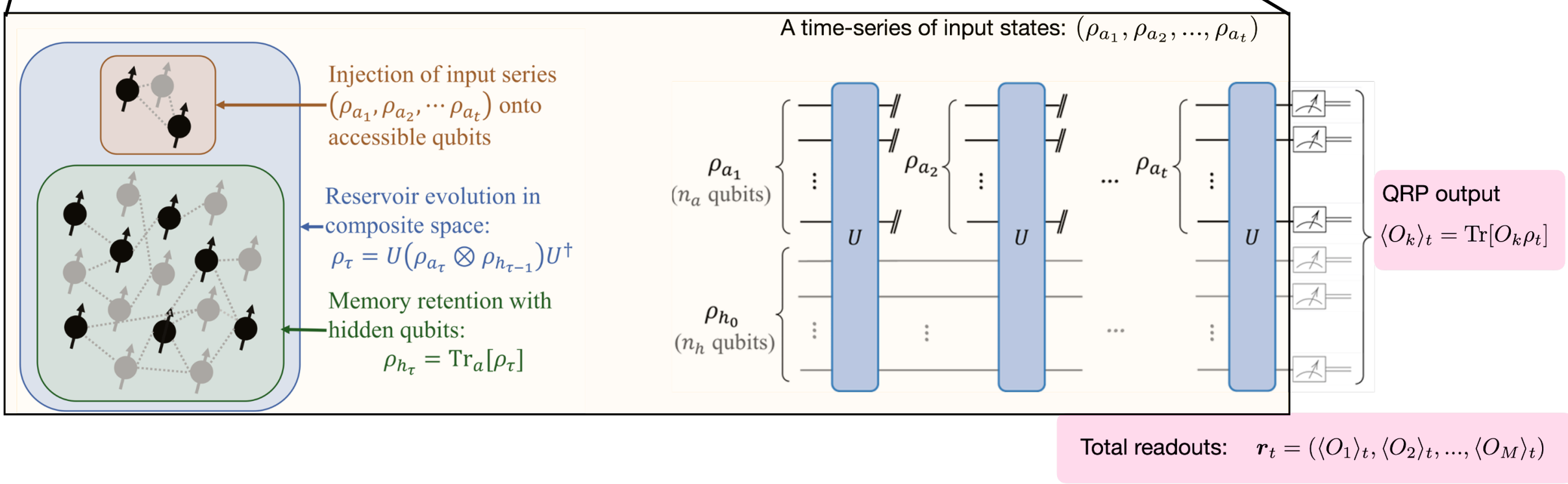
Alen Senanian[1,2], Sridhar Prabhu[1,2], Vladimir Kremenetski[2], Saswata Roy[1,2], Yingkang Cao[3,4], Jeremy Kline[2,7], Tatsuhiro Onodera[2,5], Logan G. Wright[2,5,8], Xiaodi Wu[3,4], Valla Fatemi[2] & Peter L. McMahon[2,6]

Seems promising for small quantum reservoirs, but will this scale?

Quantum Reservoir Computing in a Nutshell



Mathematical framework



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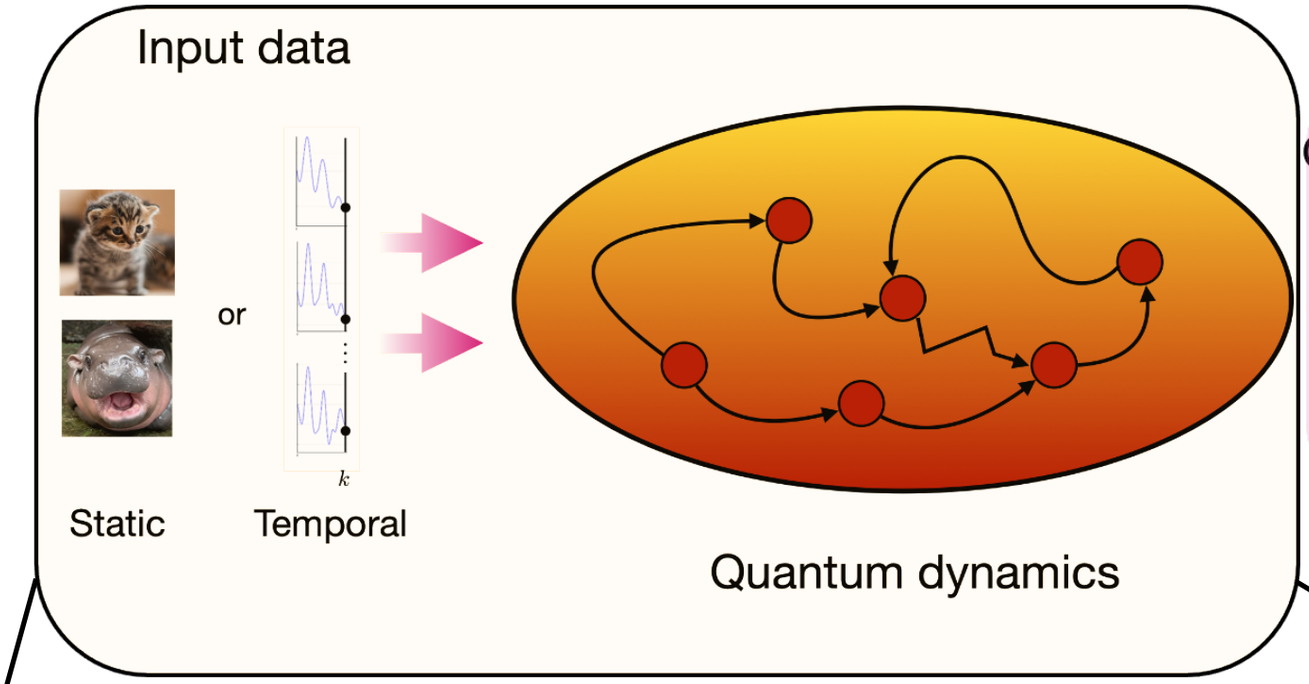
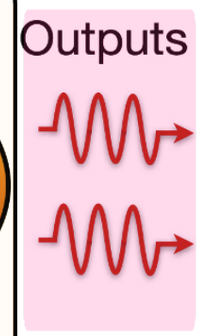
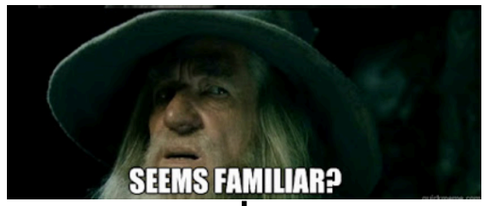




Post-process
(Linear regression)

Model
Prediction



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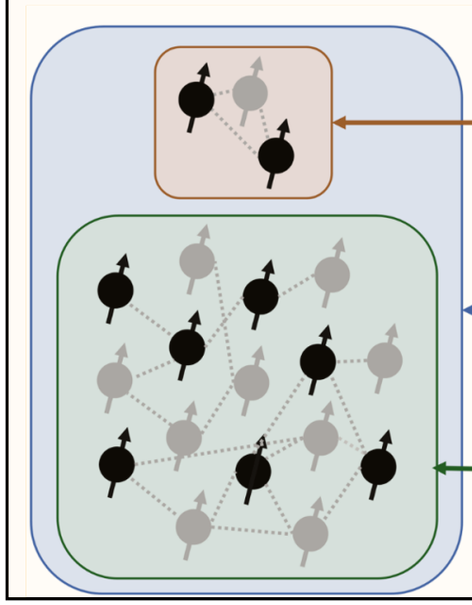
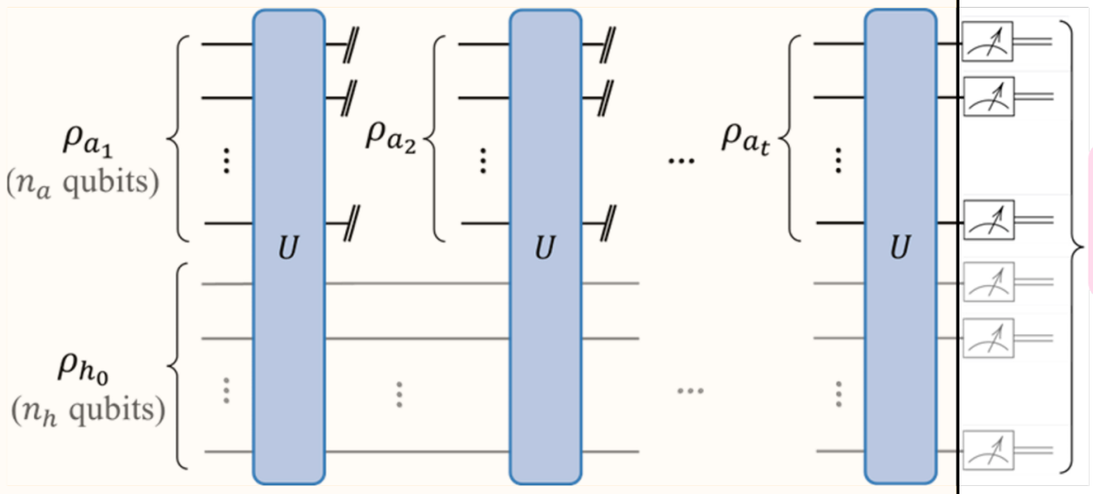


Injection of input series $(\rho_{a_1}, \rho_{a_2}, \cdots \rho_{a_t})$ onto accessible qubits

Reservoir evolution in composite space:
$\rho_\tau = U(\rho_{a_\tau} \otimes \rho_{h_{\tau-1}})U^\dagger$

Memory retention with hidden qubits:
$\rho_{h_\tau} = \mathrm{Tr}_a[\rho_\tau]$

A time-series of input states: $(\rho_{a_1}, \rho_{a_2}, \ldots, \rho_{a_t})$



QRP output
$\langle O_k \rangle_t = \mathrm{Tr}[O_k \rho_t]$

Total readouts: $\boldsymbol{r}_t = (\langle O_1 \rangle_t, \langle O_2 \rangle_t, \ldots, \langle O_M \rangle_t)$

Exponential concentration of observable readouts

$\langle O \rangle_x$ concentrates exponentially in the **system size** towards an **input-independent value**.

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Deterministic concentration

$$|\langle O \rangle_x - \mu| \leq \beta \sim \exp(-n)$$

Probabilistic concentration

$$\Pr\left[|\langle O \rangle_x - \mu| \geq \delta\right] \leq \frac{\beta}{\delta^2} \sim \exp(-n)$$

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Consequences

Sampling error $\sim 1/\sqrt{N_{\text{shot}}}$ $\longrightarrow$ $N_{\text{shot}} \sim \exp(n)$

in order to estimate $\langle O \rangle_x$ accurately
to distinguish the two inputs x, x'

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$\longrightarrow$ Barren Plateaus in VQAs

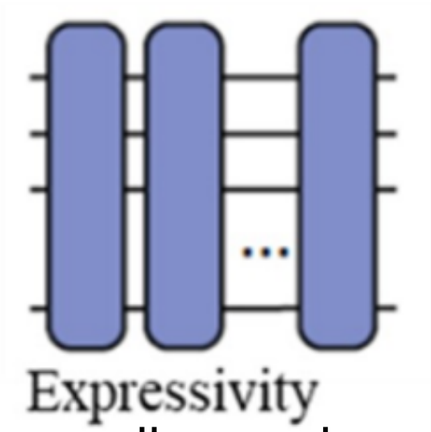
$\longrightarrow$ Generalization error in non-VQAs learning model:

Quantum Kernels Thanasilp, S., Wang, S., Cerezo, M. *et al. Nat Commun* **15**, 5200 (2024)

+ **QELMs** + **QRC** W. Xiong, … **TC**, Z. Holmes, *Quantum Machine Intelligence* (2025)

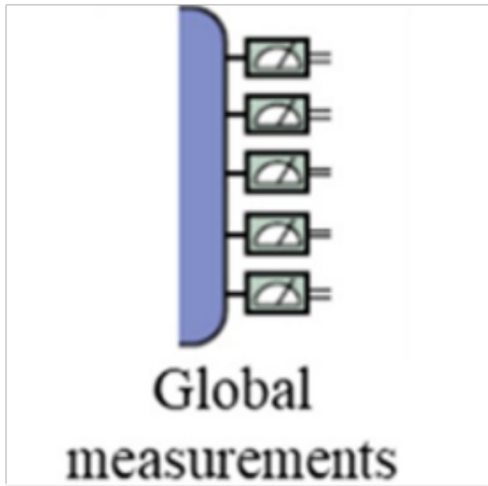
W. Xiong, … **TC**, S. Thanasilp, *under review in npj QI*

Sources of concentration in QELM

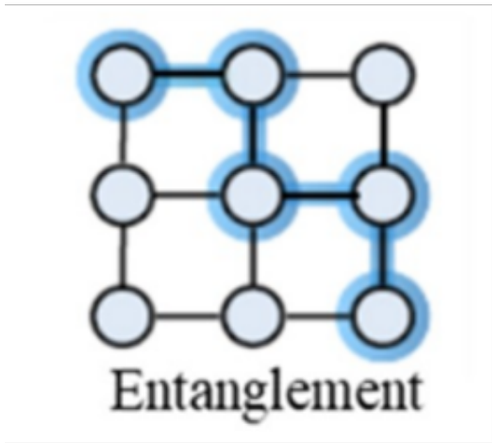


of *both* encoding and reservoir
(2-design ~ extreme scrambling)

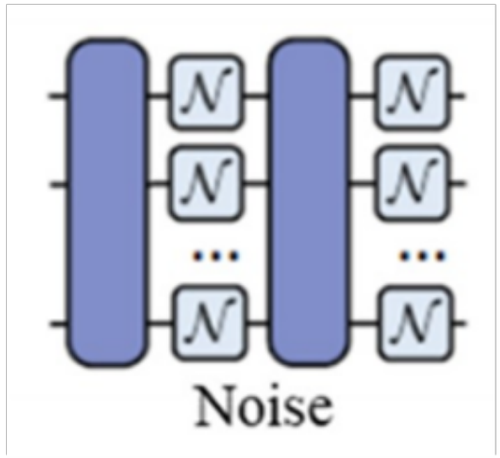
Probabilistic Concentration



Probabilistic Concentration



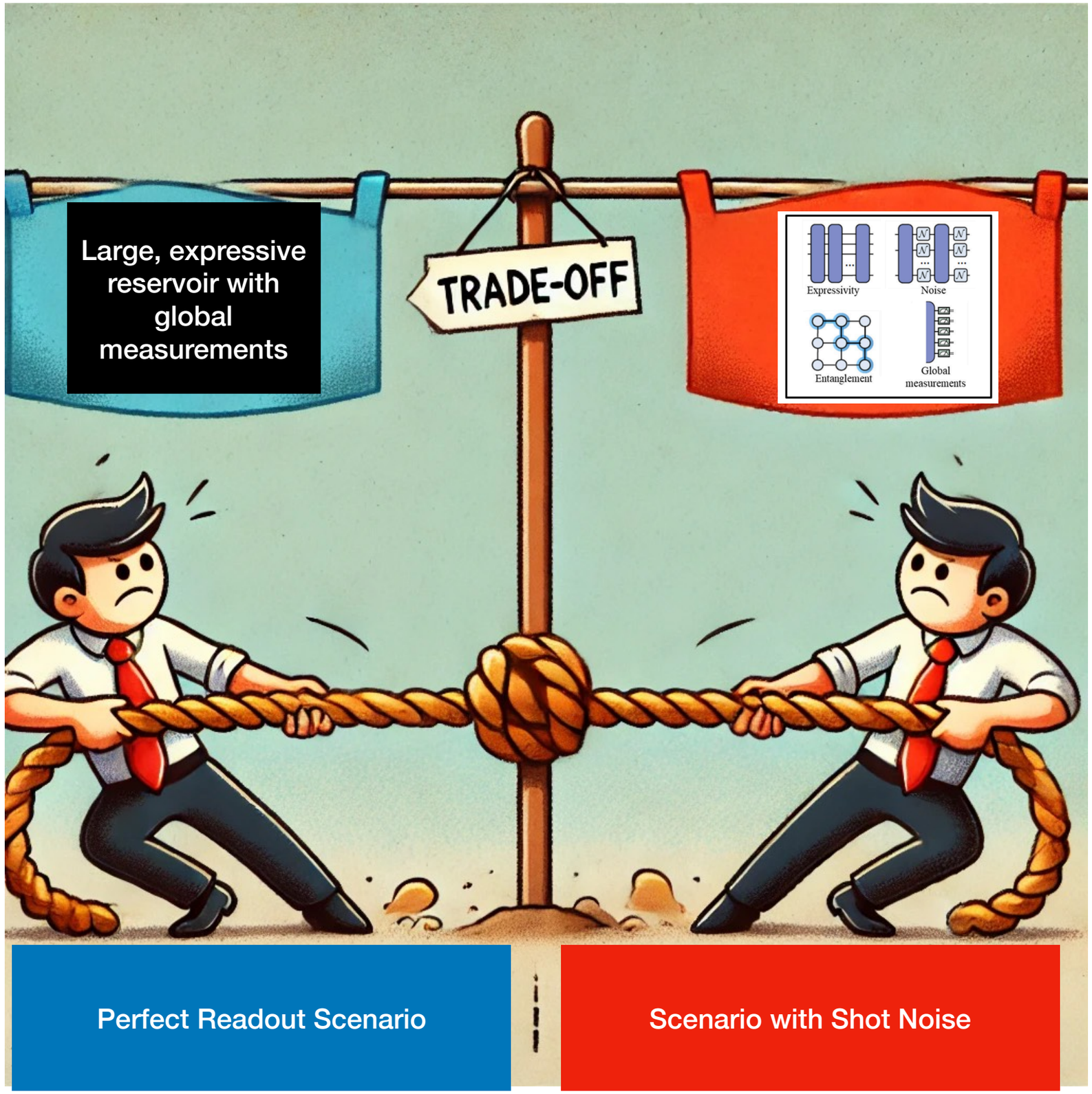
Deterministic Concentration



Deterministic Concentration

In QELM, somewhat similar story to VQAs

A tug of war between high expressivity and avoiding exponential concentration



Results for Quantum Reservoir Computing (QRC)

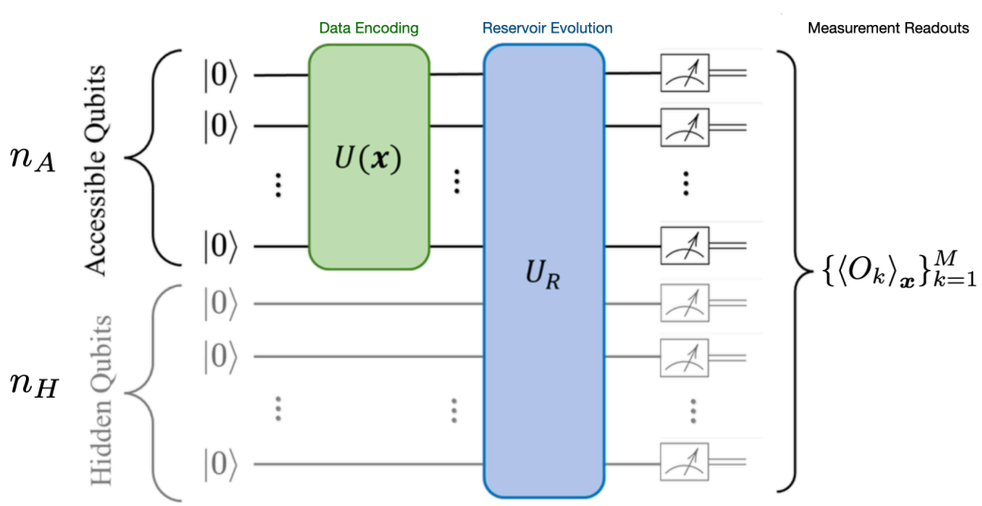
Role of scrambling and noise in temporal information processing with quantum systems

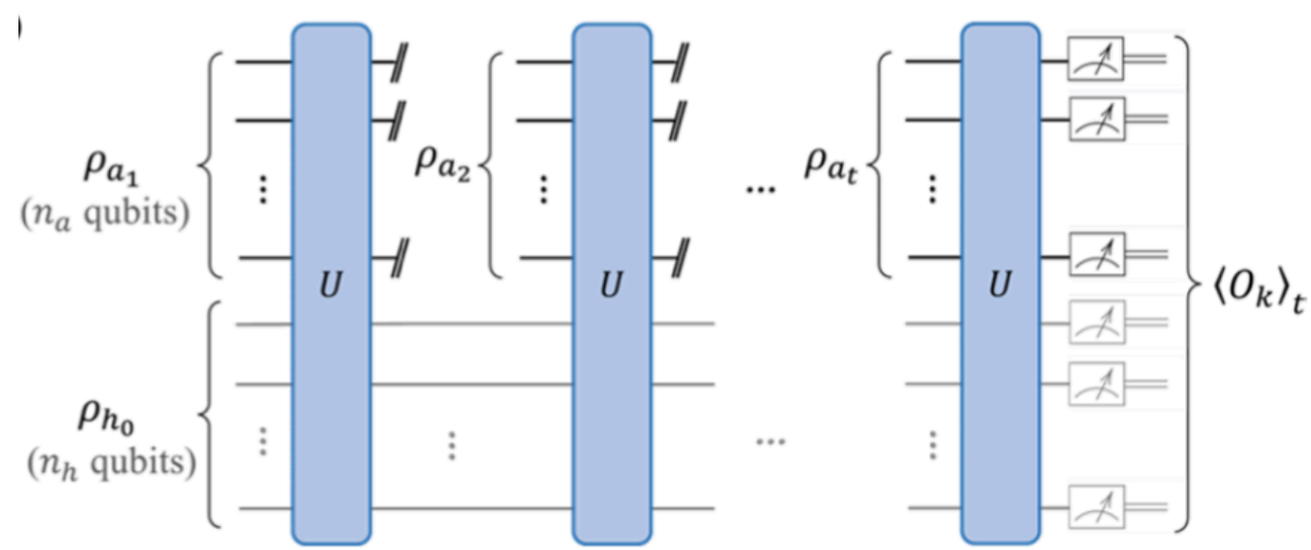
Weijie Xiong,[1,2] Zoë Holmes,[1,2] Armando Angrisani,[1,2]
Yudai Suzuki,[1,2] Thiparat Chotibut,[3] and Supanut Thanasilp[1,2,3]

[1] *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[2] *Centre for Quantum Science and Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[3] *Chula Intelligent and Complex Systems Lab, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
(Dated: May 16, 2025)

Static Input | Extend to multi-step evolution | ***Time-series* Inputs**

$\{\rho_{a_0}\}$ $\longrightarrow$ $\{\rho_{a_1}, \rho_{a_2}, \ldots, \rho_{a_t}\}$



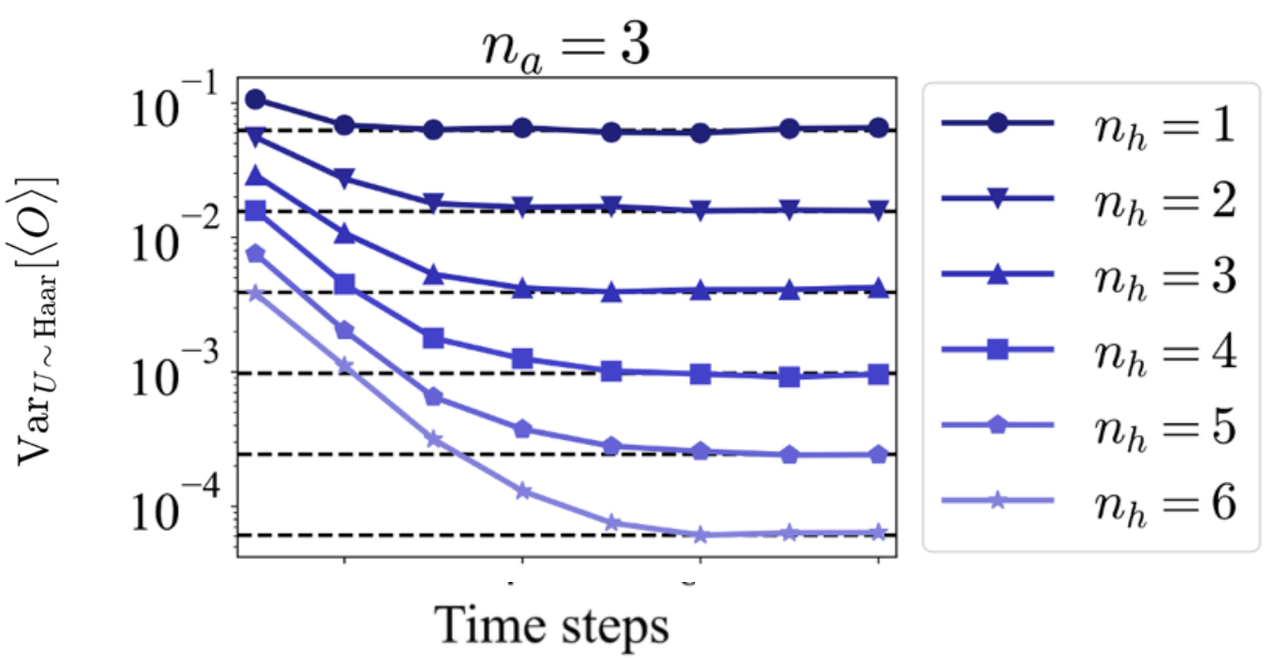


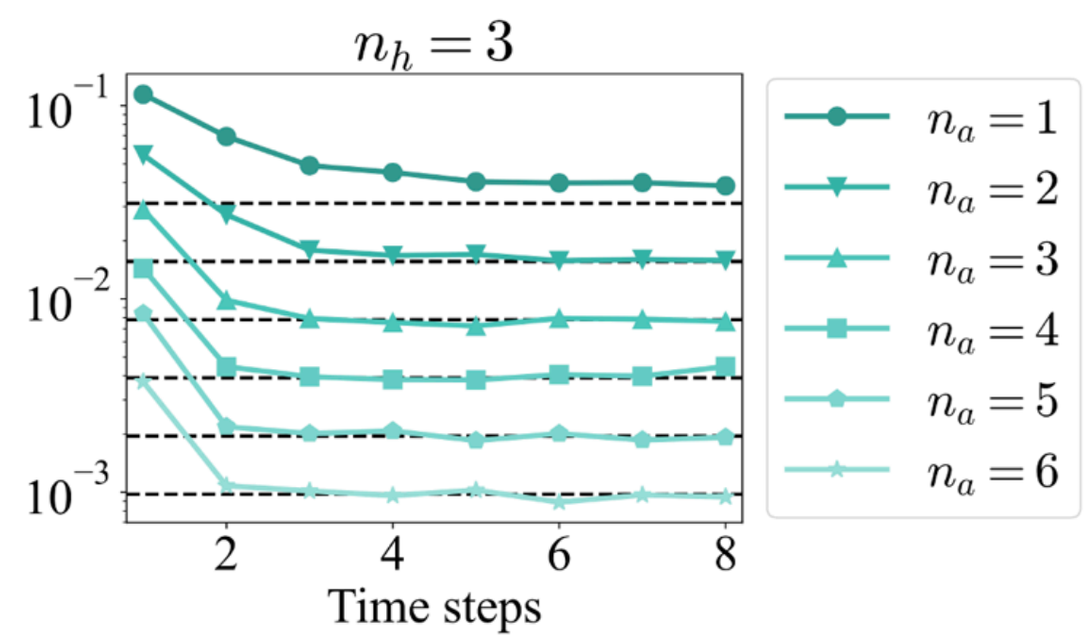
W. Xiong, … **TC**, S. Thanasilp, *under review in npj QI*

Concentration still happens, but not too bad at early times

Theorem 1 (informal) *The output variance of some observable O at some large time t under extreme scrambling reservoir dynamics vanishes exponentially with the system size:* $\mathrm{Var}_{U\sim\mathbb{U}(d_a d_h)}[\langle O\rangle_t] \in \mathcal{O}\left(\frac{\mathrm{Tr}[\mathrm{O}^2]}{d_a^2 d_h^3}\right)$ *, where* $d_a = 2^{n_a}$ *and* $d_h = 2^{n_h}$.

- For large t, output concentrates in the system size; but *no* further concentration in time.
- **Scalability barrier** for **large** QRP: output concentrates towards an *input-independent* mean!
- Consequence: **poor generalization**, despite guaranteed trainability (linear regression).





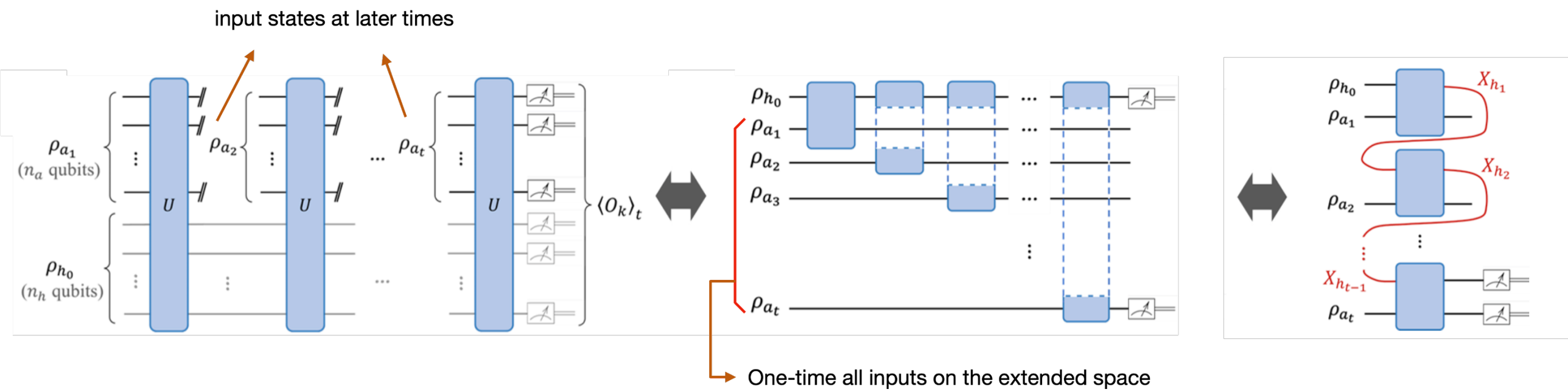
Proof strategy: express temporal correlation as a (larger) spatial correlation

Step 1

(embed time series into space)

Step 2

(recast into a standard Haar integration form)



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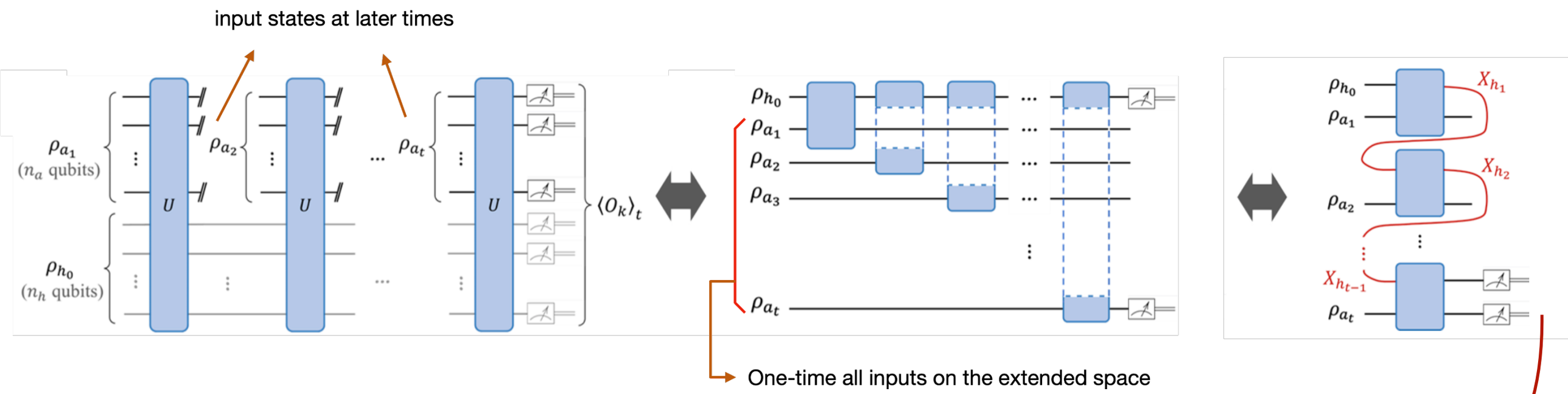


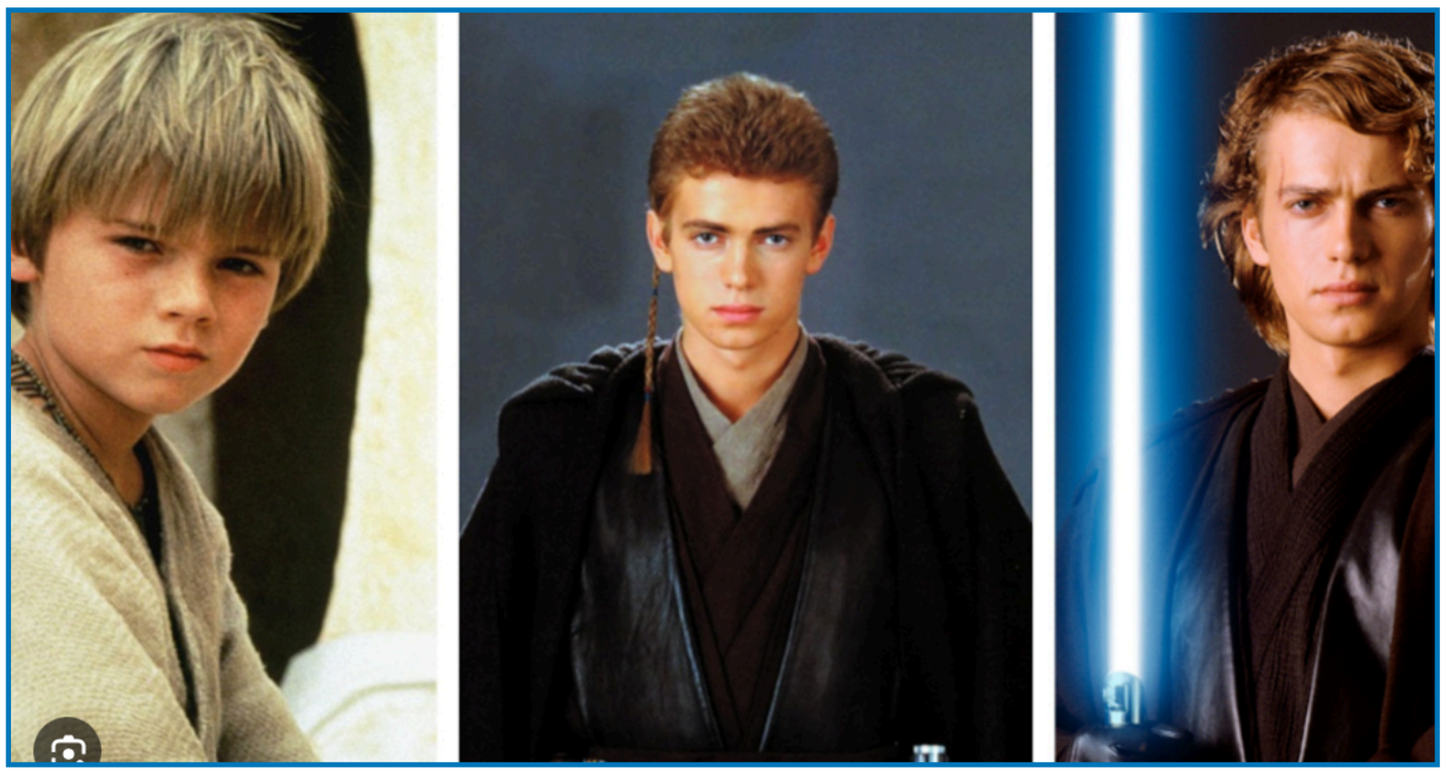
$$\langle O \rangle_t = \sum_{\boldsymbol{X}_{h_{t-1}}} \mathrm{Tr}\left[(X_{h_1}, \mathcal{I}_a; X_{h_2}, \mathcal{I}_a; \cdots; X_{h_{t-1}}, \mathcal{I}_a; O)\, U^{\otimes t} (\rho_{h_0}, \rho_{a_1}; X_{h_1}, \rho_{a_2}; X_{h_2}, \rho_{a_3}; \cdots; X_{h_{t-1}}, \rho_{a_t})\, (U^\dagger)^{\otimes t} \right]$$

- $2t$-design assumption is stronger than the typical 2-design

Storyline of quantum algorithms on NISQ machines (up to now)

This applies to VQAs, Quantum Neural Networks, Quantum Kernels, QELM, and QRC

1-20 qubits
(promising candidates)



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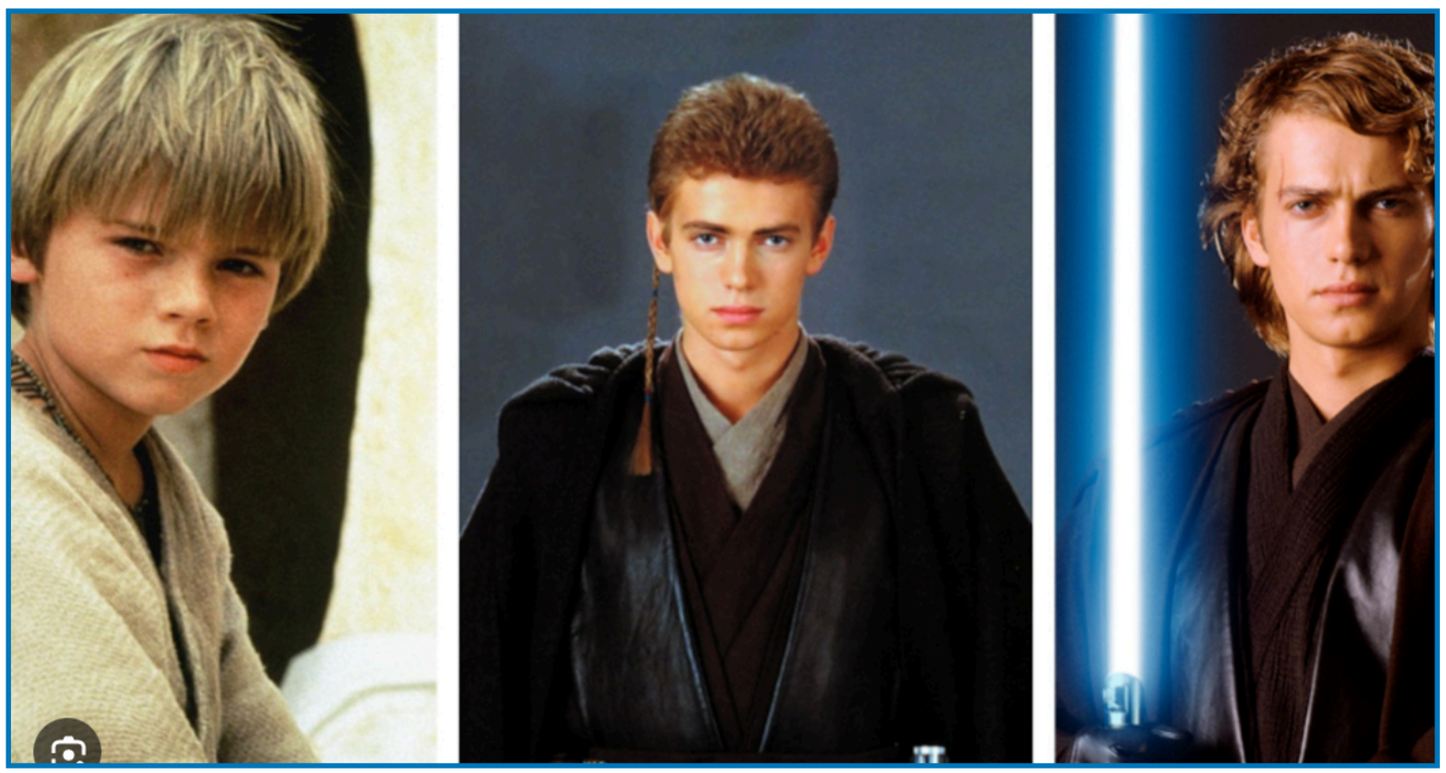
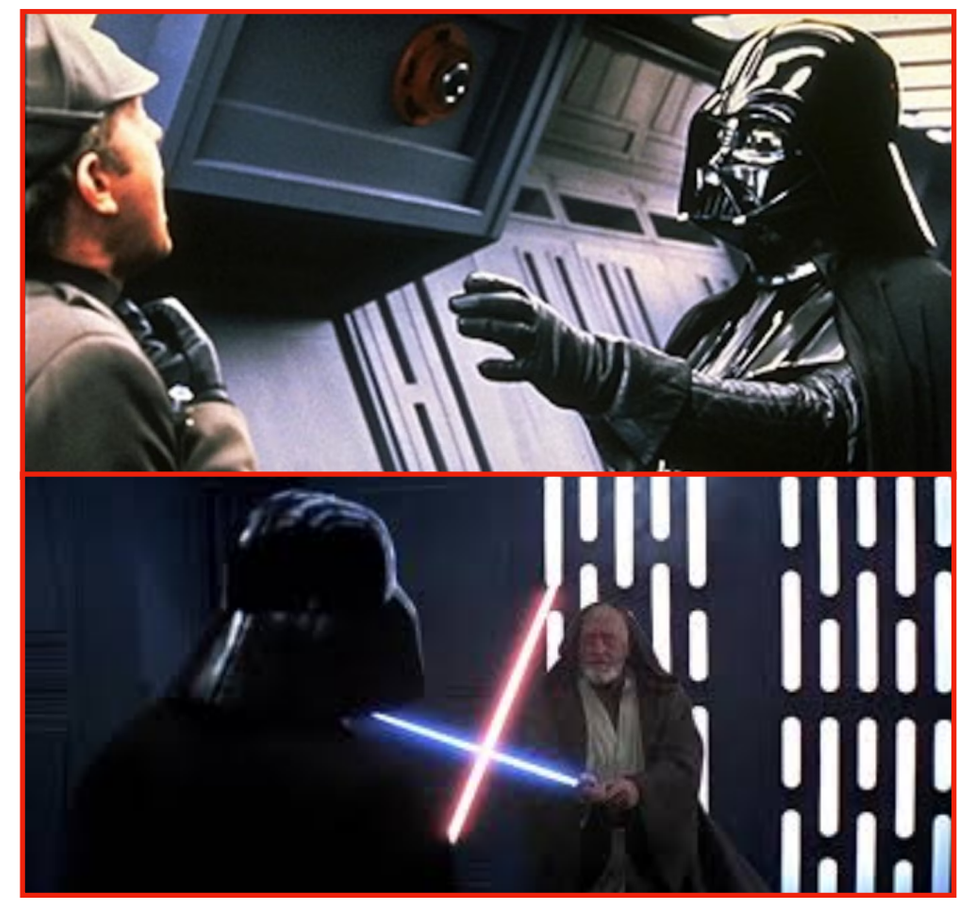
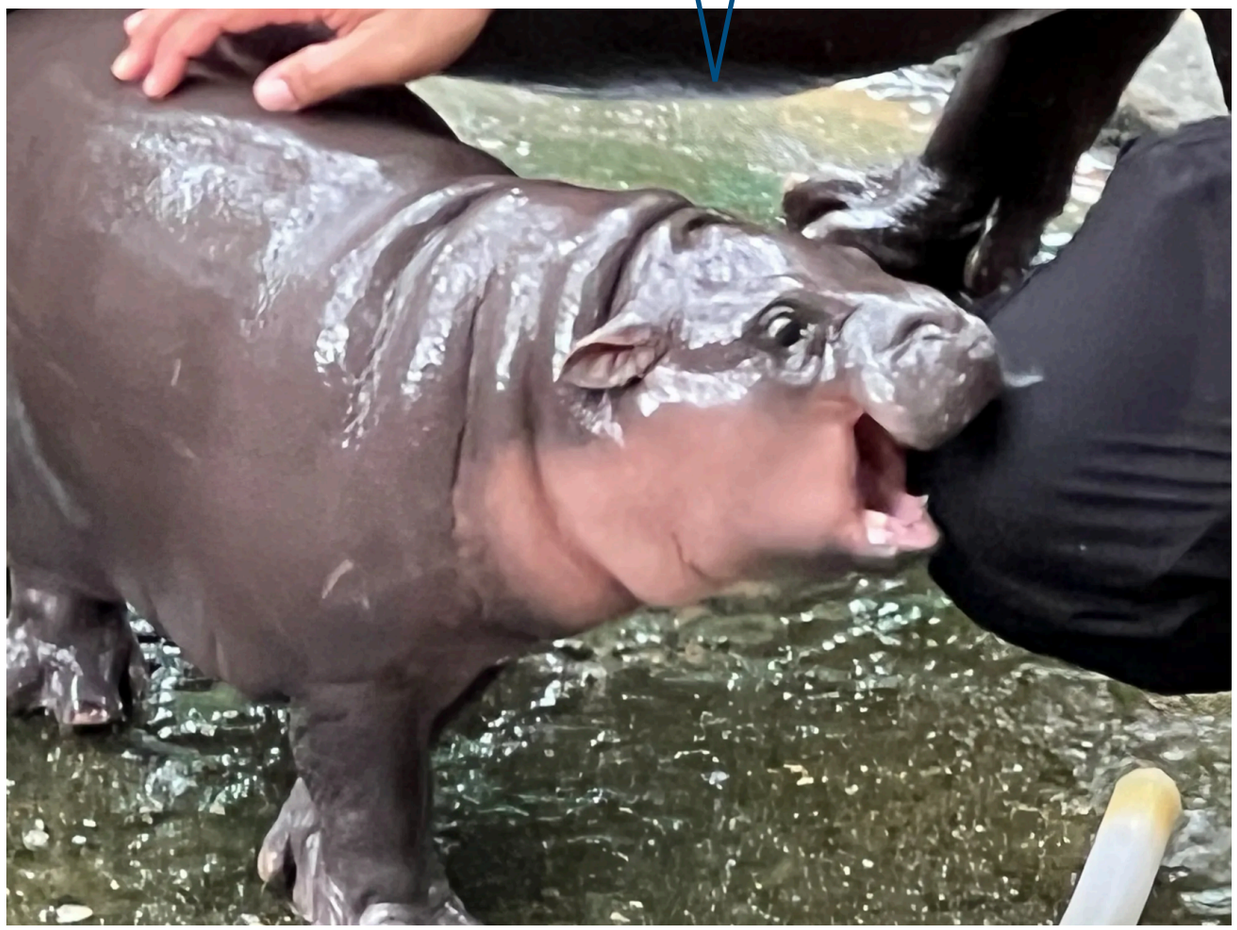


40+ qubits
(regime with hopes for quantum advantage)



Curse of Dimensionality
(Exponential Concentrations of Outputs)

Can’t noise be harnessed as computational resources?



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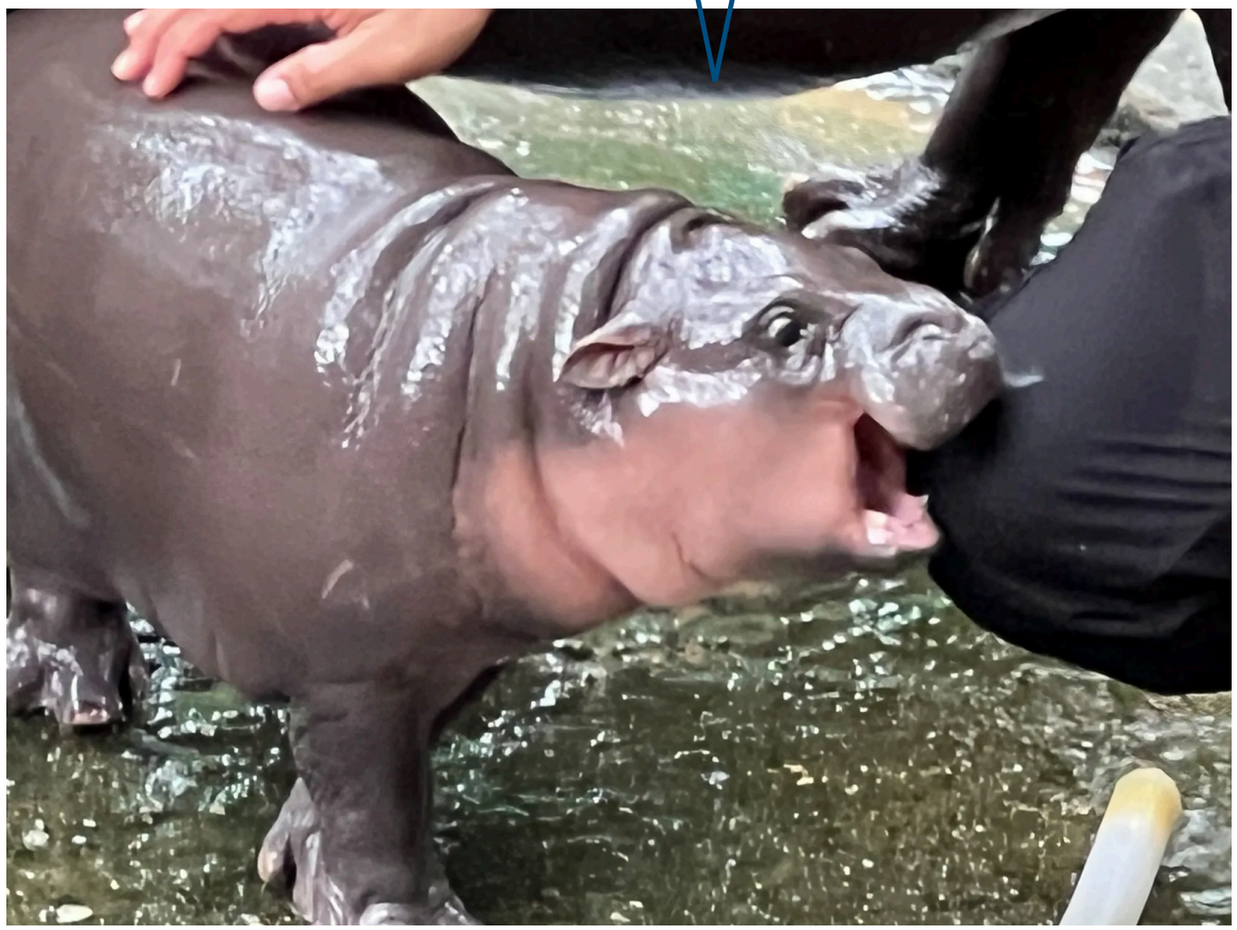


Perhaps the secrets lie here!

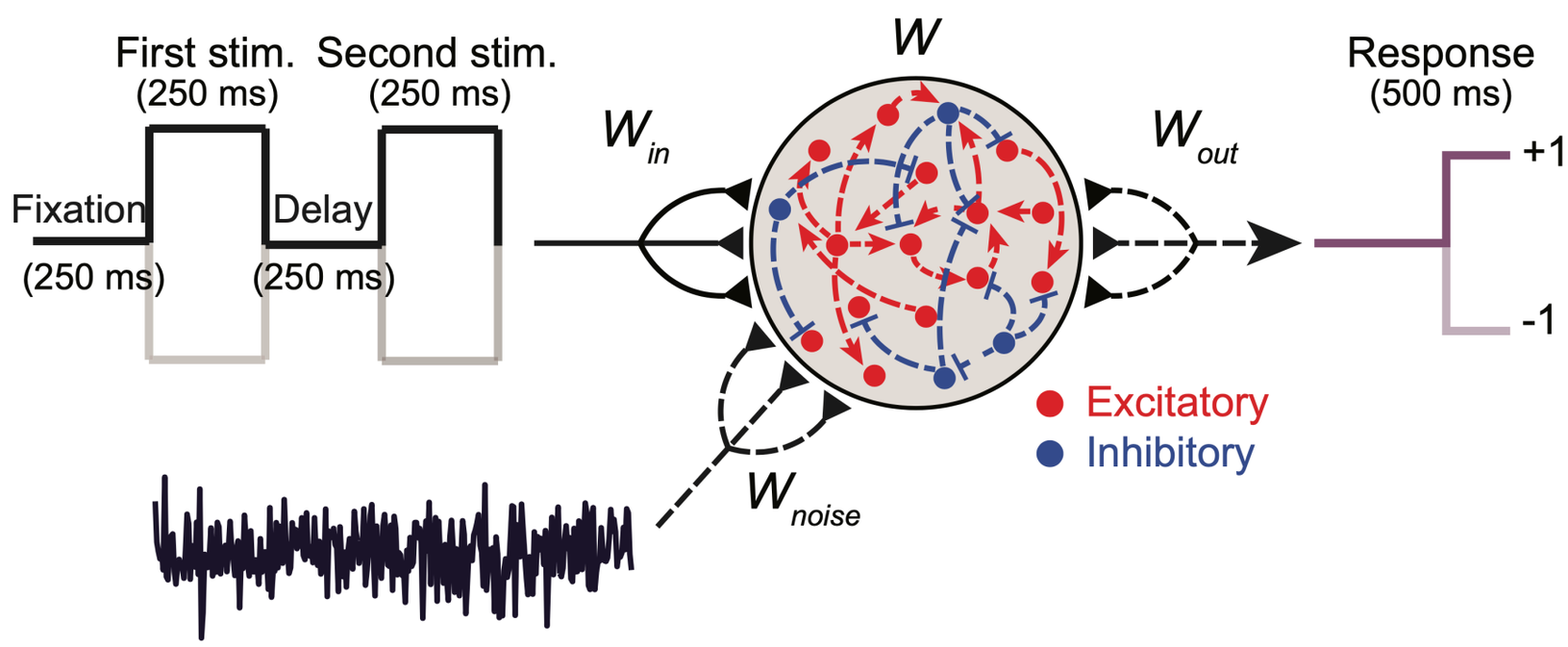
PNAS RESEARCH ARTICLE | NEUROSCIENCE

Random noise promotes slow heterogeneous synaptic dynamics important for robust working memory computation

Nuttida Rungratsameetaweemana[a,b,1], Robert Kim[b,c,1], Thiparat Chotibut[d,2], and Terrence J. Sejnowski[b,e,f,2]

Affiliations are included on p. 11.

Edited by Tirin Moore, Stanford University School of Medicine, Stanford, CA; received September 26, 2023; accepted December 6, 2024



N. Rungratsameetaweemana, R. Kim, **TC**, and T. Sejnowski, *PNAS* 2025

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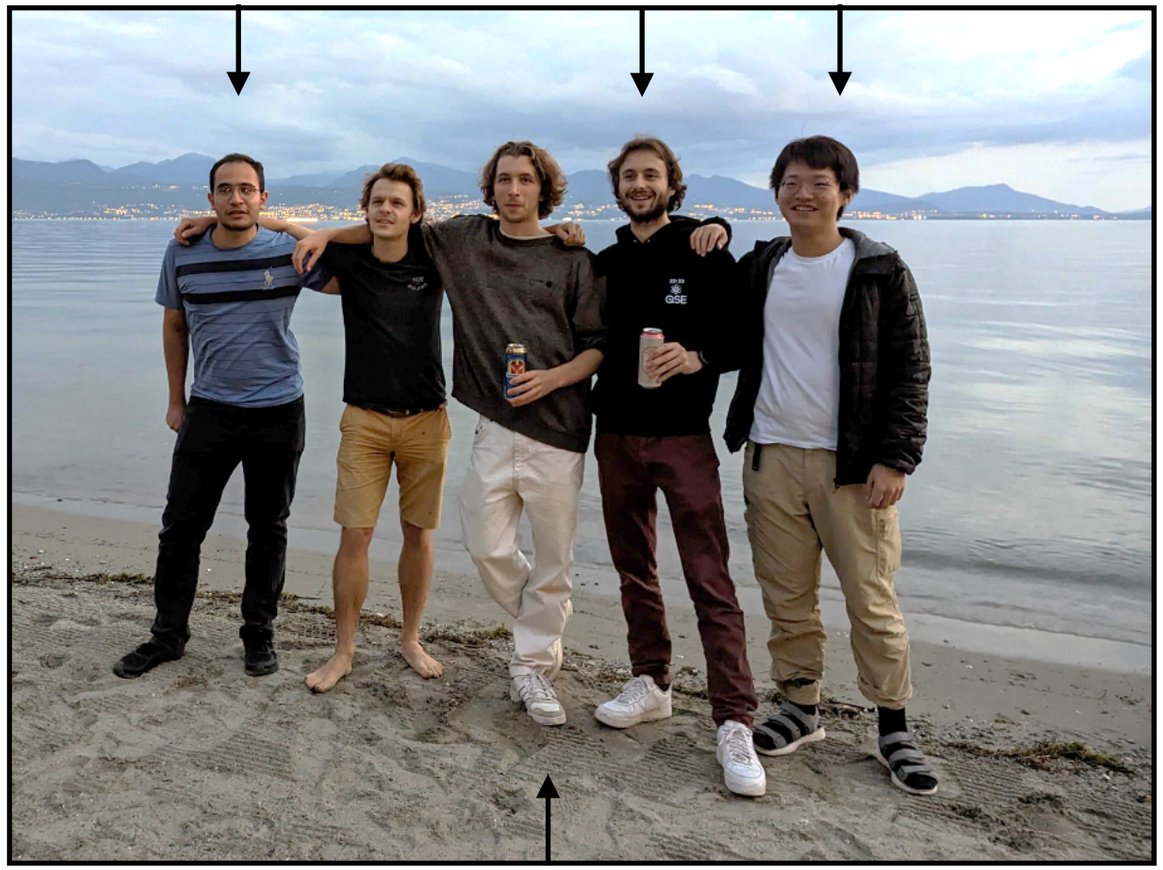

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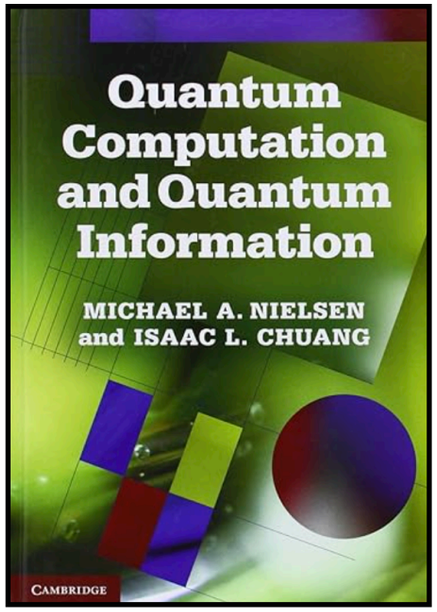
Why QELM and QRC? A Brief Detour: The Quest for Quantum Advantages



✗ Ideal (Fault-tolerant) quantum computational advantages

Textbook algorithms: Shor's, Grovers's, HHL, etc.

✓ Noisy Intermediate-Scale Quantum (NISQ) Era

Variational Quantum Algorithms (VQAs)

A unifying account of warm start guarantees for patches of quantum landscapes

Hela Mhiri,[1,2,*] Ricard Puig,[1,*] Sacha Lerch,[1] Manuel S. Rudolph,[1]
Thiparat Chotibut,[3] Supanut Thanasilp,[1,3] and Zoë Holmes[1]