VAQEM: A Variational Approach to Quantum Error Mitigation

Gokul Subramanian Ravi*

Postdoc, University of Chicago / EPiQC

UChicago: Kaitlin Smith , Fred Chong **Super.tech:** Pranav Gokhale

IBM: Nate Earnest-Noble, Ali Javadi-Abhari **Unitary Fund:** Andrea Mari

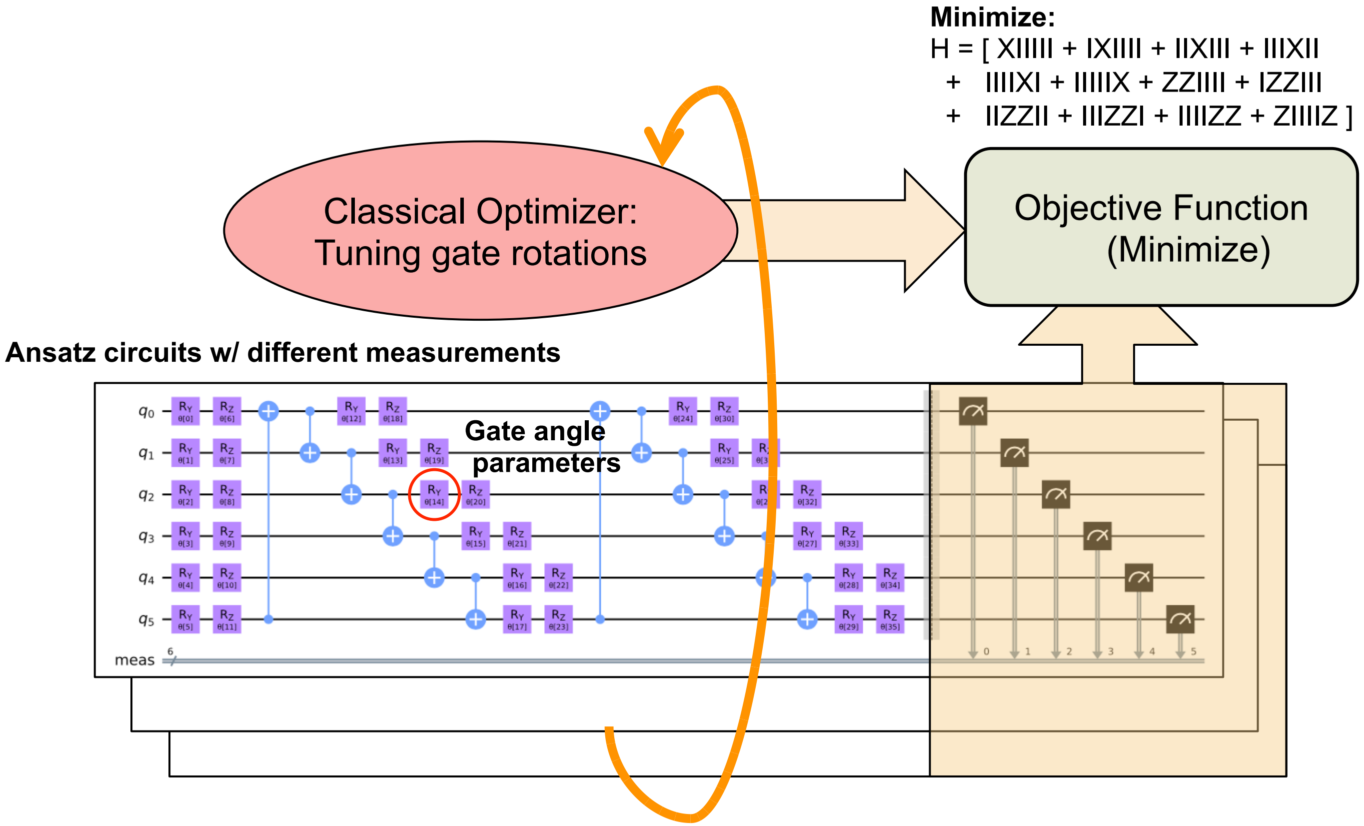
CCF-1730082/1730449, NSF Phy-1818914, DE-SC0020289, DE-SC0020331, NSF OMA-2016136, Q-NEXT DOE NQI Center, CIFellows (NSF 2030859) and IBM/CQE.

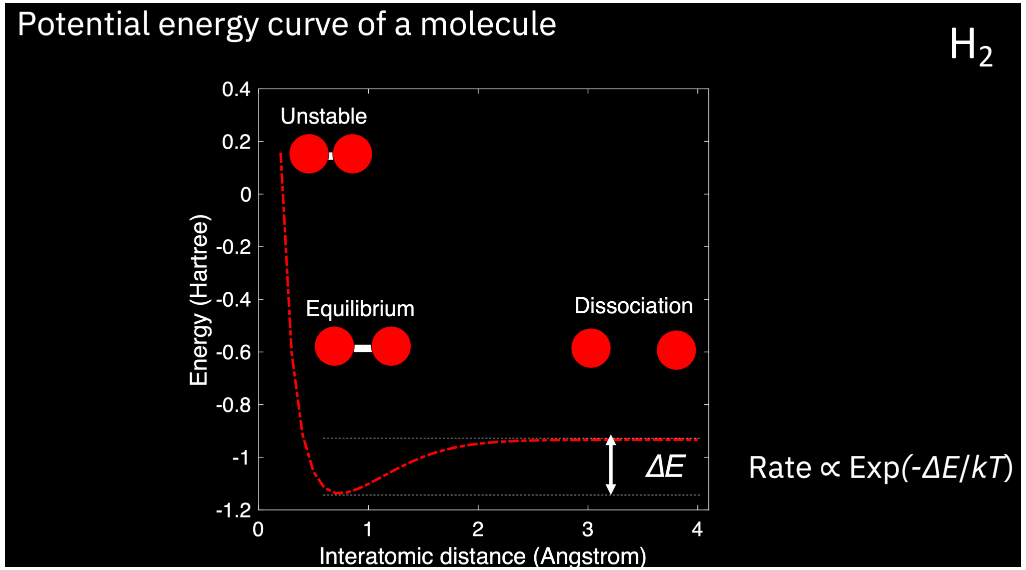
HPCA 04/04/2022

Summary: A variational approach to quantum error mitigation

- Background: VQAs are considered suitable to the NISQ era, but machine fidelity is still too low for real world applicability.
- Goal: Apply error mitigation in an optimal manner to VQAs for max fidelity – but this is challenging as device and circuit complexity increase.
- Proposal:
  - Integrate EM techniques into VQA's framework of iterative parameter tuning: enabling a feedback-based approach towards optimal EM for the application / device.
  - Targets two idle-time EM methods: insertion of dynamical decoupling sequences and single-qubit gate scheduling.
- Result: Improves the quality of the VQA measured objective by 3x on average.

Variational Quantum Algorithms



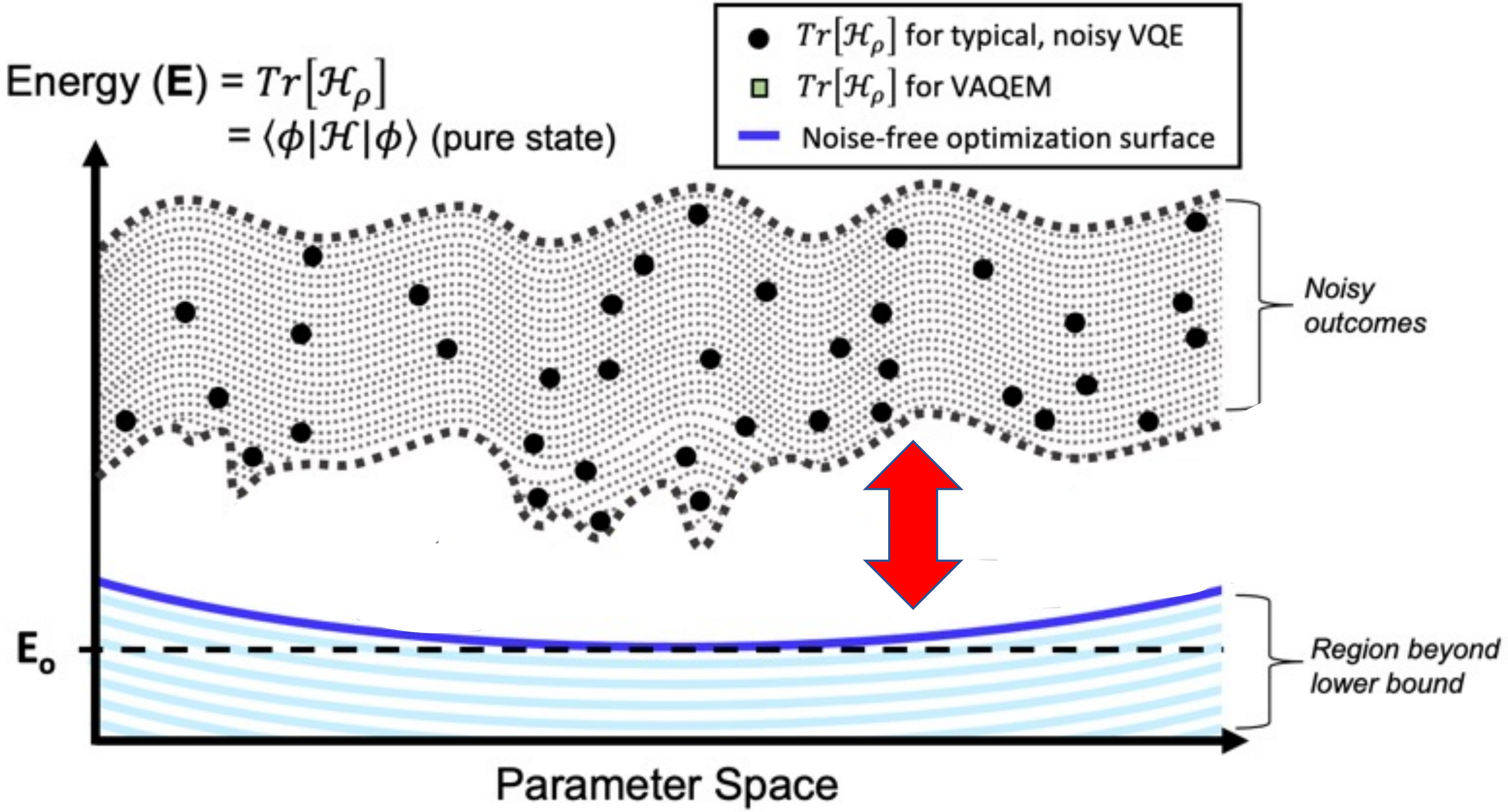


Variational principle: the energy of any trial wave-function is greater than or equal to the exact ground state energy

$$\frac{\langle \Psi(\vec{\theta}) | H | \Psi(\vec{\theta}) \rangle}{\langle \Psi(\vec{\theta}) | \Psi(\vec{\theta}) \rangle} \geq E_G$$

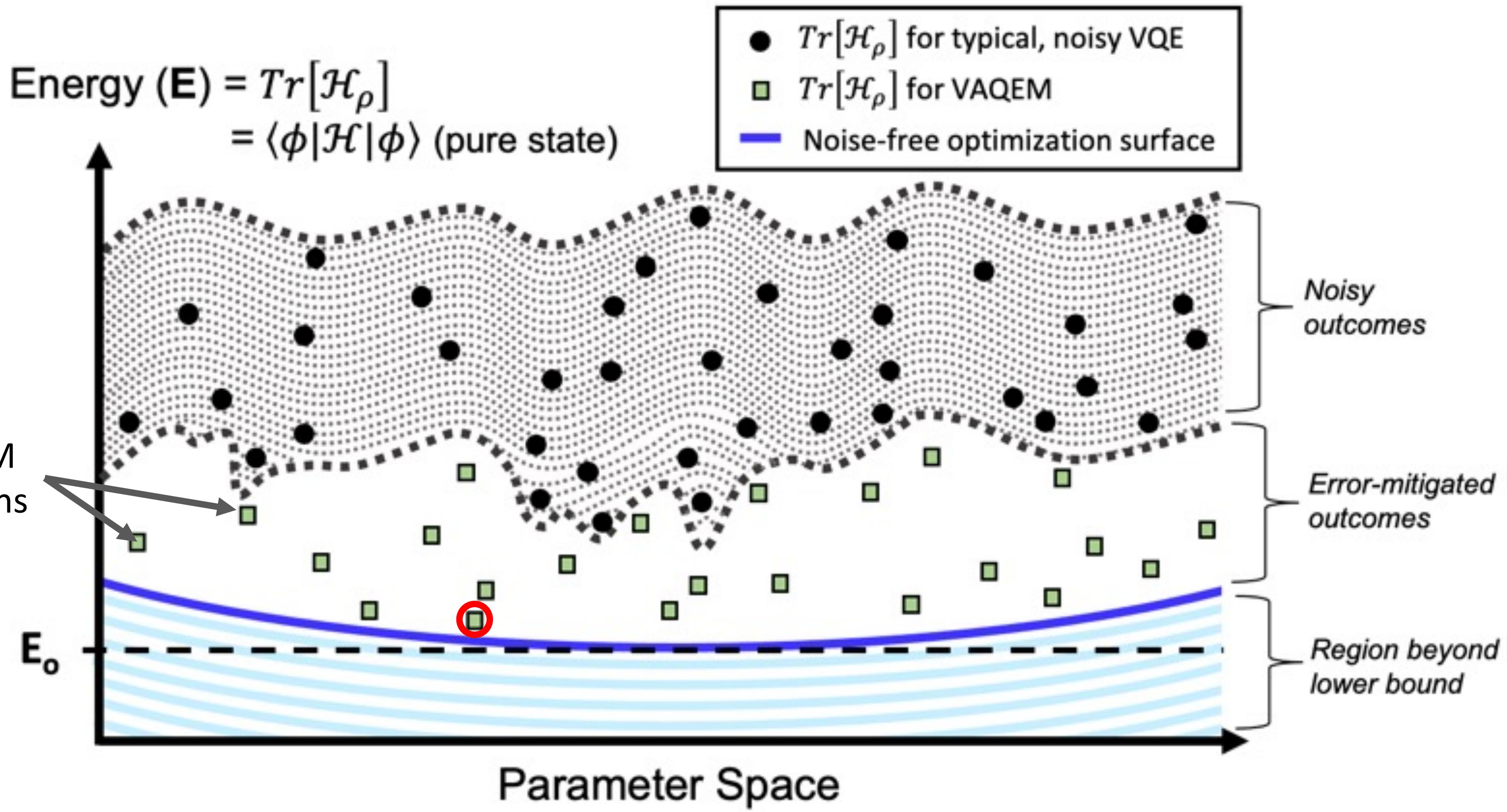
https://qiskit.org/learn/intro-qc-qh/

VQA Fidelity in the NISQ era



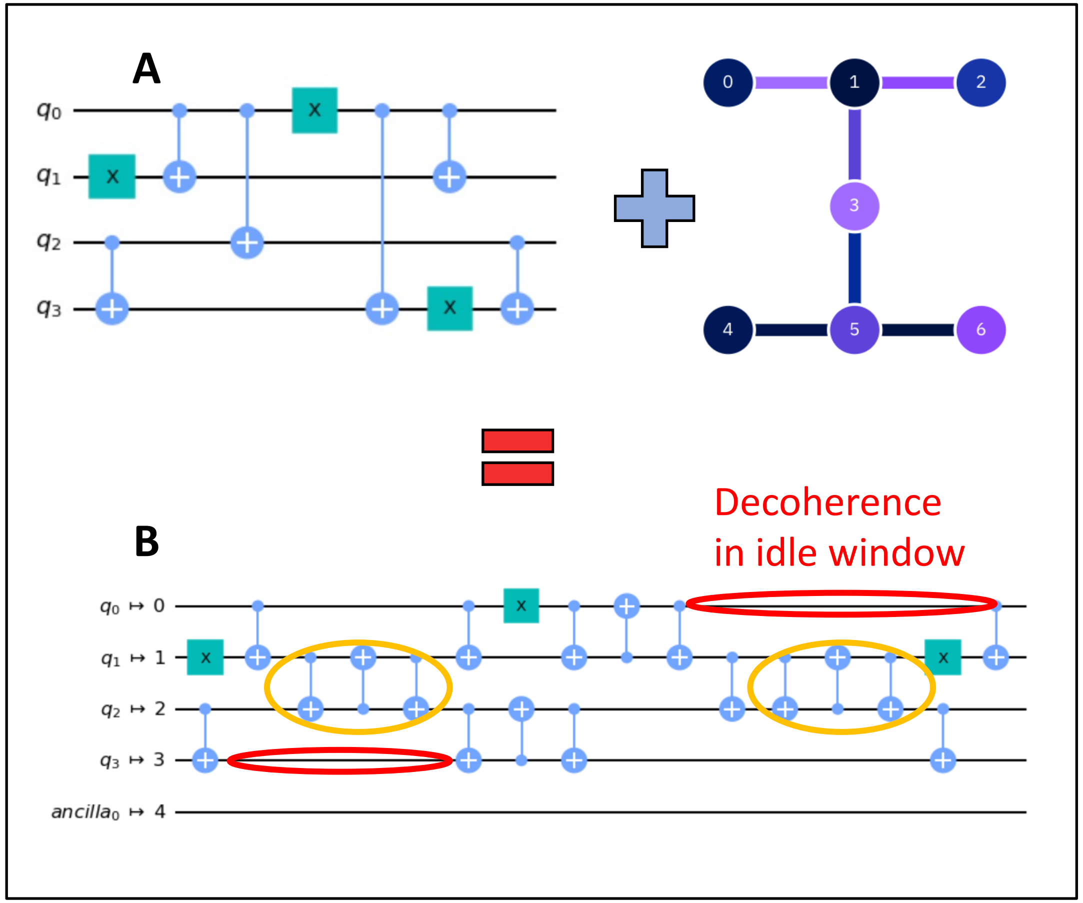
Impact of Error Mitigation

Different EM configurations

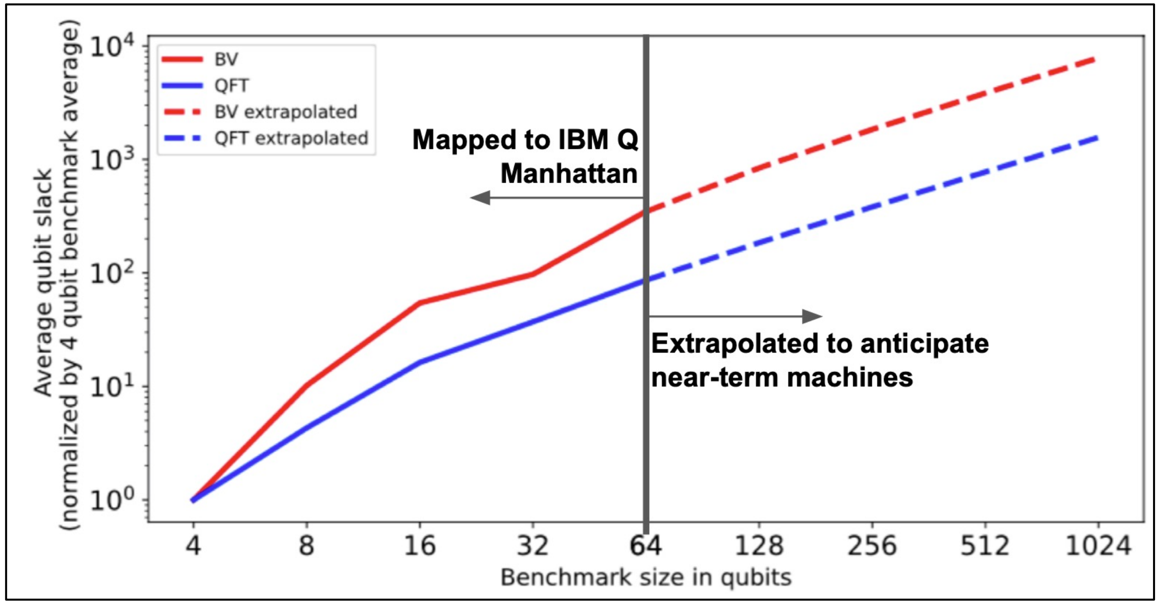


EM targeting QC Idle windows

Compiling for machines with limited connectivity leads to increased depth and long critical paths



As application sizes increases, path lengths become longer and more diverse leading to more slack

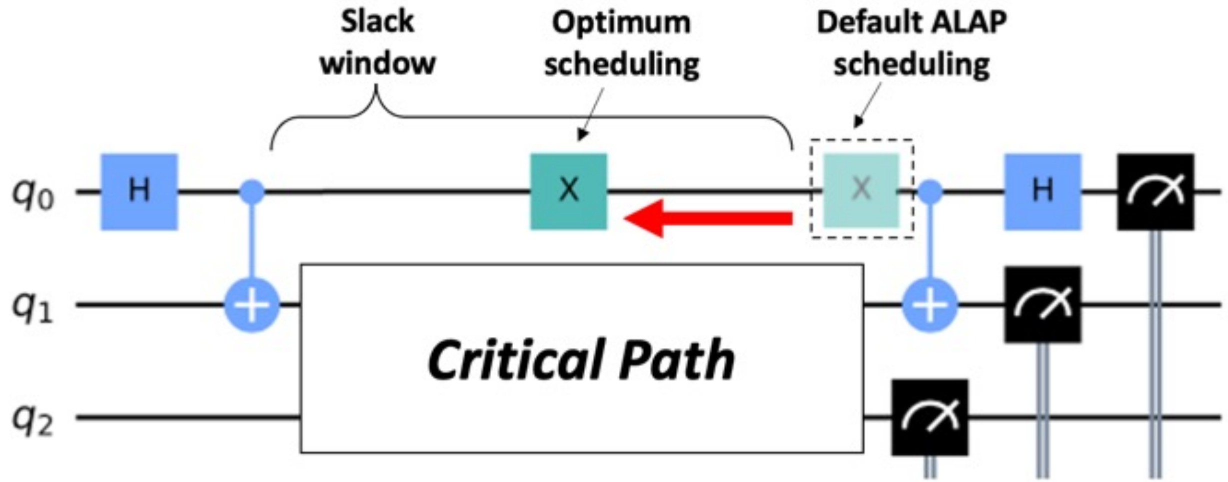


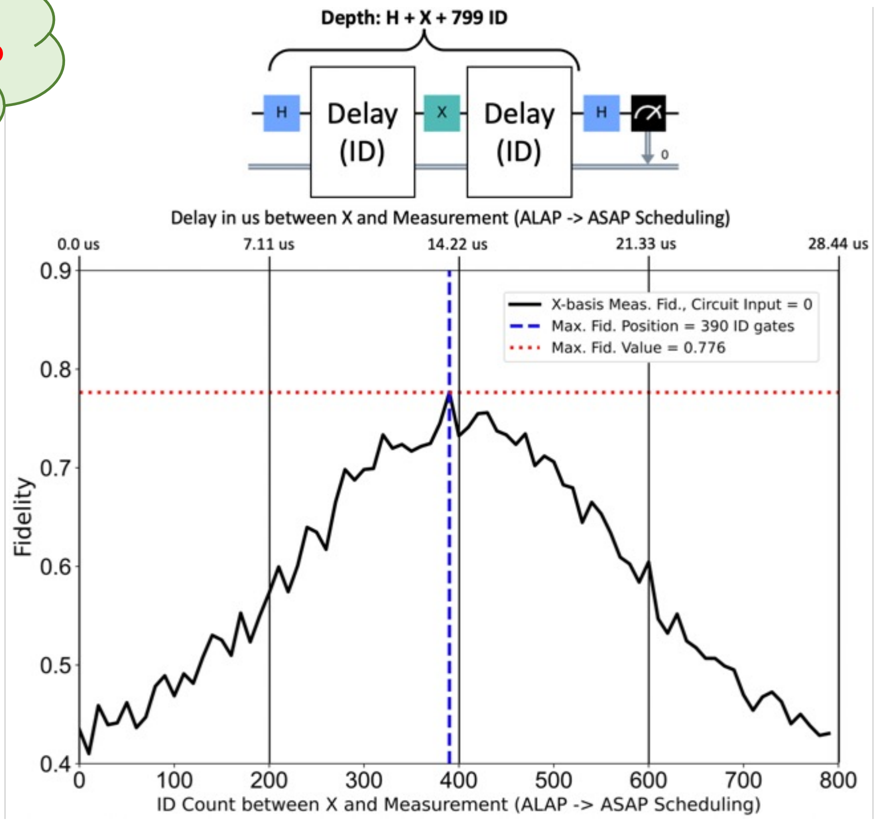
Kaitlin N. Smith , Gokul Ravi, Prakash Murali, Jonathan Baker, Nathan Earnest, Ali Javadi-Abhari, Frederic T. Chong.
TimeStitch: Error Mitigation in Quantum Computers through Instruction Scheduling. 2021

Idle Window Signal Refocusing: 1Q gate scheduling

Spin Echo Correction: Details in the paper!

optimal position?



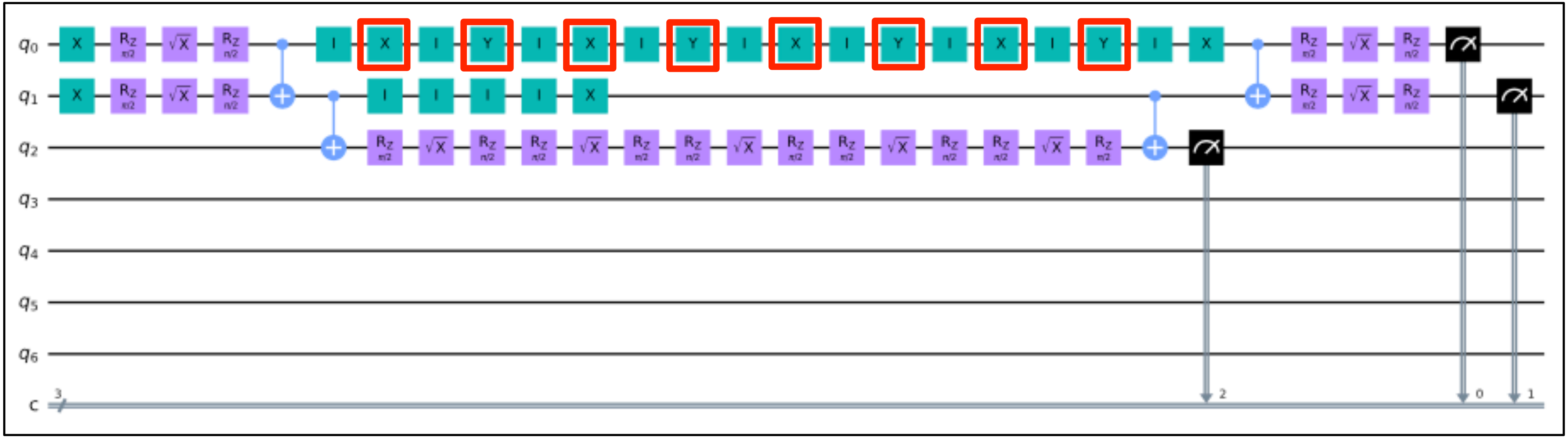


Kaitlin N. Smith , Gokul Ravi, Prakash Murali, Jonathan Baker, Nathan Earnest, Ali Javadi-Abhari, Frederic T. Chong.
TimeStitch: Error Mitigation in Quantum Computers through Instruction Scheduling. 2021

Idle Window Signal Refocusing: Dynamic decoupling

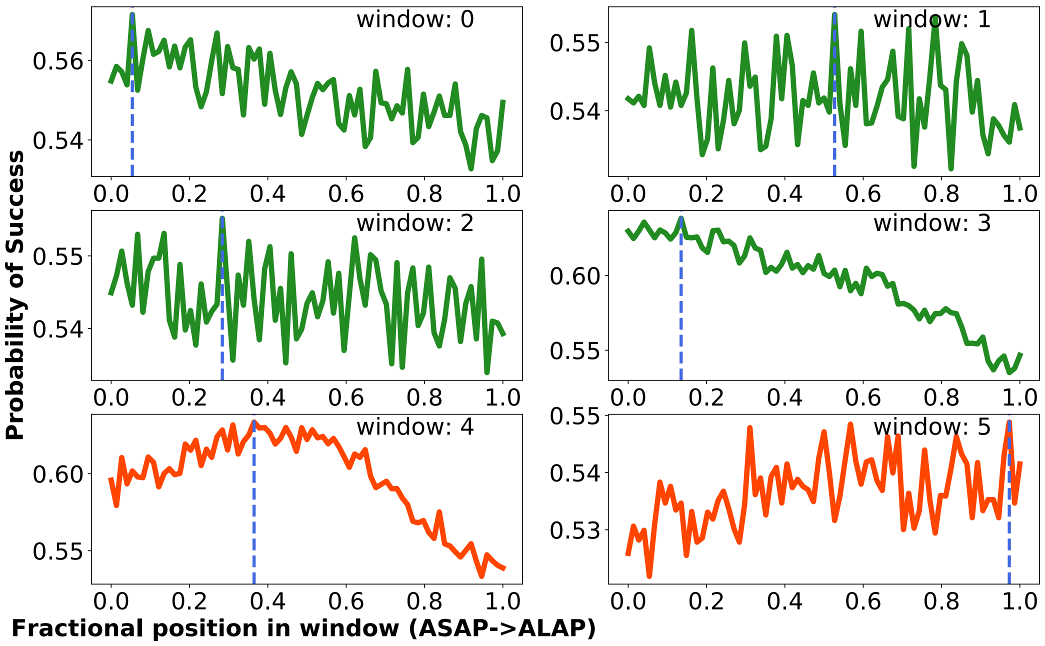
Spin Echo Correction: Details in the paper!

optimal gate types / number / spacing ?

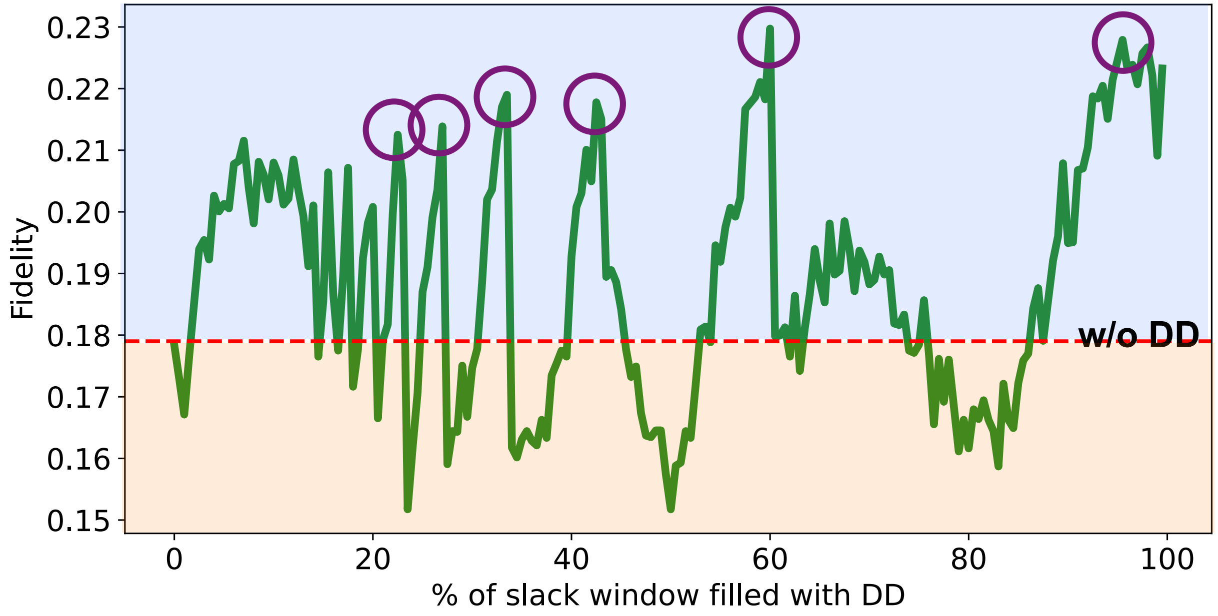


Optimizing EM: practical challenges

1) Imperfect knowledge of stimuli and their effects makes theory driven EM heuristics less effective.



1q gate scheduling



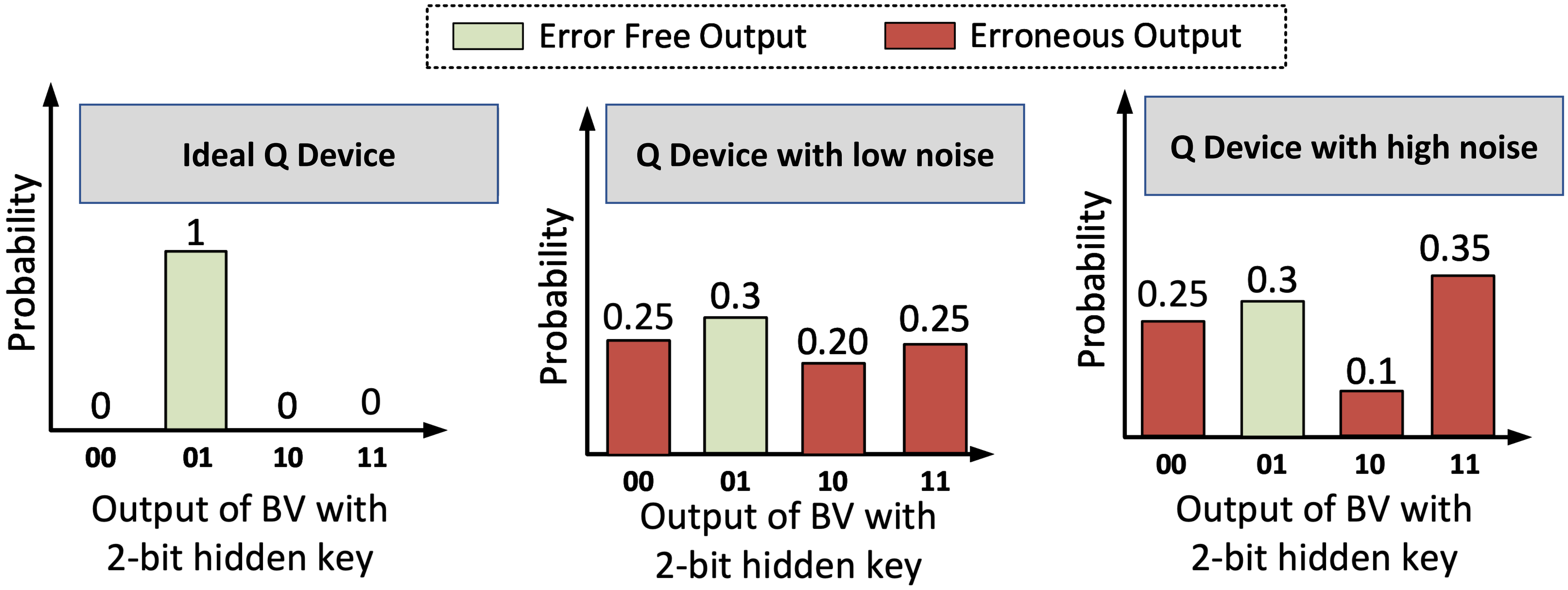
DD insertion

Optimizing EM: practical challenges

2) Micro-analyzing stimuli effects for every EM instance is not scalable.

Optimizing EM: practical challenges

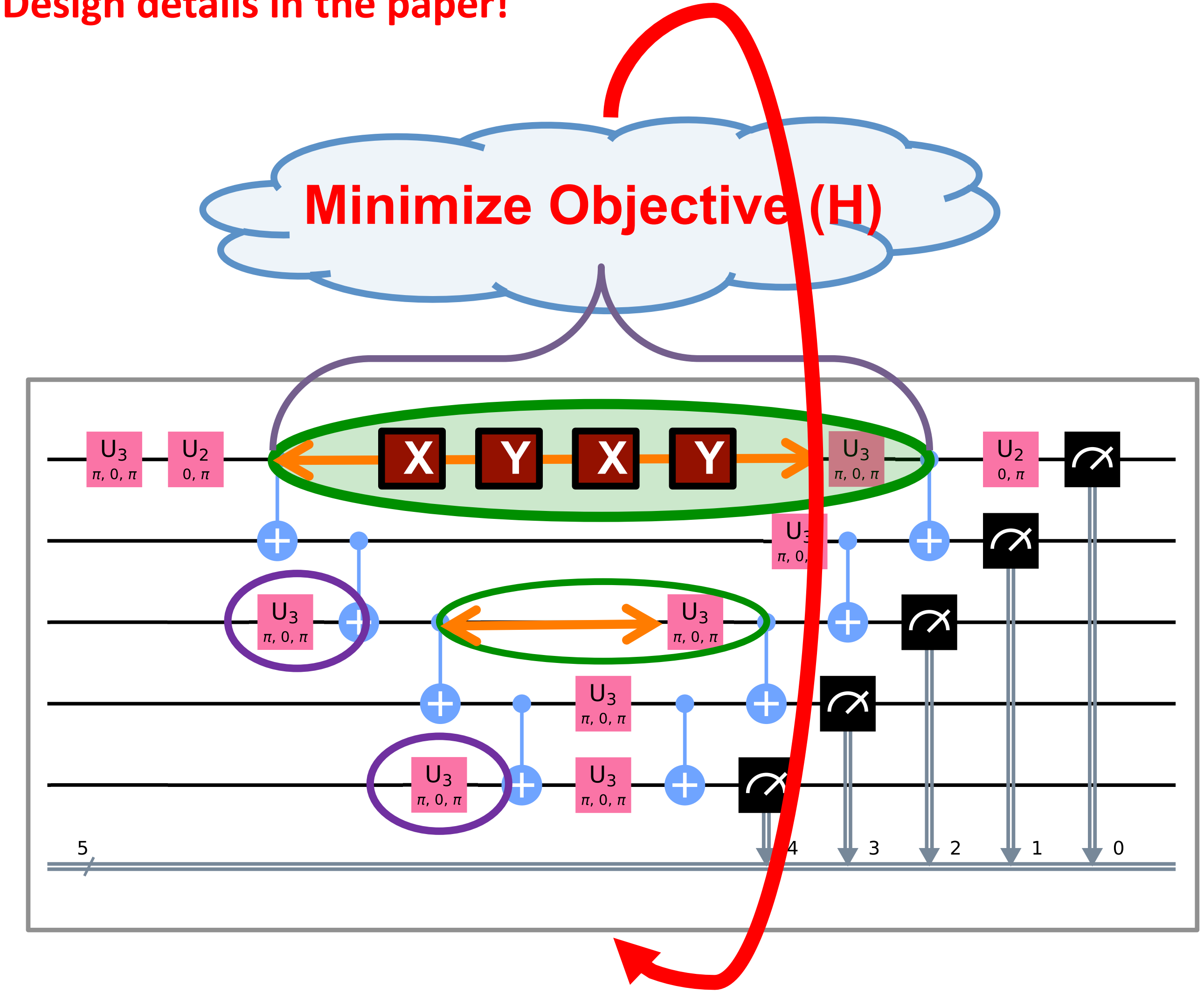
3) Stimuli-agnostic outcome driven approaches are not always possible since outcomes are often unknown and usually not of highest probability.



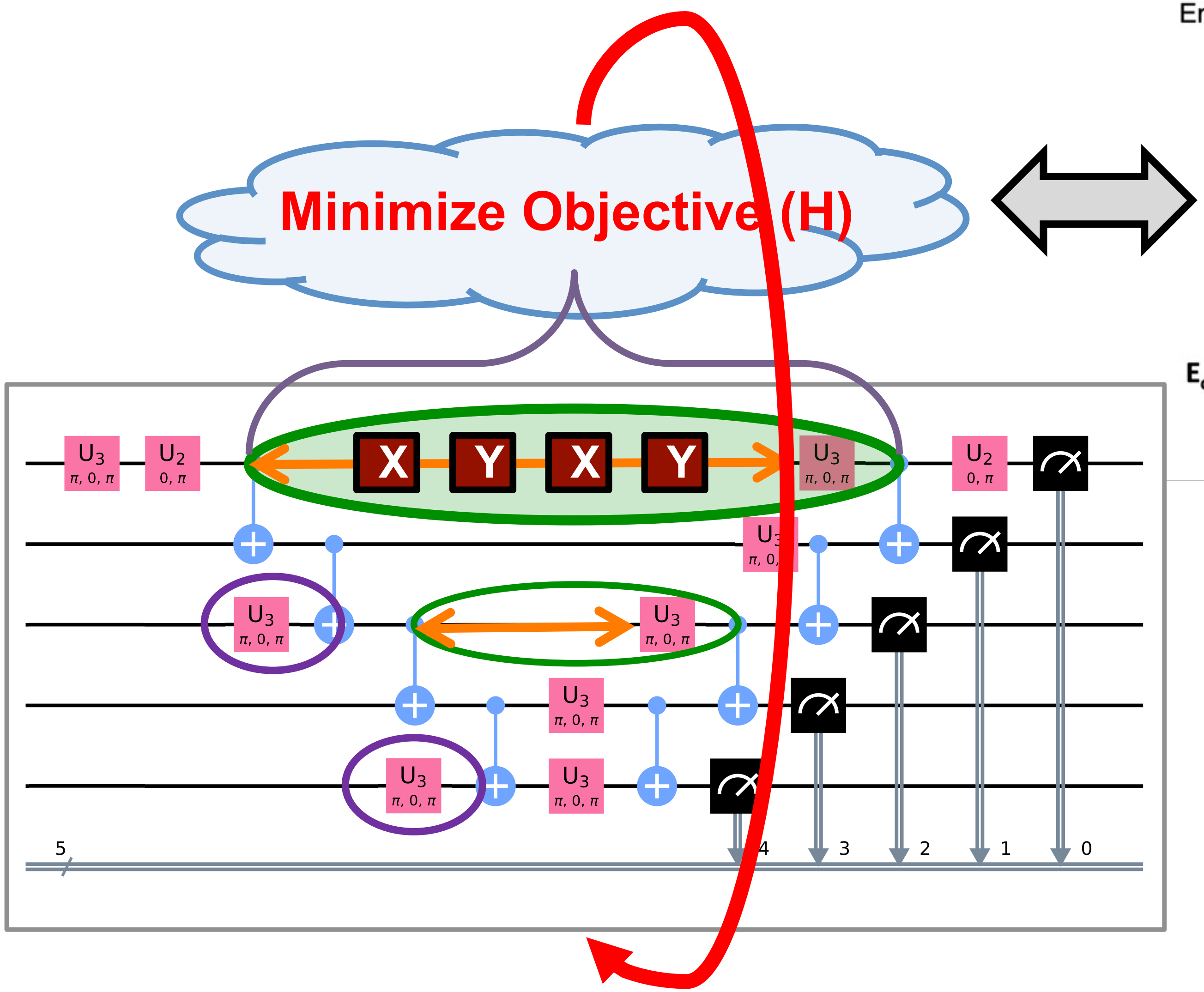
* Ensemble of Diverse Mappings MICRO2019

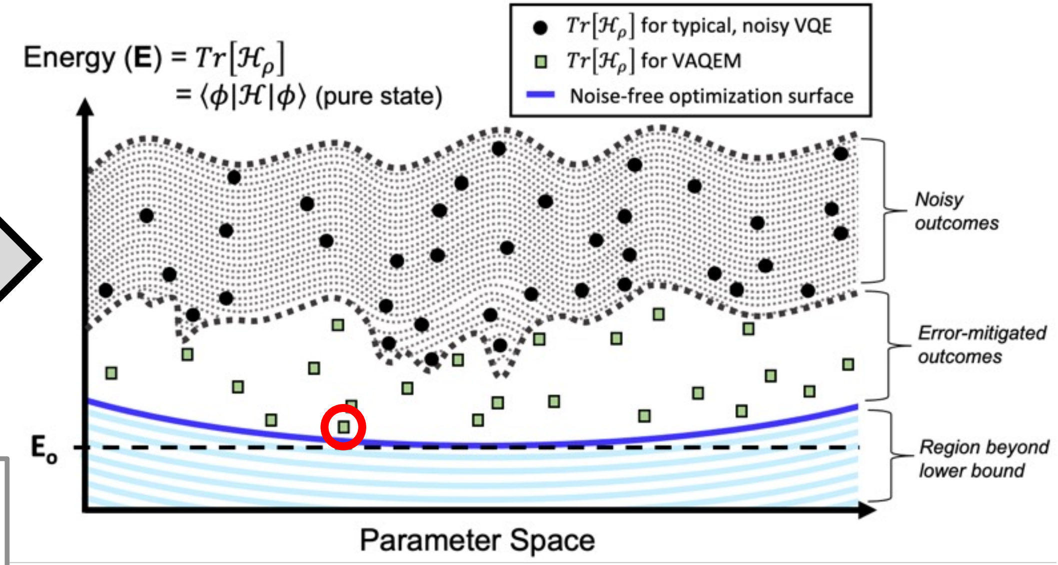
VAQEM: Tuning EM features in the VQA setting

Design details in the paper!



VAQEM: Tuning EM features in the VQA setting



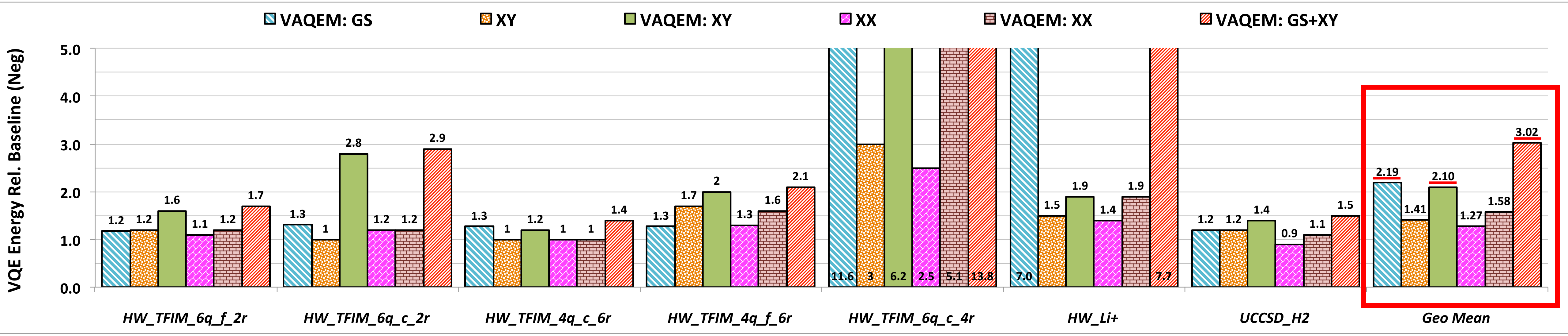


$$\frac{\langle\Psi(\vec{\theta})|H|\Psi(\vec{\theta})\rangle}{\langle\Psi(\vec{\theta})|\Psi(\vec{\theta})\rangle} \geq E_G$$

Only *quantum* EM – details in the paper!

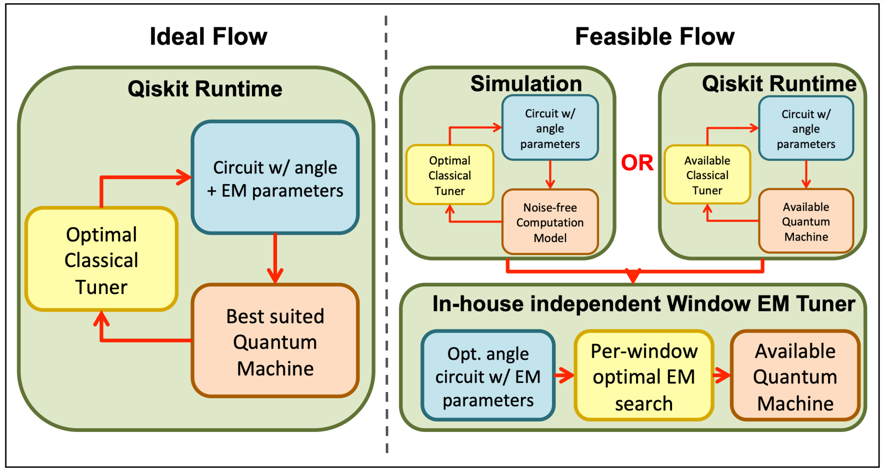
VQE benefits from VAQEM I

Bench	6q/f/2r	6q/c/2r	4q/c/6r	4q/f/6r	6q/c/4r	Li+	H2
Depth	54	31	57	101	55	90	61
# Win	42	24	22	34	30	45	26

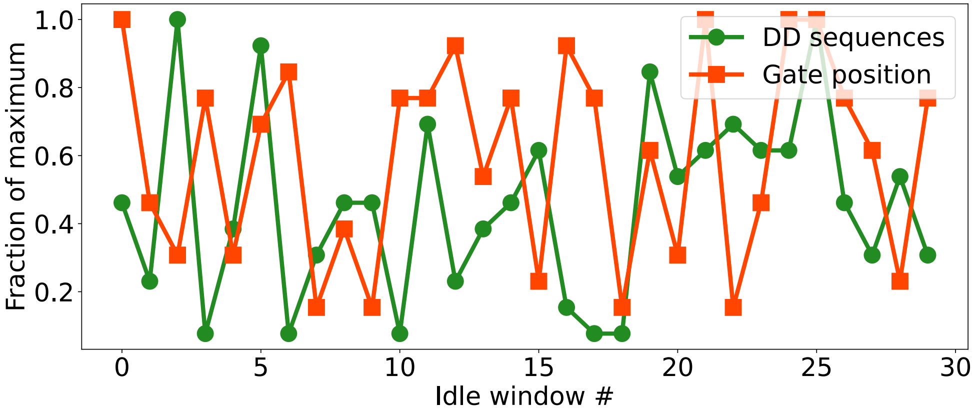


More in the paper:

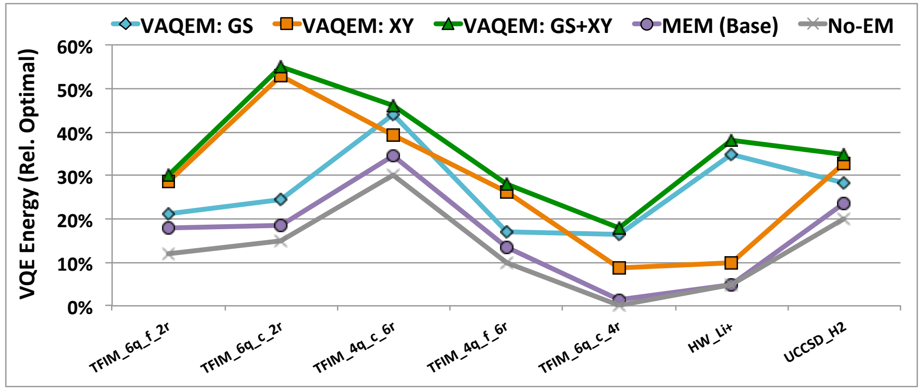
1



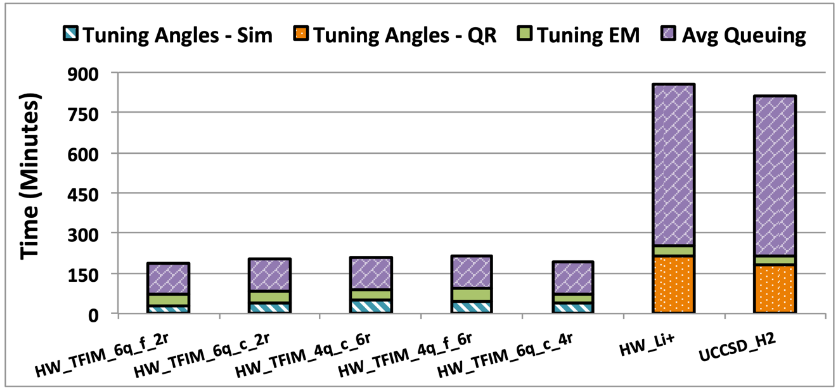
2



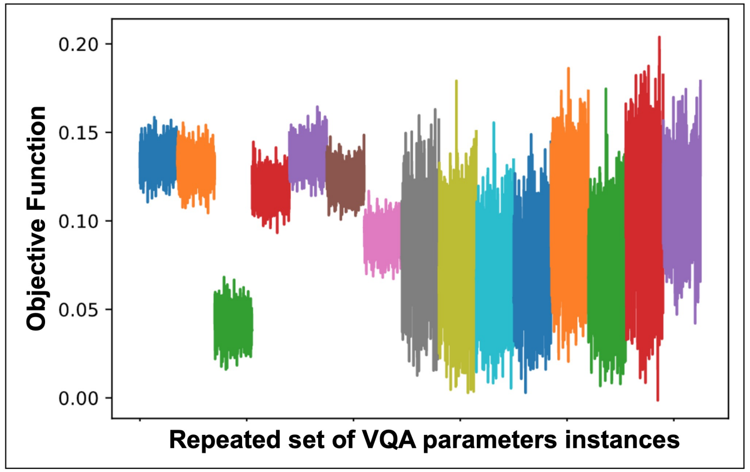
3



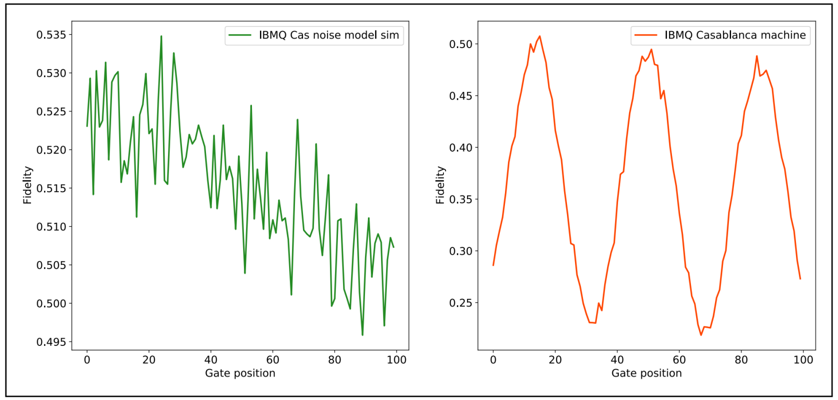
4



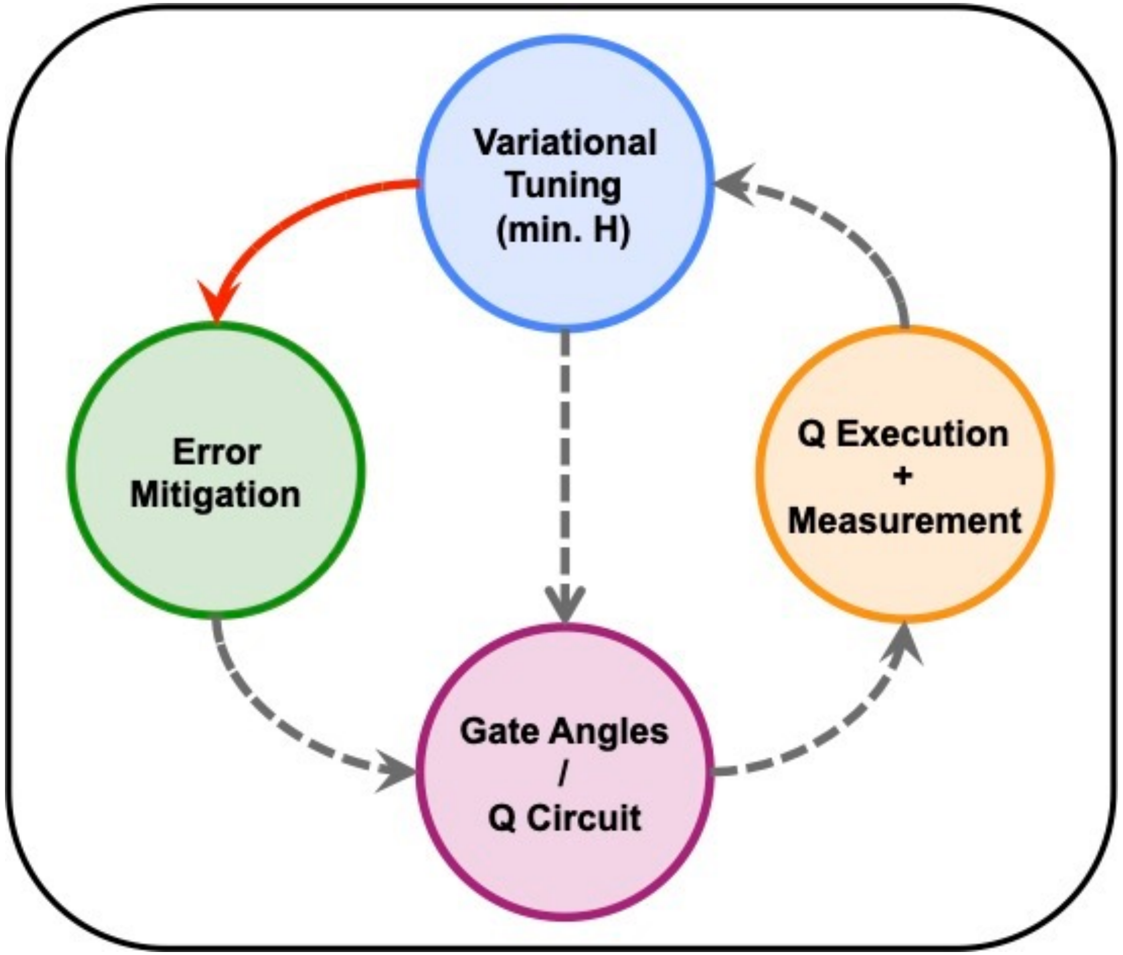
5



6



Conclusion: A variational approach to quantum error mitigation



Future Directions:

- Variationally tune more features of current EM techniques
- Integrate more EM techniques into the VAQEM framework
- Explore tunable optimizations outside of error mitigation

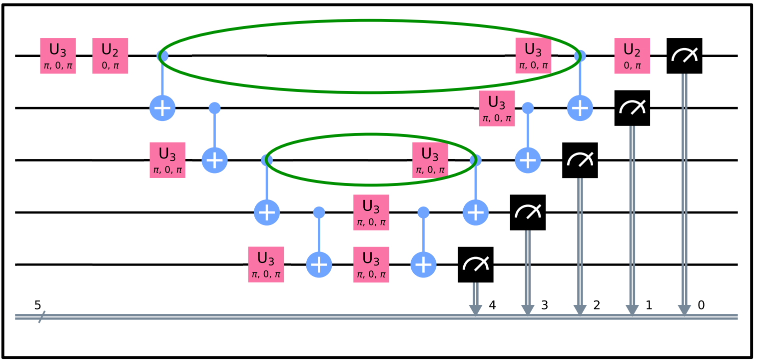
Thank you!

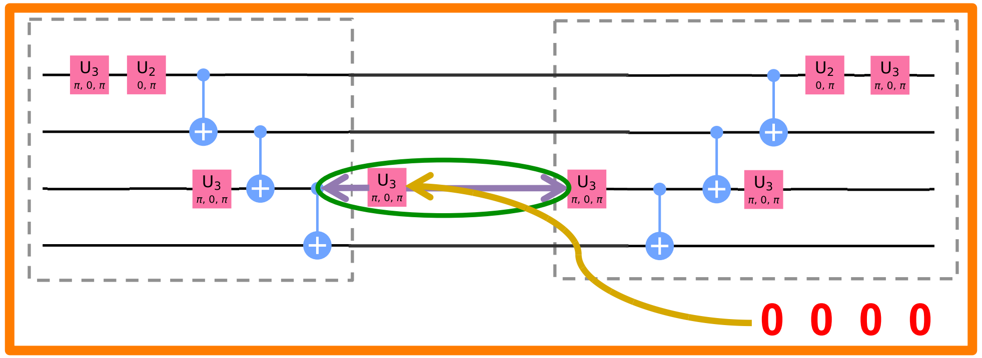
gravi@uchicago.edu

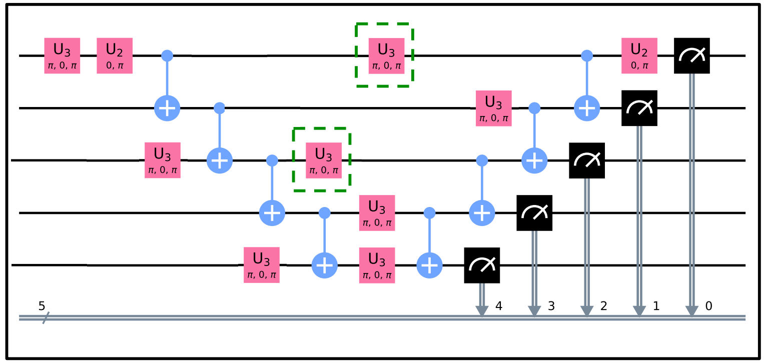
VAQEM: arXiv:2112.05821

TimeStitch: arXiv:2105.01760

Backup

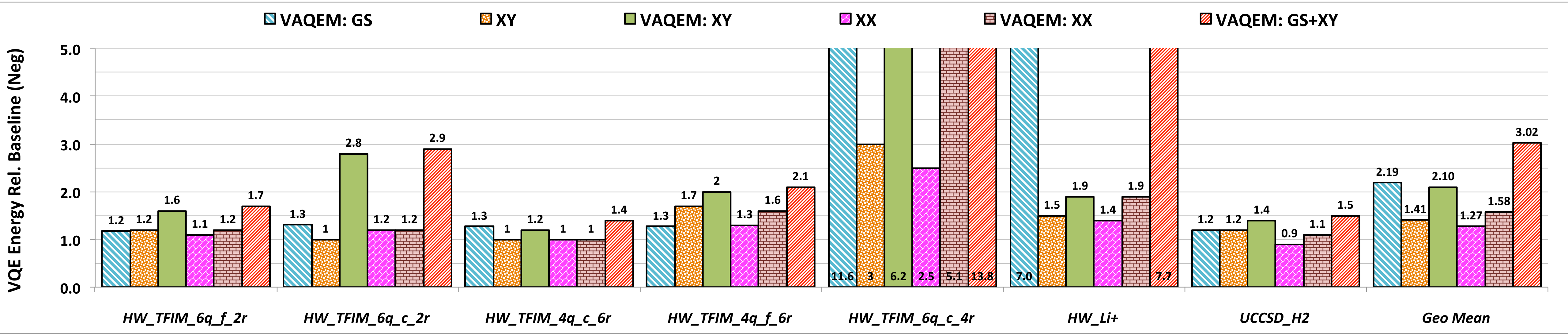

U3
π, 0, π
U2
0, π
5
4
3
2
1
0


U3
π, 0, π
U2
0, π
0 0 0 0

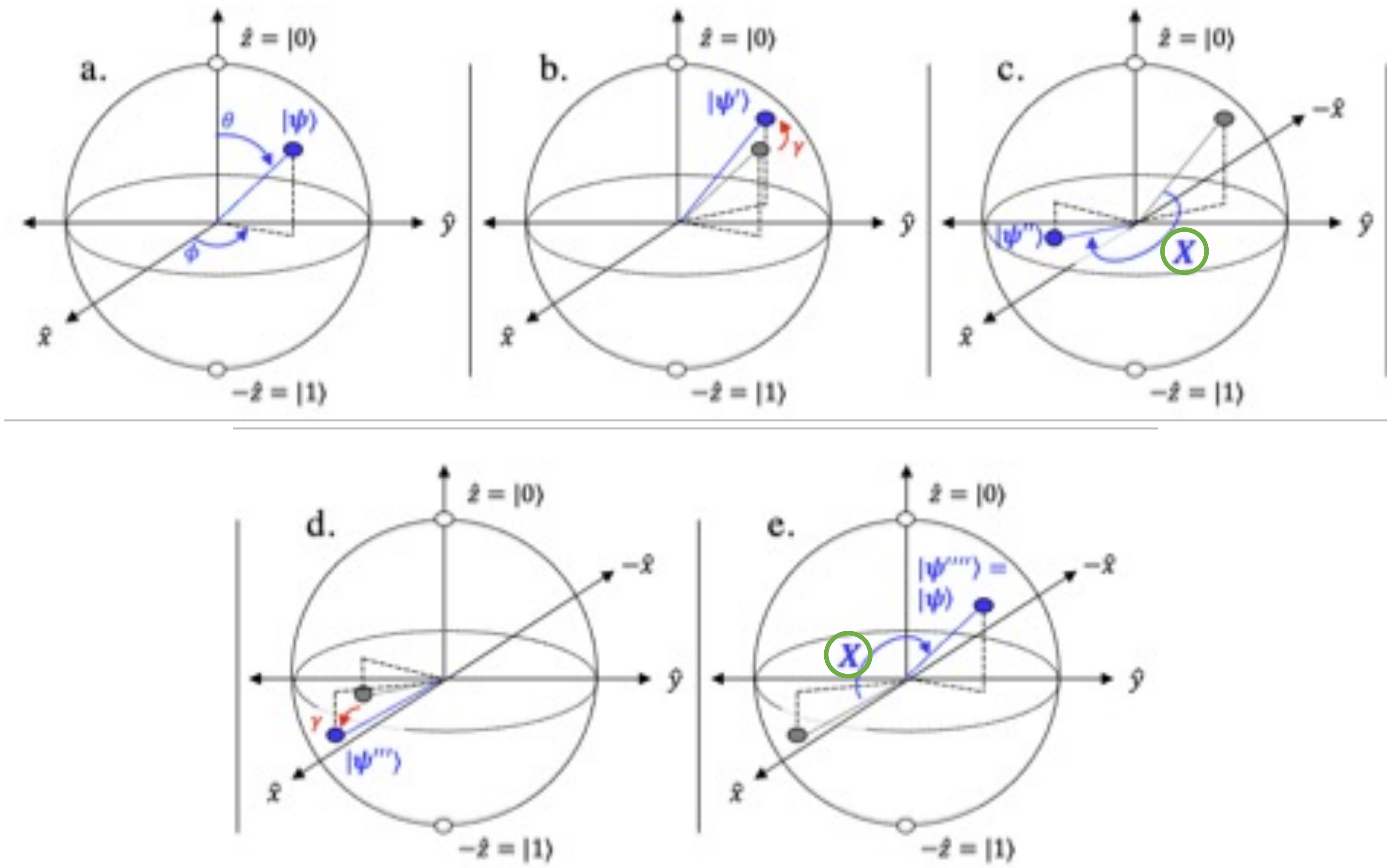

U3
π, 0, π
U2
0, π
5
4
3
2
1
0

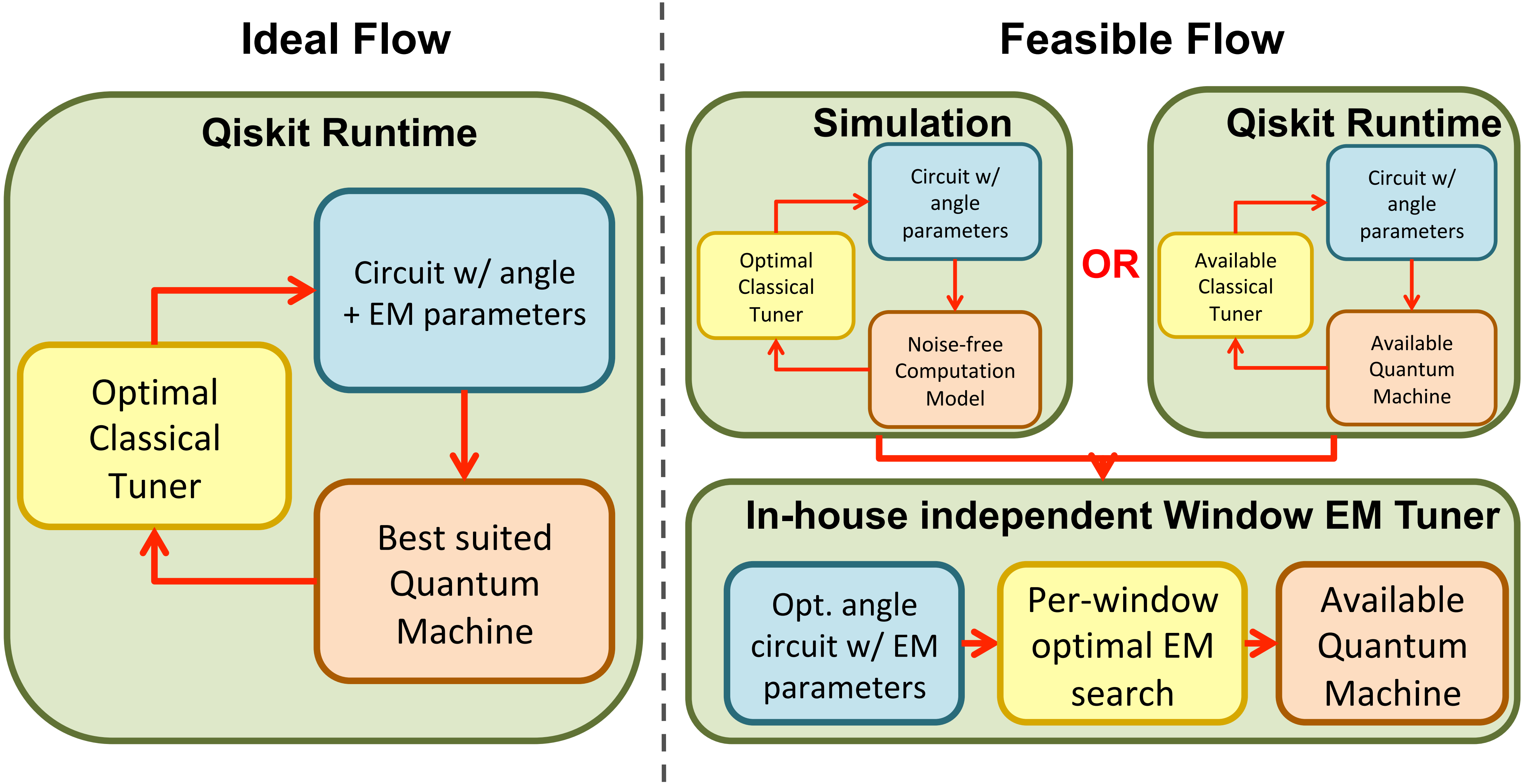
VQE benefits from VAQEM I

Bench	6q/f/2r	6q/c/2r	4q/c/6r	4q/f/6r	6q/c/4r	Li+	H2
Depth	54	31	57	101	55	90	61
# Win	42	24	22	34	30	45	26



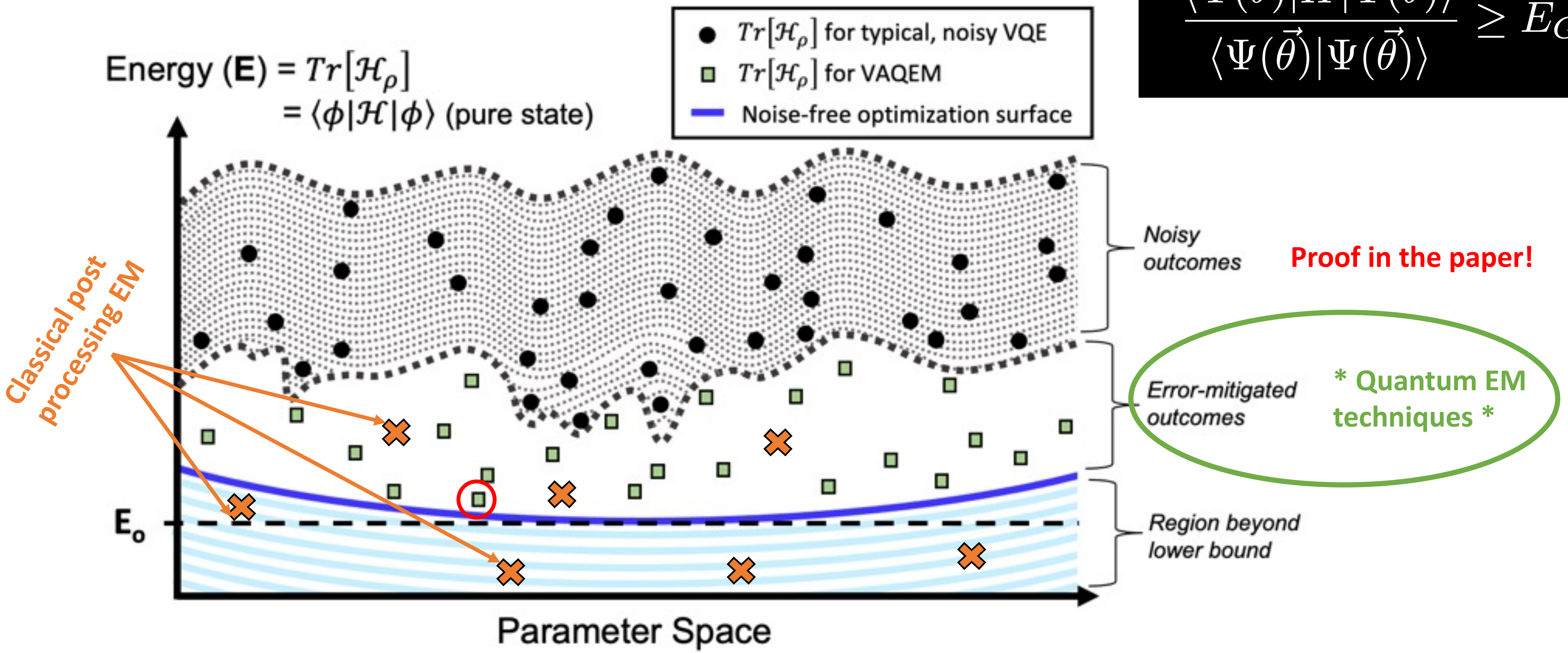
EM inspired by spin echo correction




Ideal Flow
Qiskit Runtime
Circuit w/ angle + EM parameters
Optimal Classical Tuner
Best suited Quantum Machine
Feasible Flow
Simulation
Circuit w/ angle parameters
Optimal Classical Tuner
Noise-free Computation Model
OR
Qiskit Runtime
Circuit w/ angle parameters
Available Classical Tuner
Available Quantum Machine
In-house independent Window EM Tuner
Opt. angle circuit w/ EM parameters
Per-window optimal EM search
Available Quantum Machine

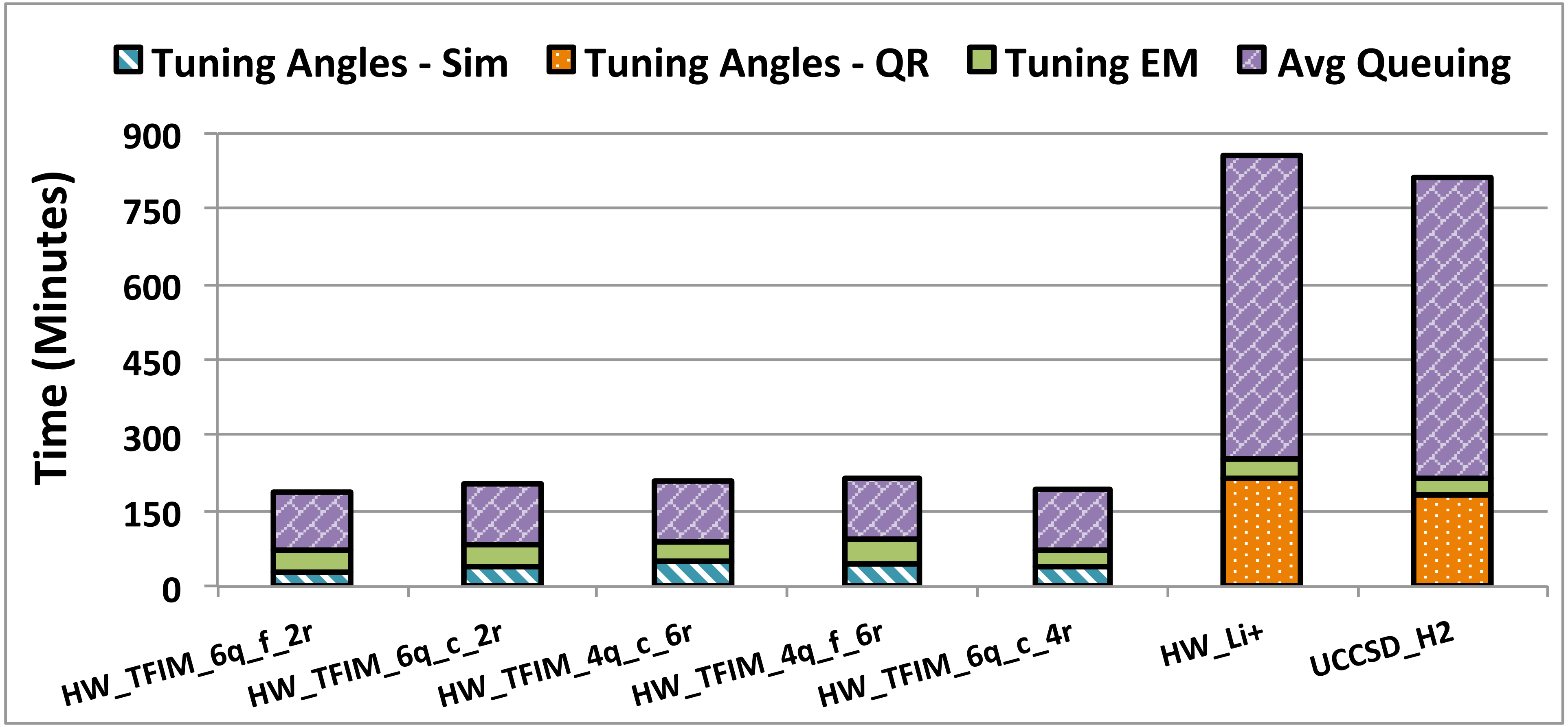
Tunable Error Mitigation Scope

$$\frac{\langle\Psi(\vec{\theta})|H|\Psi(\vec{\theta})\rangle}{\langle\Psi(\vec{\theta})|\Psi(\vec{\theta})\rangle} \geq E_G$$



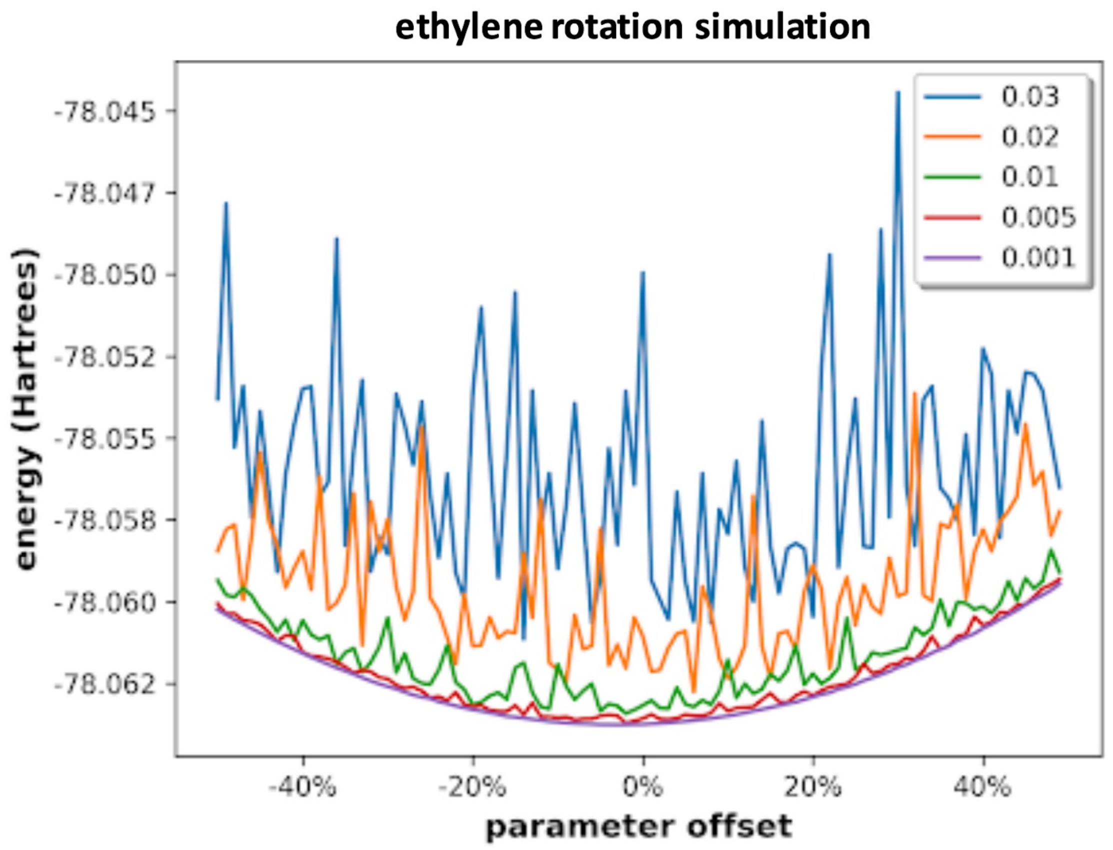
Proof in the paper!

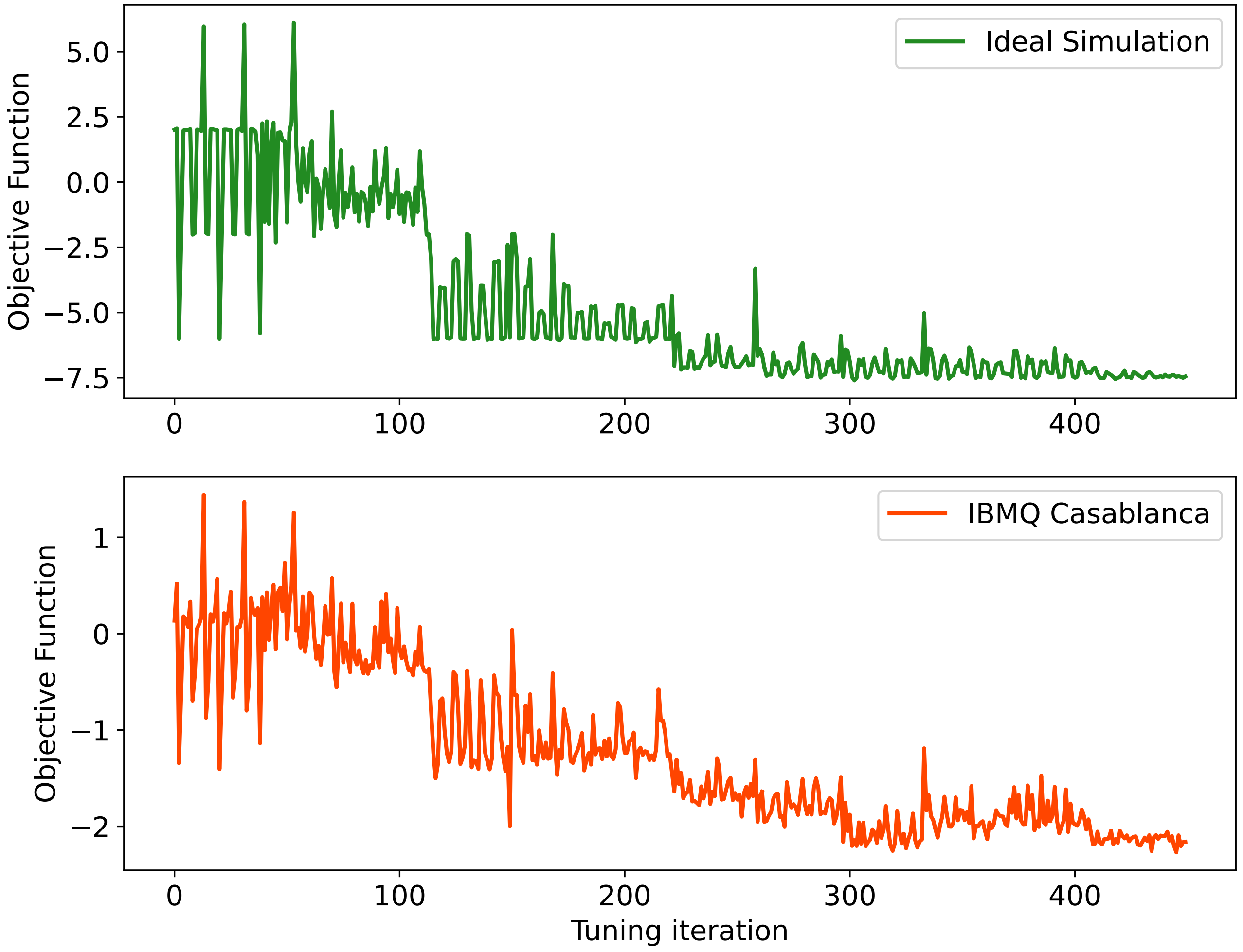
VAQEM Tuning Overheads



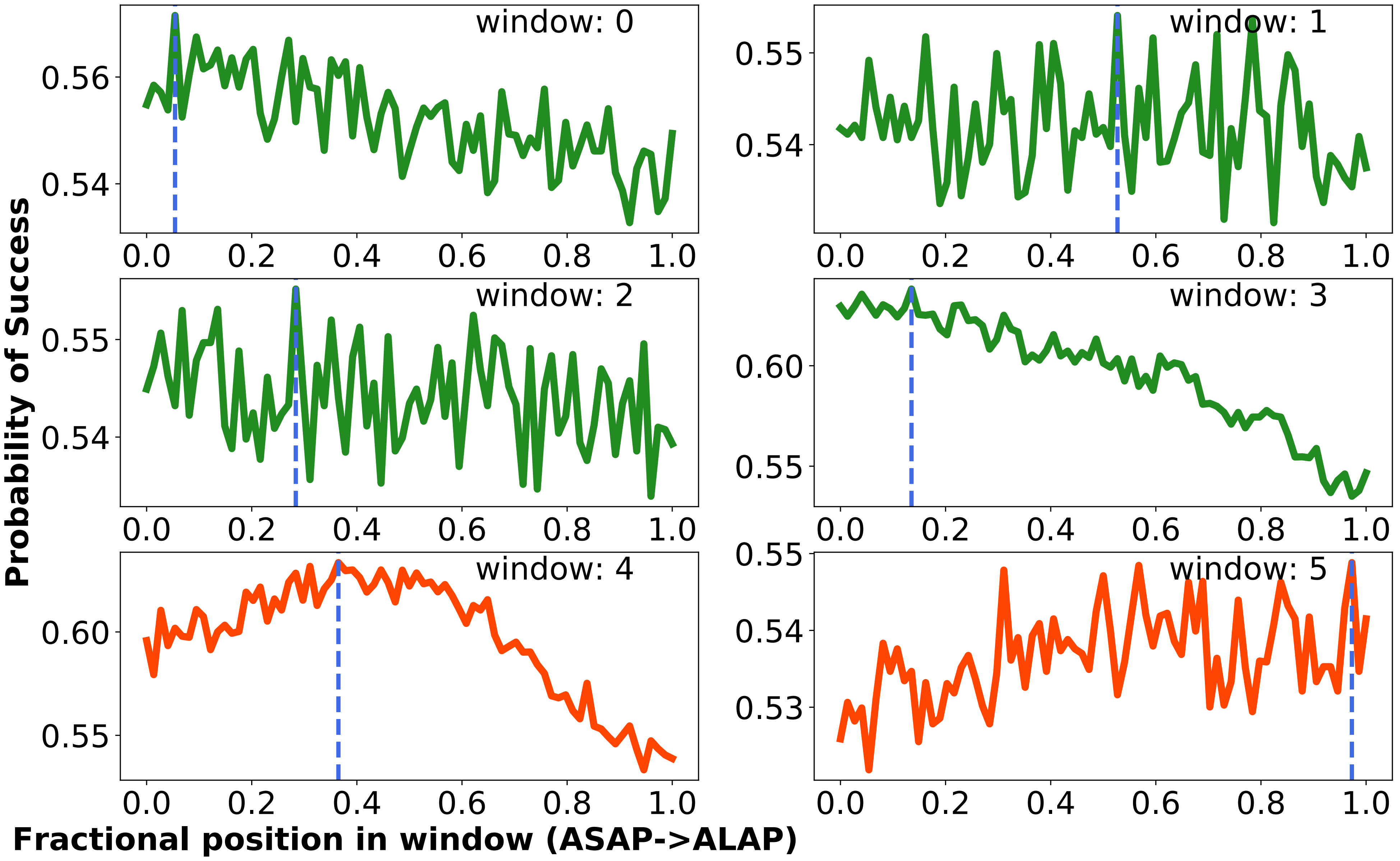
Bench	6q/f/2r	6q/c/2r	4q/c/6r	4q/f/6r	6q/c/4r	Li+	H2
Depth	54	31	57	101	55	90	61
# Win	42	24	22	34	30	45	26

VQA Fidelity in the NISQ era





* Classical Optimizers for Noisy Intermediate-Scale Quantum Devices QCE 2020


window: 0
0.56
0.54
window: 1
0.55
0.54
window: 2
0.55
0.54
window: 3
0.60
0.55
window: 4
0.60
0.55
window: 5
0.55
0.54
0.53
0.0 0.2 0.4 0.6 0.8 1.0
Probability of Success
Fractional position in window (ASAP->ALAP)