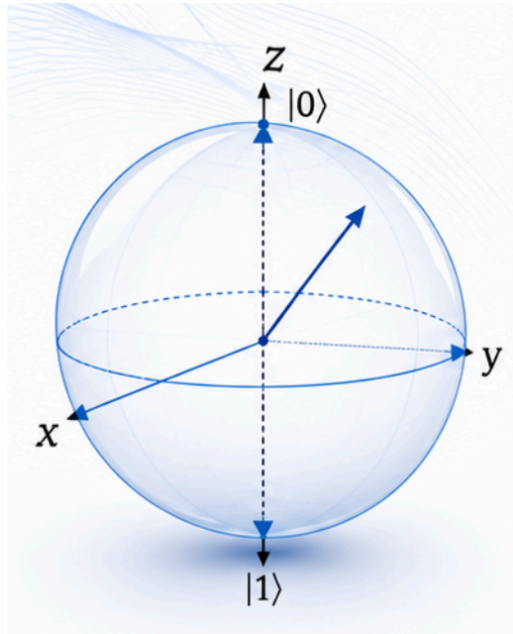


# Machine Learning for Quantum Technologies



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21st July, 2026



IIT Hyderabad



IIT Hyderabad  
भारतीय प्रौद्योगिकी संस्थान हैदराबाद  
Indian Institute of Technology Hyderabad



# Quantum Information, Computing & Control Theory Group

In our group, we are researching classical ML for quantum control, quantum error correction, quantum machine learning, neuromorphic computing, ML for Photonics/CMP, etc.



## Quantum Control

Designing control pulses and feedback strategies to steer quantum systems with high fidelity.



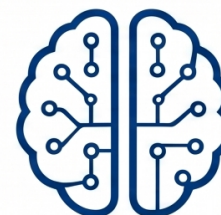
## Quantum Error Correction

Protecting fragile quantum information against noise, decoherence, and gate errors.



## Quantum Machine Learning

Using quantum systems and algorithms to enhance learning, optimization, and data analysis.



## Quantum Neuromorphic Computing

Developing brain-inspired quantum architectures for adaptive information processing.



## Machine Learning for Photonics

Applying AI/ML to design, optimize, and control photonic devices and experiments.



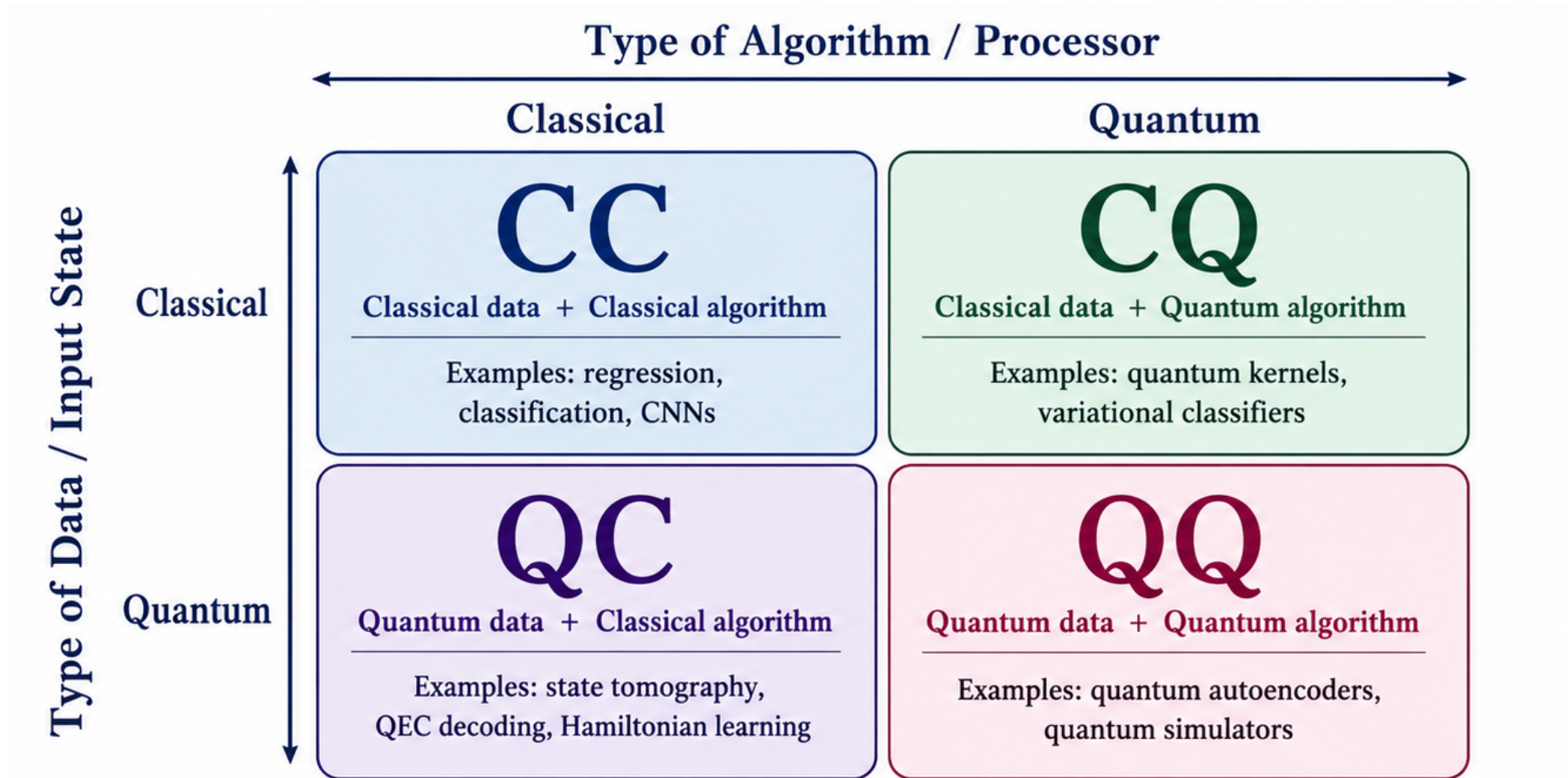
## Machine Learning for CMP

Applying machine learning to condensed matter problems such as phase identification, materials discovery, and many-body physics.

**Website:** <https://sborah53.github.io/QuICCT>

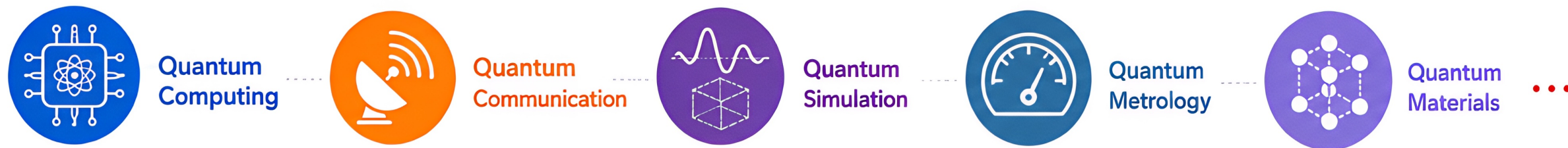


# Classical vs Quantum Data and Algorithms



In this talk, I will mostly be focussing on the **QC**, i.e., **Quantum Data + Classical algorithm**.

# Quantum Technology: Promise and Challenges



- Quantum technologies open multiple frontiers of applications across computing, communication, sensing, simulation and materials, among others.
- A central challenge is achieving precise and robust control of quantum systems in the presence of noise, decoherence, and hardware imperfections.
- Developing reliable control methods is therefore essential for turning quantum promise into practical technologies.

**The realization of practical quantum technologies will depend crucially on ingenious and reliable control protocols.**

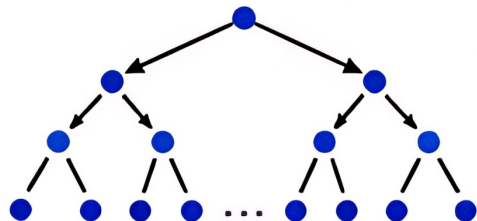
*EPJ Quantum Technology 9, 19 (2022)*



# Why ML helps in Quantum Physics

Three bottlenecks make data-driven tools valuable alongside physical models.

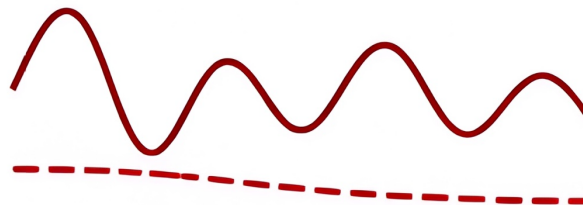
## Exponential state space



A generic  $N$ -qubit state has  $2^N$  complex amplitudes.

At  $N = 50$ , double precision needs about 18 PB.

## Imperfect, drifting control



Hardware parameters and noise change over time.

Data can calibrate effective device models.

## Limited measurements



...

$$\begin{bmatrix} a_{11} & \cdots & a_{1d} \\ \vdots & \ddots & \vdots \\ a_{d1} & \cdots & a_{dd} \end{bmatrix}$$

Tomography infers  $\rho$  from many finite-shot outcomes.

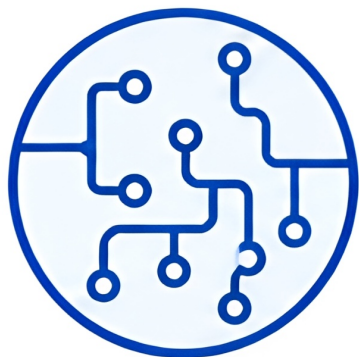
The inverse problem becomes costly as systems grow.

## A complementary ML toolkit

Learn useful predictors, controllers, and compressed representations from data.  
Combine them with physical constraints and validation.

# Two Technologies of Contemporary Times

## MACHINE LEARNING

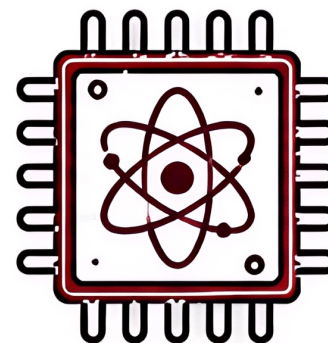


Algorithms that  
**learn patterns from  
data** and make  
intelligent  
predictions

&



## QUANTUM COMPUTING



Computers that harness  
**quantum mechanics**:  
superposition and  
entanglement to solve  
problems **beyond the reach  
of classical computers**



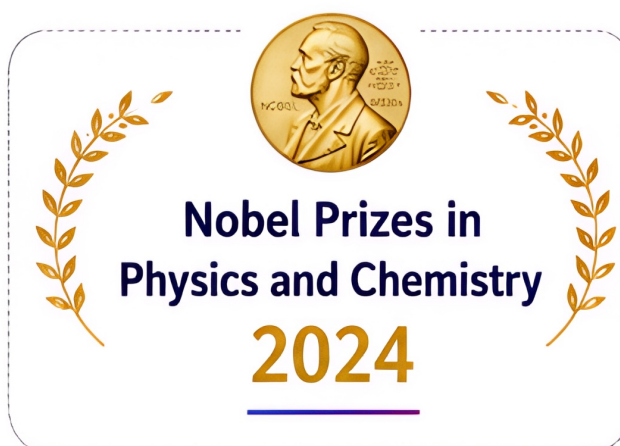
**John J. Hopfield**

Nobel Prize in Physics 2024



**Geoffrey E. Hinton**

Nobel Prize in Physics 2024



**Nobel Prizes in  
Physics and Chemistry  
2024**



**David Baker**

Nobel Prize in Chemistry 2024



**Demis Hassabis**

Nobel Prize in Chemistry 2024



**John M. Jumper**

Nobel Prize in Chemistry 2024

**ML learns from data, and QC computes with nature. Together, they shape the future.**

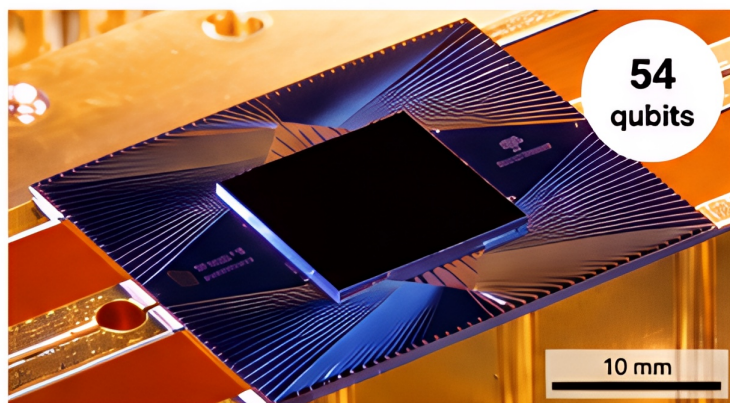


# Quantum Computing: The State of Affairs...

Quantum computing is transforming from demonstrations to fault-tolerant operations.

## 1 Quantum supremacy using a programmable superconducting processor

*Nature* | Vol 574 | 24 OCTOBER 2019



⌚ 200 seconds vs 10,000 years

💻 IBM classical cluster: 2 days

## 3 Quantum computing takes flight



*"The field is moving from scientific milestone to real-world impact."*

— William Oliver

## 2 Quantum error correction below the surface code threshold

*Nature* 638 (2025) 920–926



⌚ Benchmark: 5 minutes vs 10 septillion ( $10^{25}$ ) years



### Key enablers for progress

(1) Hardware development and (2) Reinforcement learning

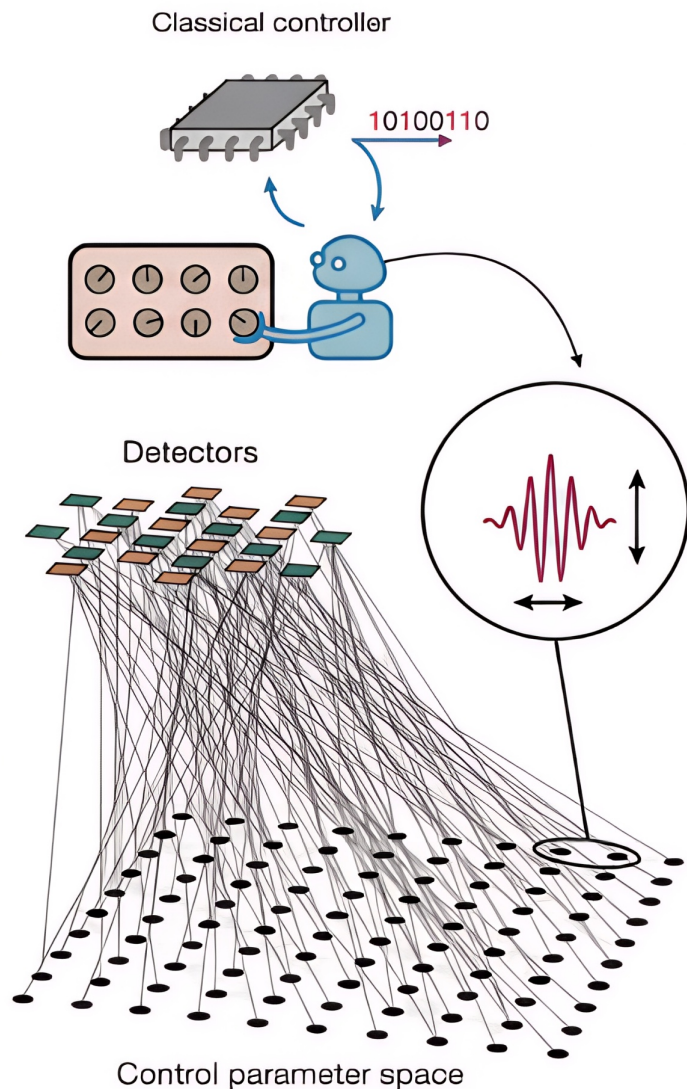


### Coherence time ( $T_2$ )

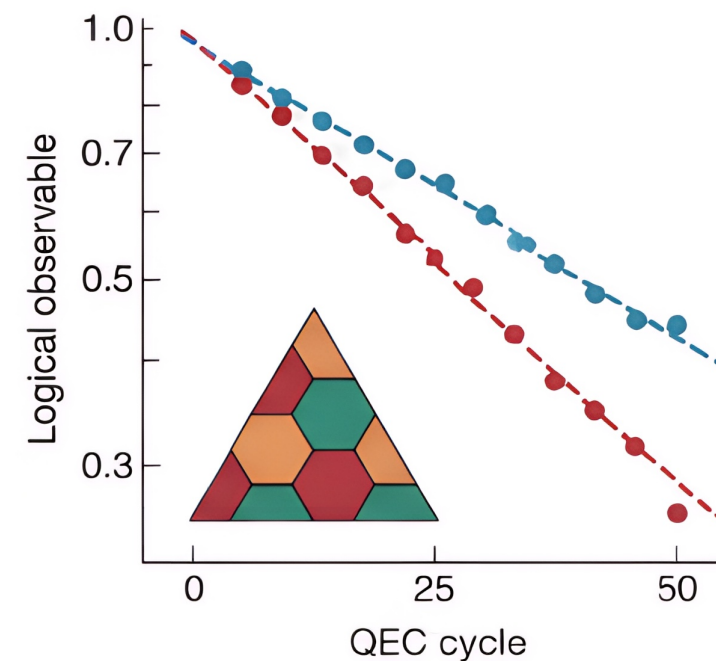
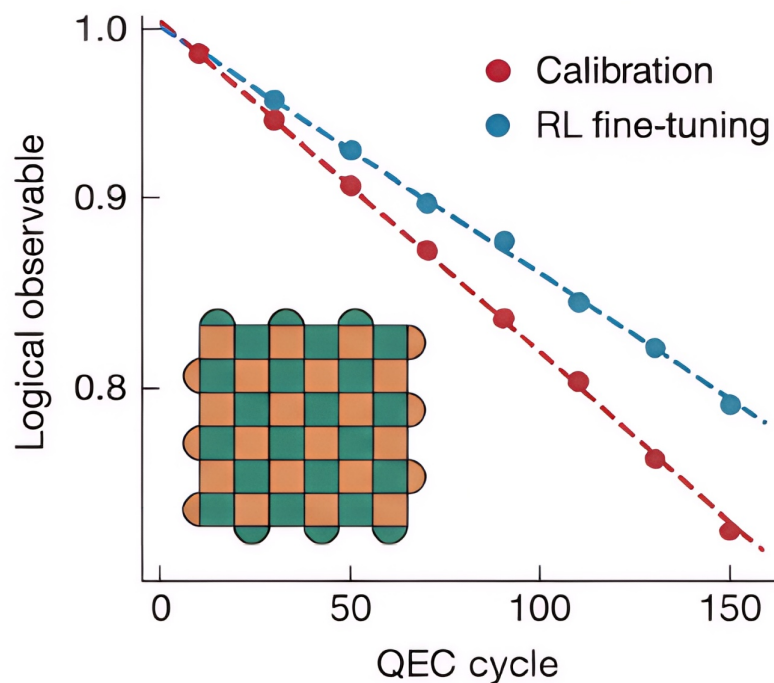
Sycamore (2019):  $\sim 20 \mu\text{s}$  | Willow (2025):  $\sim 100 \mu\text{s}$

# RL Fine-Tuning of QEC

Syndrome data guide continuous control updates during QEC



**Reported result:** 3.5x improvement in logical stability against injected drift

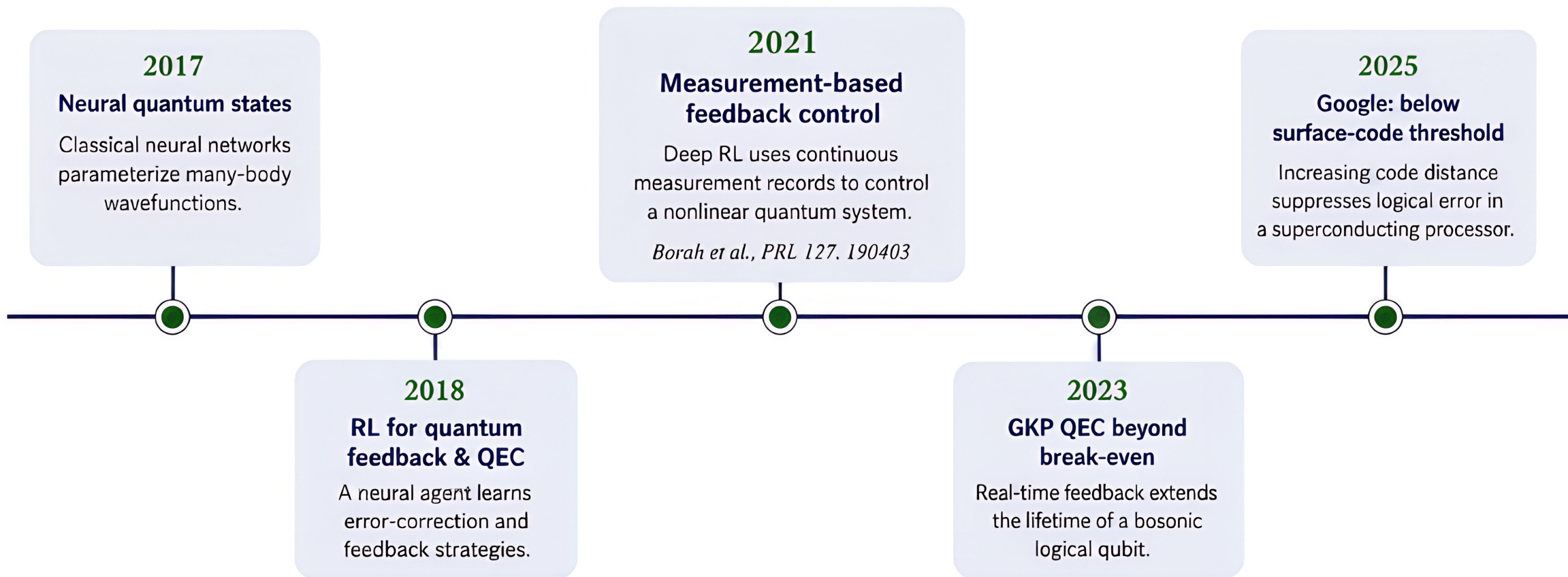


Google Quantum AI, Nature (2026). <https://doi.org/10.1038/s41586-026-10759-2>



# Classical ML for Quantum Physics: A Short Timeline

From neural wavefunctions to reinforcement learning for quantum control and error correction



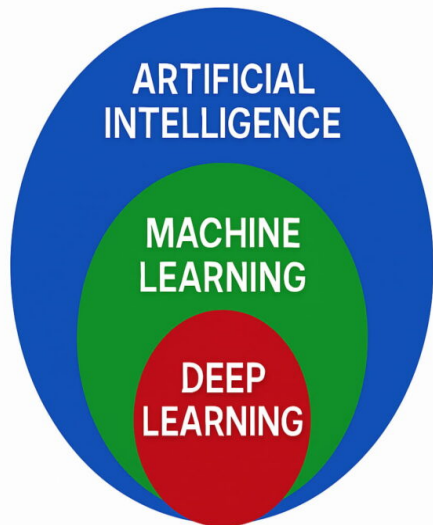
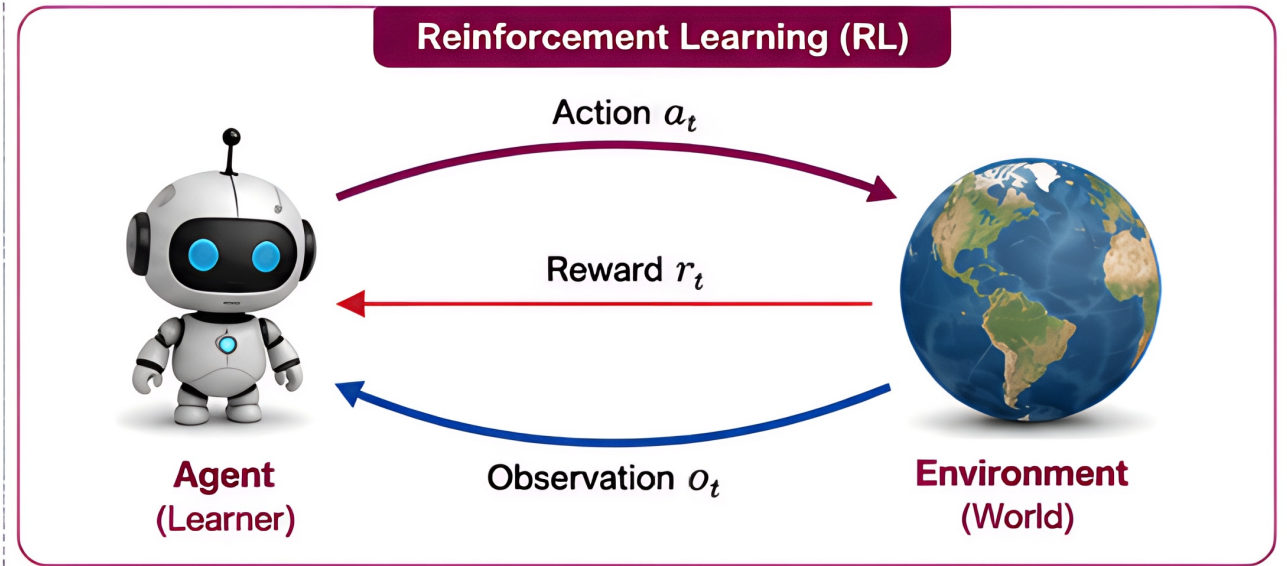
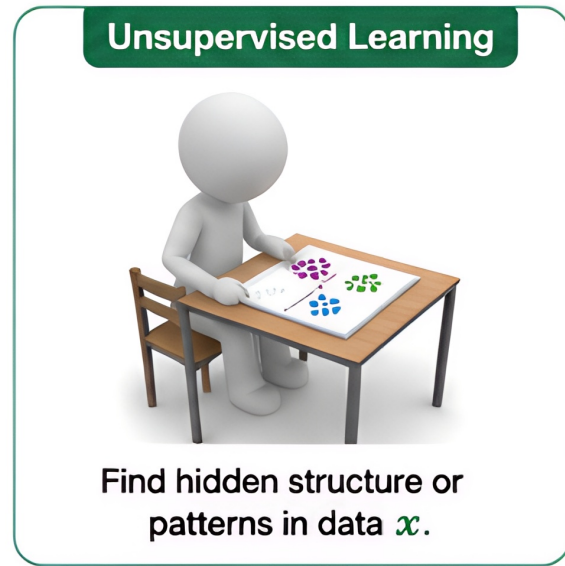
## References:

*Carleo & Troyer, Nature Physics (2017)*  
*Fosel et al. PRX (2018)*

*Sivak et al., Nature (2023)*  
*Google Quantum AI, Nature (2025)*

*Borah & Collab, PRL 127, 190403 (2021)*  
*Borah & Collab, PRL 134, 020601 (2025)*

# Foundations of Machine Learning (ML)



- ML is a subset of AI that learns from data
- There are primarily three types of machine learning, depending on the training method and the type of data available.

**Supervised learning:** Labelled dataset  $\mathcal{D} = \{(x_i, y_i)\}$ , where  $i = 1, 2, \dots, N$  (data index)

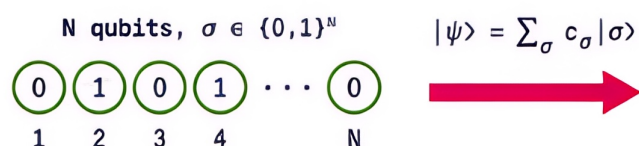
**Unsupervised learning:** Labelled dataset  $\mathcal{D} = \{(x_i)\}$ , where  $i = 1, 2, \dots, N$  (data index)

**Reinforcement learning:** No predefined data, the agent learns by itself through experiments on the environment.

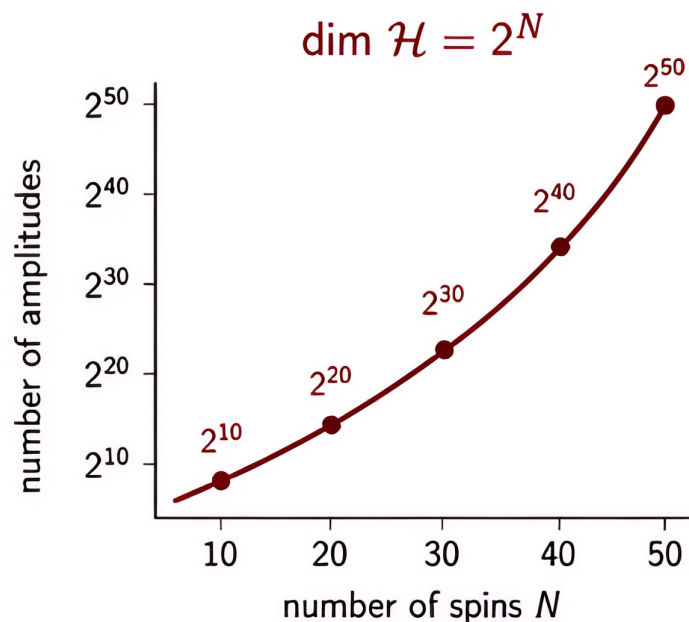


# Application 1: Neural Quantum State (NQS)

A generic N-qubit wavefunction needs exponentially many complex amplitudes

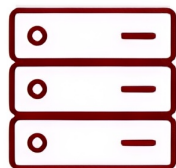


Complex amplitudes  
 $c_{\sigma} \in \mathbb{C}^{2^N}$



$N = 50 \rightarrow 2^{50}$   
complex amplitudes

$\approx 18$  PB  
at 16 bytes  
per amplitude



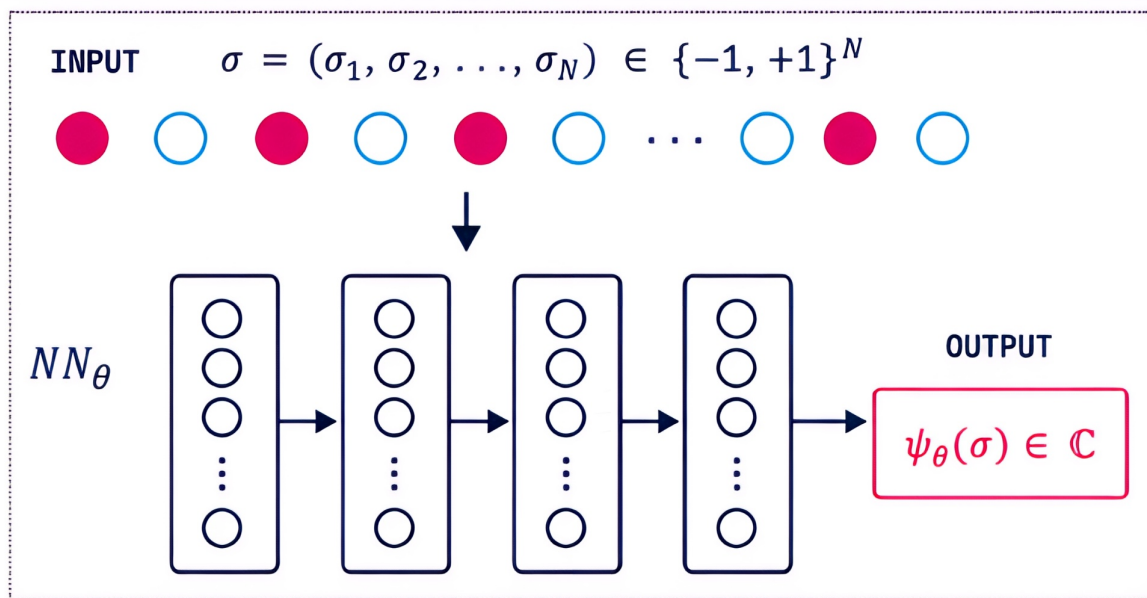
## ENTER NQS

$$\psi_{\theta}(\sigma) = NN_{\theta}(\sigma)$$

$$|\theta| \ll 2^N \quad \text{polynomial in } N$$

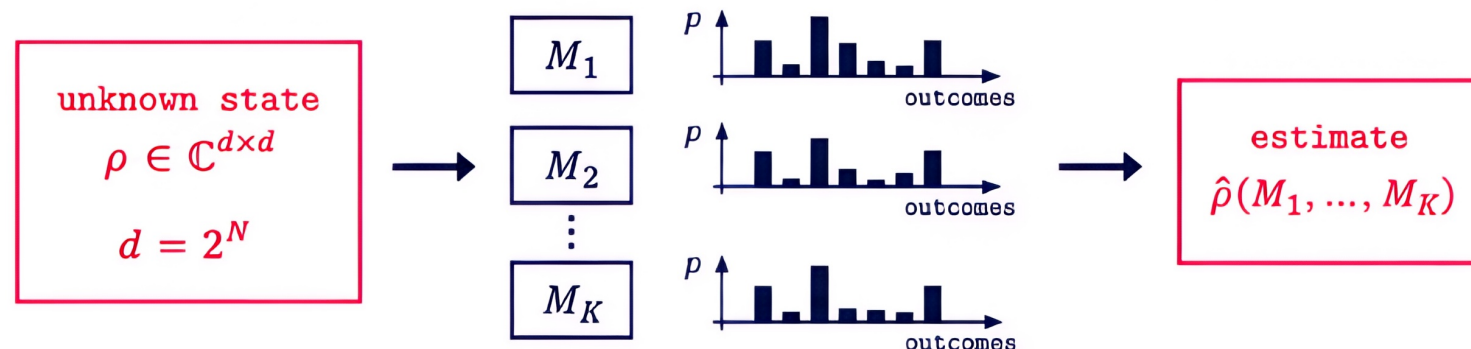
variational compression of the Hilbert space

Carleo & Troyer 2017 – Science – the seed paper.



# Application 2: Quantum State Tomography (QST)

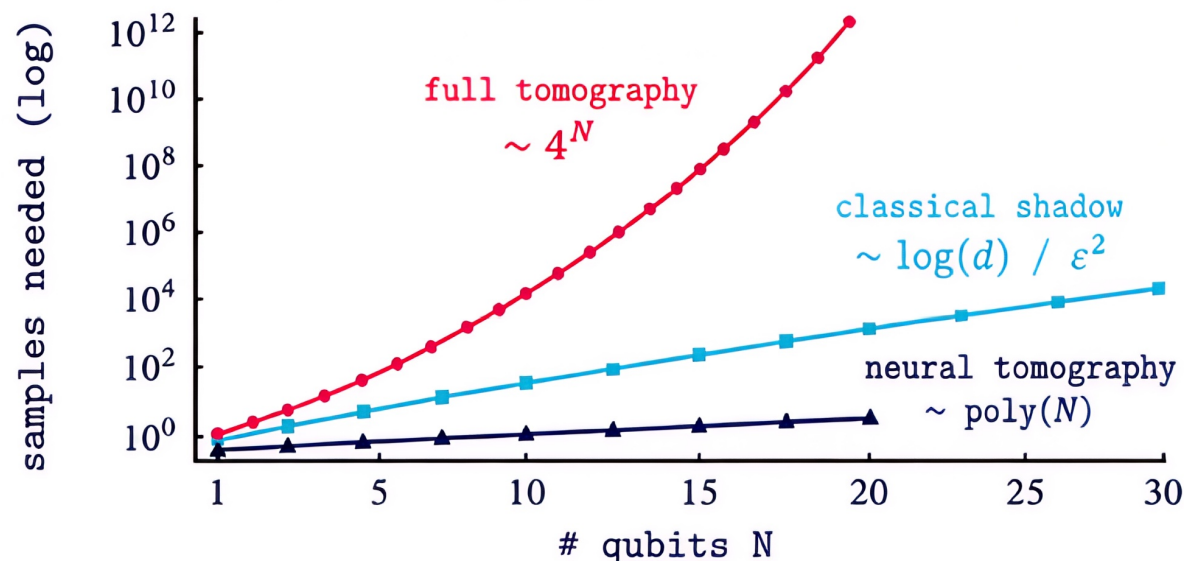
Reconstructing an arbitrary density matrix requires exponentially growing data & computation



OBJECTIVE:  $F(\rho, \hat{\rho}) \geq 1 - \varepsilon$   
BORN RULE:  $p_k = \text{Tr}(M_k \rho)$   
COMPLETENESS:  $\sum_k M_k = I$

WHY IT IS HARD

- $\rho$  has  $d^2 - 1$  real parameters
- $4^N - 1$  real parameters
- Full tomography is hopelessly for  $N \leq 20$



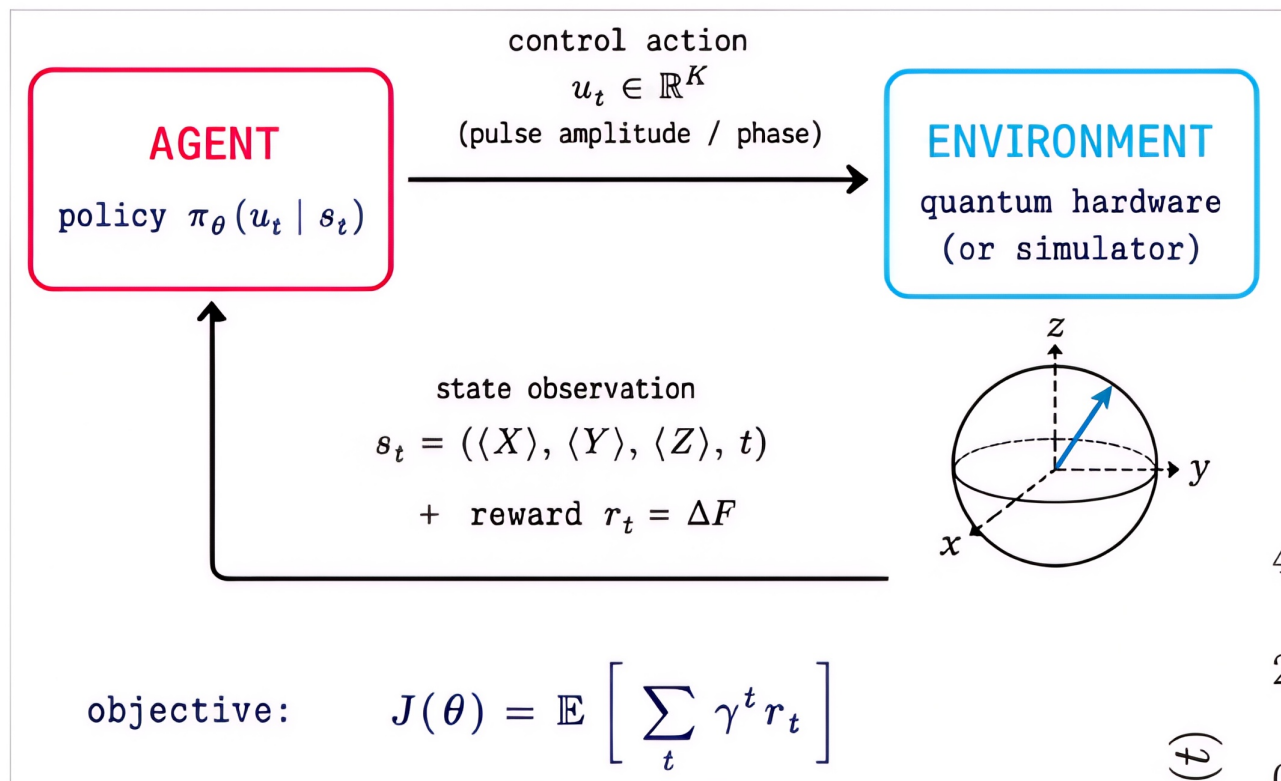
ML LANDSCAPE

Estimate  $\rho$  in  $\text{poly}(N)$  when the state has structure ML can find.

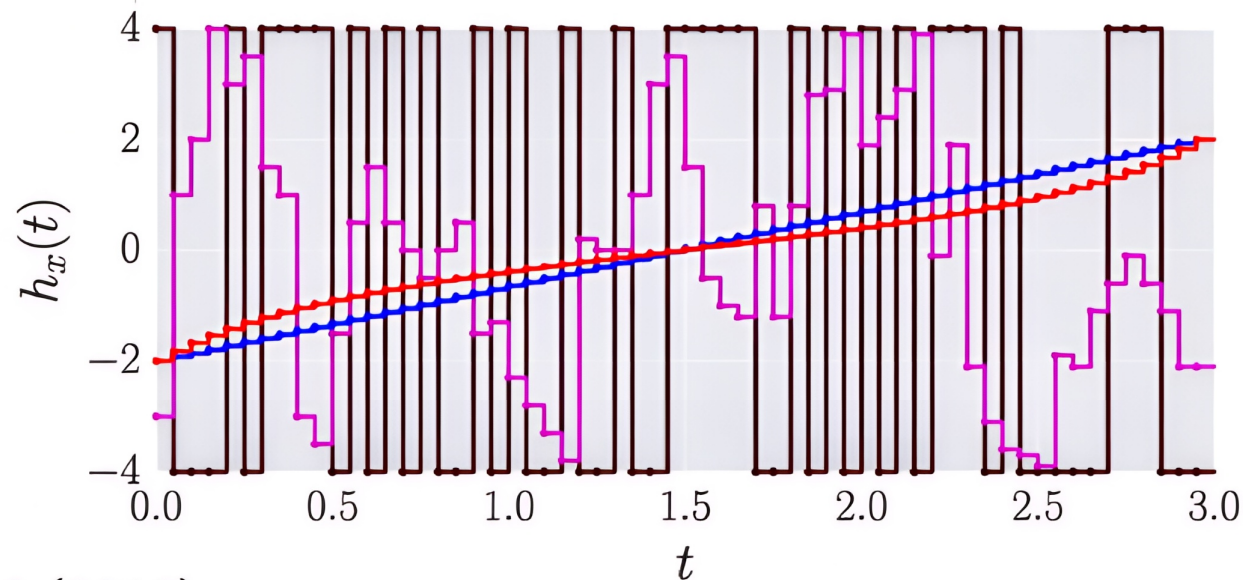
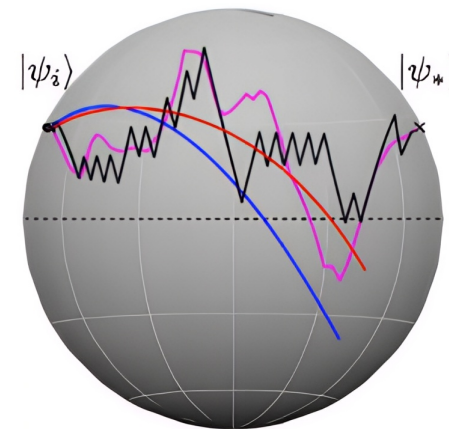
*Reference: Torai et al., Nature Physics, 14, 447 (2018)*



# Application 3: Reinforcement Learning for Pulse Discovery



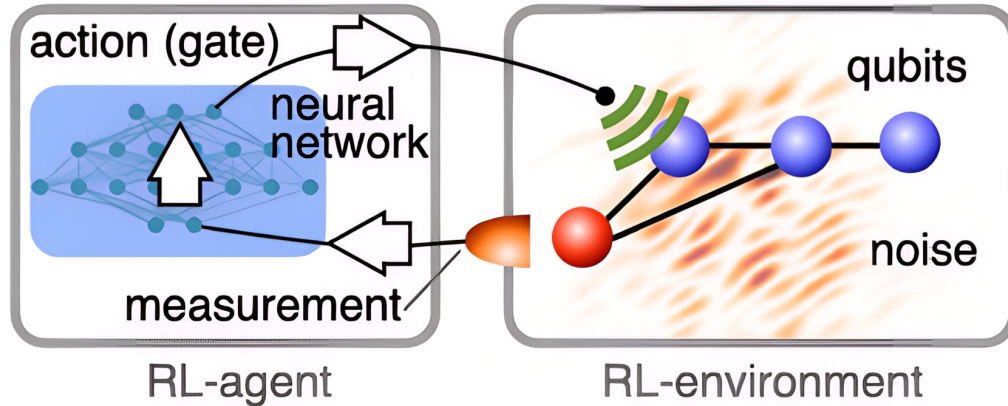
$$H = -\sigma_z - h_x(t)\sigma_x$$



**Reference:** Bukov et al., Phys. Rev. X 8, 031086 (2018)

# Application 4: RL for Quantum Error Correction (QEC) - I

## First demonstration of RL for QEC



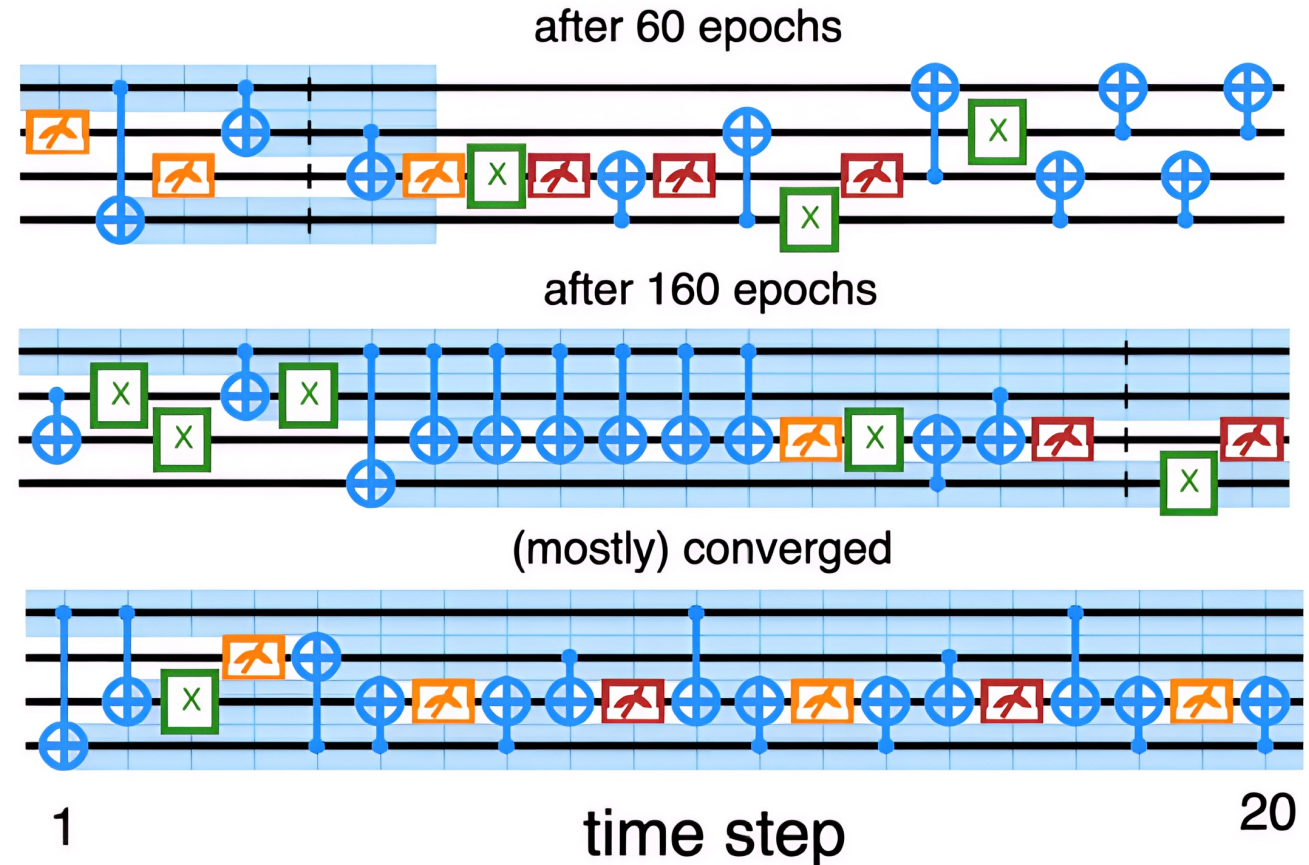
## Actions:

 CNOT

 bit-flip

 z-msmt

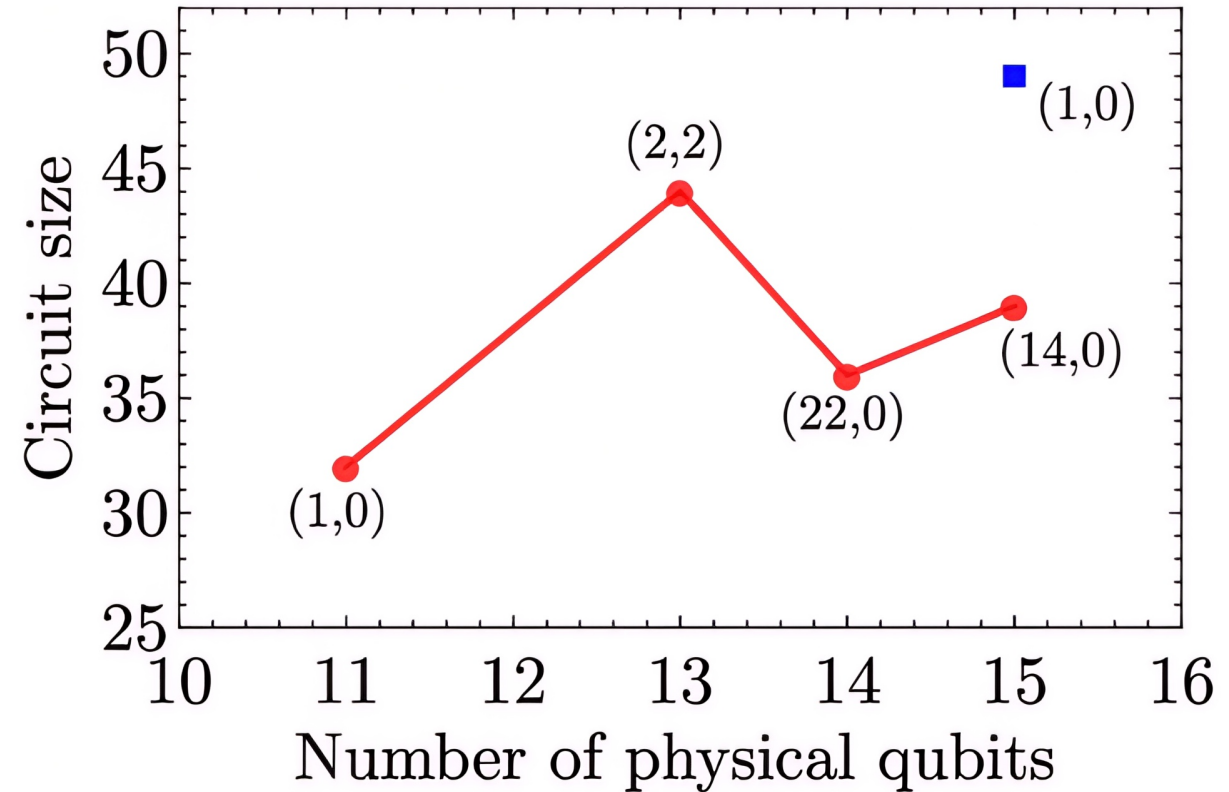
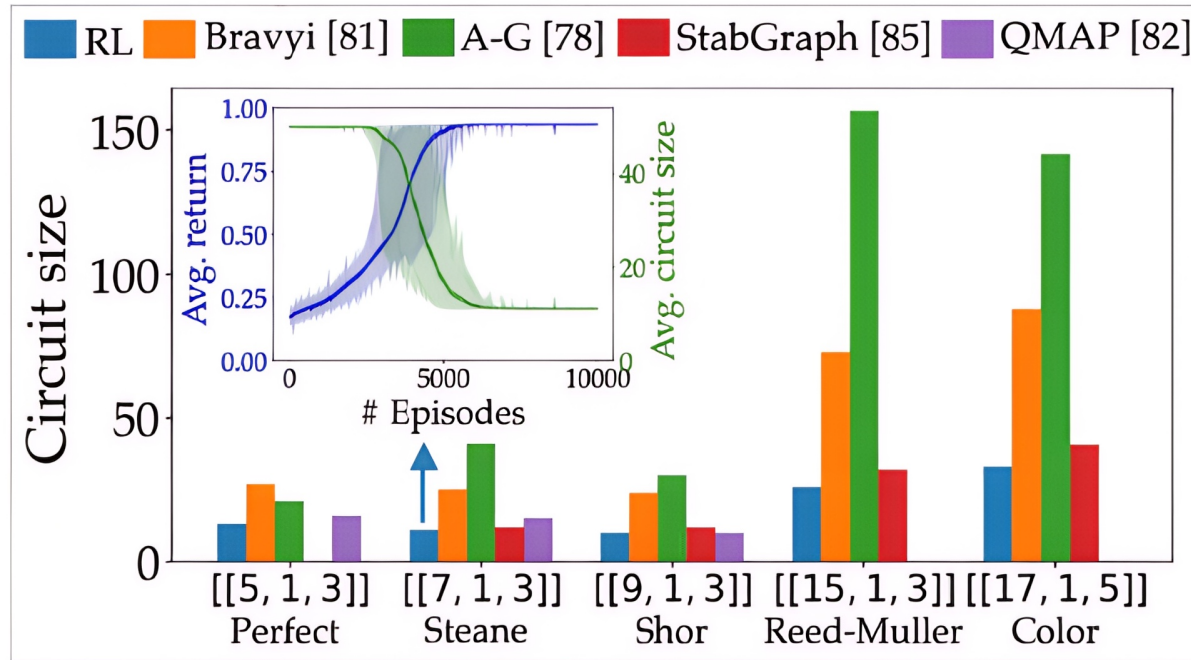
**Scalability  
Problem**



Fösel et al. from Marquard group: Phys. Rev. X 8, 031084 (2018)



# Application 4: RL for Quantum Error Correction (QEC) - II



**References:** Recent works from Marquardt group @MPL

Zen et al. PRX 15 (4), 041012 (2025)

Olle et al. npj Quantum Inf 10 (1), 126 (2024)

Borah et al. to be out soon

## KEY HIGHLIGHTS

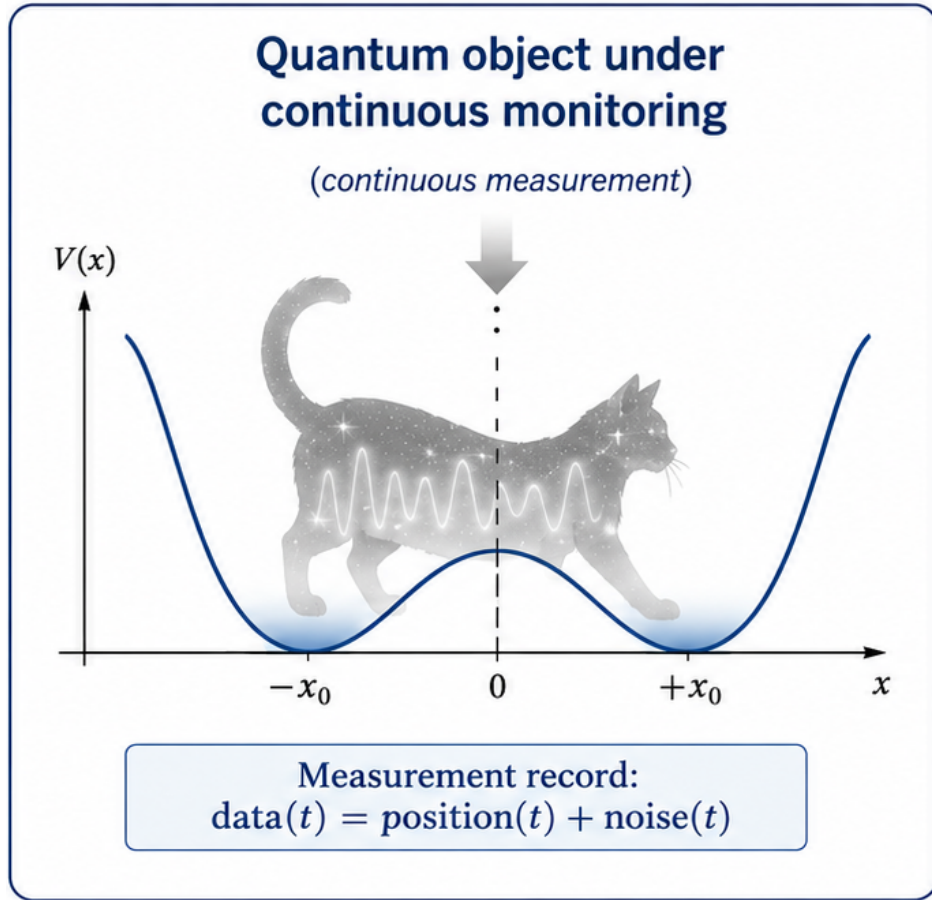
- Logical state preparation
- QEC Code discovery

Number of logical qubits:

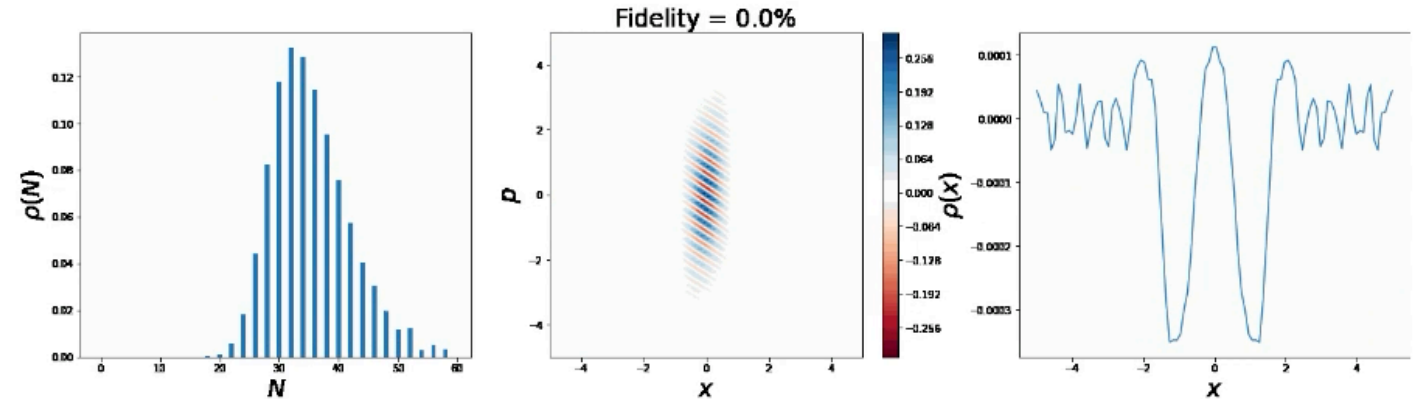
- k=1
- k=2

# Application 5: RL for Measurement-Based Feedback Control - I

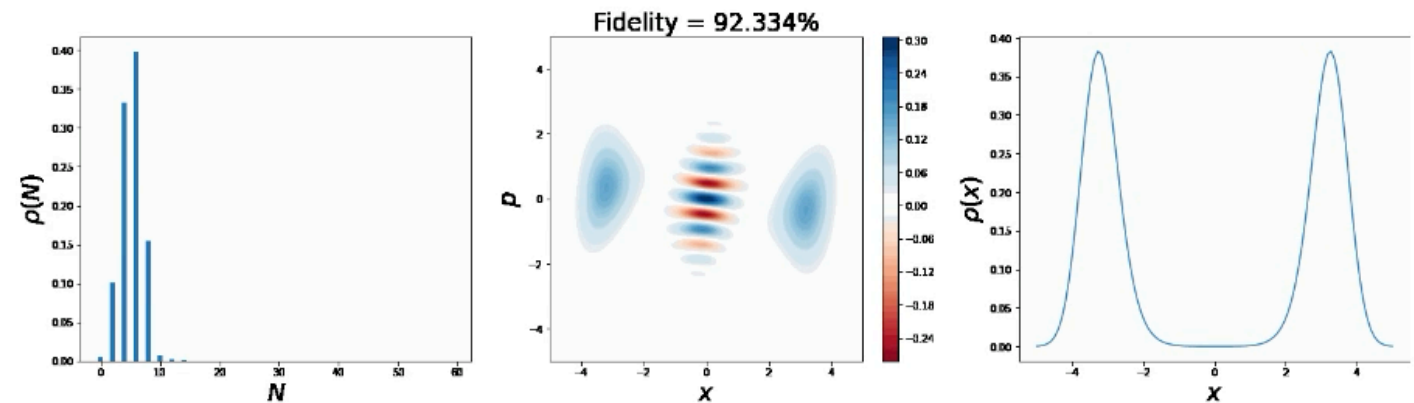
Borah & Collaborators, PRL 127, 190403 (2021)



Untrained agent



Trained agent

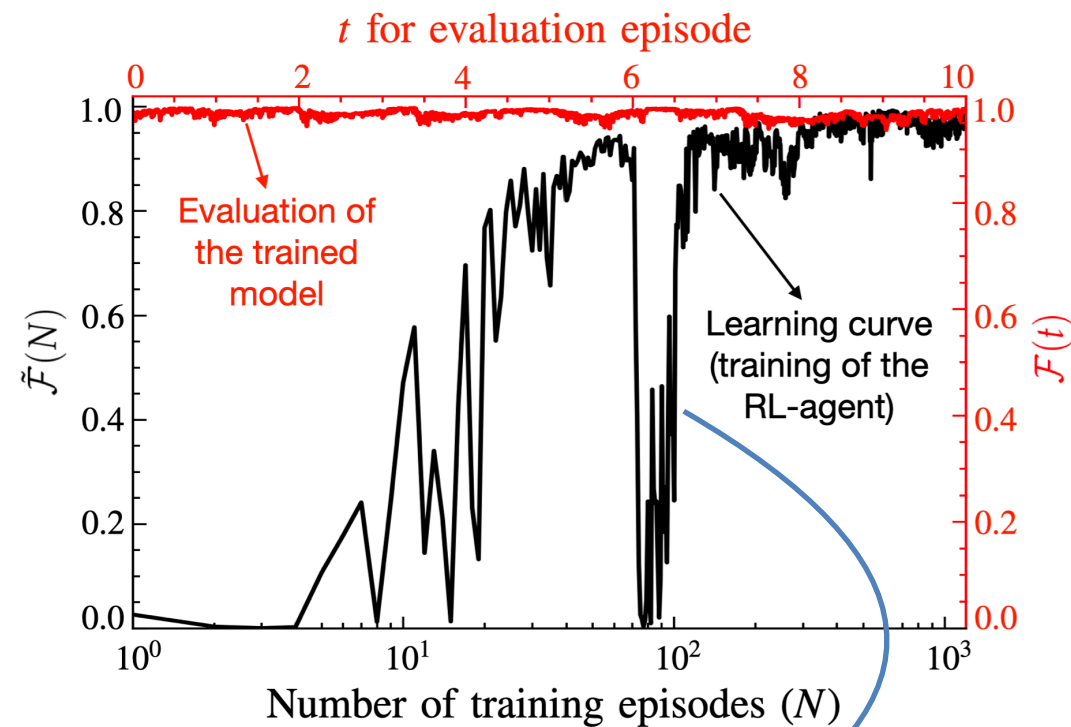
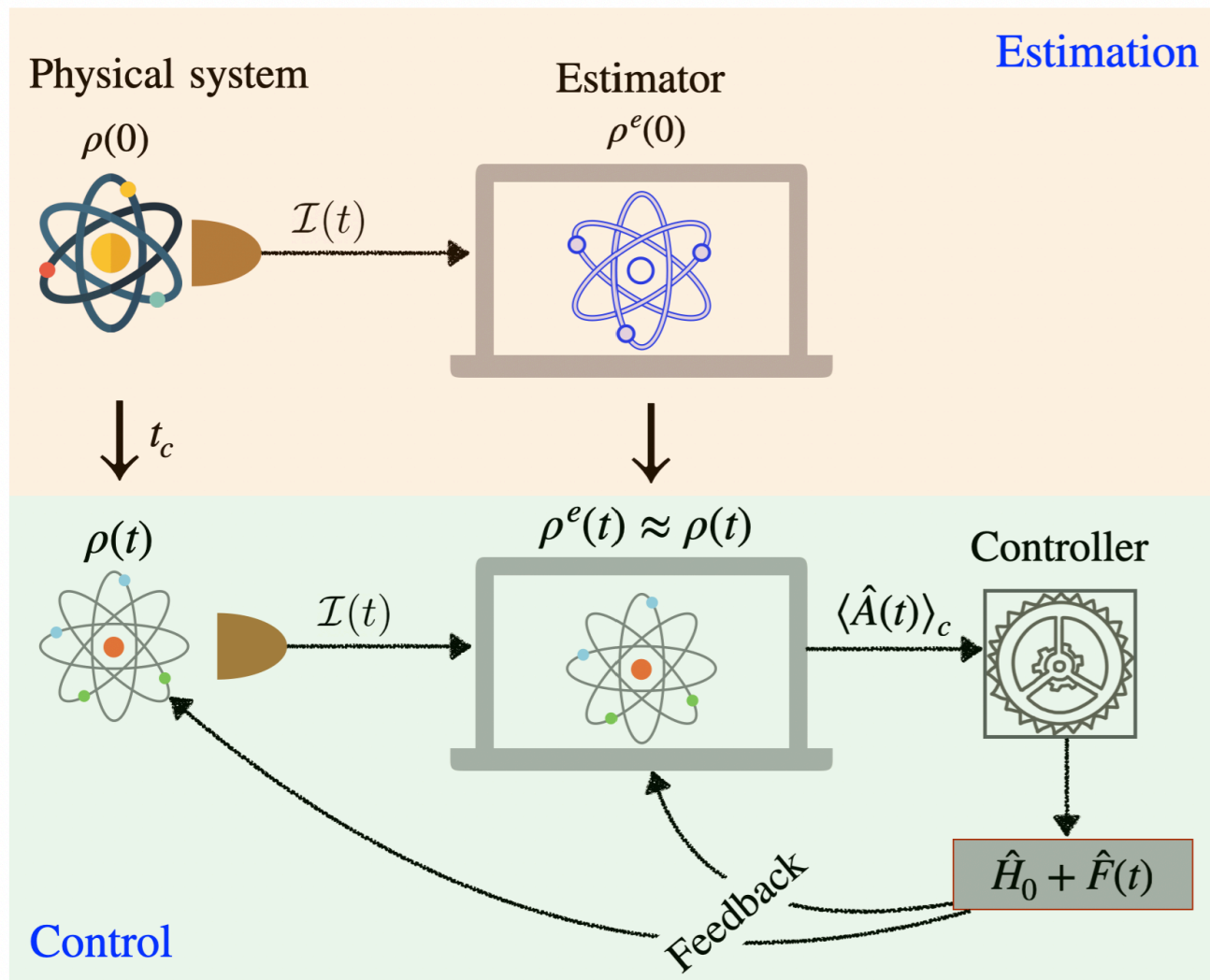


© Quantum systems can be steered by RL to achieve high fidelity in reaching a target Schrodinger-cat-like state, even when continuously monitored.



# Application 5: RL for Measurement-Based Feedback Control - II

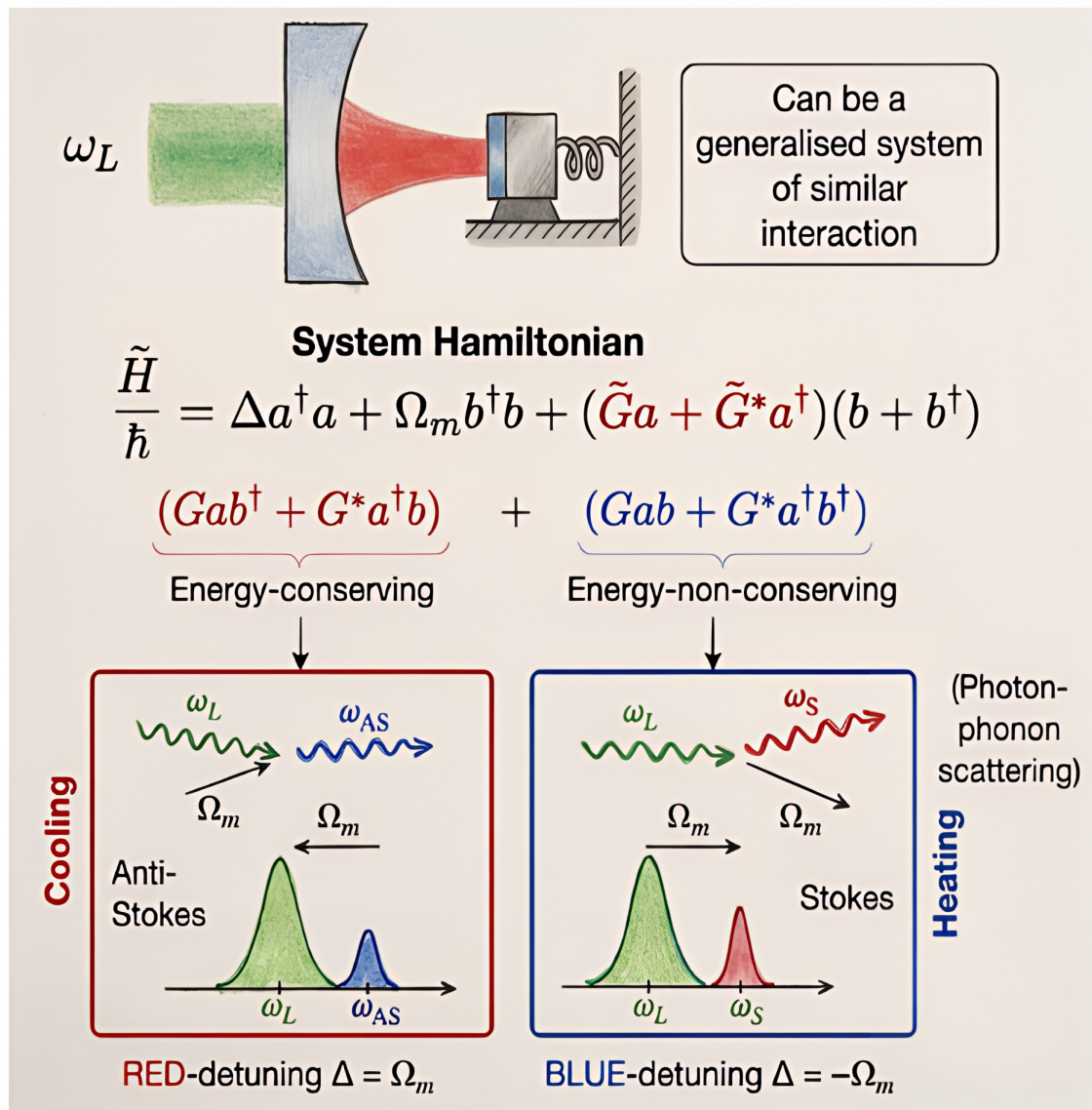
Improving the training efficiency and accuracy of the RL agent



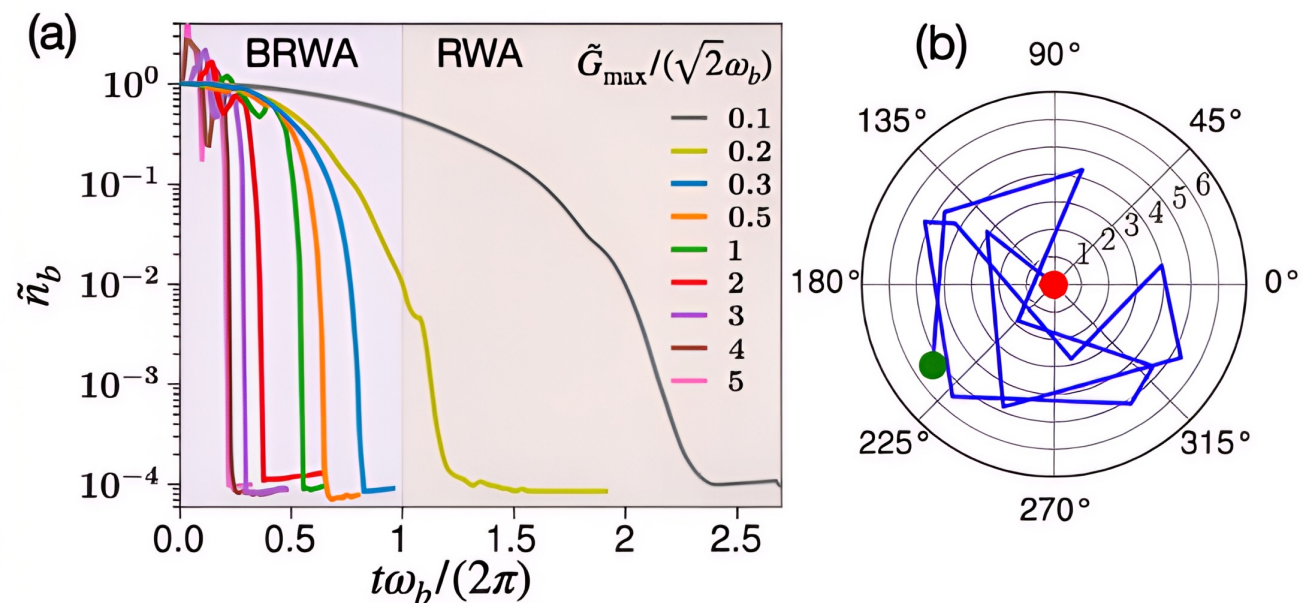
Due to the "digital twin"

Reference: Borah & Sarma, PRL 127, 190403 (2021)

# Application 6: Machine-Optimized Pulsed Cooling



Exploit full light-matter interaction (beyond RWA) greatly enhancing cooling speed



**Final photon number**

$$\tilde{n}_b = \frac{n_b}{n_b^{\text{th}}}$$

(Normalized to thermal occupation)

**Cooling rate**

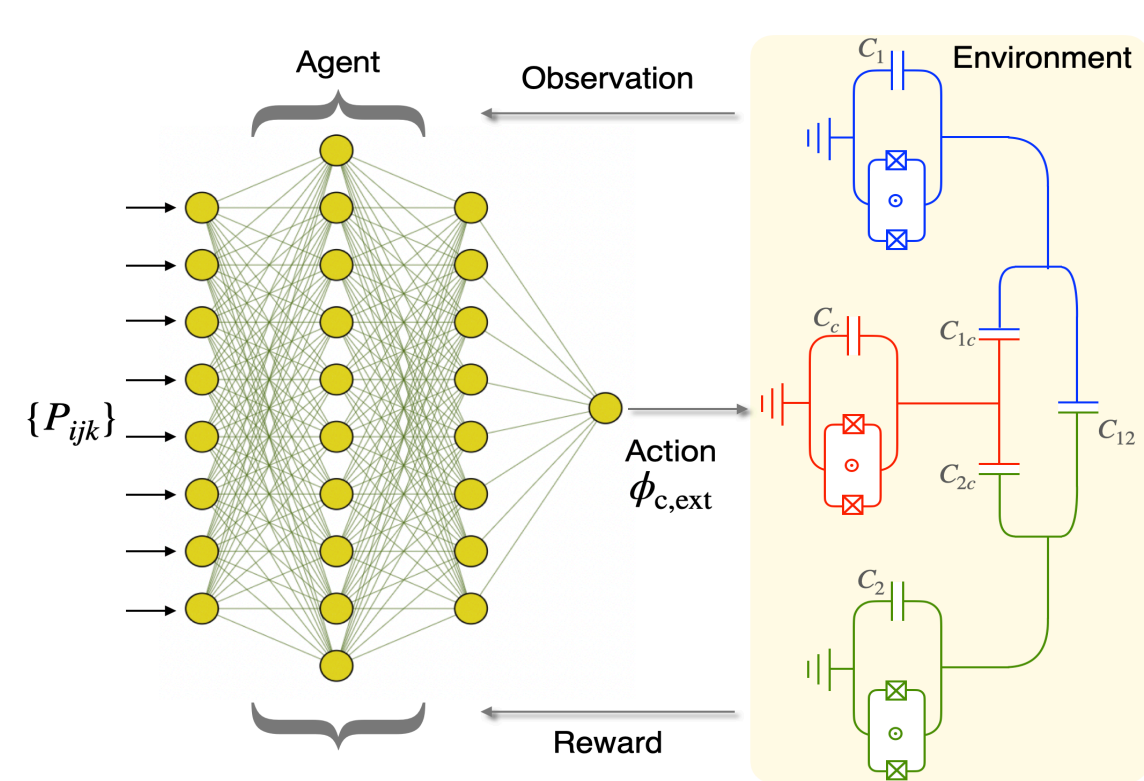
$$r(t) = \frac{1}{\tilde{n}_b}$$

(Higher is better)

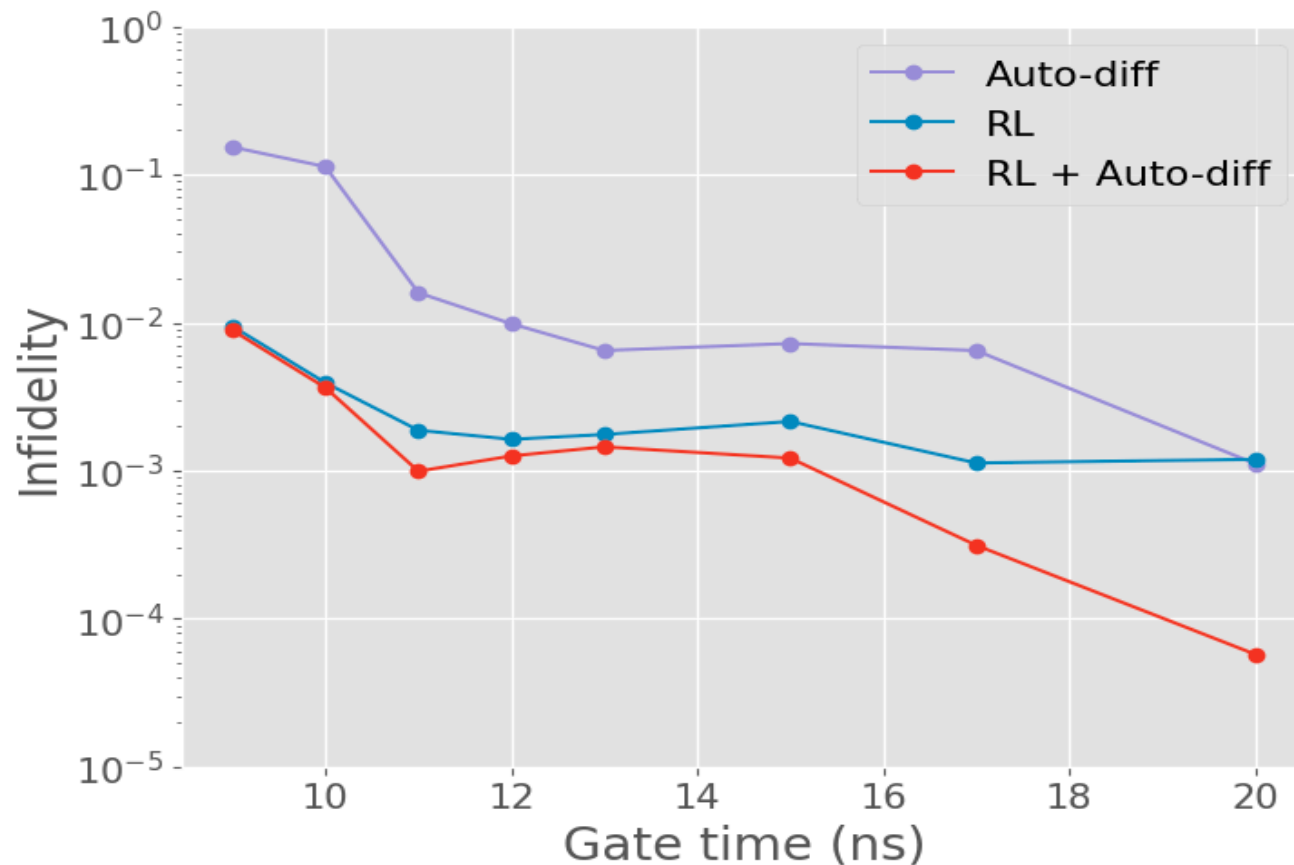
Reference: Borah & Collaborators, Phys. Rev. Res. (Letter), 4, L042038, 2022



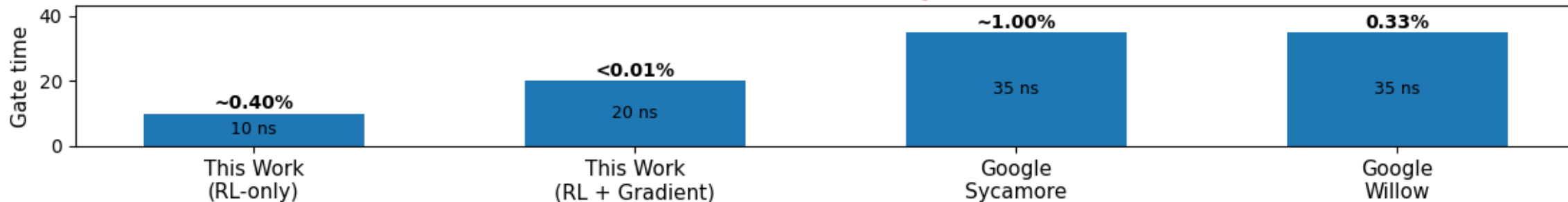
# Application 7: RL for Discovering Faster Gates



Sarma & Hartmann, Phys. Rev. Applied 23, 014015 (2025)



## Two-Qubit Gate Comparison



# Application 8: QEC with Noisy Syndromes (Continuous QEC)



## Experimental demonstration

Continuous quantum error correction has been experimentally demonstrated for a three-qubit bit-flip code.

*Nature Communications* 13, 2307 (2022)

## Noisy stabilizer measurements

$$S_1(t) = \langle ZZI \rangle(t) + \delta \xi_1(t)$$

$$S_2(t) = \langle IZZ \rangle(t) + \delta \xi_2(t)$$

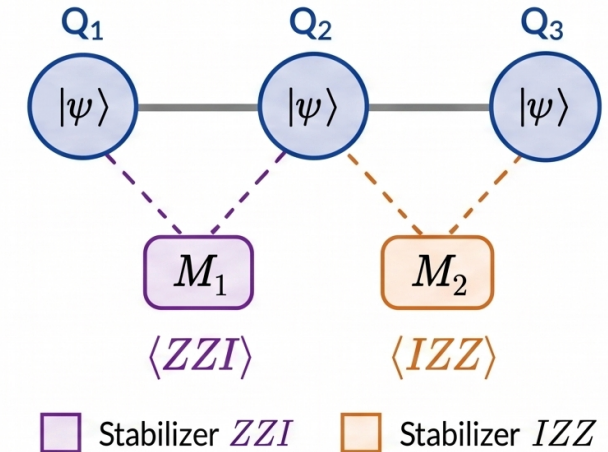


signal processing / estimation

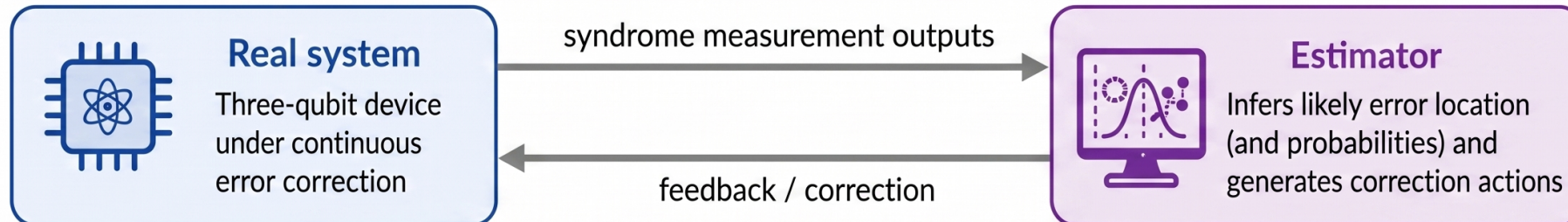


estimated syndromes /  
inferred error probabilities

## Three-qubit repetition (bit-flip) code



## Our work: measurement-based estimator scheme for continuous QEC



$$F(t) = \lambda_1(t)XII + \lambda_2(t)IXI + \lambda_3(t)IIX$$

The estimator converts noisy syndrome streams into real-time error-detection and feedback signals.

RL can act as the “digital twin” for Continuous QEC.

Borah & Collaborators: Phys. Rev. Res., 4, 033207 (2022)



# Application 9: QEC for Gottesman-Kitaev-Preskill Code - I



## Encoding a qubit in an oscillator

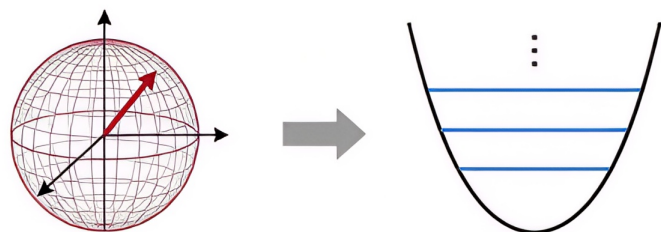
Daniel Gottesman, Alexei Kitaev, John Preskill

*Physical Review A* 64, 012310 (2001)

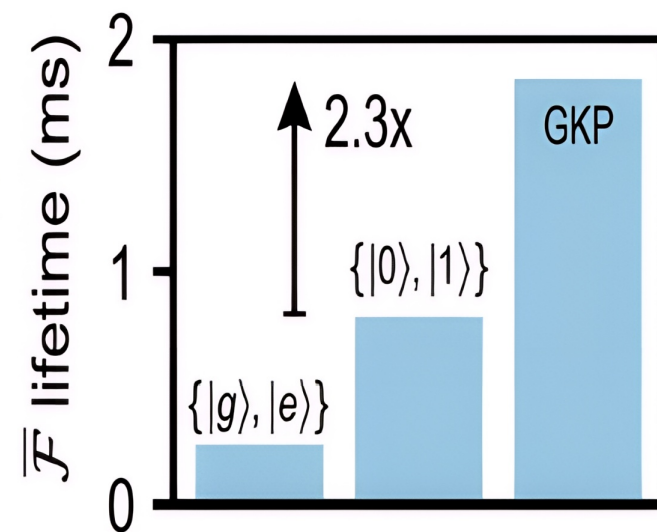
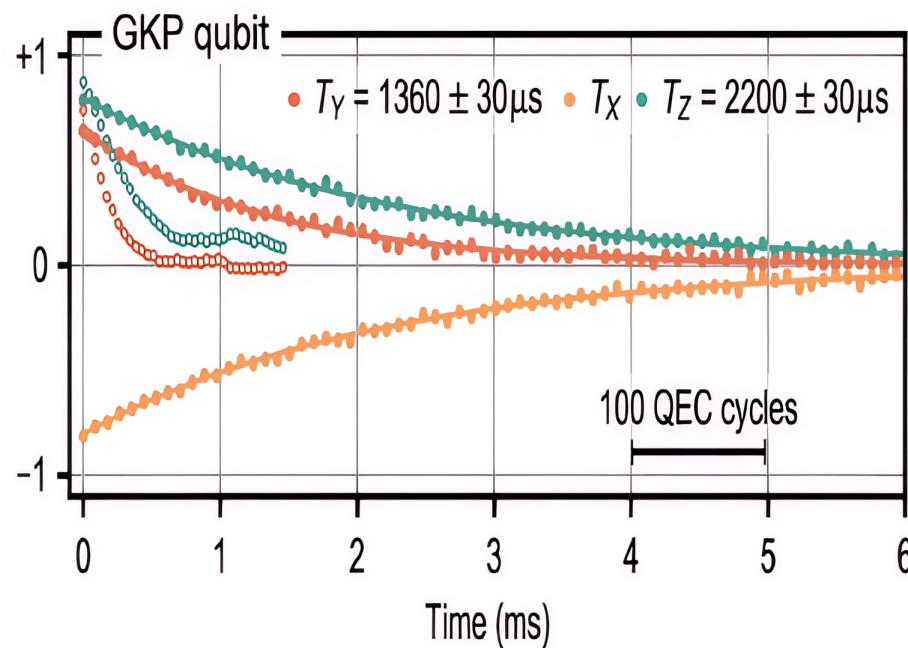
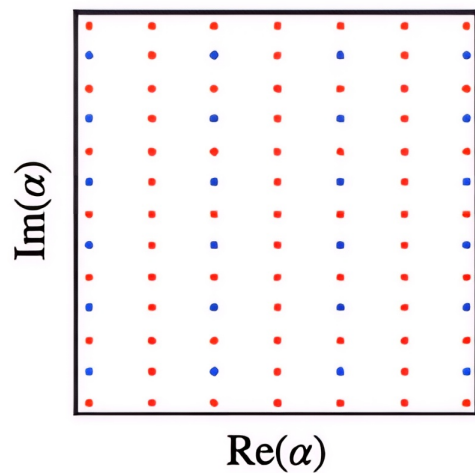
## Real-time quantum error correction beyond break-even

[V. V. Sivak](#) , [A. Eickbusch](#), [B. Royer](#), [S. Singh](#), [I. Tsioutsios](#), [S. Ganjam](#), [A. Miano](#), [B. L. Brock](#), [A. Z. Ding](#), [L. Frunzio](#), [S. M. Girvin](#), [R. J. Schoelkopf](#) & [M. H. Devoret](#) 

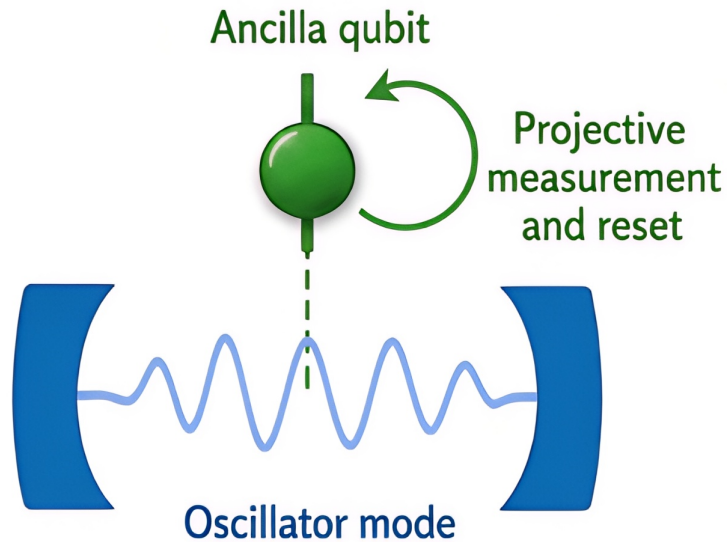
*Nature* **616**, 50–55 (2023) | [Cite this article](#)



oscillator using a lattice of states in phase space



# Application 9: QEC for Gottesman-Kitaev-Preskill Code - II



- (1) Qubit is projectively measured and reset.
- (2) Learn to control the oscillator state.
- (3) Measurements are performed at times  $t_1, t_2, \dots, t_N$ , yielding outcomes  $m_1, m_2, \dots, m_N$ .

$$\mathbf{m} = \{+1, -1, \dots, +1, -1, -1\}$$

$$\text{Feedback-GRAPE} = \text{Gradient-based optimal control} + \text{Feedback on strong measurements}$$

Trajectory-averaged reward

$$\bar{R} = \langle R(\mathbf{m}) \rangle_{\mathbf{m}} = \sum_{\mathbf{m}} P(\mathbf{m}) R(\mathbf{m})$$

This yields the working formula for *Feedback-GRAPE*:

$$\frac{\partial \bar{R}}{\partial \theta} = \left\langle \frac{\partial R(\mathbf{m})}{\partial \theta} \right\rangle_{\mathbf{m}} + \left\langle R(\mathbf{m}) \frac{\partial \ln P_{\theta}(\mathbf{m})}{\partial \theta} \right\rangle_{\mathbf{m}}$$

Parameter Update Rule

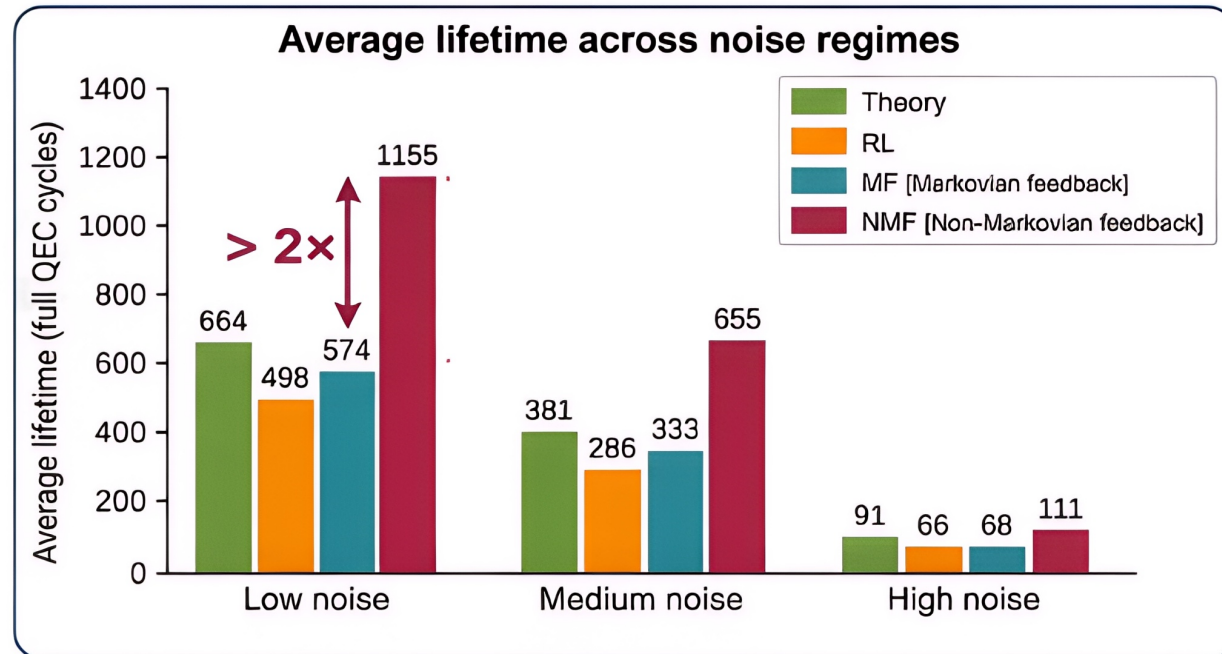
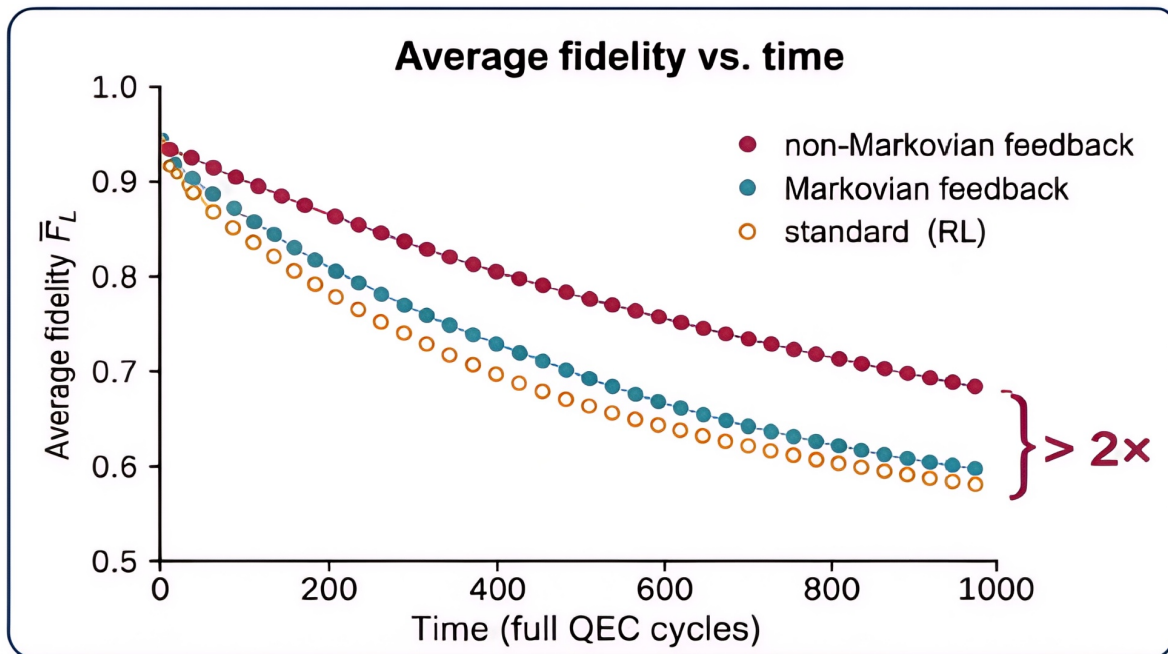
The control parameters  $\theta$  are updated iteratively using gradient ascent:

$$\theta^{(k+1)} = \theta^{(k)} + \eta \left( \frac{\partial \bar{R}}{\partial \theta} \right)_k$$

References: Porotti et al., PRX Quantum 4, 030305 (2023); Borah & collaborators, PRL, 134 (2), 020601 (2025)



# Application 9: QEC for Gottesman-Kitaev-Preskill Code - II



- ✓ We obtain more than a **2x lifetime improvement** over the standard strategy, corresponding to over **4x lifetime** beyond break-even.
- ✓ This improvement trend persists across different noise levels.

## Noise parameters

$$\tau_{\text{cycle}} = 10 \mu\text{s}$$

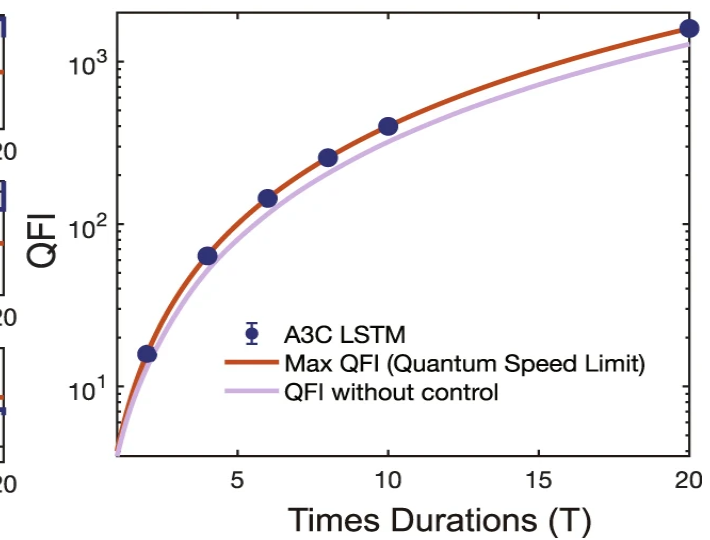
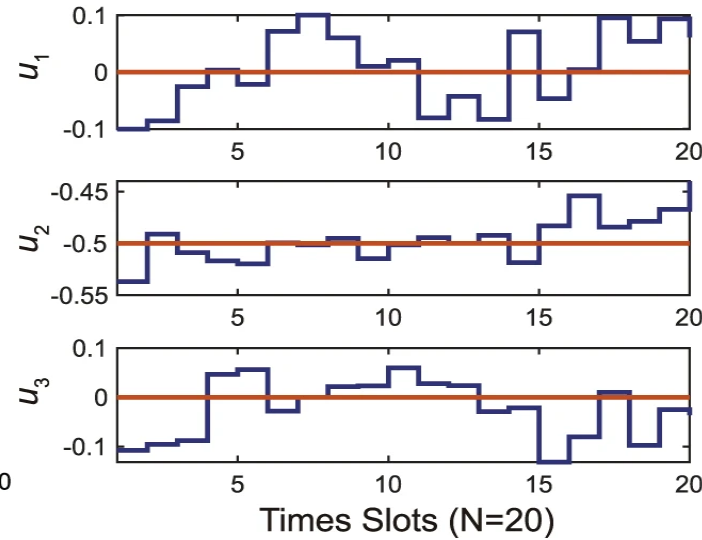
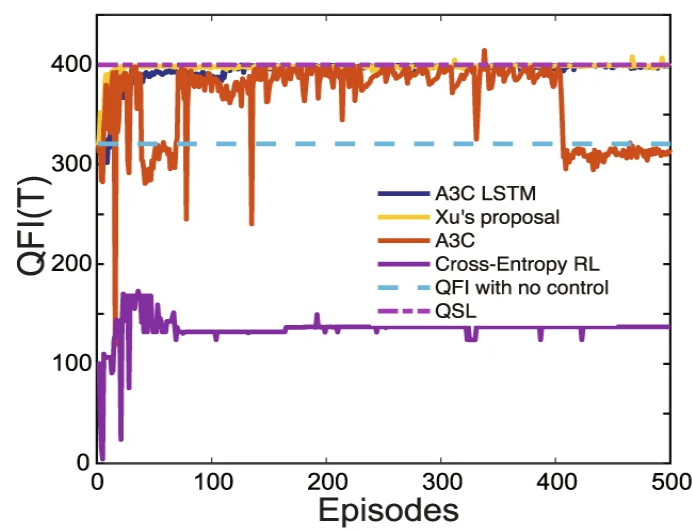
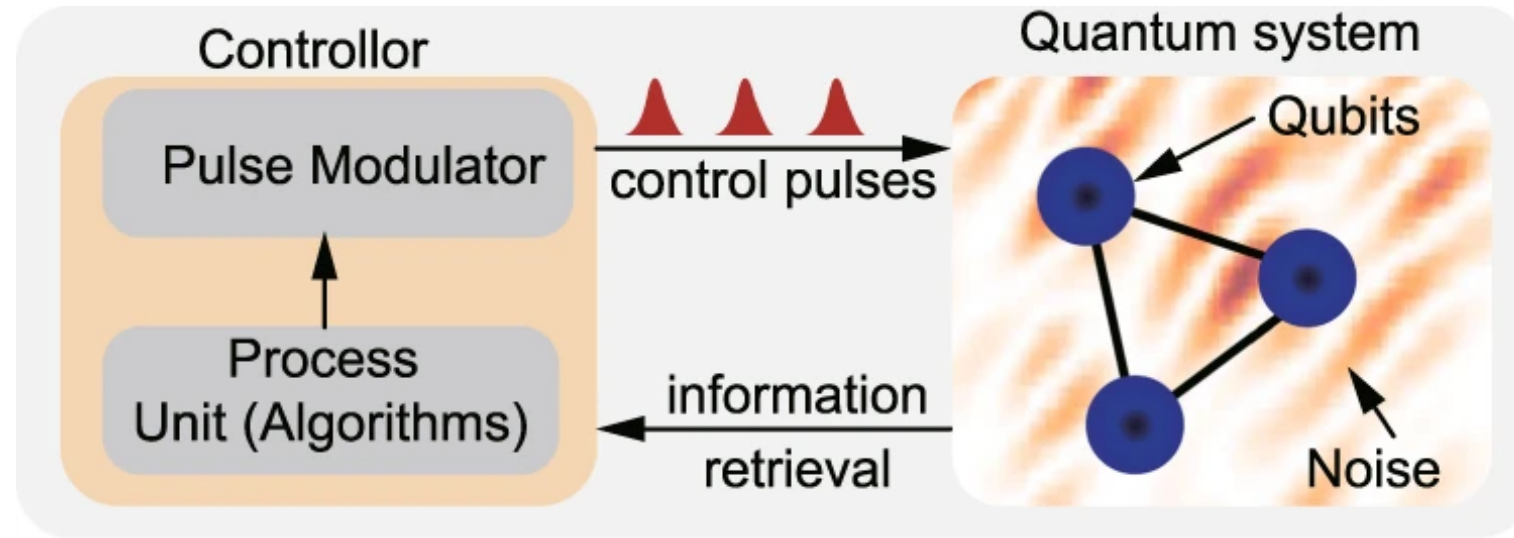
| Noise level | $T_s/\tau_{\text{cycle}}$ | $T_1/\tau_{\text{cycle}}$ | $T_2/\tau_{\text{cycle}}$ |
|-------------|---------------------------|---------------------------|---------------------------|
| Low [10]    | 61                        | 28                        | 23.8                      |
| Medium      | 49                        | 10                        | 12                        |
| High [5]    | 24.5                      | 5                         | 6                         |

[10] *Nature* **616**, 50 (2023)

[5] *Nature* **584**, 368 (2020)

References: Borah & collaborators, PRL, 134 (2), 020601 (2025)

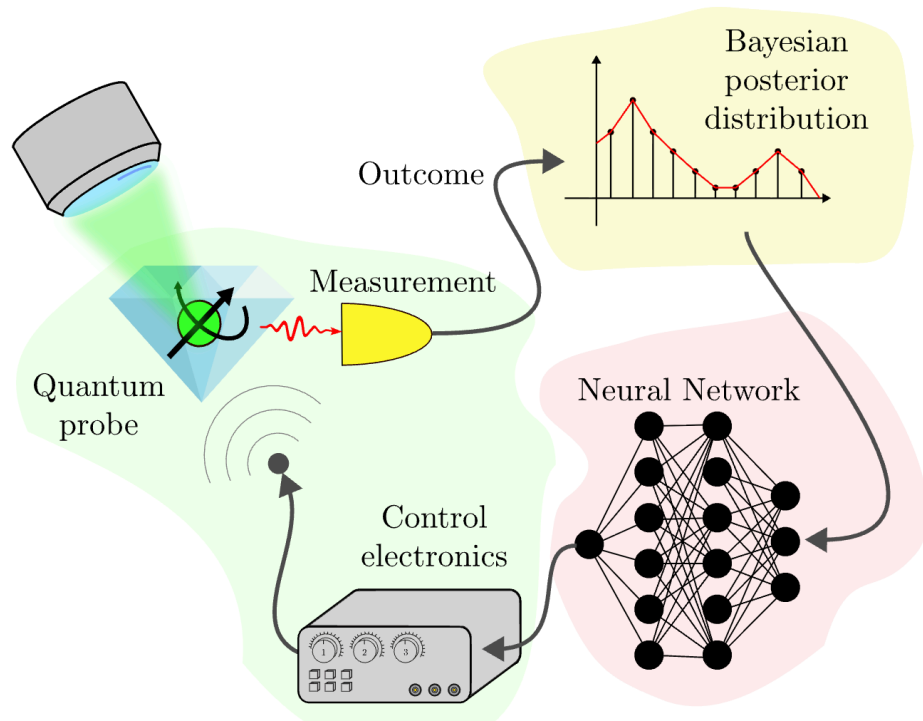
# Application 10: Machine Learning for Quantum Sensing



Xiao et al., npj Quantum Inf. 8, 2 (2022)

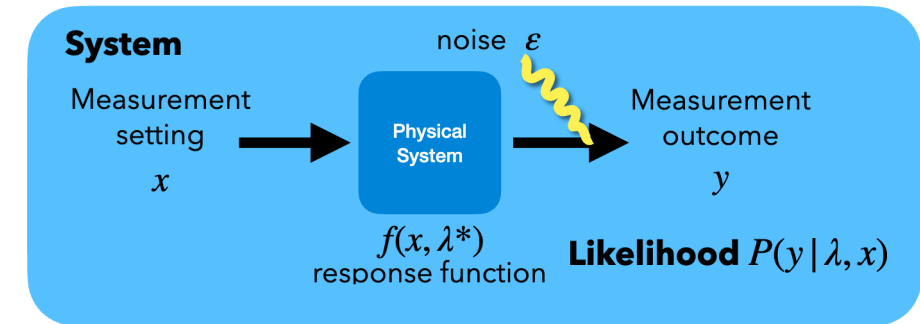
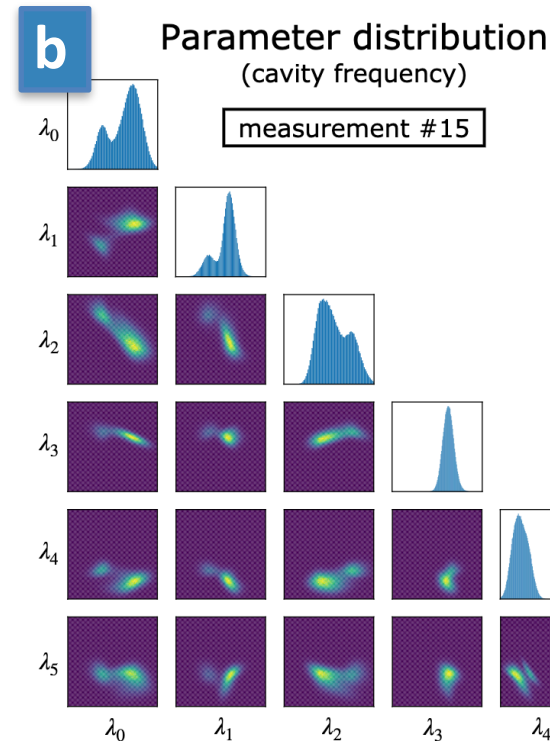
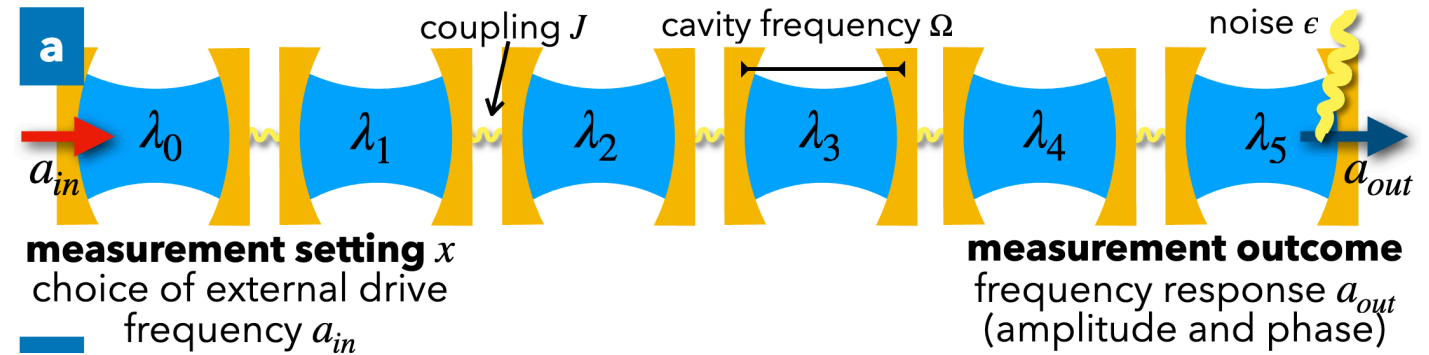


# Application 11: Machine Learning for Experiment Design



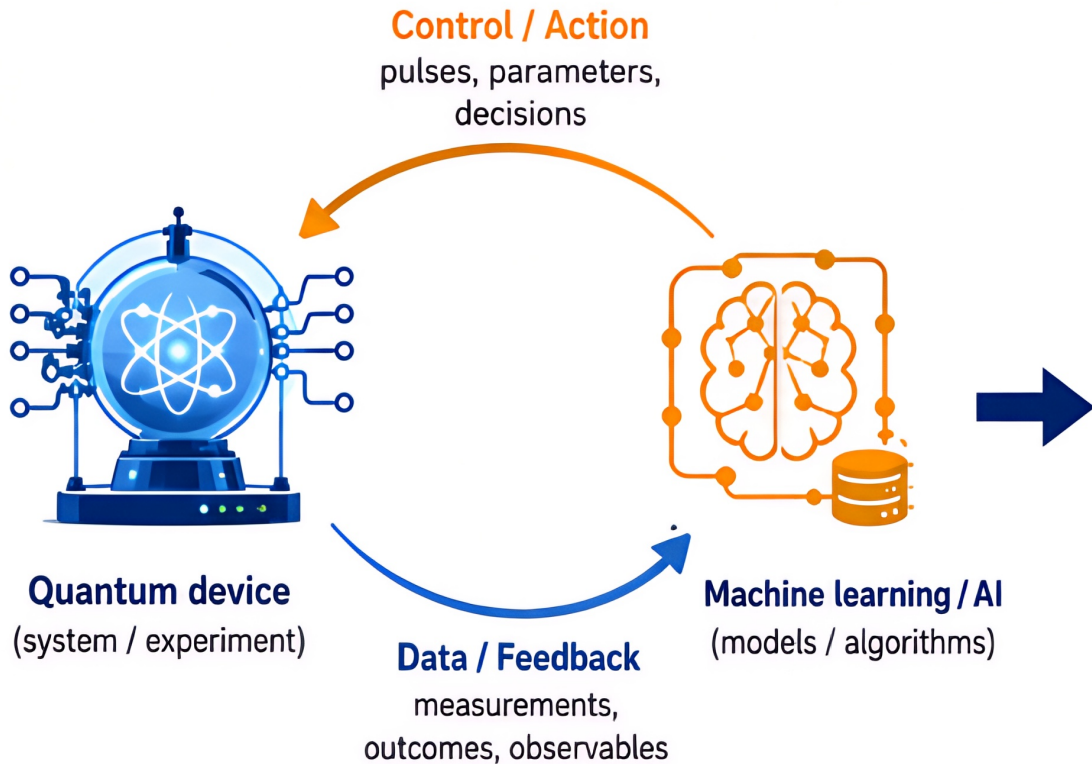
Sara & Marquardt, Mach. Learn.: Sci. Technol. 4 045022 (2022)

Belliardo et al., Int. J. Quantum Inf., 22, 6 (2024)

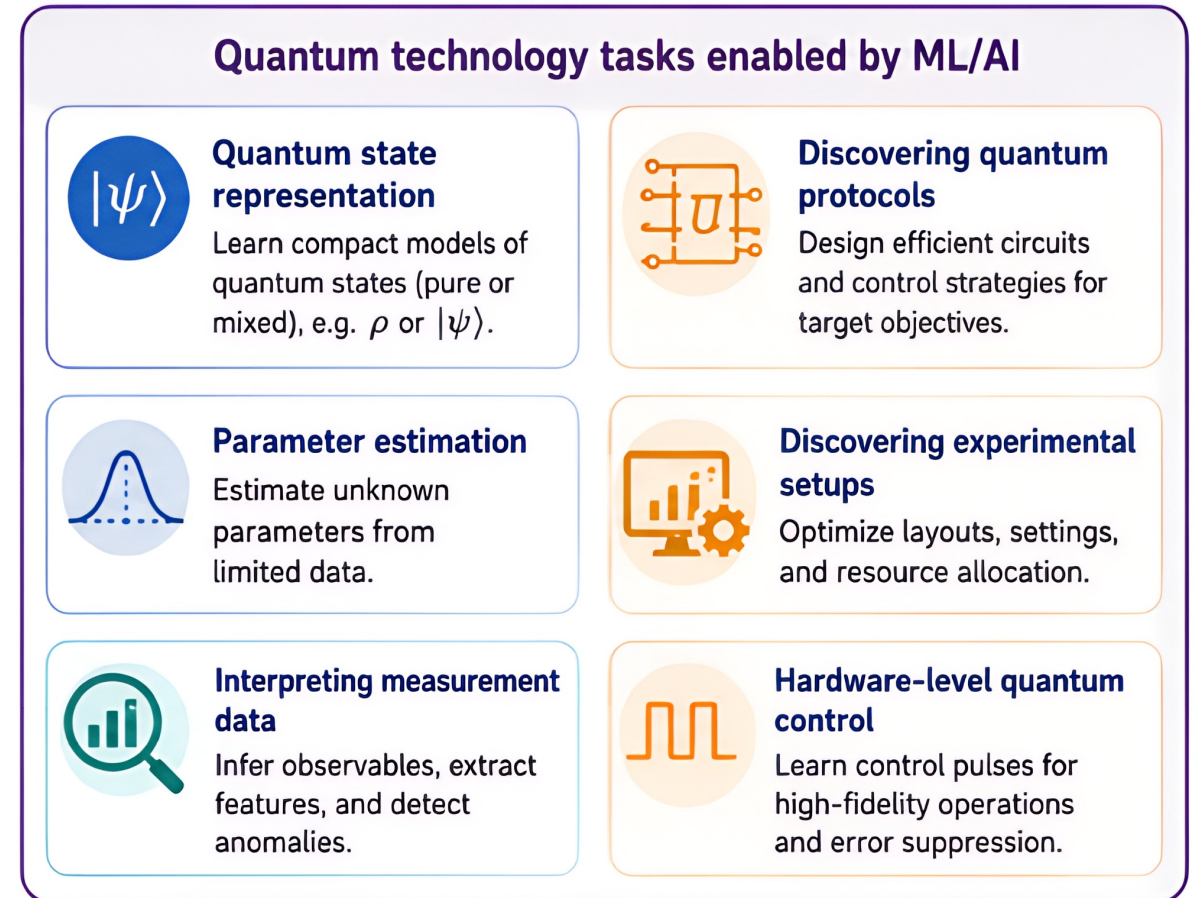


# Conclusions

Machine learning has been applied to solve a wide range of complex problems related to quantum technology.



**Outcomes:** Higher fidelity, reduced experimental cost, faster discovery, scalable quantum technologies.







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