Bridging the Gap between NISQ and FTQC

K. Gratsea, P. Johnson, C. Ryan-Anderson, A. Baczewski

17-20 Feb 2026 at IPAM in Los Angeles

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Discussion Questions:

1. What were the expectations for quantum computing in 2016 when the term NISQ was introduced, how far have we come and what are the expectations now?

2. Different researchers have different definitions of quantum advantage. Which definition are you mostly in favor of and why? Should these definitions be unified?

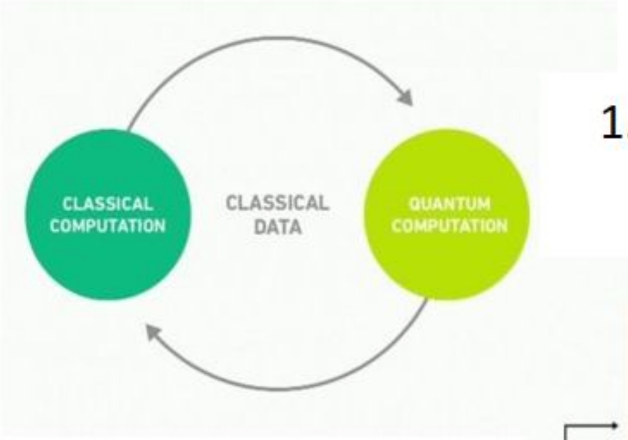
3. How can researchers bridge the gap between NISQ and FTQC?

4. Transitioning to FTQC will require multidisciplinary expertise - what do researchers from your discipline need from other disciplines? E.g., what do quantum algorithm developers need from quantum computer architects, etc.?

5. What is the most important open problem in your corner of quantum computing?

Quantum Computing regimes

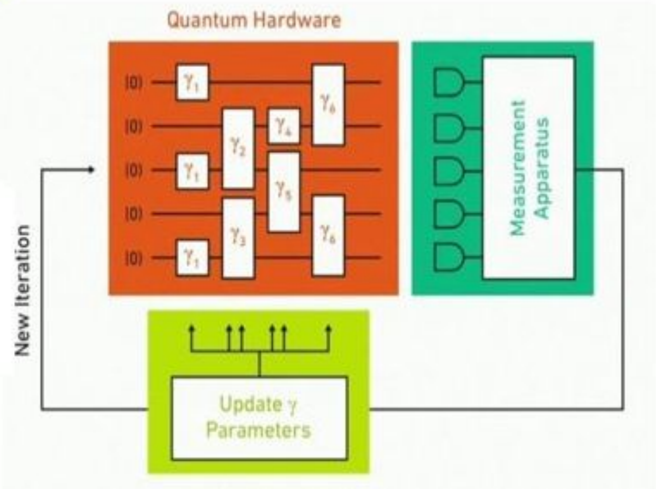
NISQ



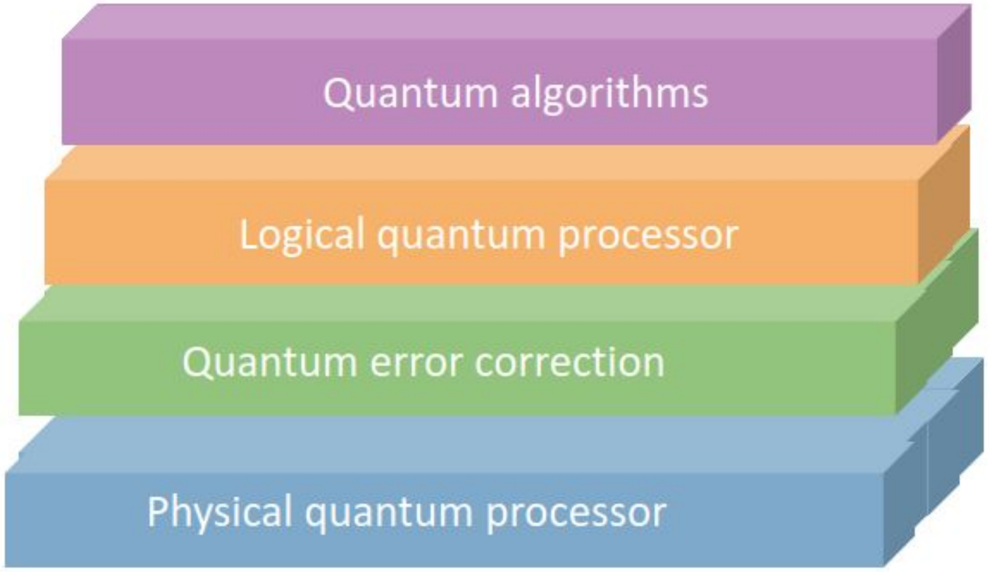
1. Hybrid quantum-classical algorithms

2. Physical qubits ~100

3. Quantum Error Mitigation

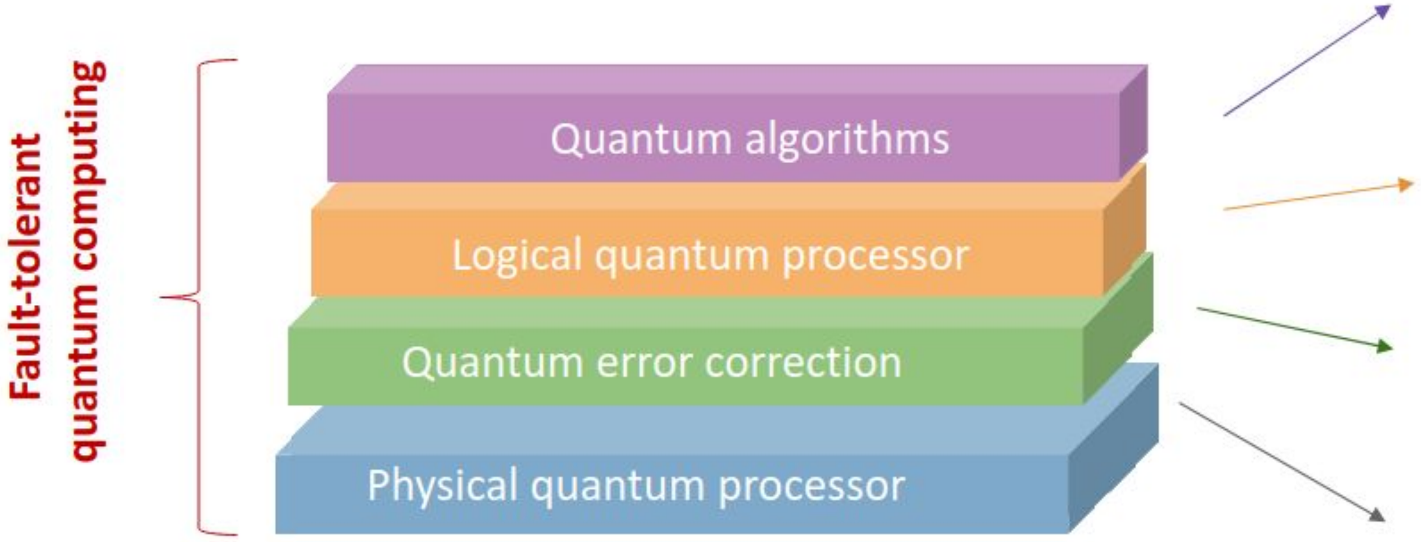


FTQC



FTQC comes with great complexity!

FTQC complexity



Results in a detailed breakdown of the circuit operations needed.

Performs compilation to layout these operations in an efficient way.

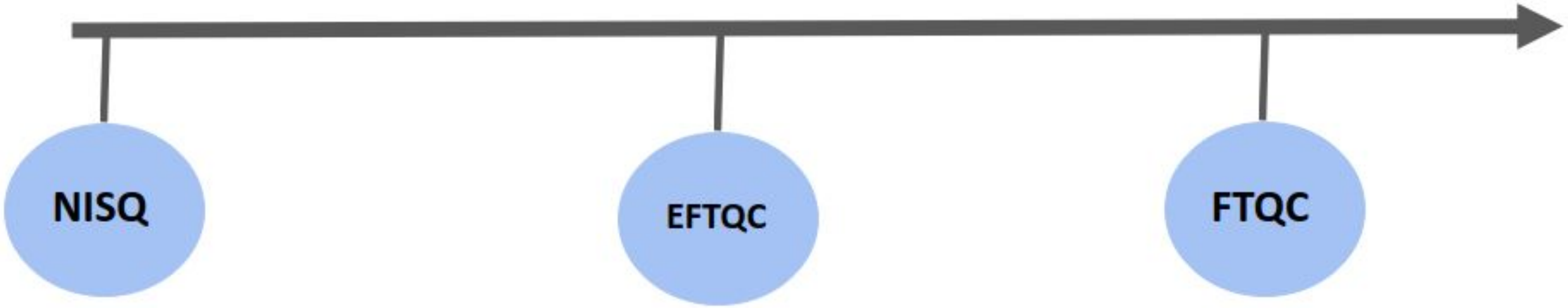
Corrects errors incurred during the computation.

Utilizes specific quantum hardware details to run the computation.

Quantum Computing regimes

1. What were the expectations for quantum computing in 2016 when the term NISQ was introduced, how far have we come and what are the expectations now?

Quantum Computing regimes



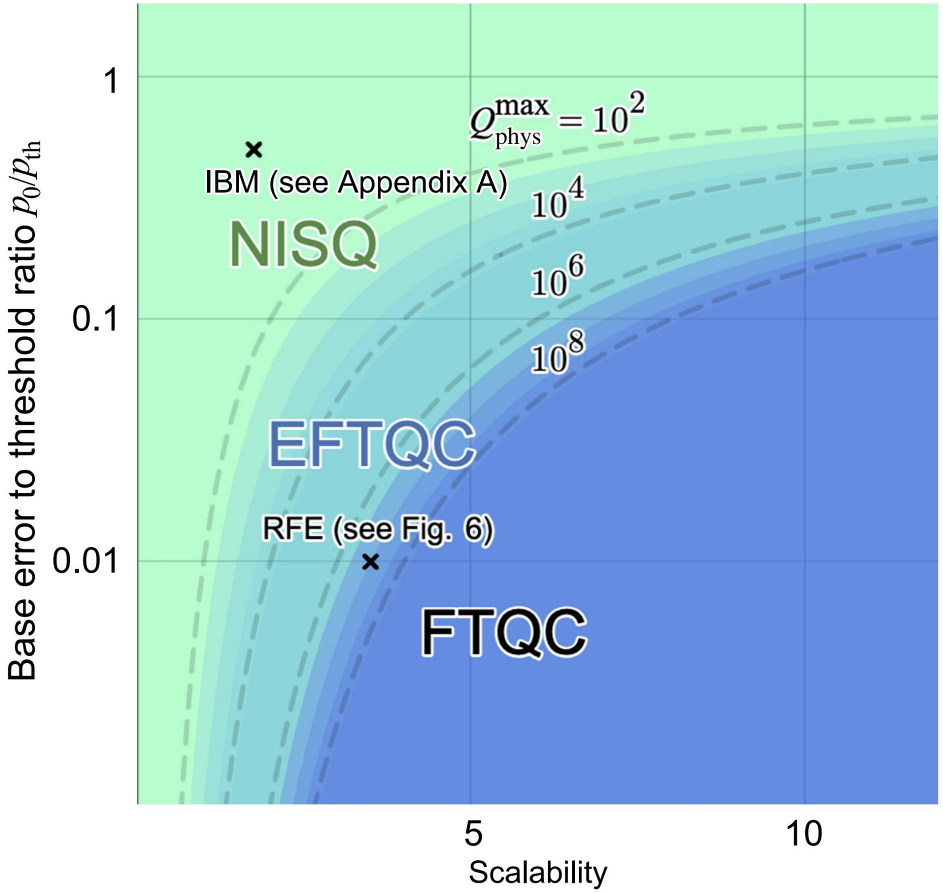
3. How can we bridge the gap between NISQ and FTQC?

Early-Fault-Tolerant Quantum Computing,
Amara Katabarwa, Katerina Gratsea, Athena Caesura & Peter D. Johnson, PRX Quantum 5, 020101 (2024).

EFTQC:

- could help move beyond this NISQ and FTQC dichotomy
- suggests some limited ability to achieve fault-tolerance

Quantum Computing regimes



- ❑ Will this regime of limited-scale quantum computers exist in a meaningful way?
- ❑ If so, will we be able to unlock quantum utility at scale in this regime?

Our results suggest that
the EFTQC regime could exist in a meaningful way:

- ✔ using the same quantum resources compared to FTQC (number of physical qubits and QEC model)
- ✔ affording the use of a larger number of logical qubits.

Achieving Utility-Scale Applications through Full-Stack Co-Design of FTQC

Katerina Gratsea, University of Wisconsin-Madison

arXiv:2510.26547, K. Gratsea and M. Otten

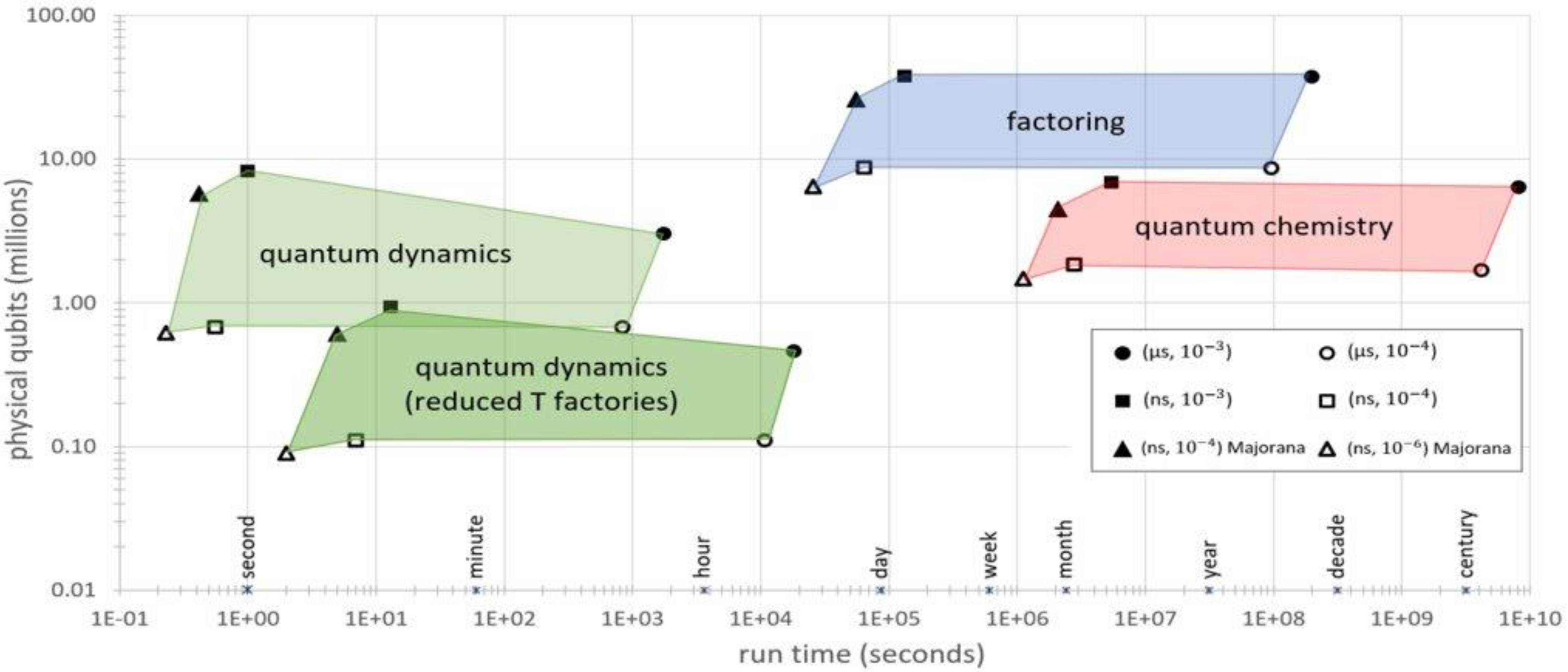
The quest for quantum applications

The Grand Challenge of Quantum Applications

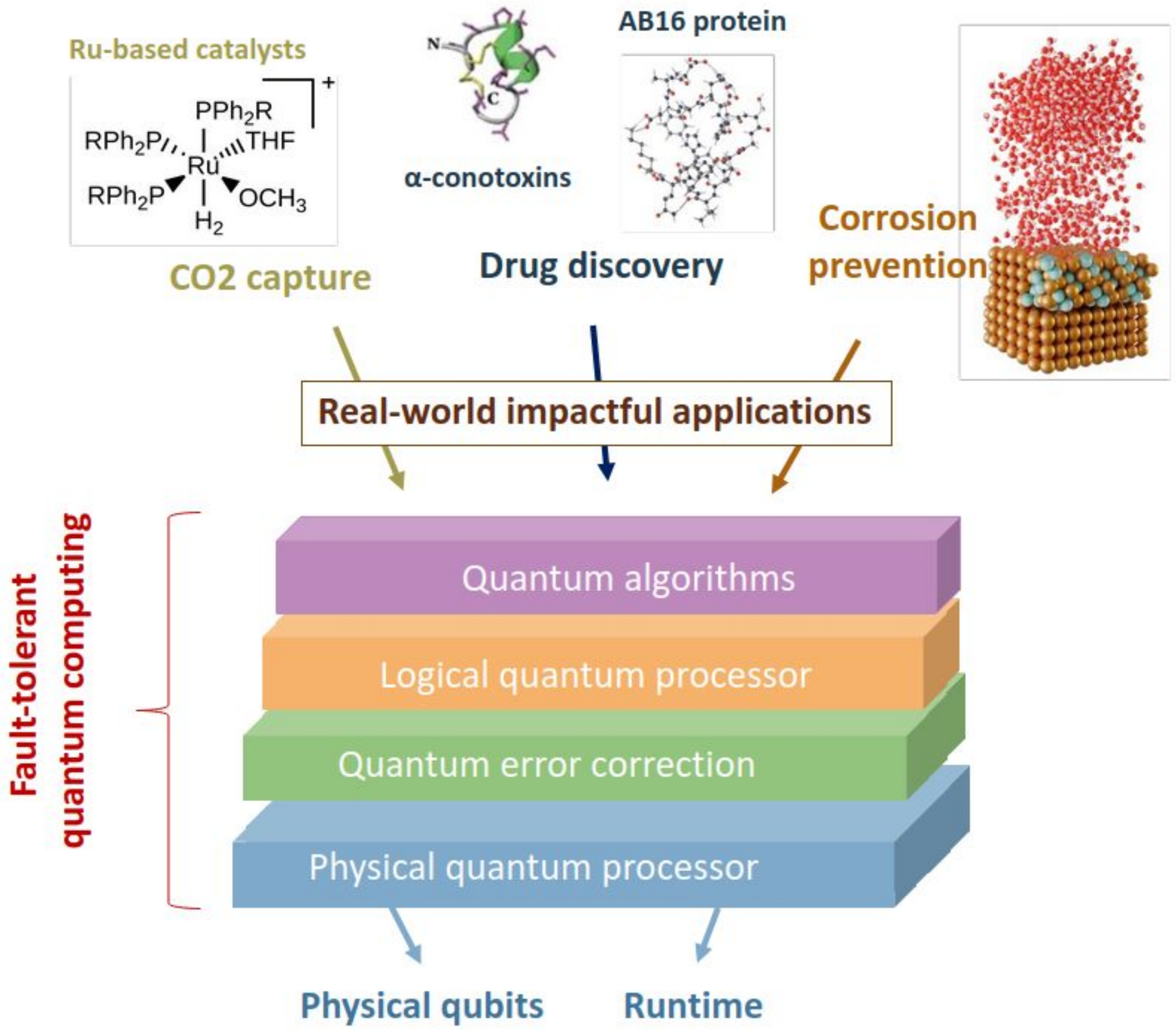
Ryan Babbush, Robbie King, Sergio Boixo, William Huggins, Tanuj Khattar, Guang Hao Low, Jarrod R. McClean, Thomas O'Brien, Nicholas C. Rubin

This perspective outlines promising pathways and critical obstacles on the road to developing useful quantum computing applications, drawing on insights from the Google Quantum AI team. We propose a five-stage framework for this process, spanning from theoretical explorations of quantum advantage to the practicalities of compilation and resource estimation. For each stage, we discuss key trends, milestones, and inherent scientific and sociological impediments. We argue that two central stages -- identifying concrete problem instances expected to exhibit quantum advantage, and connecting such problems to real-world use cases -- represent essential and currently under-resourced challenges. Throughout, we touch upon related topics, including the promise of generative artificial intelligence for aspects of this research, criteria for compelling demonstrations of quantum advantage, and the future of compilation as we enter the era of early fault-tolerant quantum computing.

When will Quantum Computers be useful?



Assessing requirements to scale to practical quantum advantage, Beverland et. al., arXiv: 2211.067629 (2022).



The necessity of Quantum Resource Estimations

- ➔ Map applications to quantum hardware metrics
- ➔ Explore the effect of advances throughout the stack
- ➔ Help co-design FTQC architectures
- ➔ Identify utility-scale applications

Quantum computations with ion-trap systems

The work of Beverland et. al. has resource estimations of Complex XVIII,
one of the stable intermediates in the ruthenium-catalyzed carbon fixation cycle.

application	planar quantum ISA requirements				qubit parameters	QEC optimization			resource requirements	
	Q	$C_{\min}$	C	M		d	F	factory ratio	physical qubits	physical run time
quantum chemistry	2740	$4.1 \cdot 10^{11}$	$4.1 \cdot 10^{11}$	$5.4 \cdot 10^{11}$	(μs, 10^{-3})	33	15	6.9%	6.4M	260 years
			$4.1 \cdot 10^{11}$		(μs, 10^{-4})	17	14	5.9%	1.6M	130 years
			$4.1 \cdot 10^{11}$		(ns, 10^{-3})	33	17	14%	6.9M	2.0 months
			$4.1 \cdot 10^{11}$		(ns, 10^{-4})	17	17	15%	1.9M	1.0 month
			$4.1 \cdot 10^{11}$		(ns, 10^{-4})*	17	19	22%	4.5M	24 mins
			$4.1 \cdot 10^{11}$		(ns, 10^{-6})*	9	19	22%	1.3M	12 days

For ion-trap systems, the runtimes are at a very high end.

Is it only an issue of the quantum hardware?

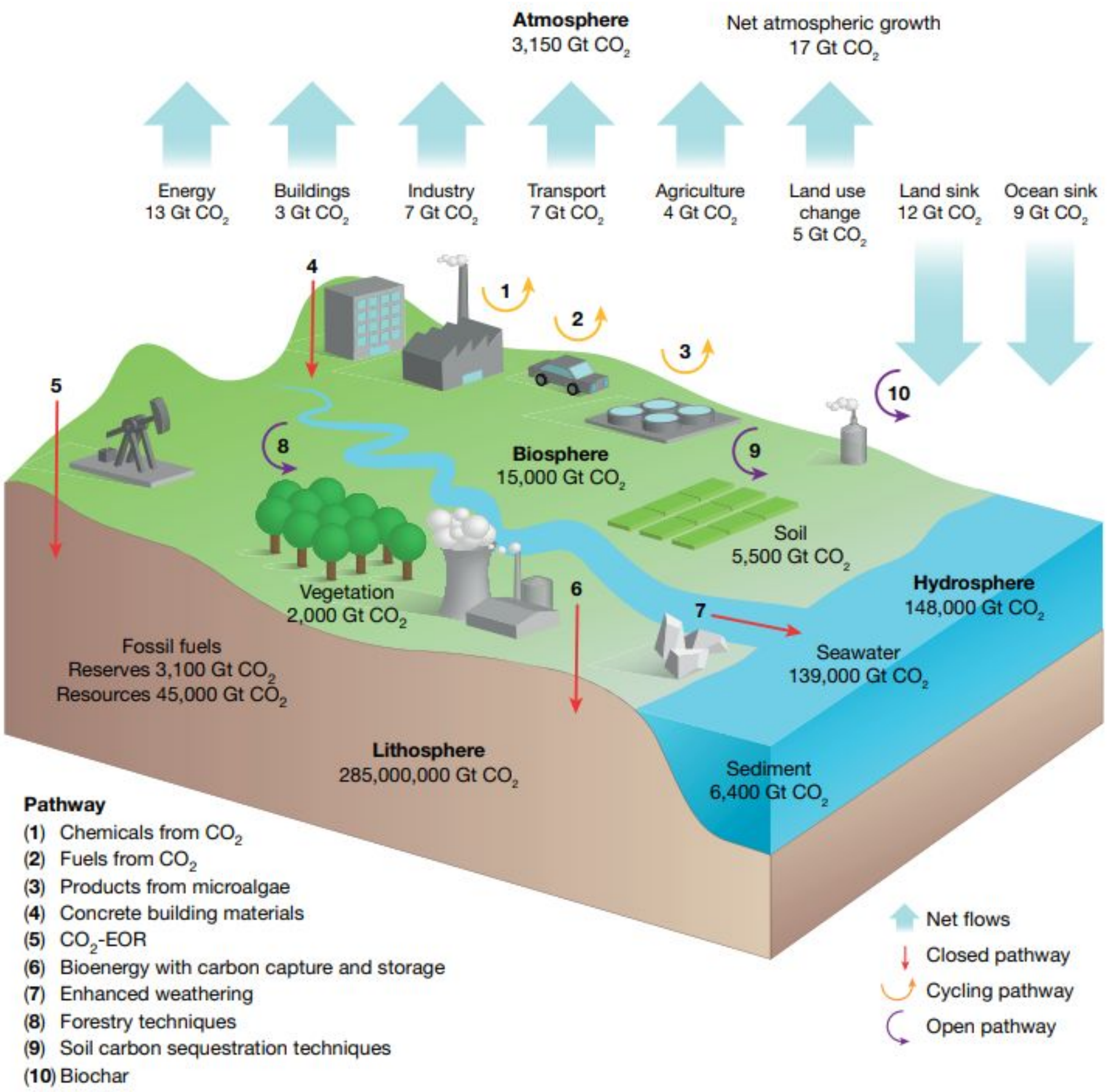
Assessing requirements to scale to practical quantum advantage, Beverland et. al., arXiv: 2211.067629 (2022).

Application:

CO2 utilization for green energy

$$CO_2 + H_2 \xrightarrow{\text{catalyst}} \{\text{renewable fuels}\} + \{\text{raw materials}\}$$

$$CO_2 + H_2 \xrightarrow{\text{Ru-based}} CH_3OH + H_2O$$



The technological and economic prospects for CO_2 utilization and removal.
Hepburn, C. *et al.* (2020). *Nature*, 575, 87–97.

Application:
CO2 utilization for green energy

$$CO_2 + H_2 \xrightarrow{\text{catalyst}} \{\text{renewable fuels}\} + \{\text{raw materials}\}$$

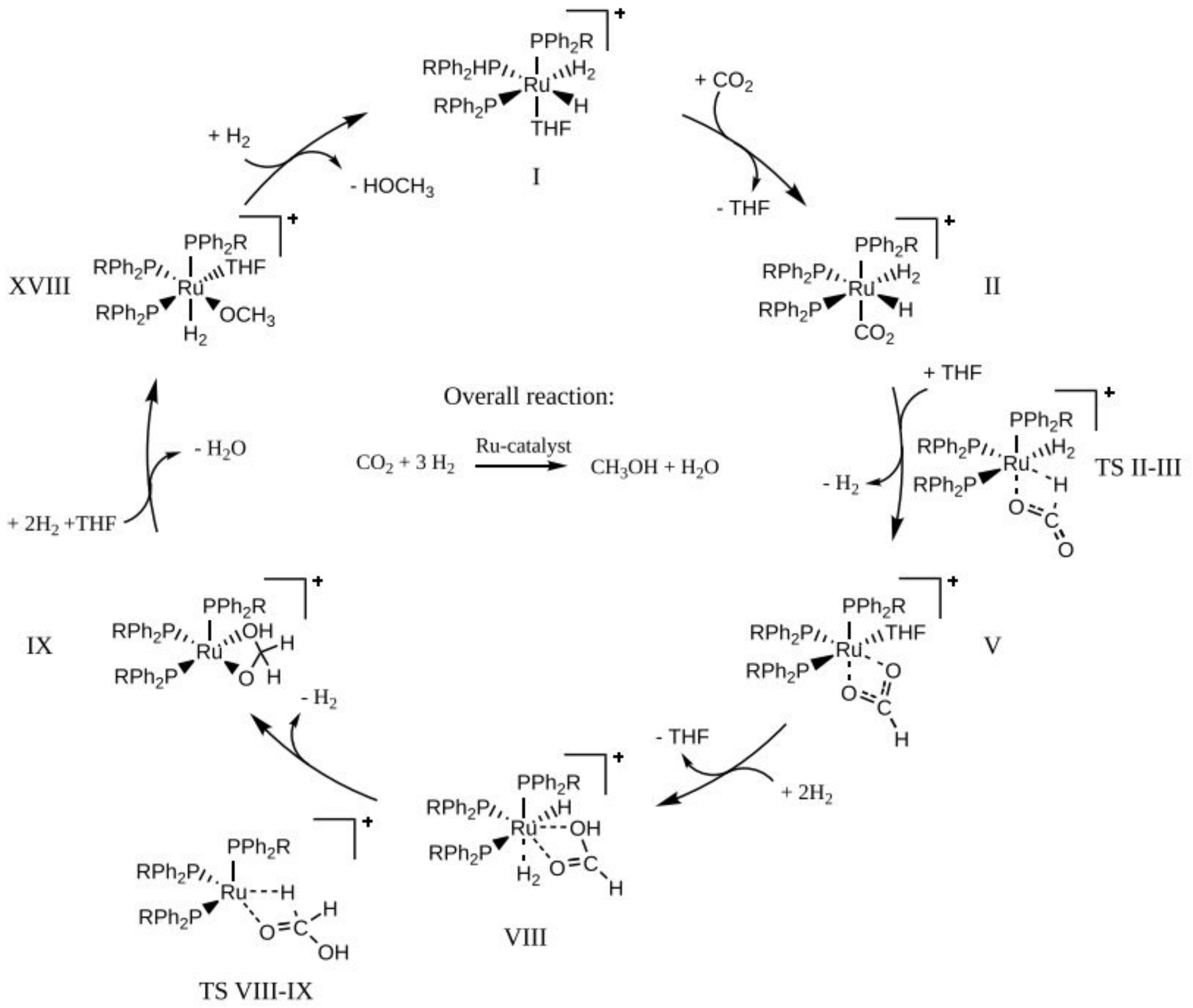
$$CO_2 + H_2 \xrightarrow{\text{Ru-based}} CH_3OH + H_2O$$

Intermediate reaction:

$$\mathrm{I} + CO_2 + 2\,H_2 \rightarrow \mathrm{XVIII} + H_2O$$

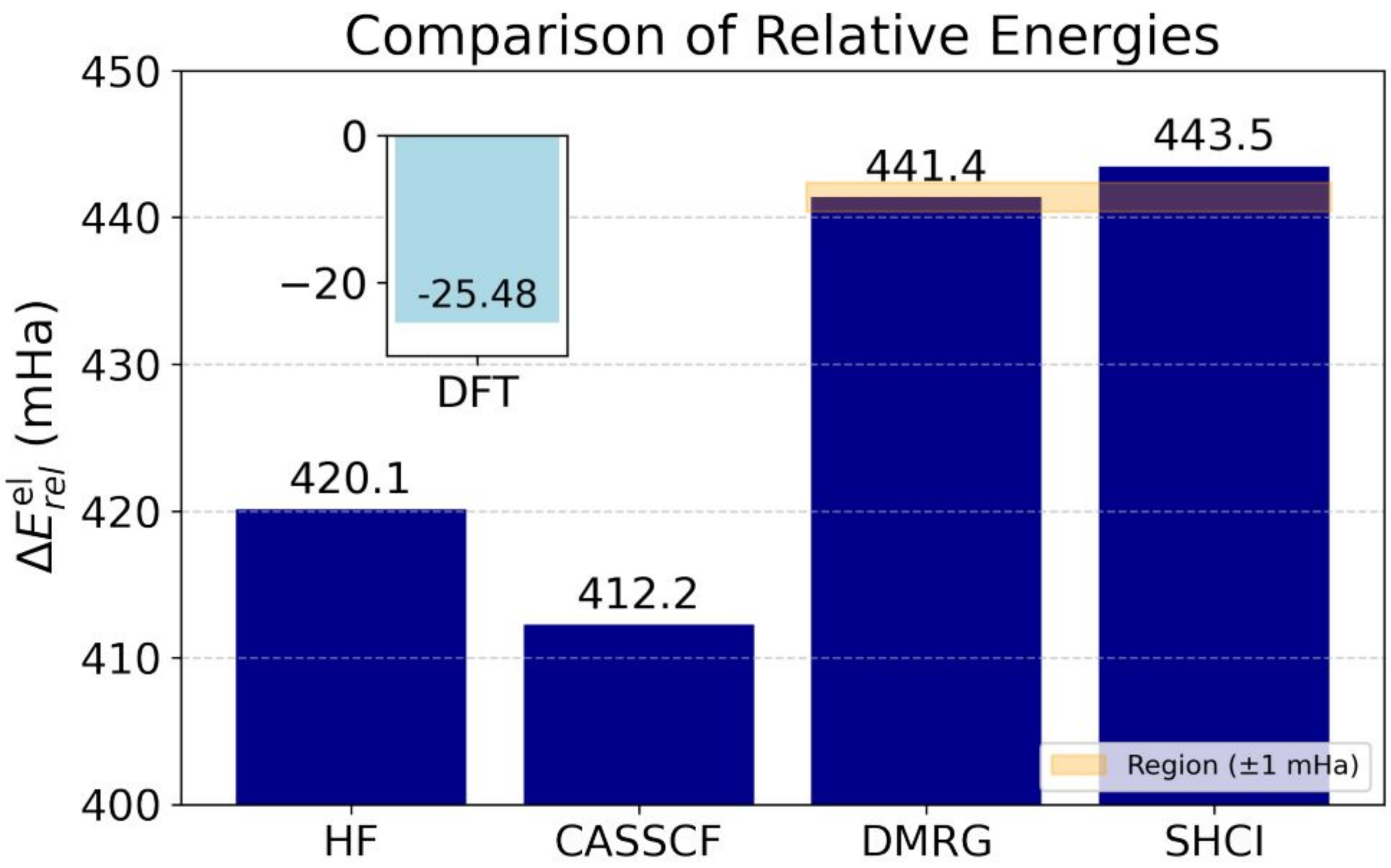
Relative Electronic Energy:

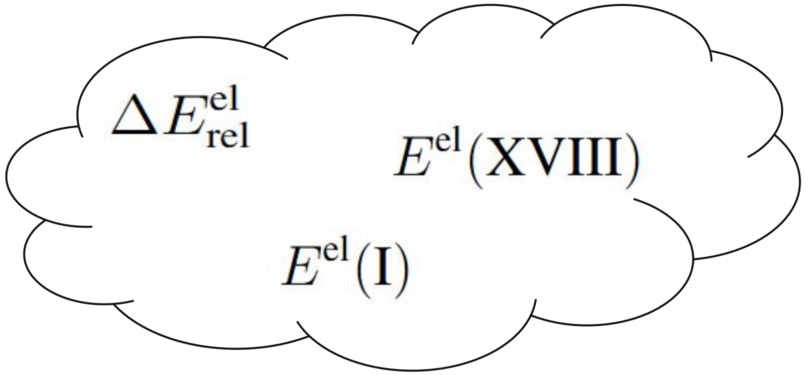
$$\Delta E^{\mathrm{el}}_{\mathrm{rel}} = E^{\mathrm{el}}(\mathrm{XVIII}) + E^{\mathrm{el}}(H_2O) - 2 \cdot E^{\mathrm{el}}(H_2) - E^{\mathrm{el}}(\mathrm{I}) - E^{\mathrm{el}}(CO_2).$$



Quantum computing enhanced computational catalysis, M. Troyer et. al. 2021, arXIv:2007.14460

Classical benchmarking



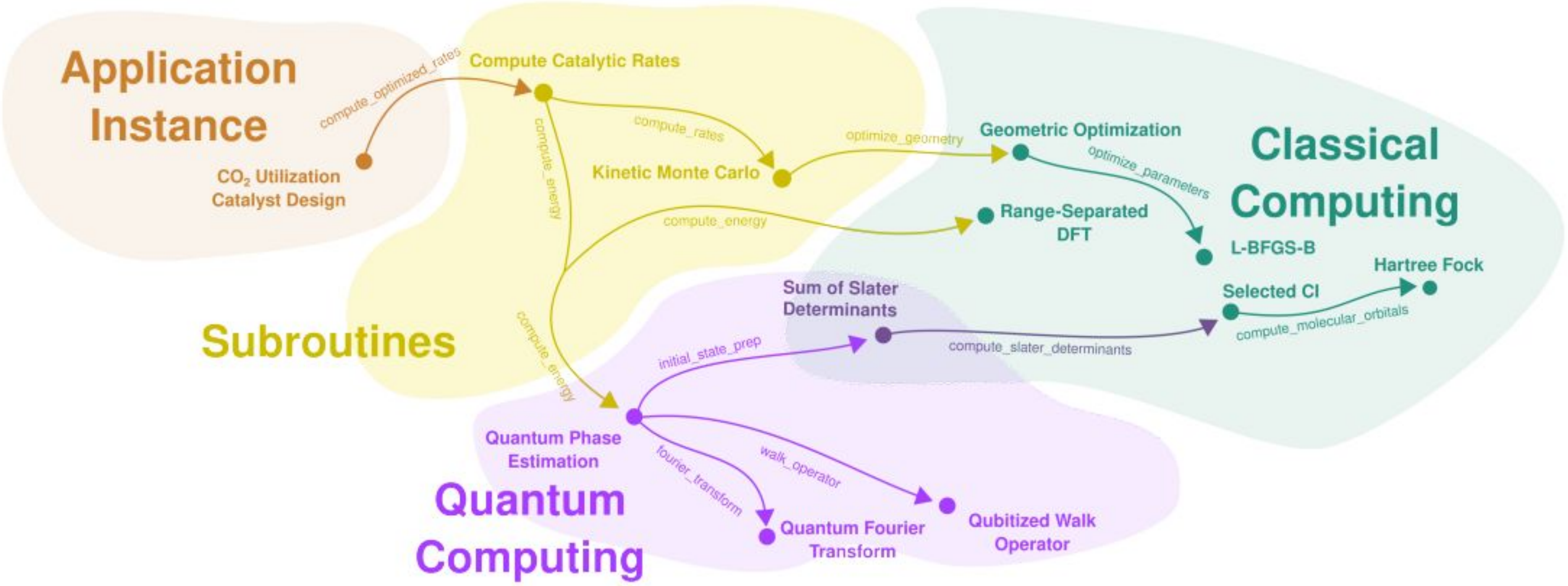


$$k \propto e^{-\Delta E/RT}$$

Accurate prediction of rates k **unlocks knowledge on**

- Temperature dependance.
- Rate-determining step.
- Catalyst optimization.

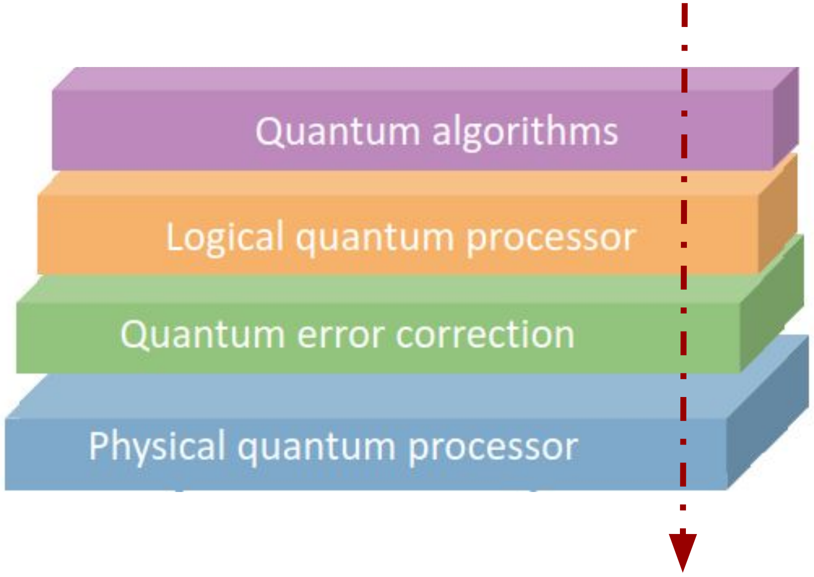
Quantum Benchmarking Graph



Can Quantum Computers help?

Problem: Complex XVIII (64e, 56o)

Total runtime: **22 years in Beverland et al.**



Total runtime: **1 day in this work.**

Changes implemented

Our work:

Enhanced Performance

with Full-Stack Co-Design:

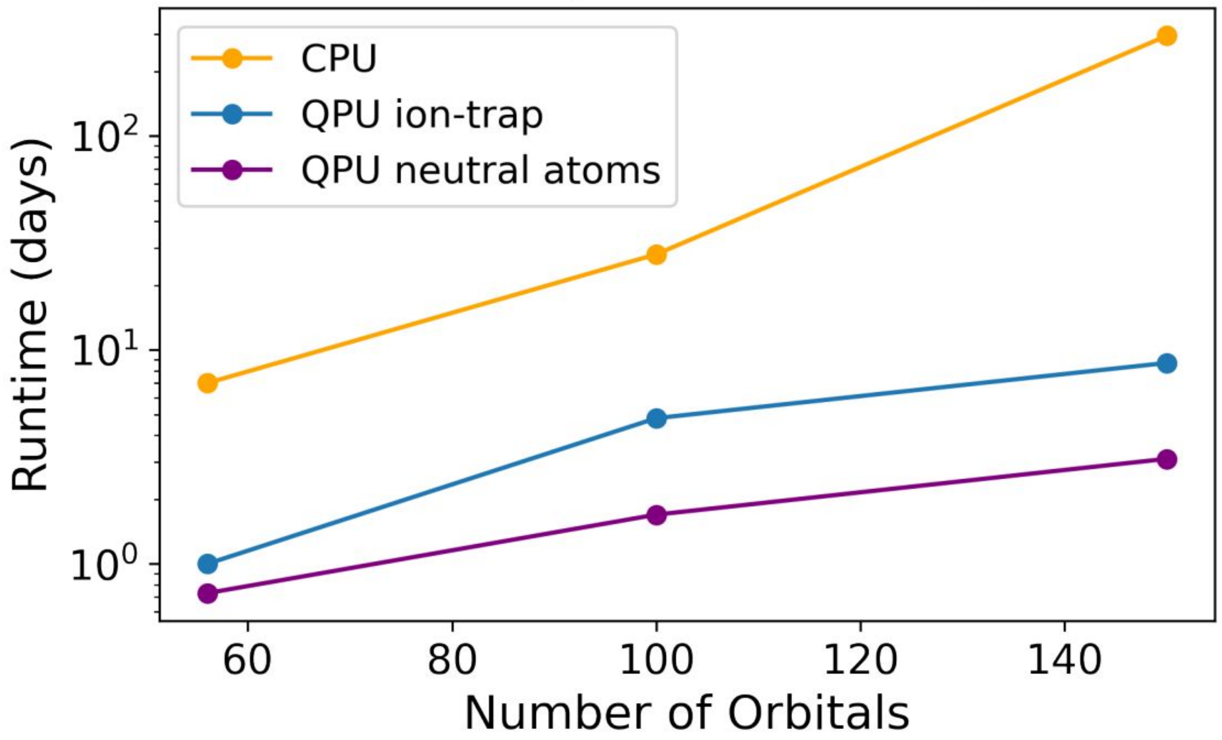
- Spectrum amplification and DFTHC quantum algorithm

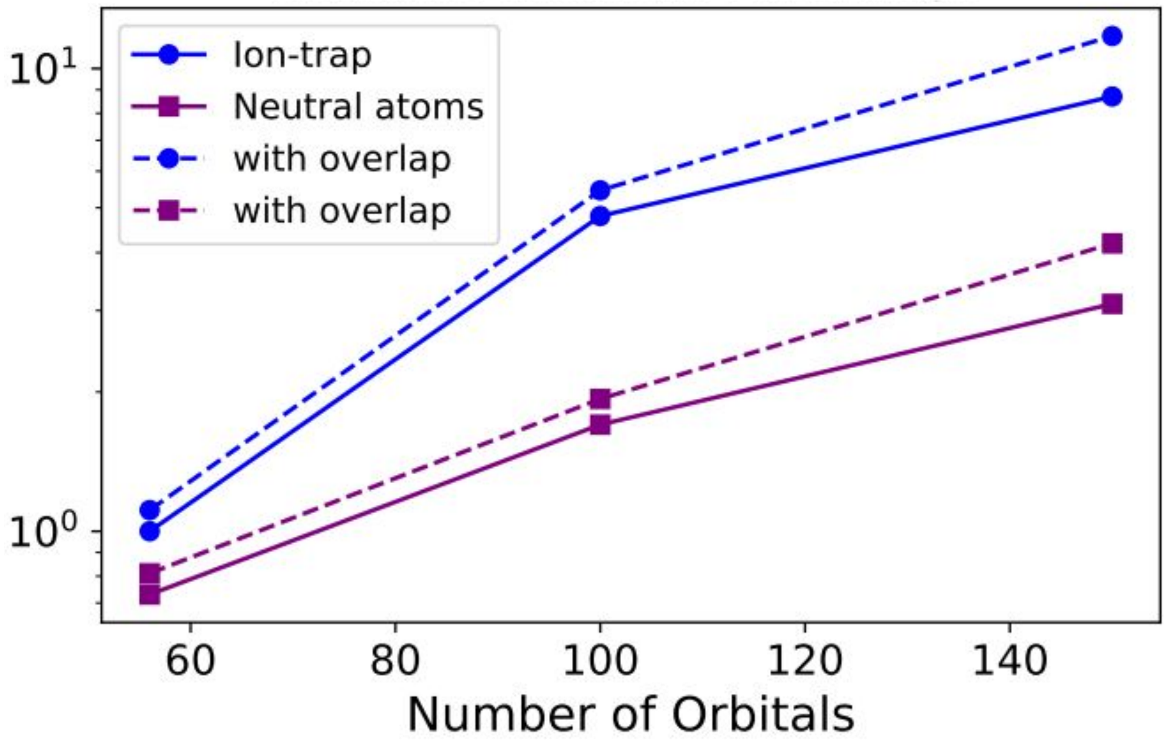
- Graph state compilation
- ZX calculus

- Magic state cultivation

- Detailed ion-trap hardware model with effective all-to-all connectivity

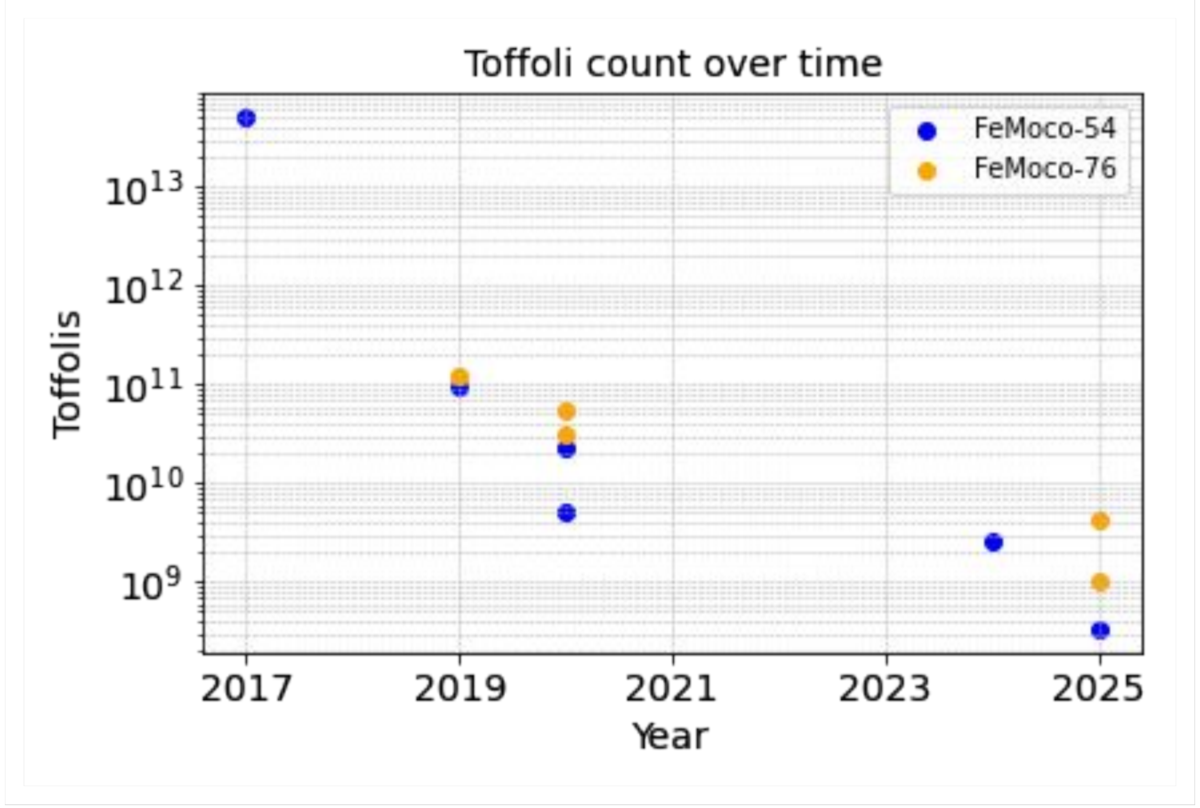
Predicted Runtime Quantum Advantage





2. Different researchers have different definitions of quantum advantage. Which definition are you mostly in favor of and why? Should these definitions be unified?

Quantum algorithmic layer



- Rubin, N. C et. al., (Feb 2025). *Fast quantum simulation of electronic structure by spectrum amplification*. arXiv:2502.15882.

- Spectrum amplification and DFTHC quantum algorithm

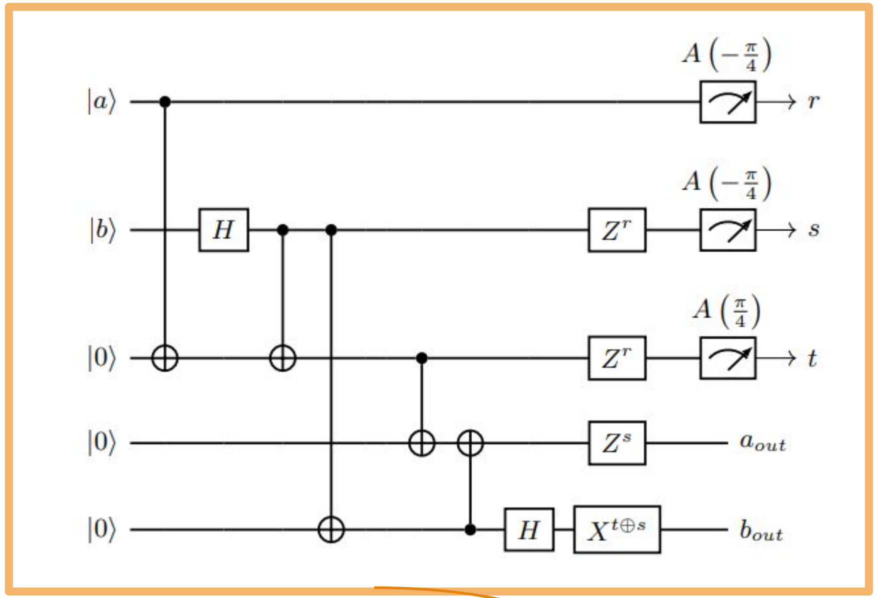
	proxy circuits	original circuits
56o - logical qubits	994	924
56o - T gates	8.2e08	8.2e08
100o - logical qubits	1872	1960
100o - T gates	4.24e09	4.24e09
150o - logical qubits	2954	2870
150o - T gates	1.12e10	1.12e10

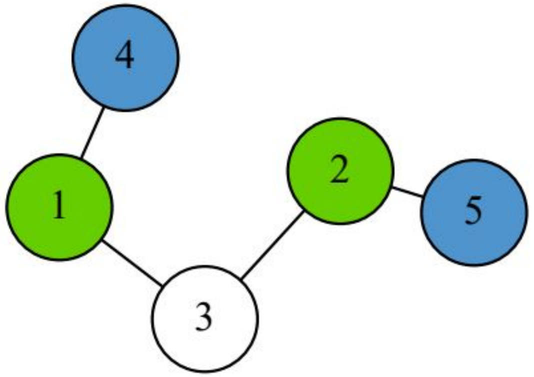
The quantum circuits are generated in pyLIQTR.

Logical quantum processor layer

- Devitt, S. J. et. al. (2022). *Compilation of algorithm-specific graph states for quantum circuits*, arXiv:2209.07345.

- Graph state compilation
- ZX calculus





The quantum circuit is mapped to an algorithm-specific graph state.

Logical quantum processor layer

- Devitt, S. J. et. al. (2022). *Compilation of algorithm-specific graph states for quantum circuits*, arXiv:2209.07345.

- Graph state compilation
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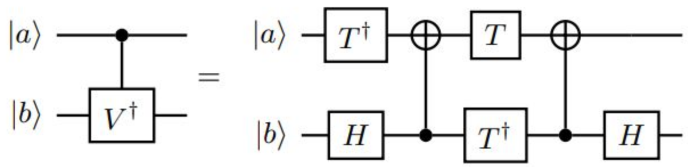
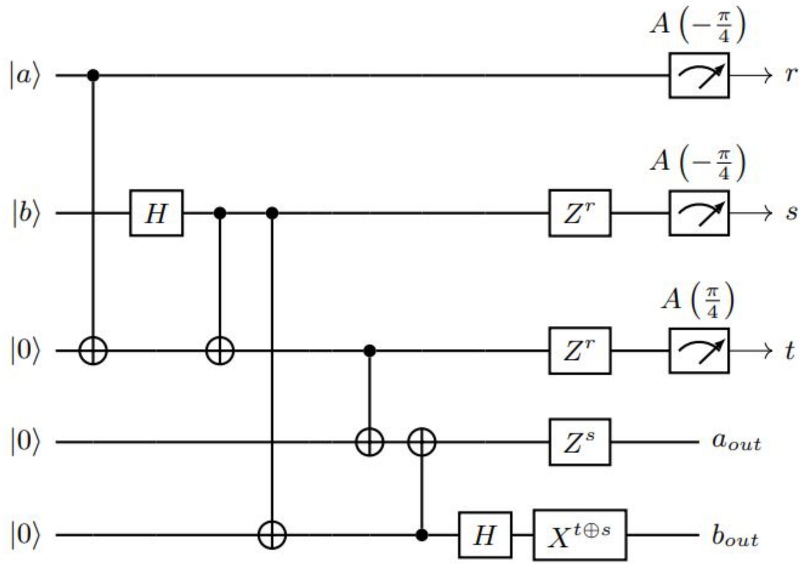
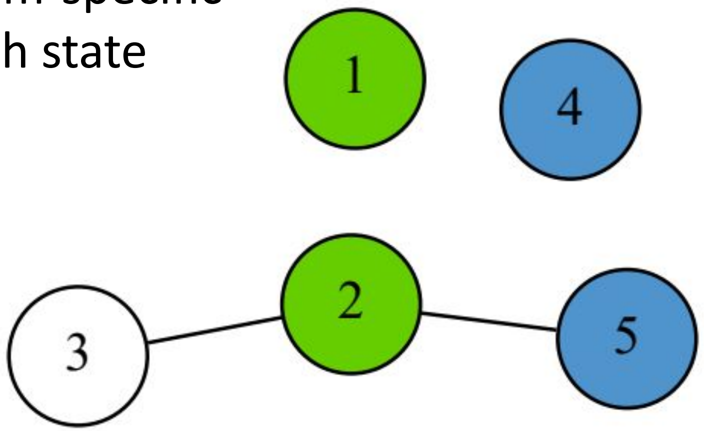
Decomposition to Clifford+T



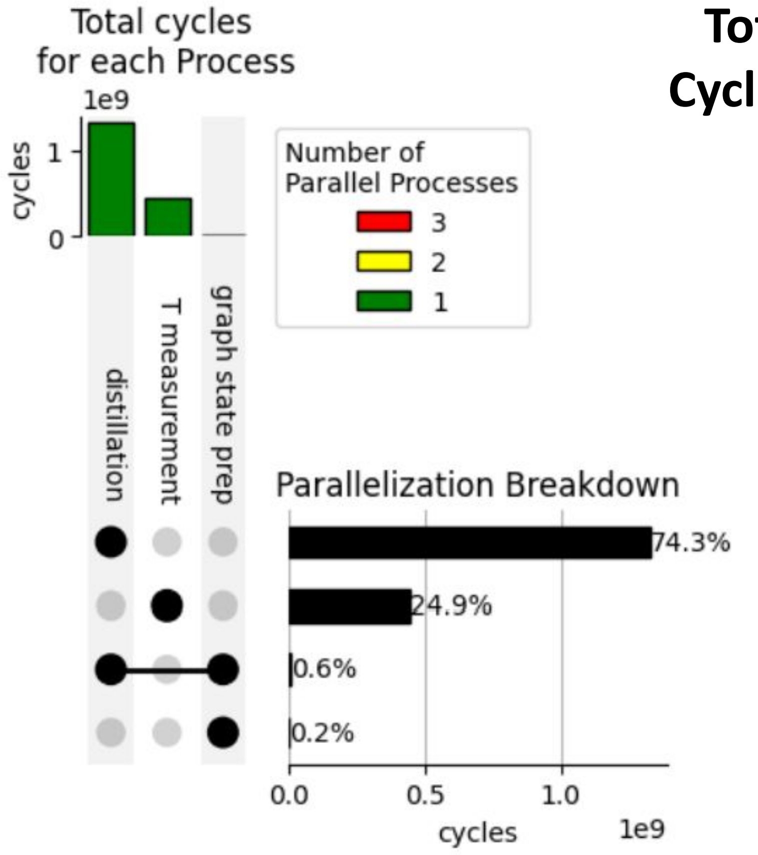
Teleported T-gate implementation



Algorithm-specific graph state



Logical quantum processor layer



Total runtime =
Cycles x cycle time

- Devitt, S. J. et. al. (2022). *Compilation of algorithm-specific graph states for quantum circuits*, arXiv:2209.07345.

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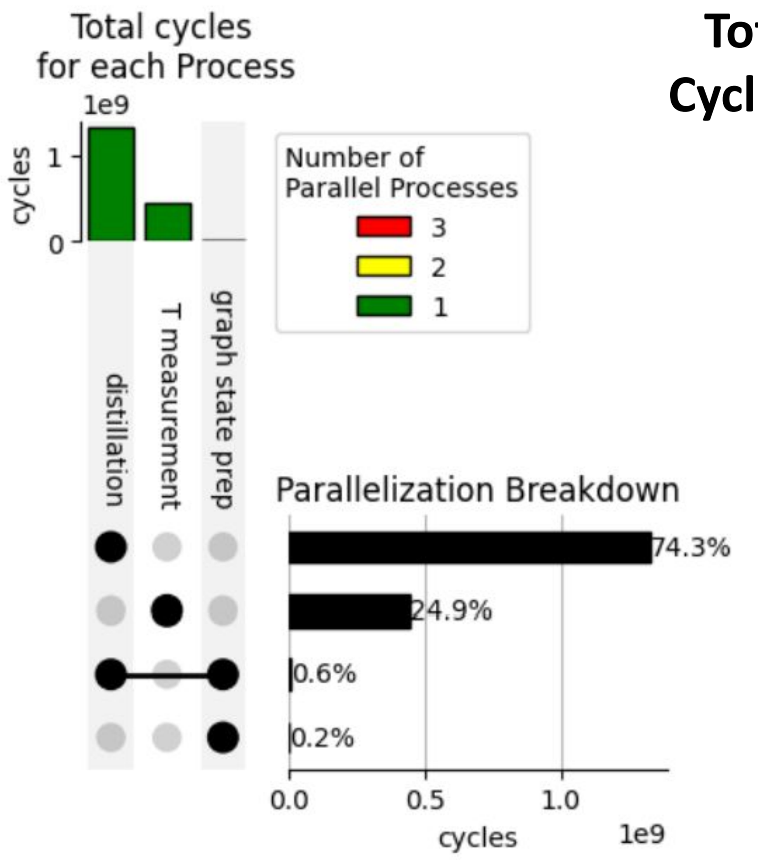
- ZX calculus

Logical quantum processor layer



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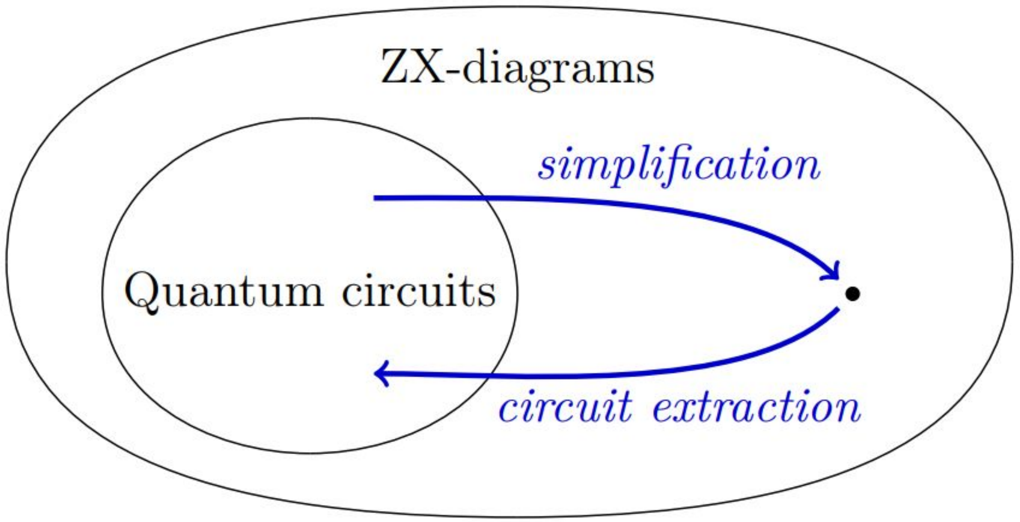


Identifies redundancies and algebraic identities

QEC implementations:

An example of a distillation protocol:

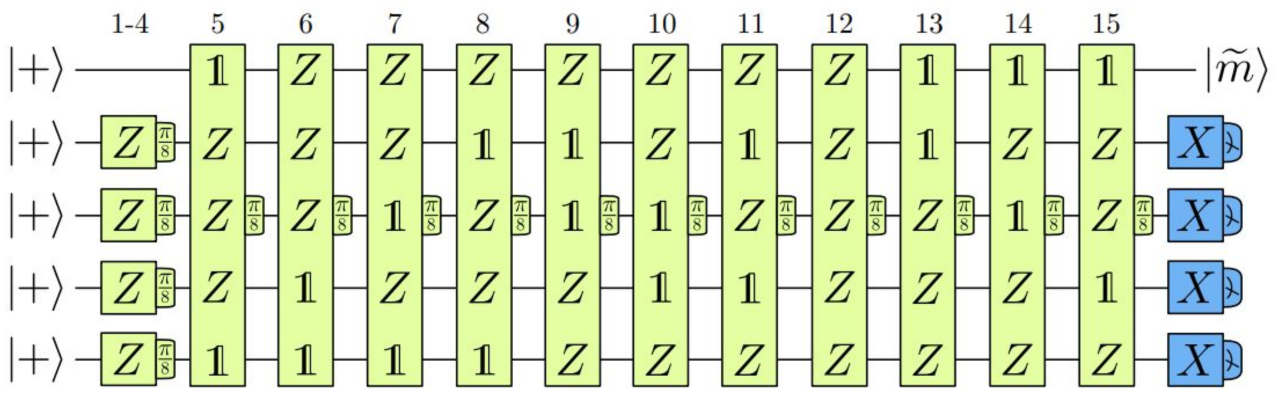


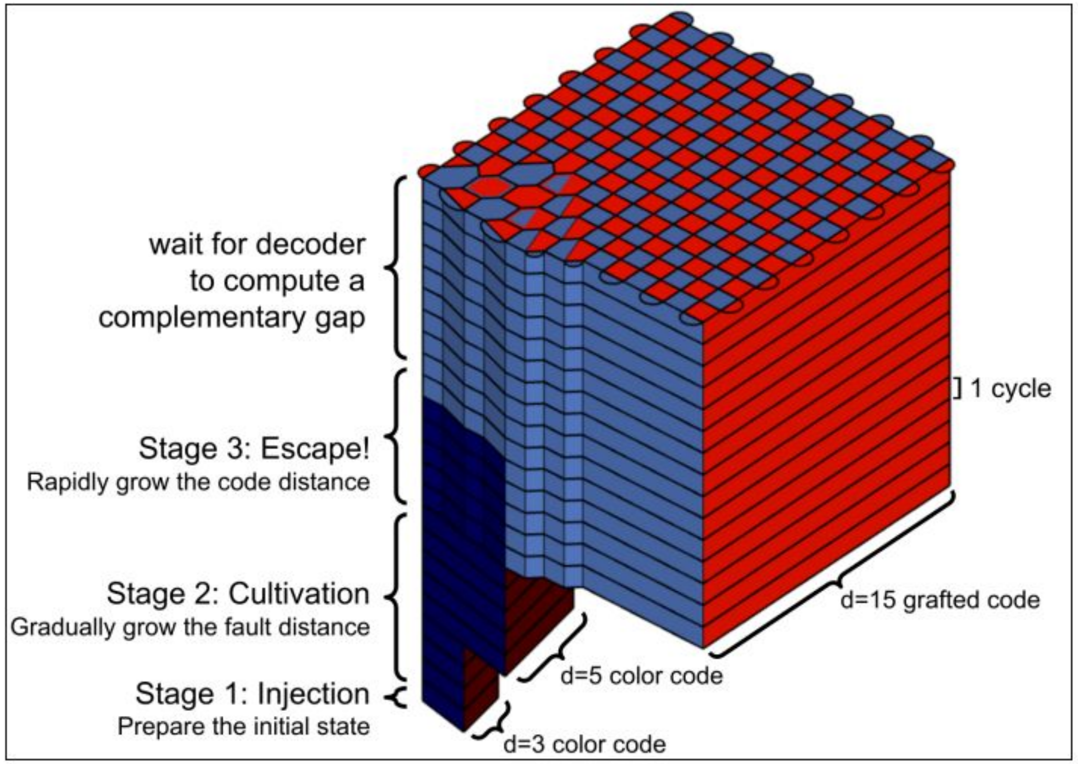
Figure 3: 15-to-1 distillation circuit.

Protocol	p_{phys}	p_{out}	Qubits	Cycles
$(15\text{-to-}1)_{7,3,3}$	10^{-4}	4.4×10^{-8}	810	18.1
$(15\text{-to-}1)_{9,3,3}$	10^{-4}	9.3×10^{-10}	1,150	18.1
$(15\text{-to-}1)_{11,5,5}$	10^{-4}	1.9×10^{-11}	2,070	30.0
$(15\text{-to-}1)^4_{9,3,3} \times (20\text{-to-}4)_{15,7,9}$	10^{-4}	2.4×10^{-15}	16,400	90.3
$(15\text{-to-}1)^4_{9,3,3} \times (15\text{-to-}1)_{25,9,9}$	10^{-4}	6.3×10^{-25}	18,600	67.8

- Litinski, D., (2024). Magic state distillation: Not as Costly as You Think. arXiv: 1905.06903.
- Gidney, C., Shutty, N., & Jones, C. (2024). *Magic state cultivation: Growing T states as cheap as CNOT gates*. arXiv: 2409.17595

- Magic state distillation

QEC implementations:



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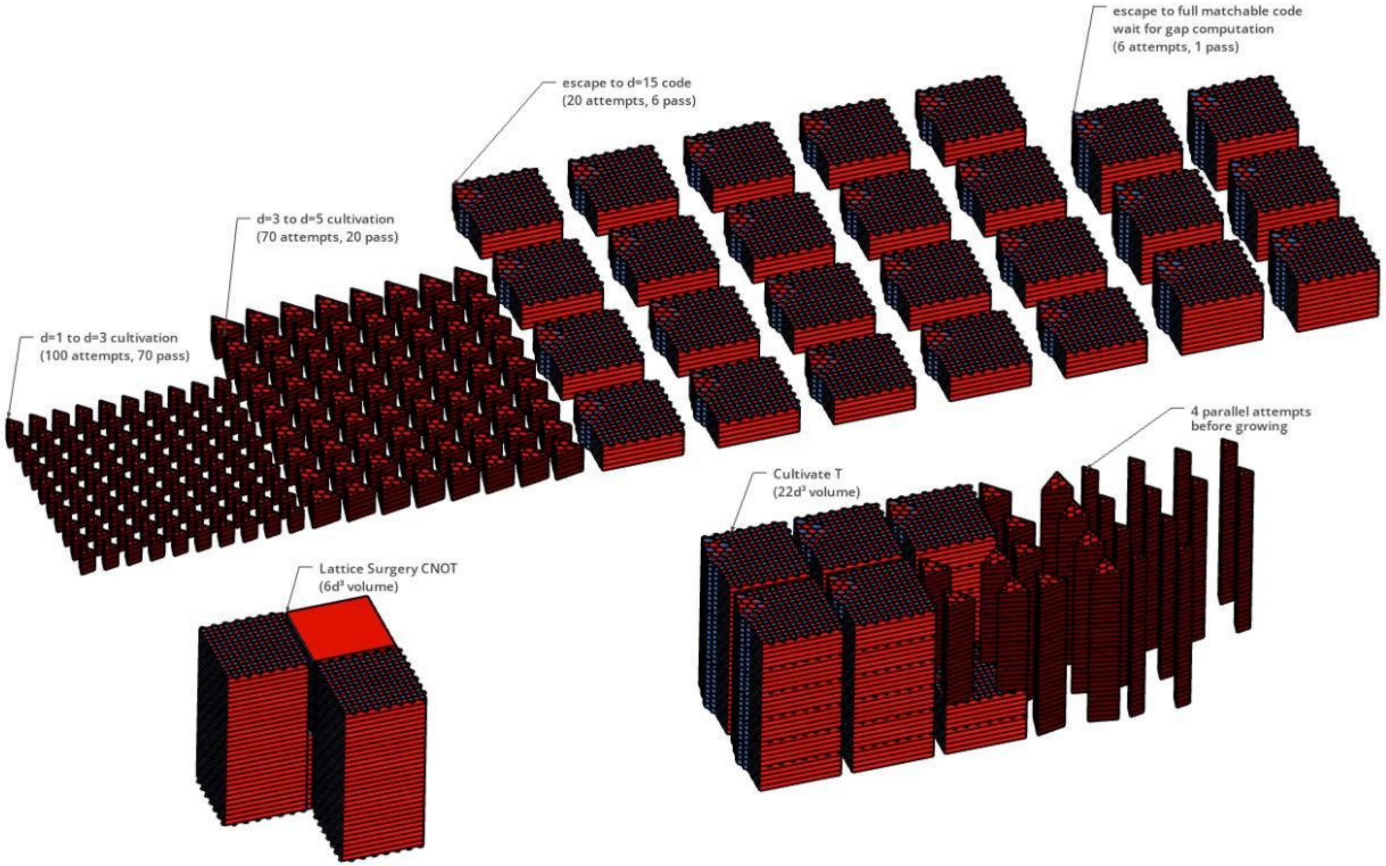
- Magic state cultivation

Magic state cultivation help save on both physical qubits and runtime.

- Pphys = 1e-4
- Pout = 1e-12
- Qubits = 9200
- Cycles = 20

QEC implementations:



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- Qubits = 9200
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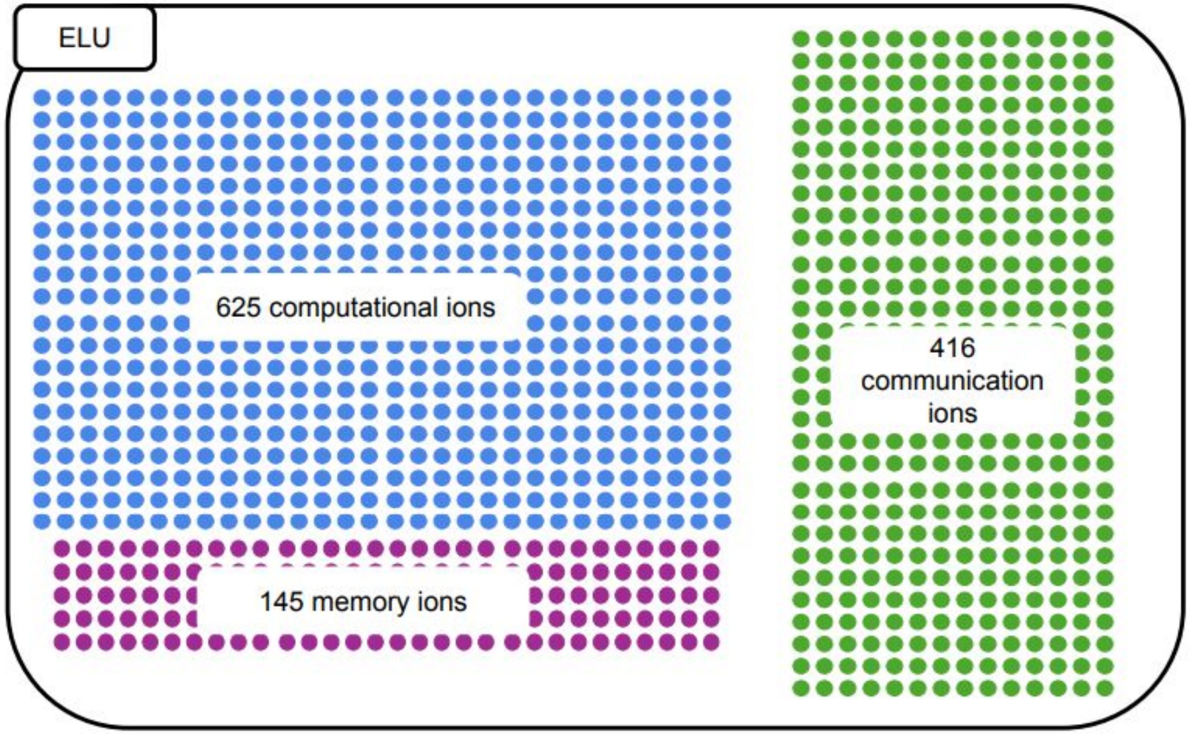
Physical processor implementations:



Elementary Logical Unit (ELU)

- Devitt, S. et. al. (2025). *Resource overheads and attainable rates for trapped-ion lattice surgery*. arXiv: 2406.18764.

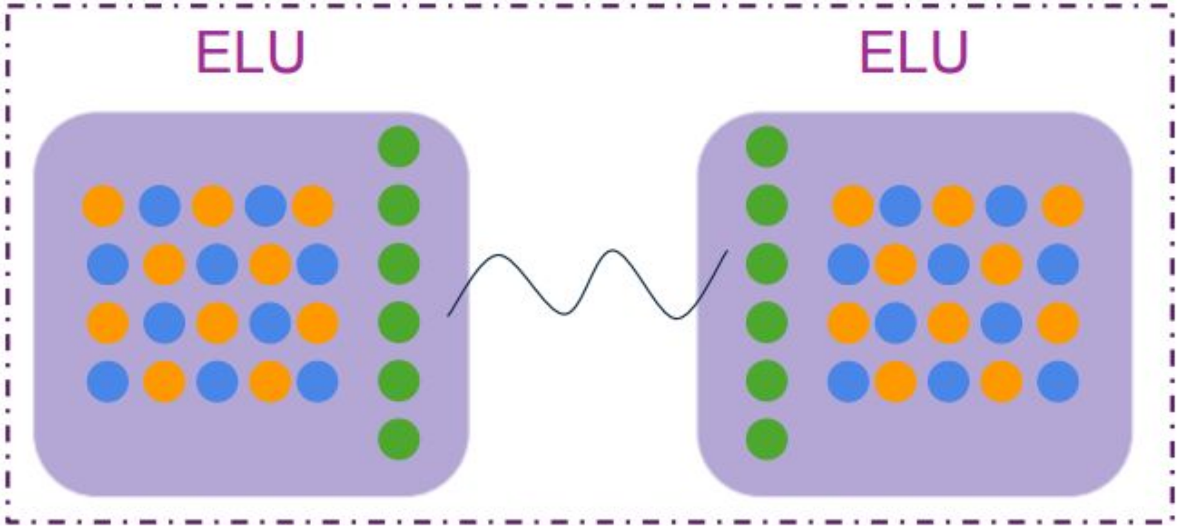
- Detailed ion-trap hardware model with effective all-to-all connectivity

- Each ELU maps to 1 logical qubit.

- ELU units can support around 1K ions.

QEC implementations:

- Hardware modeling to support T= 1e-4 seconds at the inter-ELU level.



<u>Goal:</u> Find the minimum number of communication ions that can support the 1e-4 SCC time.

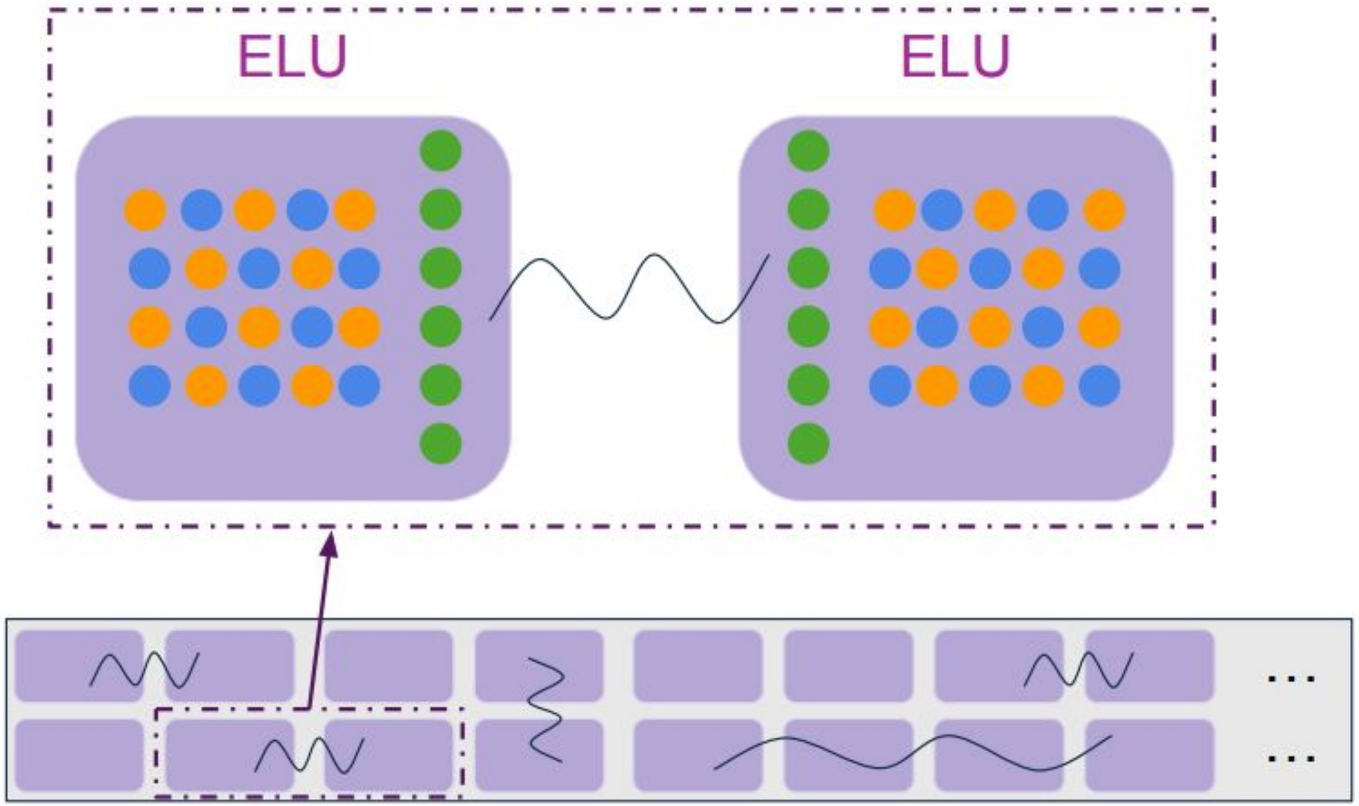
- Devitt, S. et. al. (2025). *Resource overheads and attainable rates for trapped-ion lattice surgery*. arXiv: 2406.18764.

- Detailed ion-trap hardware model with effective all-to-all connectivity

Hardware assumptions:

- Ion-to-Ion entanglement success probability p_e = 0.00416 given 10% photon collection efficiency.
- Pulse rate of 1MHz and 100 attempts.
- Required success probabilities.
- Constraint of approximately 1K physical qubits per ELU.

QEC implementations:



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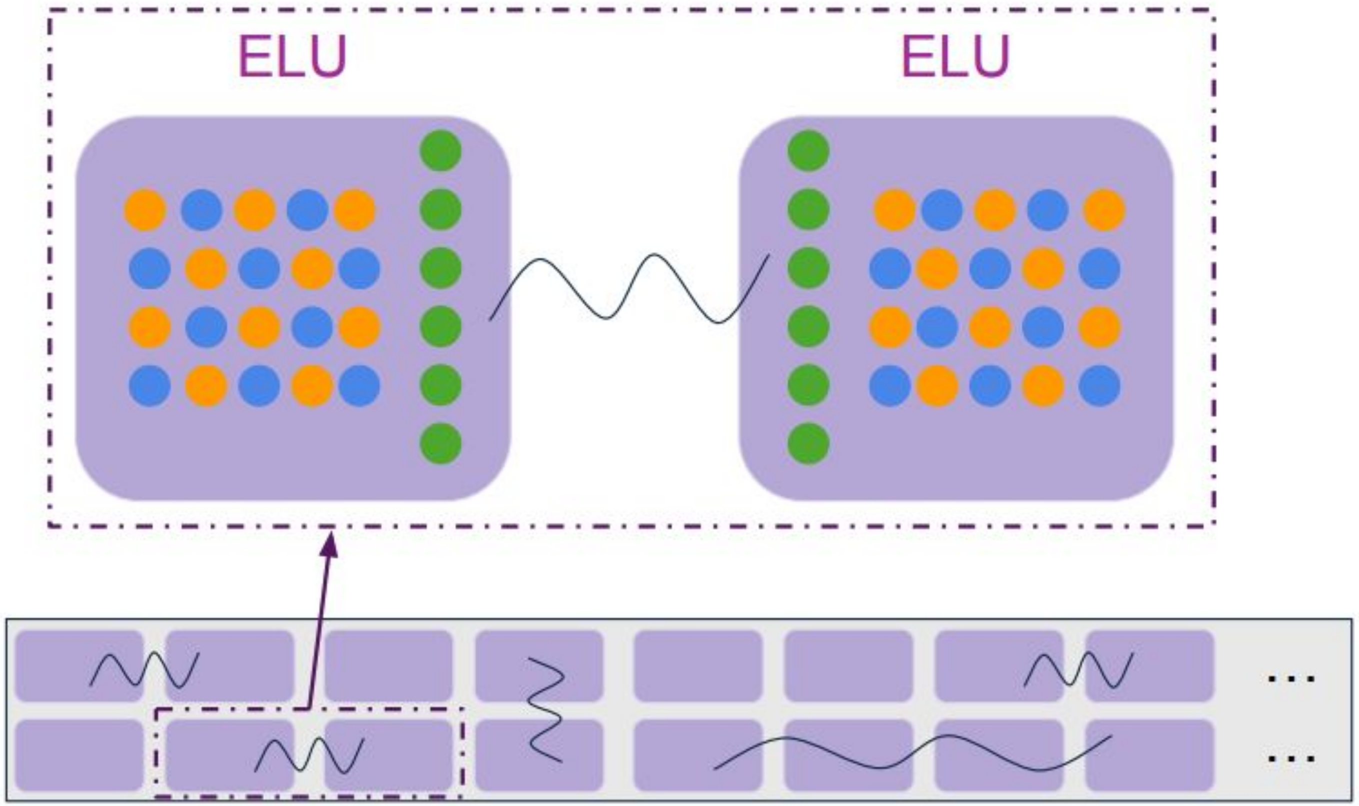
QEC implementations:



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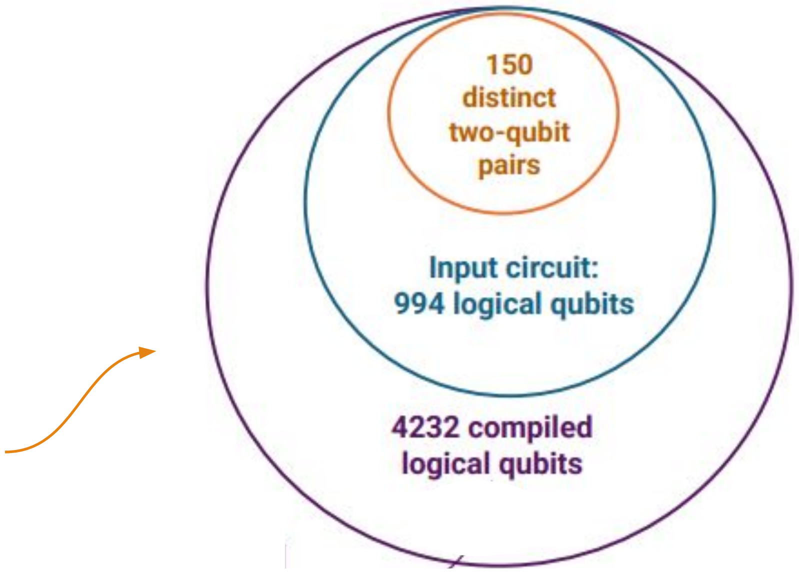
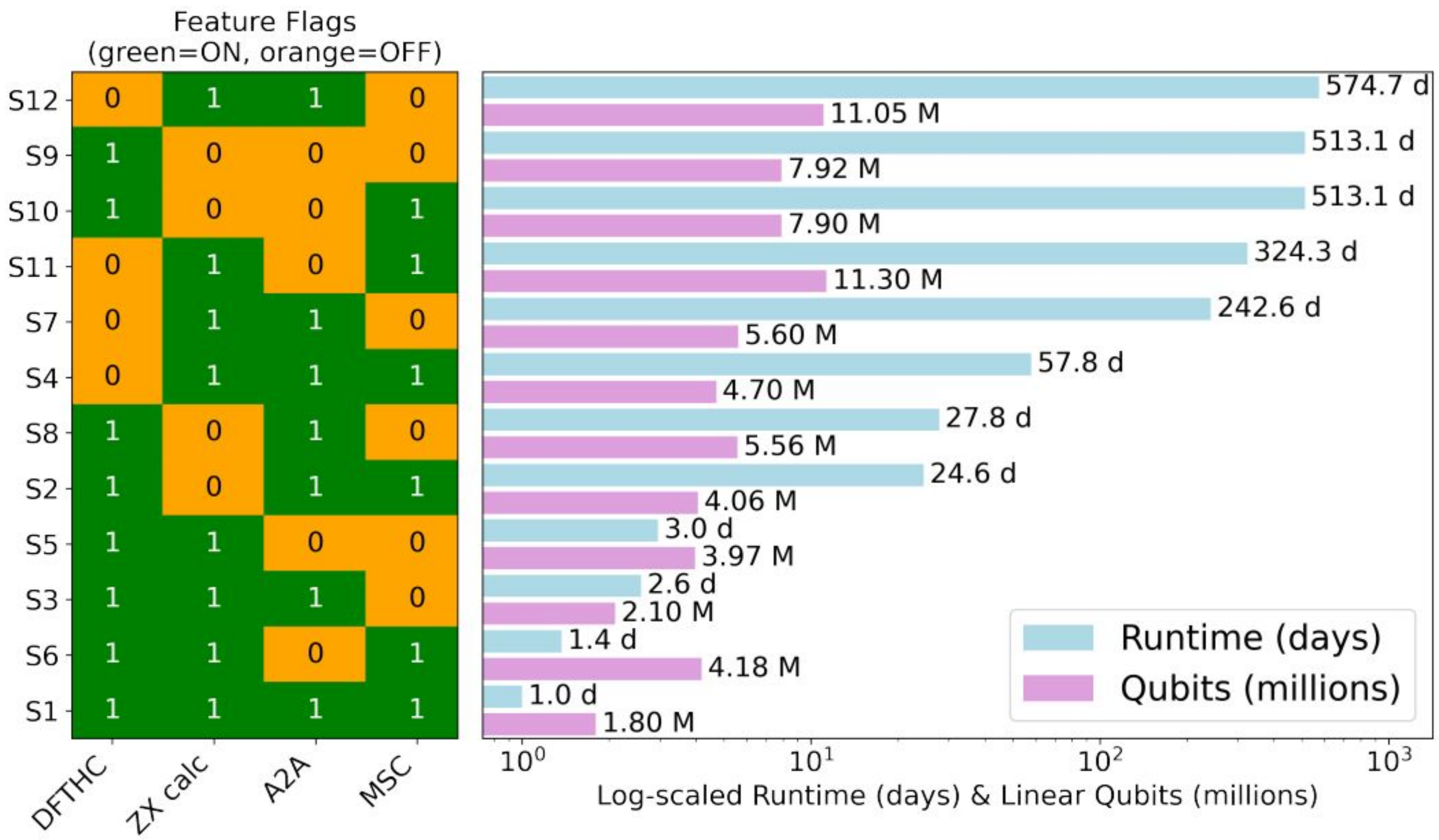


Detailed breakdown of QRE



	DFTHC	ZX calc	A2A	MSC
S12	0	1	1	0
S9	1	0	0	0
S10	1	0	0	1
S11	0	1	0	1
S7	0	1	1	0
S4	0	1	1	1
S8	1	0	1	0
S2	1	0	1	1
S5	1	1	0	0
S3	1	1	1	0
S6	1	1	0	1
S1	1	1	1	1

Detailed breakdown of QRE

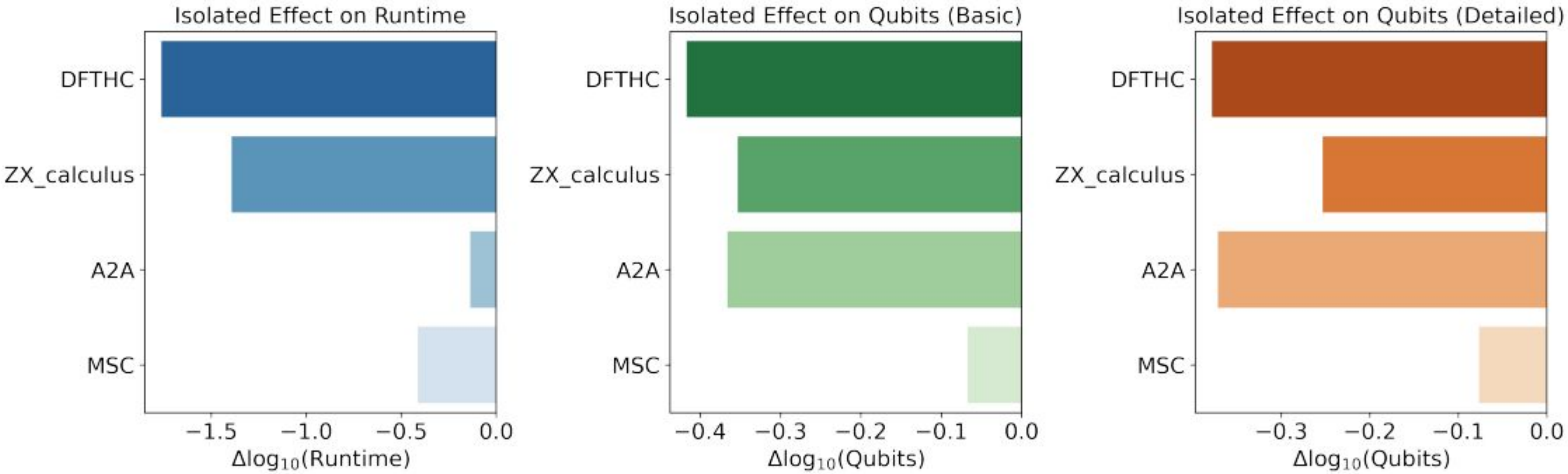
Simulation	Runtime (days)	Qubits (M)	DFTHC	ZX calculus	A2A	MSC
S1	1.0	1.8	1	1	1	1
S9	513.1	7.92	1	0	0	0
S4	57.8	4.7	0	1	1	1

Example 1:
Effect of DFTHC
quantum algorithm

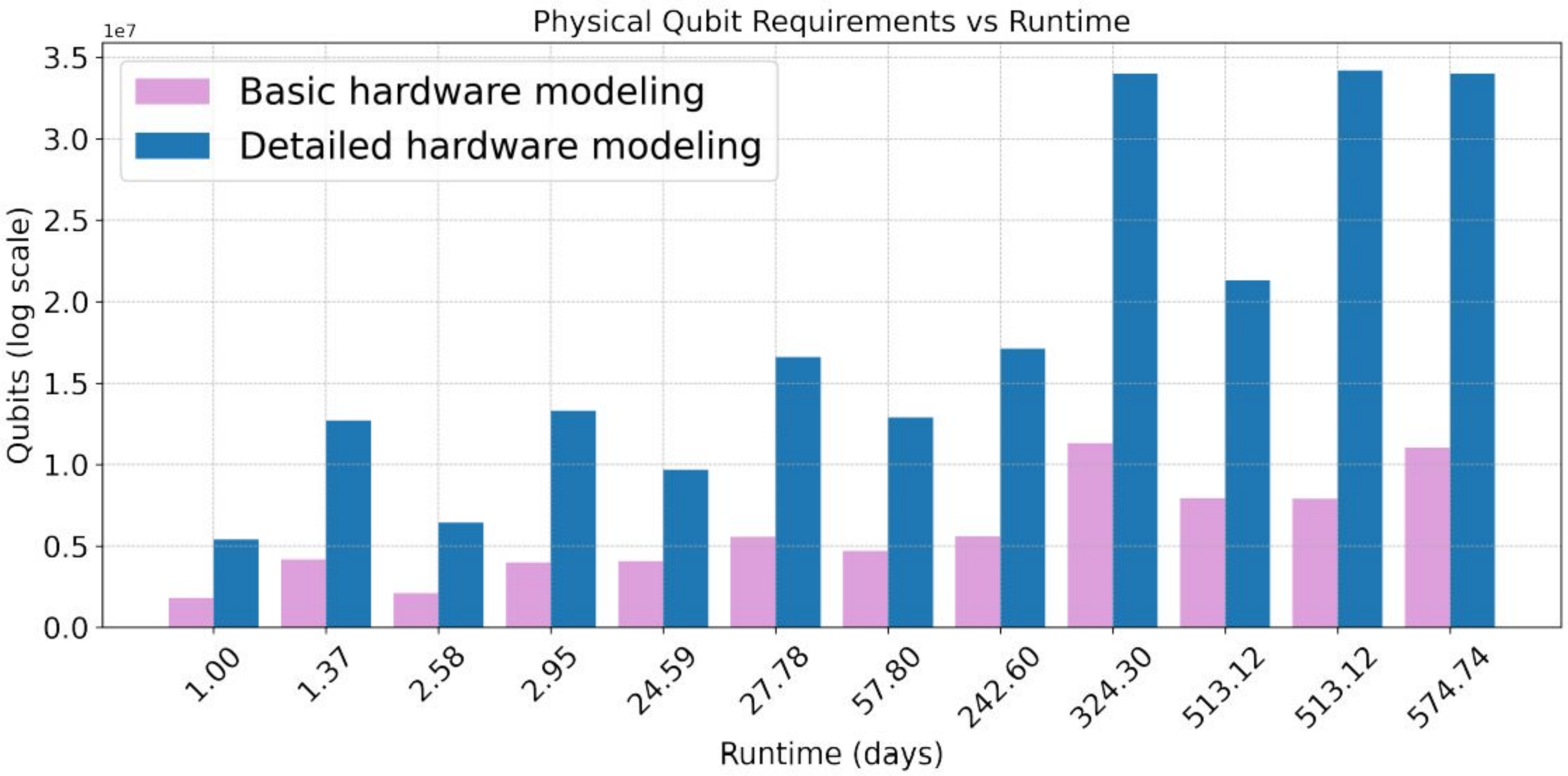
Simulation	Runtime	Qubits (M)	DFTHC	ZX calculus	A2A	MSC
S13	82 years	8.9	0	0	1	0
S7	8 months	5.6	0	1	1	0
S8	27.8 days	5.56	1	0	1	0
S3	2.6 days	2.1	1	1	1	0

Example 2:
Impact of different
combinations of the innovations

Detailed breakdown of QRE



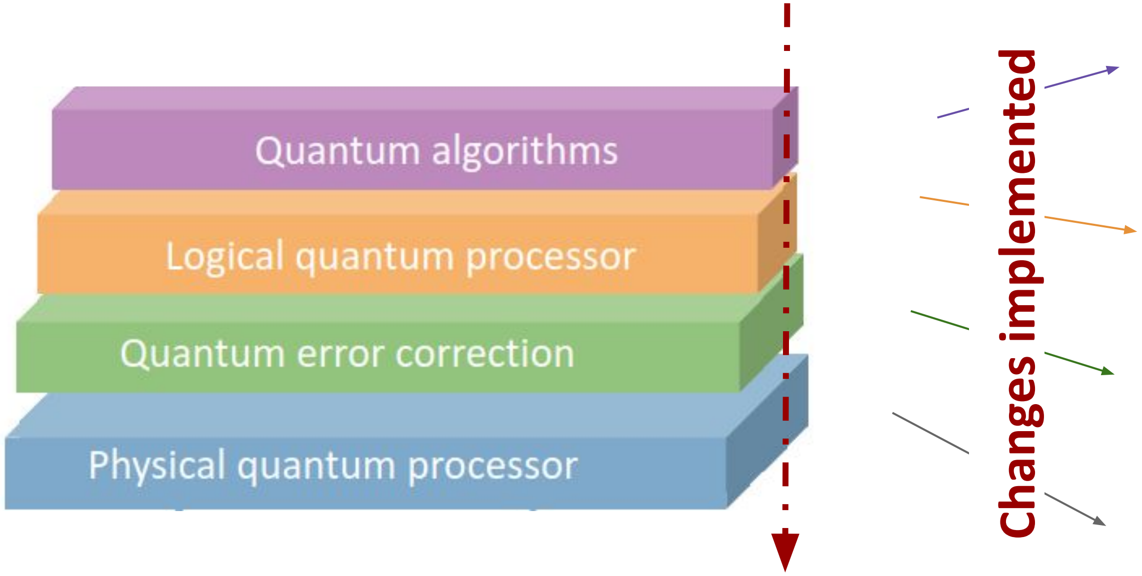
Detailed breakdown of QRE



Note on runtime estimations

Problem: Complex XVII (64e,56o)

Total runtime: **130 years in Beverland et al.***



Quantum algorithms suited for early-fault tolerant quantum computers.

Compilation methods that exploit the hardware connectivity capabilities.

State-of-the-art QEC techniques.

Detailed quantum hardware models.

Total runtime: **6 days in this work***

***Beverland et. al.considered SCC 6e-4 s vs 1e-4 in this work**

Neutral atom QRE analysis:

	Beverland et. al.	This work	This work
Hardware modelling (qubit error rate)	Not specified (1e-4)	Ion-trap (1e-4)	Neutral atoms (1e-4)
Algorithm	DF	DFTHC	DFTHC
ZX calculus	-	yes	yes
Compilation	PBC	GSC	GSC
Layout	Compact	A2A	A2A
MS Protocol	MSF	MSC	MSC
SCC time	1e-4s	1e-4s	6e-4
SCCs	7e12	8.7e08	1.0e08
Runtime	**22 yrs**	**1 day**	**17.6 hours**
Qubits	1.6M	1.8 M (5.4 M)	748K

Neutral atom QRE analysis:

	Beverland et. al.	This work	This work
Hardware modelling (qubit error rate)	Not specified (1e-4)	Ion-trap (1e-4)	Neutral atoms (1e-4)
Algorithm	DF	DFTHC	DFTHC
ZX calculus	-	yes	yes
Compilation	PBC	GSC	GSC
Layout	Compact	A2A	A2A
MS Protocol	MSF	MSC	MSC
SCC time	1e-4s	1e-4s	6e-4
SCCs	7e12	8.7e08	1.0e08
Runtime	**22 yrs**	**1 day**	**17.6 hours**
Qubits	1.6M	1.8 M (5.4 M)	748K

Thompson, J. D. et.al. (2022). Erasure conversion for fault-tolerant quantum computing in alkaline-earth Rydberg atom arrays. *Nature Communications*, 13, 4657.

Erasure conversion enabled by high-fidelity atom loss detection in neutral atom arrays raises the error threshold to 4.15e-2 from 1.4e-2 typically used.

$$p_{\log} = A \left(\frac{p_{\text{phys}}}{p_{\text{th}}} \right)^{\frac{d+1}{2}}$$

Results to both smaller runtime and physical qubit counts.

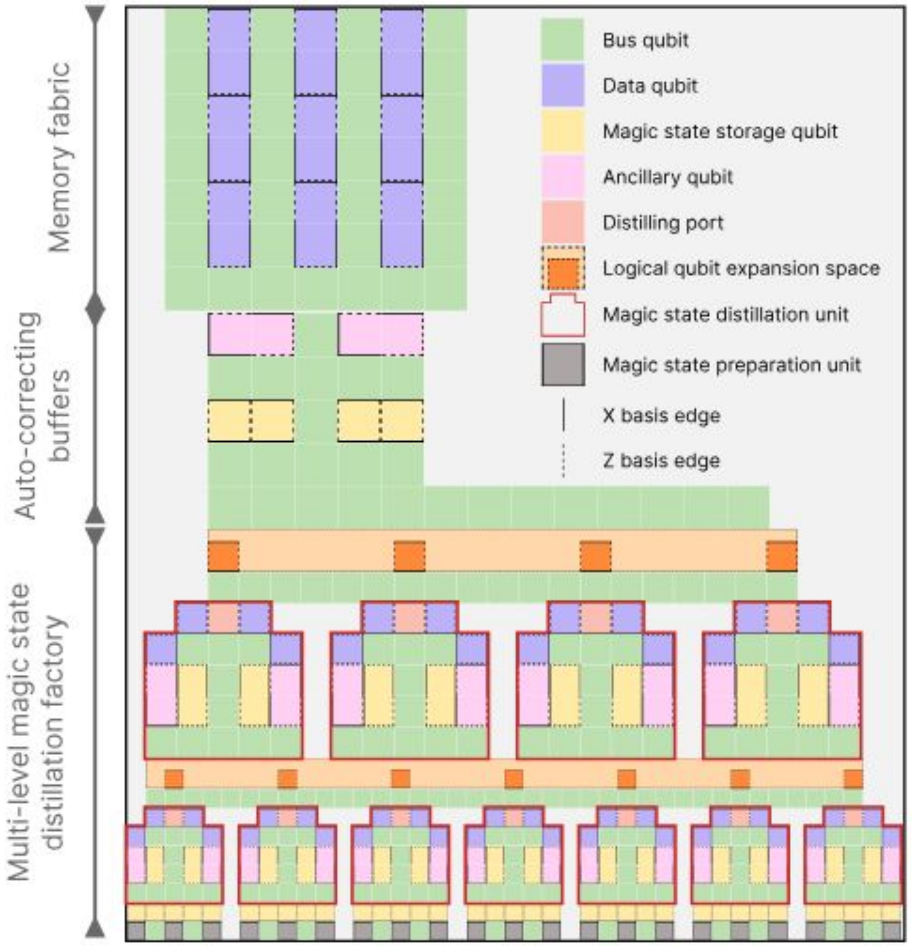
Superconducting qubits QRE analysis:

arXiv:2411.10406

How to Build a Quantum Supercomputer: Scaling from Hundreds to Millions of Qubits

Masoud Mohseni,[1,2,*] Artur Scherer,[3] K. Grace Johnson,[1] Oded Wertheim,[4] Matthew Otten,[5] Namit Anand,[1,6,7] Navid Anjum Aadit,[8] Yuri Alexeev,[9] Gilad Ben-Shach,[4] Kirk M. Bresniker,[10] Kerem Y. Camsari,[8] Barbara Chapman,[11] Soumitra Chatterjee,[11] Gebremedhin A. Dagnew,[3] Tom Dvir,[4] Aniello Esposito,[10] Farah Fahim,[12] Marco Fiorentino,[1] Archit Gajjar,[2] Katerina Gratsea,[5] Gaurav Gyawali,[1] Christian Heiter,[1] Ali Kavaki,[3] Abdullah Khalid,[3] Xiangzhou Kong,[3] Bohdan Kulchytskyy,[3] Elica Kyoseva,[9] Ruoyu Li,[13] P. Aaron Lott,[6,7] Igor L. Markov,[14] Robert F. McDermott,[5,15] Giacomo Pedretti,[2] Pooja Rao,[9] Eleanor Rieffel,[7] Allyson Silva,[3] John Sorebo,[14] Panagiotis Spentzouris,[12] Ziv Steiner,[4] Boyan Torosov,[3] Davide Venturelli,[16,7] Robert J. Visser,[13] Zak Webb,[3] Xin Zhan,[1] Michael Ferguson,[1] Yonatan Cohen,[4] Pooya Ronagh,[3,17,18,19] Alan Ho,[15] Raymond G. Beausoleil,[1,2] and John M. Martinis[15,†]

Complex XVIII System			
# Orbitals	**56**	**100**	**150**
# Log. Qubits	924	1960	2870
# T gates	8.2×10^8	4.2×10^9	1.1×10^{10}
Desired Parameters Set:			
Time-optimal			
Phys. Runtime	2.2 hours	11.1 hours	1.2 days
# Phys. Qubits	2.9×10^6	6.4×10^6	9.1×10^6
Space-optimal			
Phys. Runtime	8.1 hours	5.1 days	2.3 days
# Phys. Qubits	2.6×10^6	6.0×10^6	8.9×10^6



TopQAD software

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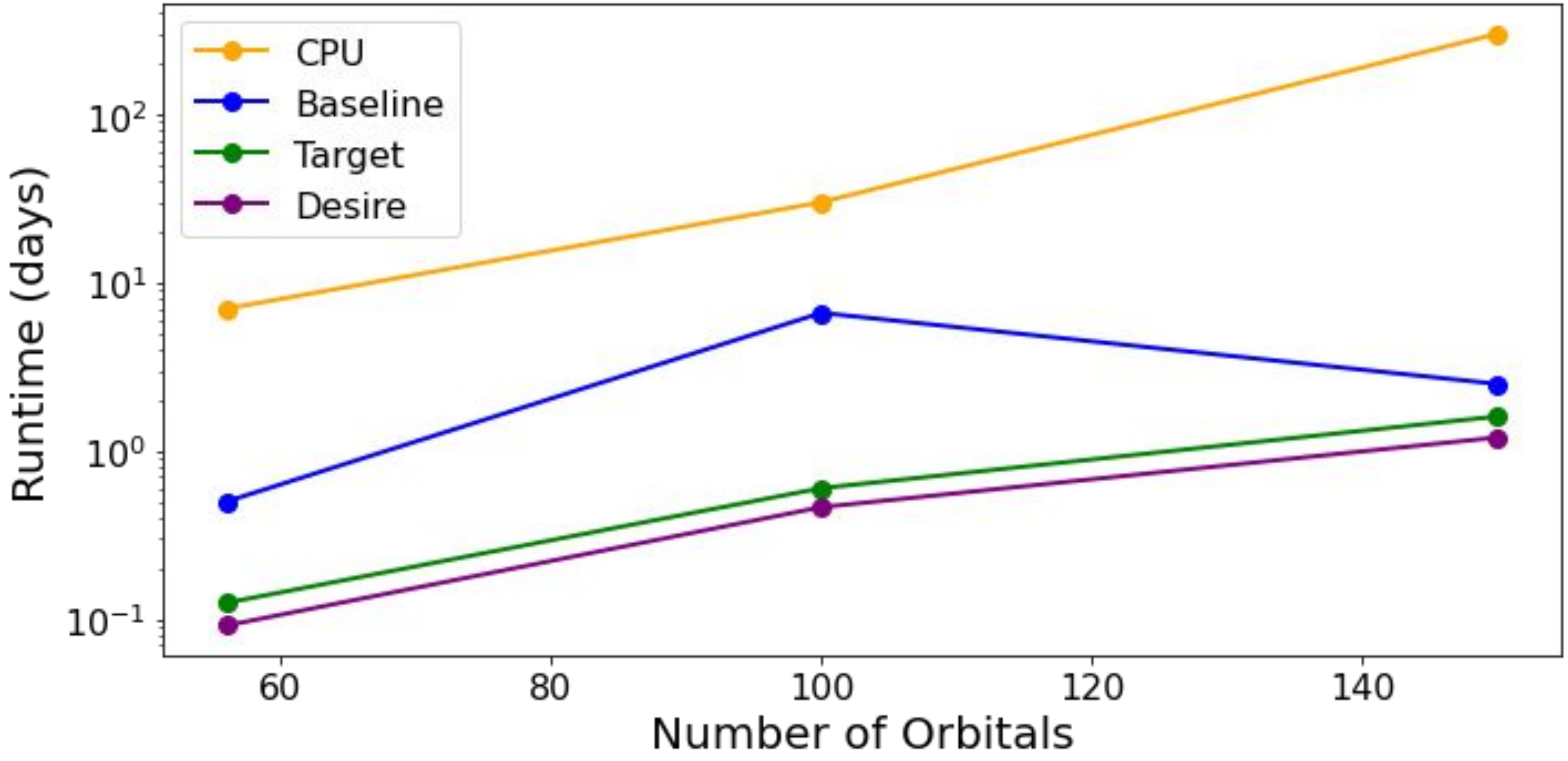
Complex XVIII System

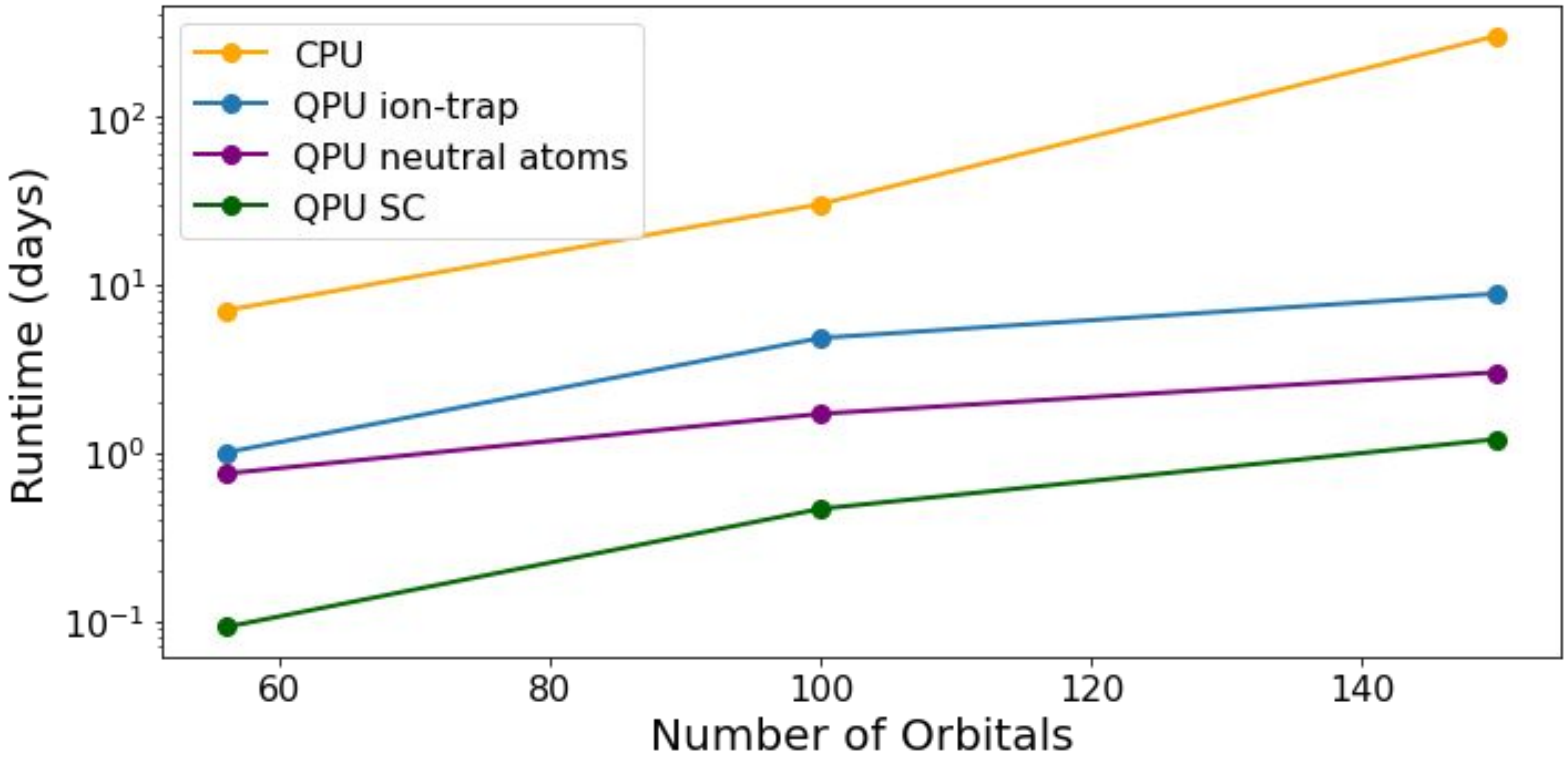
# Orbitals	**56**	**100**	**150**
# Log. Qubits	924	1960	2870
# T gates	8.2×10^8	4.2×10^9	1.1×10^{10}
Baseline Parameters Set:			
Time-optimal			
Phys. Runtime	12.0 hours	6.6 days	2.5 days
# Phys. Qubits	5.7×10^7	9.7×10^7	1.4×10^9
Space-optimal			
Phys. Runtime	7.2 days	17.2 days	54.9 days
# Phys. Qubits	3.3×10^7	7.5×10^7	1.2×10^8
Target Parameters Set:			
Time-optimal			
Phys. Runtime	3.0 hours	14.4 hours	1.6 days
# Phys. Qubits	5.4×10^6	1.1×10^7	1.6×10^7
Space-optimal			
Phys. Runtime	1.3 days	4.1 days	3.1 days
# Phys. Qubits	4.4×10^6	1.0×10^7	1.5×10^7

TopQAD software

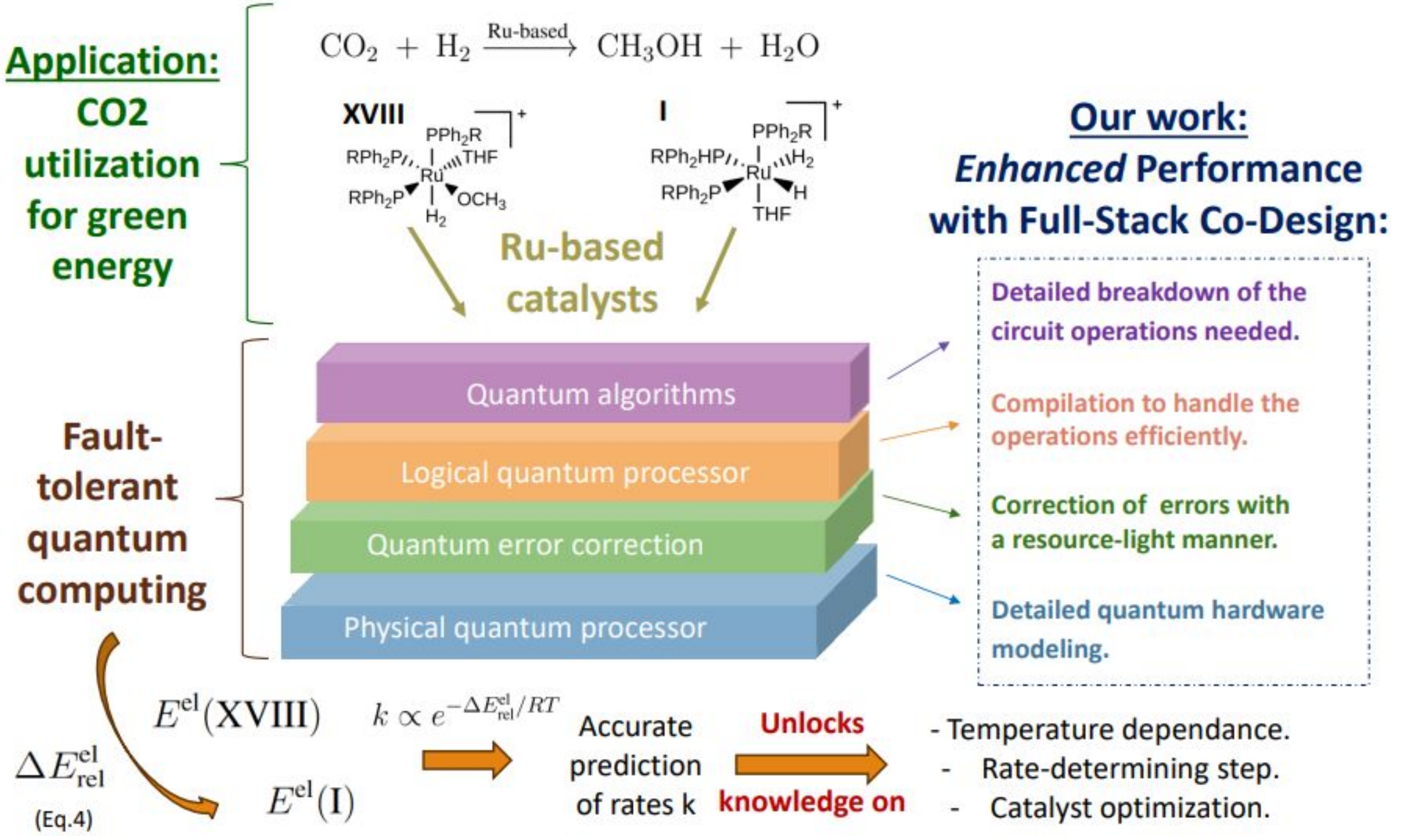
Predicted Runtime Quantum Advantage:



Predicted Runtime Quantum Advantage:



In a nutshell:



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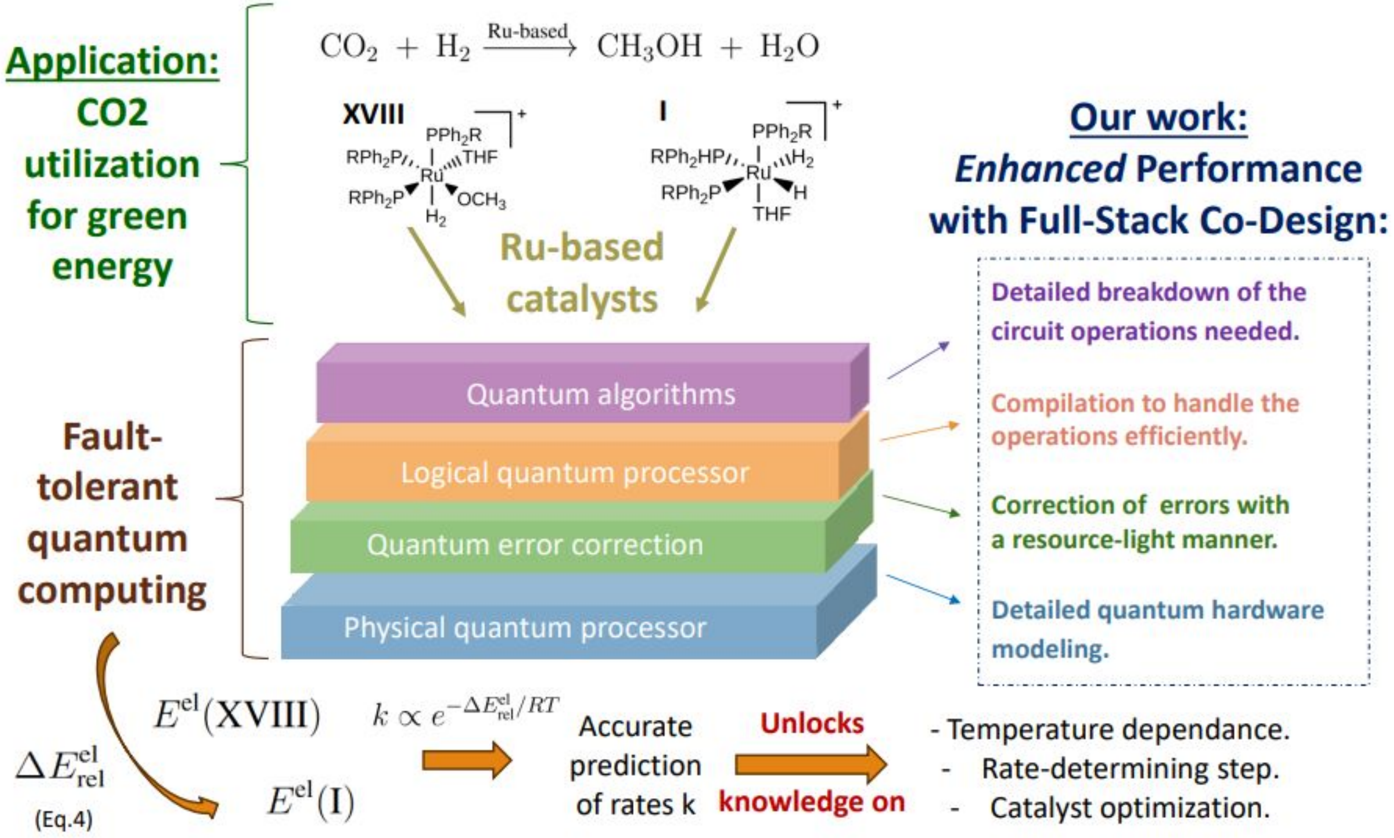
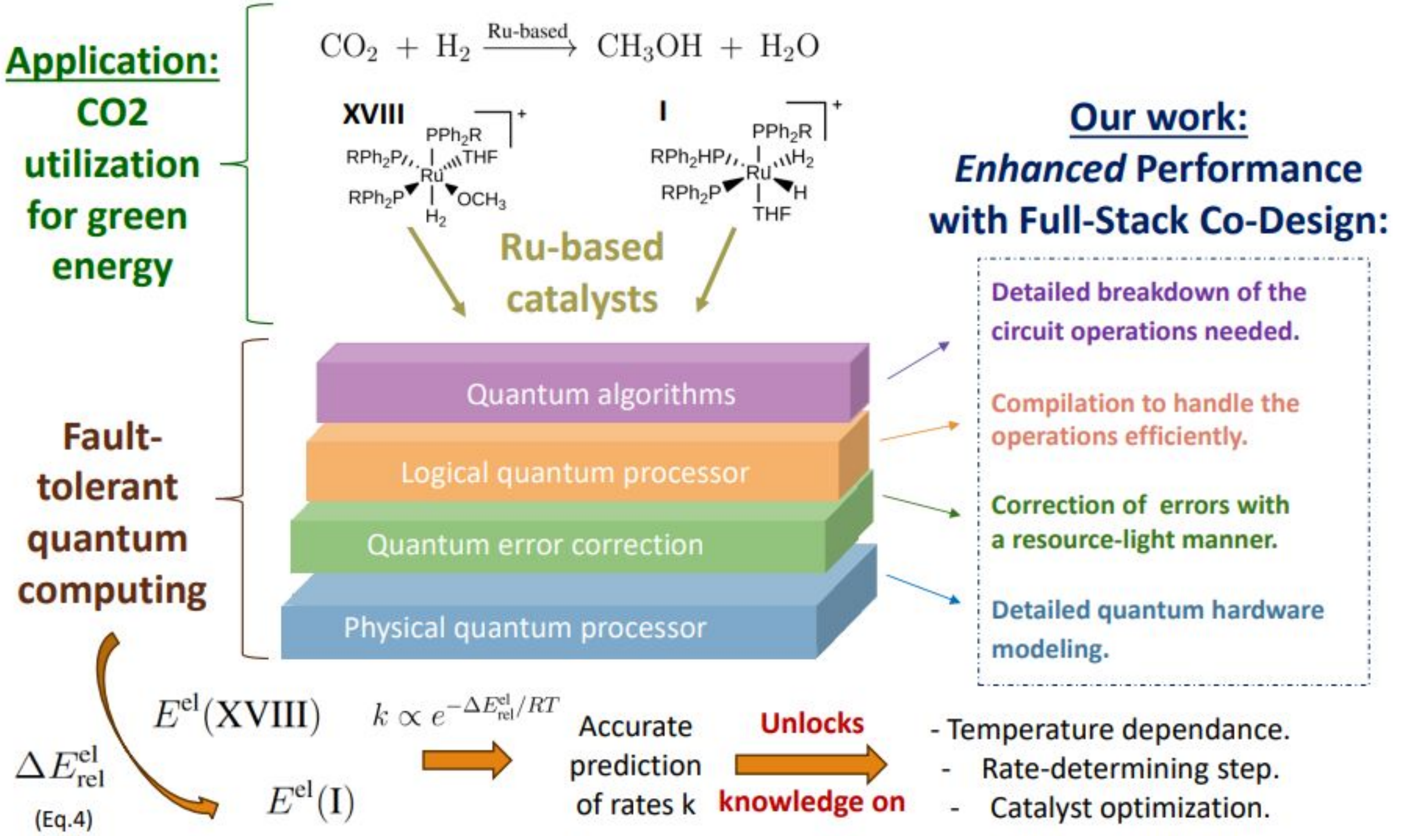


4. Transitioning to FTQC will require multidisciplinary expertise - what do researchers from your discipline need from other disciplines? E.g., what do quantum algorithm developers need from quantum computer architects, etc.?

5. What is the most important open problem in your corner of quantum computing?

In a nutshell:



For quantum computing to fulfill its potential:

- ➢ all layers of computation must advance in parallel,
- ➢ Quantum Resource Estimations can guide R&D efforts and
- ➢ identification of utility-scale applications is crucial for real-world impact.

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