Accurate State Preparation on Noisy Quantum Devices

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Variationally Scheduled Quantum Simulation [Phys. Rev. A 103, 052435 (2021)] SM/Buck/Senicourt/Zaribafiyan

VanQver: The Variational and Adiabatically Navigated Quantum Eigensolver [New J. Phys. 22, 053023 (2020)] SM/Yamazaki/Senicourt/Huntington/Zarifbafiyan

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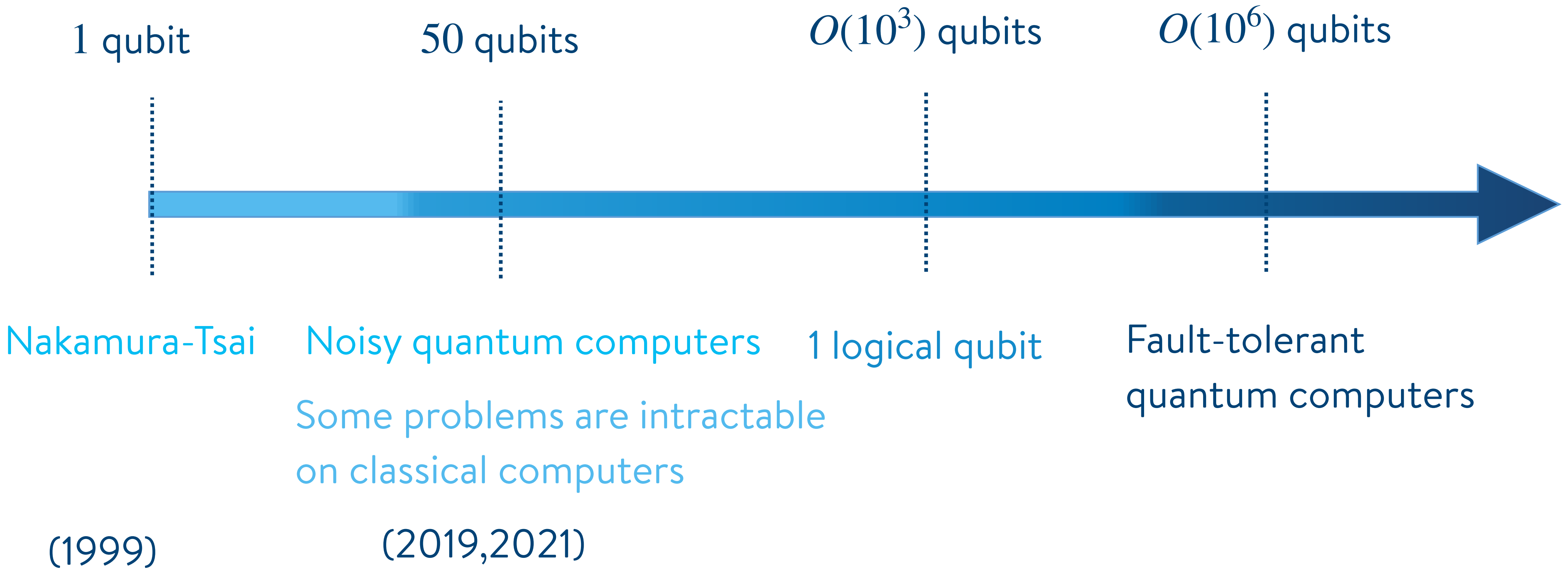
Quantum Computing



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Quantum State Preparation

Quantum chemistry

- Ground state / excited state energies
- Chemical reaction rates, reaction pathway, response to external fields, etc.

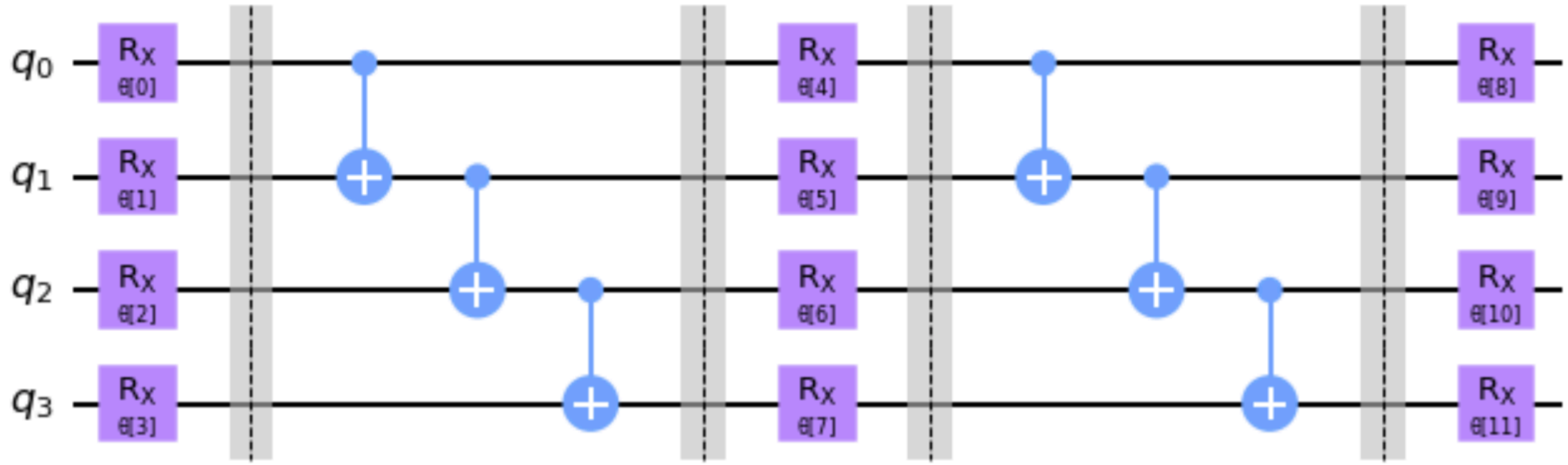
Quantum physics

- Spontaneous symmetry breaking
- Topological phases

Optimization

- Scheduling, finance,
  machine learning

Variational Quantum Eigensolver



Parametrized circuit: $U(\theta_i)$

Ansatz $|\psi(\theta_i)\rangle = U(\theta_i)|\mathbf{0}\rangle$

Minimize $E(\theta_i) = \langle\psi(\theta_i)|H|\psi(\theta_i)\rangle$

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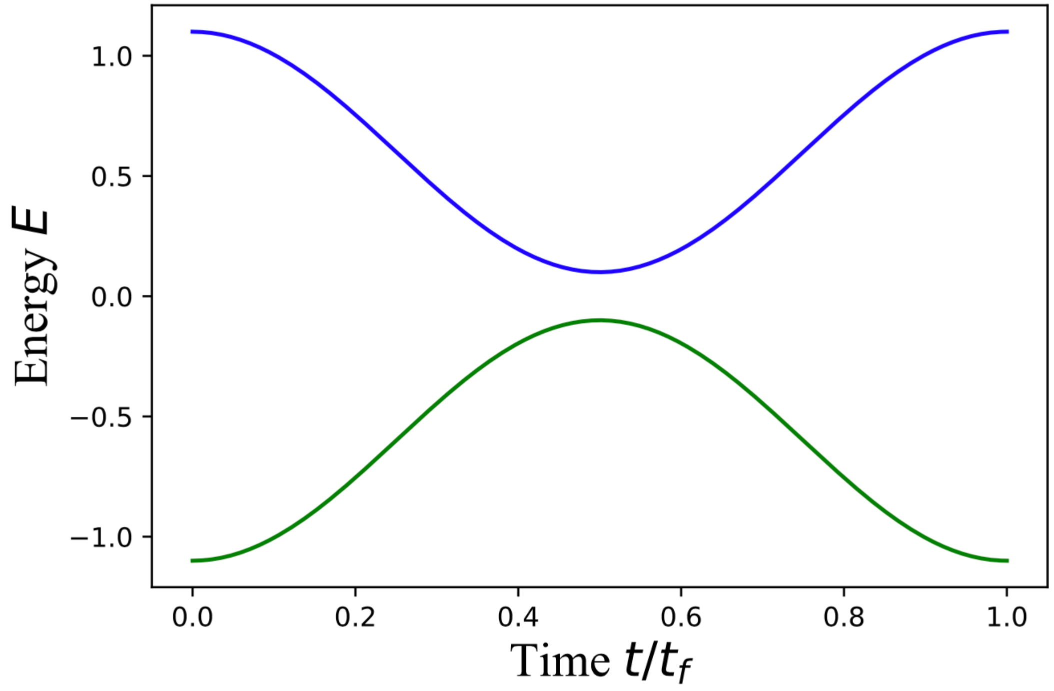
Adiabatic State Preparation

Quantum annealing for Ising models:

$$H = -(1 - t/t_f)\sum_i X_i + (t/t_f)\sum_{ij} h_{ij} Z_i Z_j$$



Transition probability

$$p \sim \exp\left(-\frac{\pi}{2}(\Delta E)^2 \cdot t_f\right)$$

Evolution time

$$t_f \gg \frac{1}{(\Delta E)^2}$$

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Energy Gap Amplification

- Non-stoquastic Hamiltonian

  For instance: Farhi/Goldstone/Gutmann 2002, Seki/Nishimori 2012, Crosson/Farhi/Lin/Lin/Shor 2014

- Inhomogeneous transverse field

  For instance: Farhi/Goldstone/Gosset/Gutmann/Meyer/Shor 2011, Dickson/Amin 2011, Susa/Yamashiro/Yamamoto/Nishimori 2018

- Reverse annealing

  For instance: Perdomo-Ortiz/Venegas-Andraca/Aspuru-Guzik 2010, Chancellor 2017, Ohkuwa/Nishimori/Lidar 2018

- Error suppression

  For instance: Matsuura/Nishimori/Albash/Lidar 2015

- Quantum-walk

  For instance: Somma/Boixo 2013

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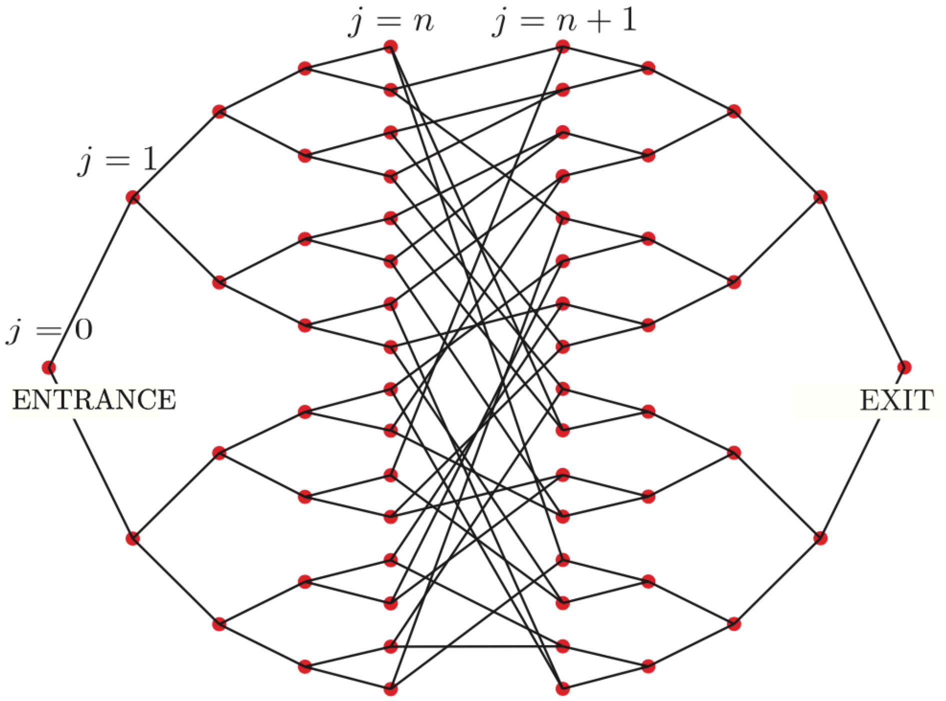
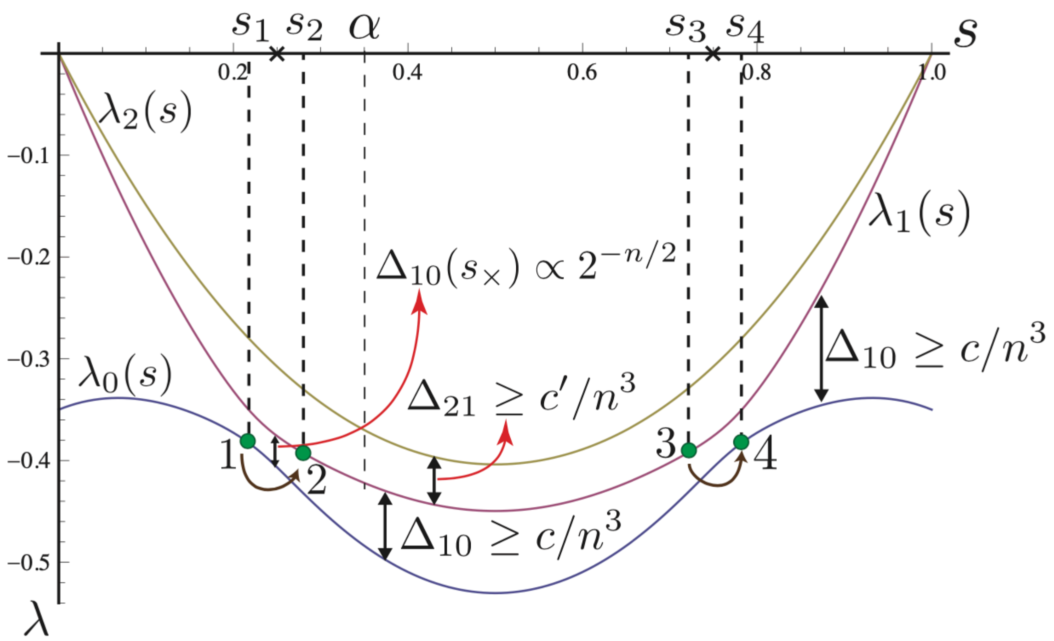
Diabatic Transitions





Nagaj/Somma/Kieferova (2012)

Motivation for the Project

Long-term perspective

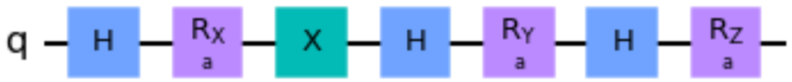
Gaining a better understanding of essential factors for realizing quantum speedup

Short-term perspective

Obtaining accurate results on noisy quantum devices

Adiabatic state preparation on near-term quantum devices

Shallow circuit	Deep circuit
Short computational time	Long computational time



Pros: Coherent

Cons: Diabatic transitions

Cons: Decoherent

Pros: Adiabatic process

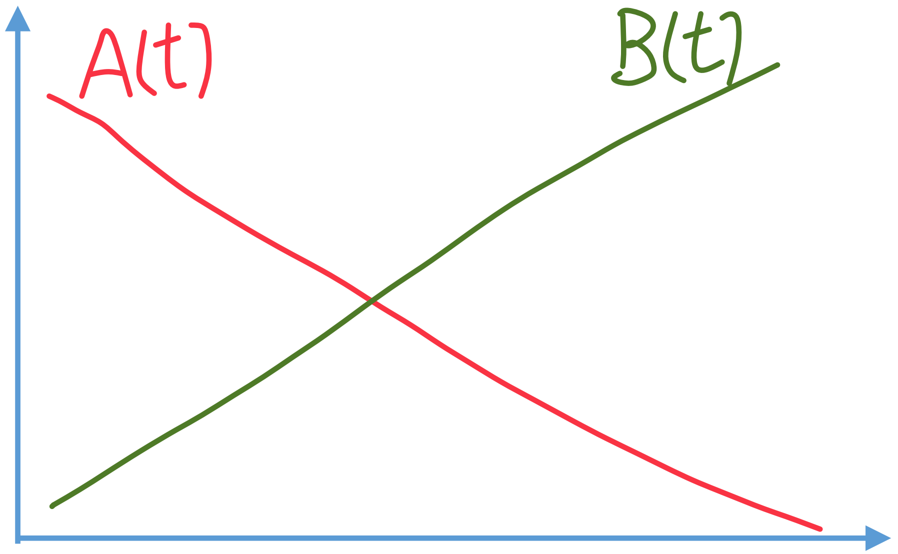
Variational Approach in Adiabatic State Preparation

SM/Buck/Senicourt/Zaribafiyan (2020)

Initial Hamiltonian H_{ini} → Final Hamiltonian H_{fin}

$$H(t) = A(t)H_{\text{ini}} + B(t)H_{\text{fin}}$$

Standard QA



Time

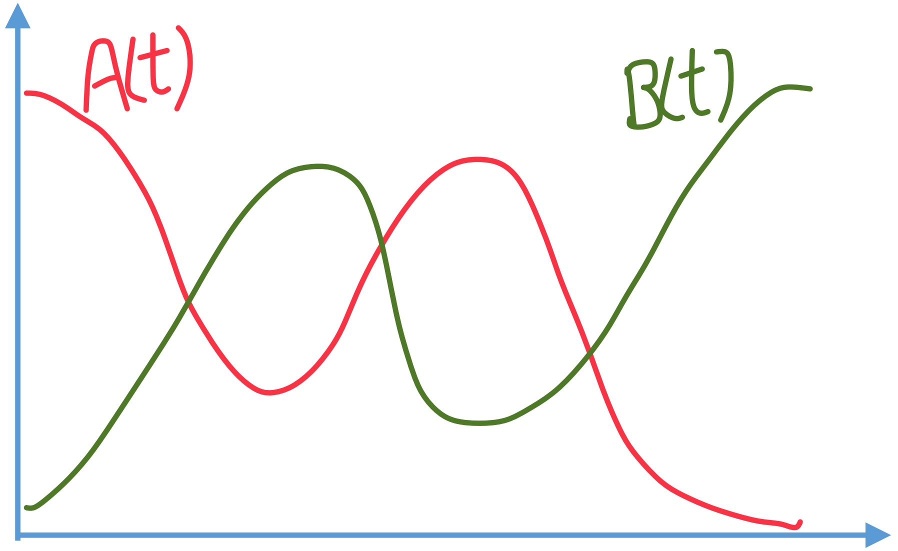
Variational Approach in Adiabatic State Preparation

SM/Buck/Senicourt/Zaribafiyan (2020)

Initial Hamiltonian H_{ini} → Final Hamiltonian H_{fin}

$$H(t) = A(t)H_{\text{ini}} + B(t)H_{\text{fin}}$$

Find the optimal schedule functions $A(t)$ and $B(t)$ ***variationally*** so that the final state is as close as possible to the ground state of H_{fin}



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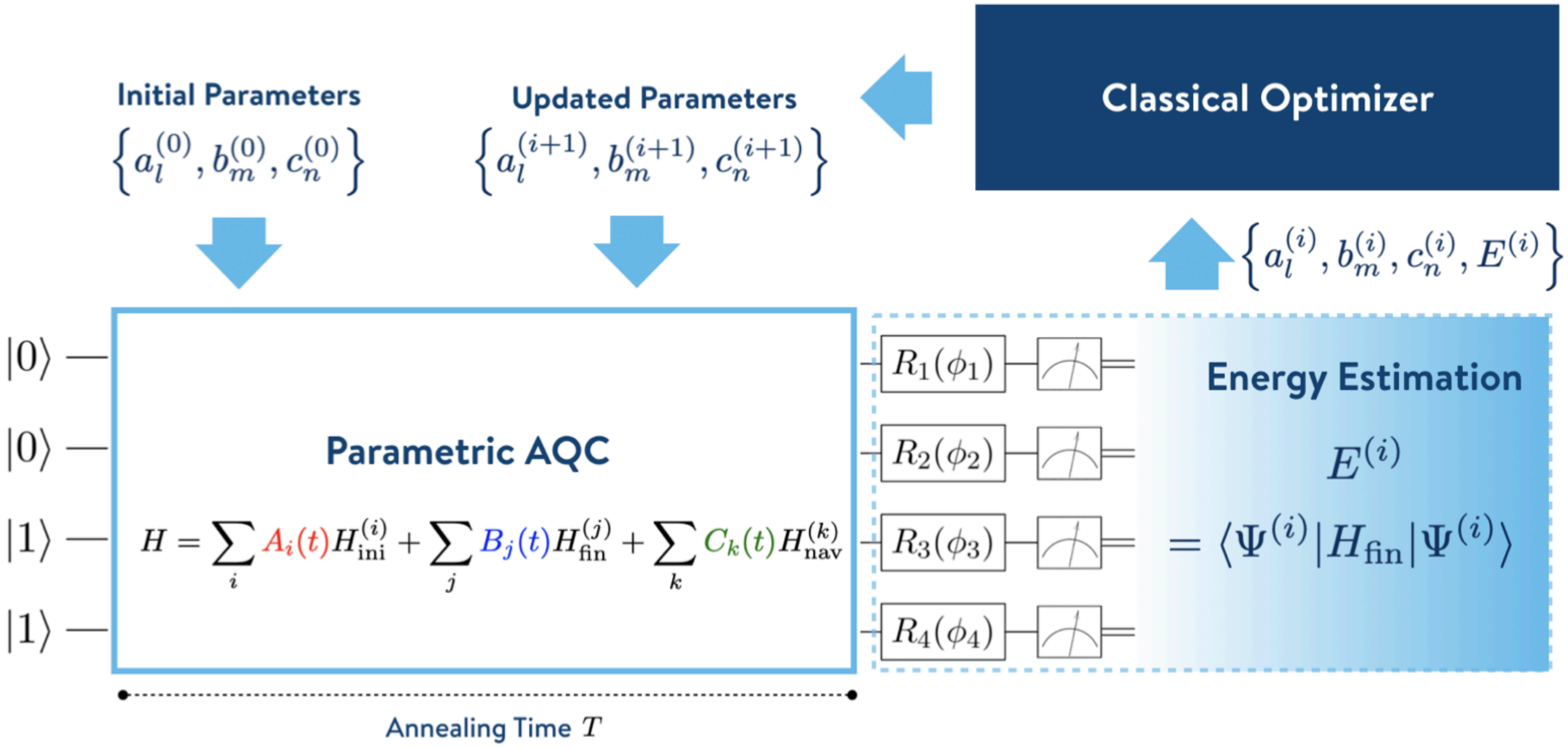


Initial Parameters
$\{a_l^{(0)}, b_m^{(0)}, c_n^{(0)}\}$
Updated Parameters
$\{a_l^{(i+1)}, b_m^{(i+1)}, c_n^{(i+1)}\}$
Classical Optimizer
$\{a_l^{(i)}, b_m^{(i)}, c_n^{(i)}, E^{(i)}\}$
$|0\rangle$
$|0\rangle$
$|1\rangle$
$|1\rangle$
Parametric AQC
$H = \sum_i A_i(t) H_{\text{ini}}^{(i)} + \sum_j B_j(t) H_{\text{fin}}^{(j)} + \sum_k C_k(t) H_{\text{nav}}^{(k)}$
$R_1(\phi_1)$
$R_2(\phi_2)$
$R_3(\phi_3)$
$R_4(\phi_4)$
Energy Estimation
$E^{(i)} = \langle \Psi^{(i)} | H_{\text{fin}} | \Psi^{(i)} \rangle$
Annealing Time T

Initial Hamiltonian $H_{\text{ini}} = \sum_{\alpha} H_{\text{ini}}^{\alpha}$

Final Hamiltonian $H_{\text{fin}} = \sum_{\beta} H_{\text{fin}}^{\beta}$

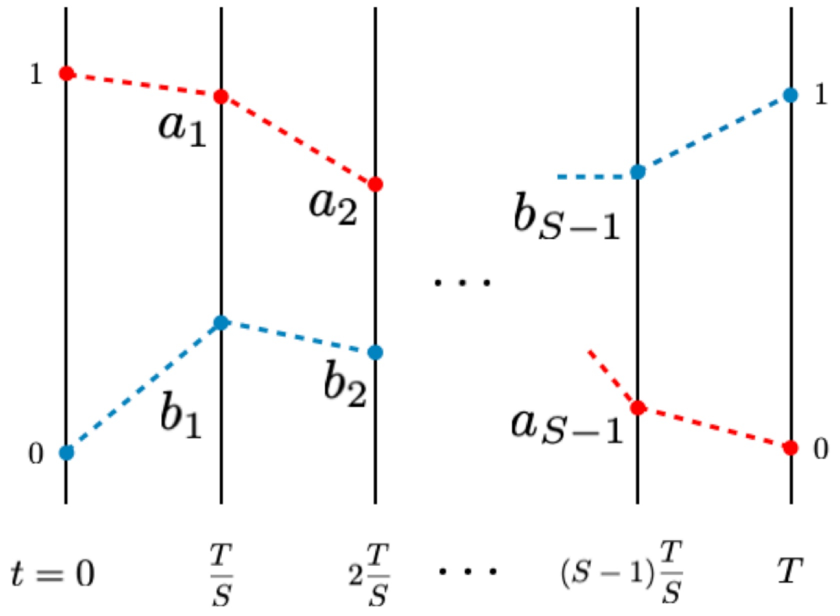
$$H = \sum_{\alpha=1}^{N_I} A_\alpha(t) H_{\text{ini}}^{\alpha} + \sum_{\beta=1}^{N_F} B_\beta(t) H_{\text{fin}}^{\beta}$$

Parameters:

Split terms in H_{ini} into N_I groups

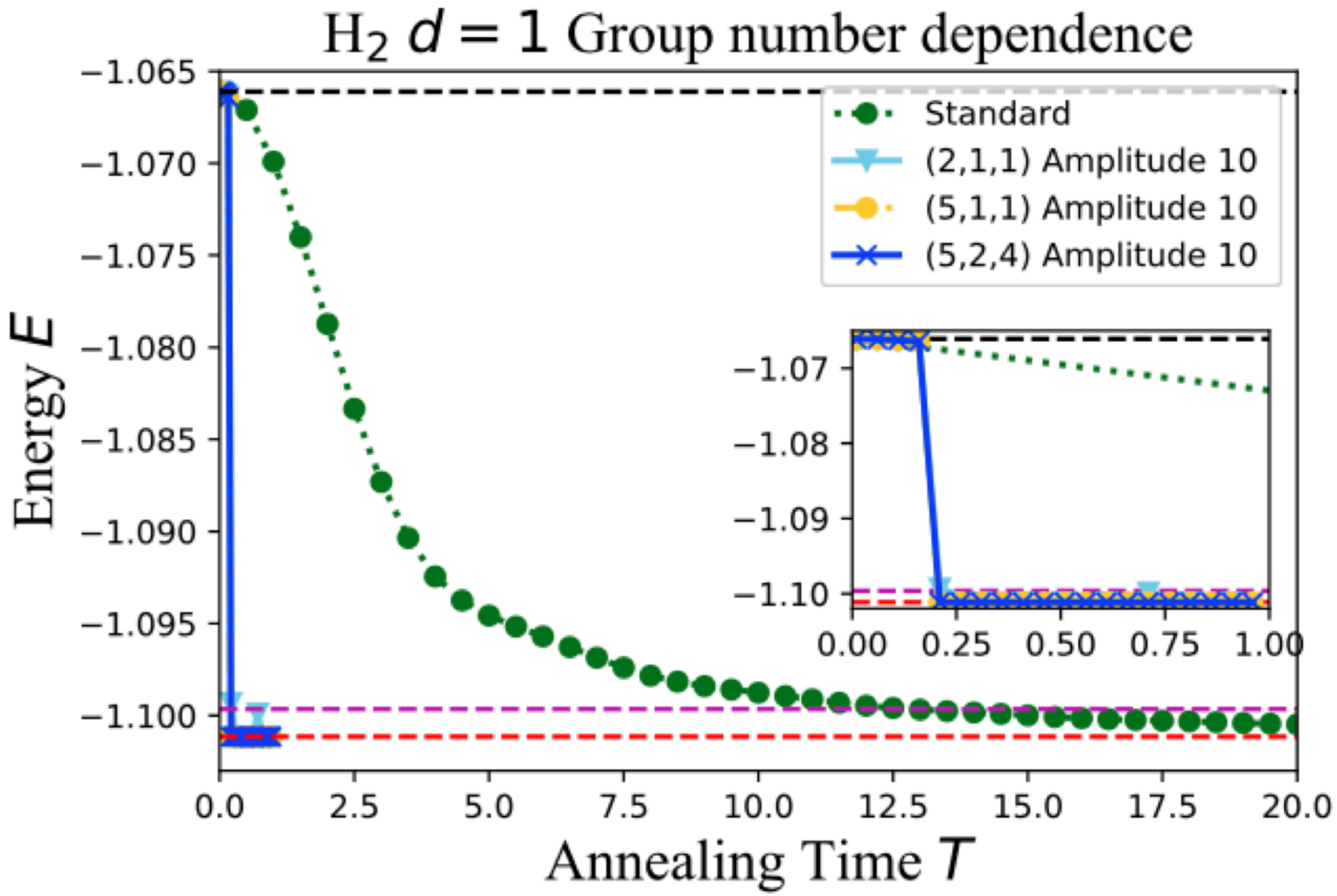
Split terms in H_{fin} into N_F groups

Split computation time T into N_S intervals

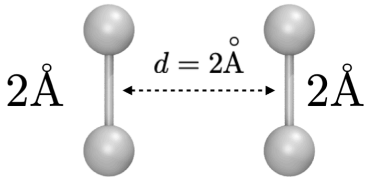


Numerical Results

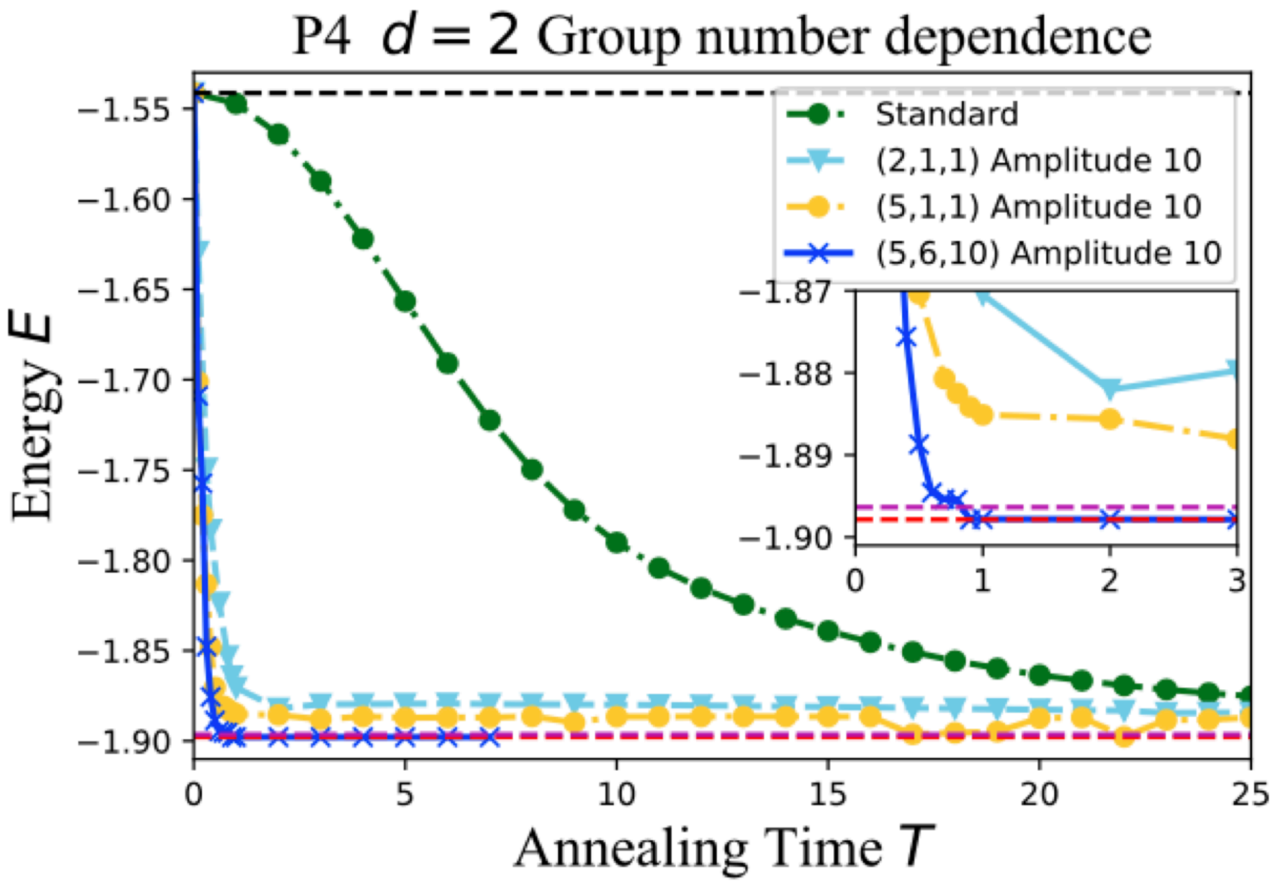
Hydrogen molecule



P4: Hydrogen atoms that form a square



Difficult due to degeneracy



Time to Chemical Accuracy

- Standard case: $T = 456$

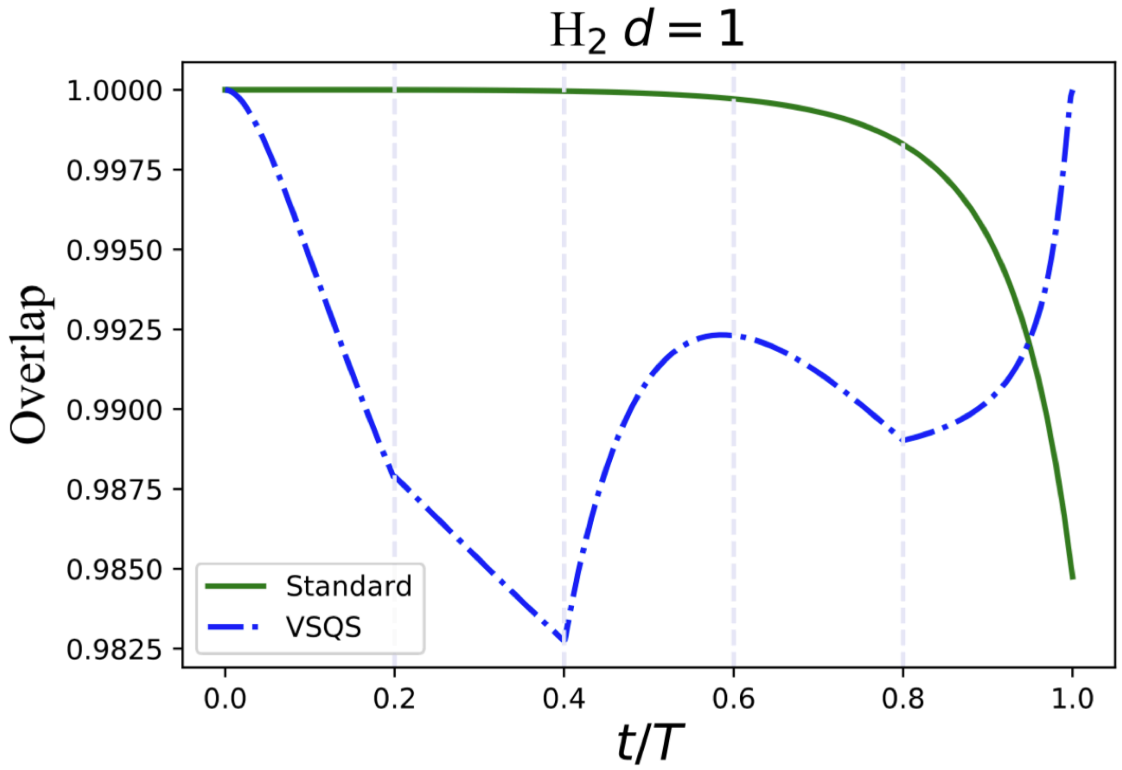
Overlap with Instantaneous Ground States

How closely does the quantum state follow adiabatic evolution?

Quantum state at t: $$|\psi(t)\rangle = \mathcal{T}\exp(-i\int_{s=0}^{t} H(s)ds)\,|\psi(0)\rangle$$

Instantaneous ground state: $$H(t)\,|\phi(t)\rangle = E_0(t)\,|\phi(t)\rangle$$

$|\langle\phi(t)|\psi(t)\rangle|$



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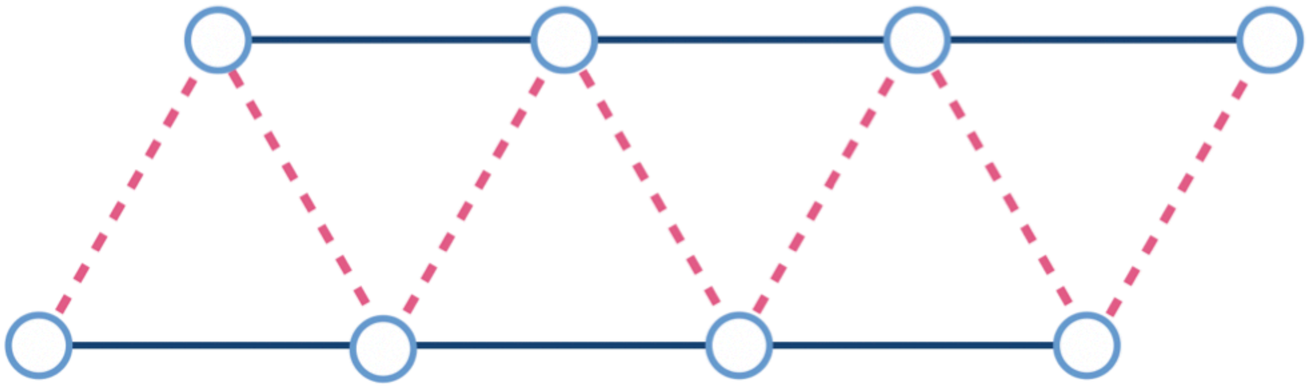
Ising Model

Triangle lattice

Frustration

Random couplings

$$H = \sum_{ij} h_{ij} Z_i Z_j + \sum_{i} h_i Z_i$$



Ferromagnetic couplings

Antiferromagnetic couplings

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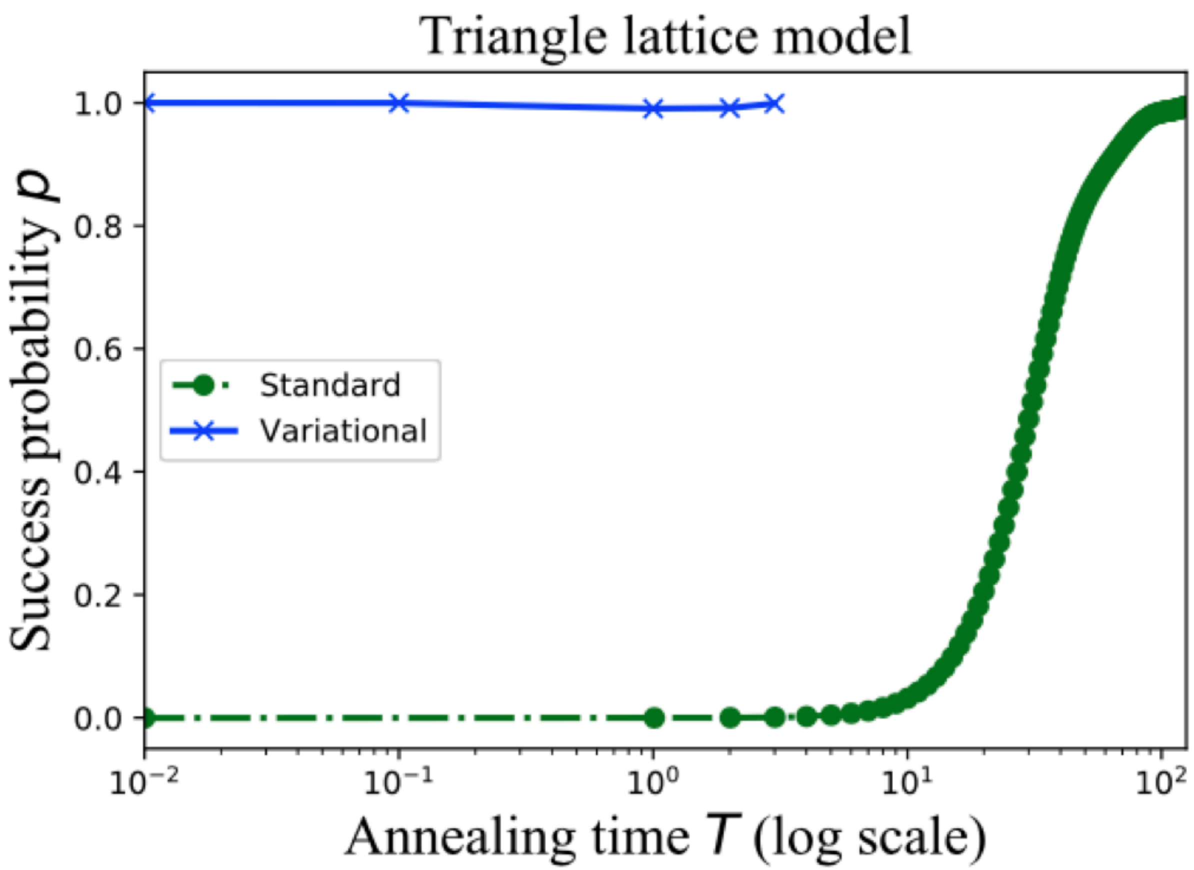
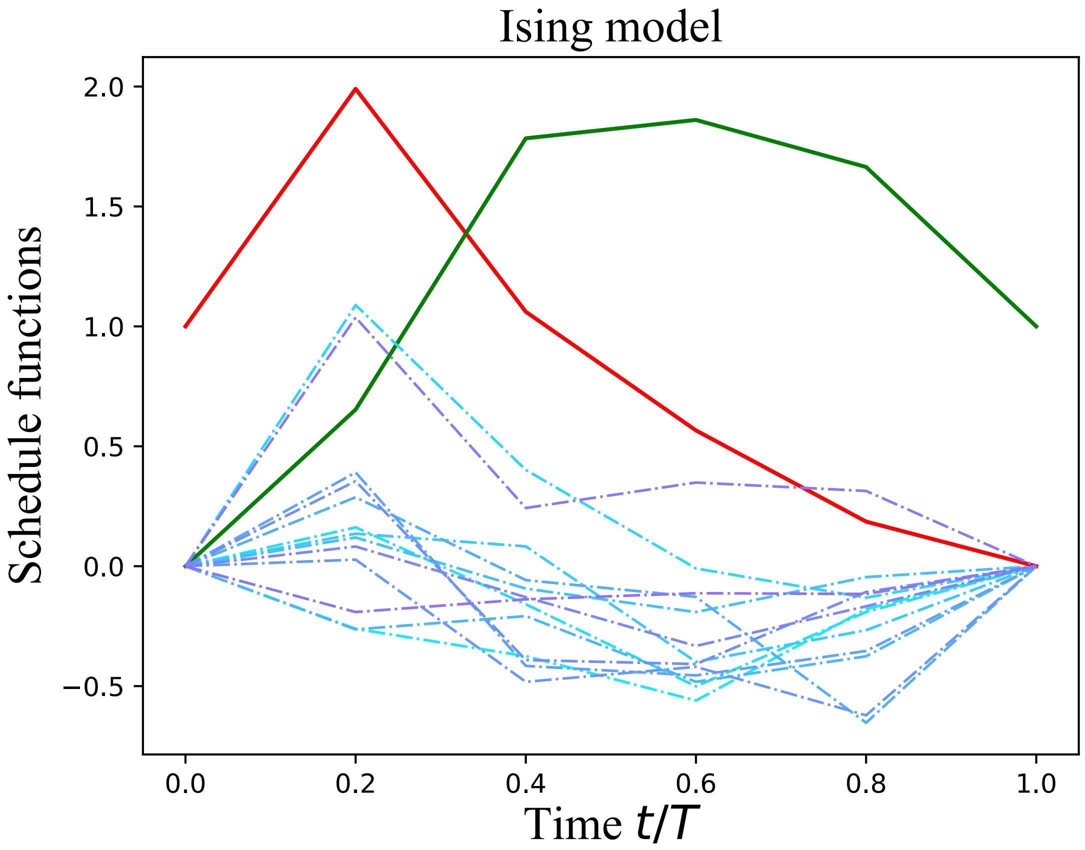
Numerical Results



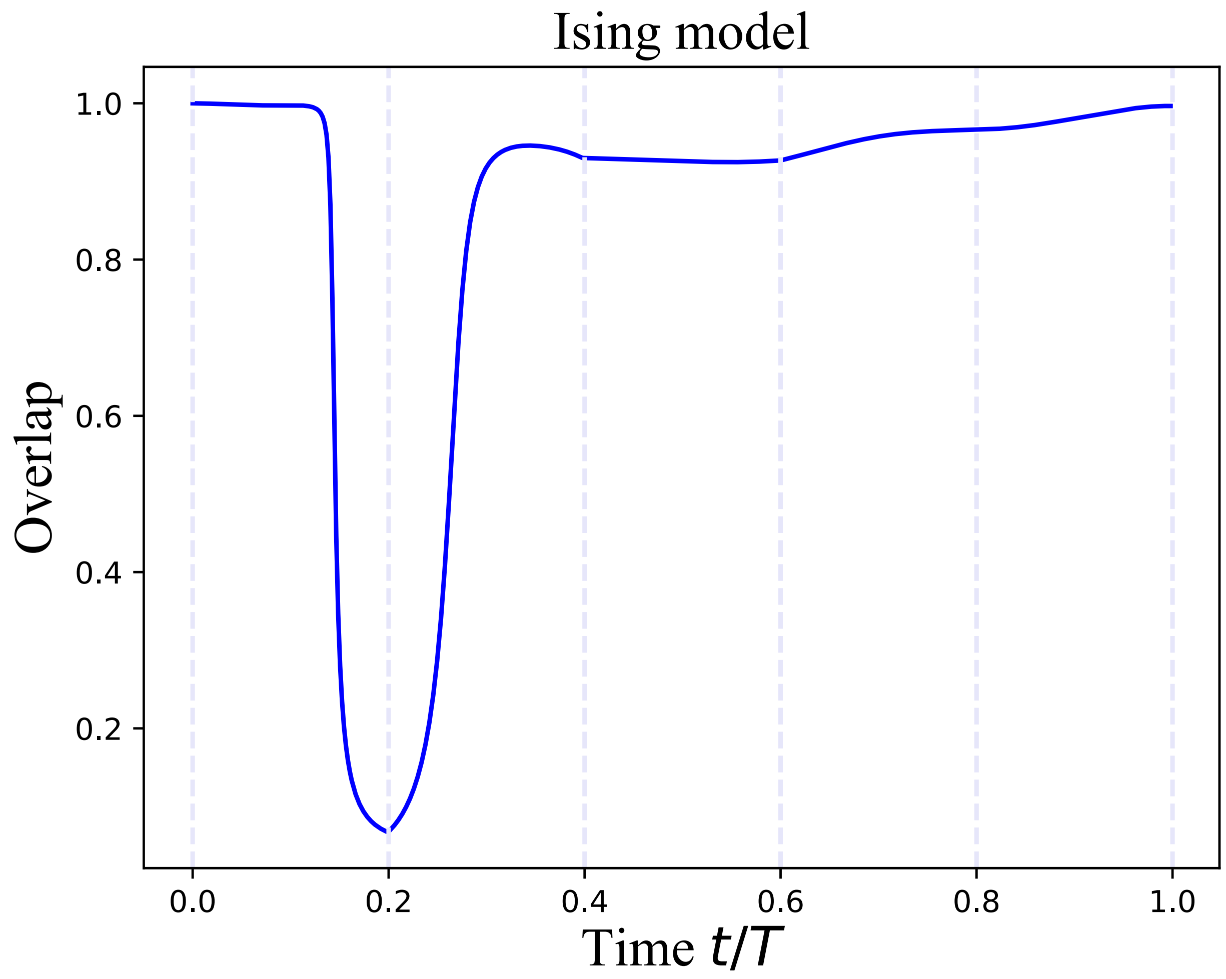
Optimal Schedule Functions

$$H(t) = A(t)H_{\text{ini}} + B(t)H_{\text{Ising}} + \sum_{ij} C_{ij}(t)X_iX_j$$

"Non-stoquastic terms"



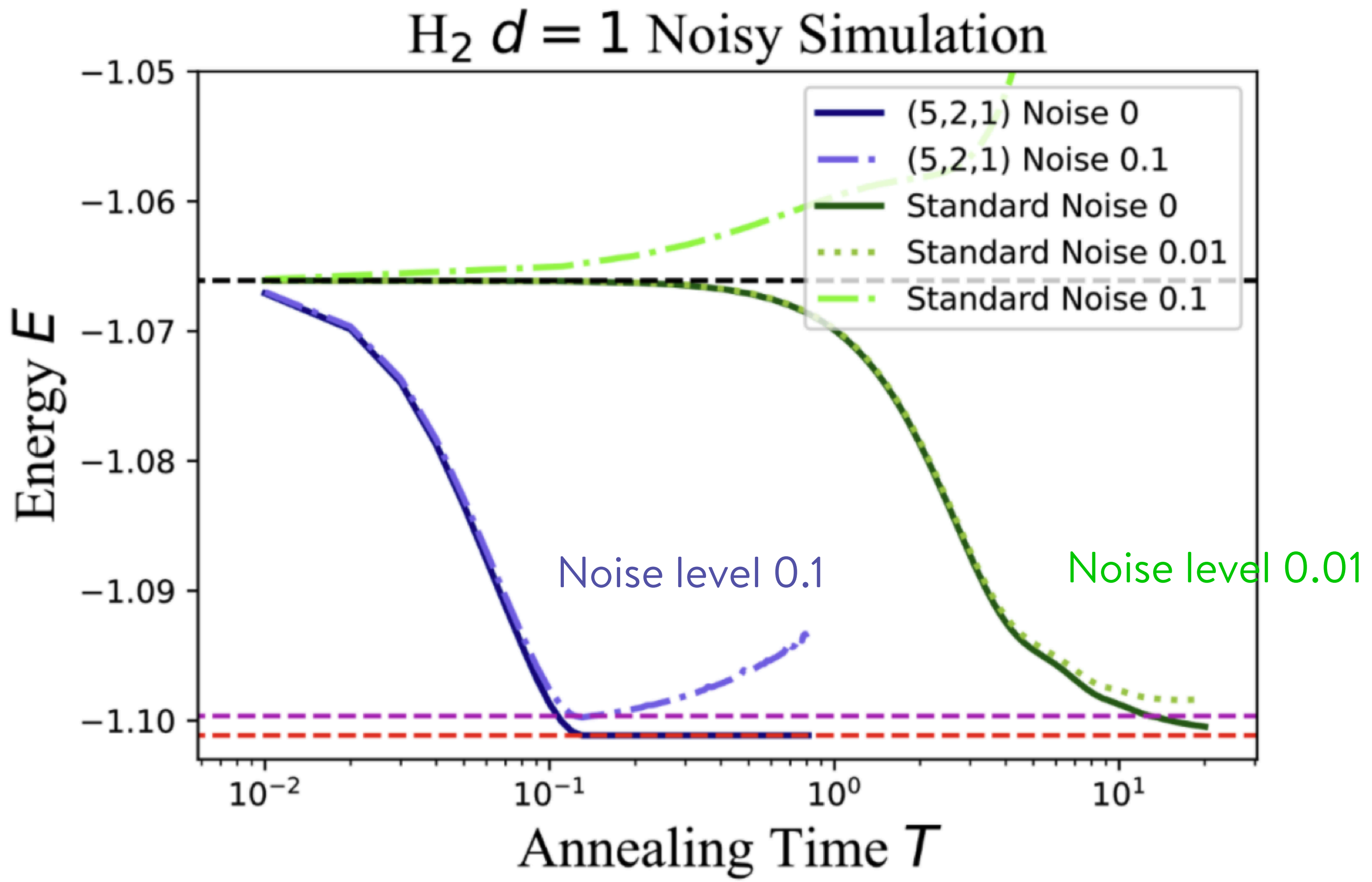
Overlap with Instantaneous Ground States



$|\langle\phi(t)\,|\,\psi(t)\rangle|$

Decoherence

Lindblad master equation with bit-flip errors (thermalization)



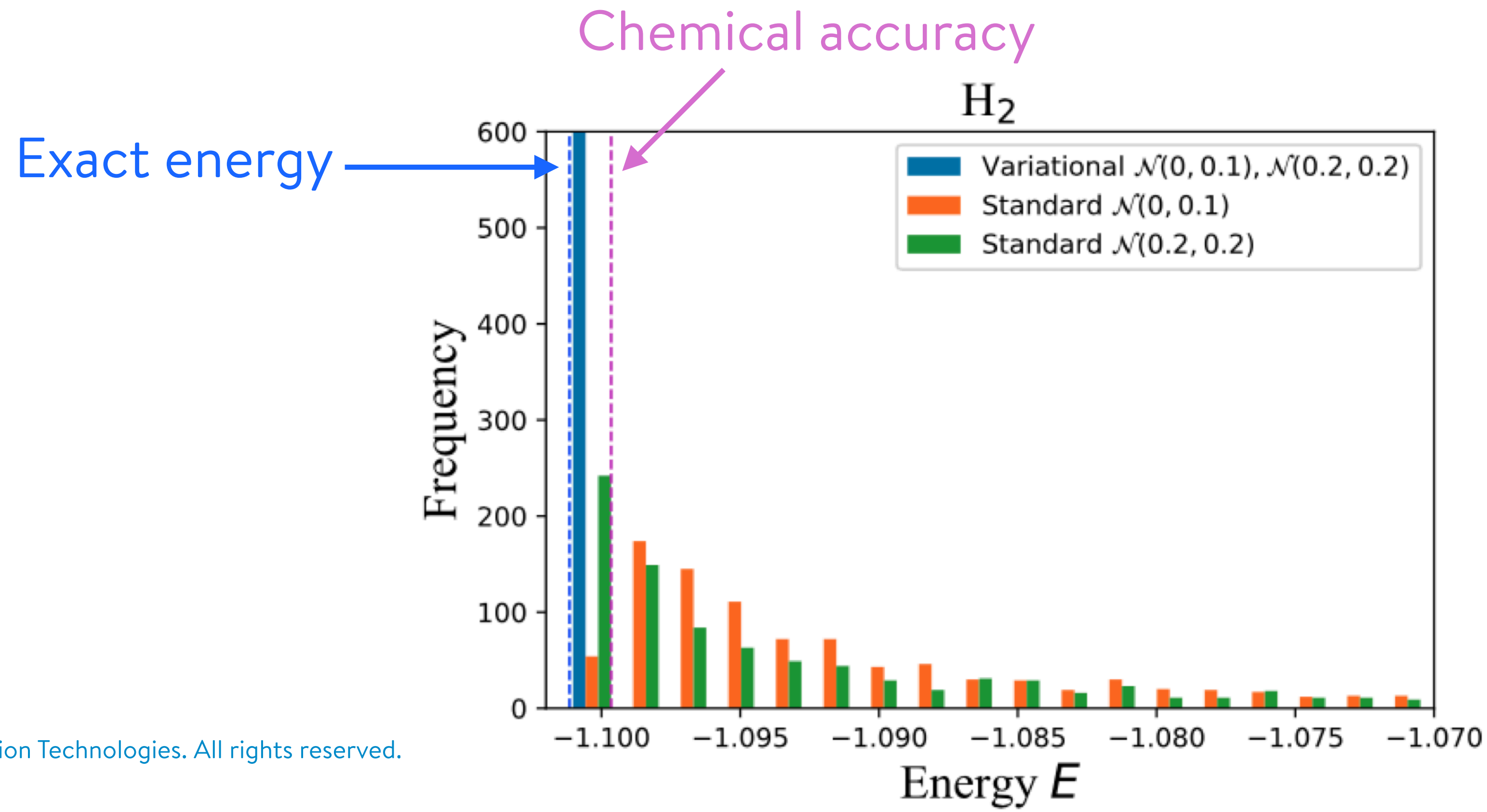
Coherent Errors

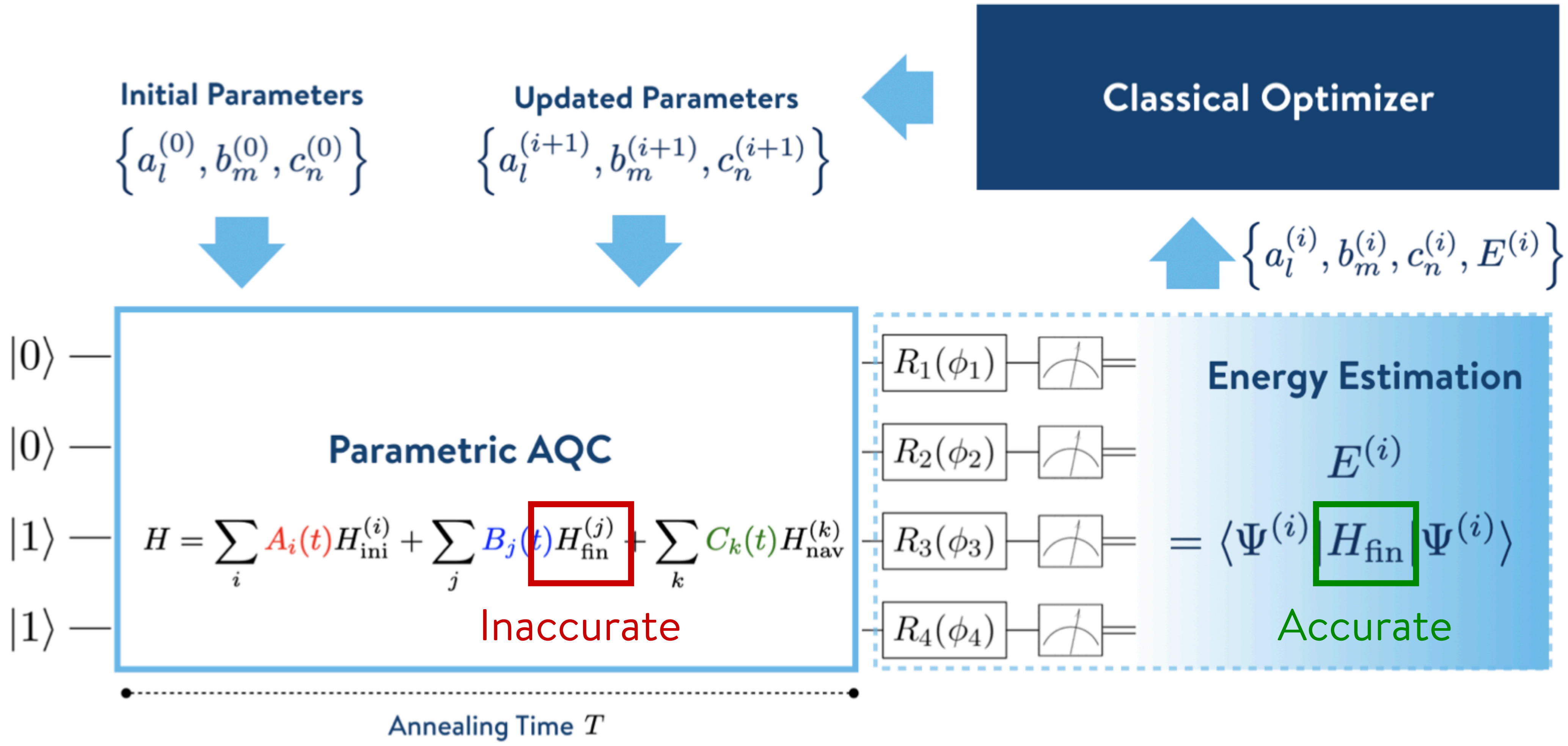
H_{final} may not be accurately implemented on quantum devices (inaccurate controls)

Variational approach

Quantum device: generate a quantum state by using inaccurate $\tilde{H}_{\text{final}}$

Classical optimization: find optimal schedule by minimizing accurate H_{final}





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$H = \sum_i A_i(t) H_{\text{ini}}^{(i)} + \sum_j B_j(t) H_{\text{fin}}^{(j)} + \sum_k C_k(t) H_{\text{nav}}^{(k)}$
Inaccurate
$R_1(\phi_1)$
$R_2(\phi_2)$
$R_3(\phi_3)$
$R_4(\phi_4)$
Energy Estimation
$E^{(i)}$
$= \langle \Psi^{(i)} | H_{\text{fin}} | \Psi^{(i)} \rangle$
Accurate
Annealing Time T

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Summary

Quantum state preparation is quite generic in various applications of quantum computing.

We have considered a variational method in the framework of adiabatic state preparation.

Variational state preparation provides a framework for obtaining accurate results on noisy quantum devices.

- Decoherence
- Coherent errors

Diabatic transitions are a key element for solving problems efficiently.

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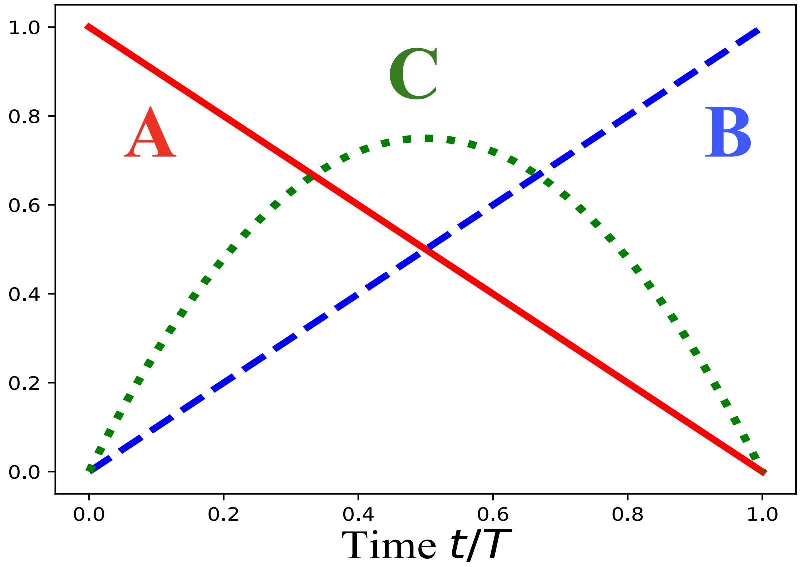
VanQver: A Variational and Adiabatically Navigated Quantum Eigensolver

$$H(t, \vec{\eta}, \vec{\theta}) = A(t) H_{\mathrm{ini}}(\vec{\eta}) + B(t) H_{\mathrm{fin}} + C(t) H_{\mathrm{nav}}(\vec{\theta})$$

Navigator Hamiltonian



Variational Parameters: $\{\vec{\eta}, \vec{\theta}\}$

[NPB 22 053023]

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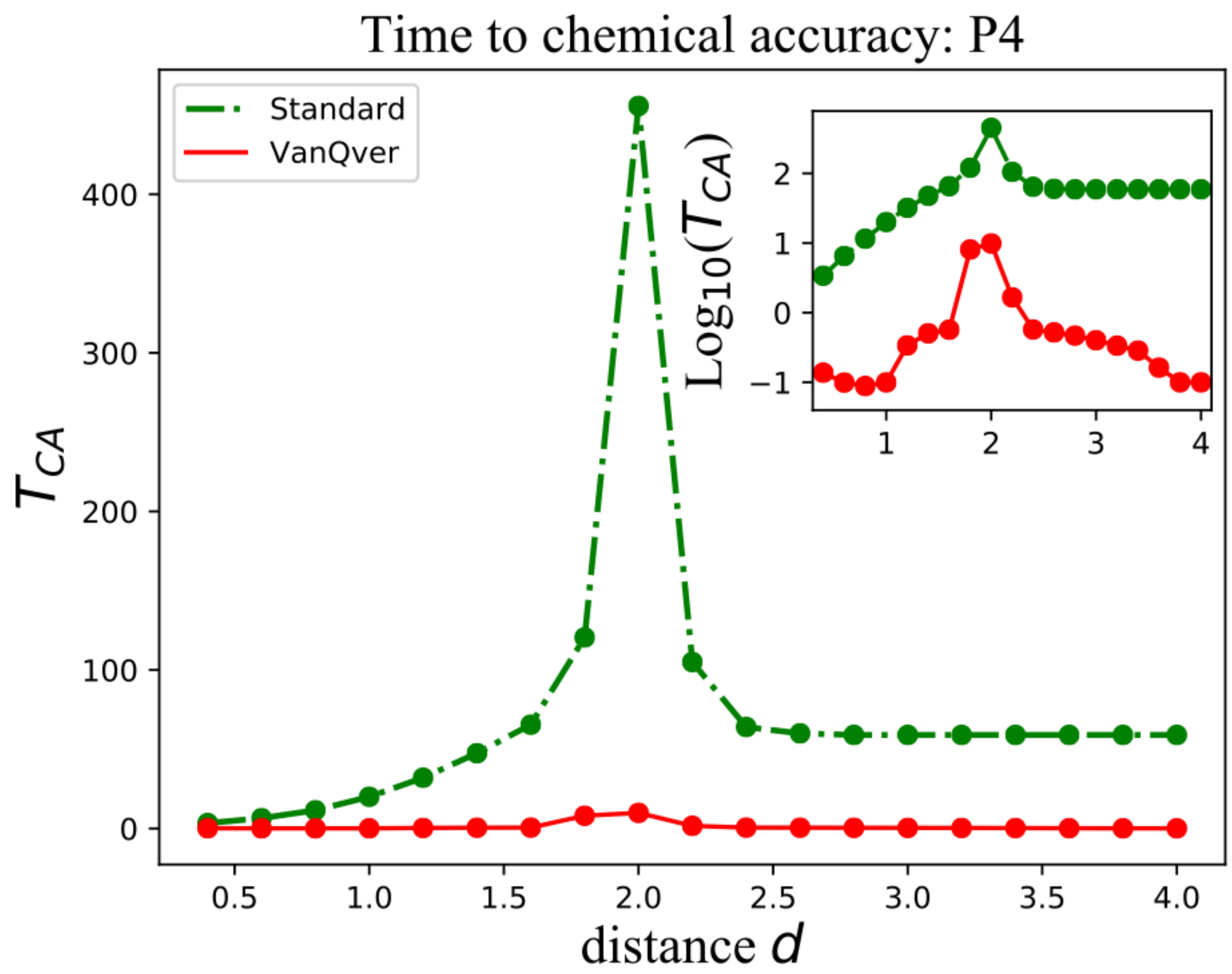
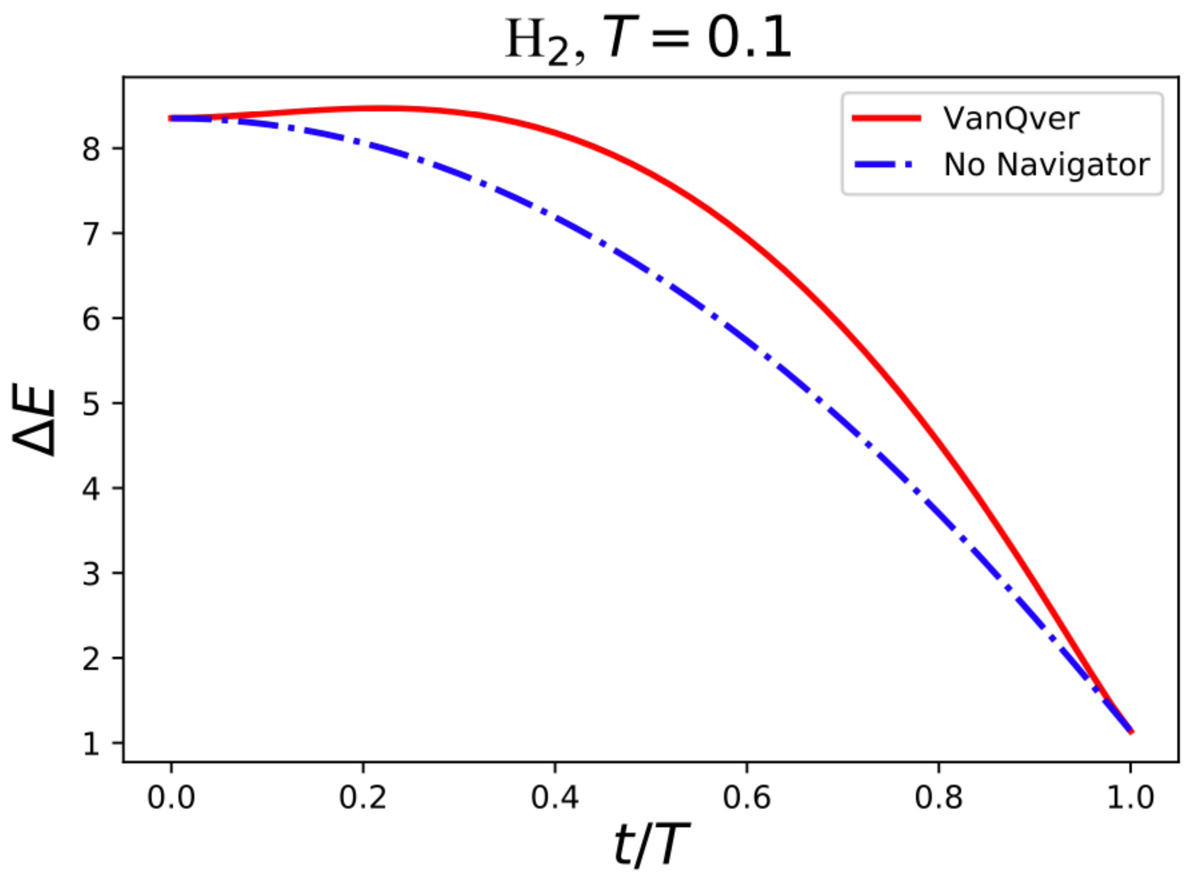

Time to chemical accuracy: P4
Standard
VanQver
400
300
200
100
0
T_{CA}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
distance d
$\text{Log}_{10}(T_{CA})$
2
1
0
−1
1
2
3
4

Energy Gap



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Ground State Overlap