Quantum Computation for Nuclear Physics

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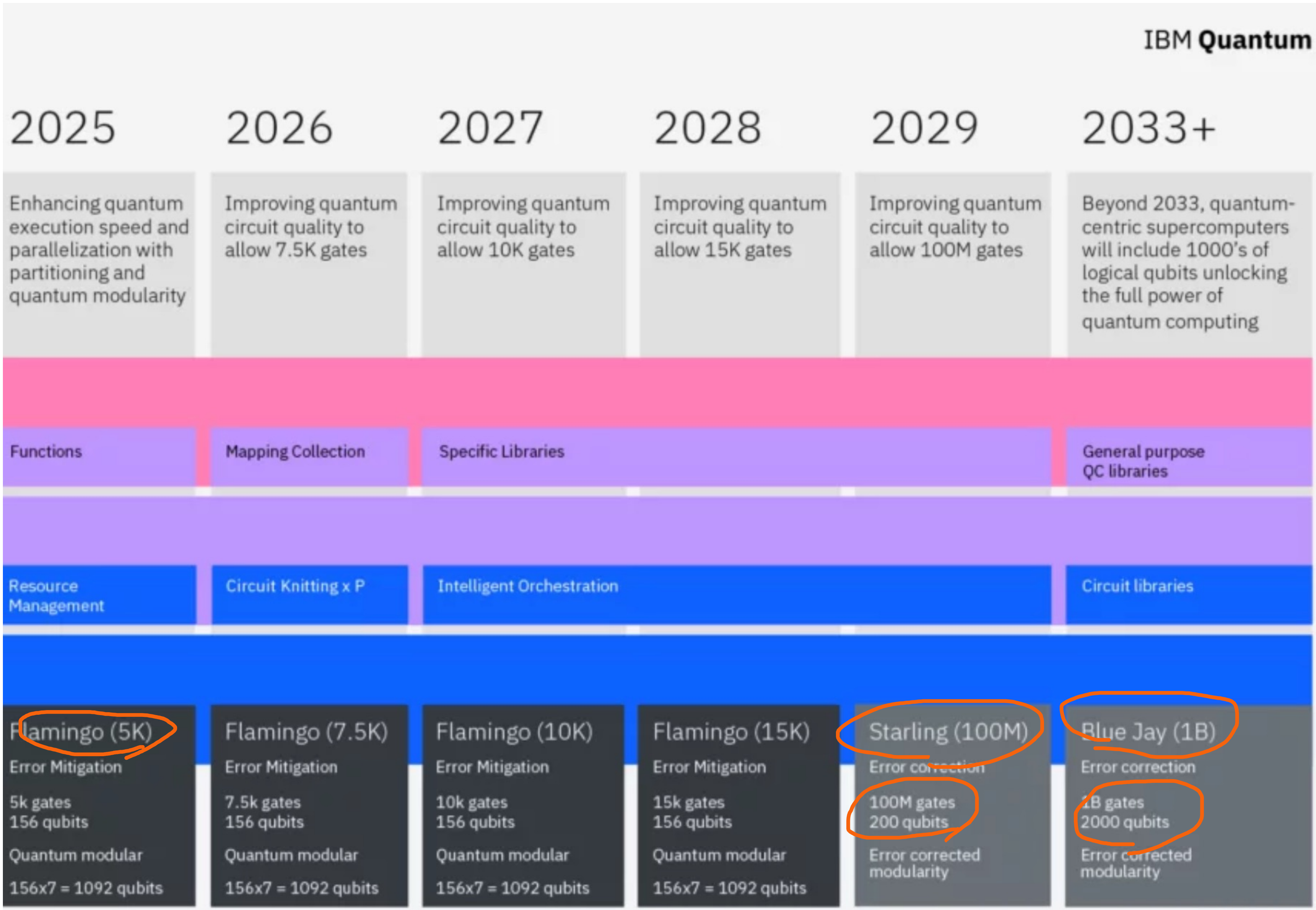
IBM Quantum Roadmap



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Showing quantum advantage on important problems. (See Yu-Ting Chen's talk)

What QIS can contribute to NP and vise versa.

Quantum or Classical

- Seeing quantum effects in macroscopic objects

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NOBELPRISET I FYSIK 2025
THE NOBEL PRIZE IN PHYSICS 2025
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John M. Martinis
University of California, USA
”för upptäckten av makroskopisk kvantmekanisk tunnling och energikvantisering i en elektrisk krets”
“for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit”
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Quantum vs Classical

- Seeing quantum effects in macroscopic objects such as Schrodinger's cat (2012 Nobel), BEC (2001 Nobel), Superconducting qubit (2025 Nobel)
- Quantum effects tend to disappear due to phase decoherence by interacting with the environment (see Meher's talk)

Computation

- Classical: Performing any mapping between any two binary strings

  Universal gate sets: {AND, OR, NOT}; {NAND};…

- Quantum: Performing any unitary evolution (SU(2N)) to any two quantum states described by N qubits

  Universal gate sets: {H,T,CNOT}

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix} \quad \mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Quantum vs Classical Computations

- Memory:

  Classical: n bits can store an integer from 0 to $2^n - 1$. Quantum: n-qubits can store $2^n - 1$ complex numbers.
- However, if entanglement is lost (due to decoherence) such that the n-qubit state becomes a cross product state, then only n-1 complex numbers can be stored.
- Superposition allows the 2^n states to be studied at the same time.

HEP QFT

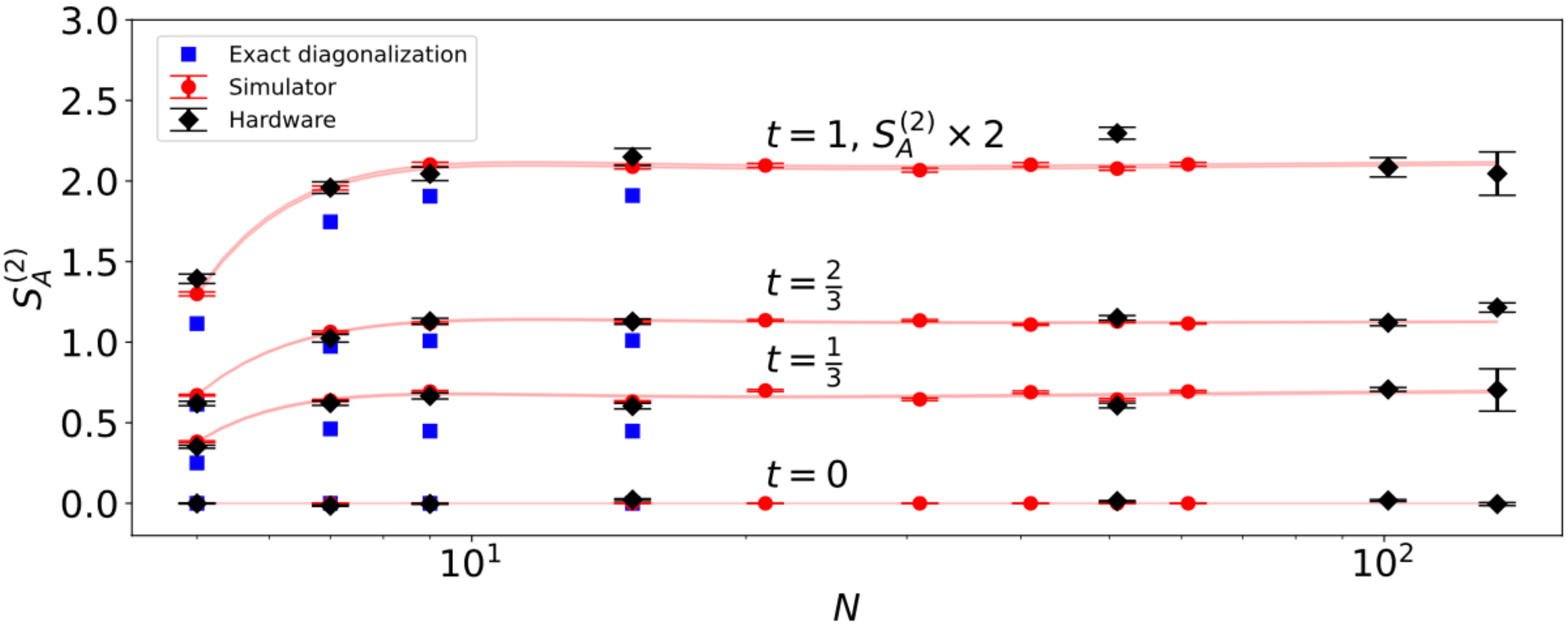
- QFT = QM + SR
- QM: canonical quantization or path integral (SR manifest)
- Path integral convenient when some paths are more important than the others (e.g. perturbative: analytical results, non-perturbative: important sampling)
- Non-perturbative case: lattice QCD as a primary example. Discretization, Monte Carlo, going to Euclidean space to avoid a sign problem and real time dependence challenging

Can Canonical Quantization Cure These Problems?

- In principle, yes. (This is what drives quantum computing.) But lots of challenges in building quantum computers. (The environment is asking our quantum state to do something we don't want all the time.)
- Time evolution easy, state preparation hard.

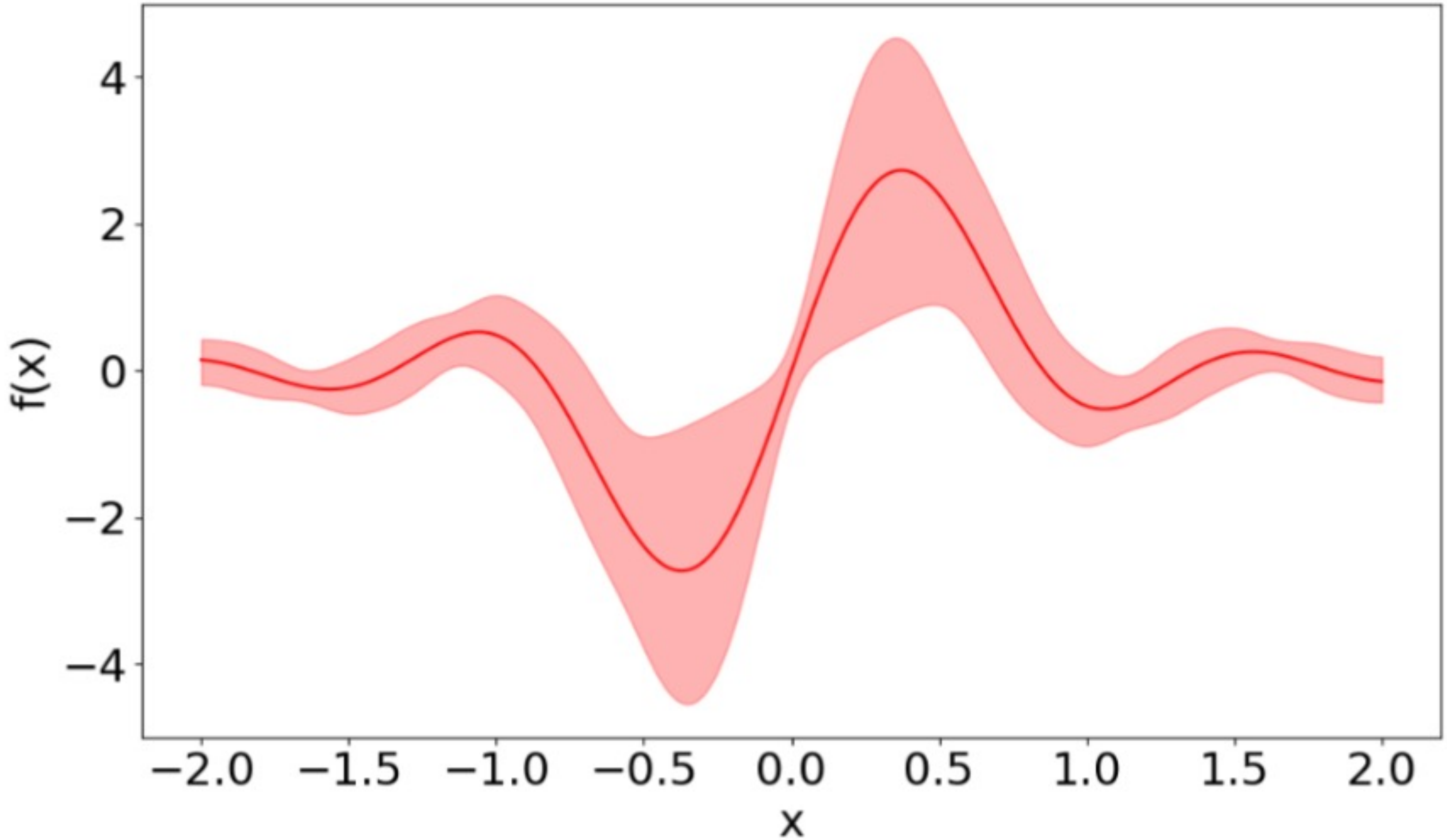
Thermalization of a Quantum System

JWC, Y.T. Chen, G. Meher, B. Müller, A. Schäfer, X. Yao,
2603.23948



(b) $N_A = 2$.

First PDF Result with a Quantum Computer

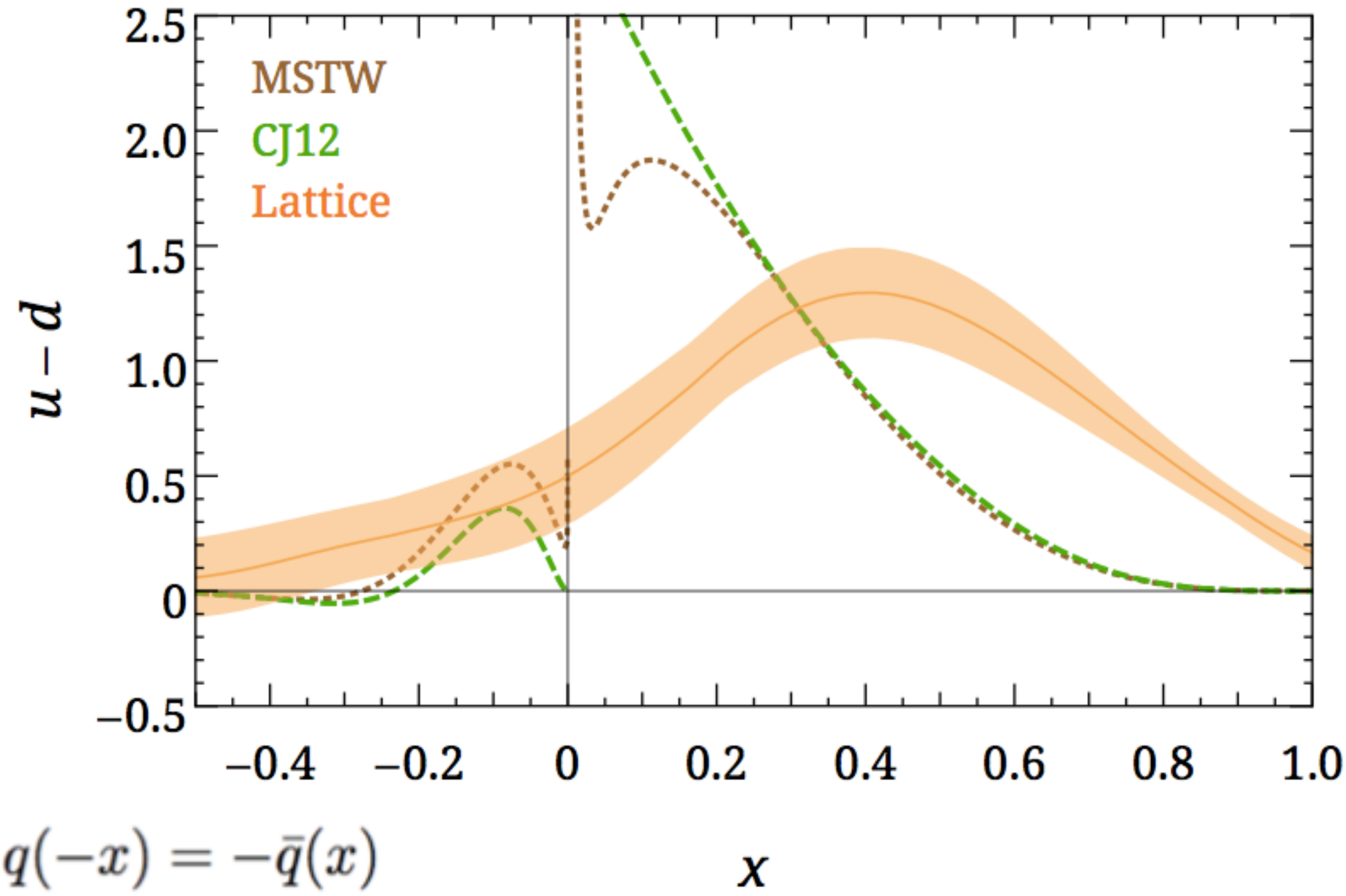


$$\int_{-1}^{1} dx\, x f(x) = 1.04^{+0.66}_{-0.76}, \qquad \int_{0}^{1} dx\, f(x) = 1.37^{+0.89}_{-1.02}$$

arXiv: 2506.16829

1^{st} LaMET Calculation

Lin, JWC, Cohen, Ji (1402.1462)



$q(-x) = -\bar{q}(x)$

Welcome to Join Us and Enjoy the Ride!