Quantum Artificial Intelligence

Vincenzo Lipardi

Quantum Tracking Mini Workshop
12-05-2026

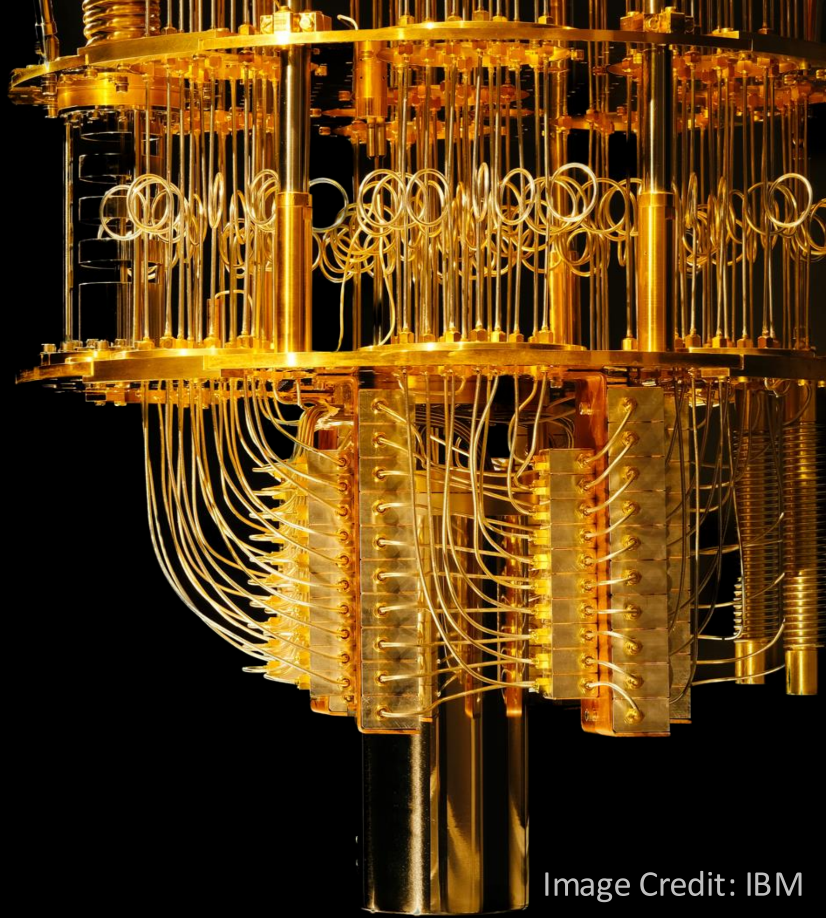

Image Credit: IBM

- Monte Carlo Tree Search for Quantum Circuit Design
- A Study on Quantum Magic using Machine Learning
- Magic-informed Quantum Architecture Search

Maastricht University

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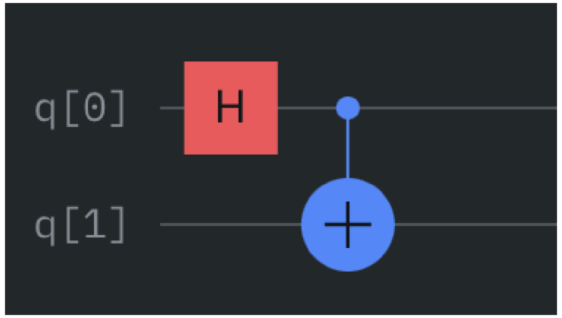
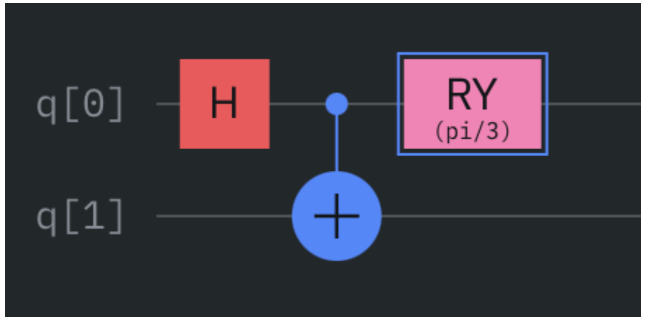
NISQ devices dispose of limited resources

- Limited number of **qubits**
- Limited **connectivity** between qubits
- Quantum **noise**

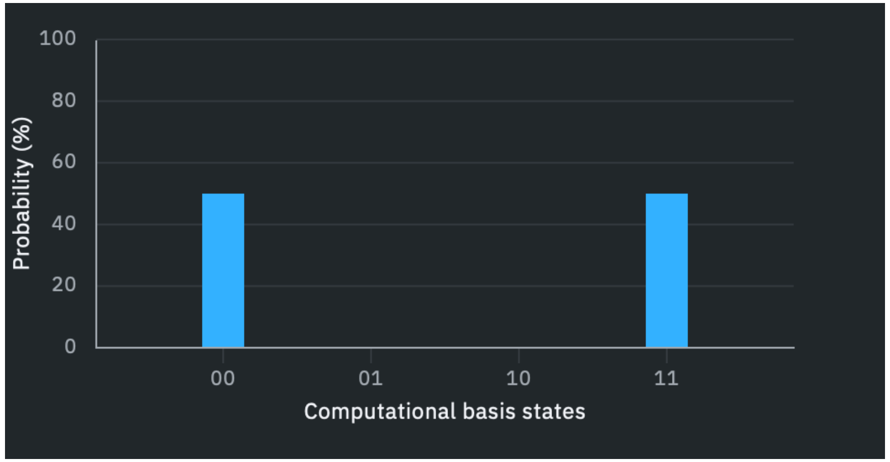
What can we achieve with currently available quantum computers?

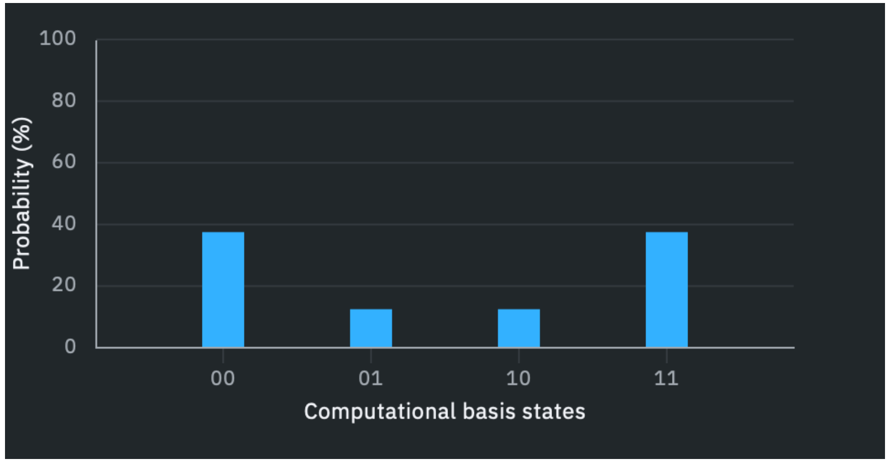
Circuit-based Quantum Computing



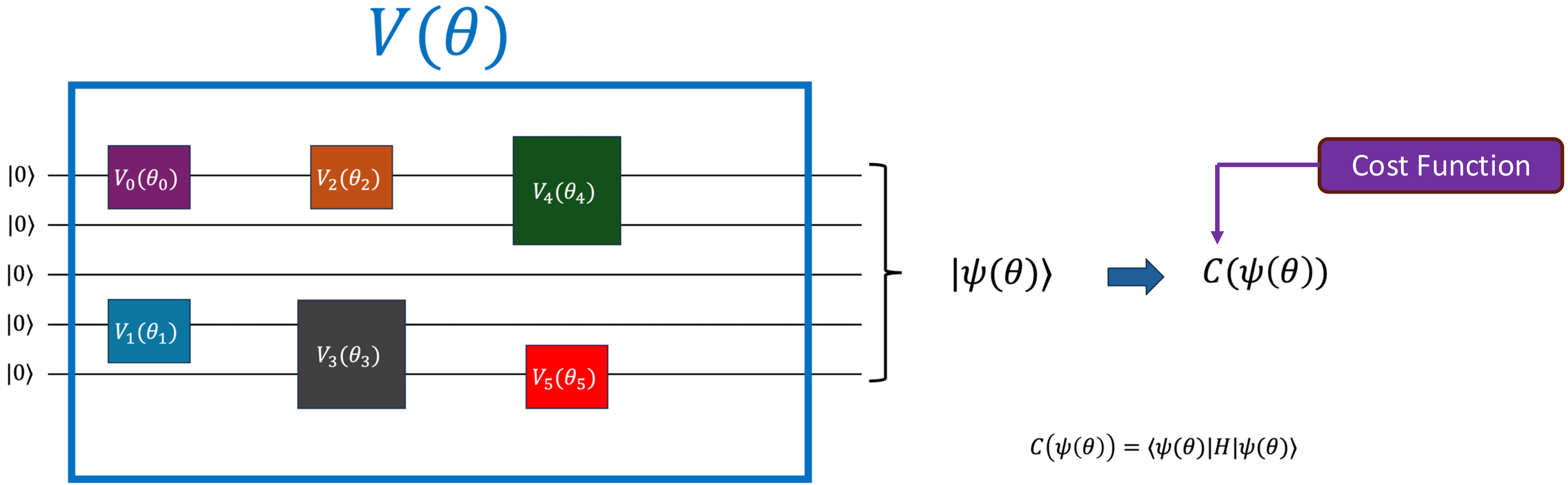


Add Gate $R_y\left(\frac{\pi}{3}\right)$





Encode the Problem in a Parameterized Quantum Circuit



$C(\psi(\theta)) = \langle\psi(\theta)|H|\psi(\theta)\rangle$

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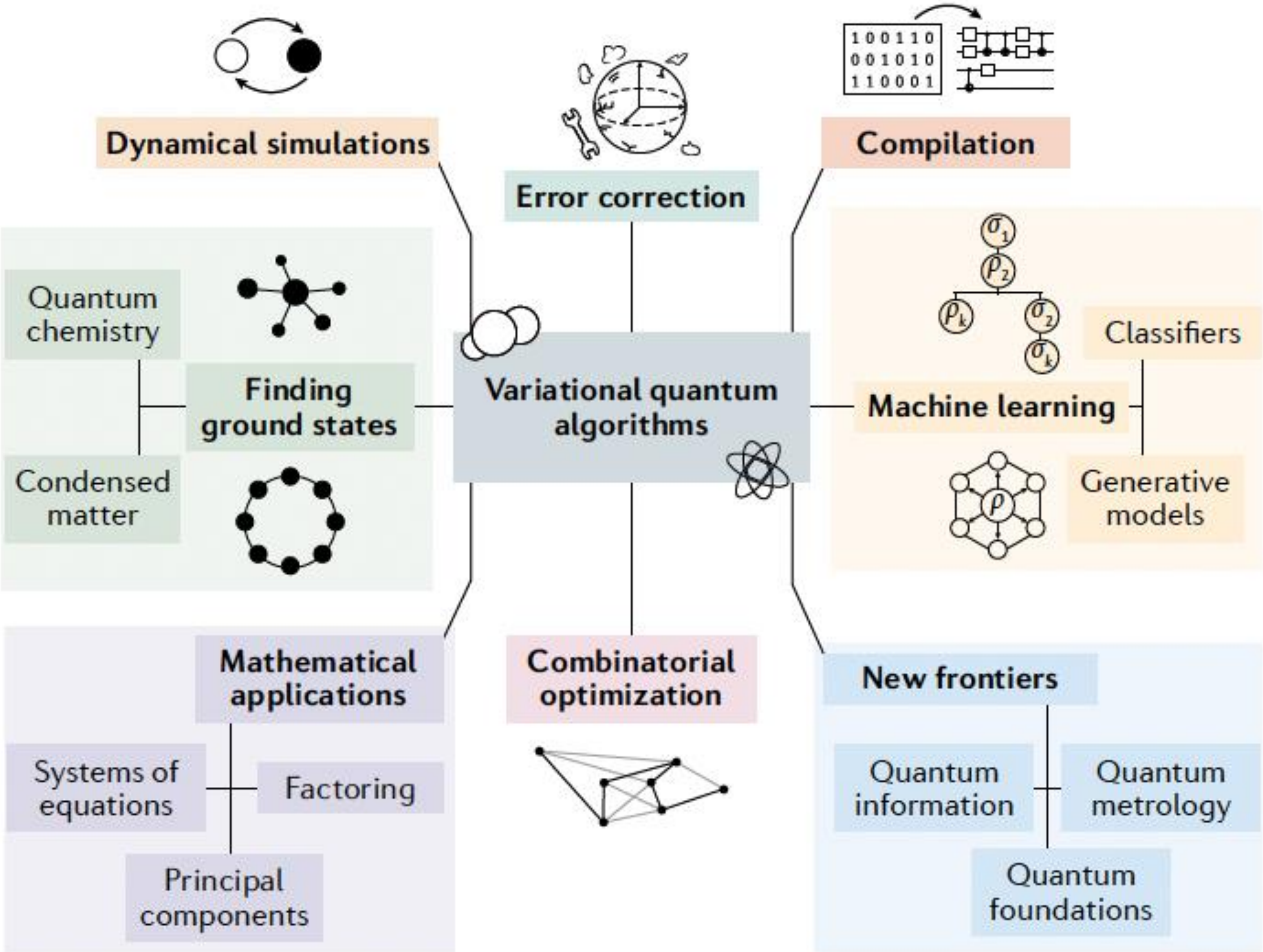
What can we achieve with currently available quantum computers?

Variational Quantum Algorithms

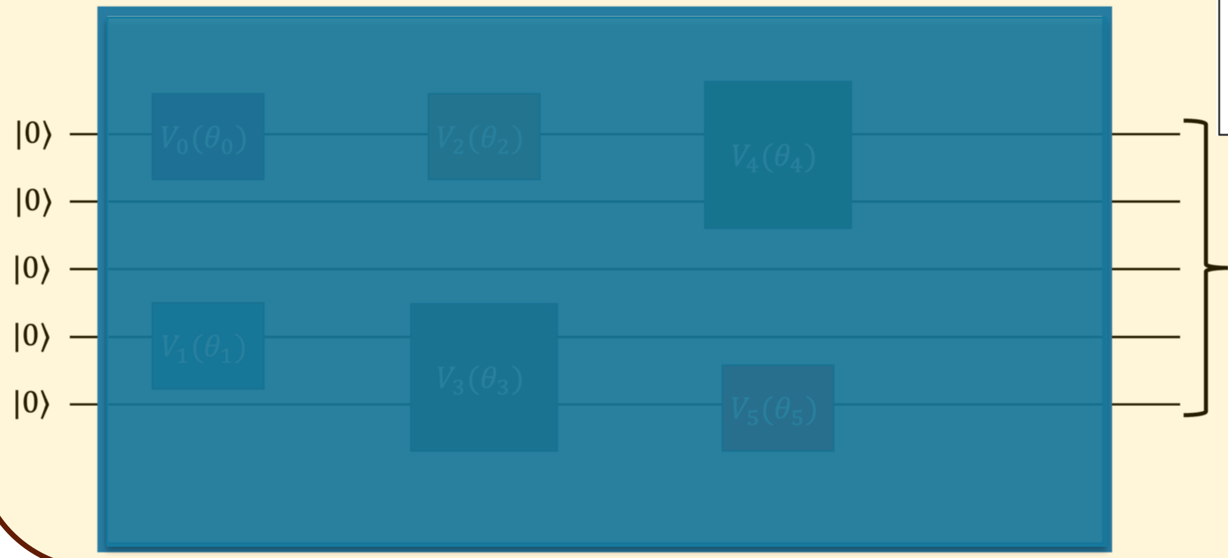
Variational Quantum Algorithms have a wide range of applications

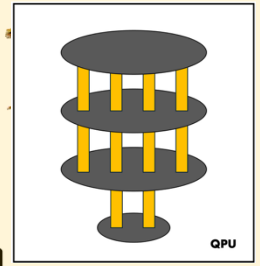


Cerezo, Marco, et al. "Variational quantum algorithms." Nature Reviews Physics 3.9 (2021): 625-644.

Variational Quantum Algorithms: a hybrid quantum-classical approach

$V(\theta)$

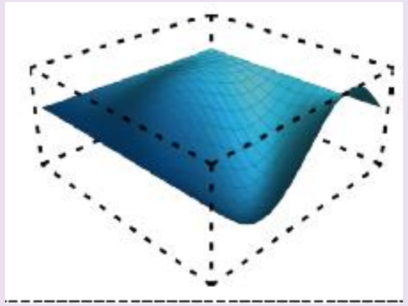




$|\psi(\theta)\rangle \rightarrow C(|\psi(\theta)\rangle)$

Classical Optimizer

$$\arg\min_{\theta} C(|\psi(\theta)\rangle)$$



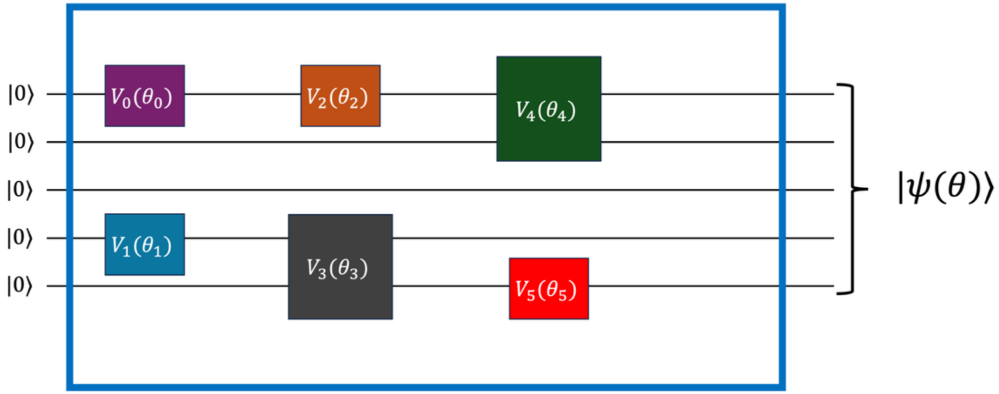
Quantum Architecture Search

Variational Quantum State: $|\psi(\theta)\rangle = V(\theta)|0\rangle$

$\theta = (\theta_0, \theta_1, \dots, \theta_l) \in \mathbb{R}^l$

Variational Ansatz: $V(\theta) = \prod_{i=1}^{l} V_i(\theta_i)$

$V(\theta)$



How do we determine the structure of the circuit to optimize?

The New York Times
https://www.nytimes.com › World › Asia Pacific

Google's Computer Program Beats Lee Se-dol in Go ...

15 Mar 2016 — **AlphaGo's 4-1 victory** was a historic stride for computer programmers and artificial intelligence researchers.

The Guardian
https://www.theguardian.com › technology › mar › goo...

Google's AlphaGo AI defeats human in first game of Go ...

9 Mar 2016 — Machine takes 1-0 lead in historic five-game matchup between computer program developed by DeepMind and world's best **Go** player Lee Sedol. Read more

Nature
https://www.nature.com › news

The Go Files: AI computer wraps up 4-1 victory ... - Nature

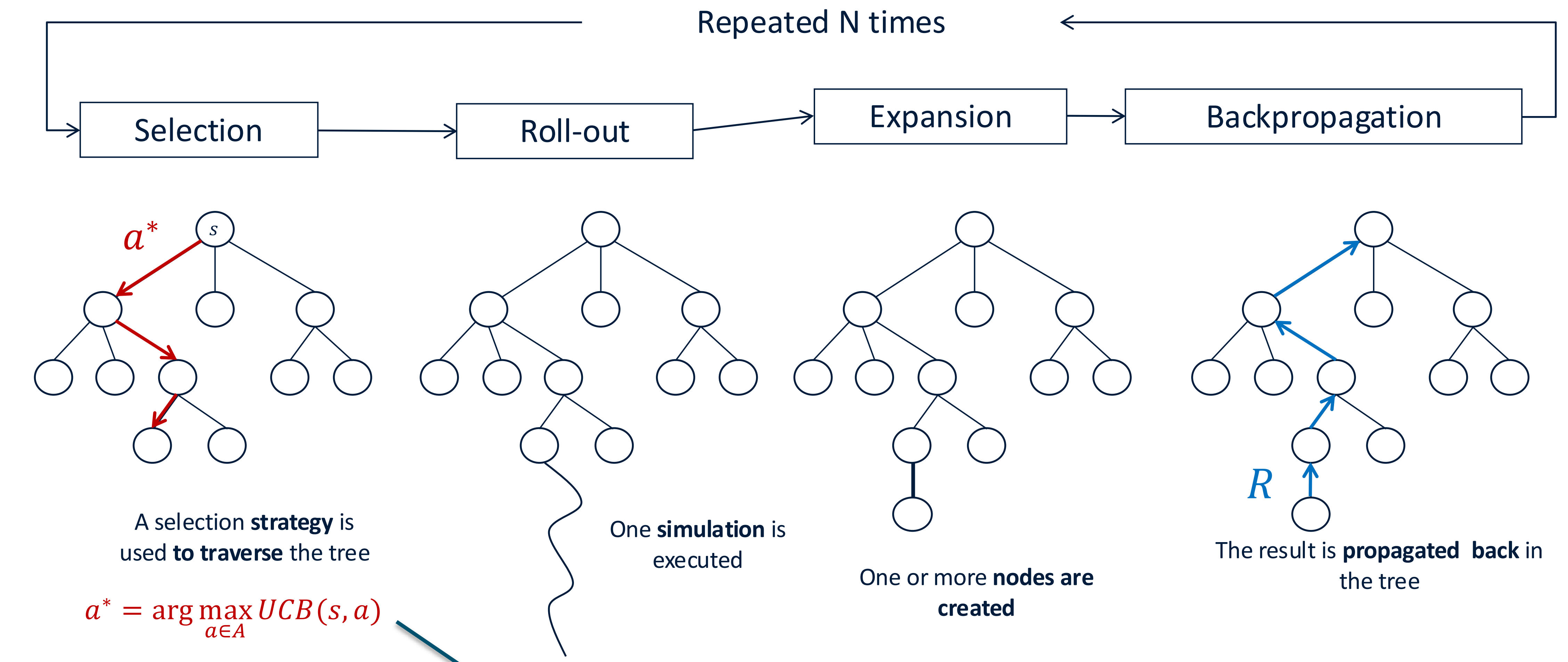
Nature reports from **AlphaGo's victory in Seoul**. ... News; Published: 15 March 2016. The Go Files: AI computer wraps up 4-1 victory against human champion. Read more

BBC
https://www.bbc.com › news › technology-35785875

Google's AlphaGo beats Go master Lee Se-dol

12 Mar 2016 — A **computer program has beaten a master Go player 3-0** in a best-of-five competition, in what is seen as a landmark moment for artificial intelligence. Read more

Monte Carlo Tree Search on Parametrized Quantum Circuits



A selection **strategy** is used **to traverse** the tree

One **simulation** is executed

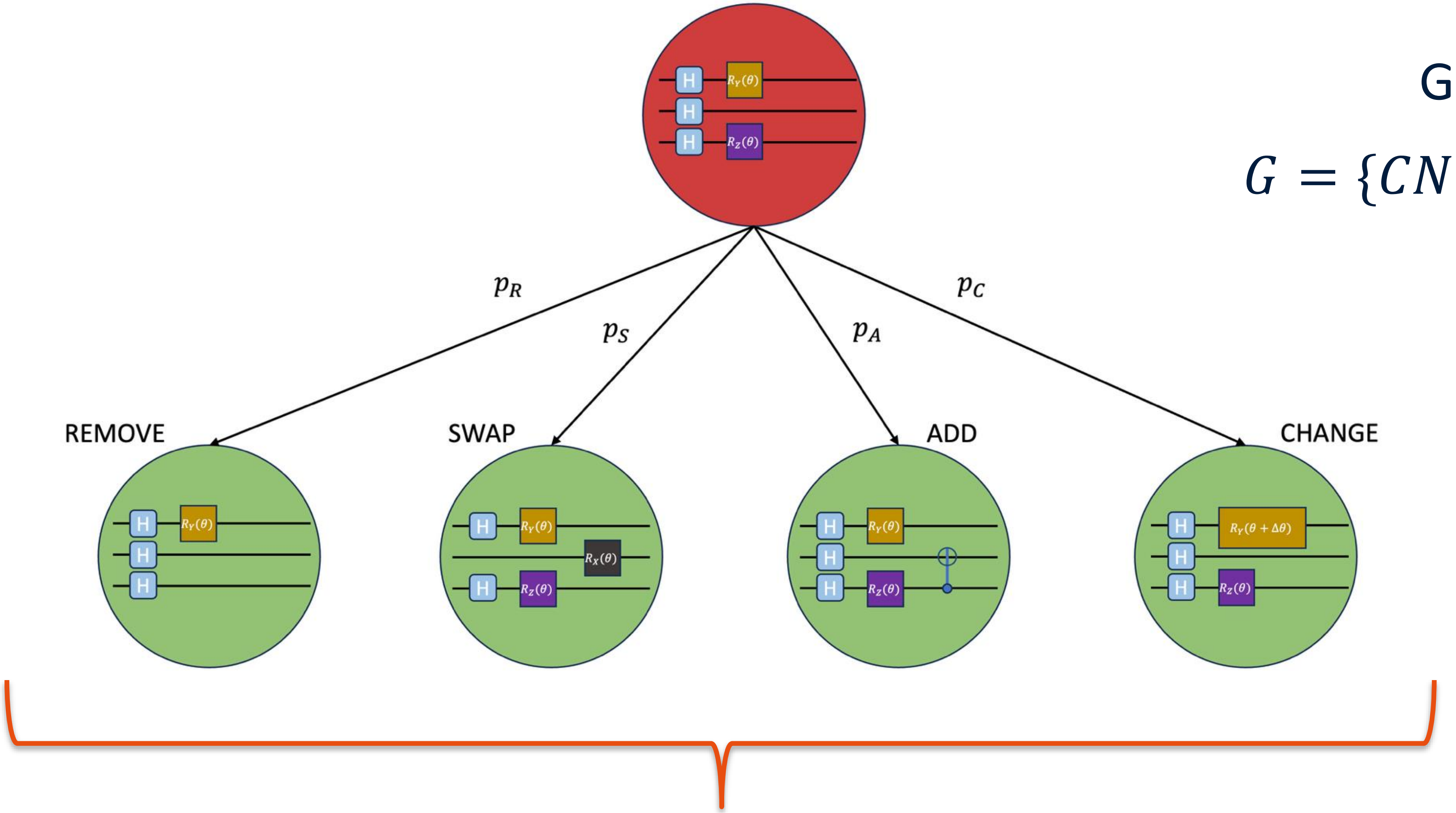
One or more **nodes are created**

The result is **propagated back** in the tree

$$a^* = \arg\max_{a \in A} UCB(s,a)$$

$$UCT(s,a) = \bar{q} + c\sqrt{\frac{\log N_s}{N_{s,a}}}$$

The action space is discrete

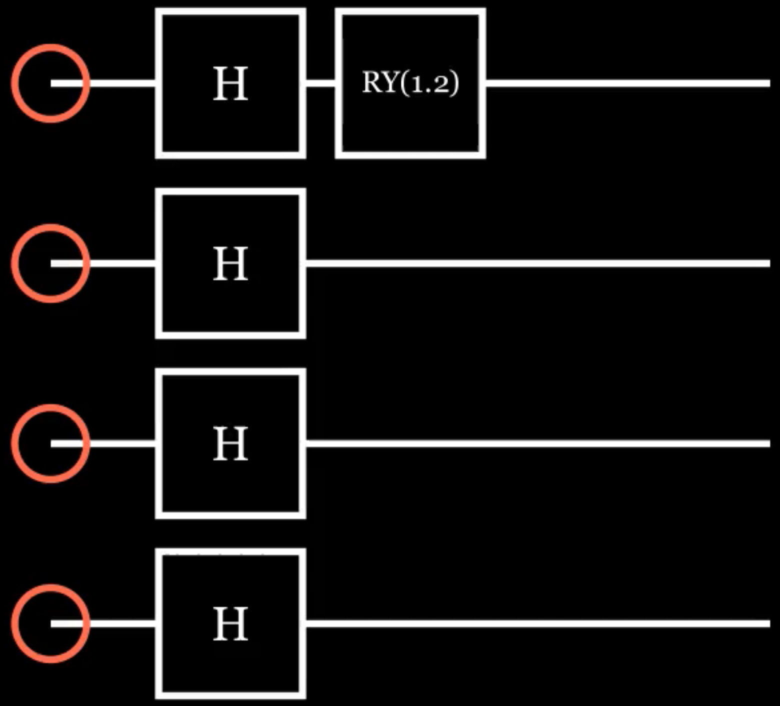


k Nodes

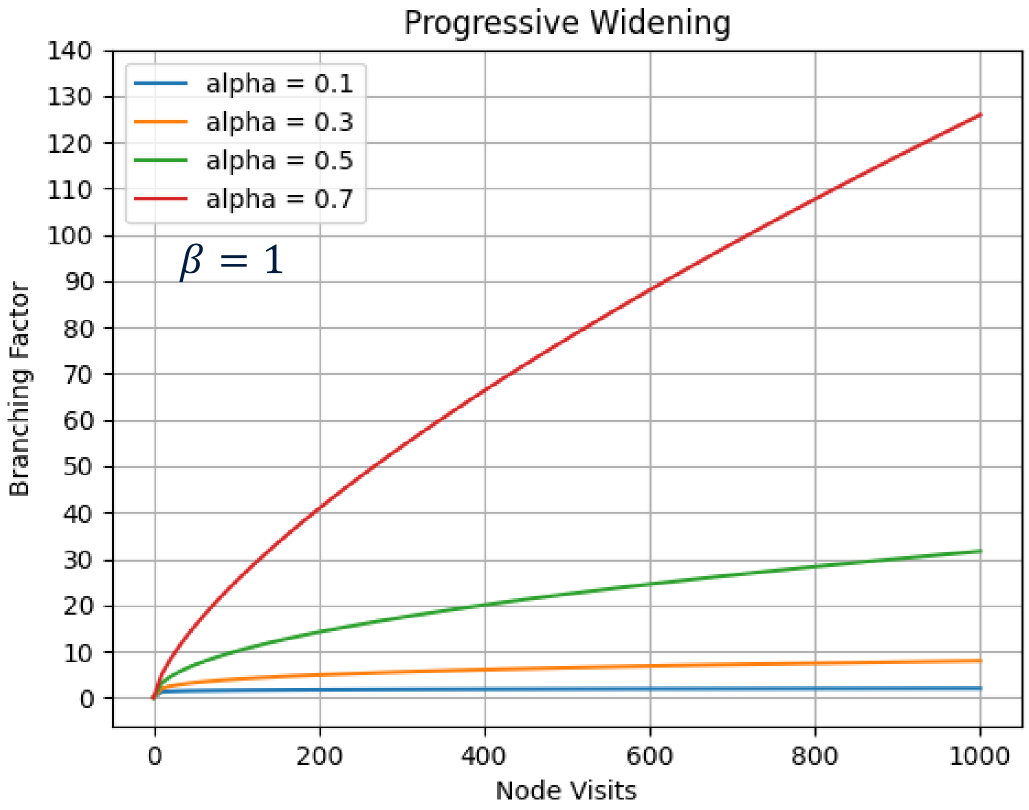
Gate set

$$G = \{CNOT, R_X, R_Y, R_Z\}$$

Franken, Lukas, et al. "Quantum circuit evolution on nisq devices." *2022 IEEE Congress on Evolutionary Computation (CEC)*. IEEE, 2022.


H
RY(1.2)
H
H
H

The action space is finite

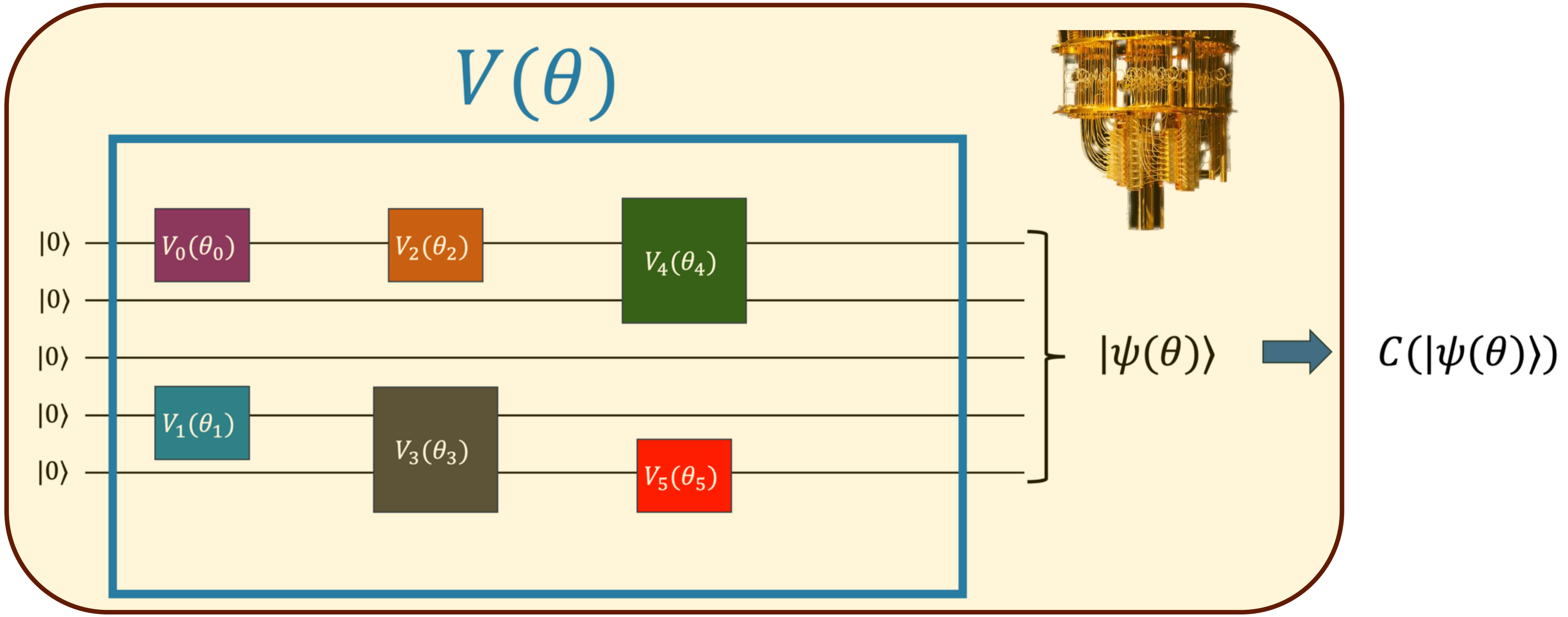


$$k_s = [\beta N_s^{\alpha}]$$

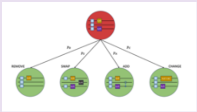
$$\alpha \in]0,1[\ , \ \beta > 0$$

$$N_s = Number\ of\ visits\ at\ node\ s$$
$$k_s = Number\ of\ children\ of\ node\ s$$

Chaslot, G.M.J.-B., Winands, M.H.M., van den Herik, H.J., Uiterwijk, J.W.H.M., Bouzy, B.: Progressive strategies for Monte-Carlo Tree Search. New Mathematics and Natural Computation 4(03), 343–357 (2008)



Monte Carlo Tree Search

- Selection strategy: **Upper Confidence Bound**
- Action space is discretized by 
- **Progressive widening** to deal with an infinite number of actions

Domains of Application

Ground State Energy Estimation

1. Hydrogen: H_2
2. Lithium Hydride: LiH
3. Water: H_2O

Quantum Random Circuits

Different sizes:

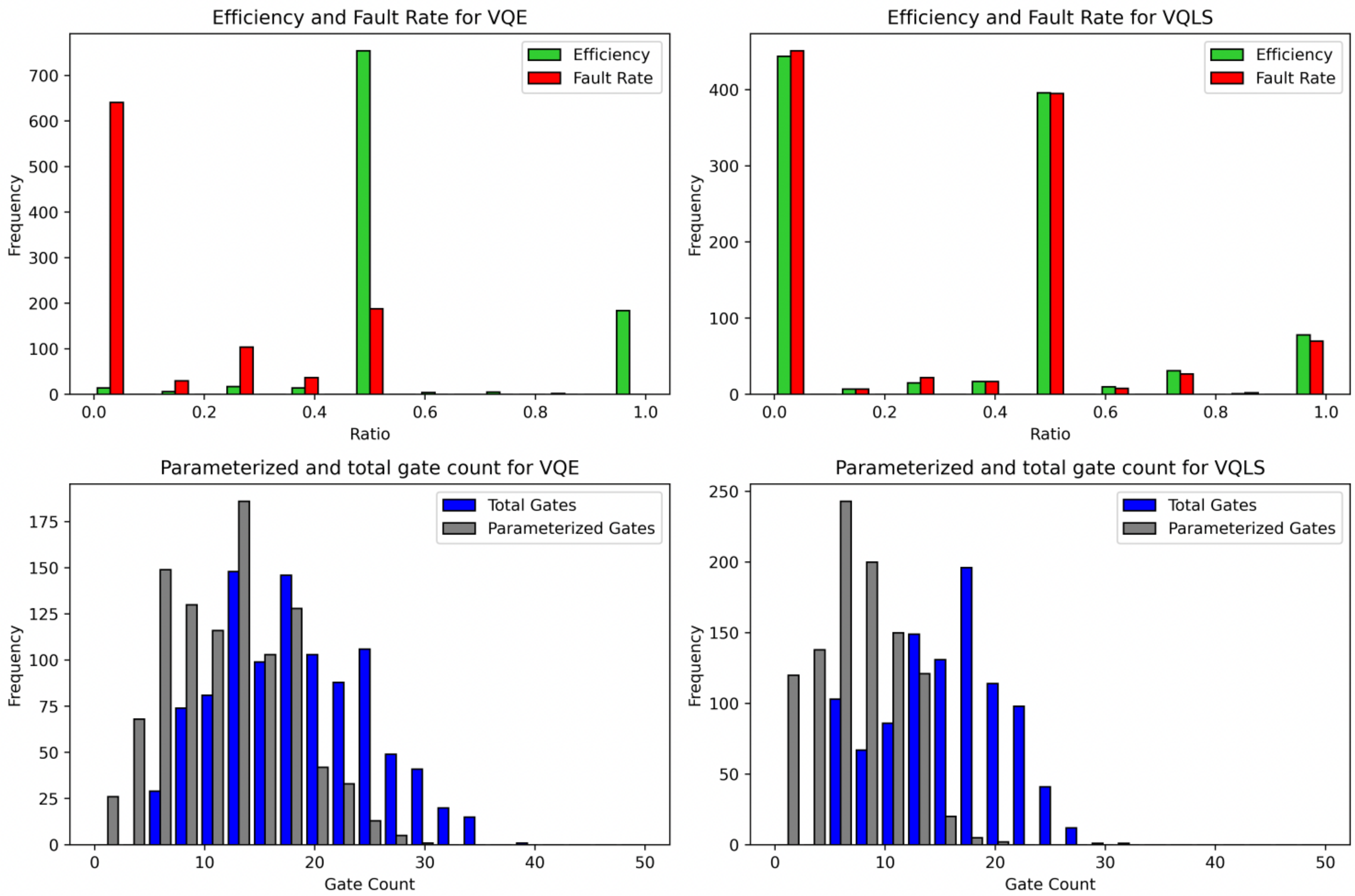
- Number of qubits
- Number of gates

Systems of Linear Equations

Particle Track Reconstruction

Max Cut

Machine Learning


Efficiency and Fault Rate for VQE
Efficiency
Fault Rate
Frequency
Ratio
Efficiency and Fault Rate for VQLS
Efficiency
Fault Rate
Frequency
Ratio
Parameterized and total gate count for VQE
Total Gates
Parameterized Gates
Frequency
Gate Count
Parameterized and total gate count for VQLS
Total Gates
Parameterized Gates
Frequency
Gate Count

ADVANCED QUANTUM TECHNOLOGIES

Research Article | Open Access

Quantum Circuit Design using a Progressive Widening Enhanced Monte Carlo Tree Search

Vincenzo Lipardi, Domenica Dibenedetto, Georgios Stamoulis, Mark H.M. Winands

First published: 11 June 2025 | https://doi.org/10.1002/qute.202500093

Variational Quantum Algorithms for Particle Track Reconstruction

Vincenzo Lipardi, Xenofon Chiotopoulos, Jacco A. de Vries, Domenica Dibenedetto, Kurt Driessens, Marcel Merk, Mark H.M. Winands

Quantum Computing is a rapidly developing field with the potential to tackle the increasing computational challenges faced in high-energy physics. In this work, we explore the potential and limitations of variational quantum algorithms in solving the particle track reconstruction problem. We present an analysis of two distinct formulations for identifying straight-line tracks in a multilayer detection system, inspired by the LHCb vertex detector. The first approach is formulated as a ground-state energy problem, while the second

Is it better than classical ?

Nonstabilizerness Estimation
using
Graph Neural Networks

What is nonstabilizerness?

Why nonstabilizerness?

Gottesman-Knill Theorem

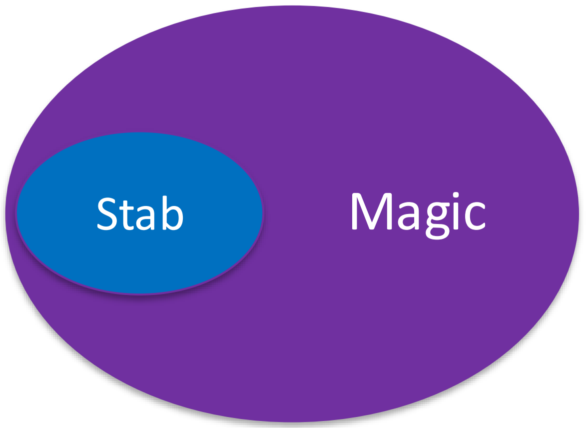
Any quantum computer performing only Clifford operations can be **perfectly simulated in polynomial time** on a classical computer.

[Gottesman, D. (1998). The Heisenberg representation of quantum computers. *arXiv preprint quant-ph/9807006*]

What are Clifford operations?

What are Clifford operations?

Clifford gates	Non-Clifford gates
$CNOT, H, S$	T
$CNOT$ and $R_X(\theta), R_Y(\theta), R_Z(\theta)$ for specific θ	$R_X(\theta), R_Y(\theta), R_Z(\theta)$ For all the remaining θ
Stabilizer states	**Nonstabilizer states (or Magic states)**



Gottesman-Knill Theorem

"Any quantum computer performing only Clifford operations can be **perfectly simulated in polynomial time** on a classical computer."

[Gottesman, D. (1998). The Heisenberg representation of quantum computers. *arXiv preprint quant-ph/9807006*]

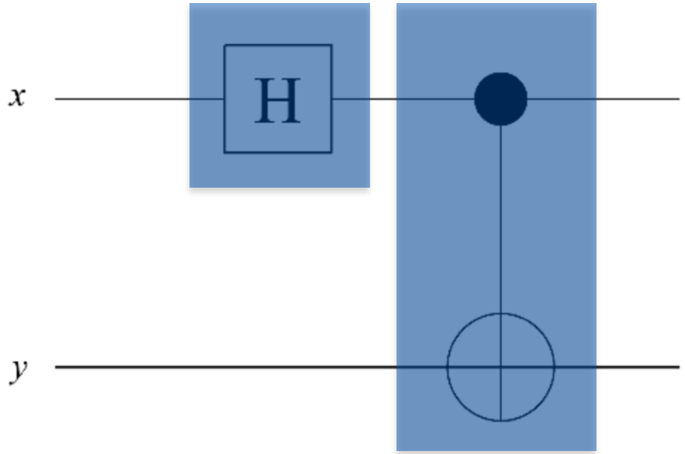
Can we create a universal gate set using exclusively Clifford gates?

No!

$$G = \{CNOT, H, S, T\}$$

The amount of non–Clifford resources necessary to create a quantum state is called nonstabilizerness (or magic)!

The Quest for Quantum Advantage

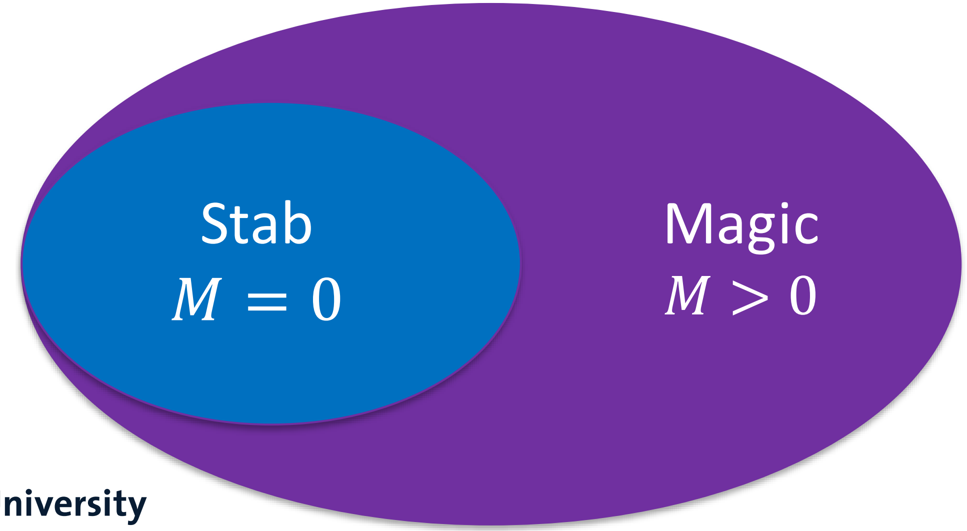


H and CNOT are Clifford gates

Entanglement is not the only resource for quantum advantage

The **nonstabilizerness**, or “magic”, is a fundamental resource for **quantum advantage**

How do we **measure** the nonstabilizerness of quantum states?



M is a
stabilizer monotone

Stabilizer Rényi Entropy (SRE)

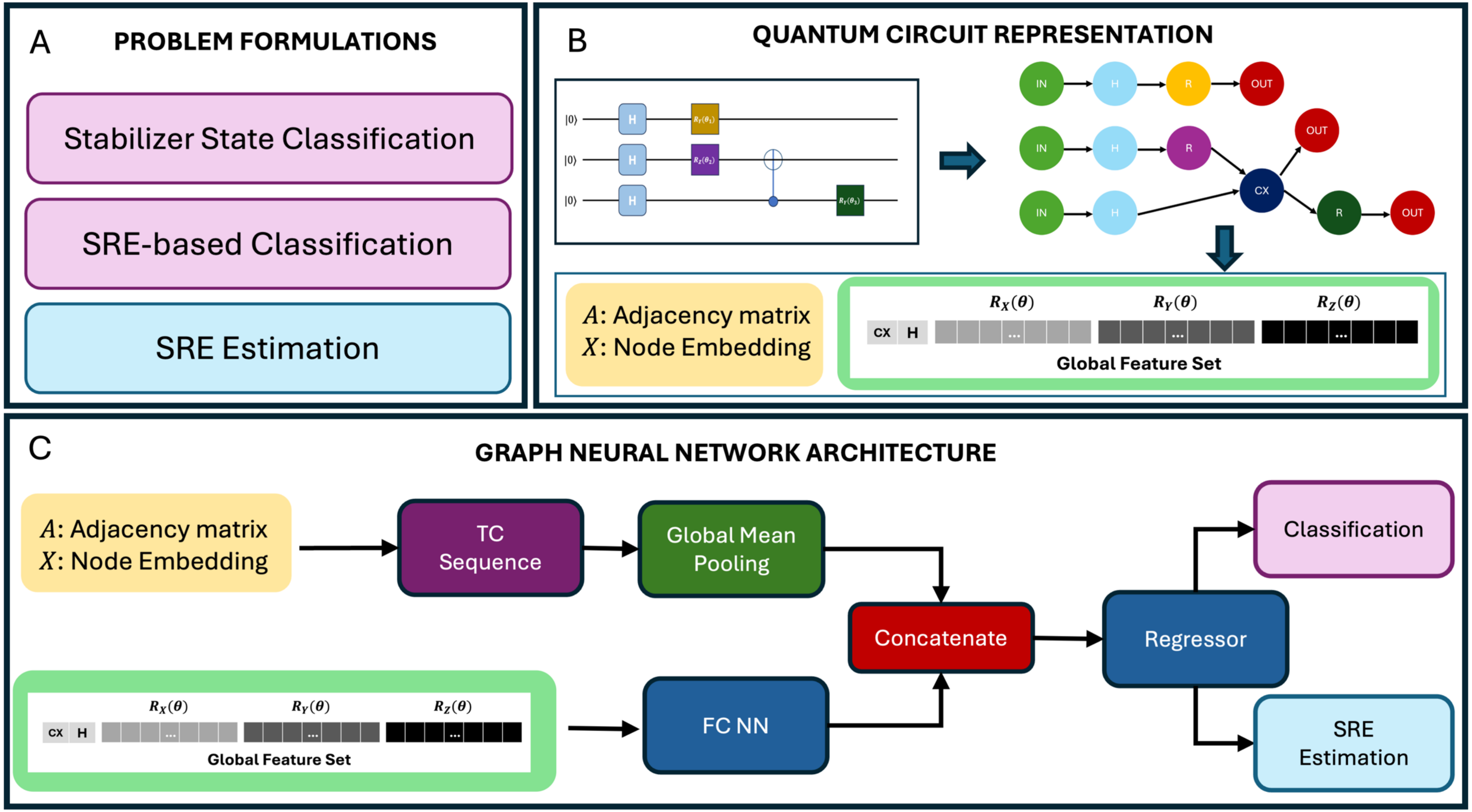
Favourable computational properties	Suitable for experiments on real quantum hardware

$$M_2(\rho) = -\ln \sum_{P \in \mathcal{P}_n} \Xi_P^2(\rho) - \ln(2^n)$$

Where $\Xi_P(\rho) = \frac{1}{2^n} Tr(\rho P)^2$ and $\mathcal{P}_n$ is the set of **4^n Pauli strings**

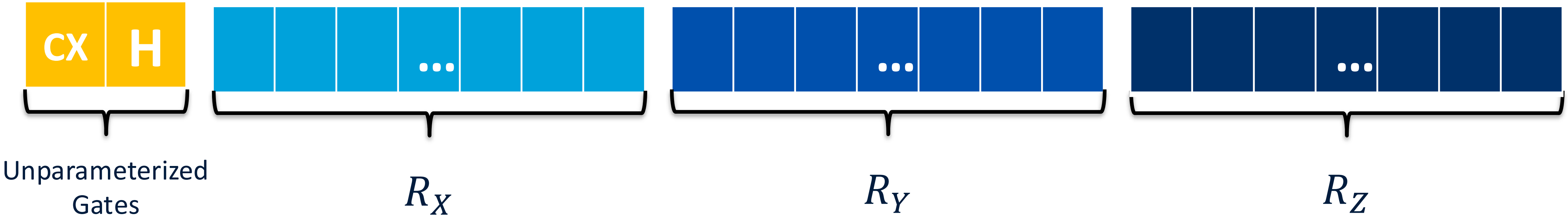
[Leone, L., Oliviero, S. F., & Hamma, A. (2022). Stabilizer rényi entropy. *Physical Review Letters*, *128*(5), 050402]
[Oliviero, S. F., Leone, L., Hamma, A., & Lloyd, S. (2022). Measuring magic on a quantum processor. *npj Quantum Information*, *8*(1), 148]

A Graph Neural Network Approach to Nonstabilizerness Estimation



Quantum Circuit Representation on Classical Computers

TABULAR REPRESENTATION BASED ON GATE COUNT

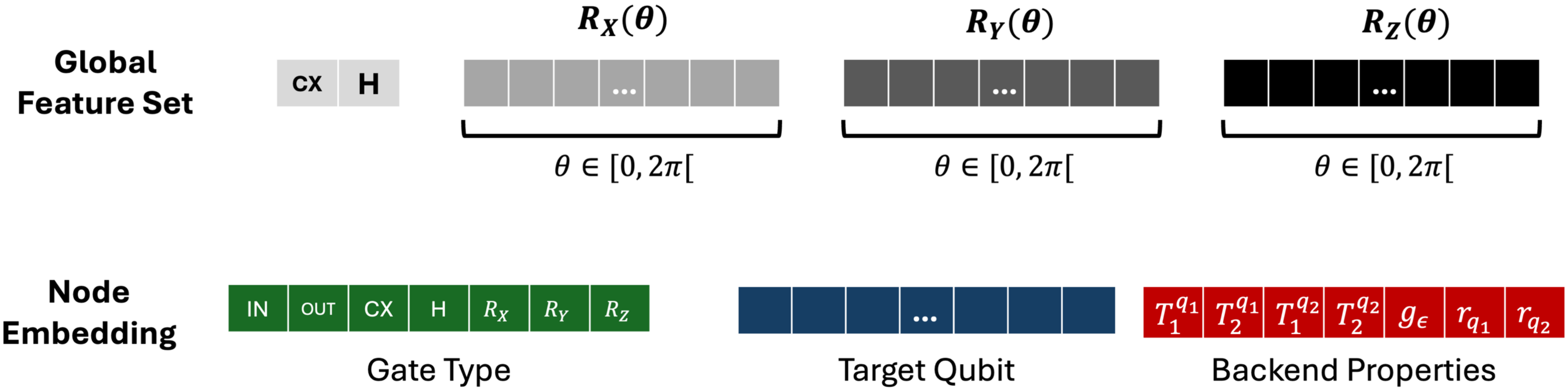


2 + 50 + 50 + 50 = 152 Features

[Liao, H., Wang, D. S., Sitdikov, I., Salcedo, C., Seif, A., & Minev, Z. K. (2024). Machine learning for practical quantum error mitigation. Nature Machine Intelligence, 6(12)]

Quantum Circuit Representation on Classical Computers

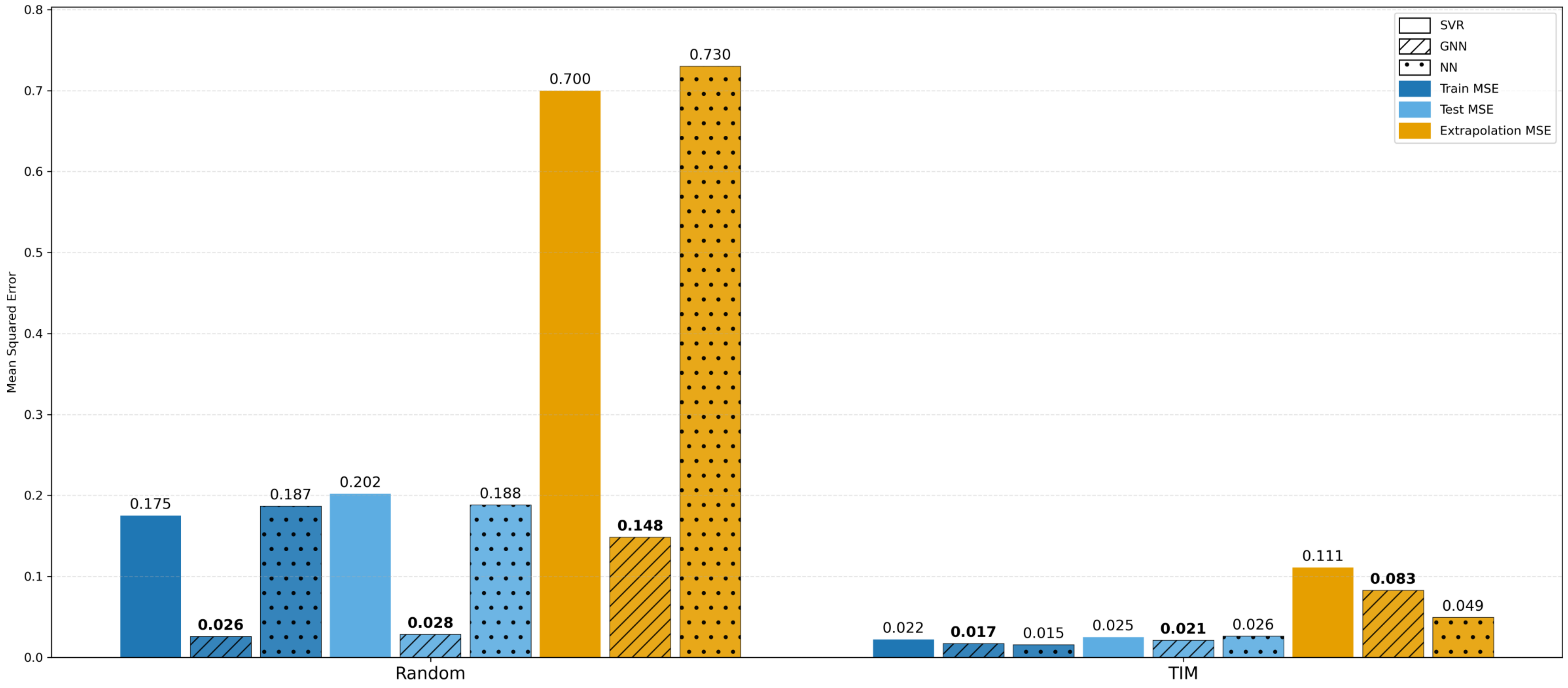
GRAPH-BASED REPRESENTATION



Extrapolation Capabilities in SRE Estimation

Testing GNN on circuits with **a higher number of qubits**

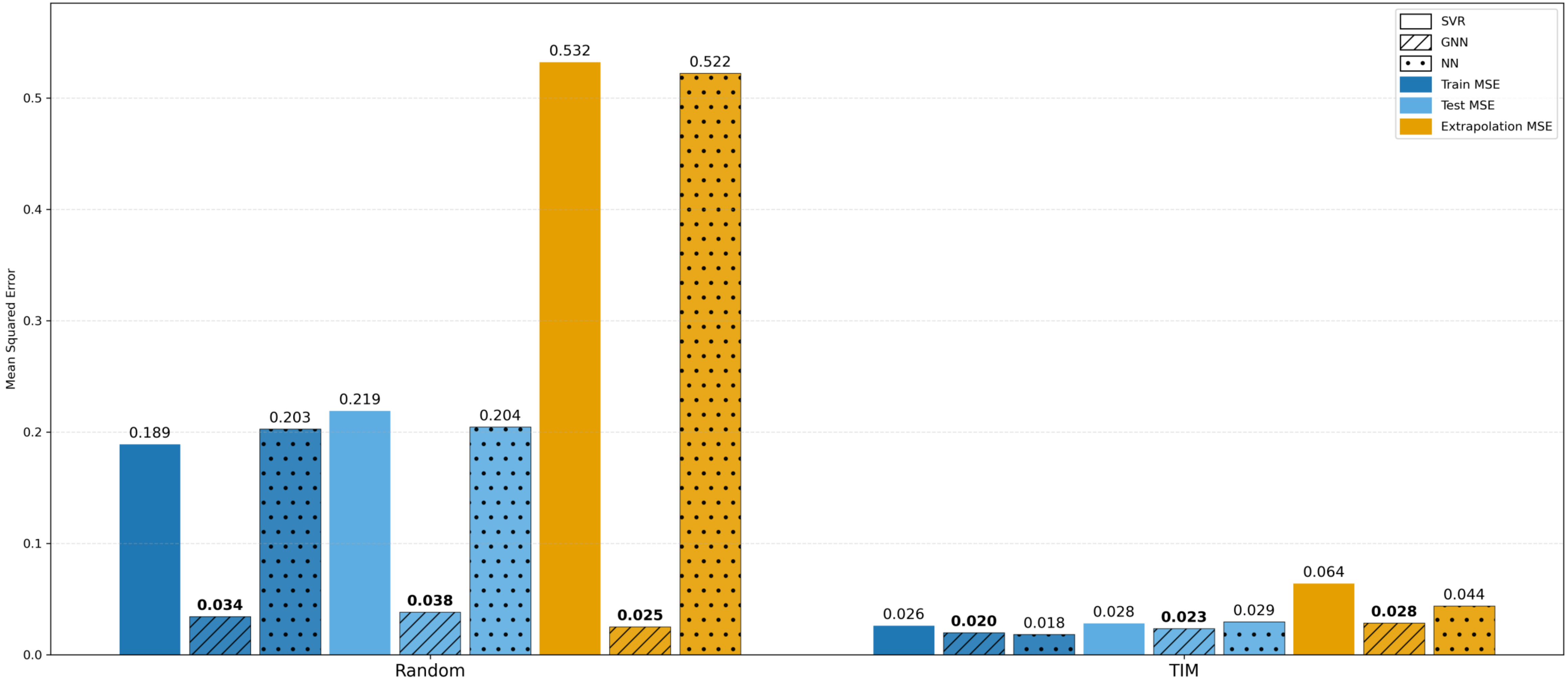
Extrapolation on number of qubits



Extrapolation Capabilities in SRE Estimation

Testing GNN on circuits with **a higher gate count**

Extrapolation on gate count



A Study on Stabilizer Rényi Entropy Estimation Using Machine Learning

Publisher: IEEE Cite This PDF

Vincenzo Lipardi ; Domenica Dibenedetto ; Georgios Stamoulis ; Mark H.M. Winands All Authors

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Nonstabilizerness estimation using graph neural networks

Vincenzo Lipardi*, Domenica Dibenedetto, Georgios Stamoulis, Evert van Nieuwenburg and Mark H M Winands

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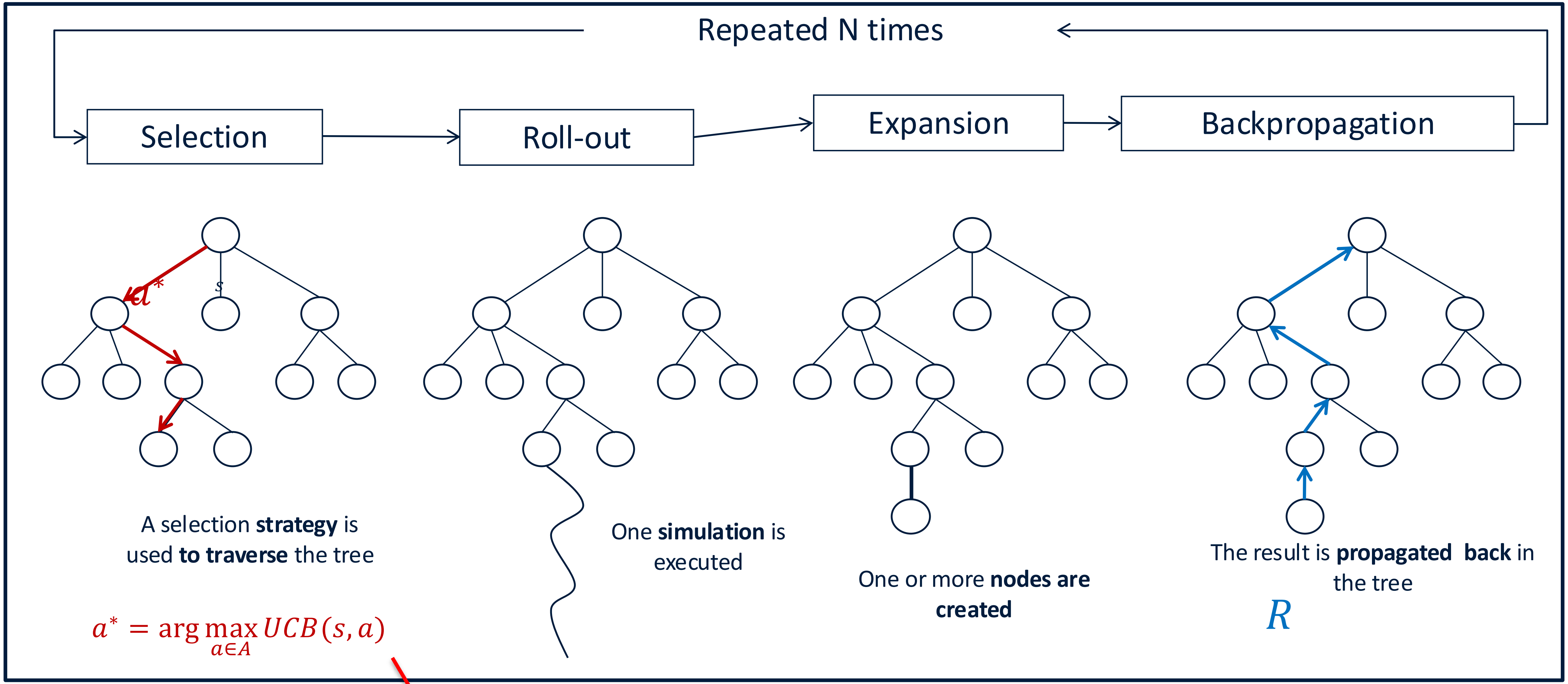
Machine Learning: Science and Technology, Volume 7, Number 2

Citation Vincenzo Lipardi *et al* 2026 *Mach. Learn.: Sci. Technol.* **7** 025027

DOI 10.1088/2632-2153/ae4b08

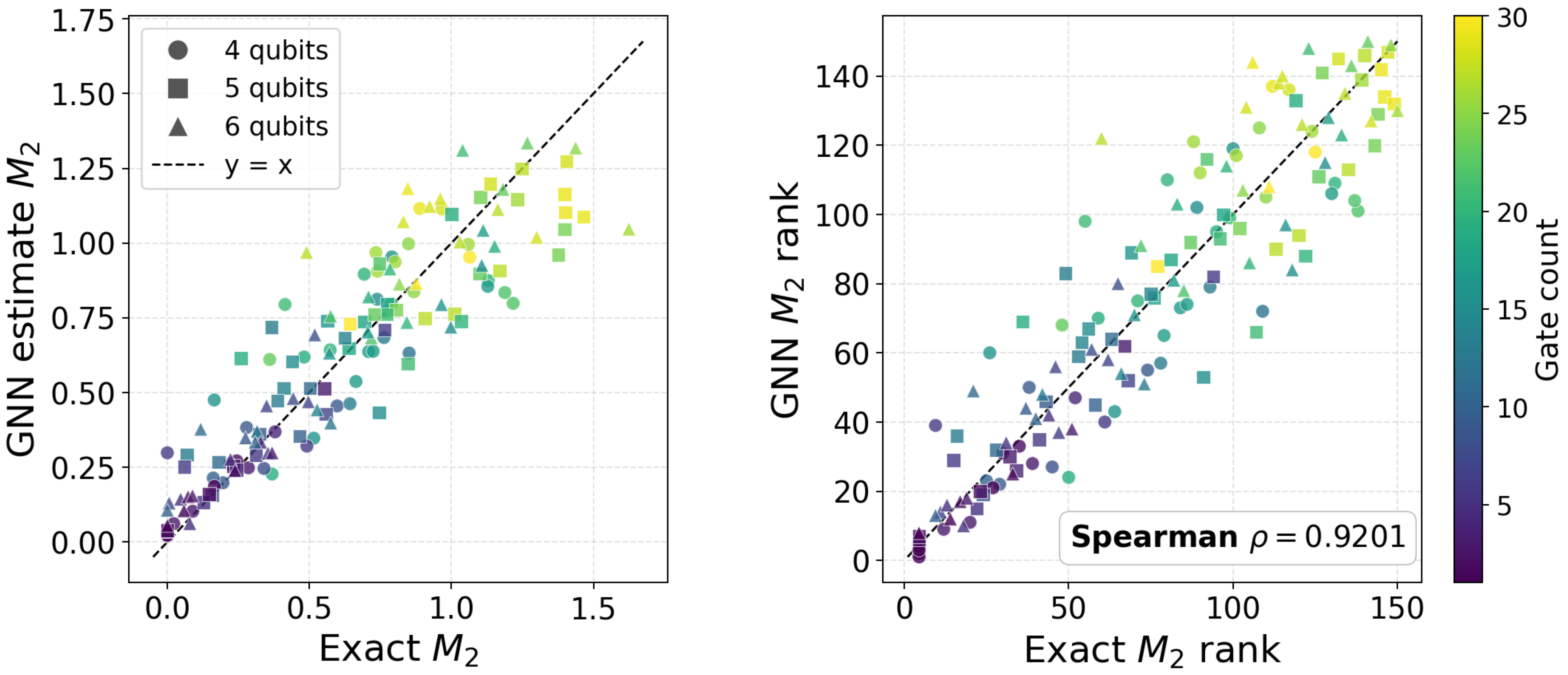
Magic-Informed Quantum Architecture Search

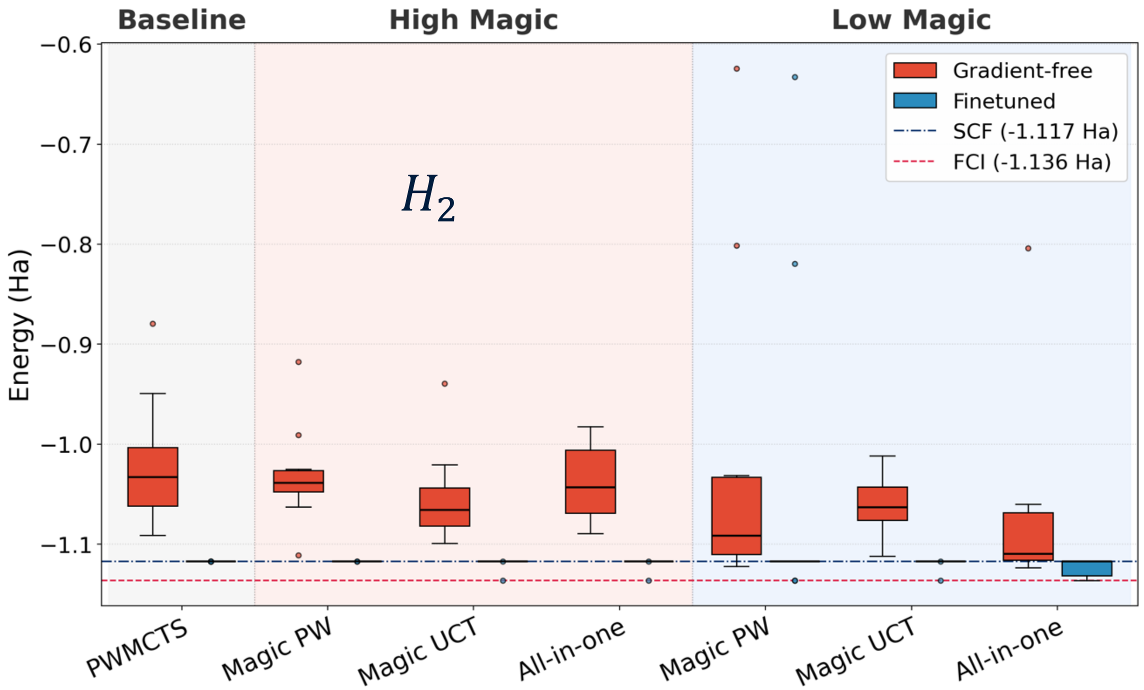
Magic-based bias in the Selection Strategy

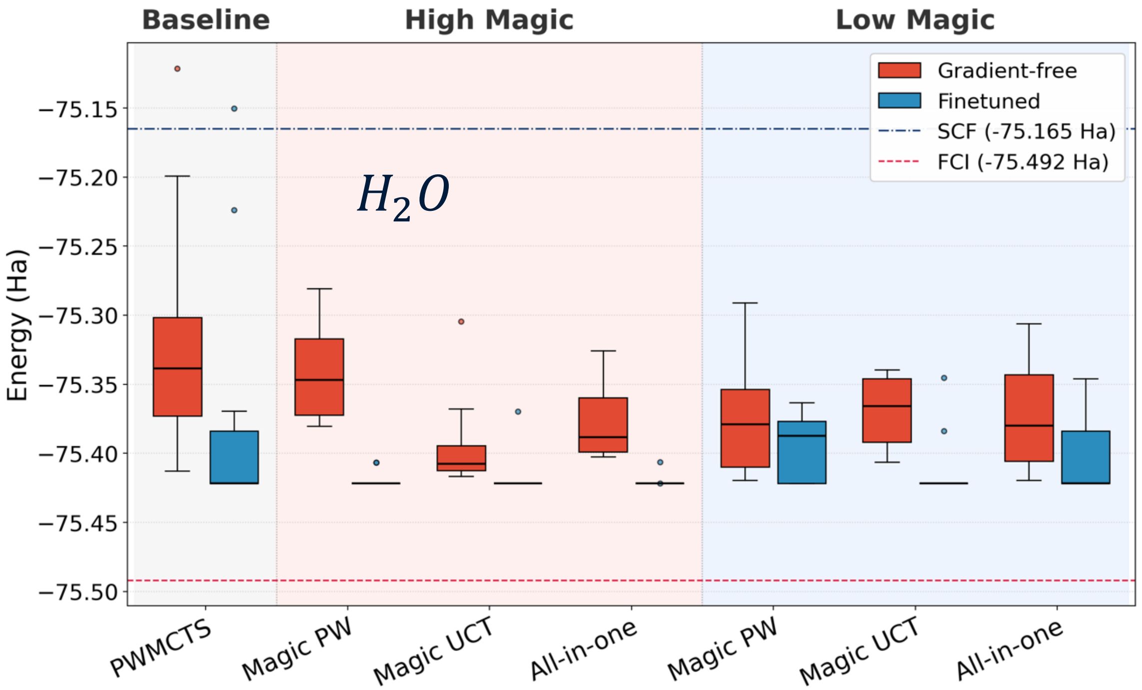


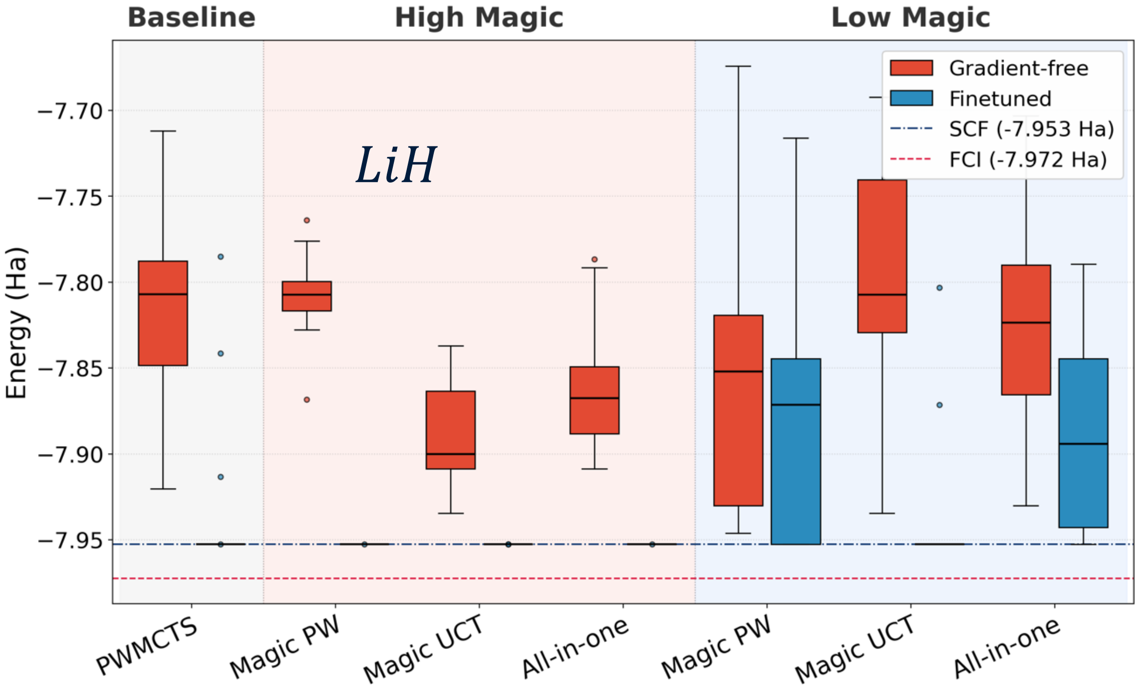
$$UCT(s,a) = \bar{q} + c\sqrt{\frac{\log N_s}{N_{s,a}}} \quad \Rightarrow \quad PUCT(s,a) = \bar{q} + p_{MAGIC} \cdot c\sqrt{\frac{\log N_s}{N_{s,a}}}$$

GNN performance for PWMCTS



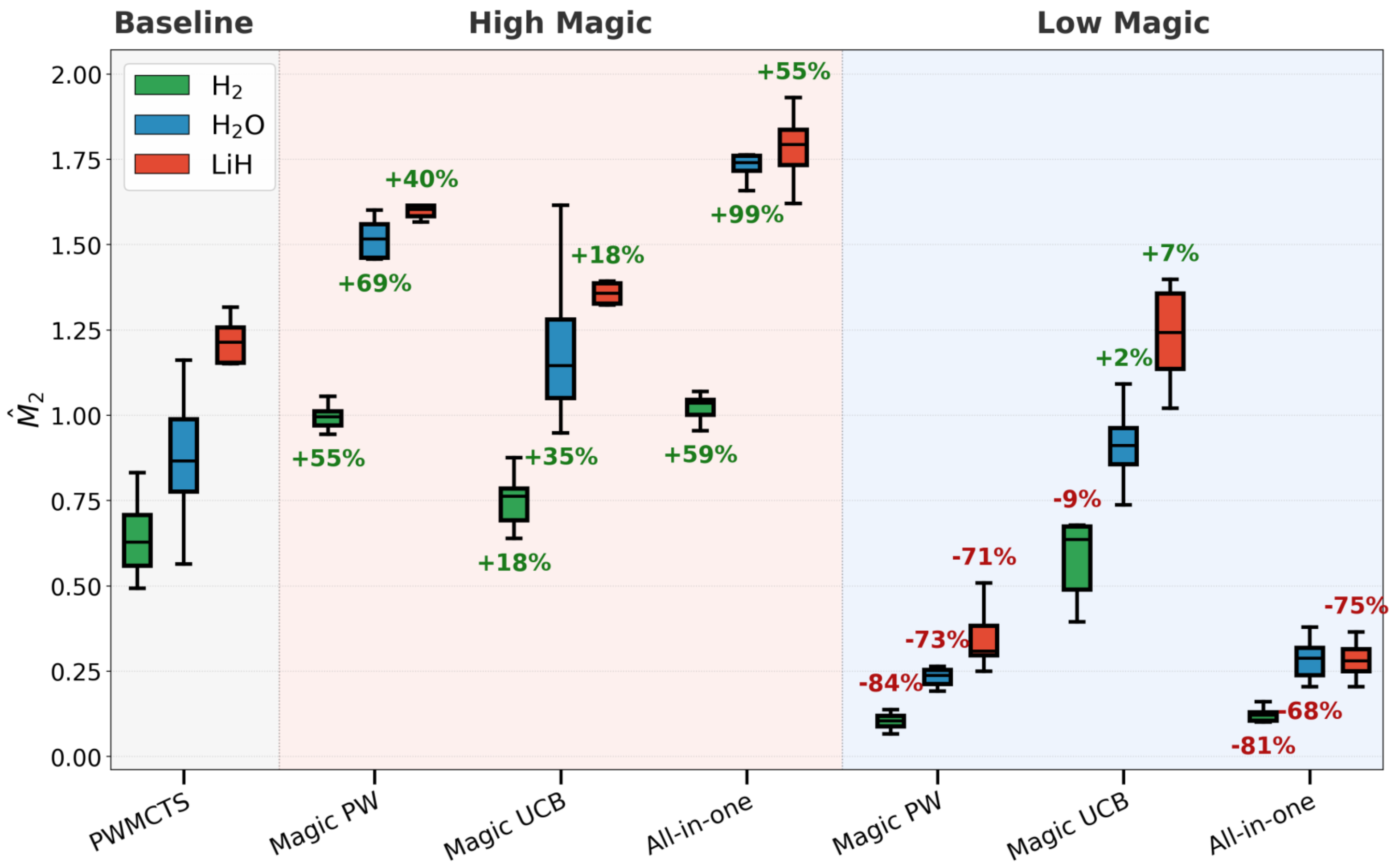




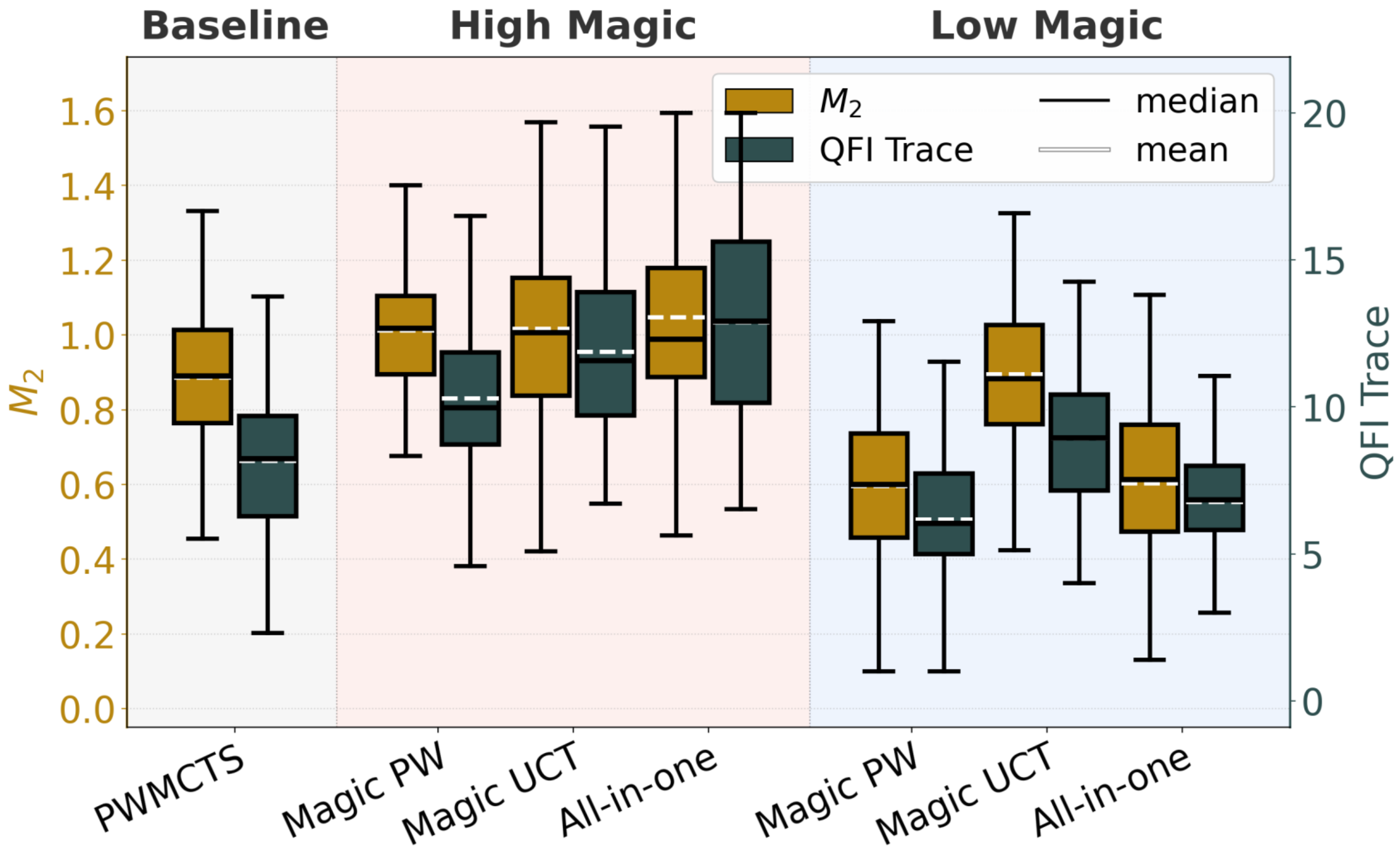


Maastricht University

Average magic in the tree



Average magic on the final circuits



Magic-Informed Quantum Architecture Search

Vincenzo Lipardi, Domenica Dibenedetto, Georgios Stamoulis, Mark H.M. Winands

Nonstabilizerness, commonly referred to as magic, is a fundamental resource underpinning quantum advantage. In this paper, we propose a magic-informed quantum architecture search (QAS) technique that enables control over a quantum resource within the general framework of circuit design. Inspired by the AlphaGo approach, we tackle the problem with a Monte Carlo Tree Search technique equipped with a Graph Neural Network (GNN) that estimates the magic of candidate quantum circuits. The GNN model induces a magic-based bias that steers the search toward either high- or low-magic regimes, depending on the target objective. We benchmark the proposed magic-informed QAS technique on both the