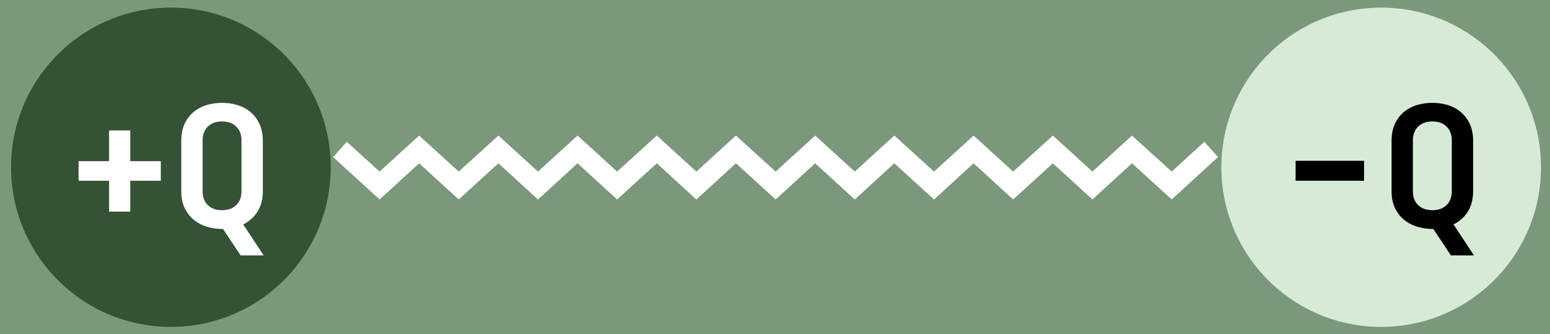
Analysis of the confinement string in (2+1)d Quantum Electrodynamics with quantum computing

Arianna Crippa,
Karl Jansen & Enrico Rinaldi



Perugia 8. May 2025

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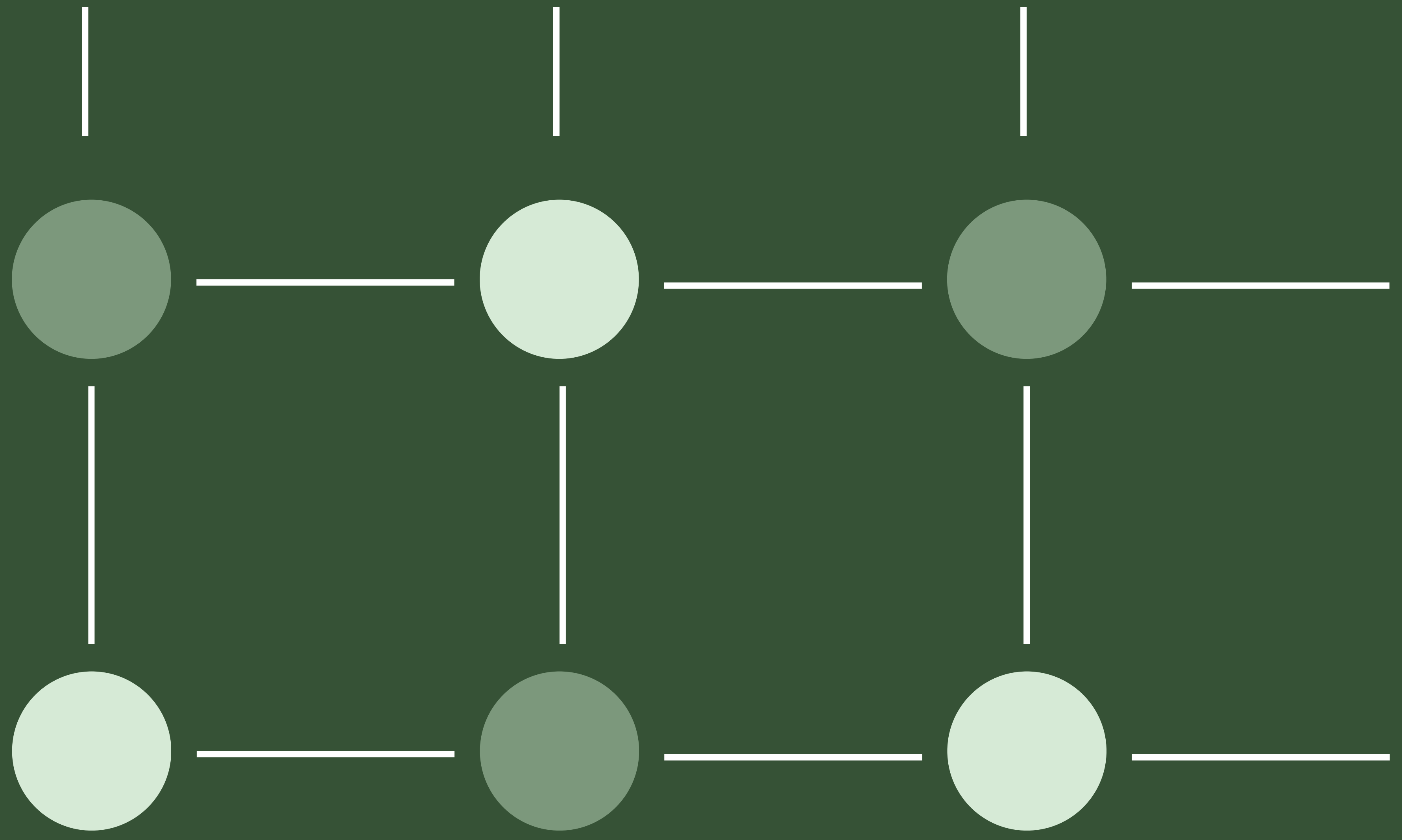
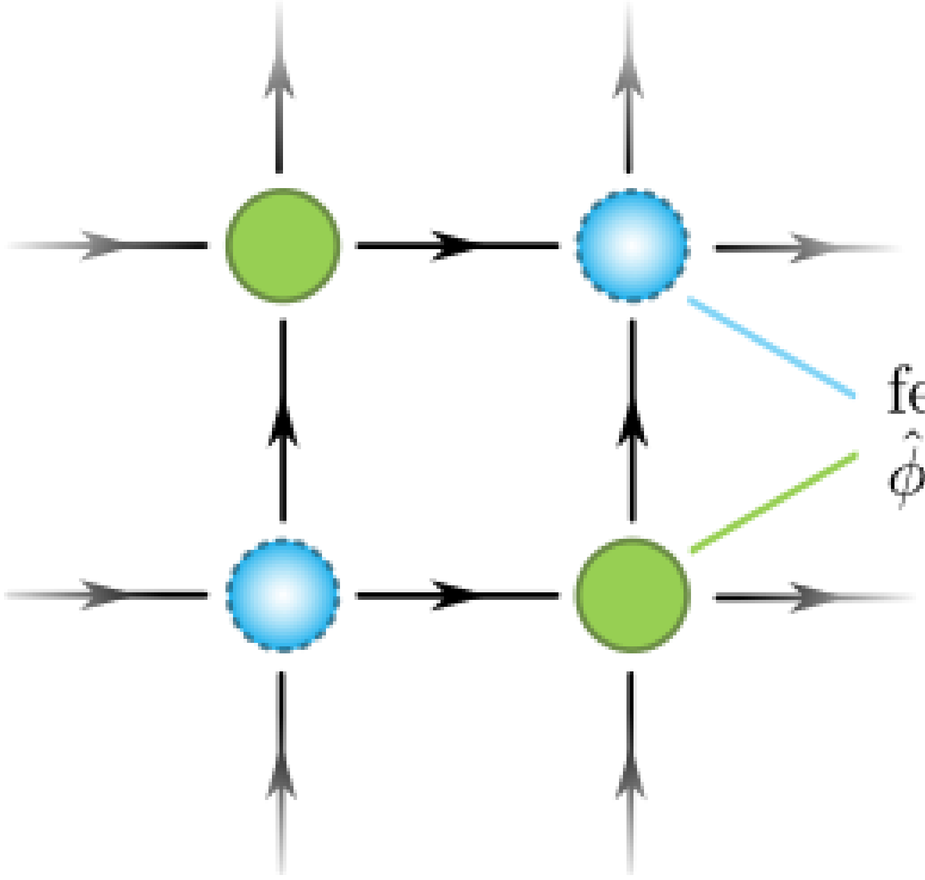
2+1D QED on the lattice



Lattice Hamiltonian

Lattice Hamiltonian



FERMIONIC HAMILTONIAN

$$\hat{H}_m = m \sum_{\vec{n}} (-1)^{n_x+n_y} \hat{\phi}^{\dagger}_{\vec{n}} \hat{\phi}_{\vec{n}}$$

$$\hat{H}_{kin} = \frac{i}{2} \sum_{\vec{n}} (\phi^{\dagger}_{\vec{n}} \hat{U}_{\vec{n},x} \phi_{\vec{n}+x} - h.c.)$$

$$- \frac{(-1)^{n_x+n_y}}{2} \sum_{\vec{n}} (\phi^{\dagger}_{\vec{n}} \hat{U}_{\vec{n},y} \phi_{\vec{n}+y} + h.c.)$$

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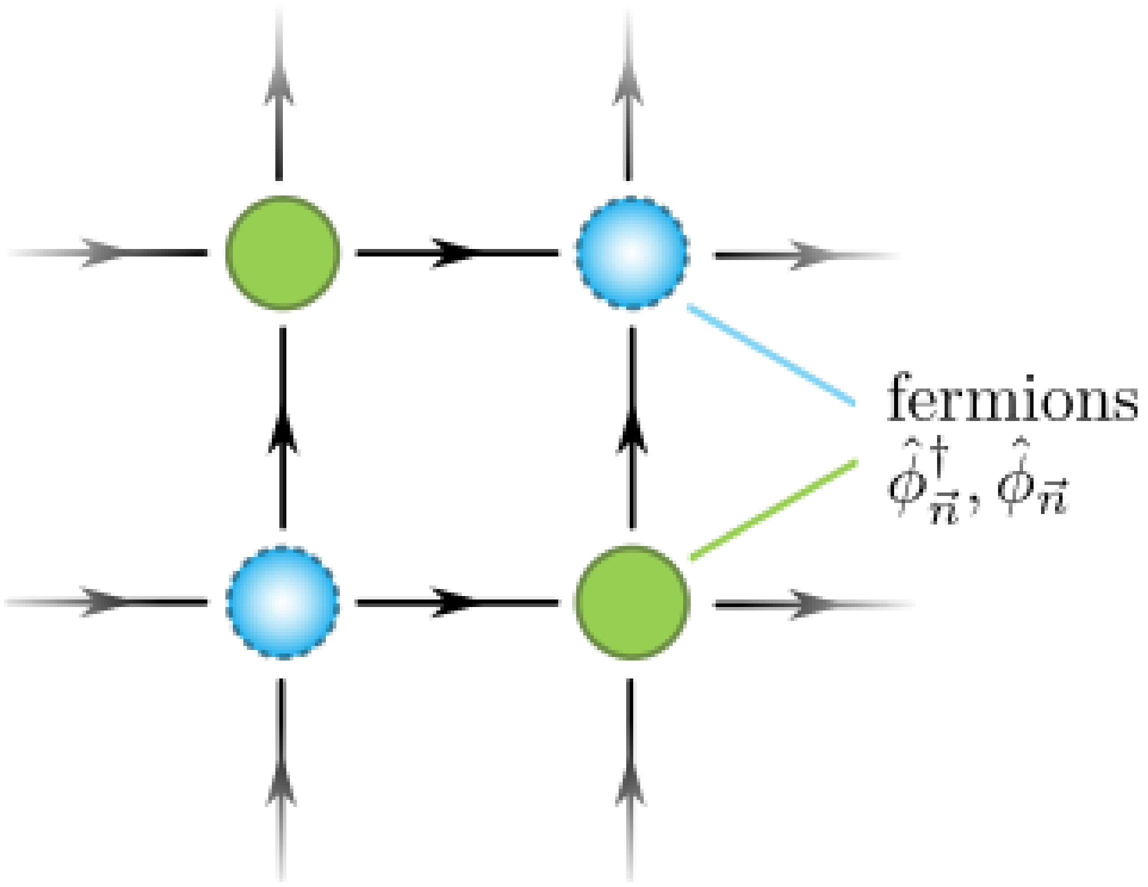

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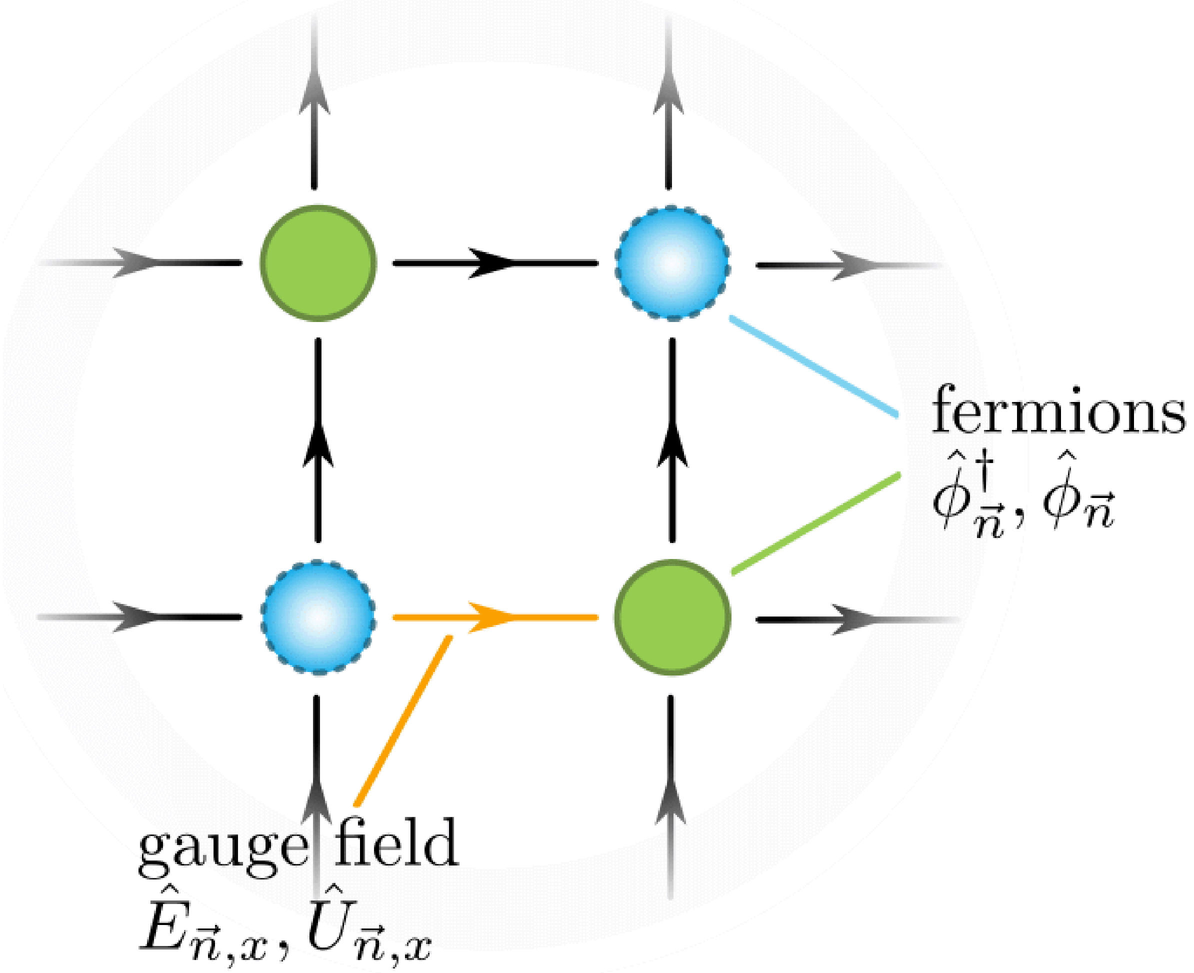

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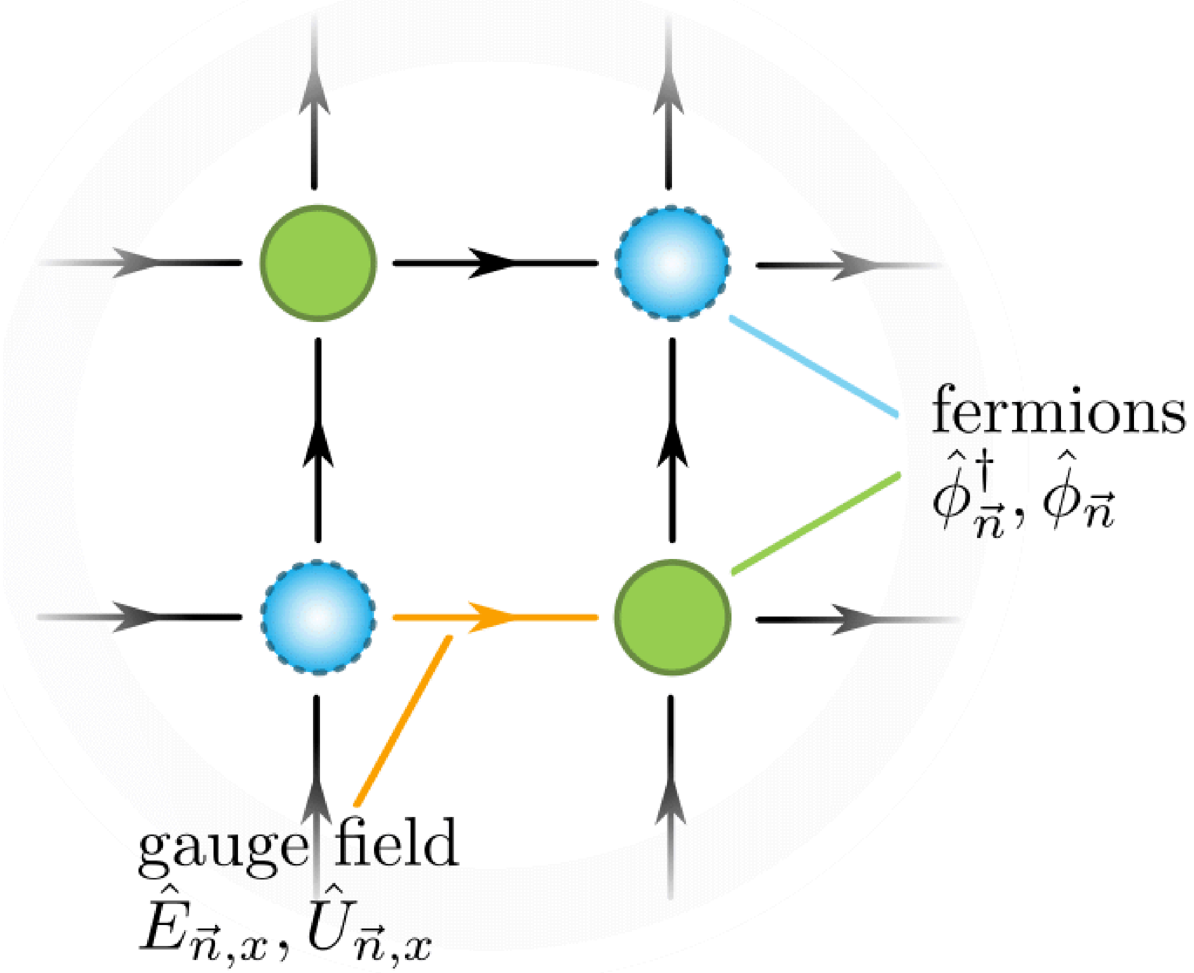
Lattice Hamiltonian



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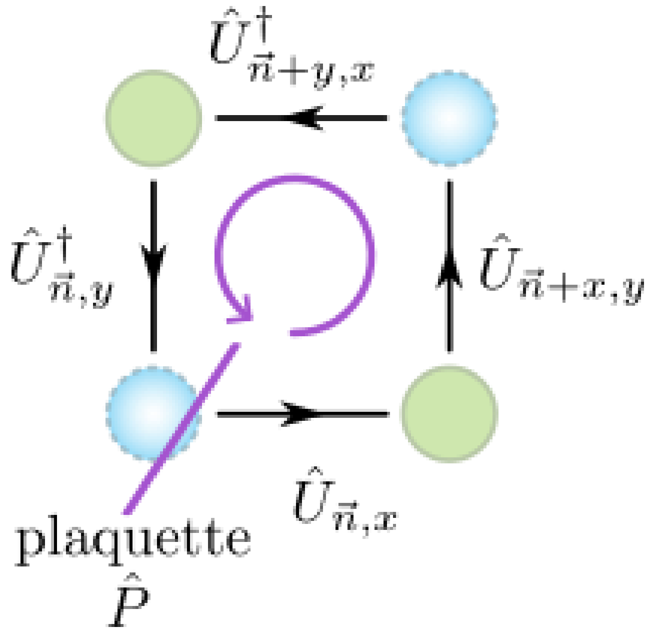

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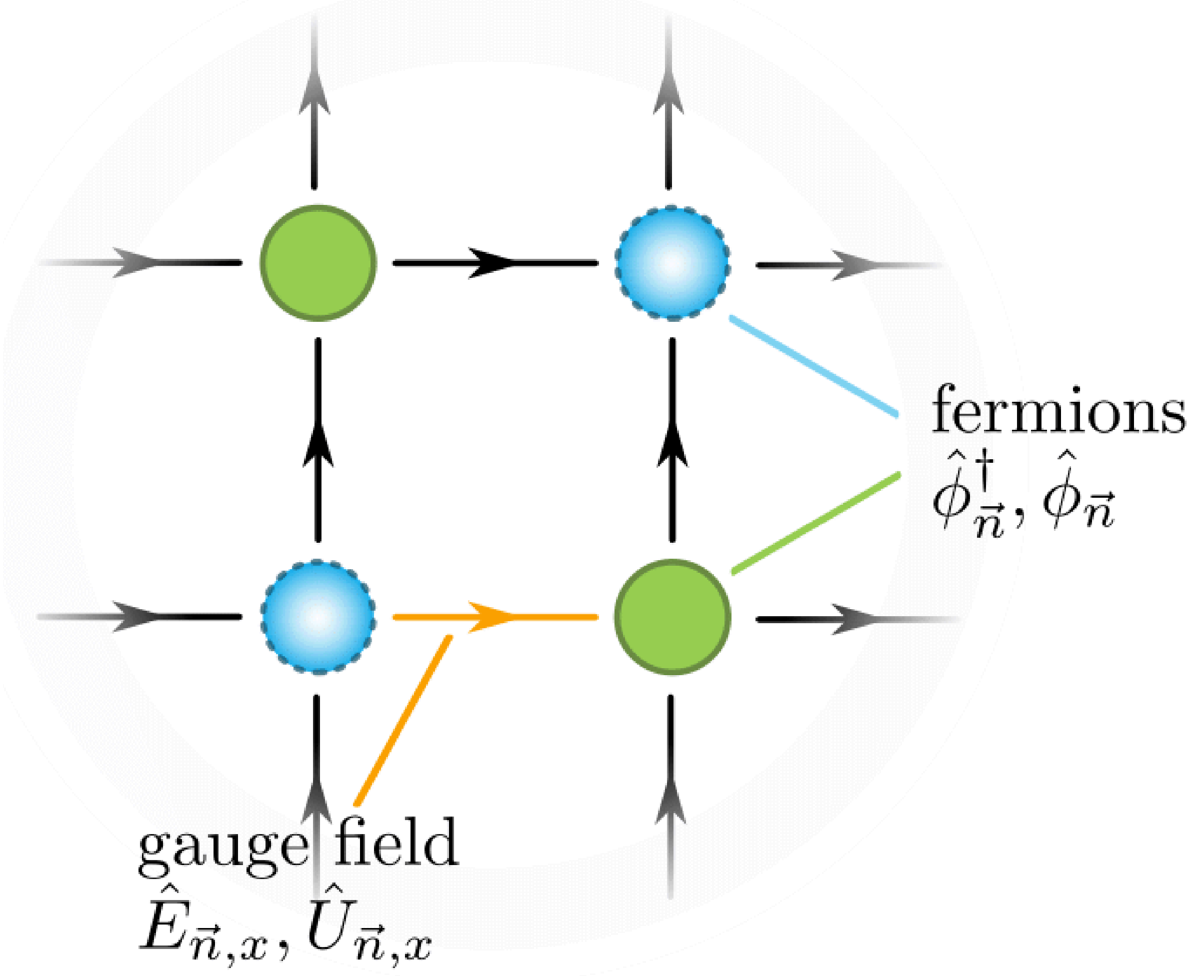

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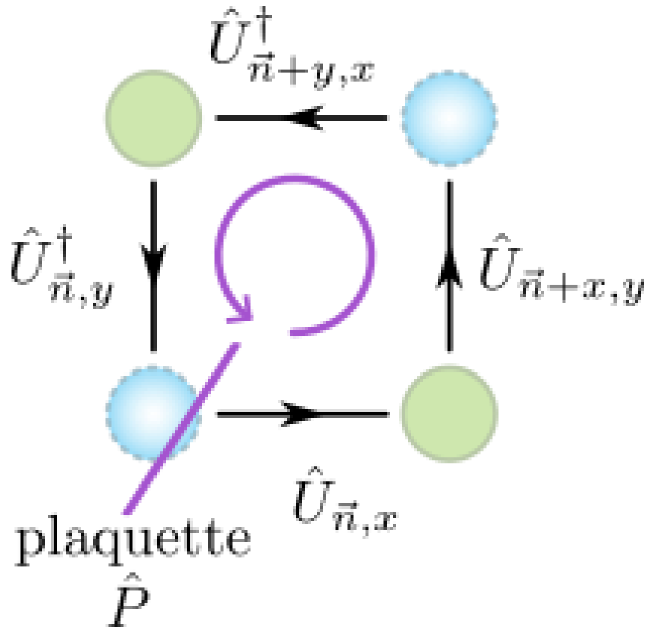
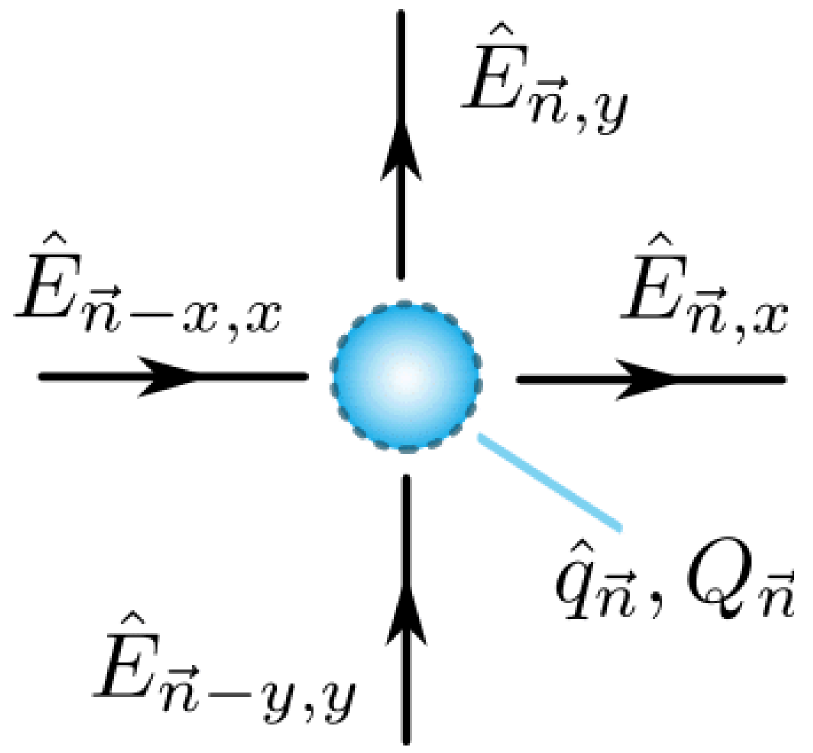


For simplicity *a=1*.

Lattice Hamiltonian

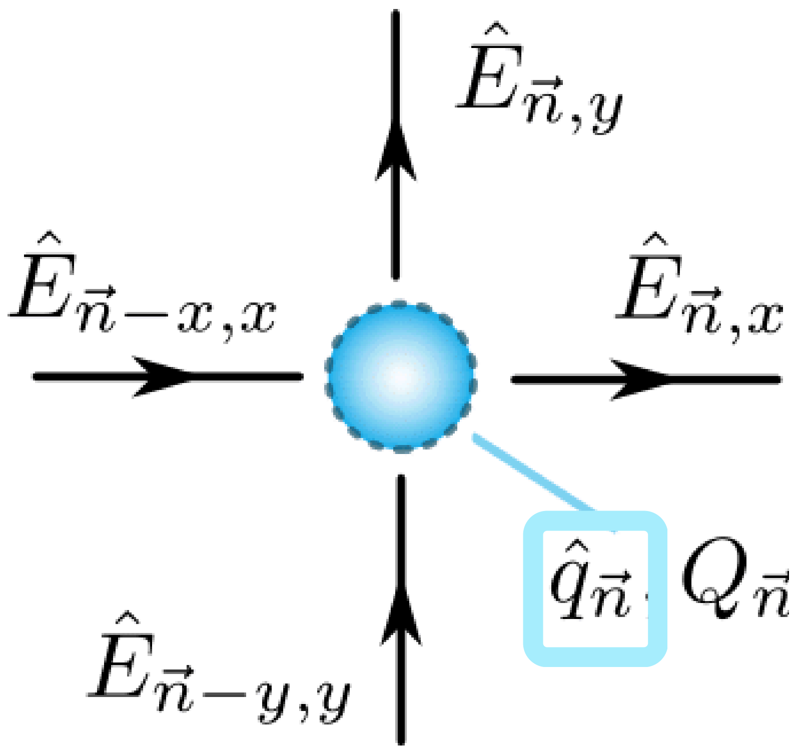
GAUSS'S LAW



$$\left[\sum_{\mu=x,y}\left(\hat{E}_{\vec{n},\mu}-\hat{E}_{\vec{n}-\mu,\mu}\right)-\hat{q}_{\vec{n}}-Q_{\vec{n}}\right]|\Phi\rangle=0 \iff |\Phi\rangle\in\mathcal{H}_{\text{phys.}}$$

Lattice Hamiltonian

GAUSS’S LAW



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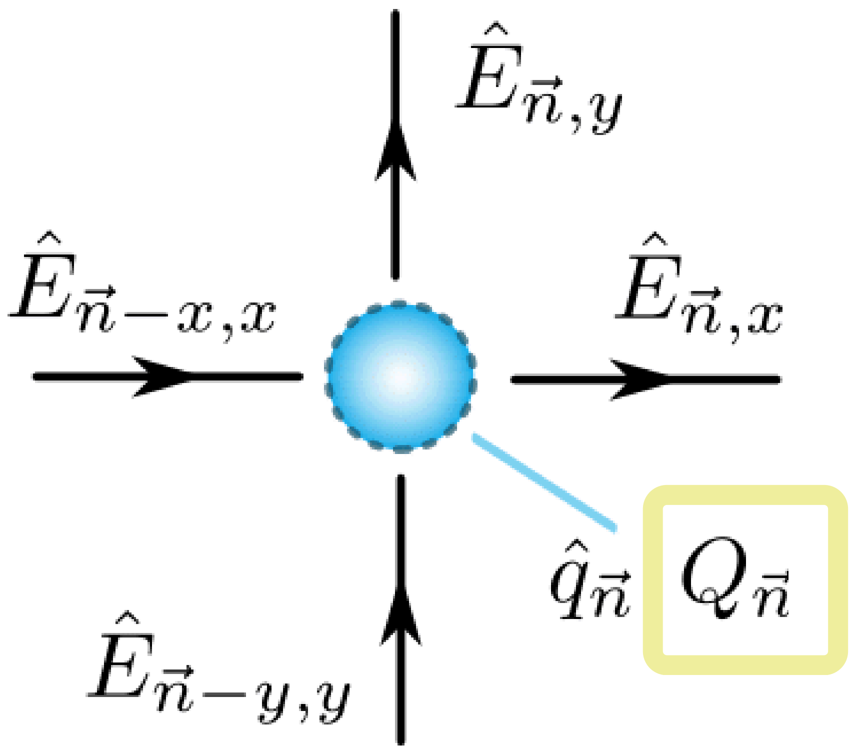
DYNAMICAL CHARGES

Lattice Hamiltonian

GAUSS'S LAW



STATIC CHARGES

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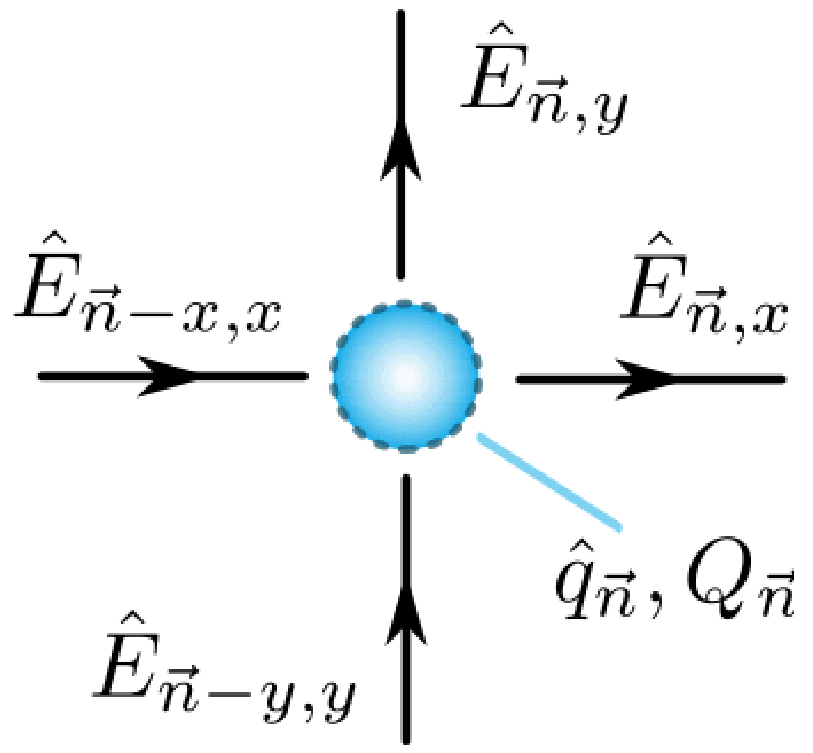

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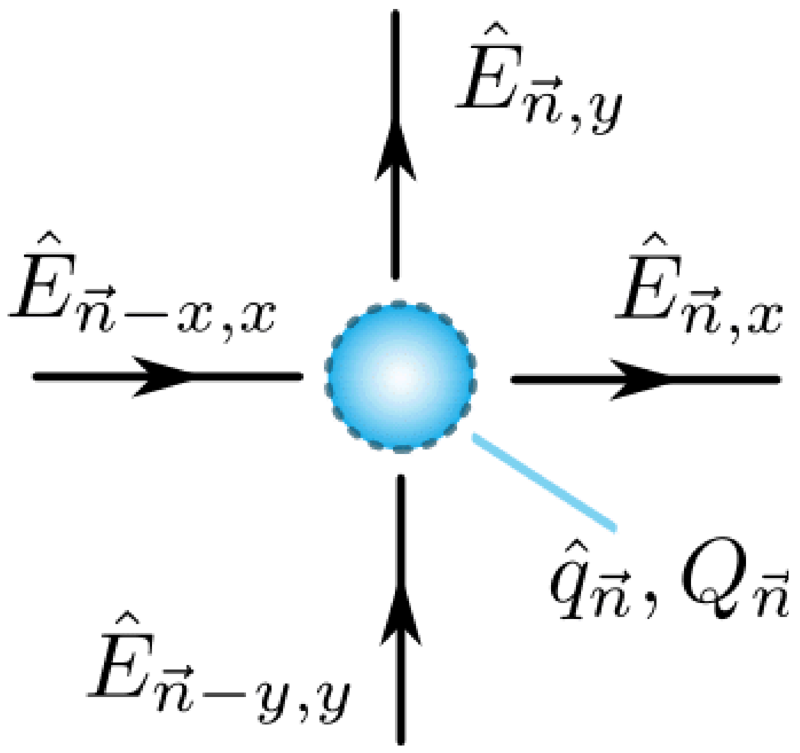
Solve system of equations

Lattice Hamiltonian

GAUSS'S LAW



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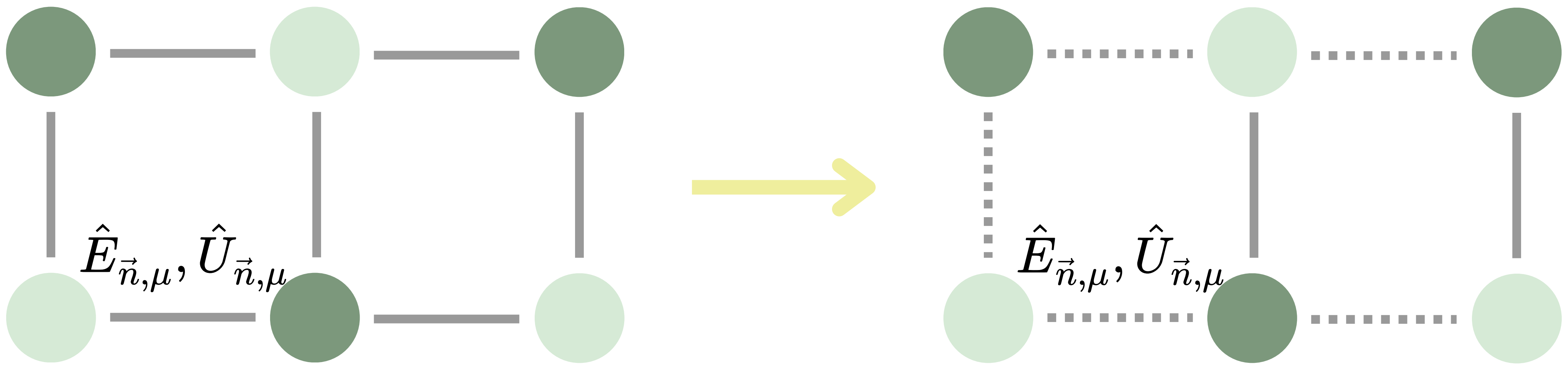
Solve system of equations

Subset of dynamical links



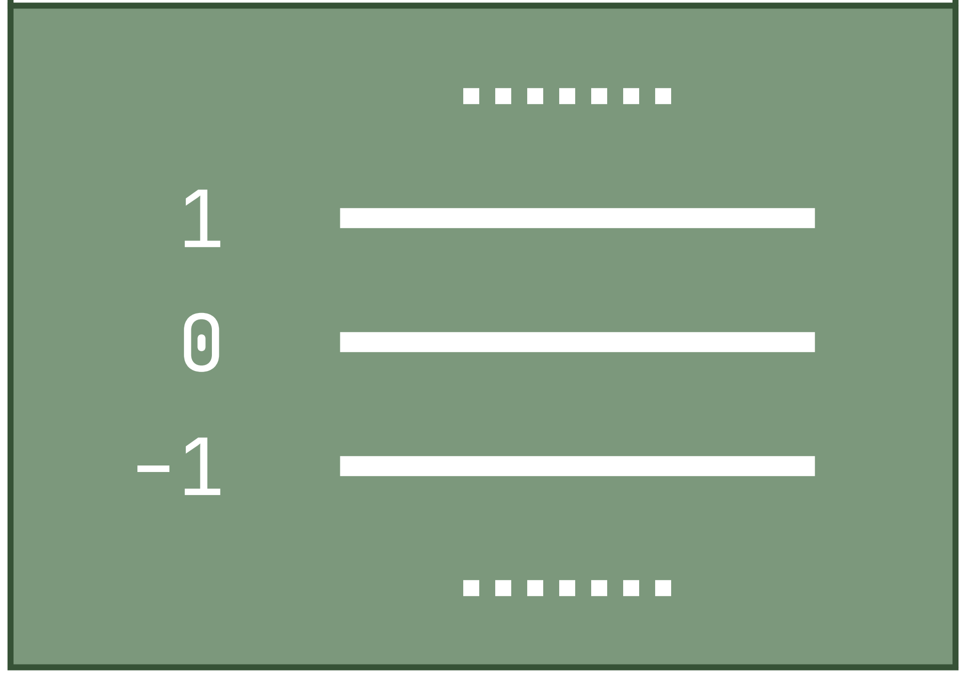
Truncation of gauge fields

Truncation of gauge fields

Compact U(1) group.

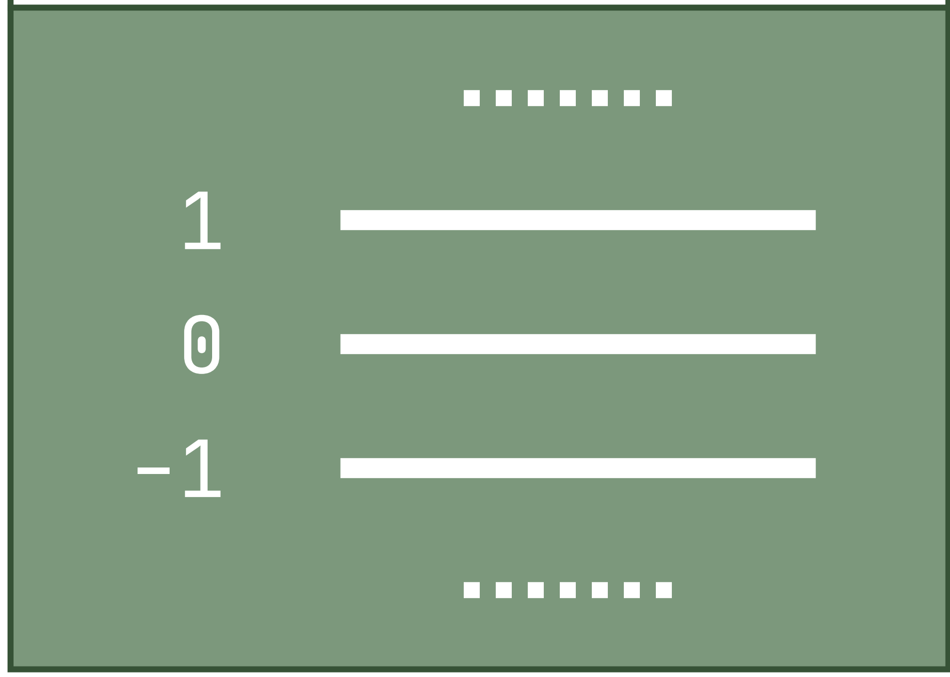
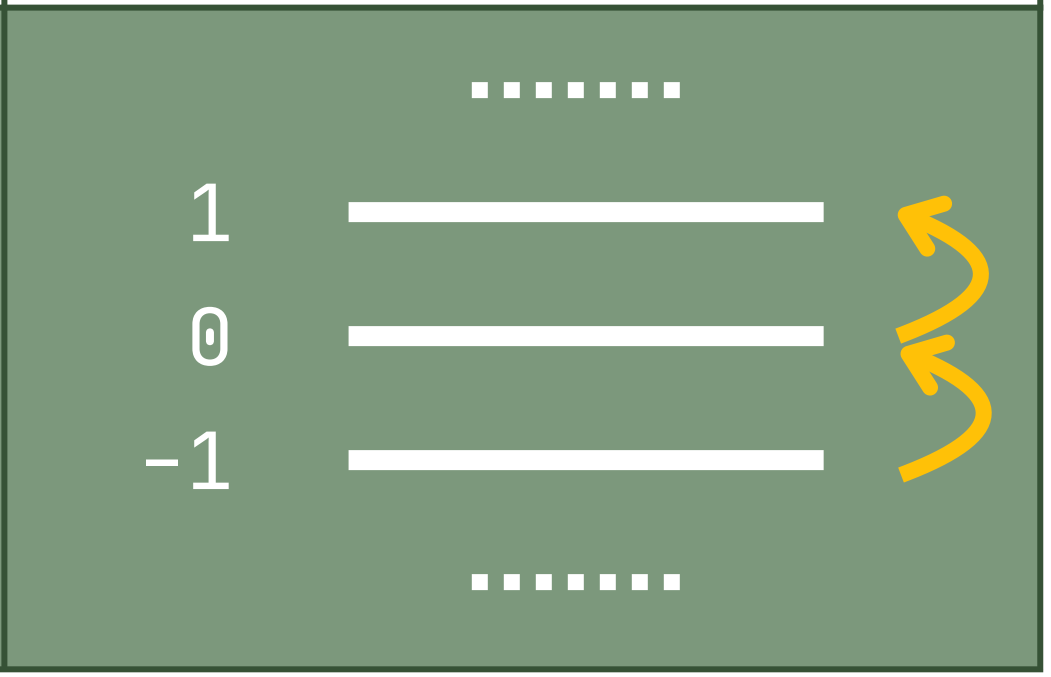
$$\hat{E}_{\vec{n},\mu}|e_{\vec{n},\mu}\rangle = e_{\vec{n},\mu}|e_{\vec{n},\mu}\rangle$$

$$e_{\vec{n},\mu} \in [-l, l]$$



Truncation of gauge fields

Compact U(1) group.

$\hat{E}_{\vec{n},\mu}\vert e_{\vec{n},\mu}\rangle = e_{\vec{n},\mu}\vert e_{\vec{n},\mu}\rangle$ $e_{\vec{n},\mu} \in [-l, l]$	$\hat{U}_{\vec{n},\mu}\vert e_{\vec{n},\mu}\rangle = \vert e_{\vec{n},\mu} + 1\rangle$
	

$$[\hat{E}_{\vec{n},\mu}, \hat{U}_{\vec{m},\nu}] = \delta_{\vec{n},\vec{m}}\delta_{\mu,\nu}\hat{U}_{\vec{m},\nu}$$

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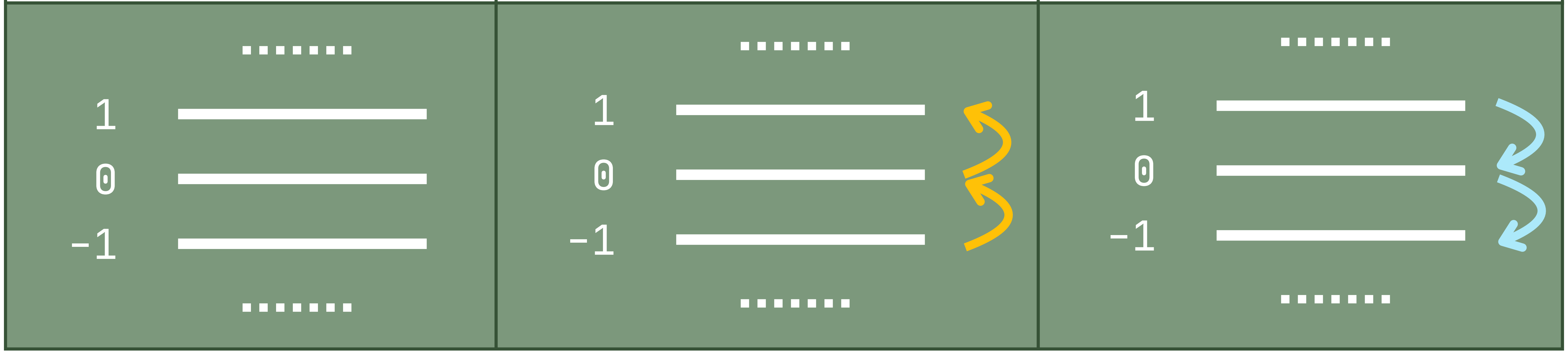
$\hat{E}_{\vec{n},\mu}\lvert e_{\vec{n},\mu}\rangle = e_{\vec{n},\mu}\lvert e_{\vec{n},\mu}\rangle$ $e_{\vec{n},\mu} \in [-l, l]$	$\hat{U}_{\vec{n},\mu}\lvert e_{\vec{n},\mu}\rangle = \lvert e_{\vec{n},\mu} + 1\rangle$	$\hat{U}^{\dagger}_{\vec{n},\mu}\lvert e_{\vec{n},\mu}\rangle = \lvert e_{\vec{n},\mu} - 1\rangle$

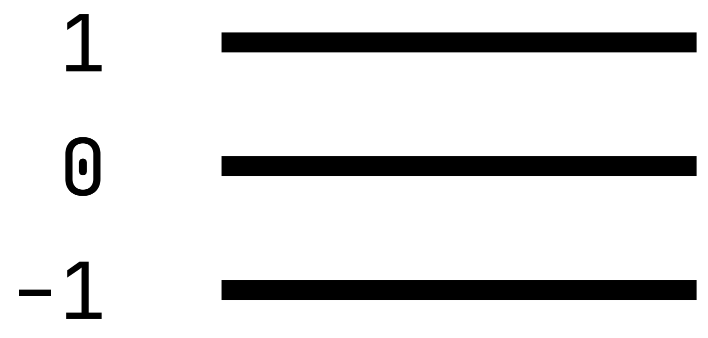


$$[\hat{E}_{\vec{n},\mu}, \hat{U}_{\vec{m},\nu}] = \delta_{\vec{n},\vec{m}}\delta_{\mu,\nu}\hat{U}_{\vec{m},\nu} \qquad [\hat{E}_{\vec{n},\mu}, \hat{U}^{\dagger}_{\vec{m},\nu}] = -\delta_{\vec{n},\vec{m}}\delta_{\mu,\nu}\hat{U}^{\dagger}_{\vec{m},\nu}$$

Quantum Computing methods

Quantum circuits for gauge fields

Example of truncation l=1:



Quantum circuits for gauge fields

Example of truncation l=1:

1	———
0	———
-1	———

$|-1\rangle_{\text{ph.}} \mapsto |00\rangle$

$|0\rangle_{\text{ph.}} \mapsto |01\rangle$

$|1\rangle_{\text{ph.}} \mapsto |11\rangle$

$|10\rangle$

Quantum circuits for gauge fields

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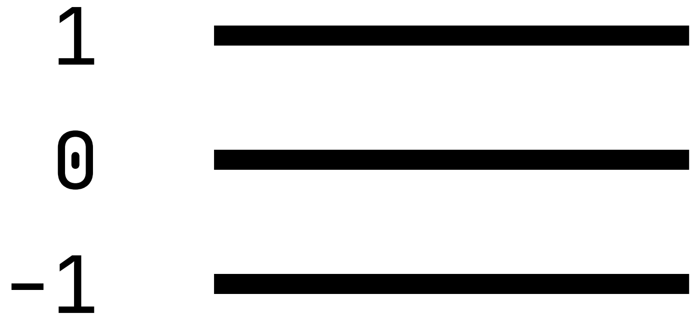

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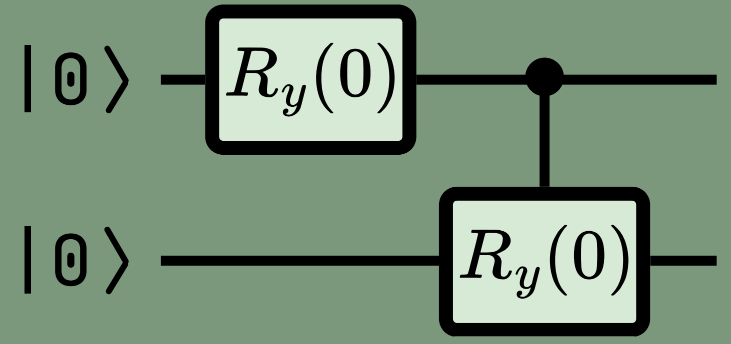

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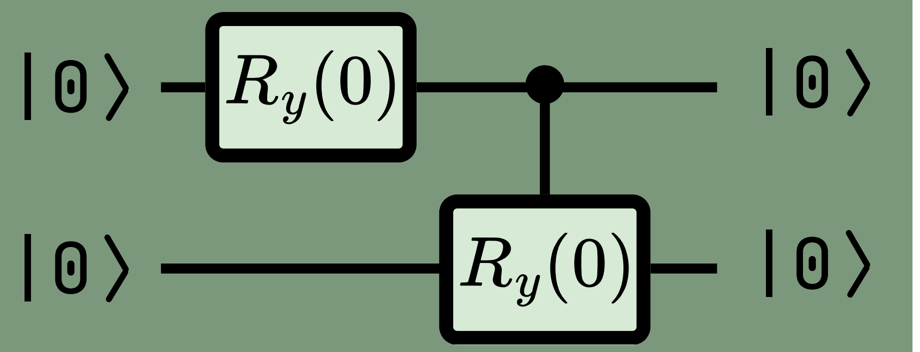

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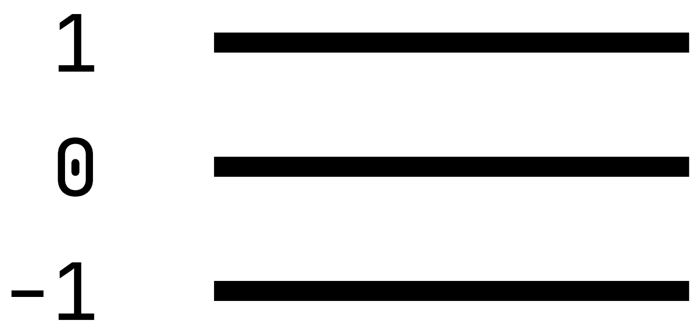

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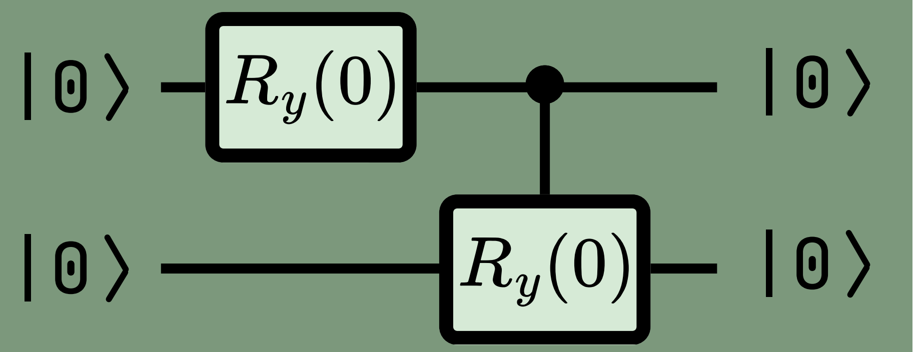

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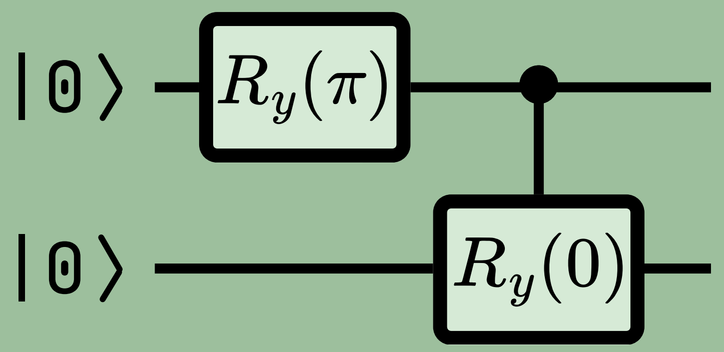

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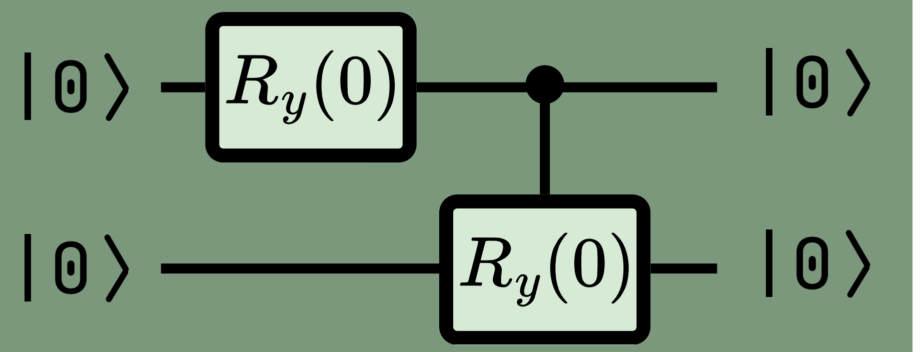

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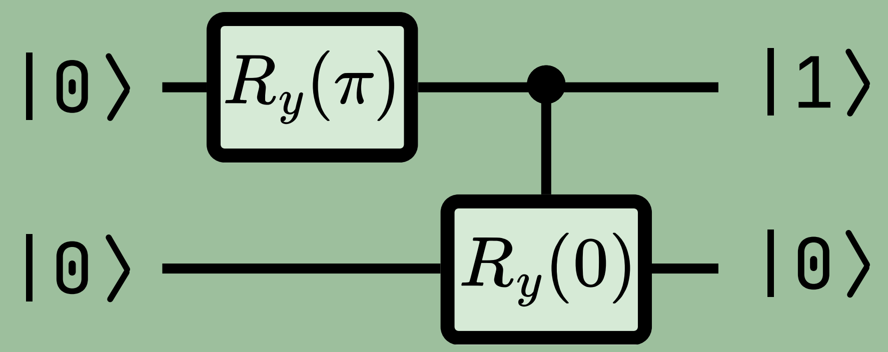

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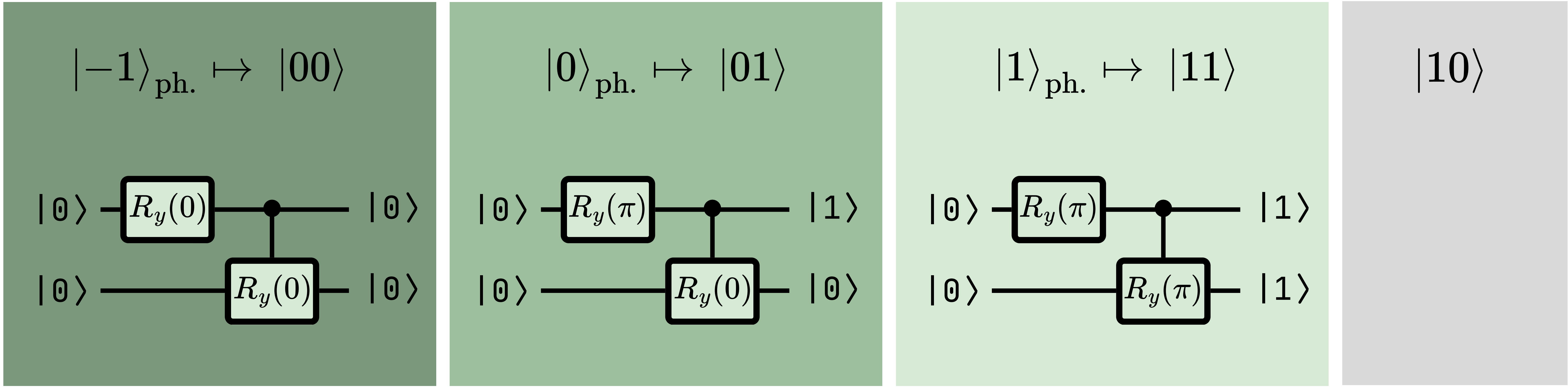

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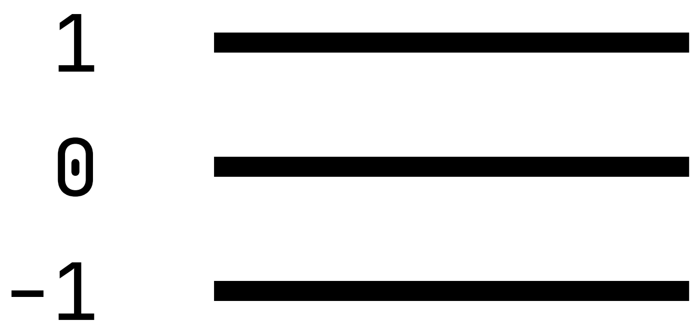
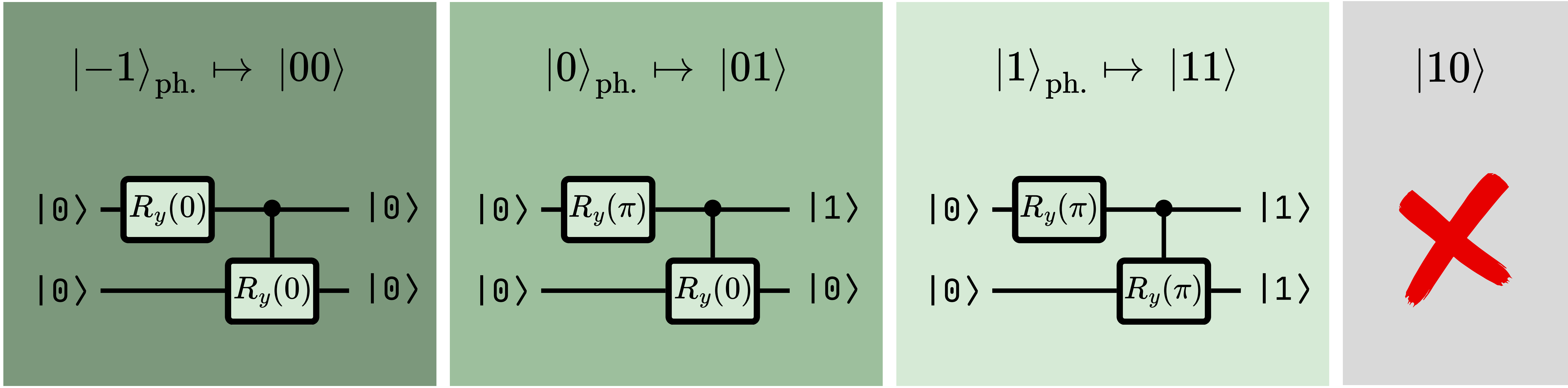


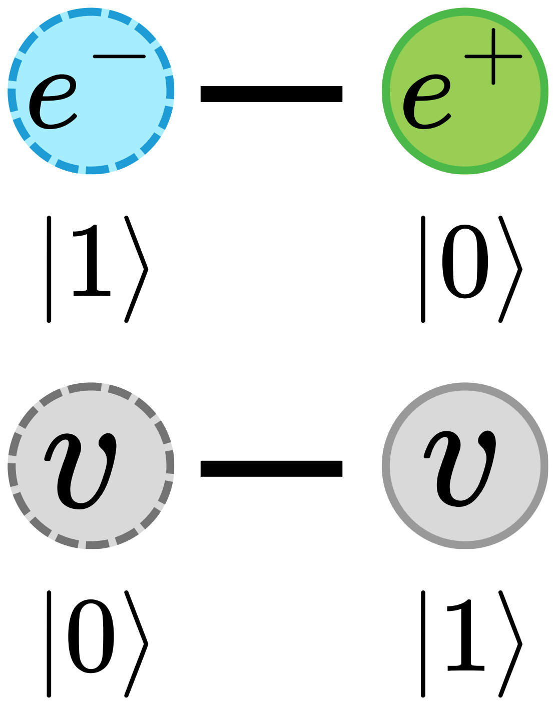


Quantum circuits for fermions

Quantum circuits for fermions

Zero total charge

EVEN **ODD**



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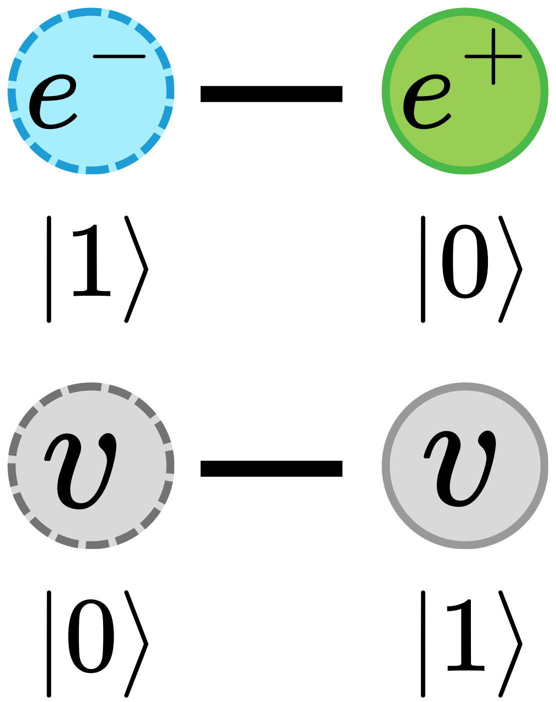

Preserve parity

$$|0^n \dots 1^m\rangle$$

$$n = m$$

Quantum circuits for fermions

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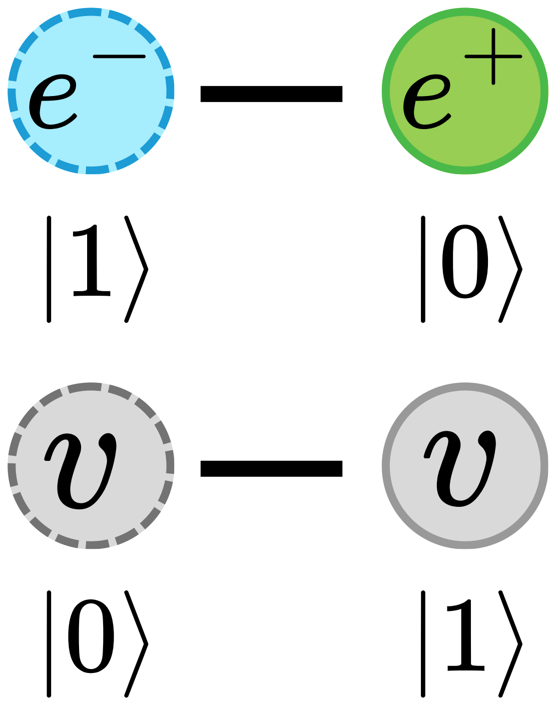
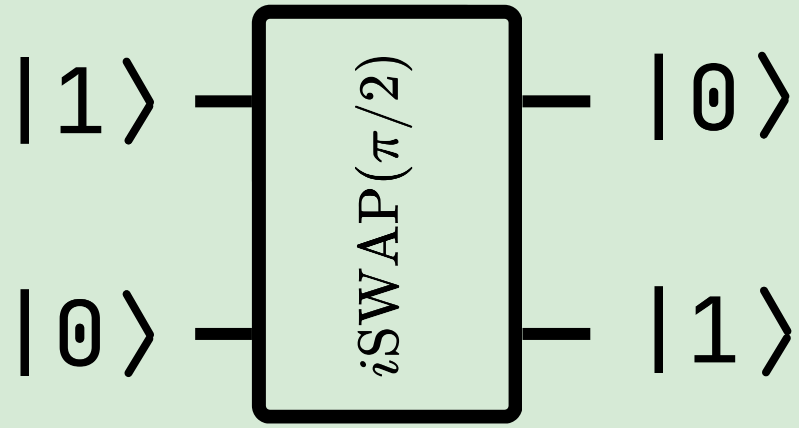


$$|0^n \dots 1^m\rangle$$

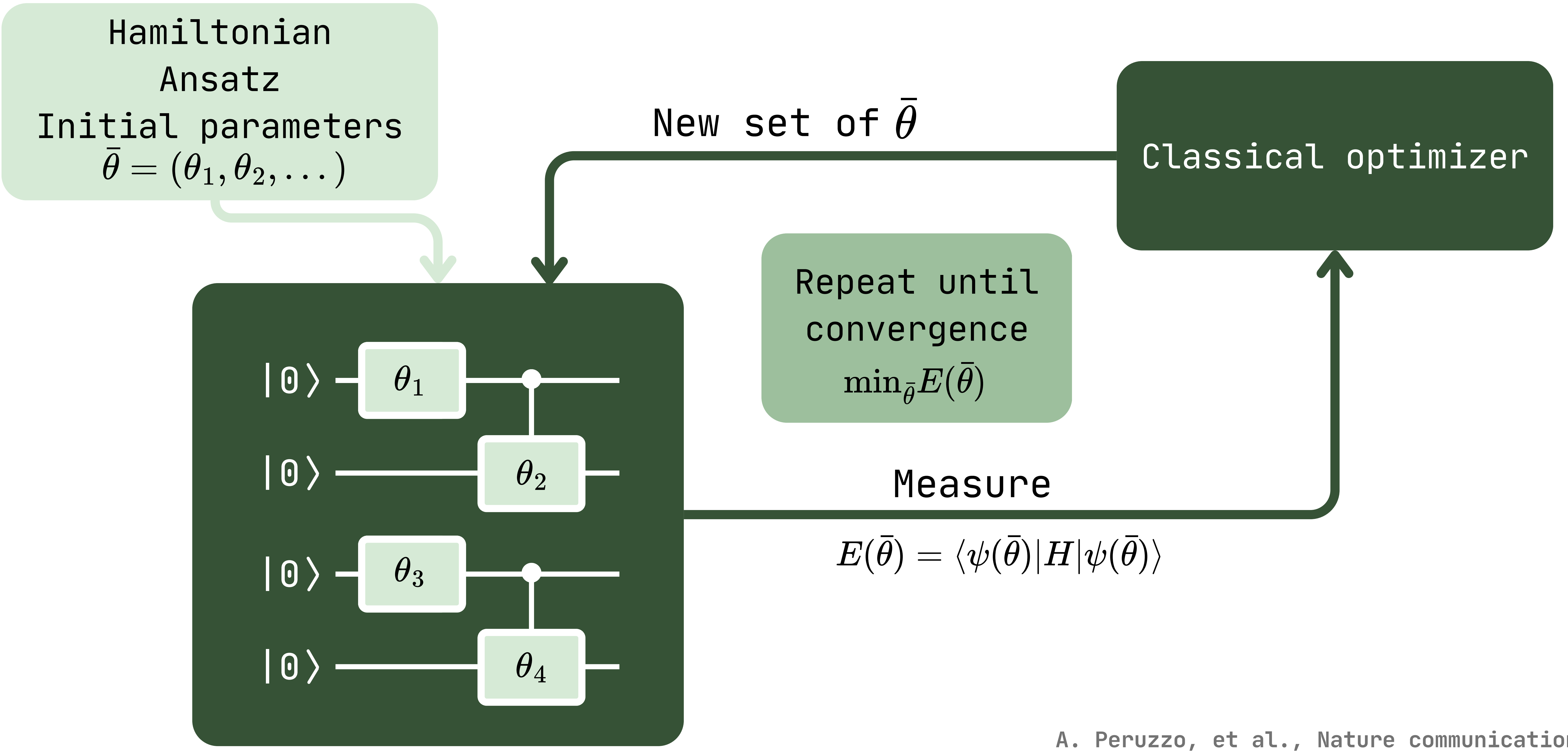
$$n = m$$

$$iSWAP_{j,k}(\theta) = e^{-i\frac{\theta}{4}(\sigma^x_j\sigma^x_k + \sigma^y_j\sigma^y_k)}$$



D. Paulson, et al., PRX Quantum 2,030334 (2021)

Variational quantum algorithm



A. Peruzzo, et al., Nature communications 5, 4213 (2014)

Electric flux configurations of the static potential

Electric flux configurations of the static potential

- Study confinement and string breaking phenomena.

Electric flux configurations of the static potential

- Study confinement and string breaking phenomena.
- Direct visualization of electric fluxes & probabilities of relevant states.

Static potential

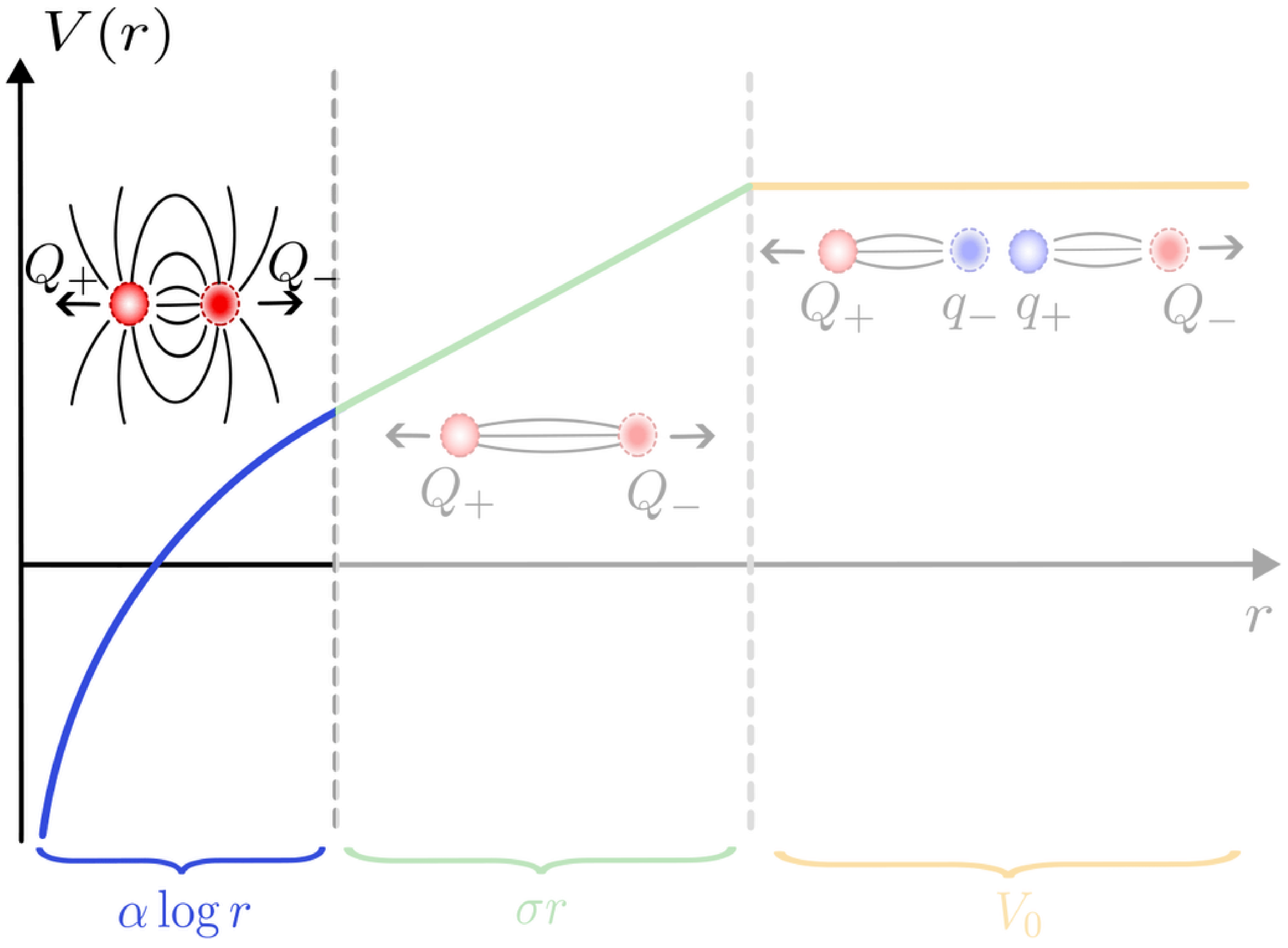
QED 2+1D

$$V(r) = \alpha \log r + \sigma r + V_0$$

Static potential

QED 2+1D

$$V(r) = \boxed{\alpha \log r} + \sigma r + V_0$$



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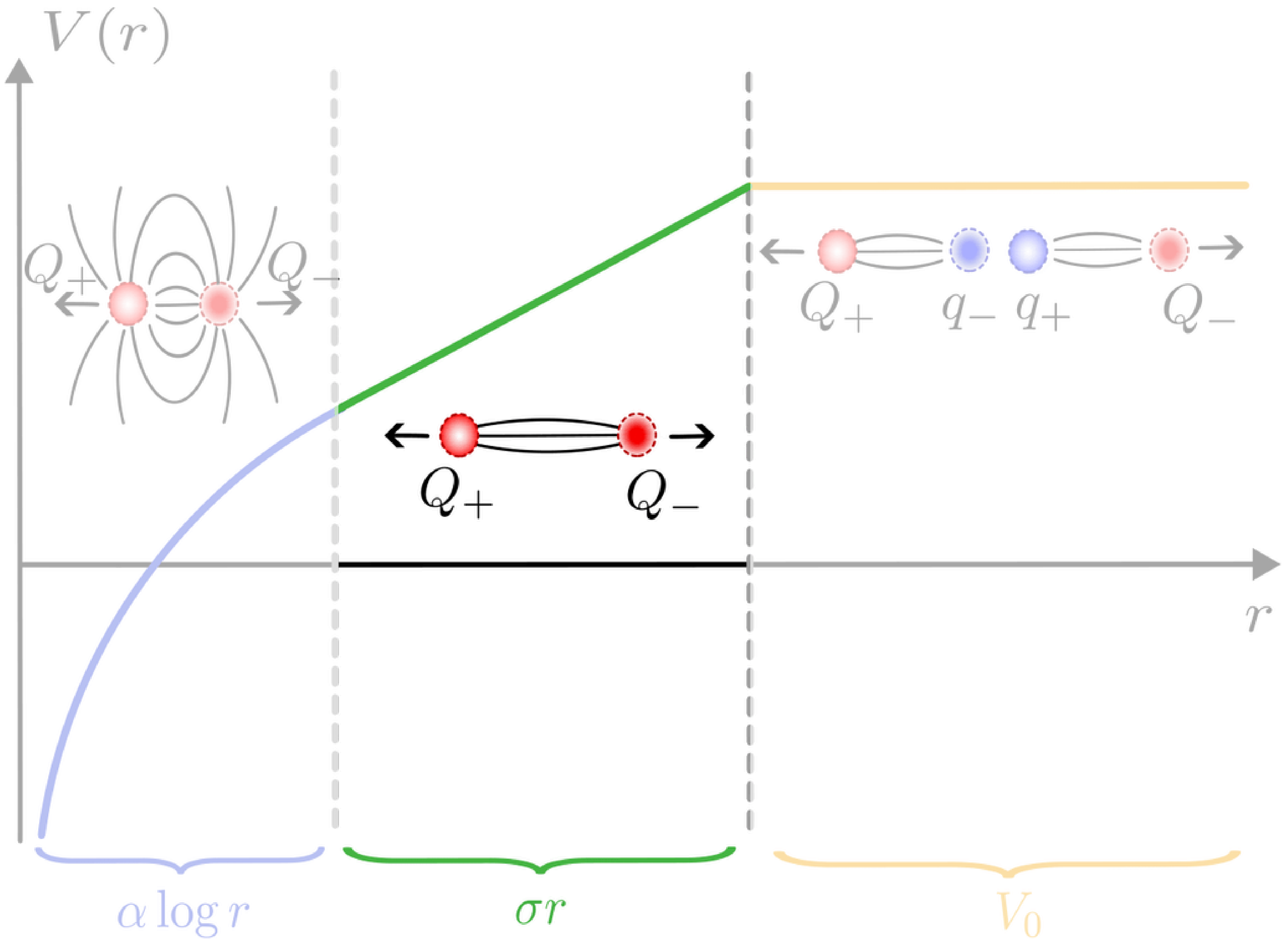

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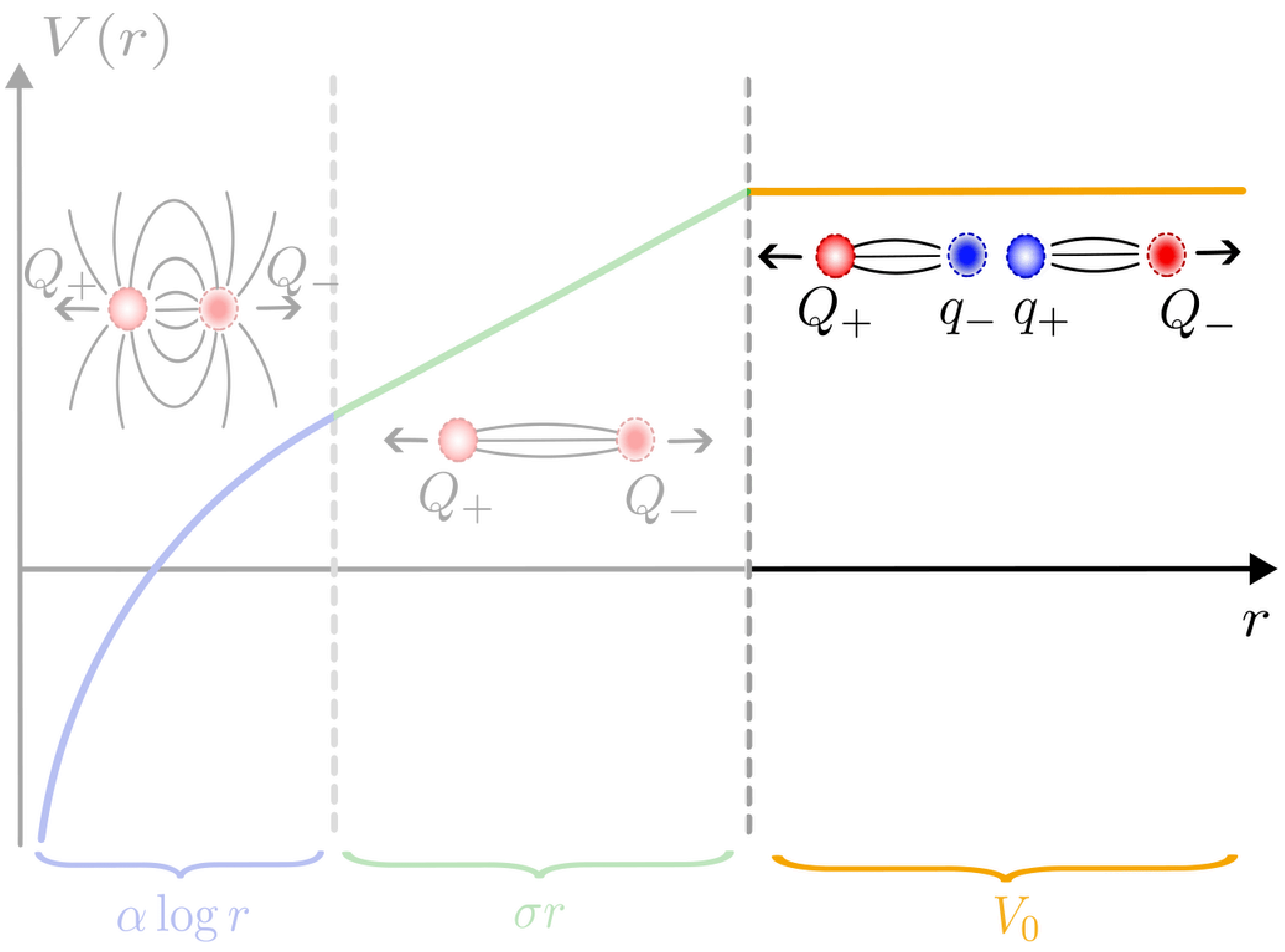
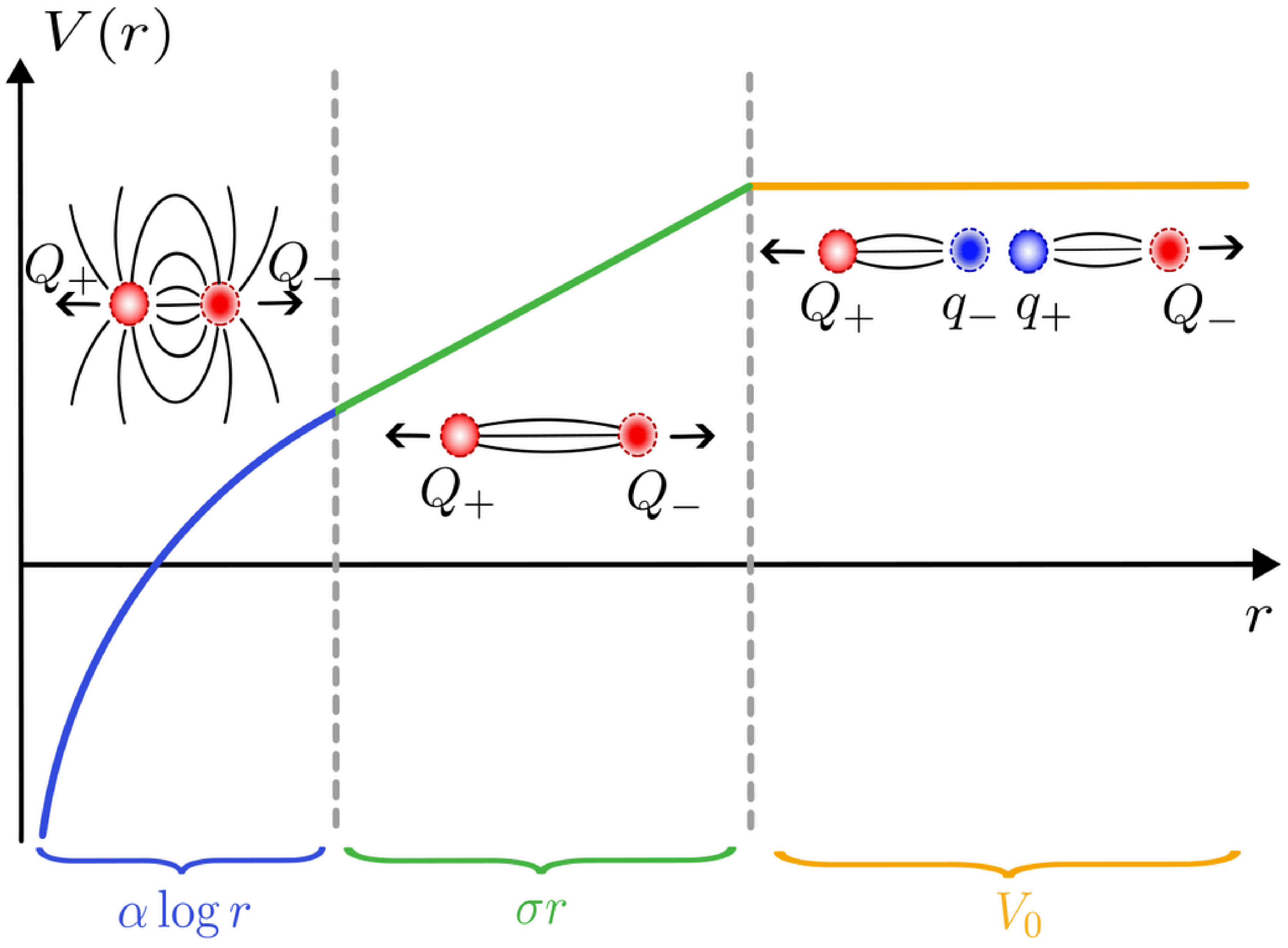


Static potential

QED 2+1D

$$V(r) = \alpha \log r + \sigma r + V_0$$

$$r = a r_{latt}$$



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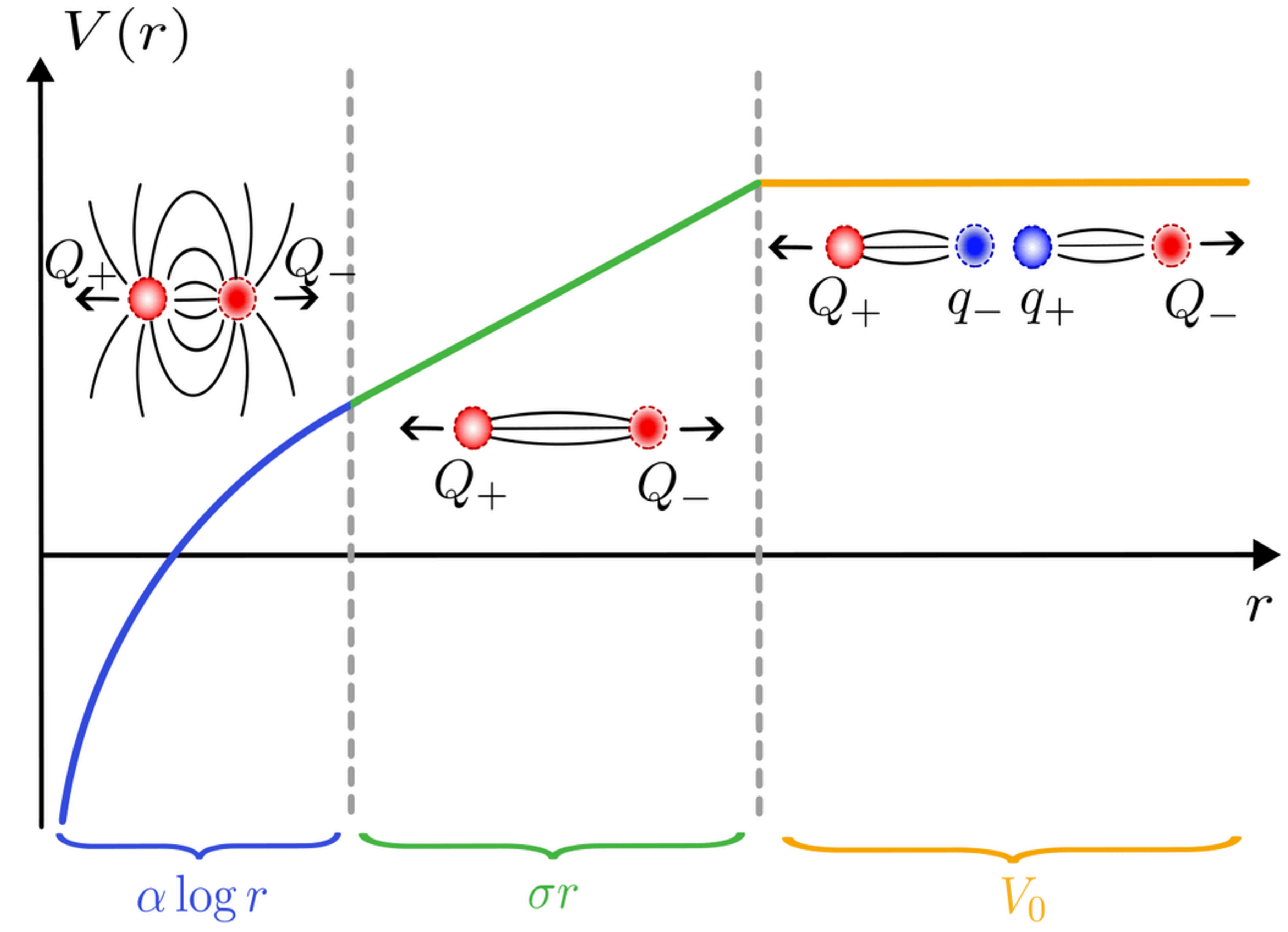
$$g \mapsto g(a)$$



Static potential
QED 2+1D

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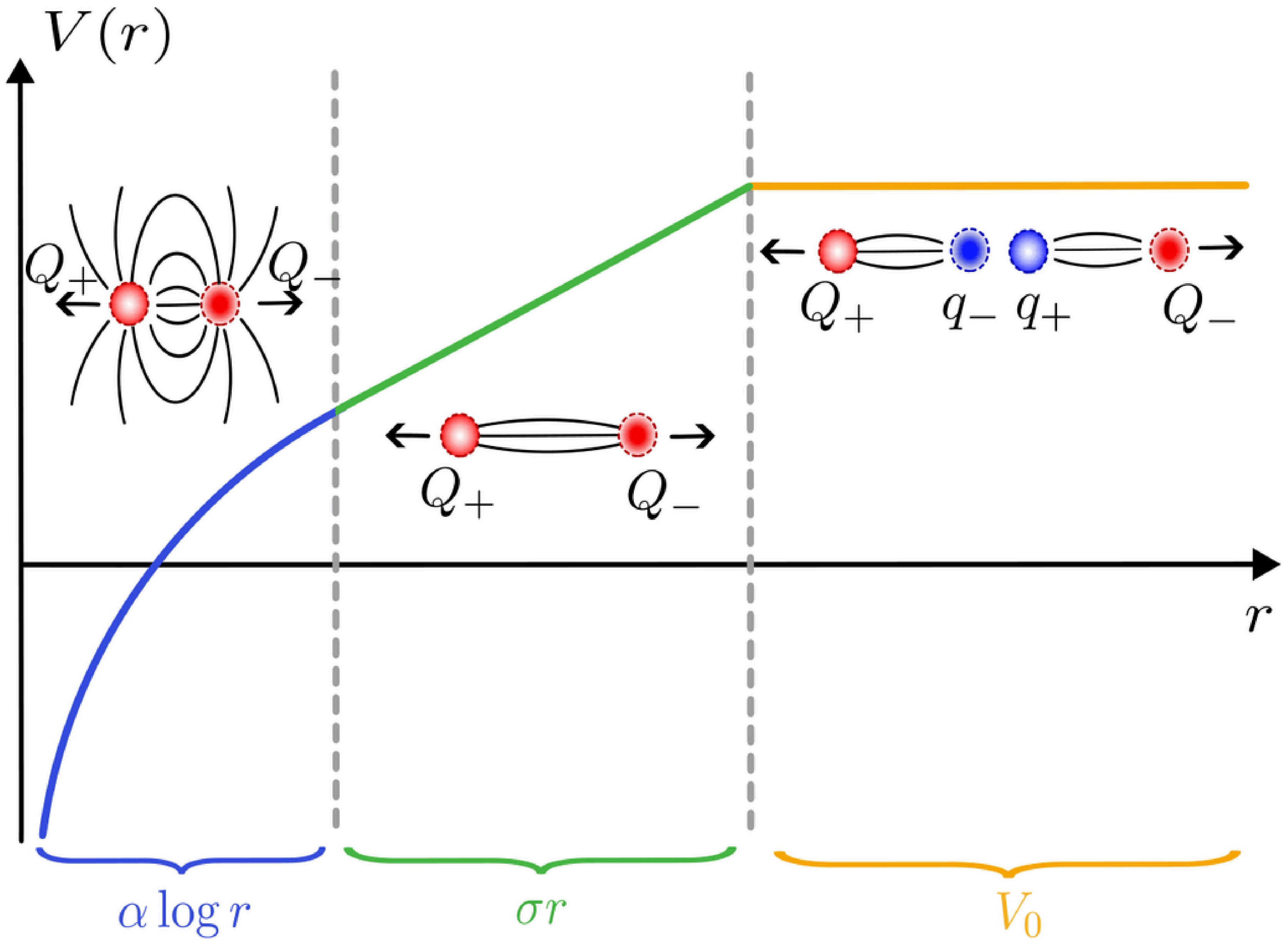
$$r = a r_{latt}$$

$$g \mapsto g(a)$$

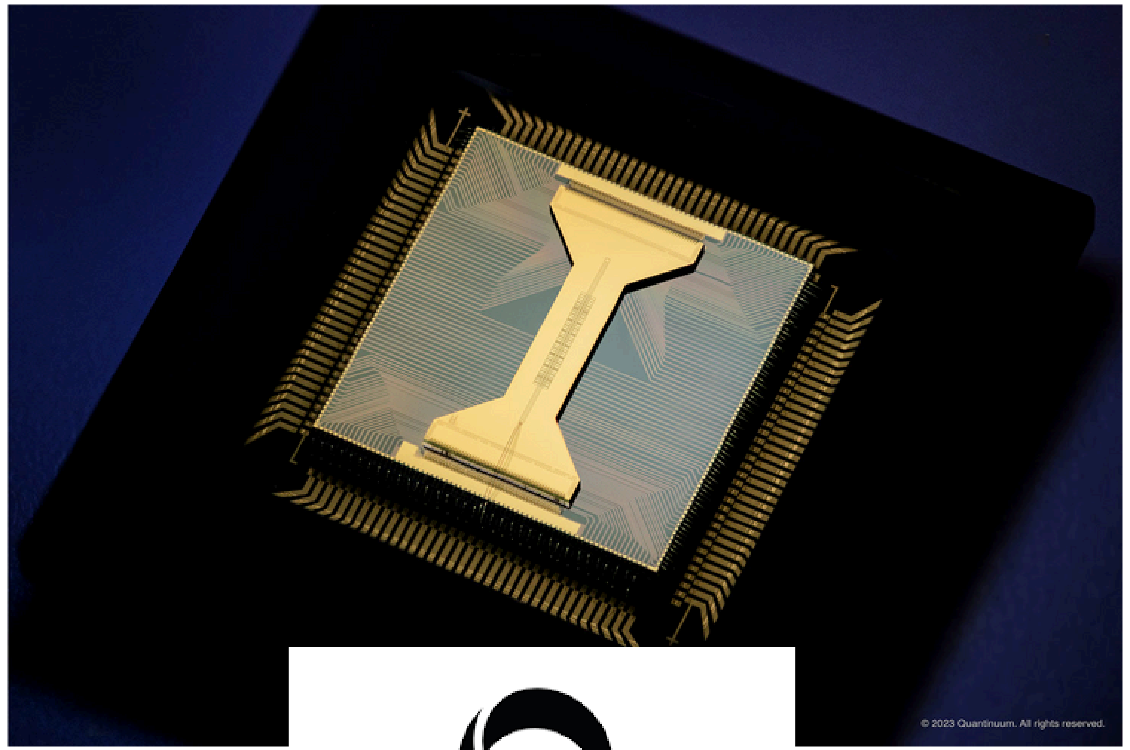
$$V(r) \to V(g)$$



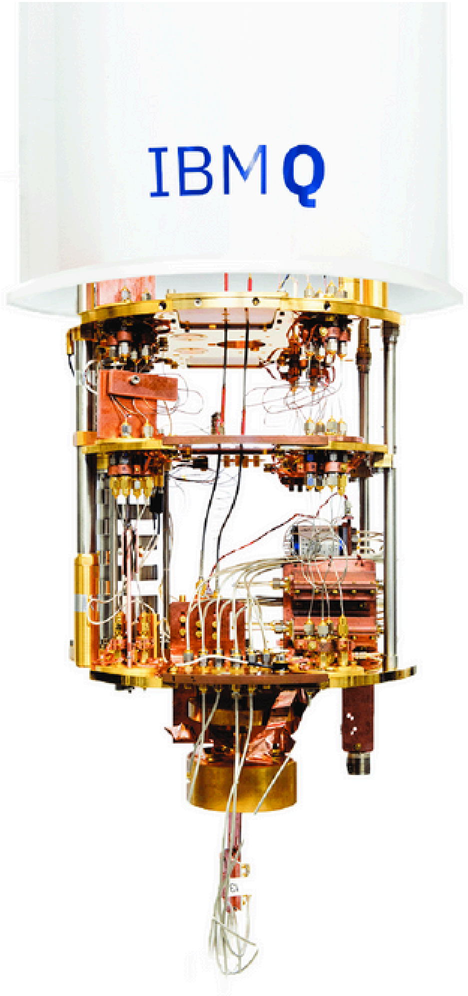
Quantum Hardware

Quantum Hardware

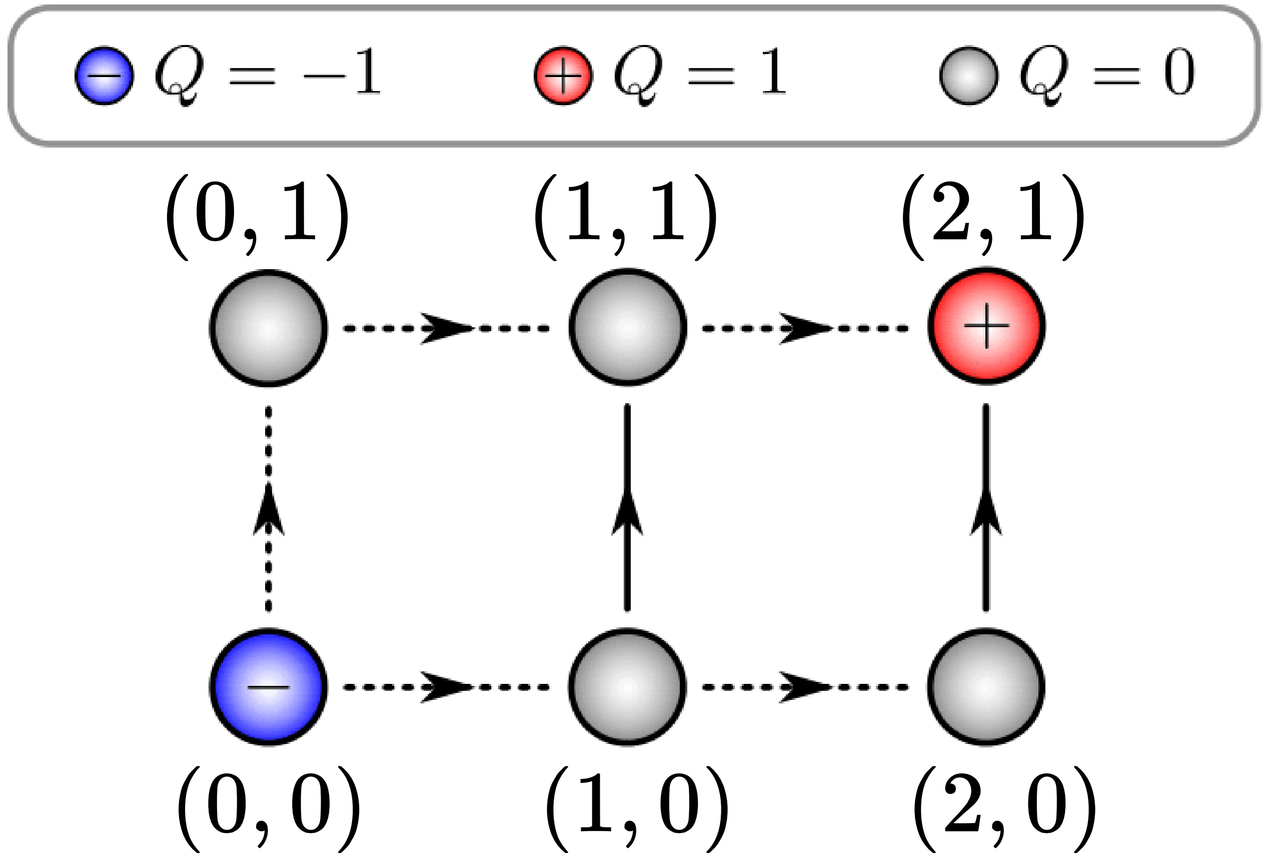
Ion trap	Superconducting
H1-1 20 qubits	ibm_fez 156 qubits



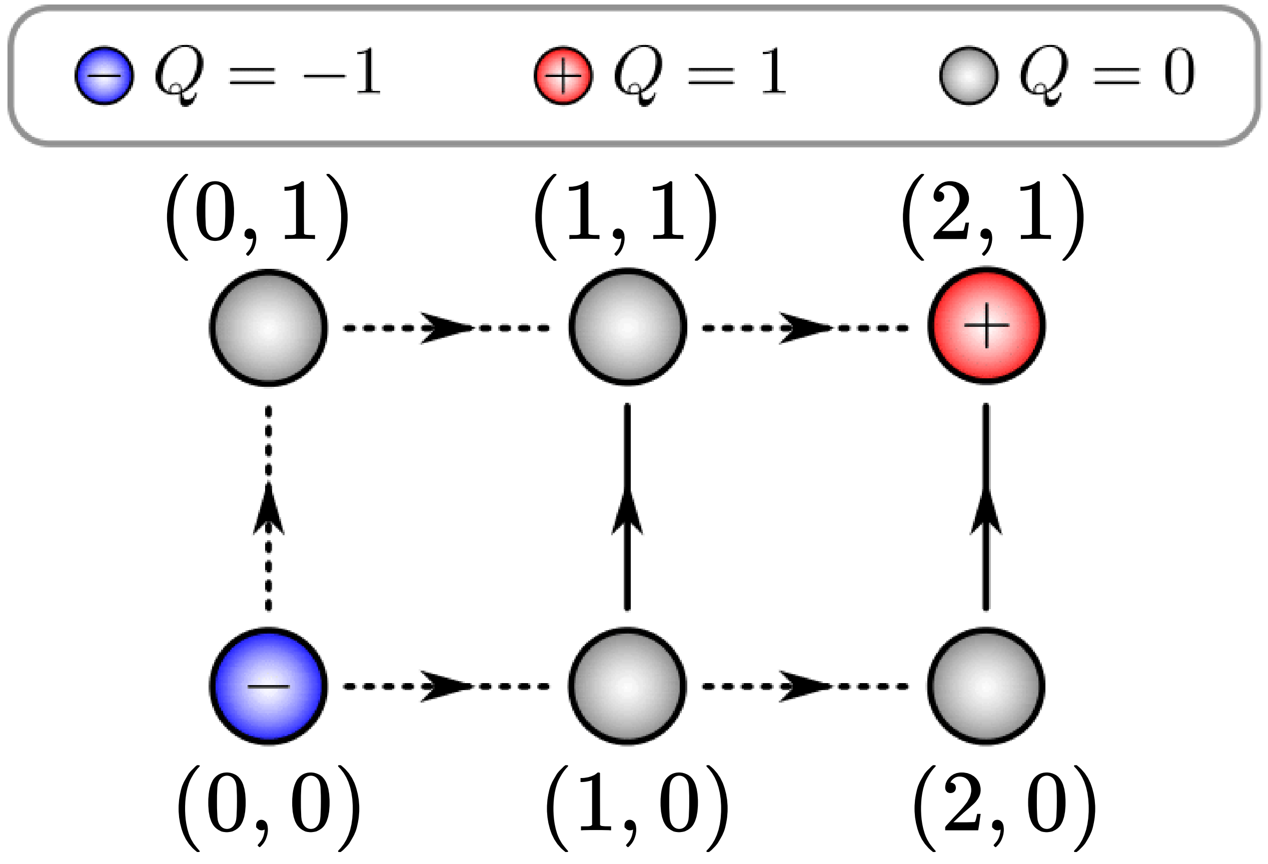
QUANTINUUM

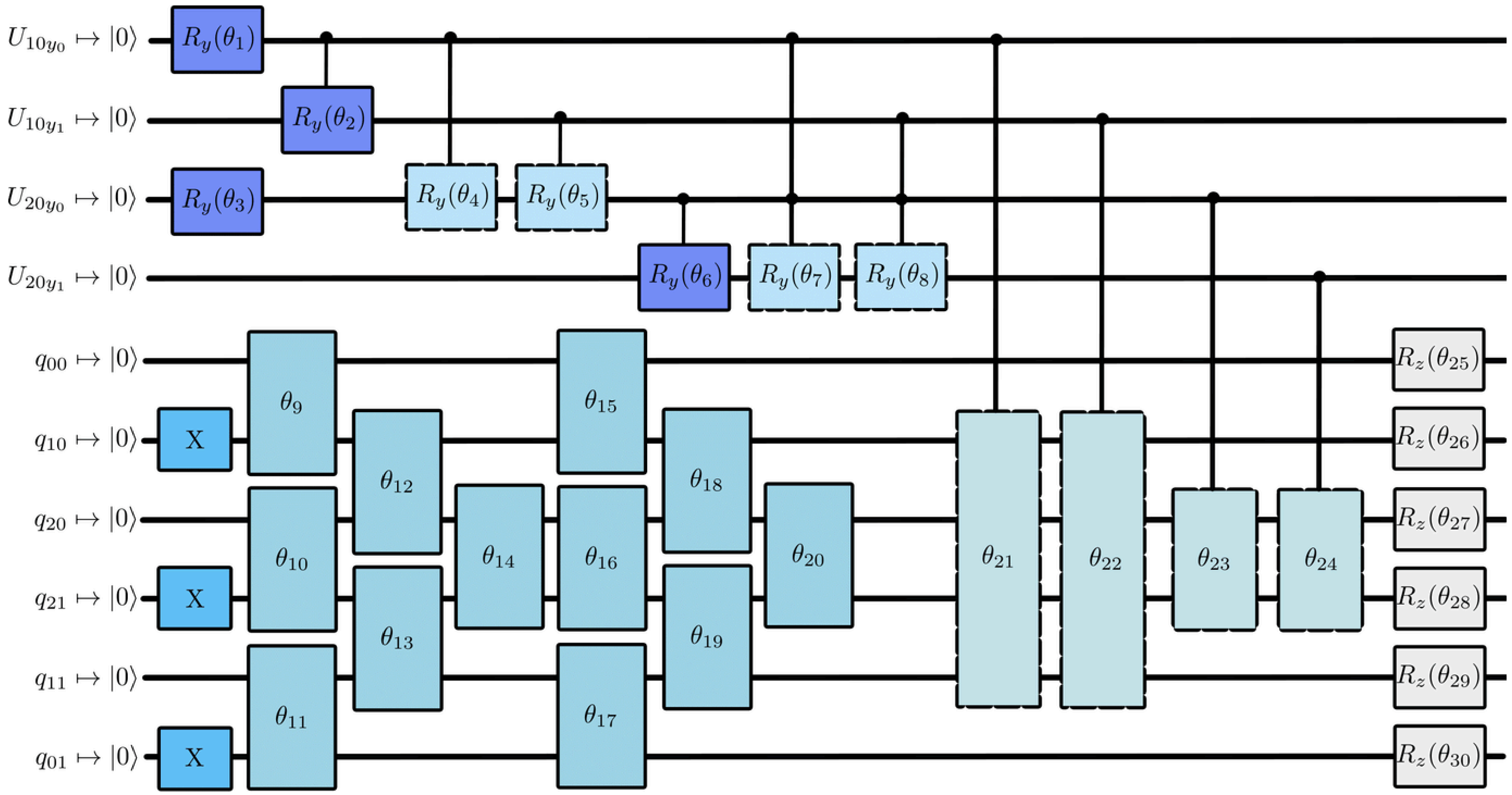


Quantum circuit

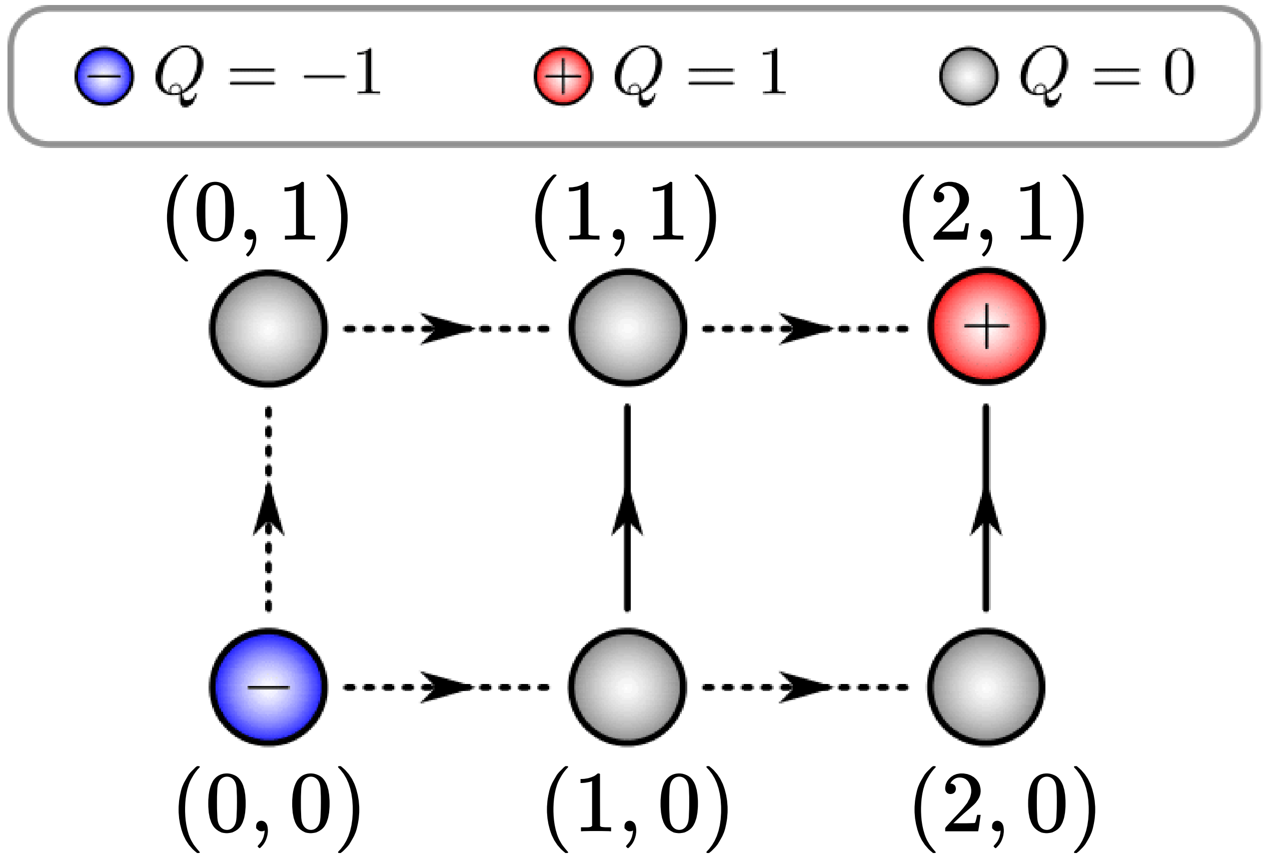


Quantum circuit

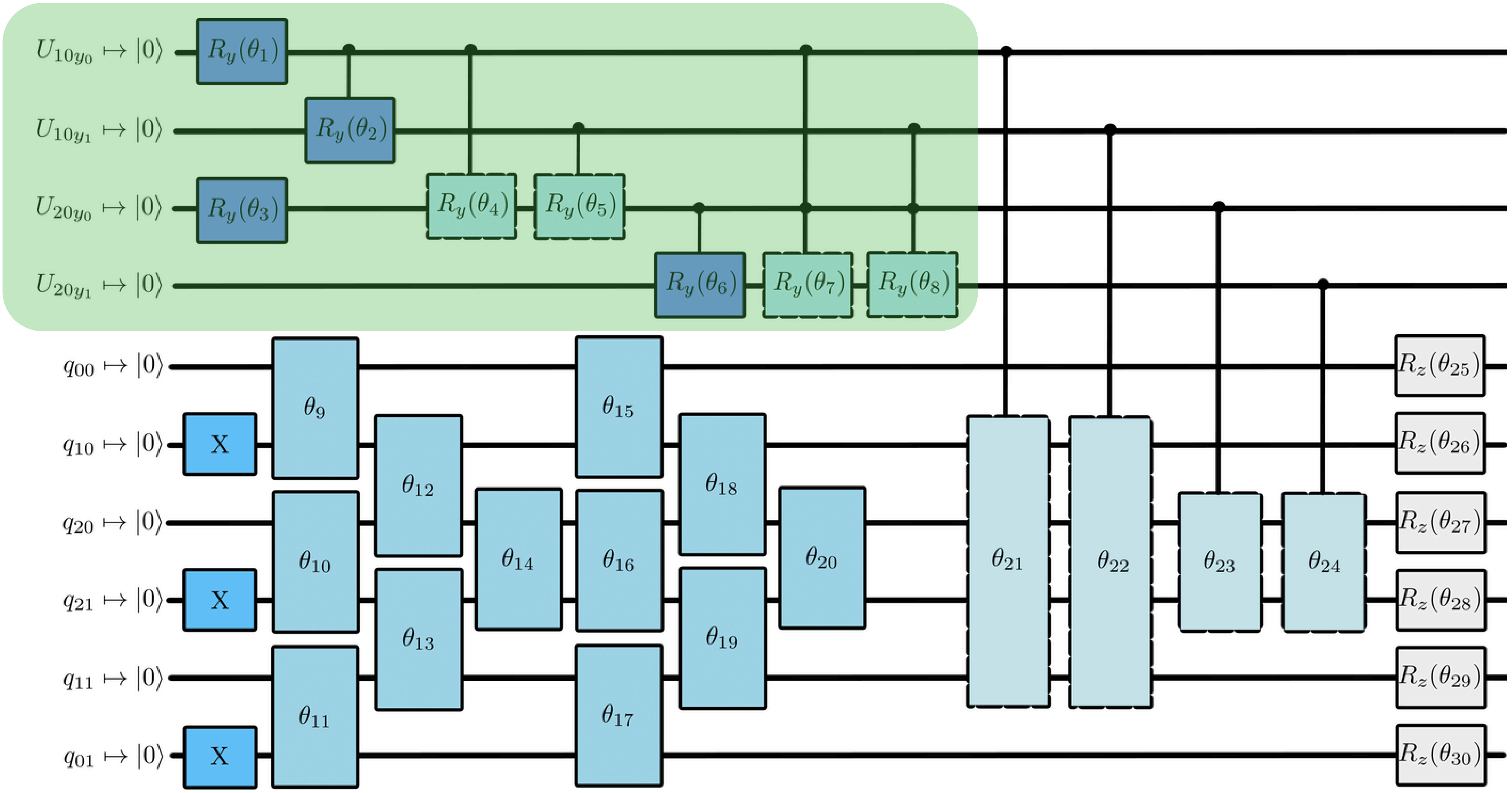




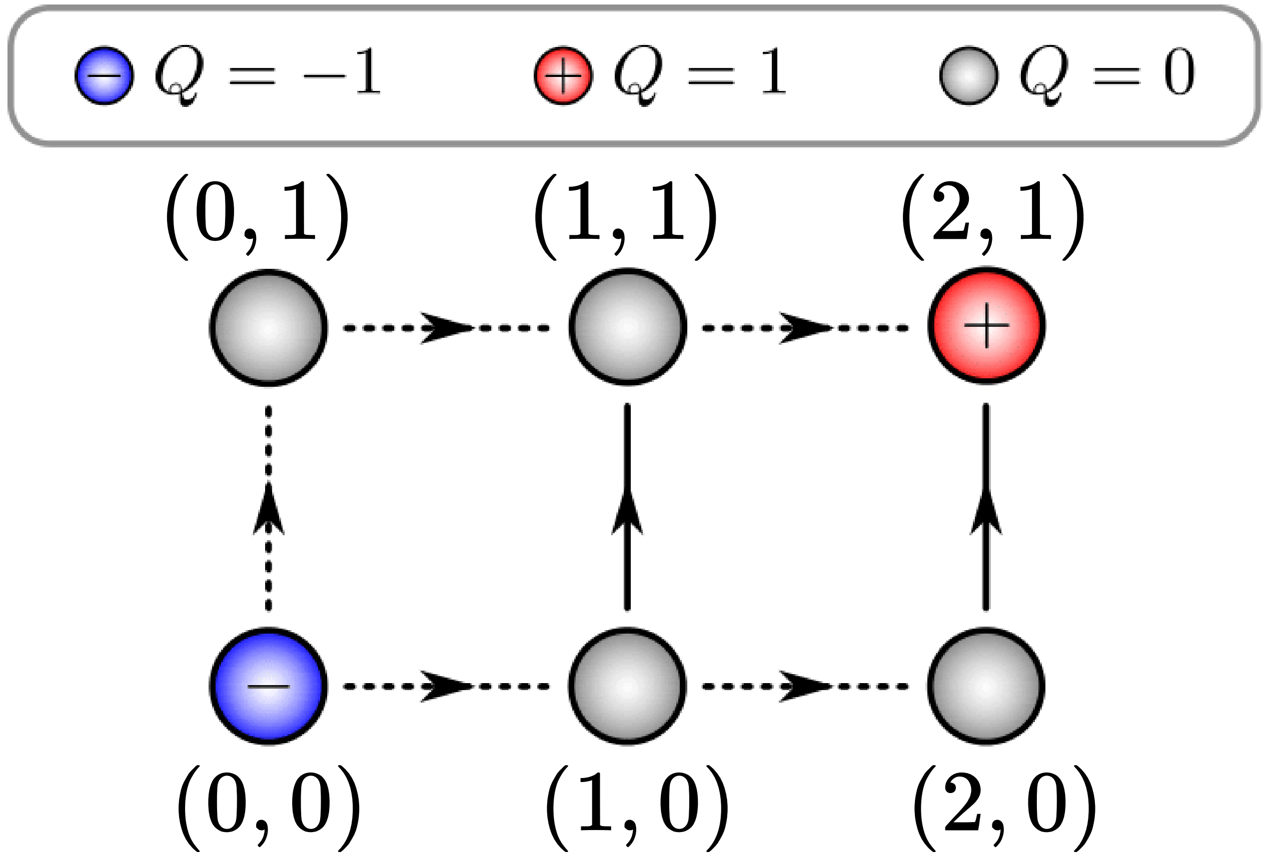
Quantum circuit

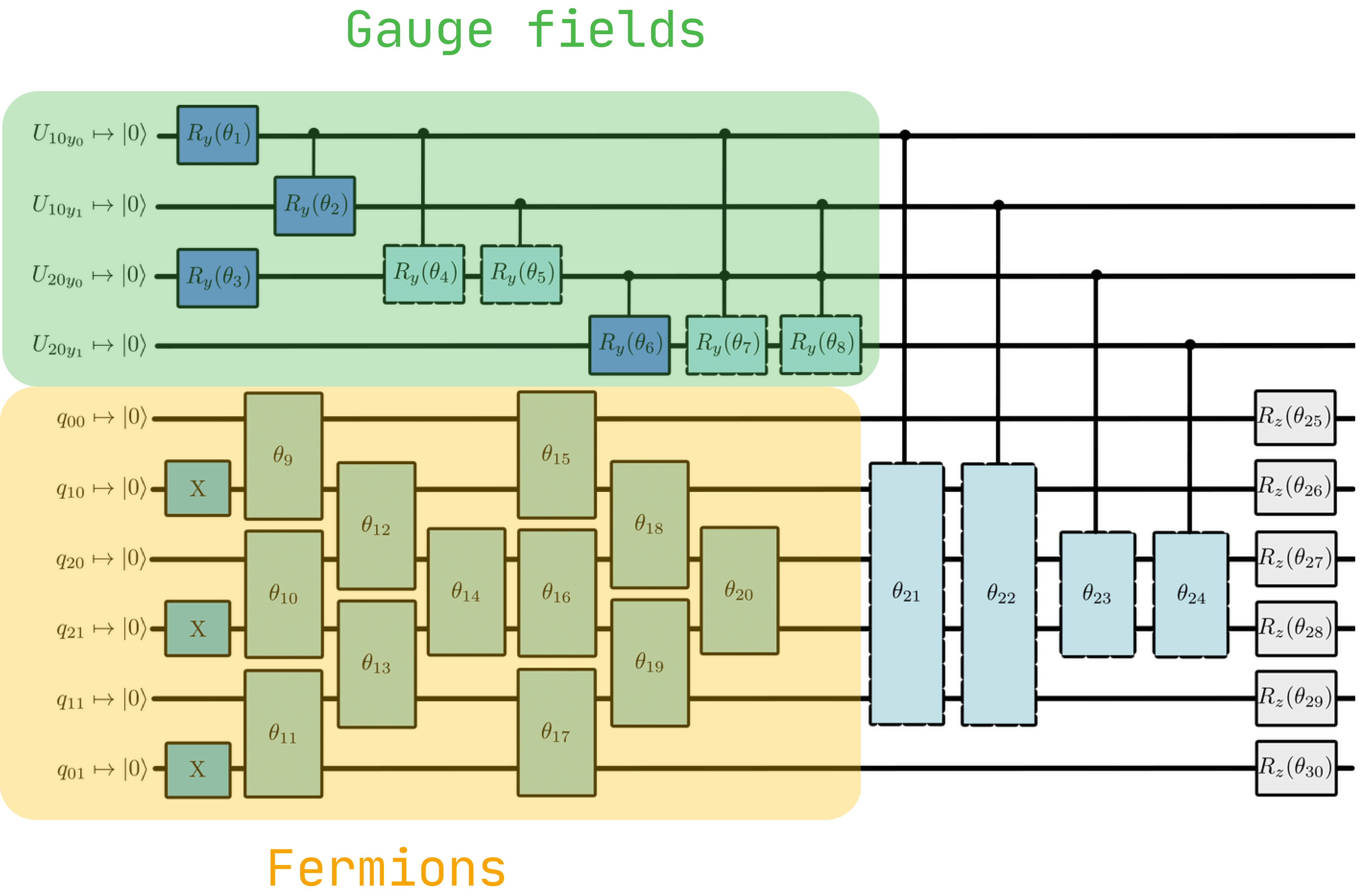


Gauge fields

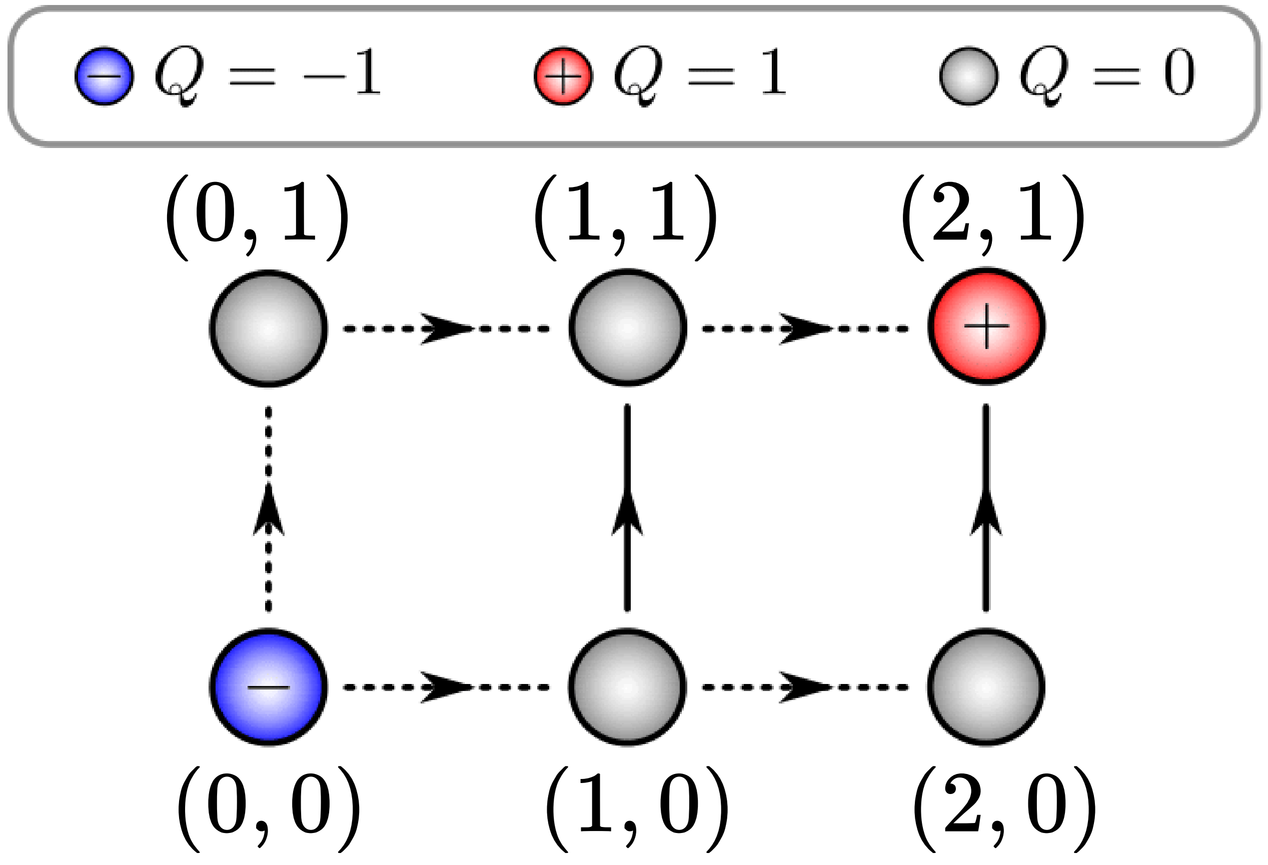


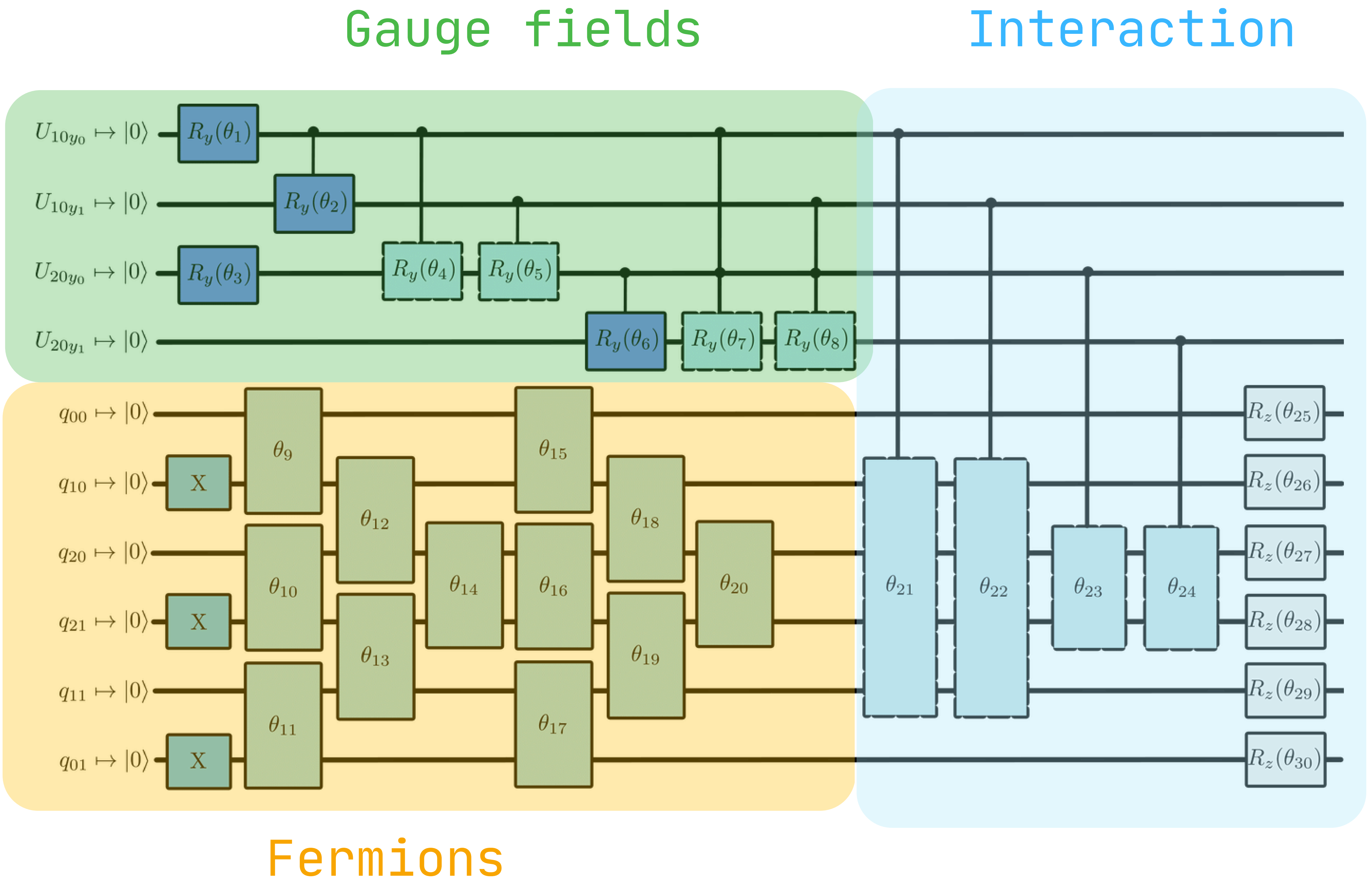
Quantum circuit





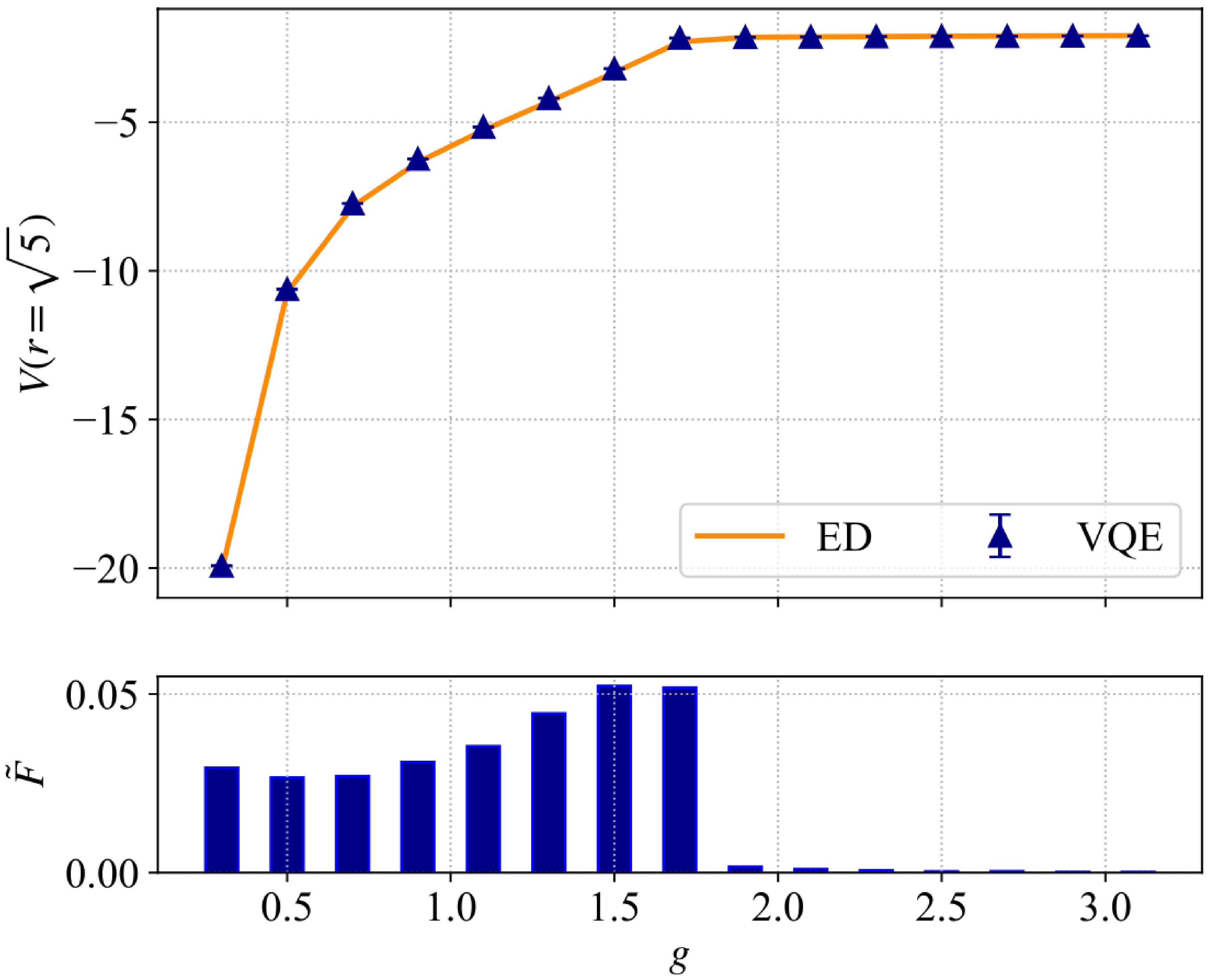
Quantum circuit





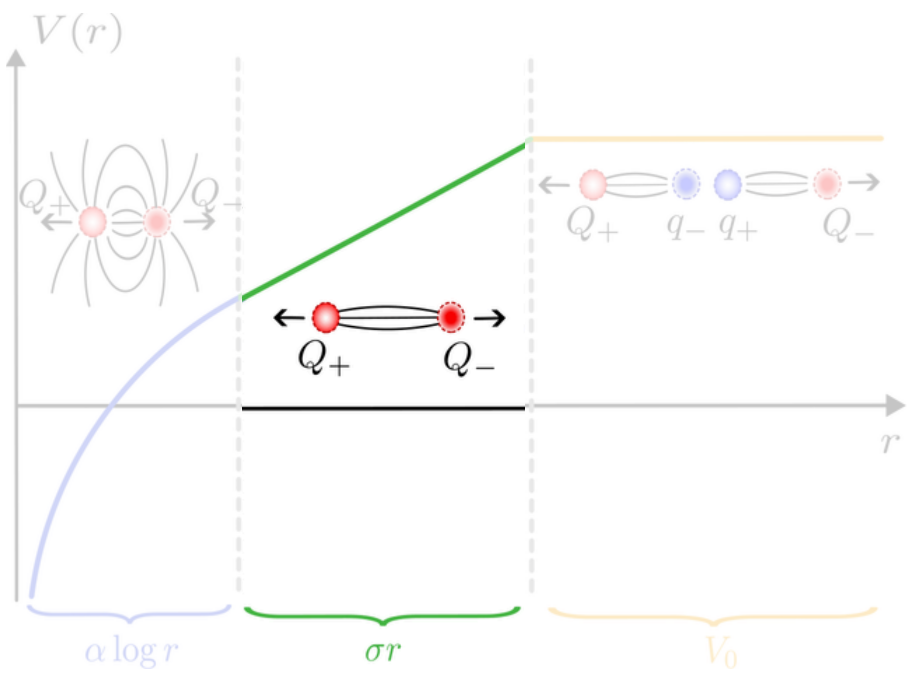
VQE results

Noiseless variational quantum results (NFT and 10^4 shots)



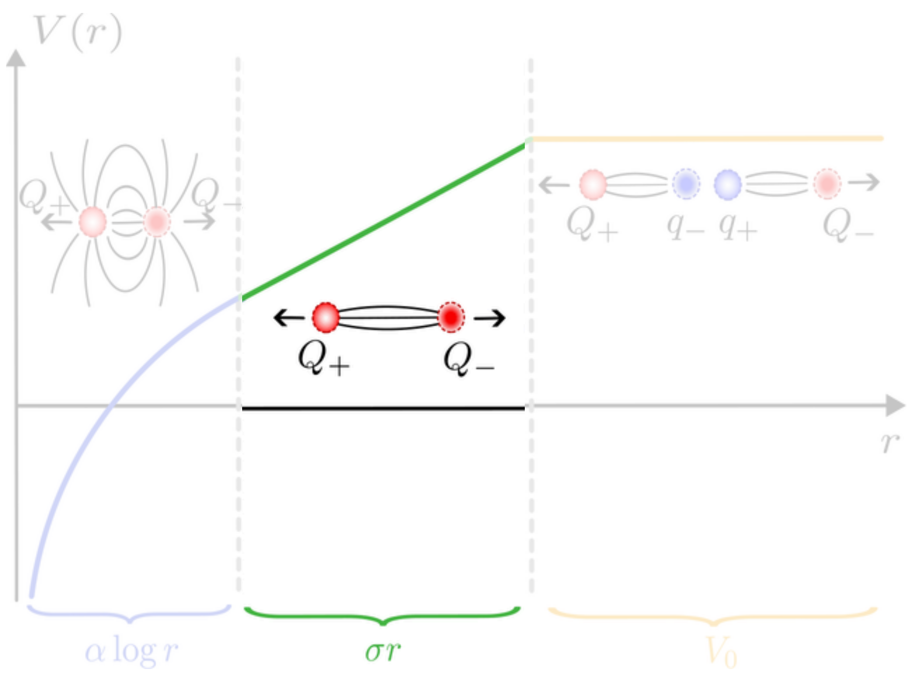
Quantum Hardware Results

Quantum Hardware Results

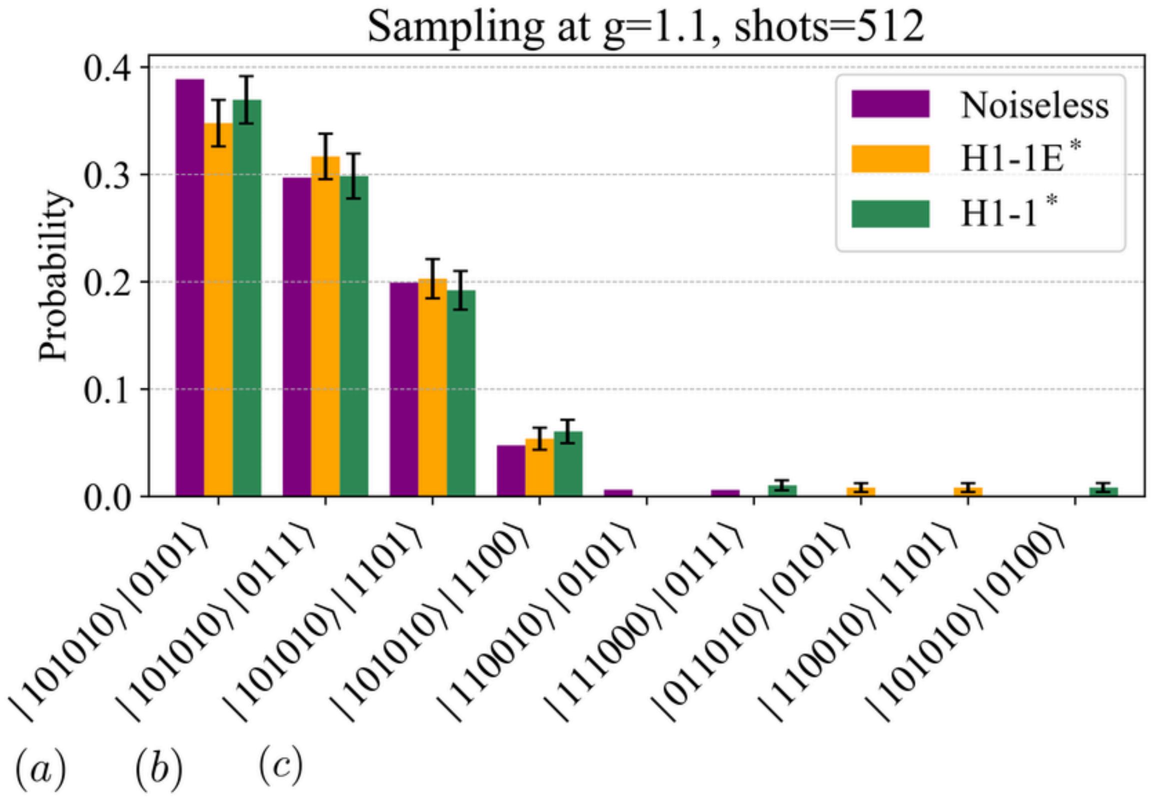


A. Crippa, K. Jansen, E. Rinaldi, arXiv:2411.05628

Quantum Hardware Results



Ion trap



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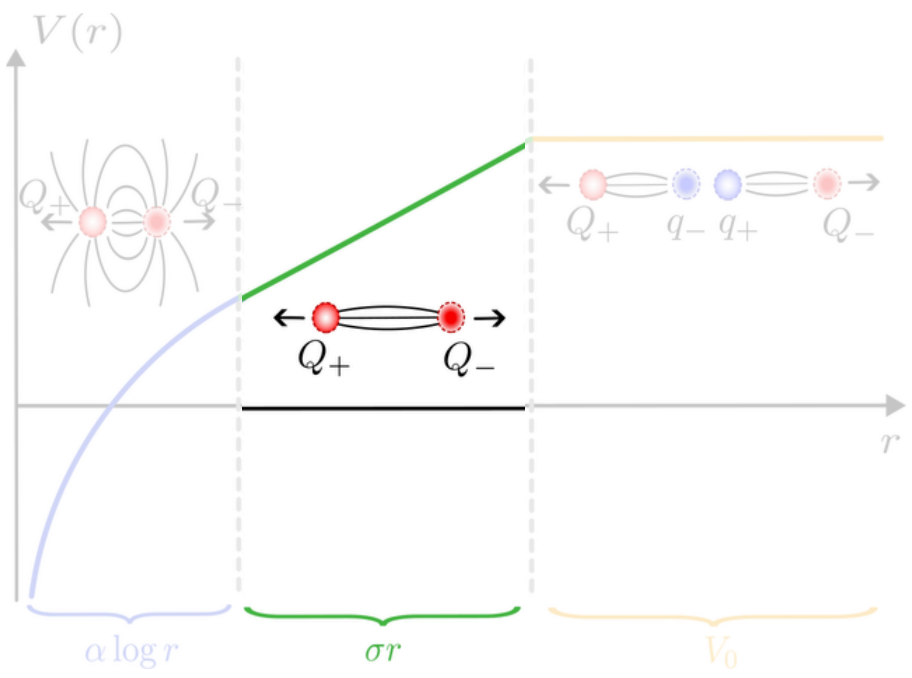
Quantum Hardware Results



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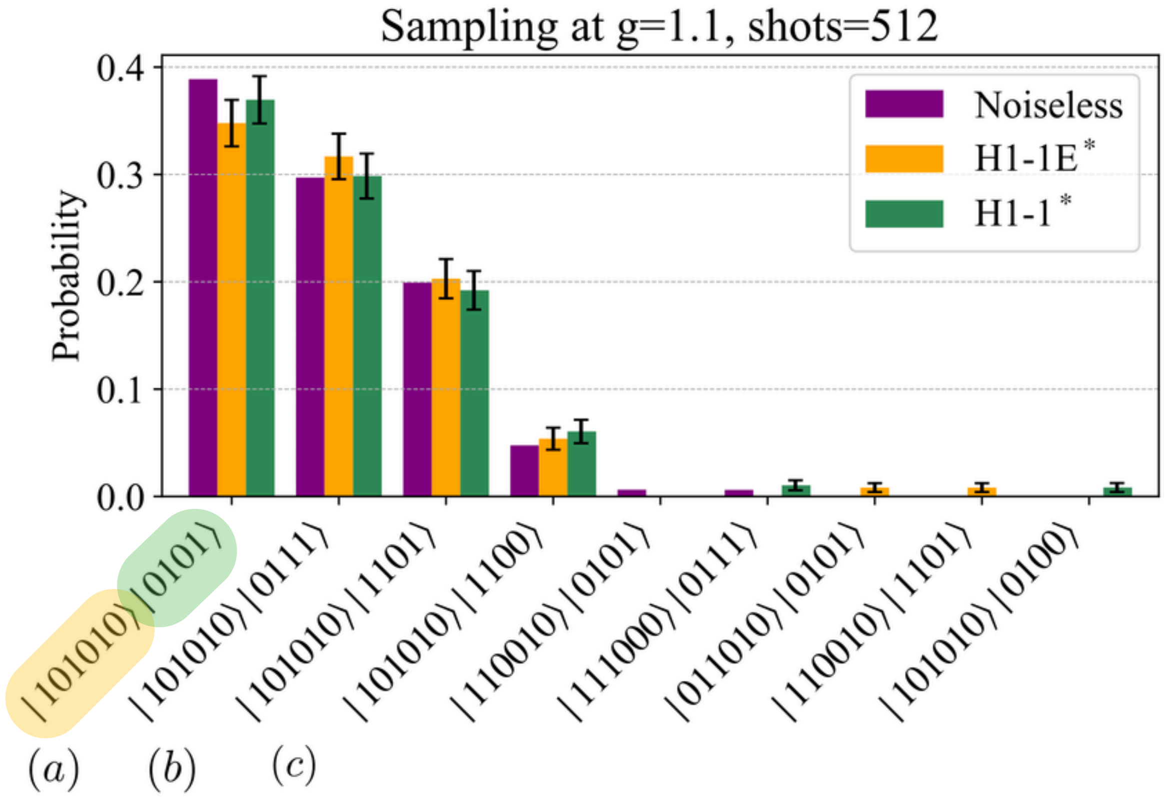
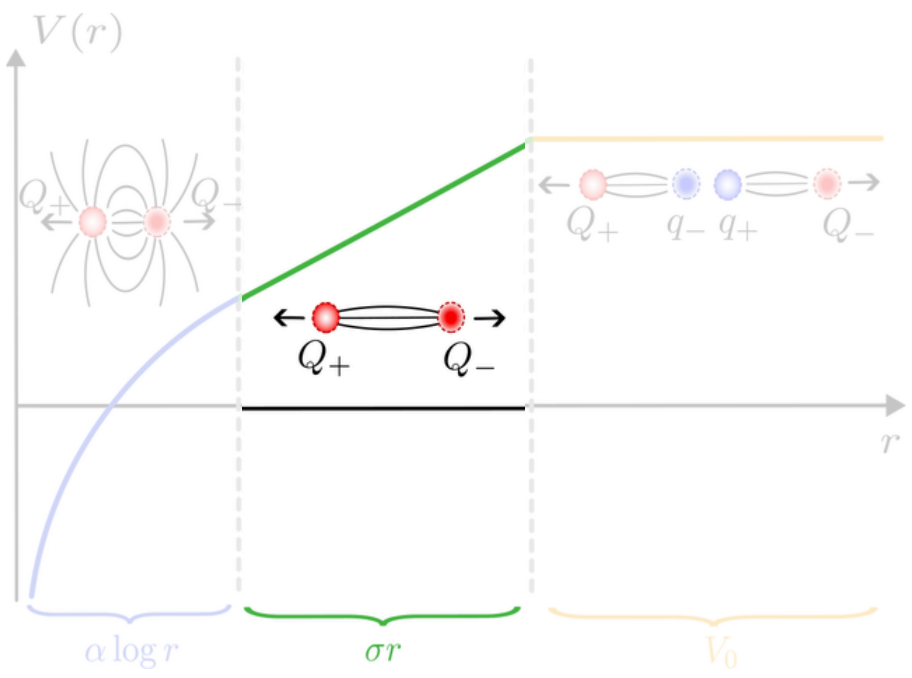


$|101010\rangle \otimes |0101\rangle$

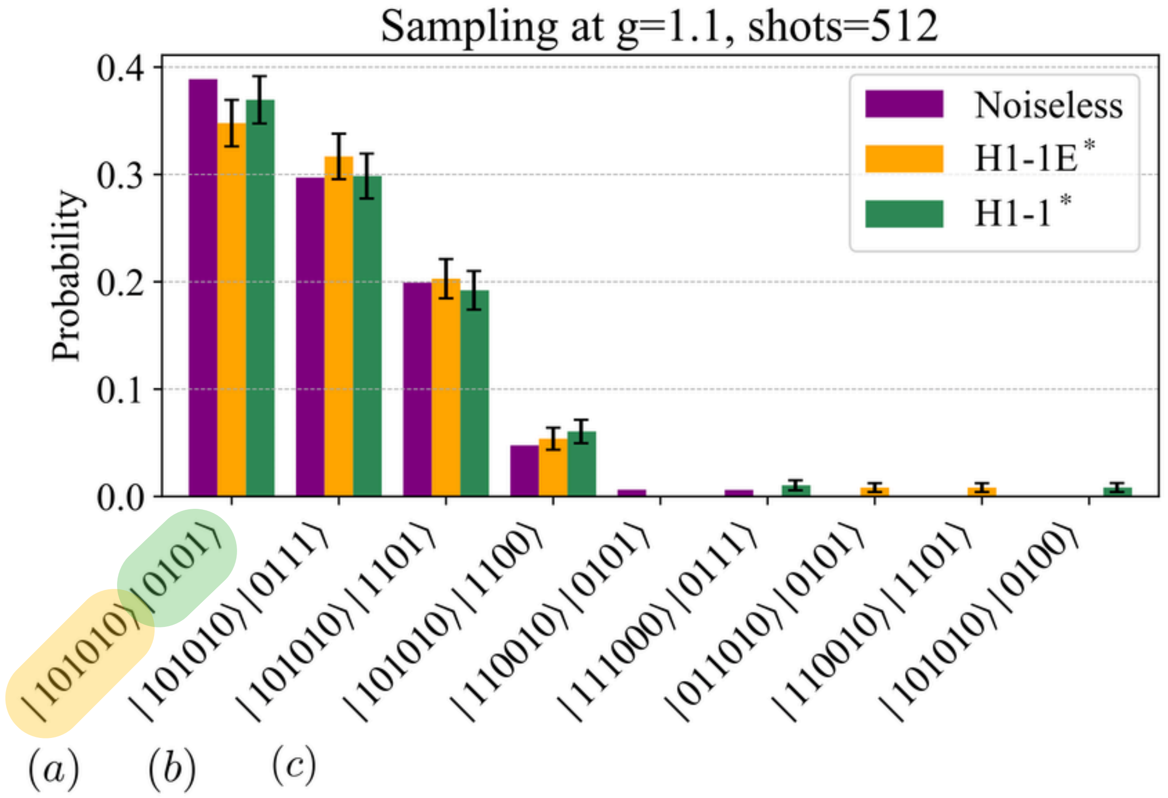
$|q_{01}q_{11}q_{21}q_{20}q_{10}q_{00}\rangle \otimes |U_{20y}U_{10y}\rangle$

A. Crippa, K. Jansen, E. Rinaldi, arXiv:2411.05628

Quantum Hardware Results



Ion trap



$|101010\rangle \otimes |0101\rangle$

$|q_{01}q_{11}q_{21}q_{20}q_{10}q_{00}\rangle \otimes |U_{20y}U_{10y}\rangle$

EVEN	ODD
$\|0\rangle$	$\|1\rangle$
v	v

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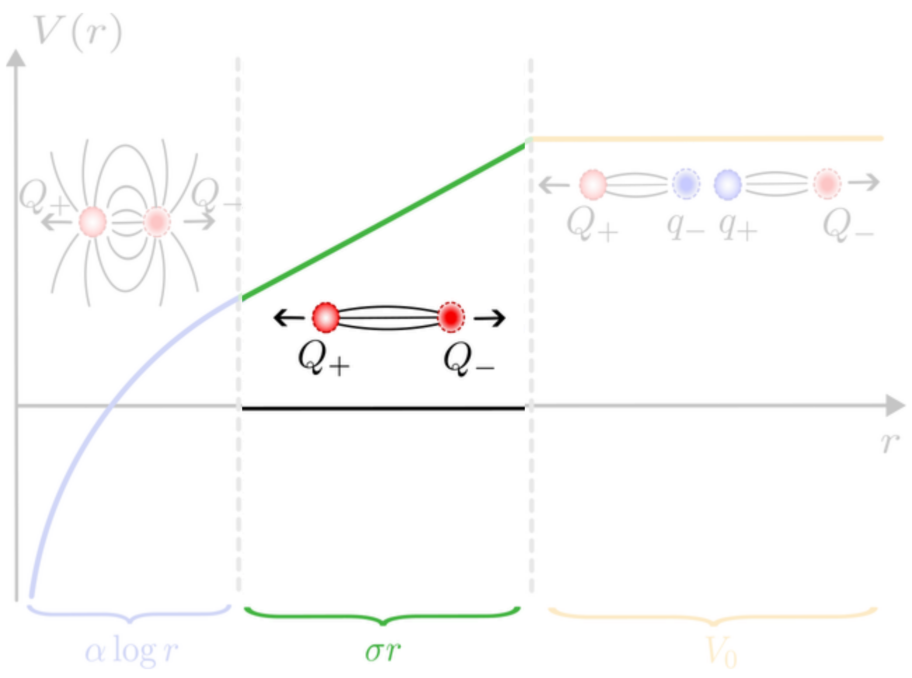
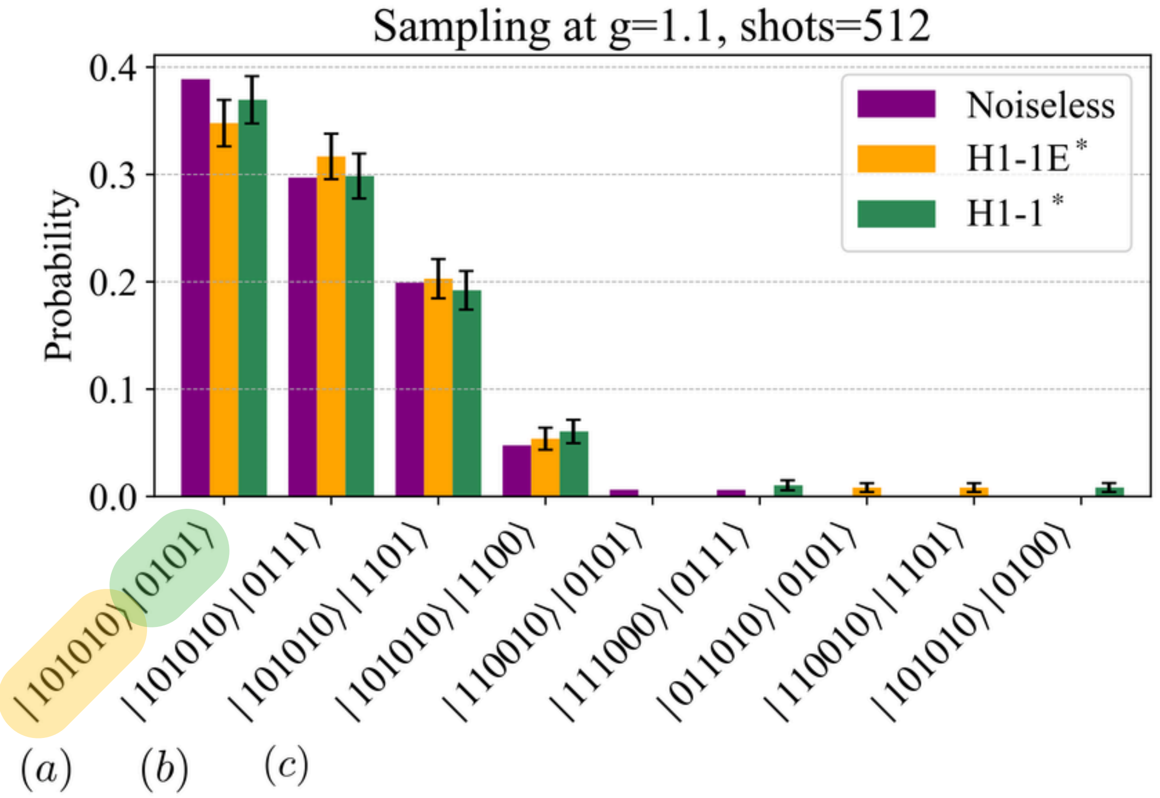
Quantum Hardware Results



Ion trap



$|101010\rangle \otimes |0101\rangle$

$|q_{01}q_{11}q_{21}q_{20}q_{10}q_{00}\rangle \otimes |U_{20y}U_{10y}\rangle$

EVEN $|0\rangle$ **ODD** $|1\rangle$

$|01\rangle \mapsto |0\rangle_{\text{ph.}}$

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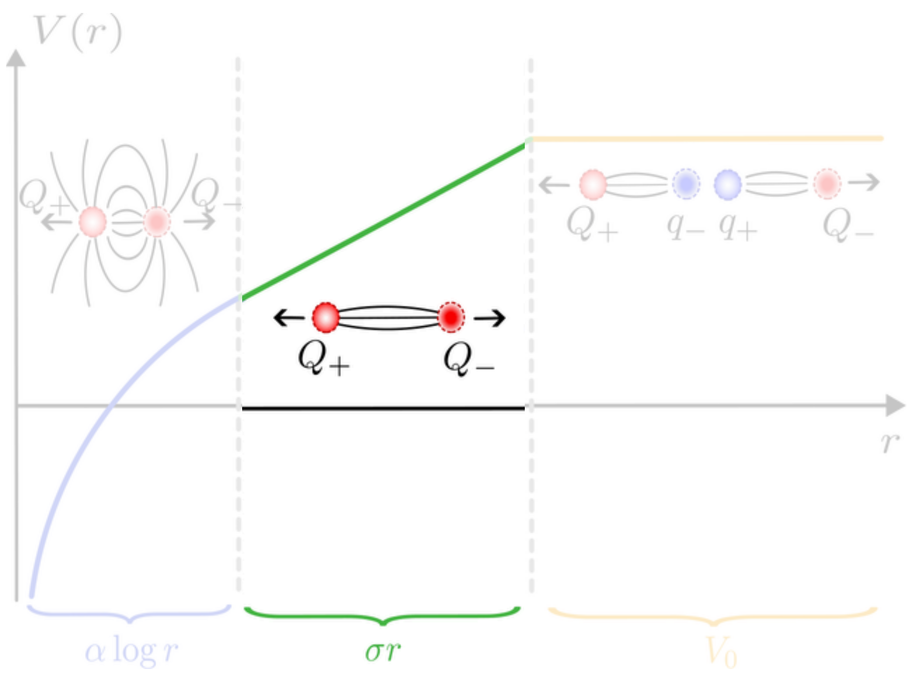
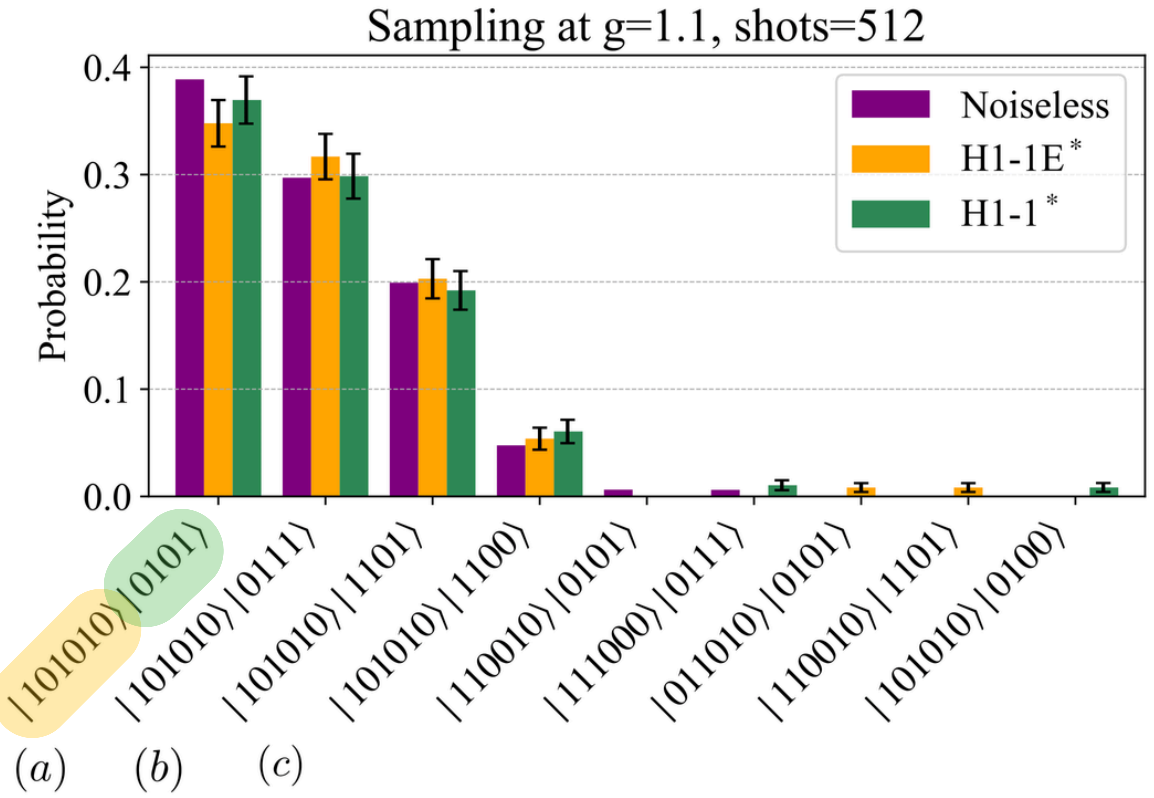
Quantum Hardware Results

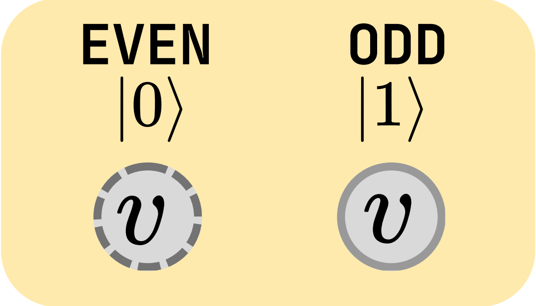


Ion trap

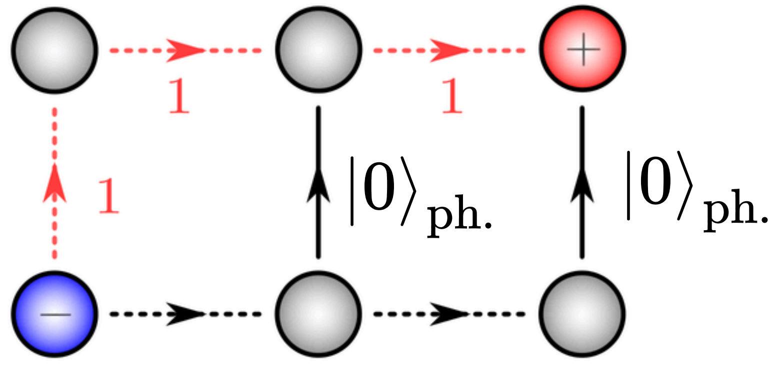


$$|101010\rangle \otimes |0101\rangle$$

$$|q_{01}q_{11}q_{21}q_{20}q_{10}q_{00}\rangle \otimes |U_{20y}U_{10y}\rangle$$



$$|01\rangle \mapsto |0\rangle_{\text{ph.}}$$



(a)

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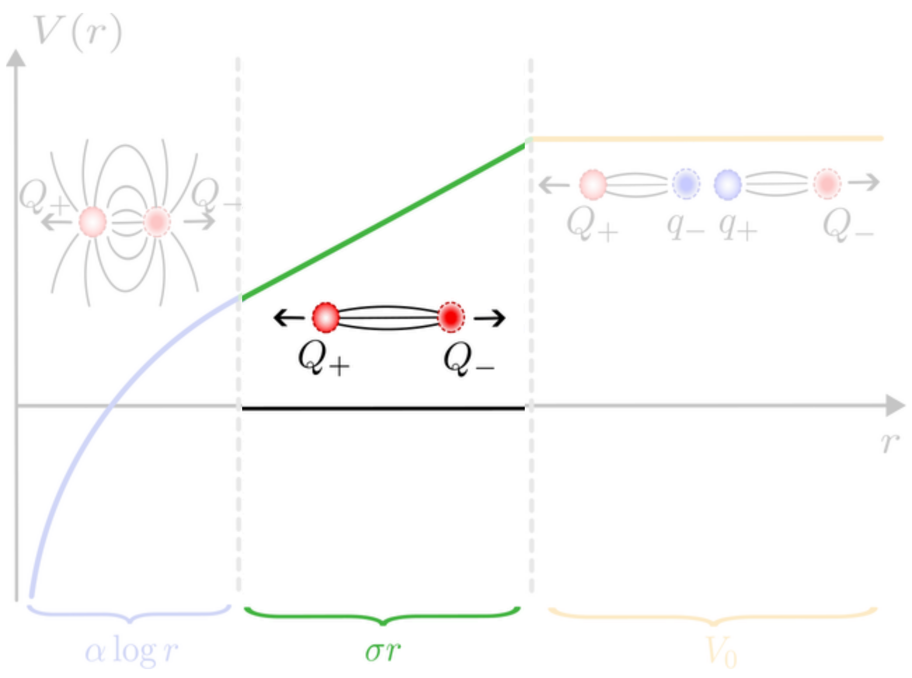
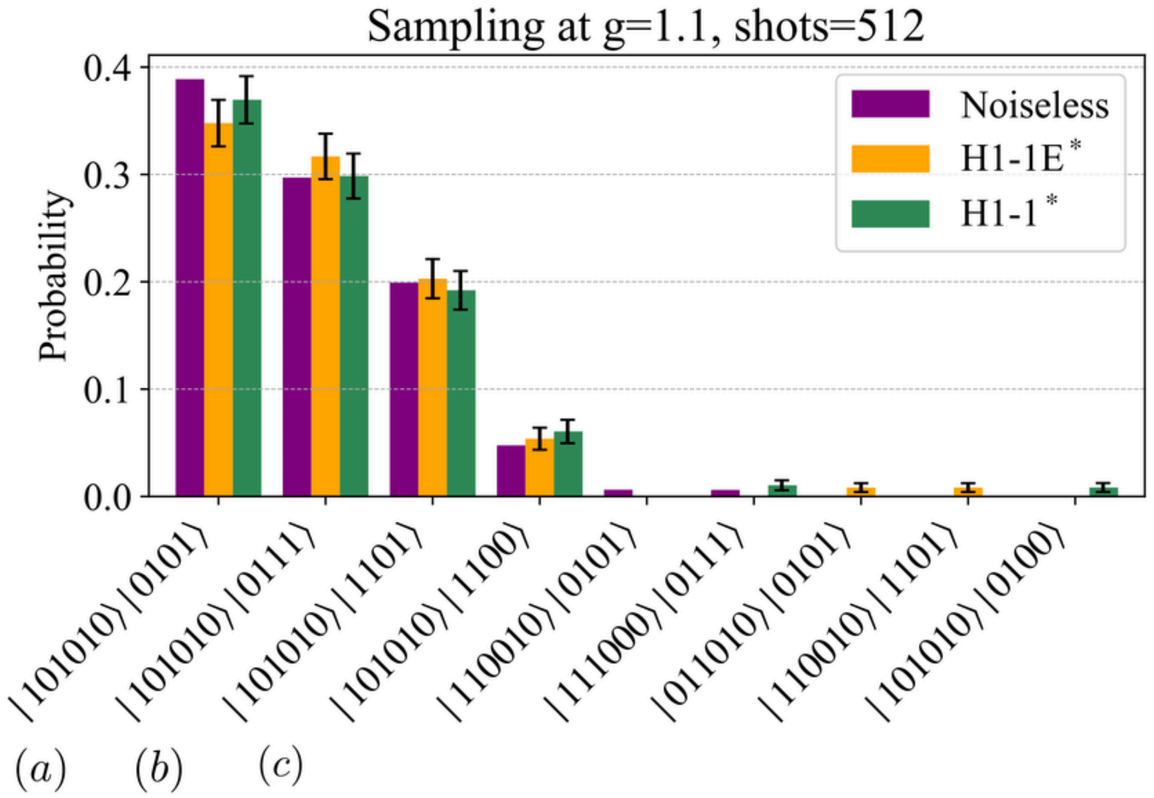
Quantum Hardware Results



Ion trap



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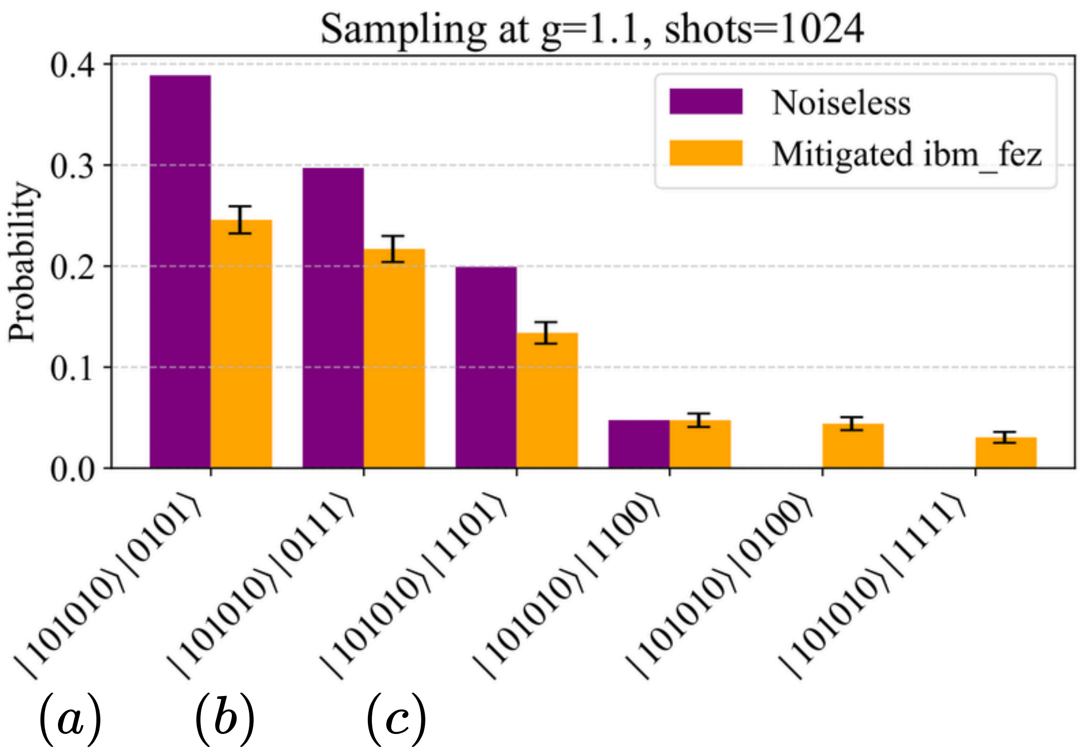
Superconducting



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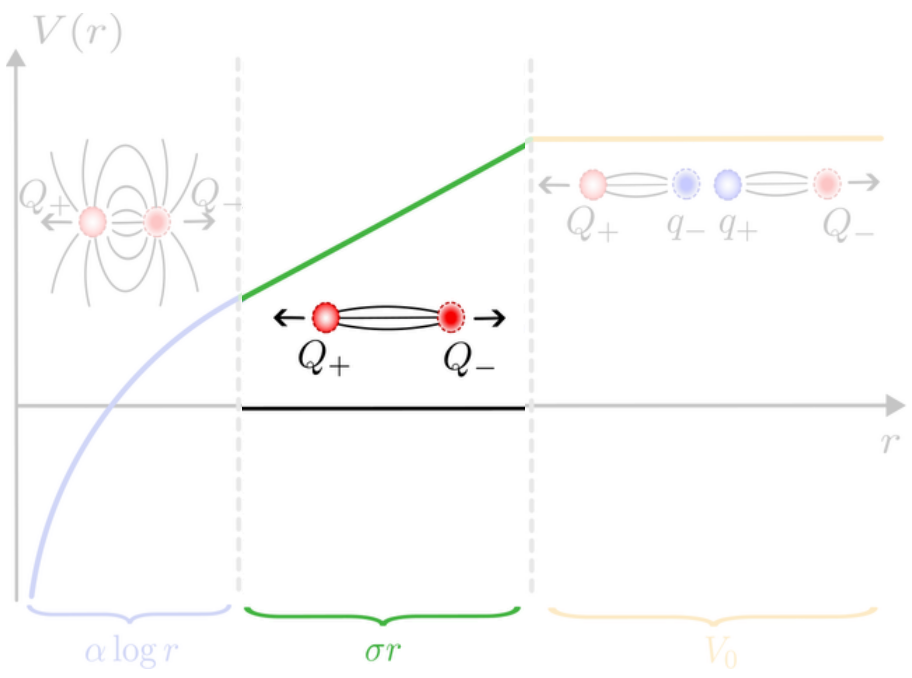
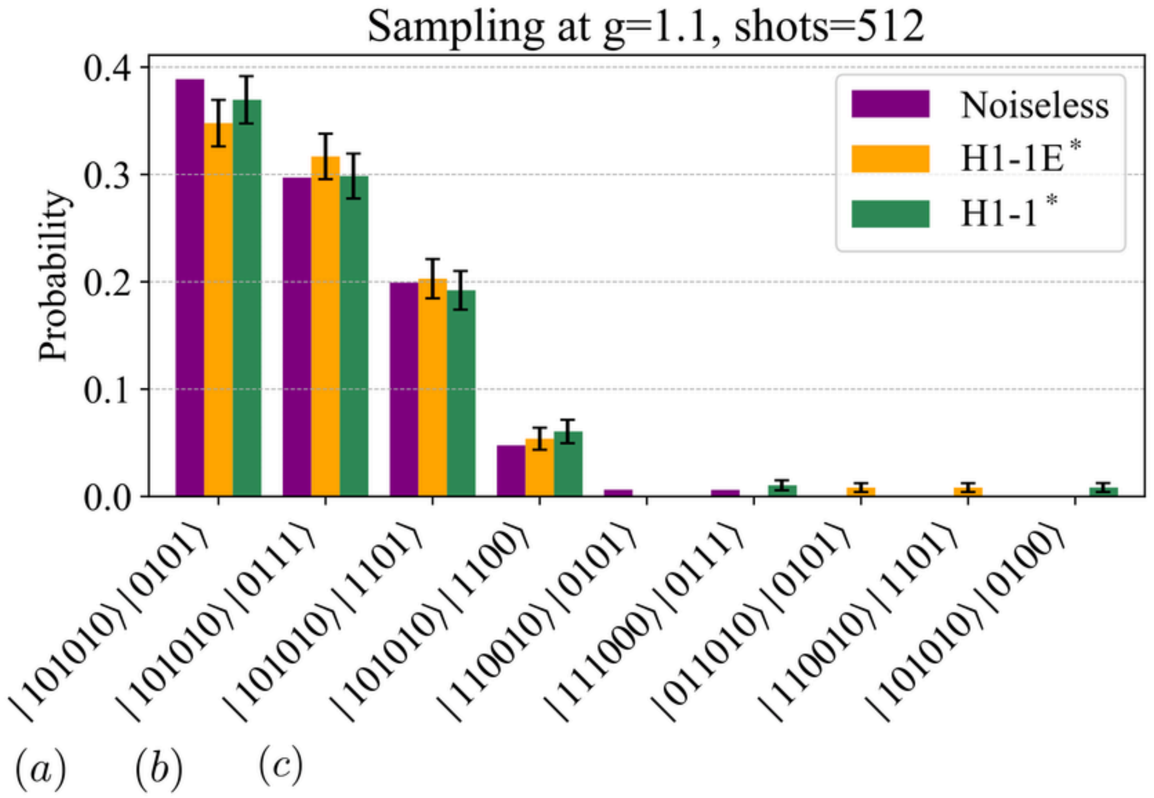
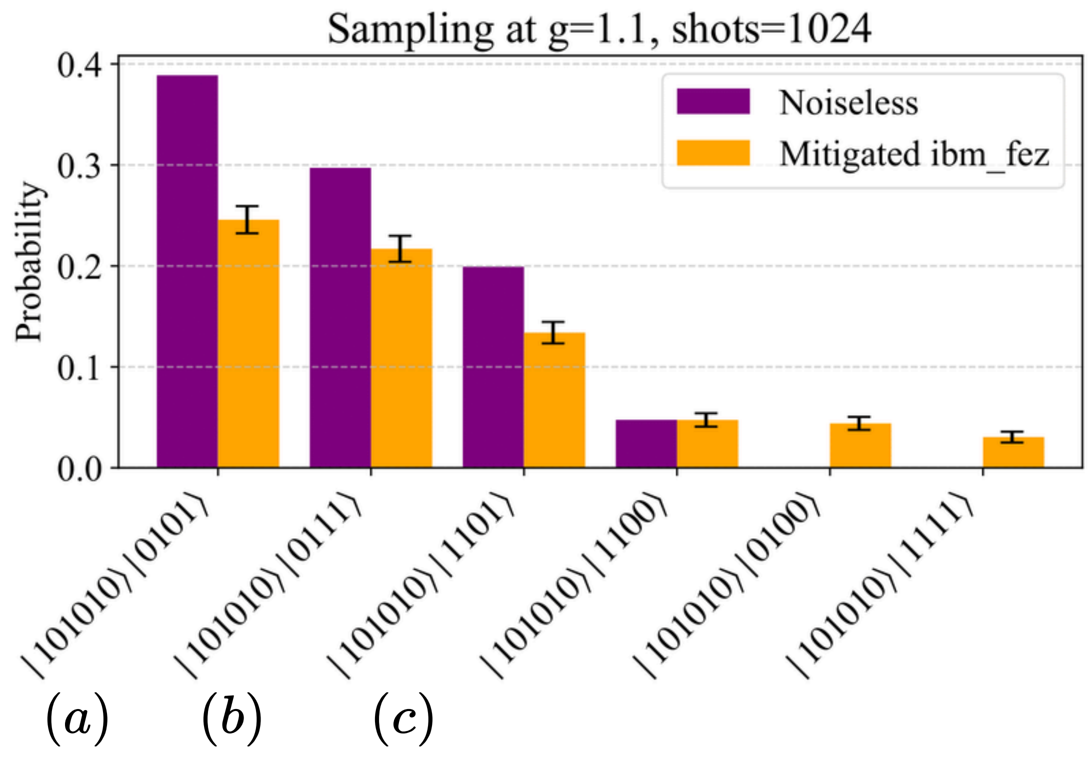
Quantum Hardware Results

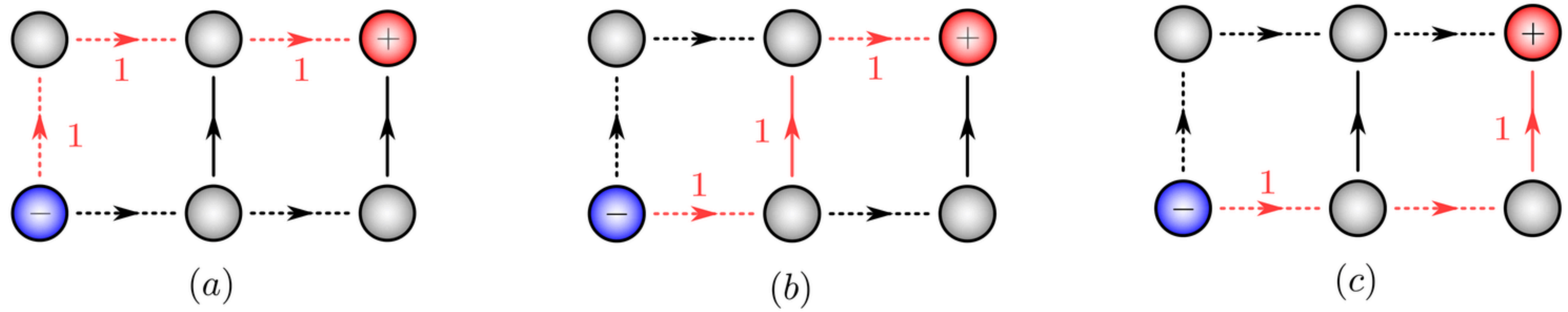


Ion trap

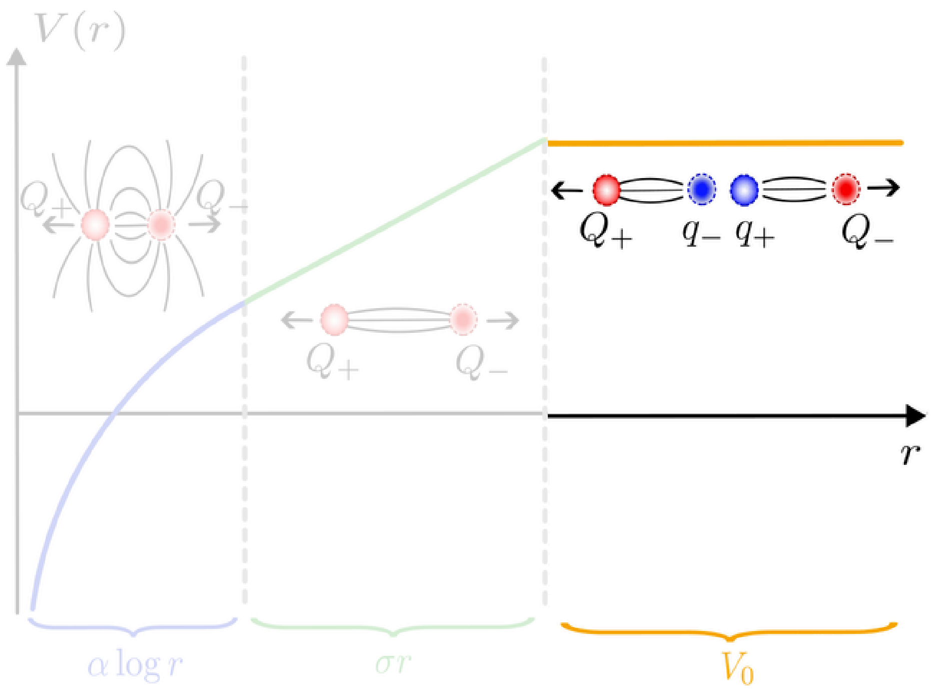


Superconducting



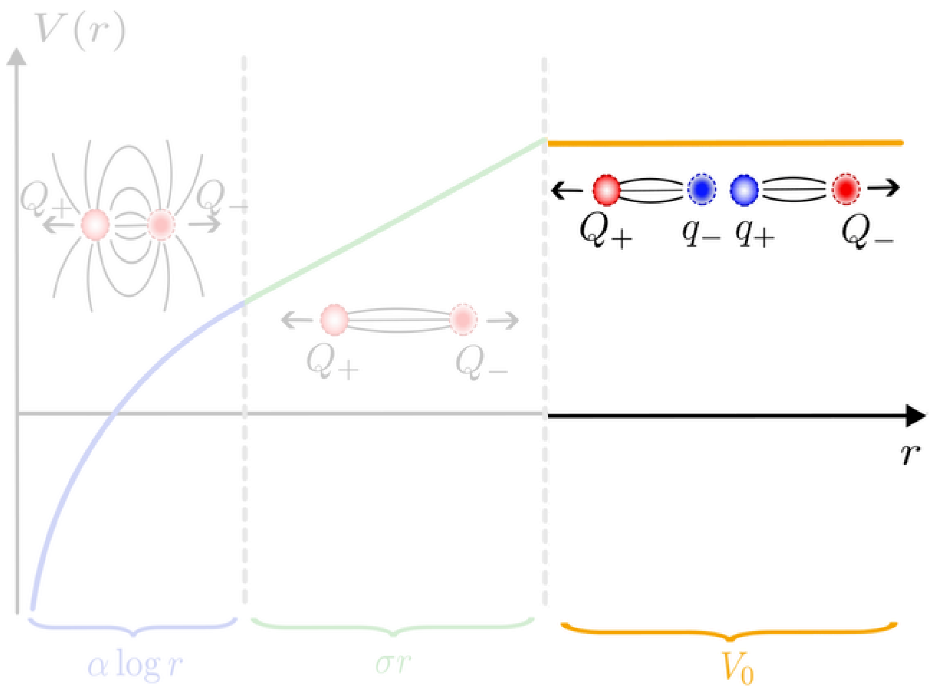


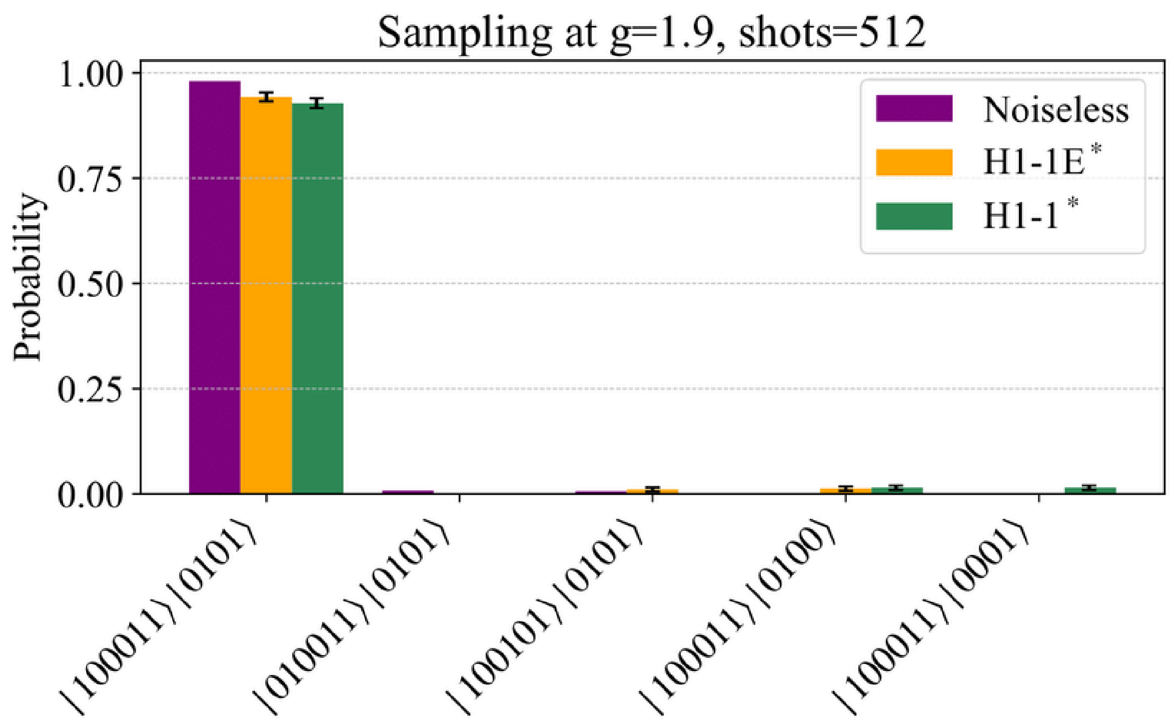
Quantum Hardware Results



Quantum Hardware Results

Ion trap





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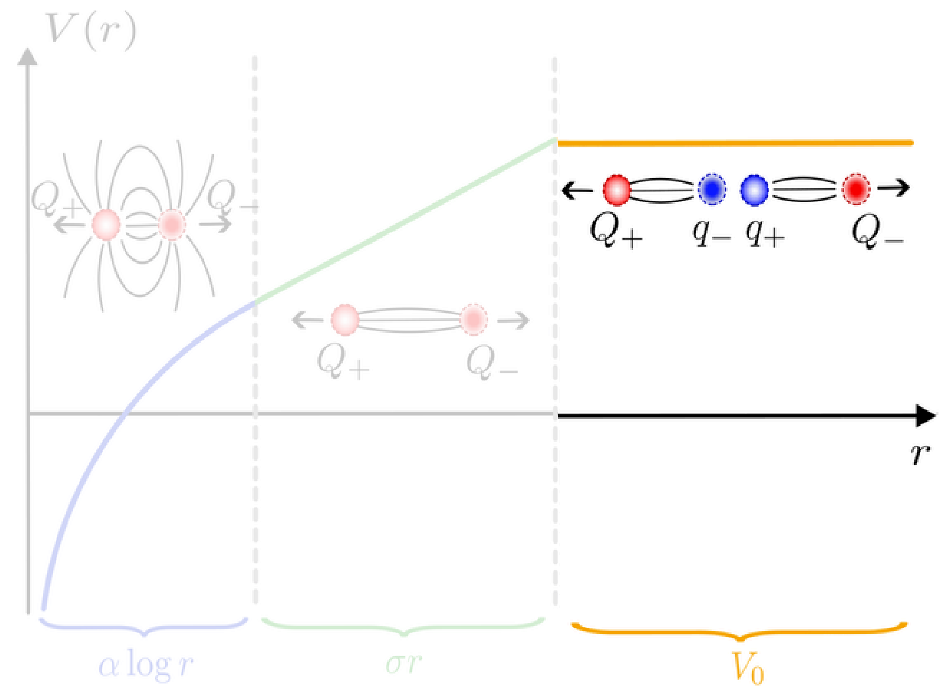
Quantum Hardware Results



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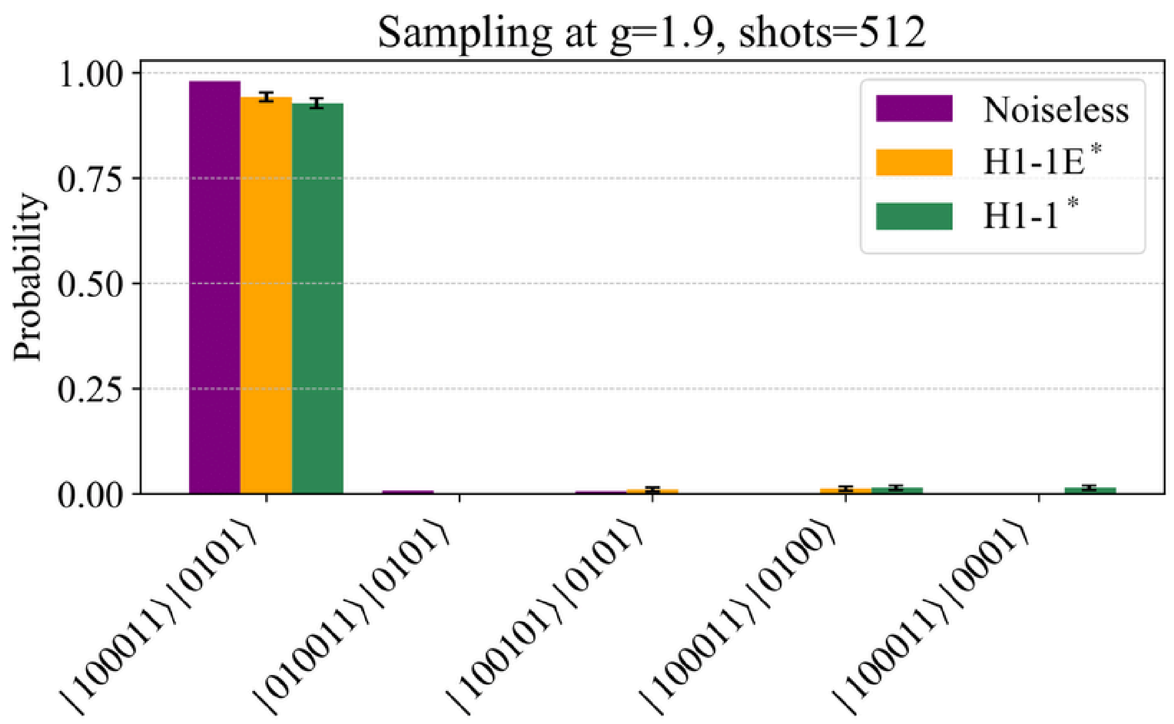

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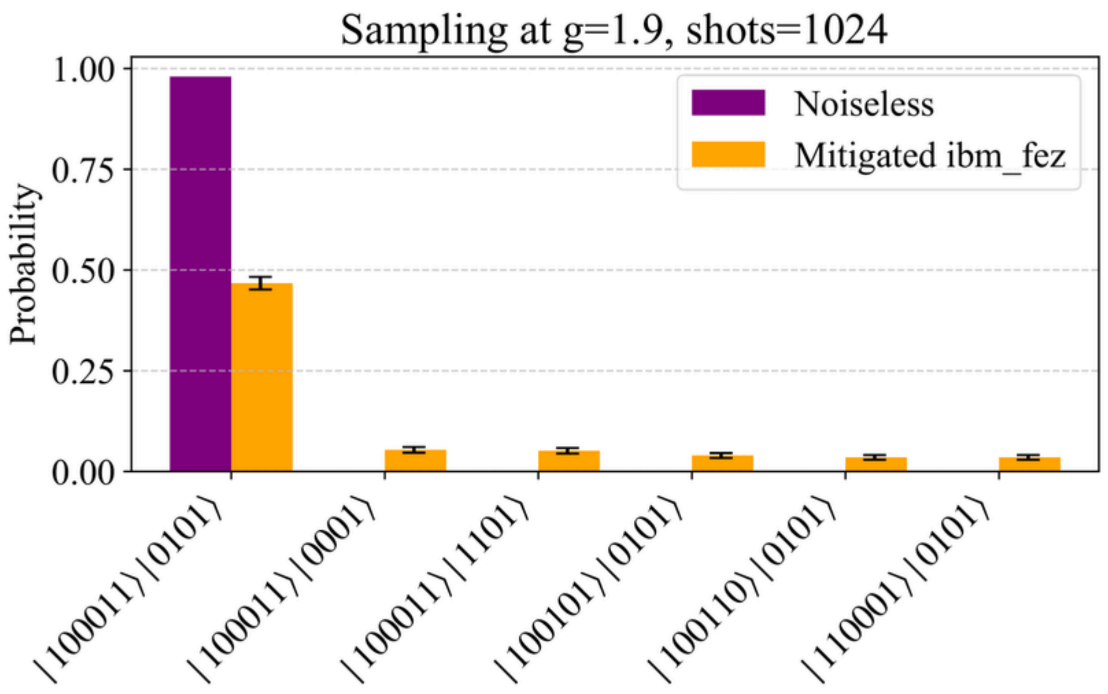
Superconducting



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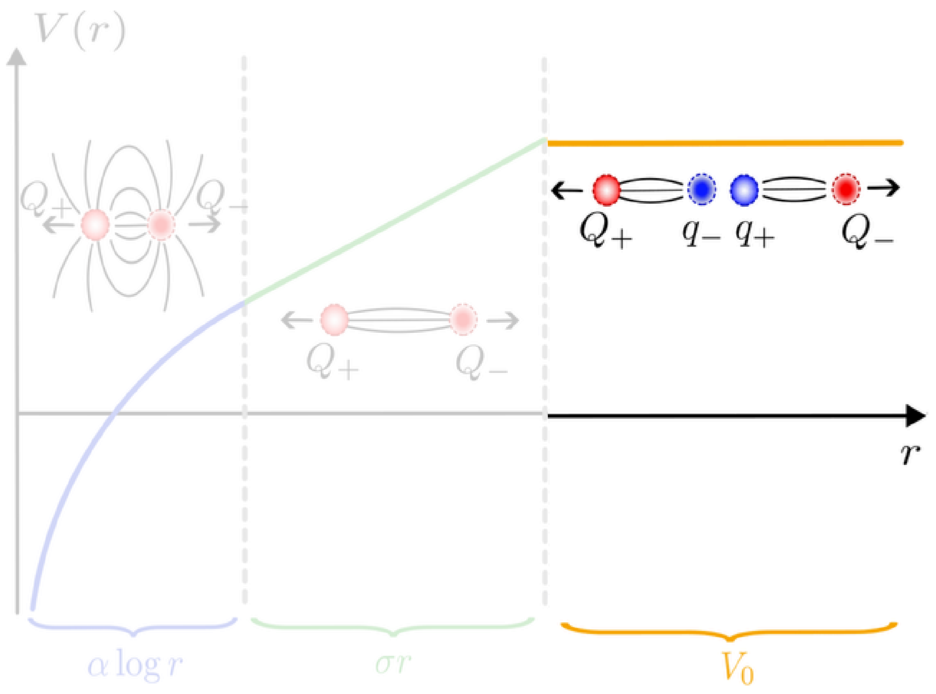
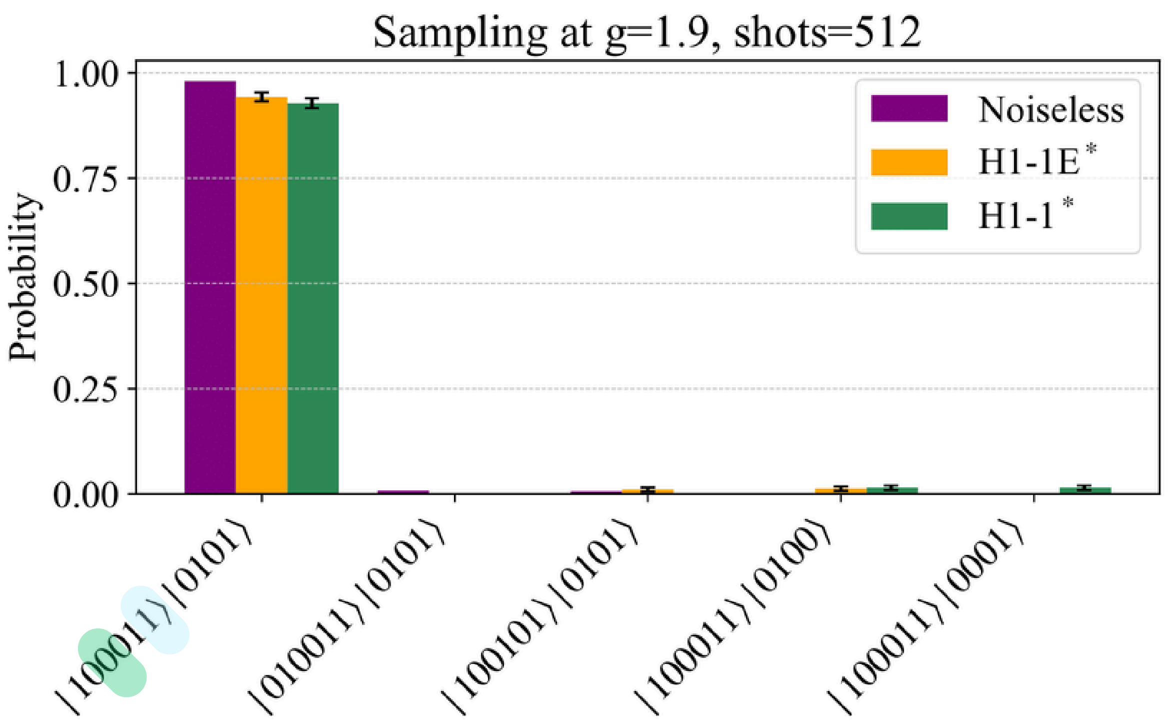
Quantum Hardware Results



Ion trap



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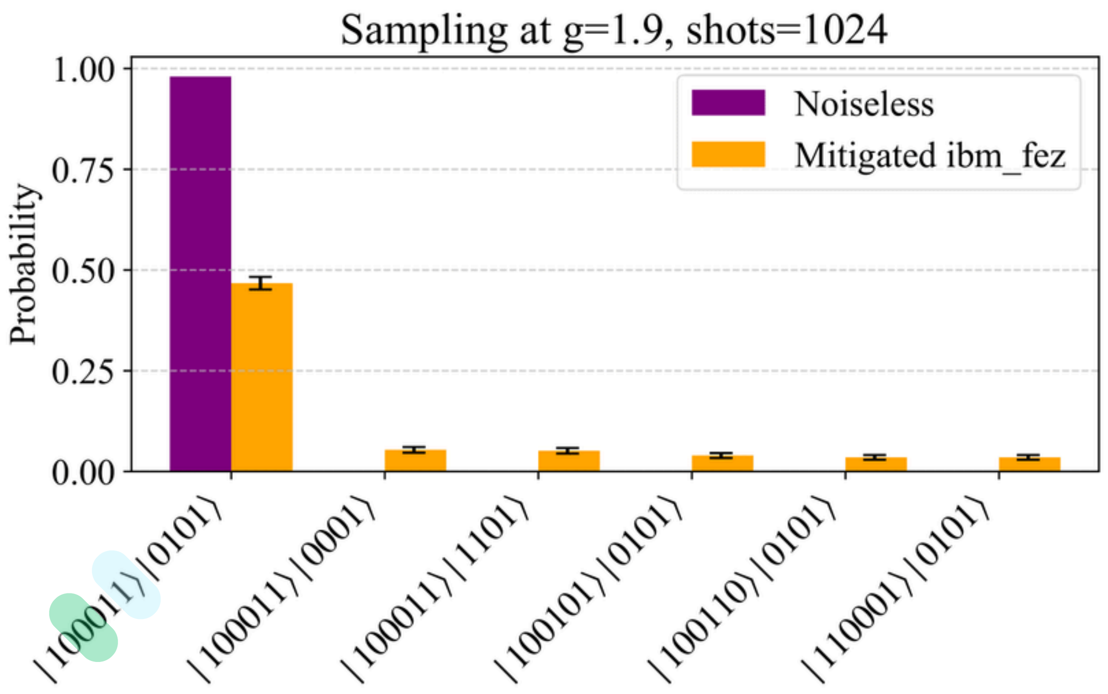
Superconducting



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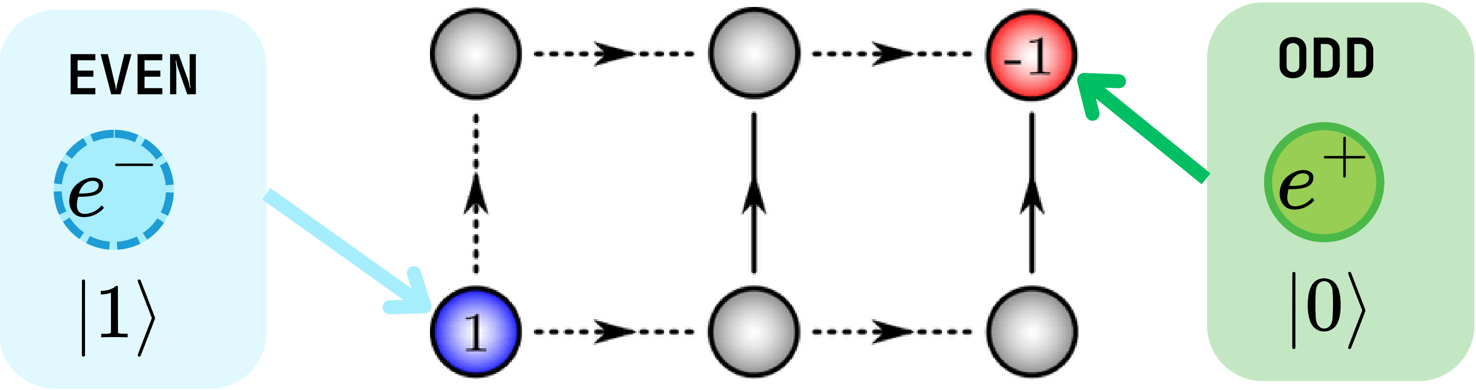
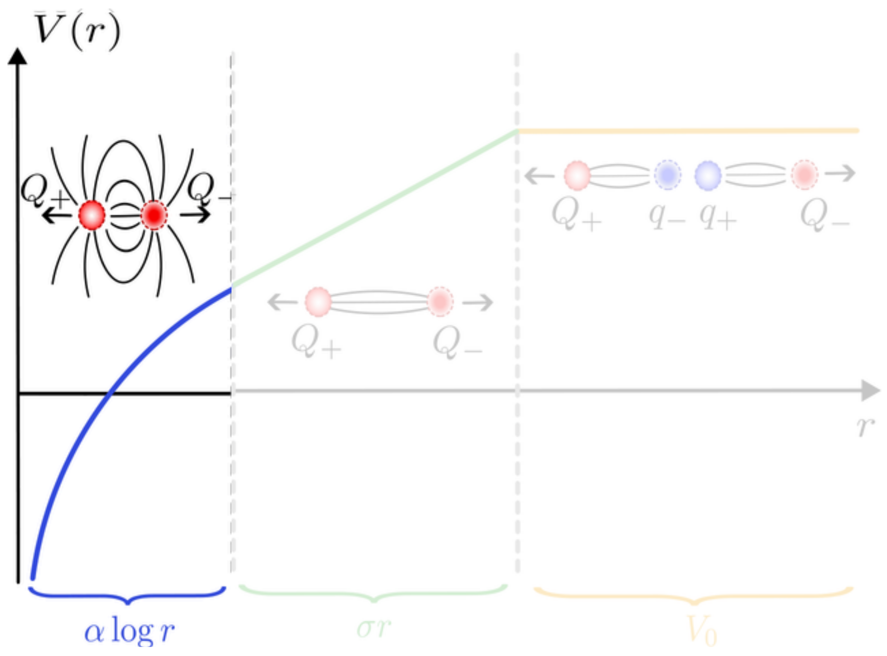
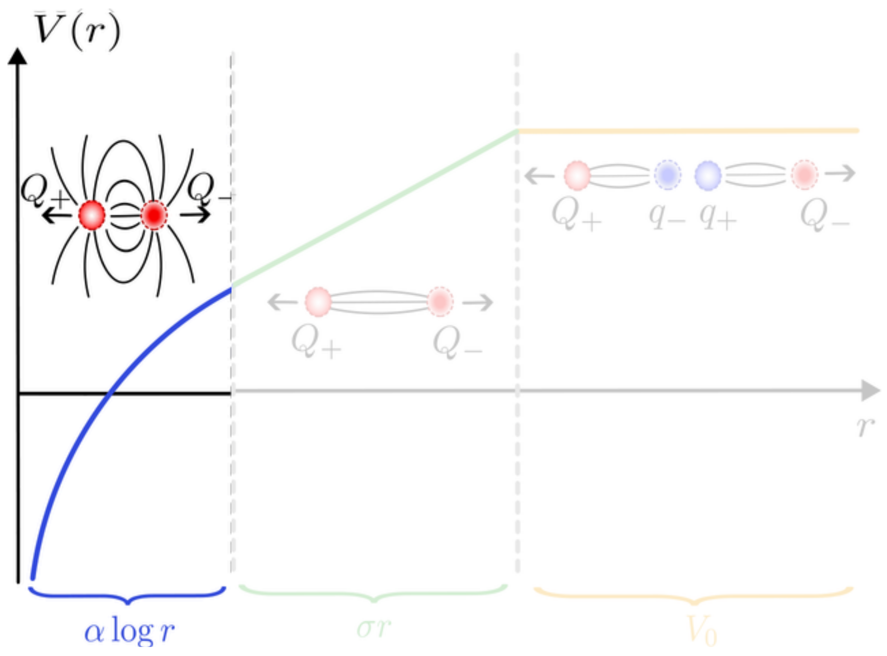


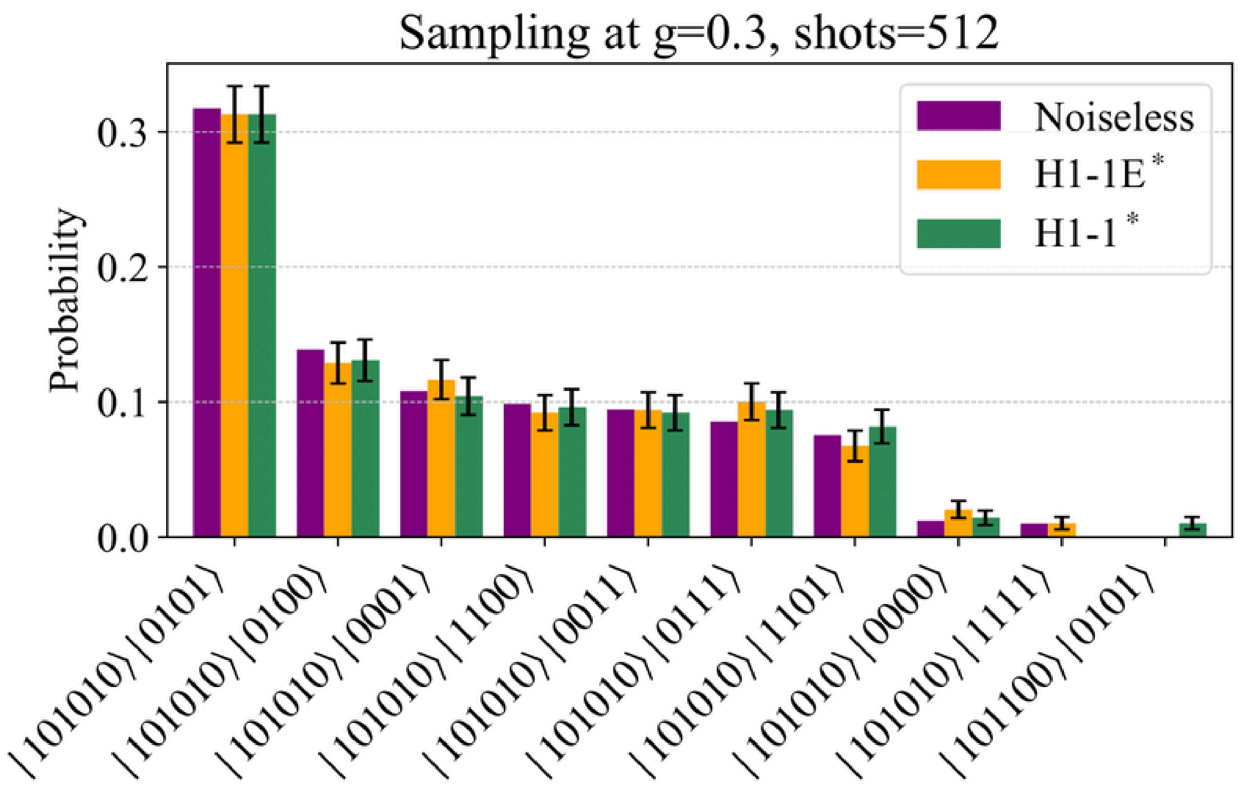
Quantum Hardware Results



Quantum Hardware Results

Ion trap





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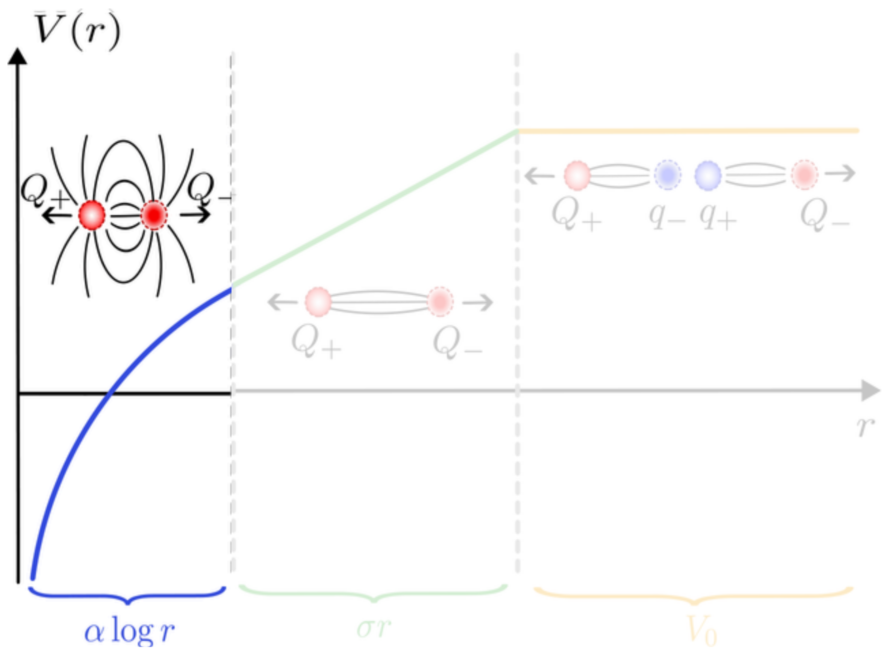
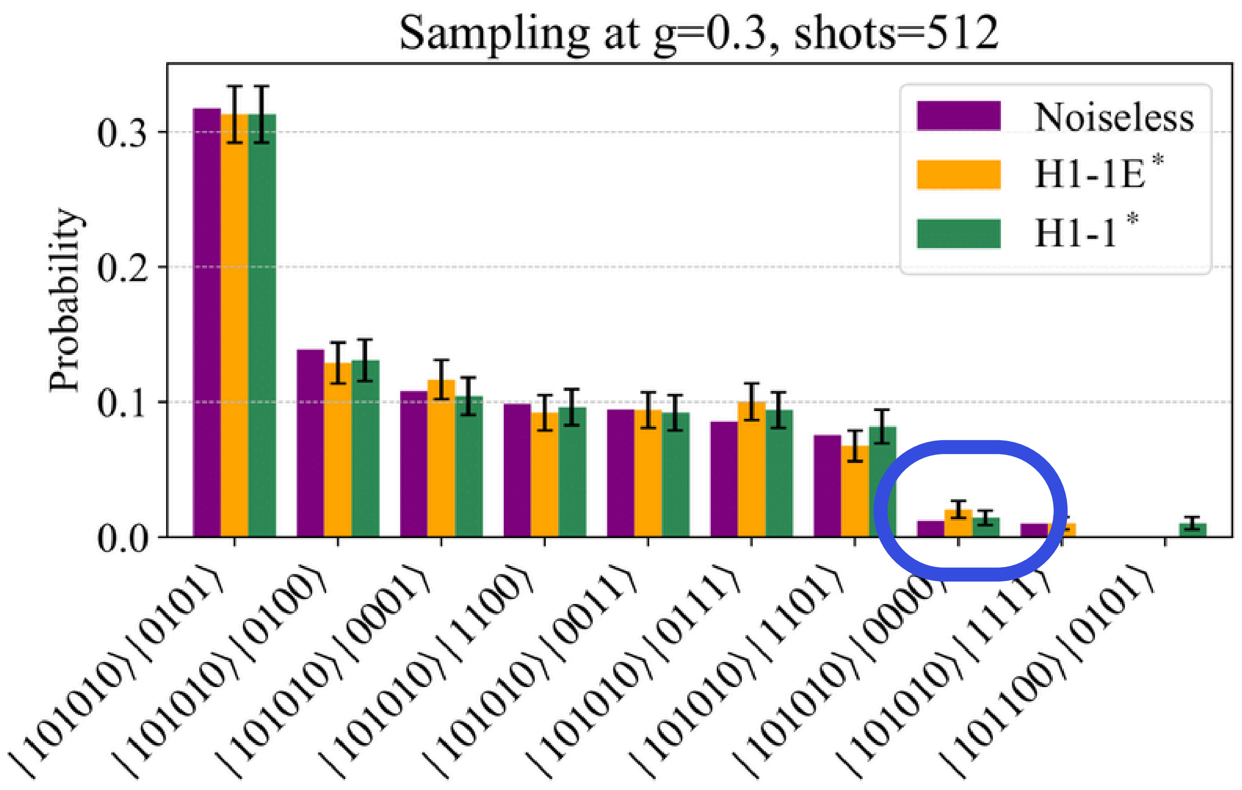
Quantum Hardware Results

Ion trap





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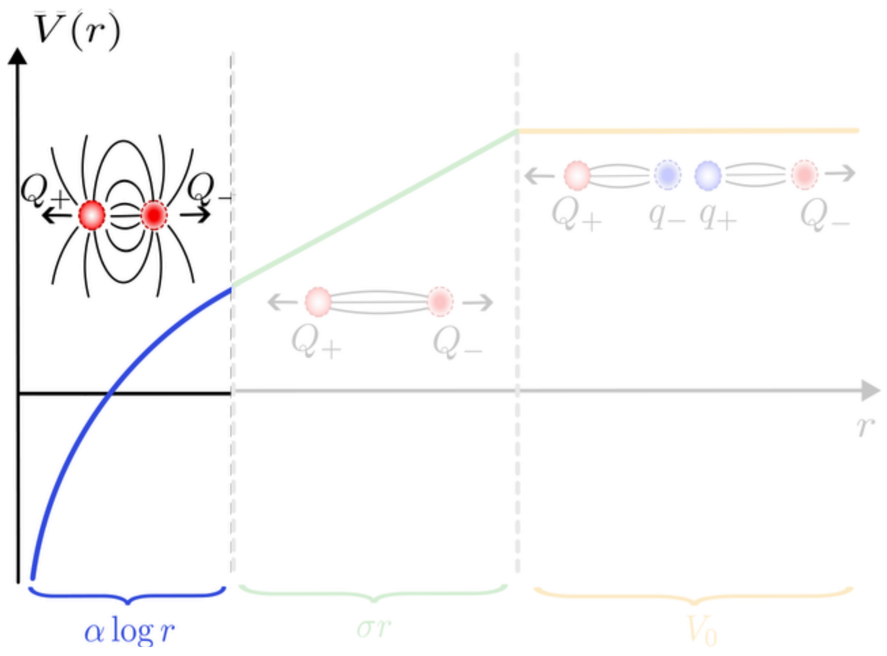
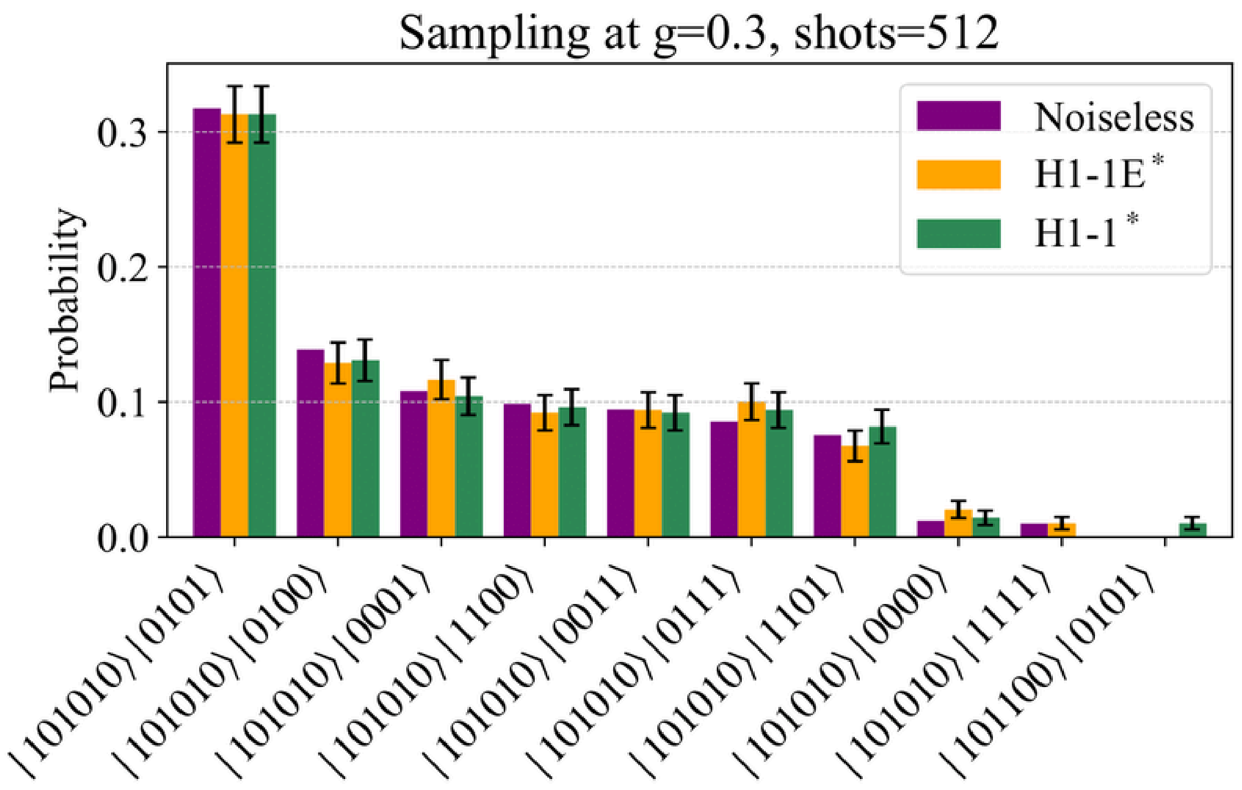
Quantum Hardware Results



Ion trap



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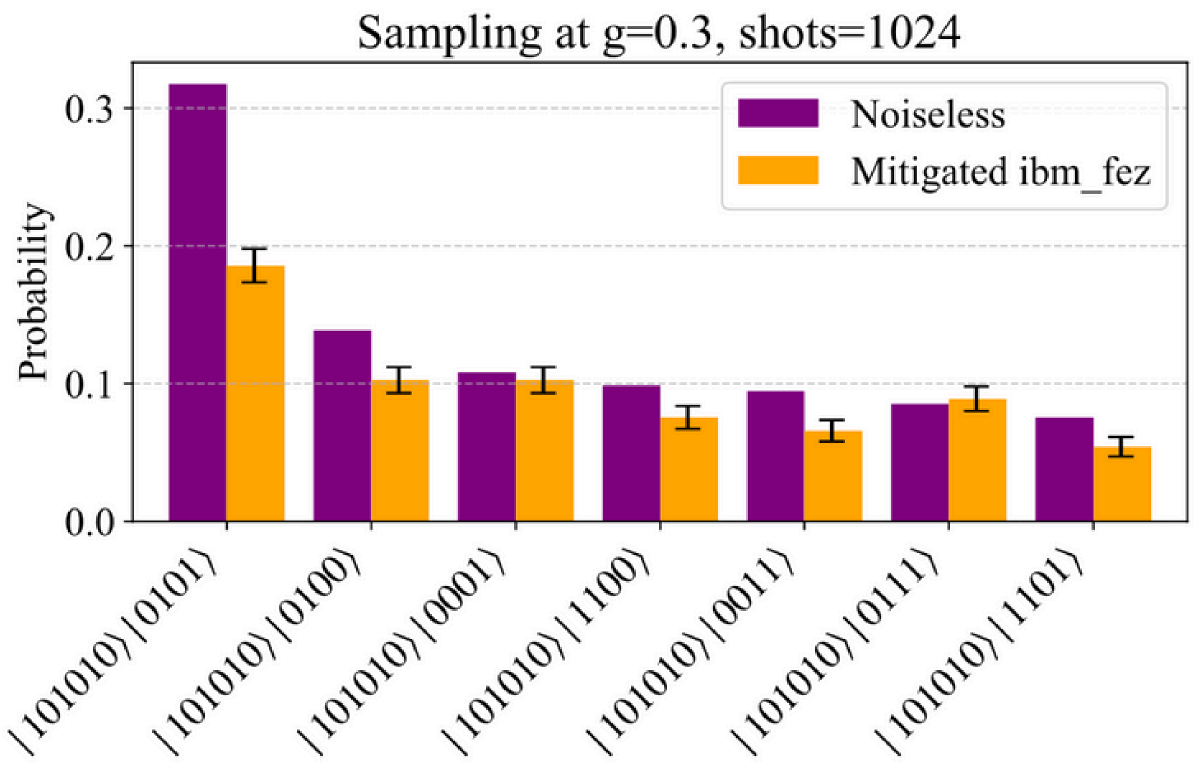
Superconducting



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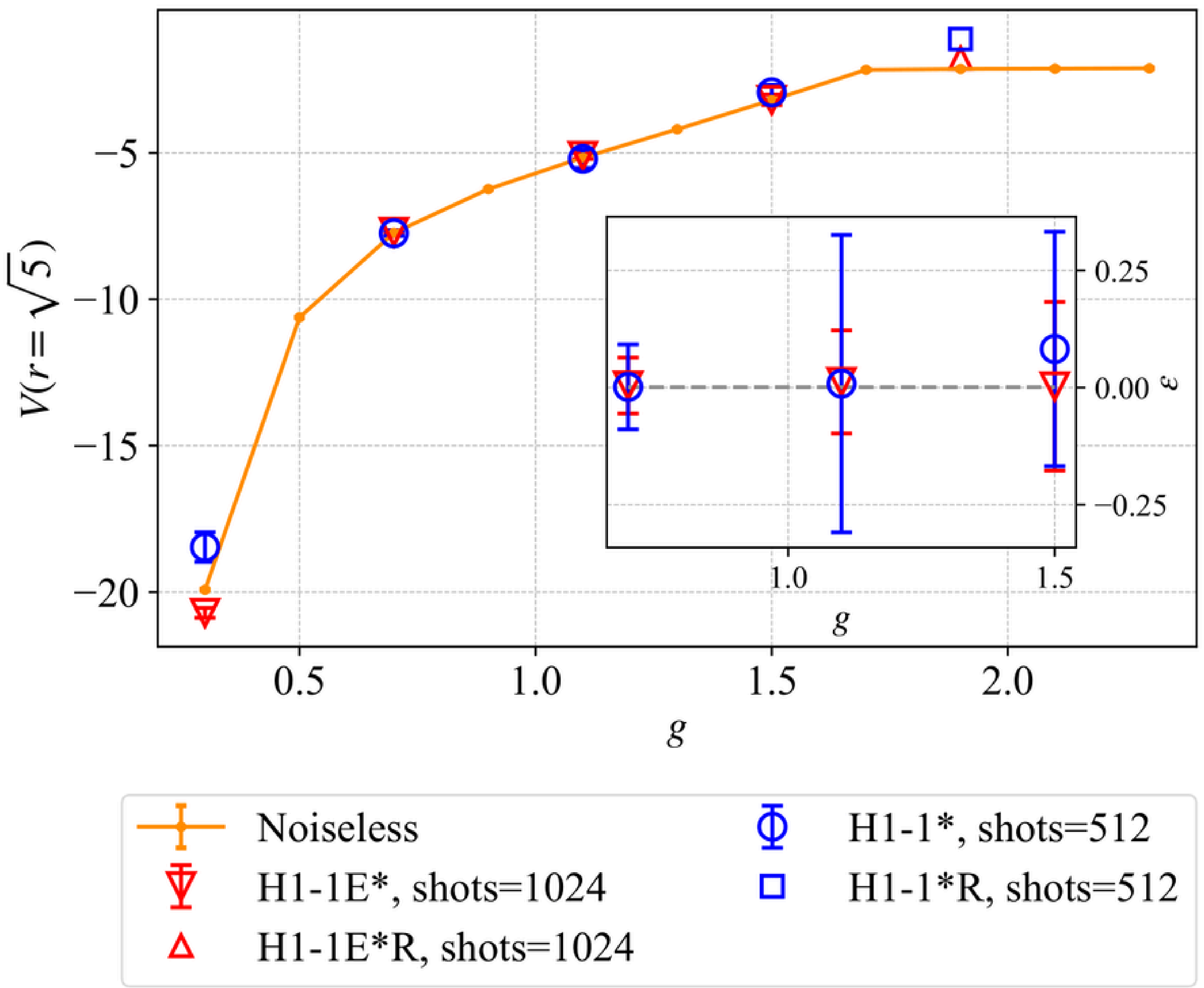
Quantum Hardware Results

Static potential

Quantum Hardware Results

Static potential

Ion trap



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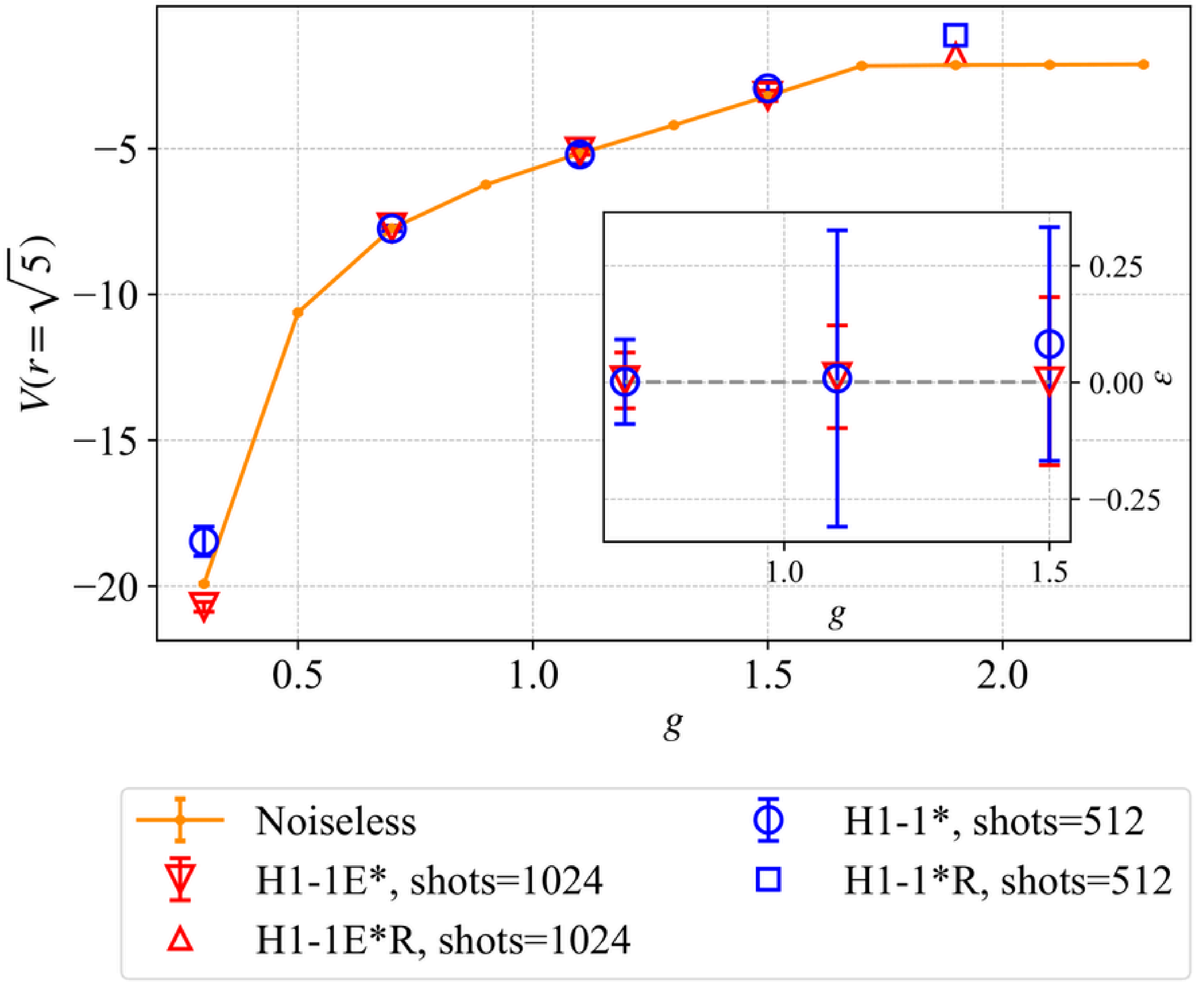
Quantum Hardware Results

Static potential

Ion trap



Emulator

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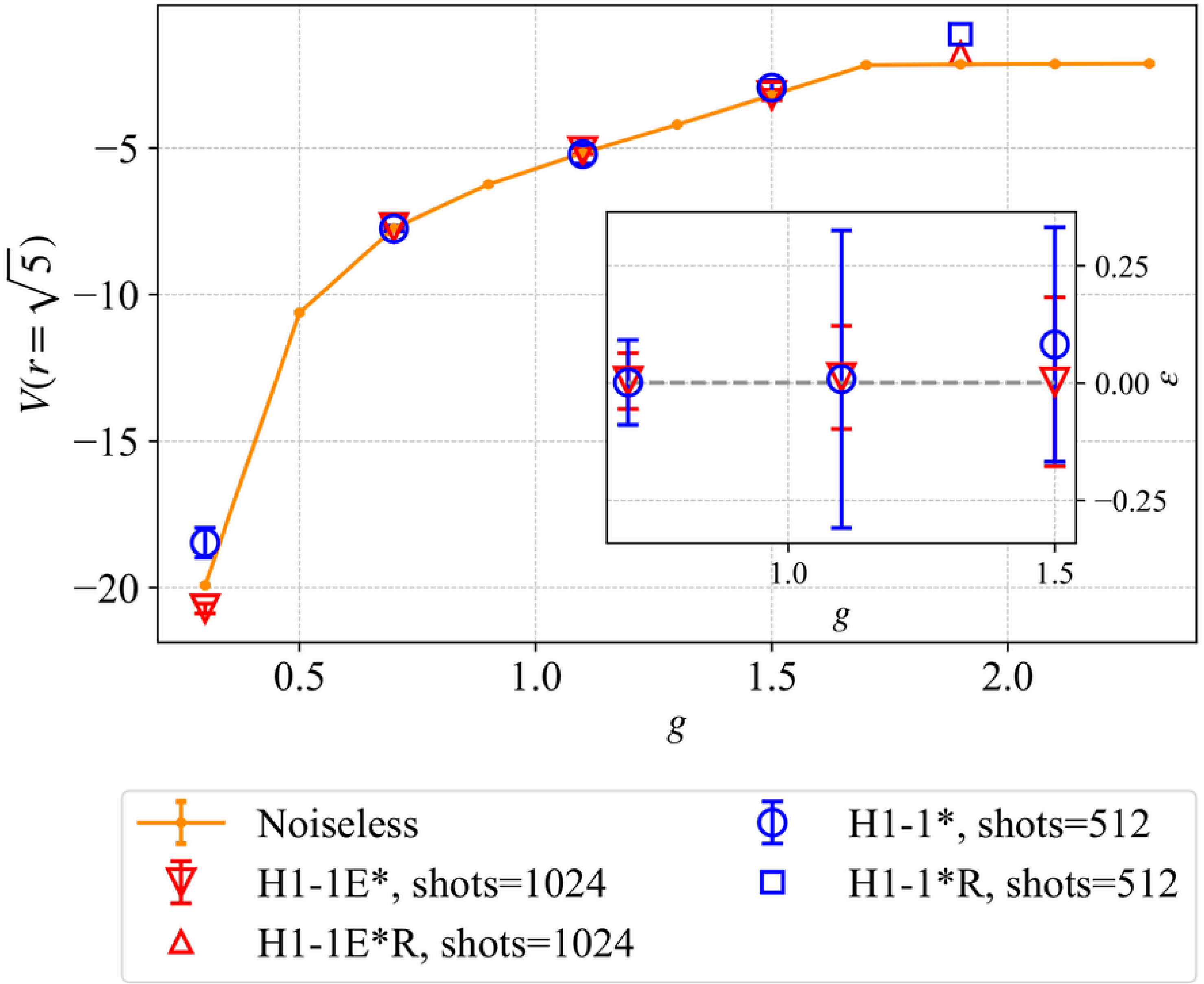
Quantum Hardware Results

Static potential

Ion trap



Emulator

Real hardware

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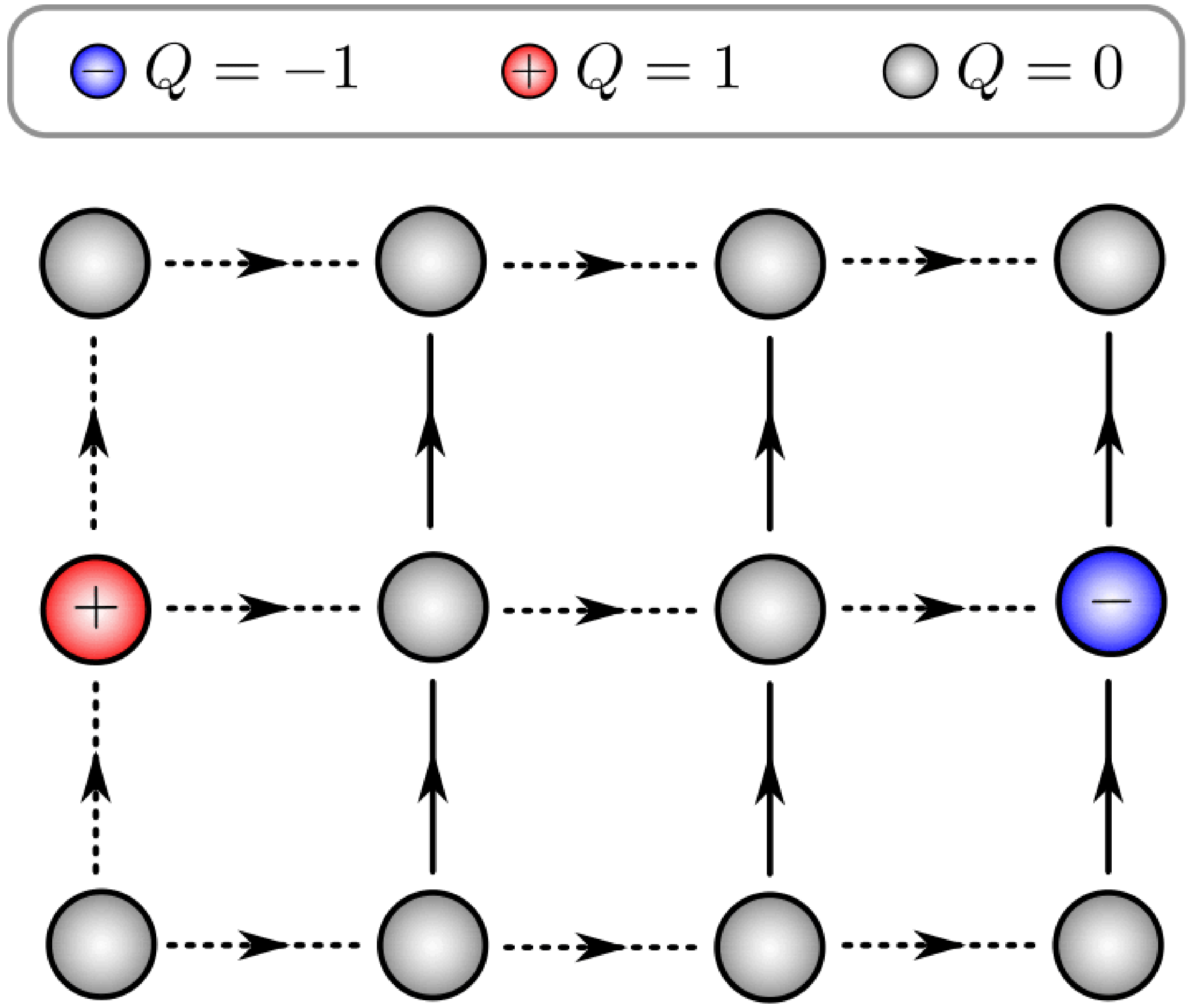
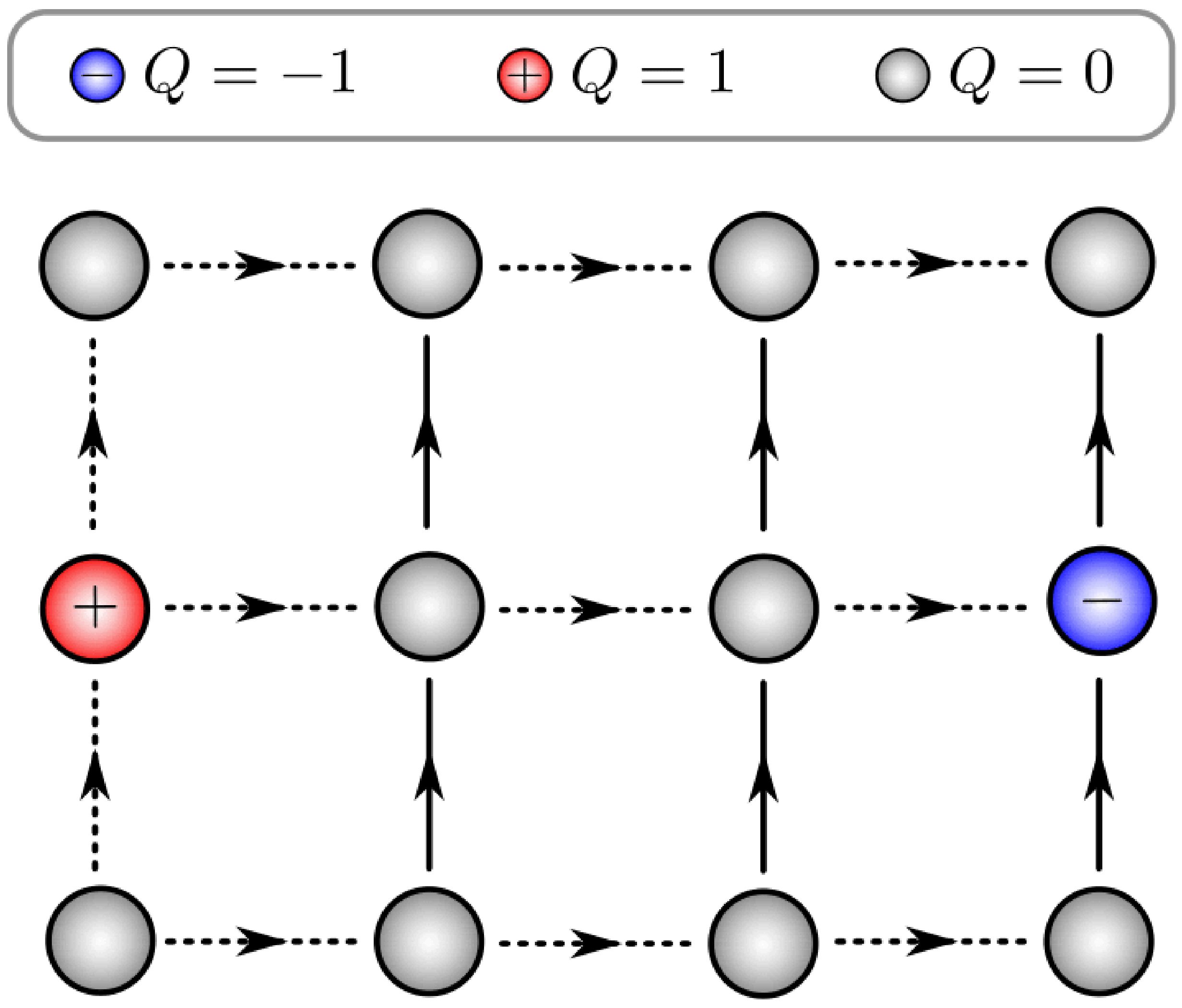
Quantum circuit

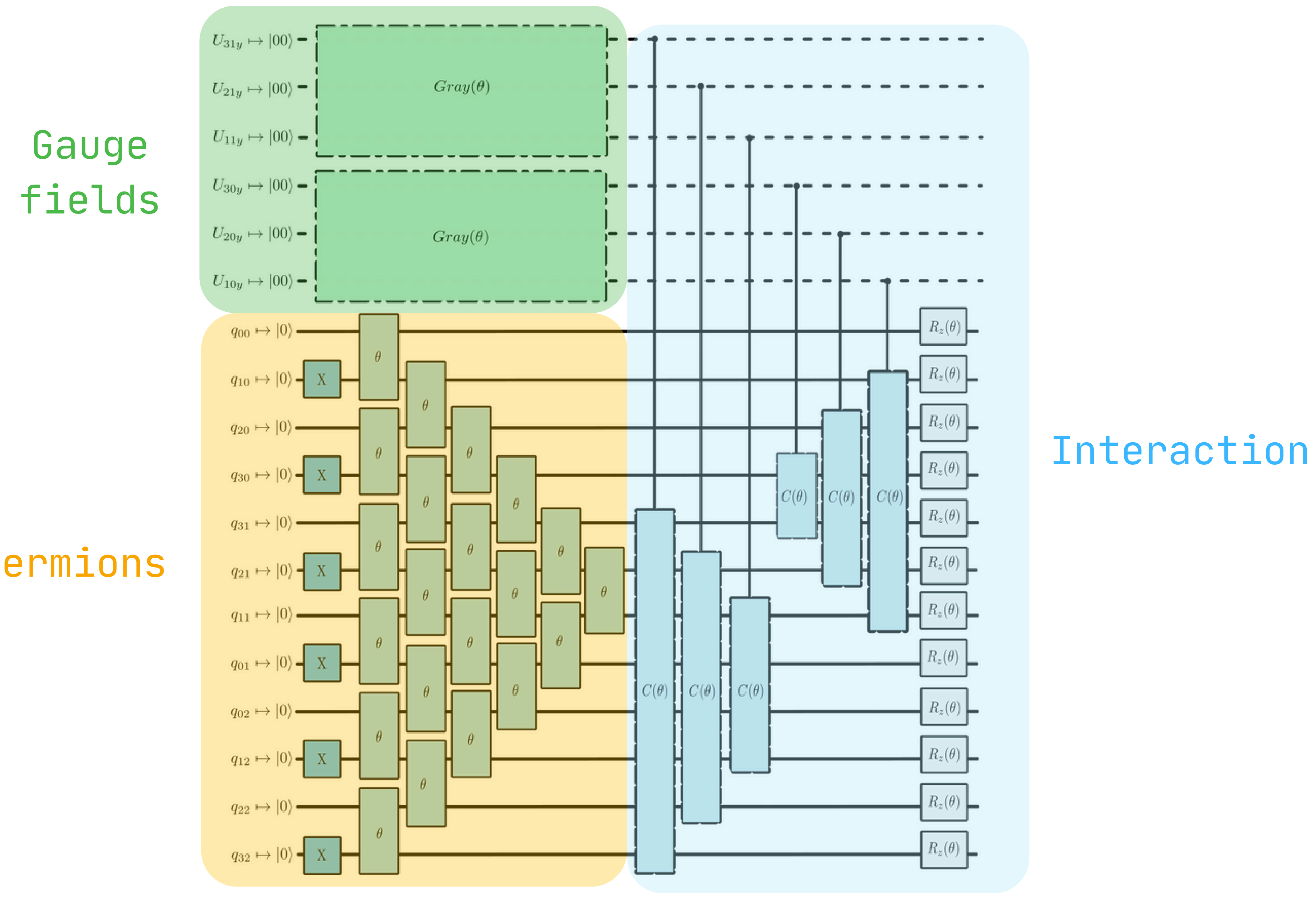
4x3 system



Quantum circuit

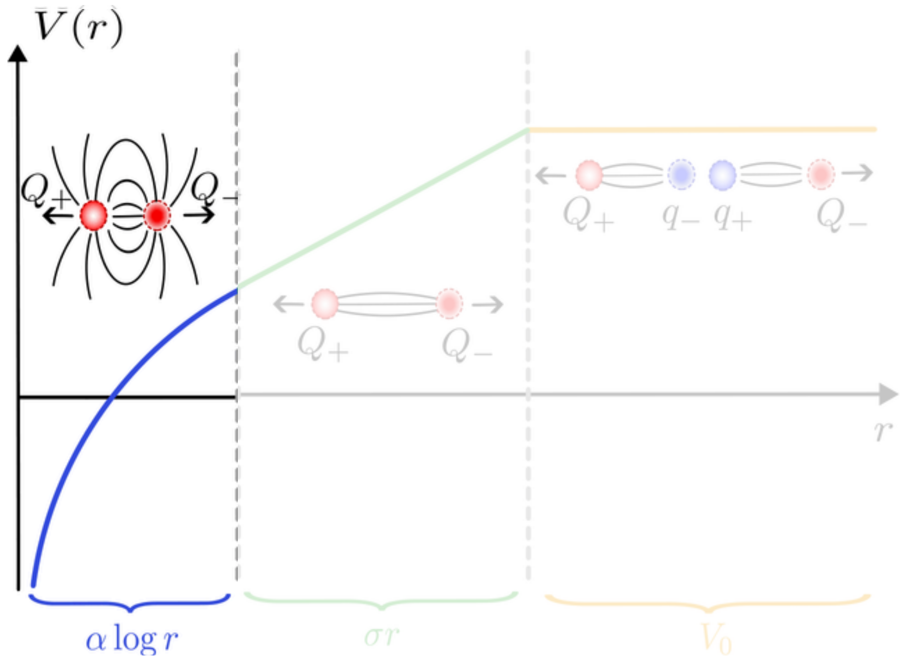
4x3 system





Quantum Hardware Results

Quantum Hardware Results



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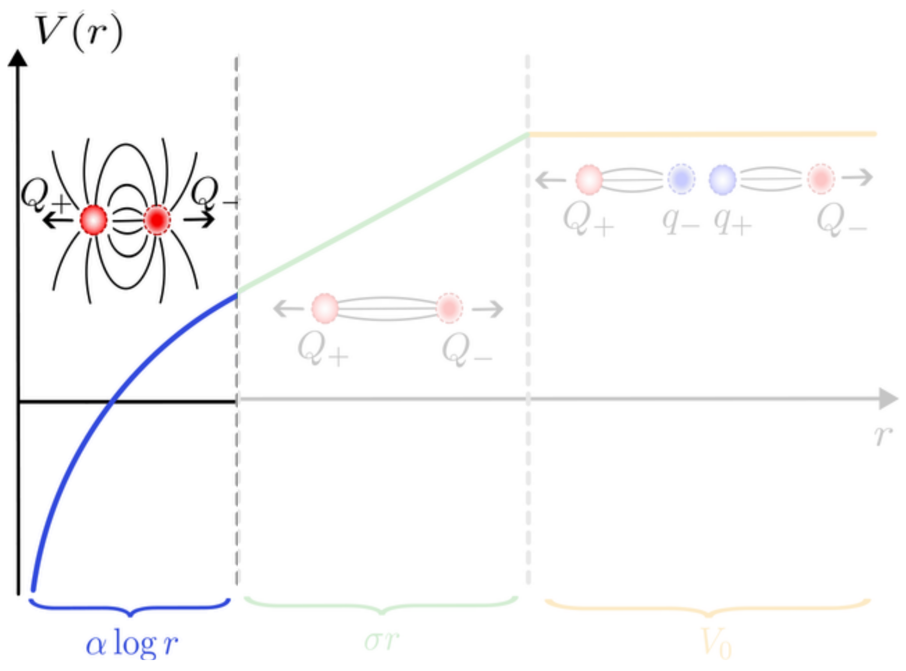
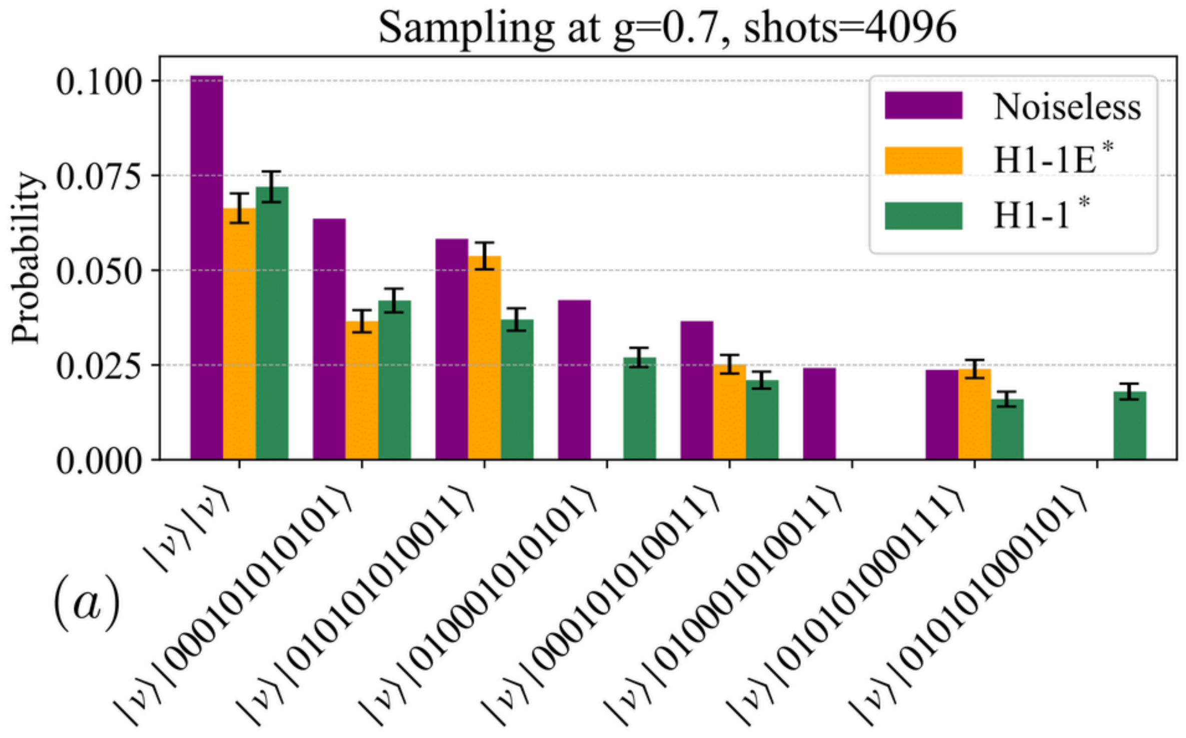
Quantum Hardware Results





(a)

(b)

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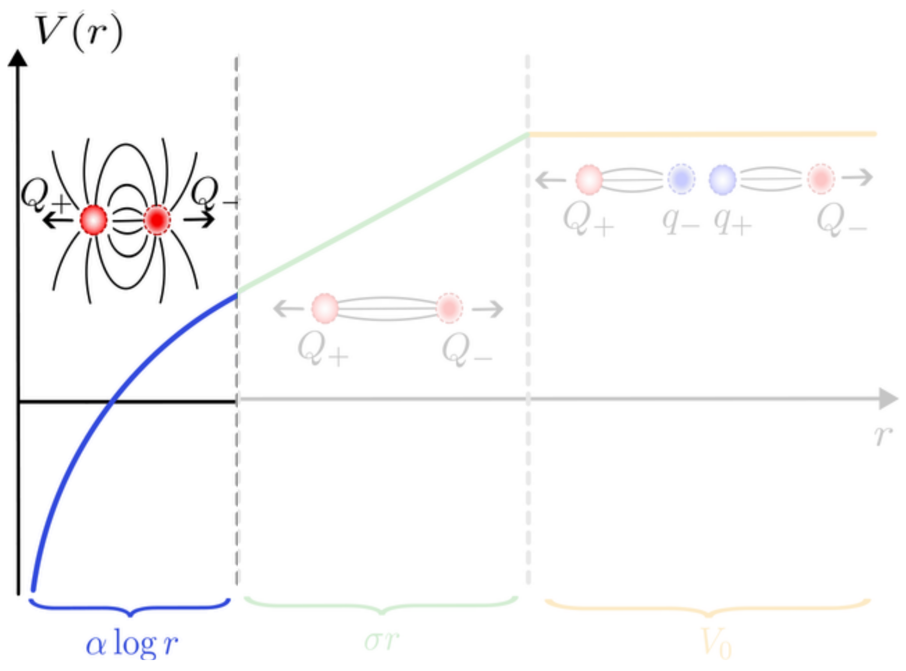
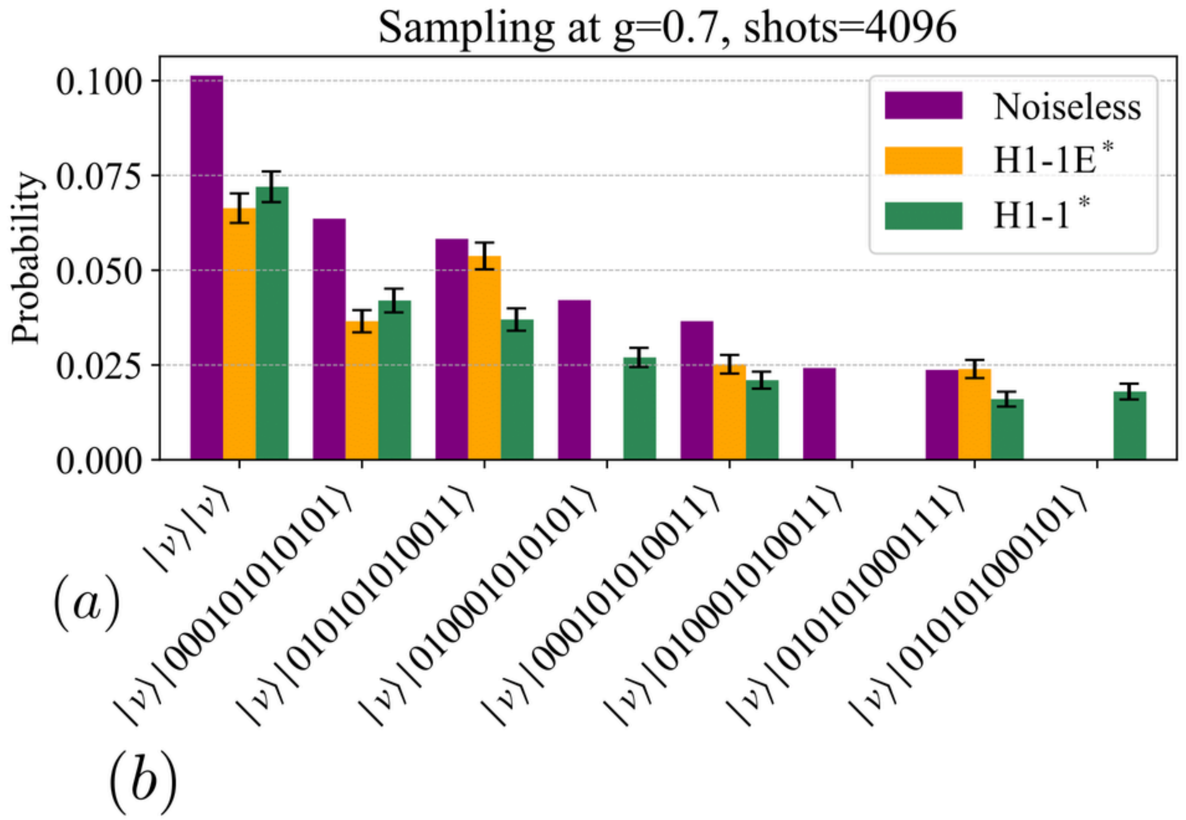
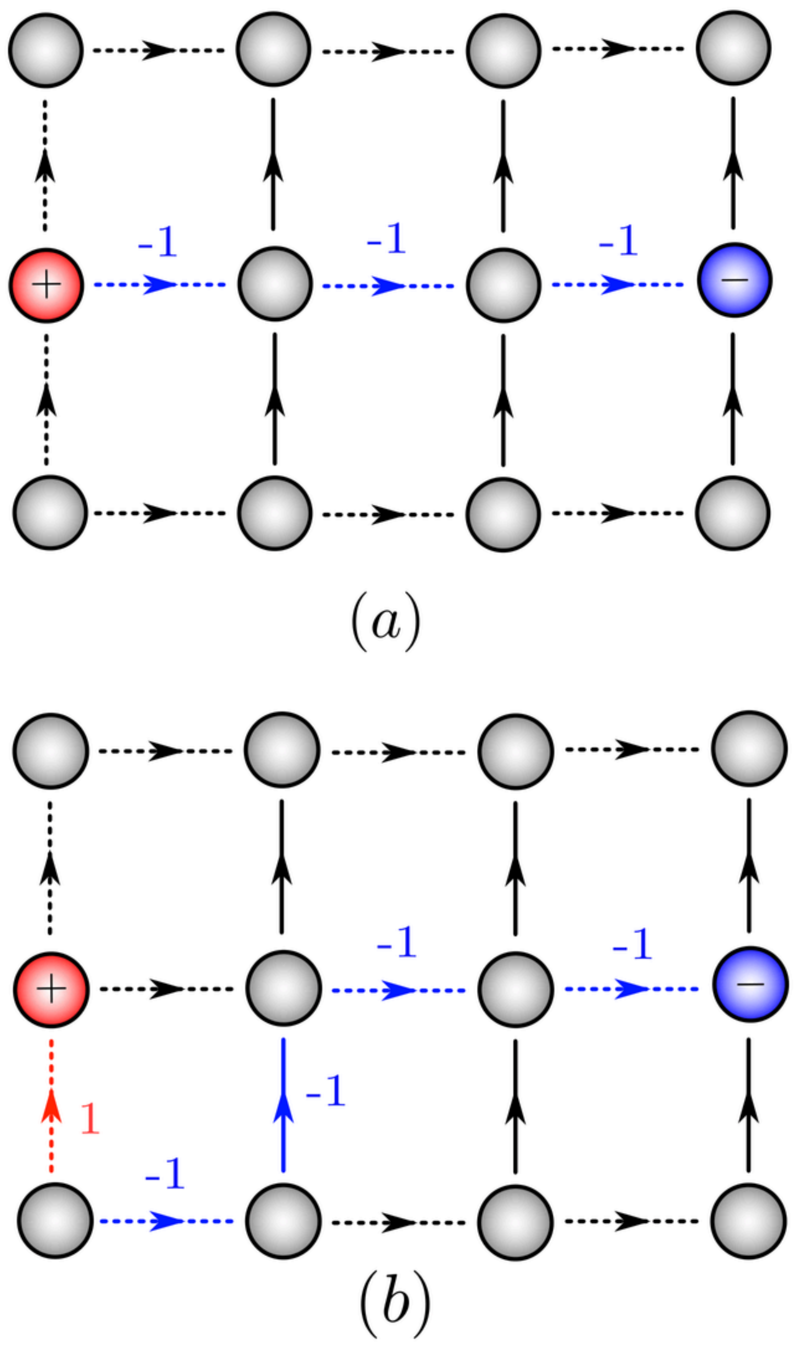
Quantum Hardware Results







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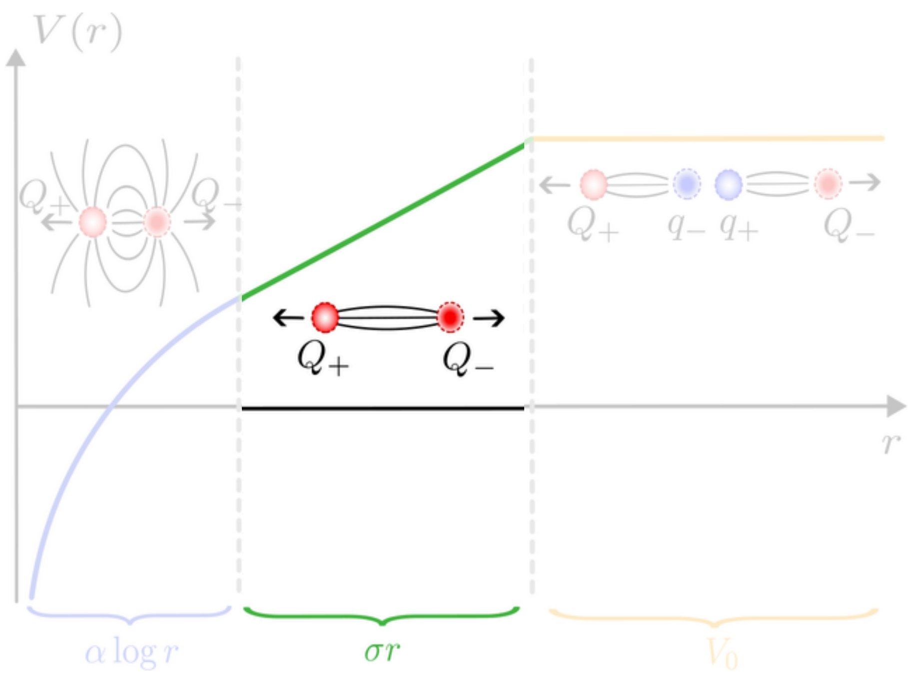
Quantum Hardware Results



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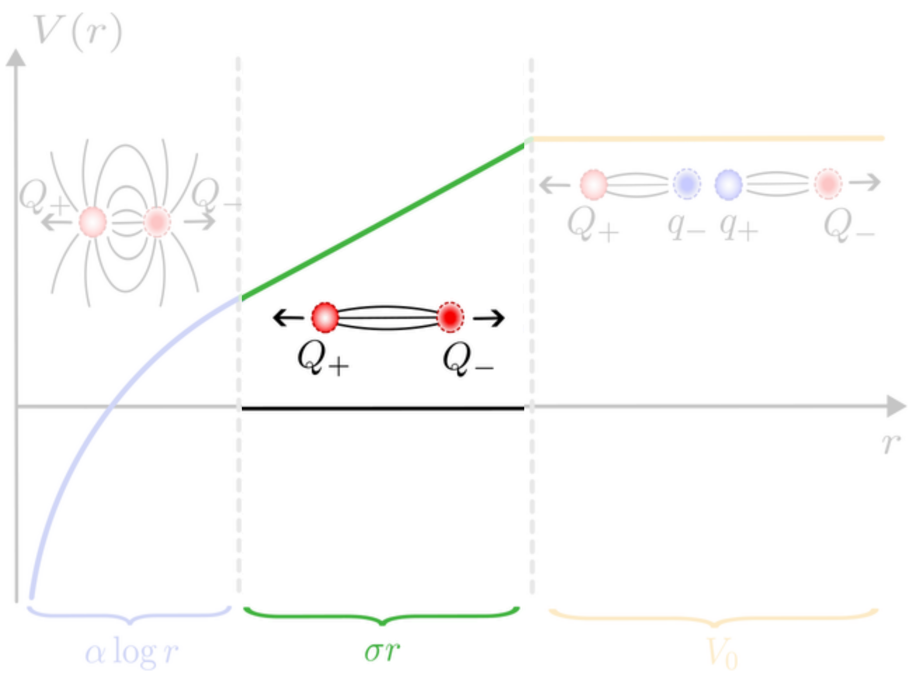
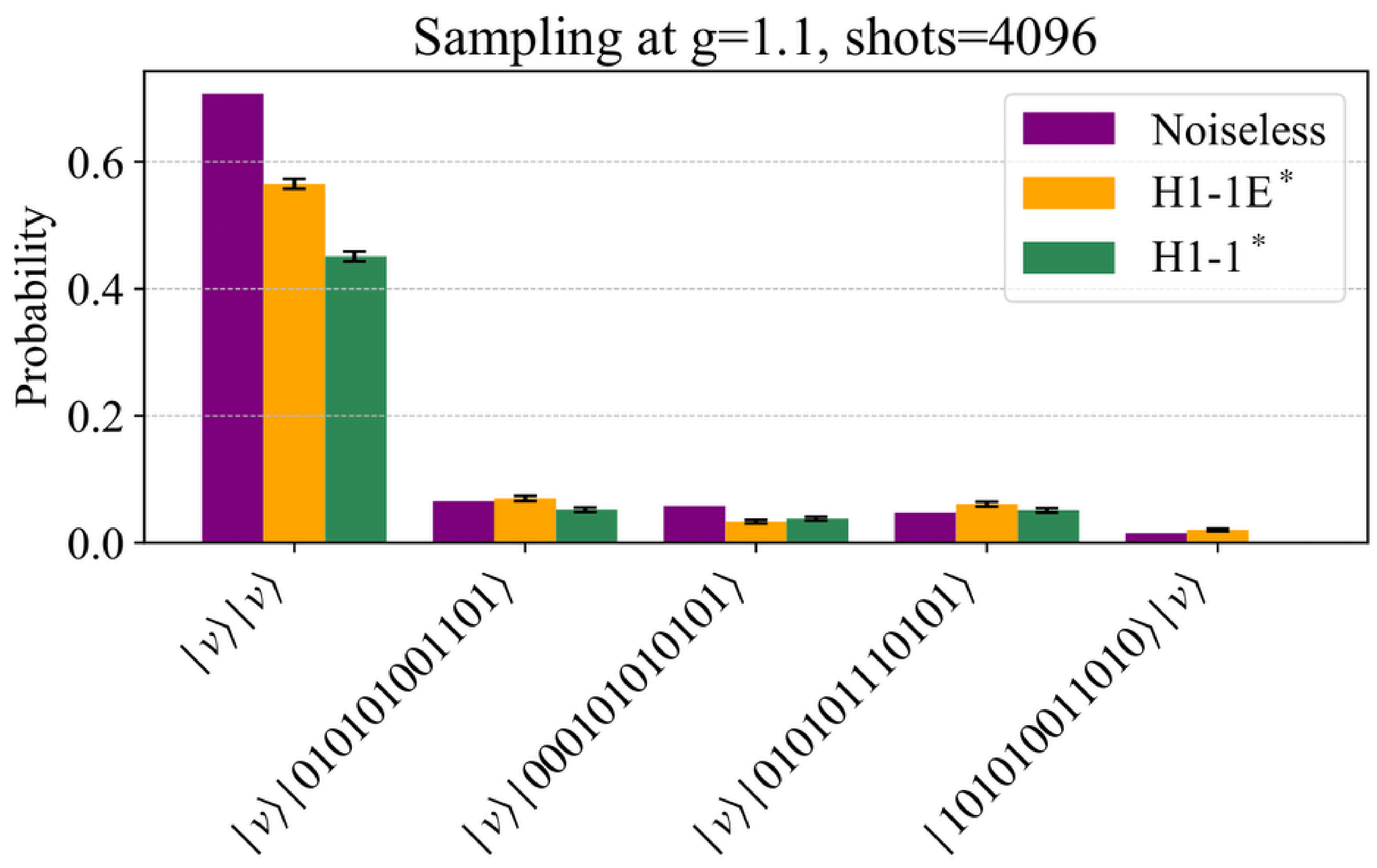
Quantum Hardware Results





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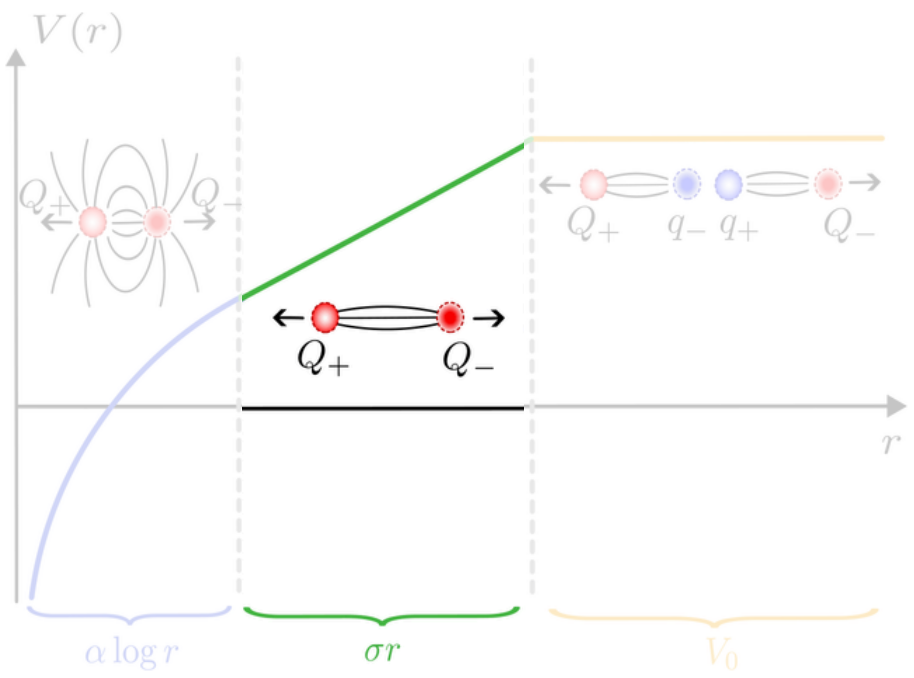
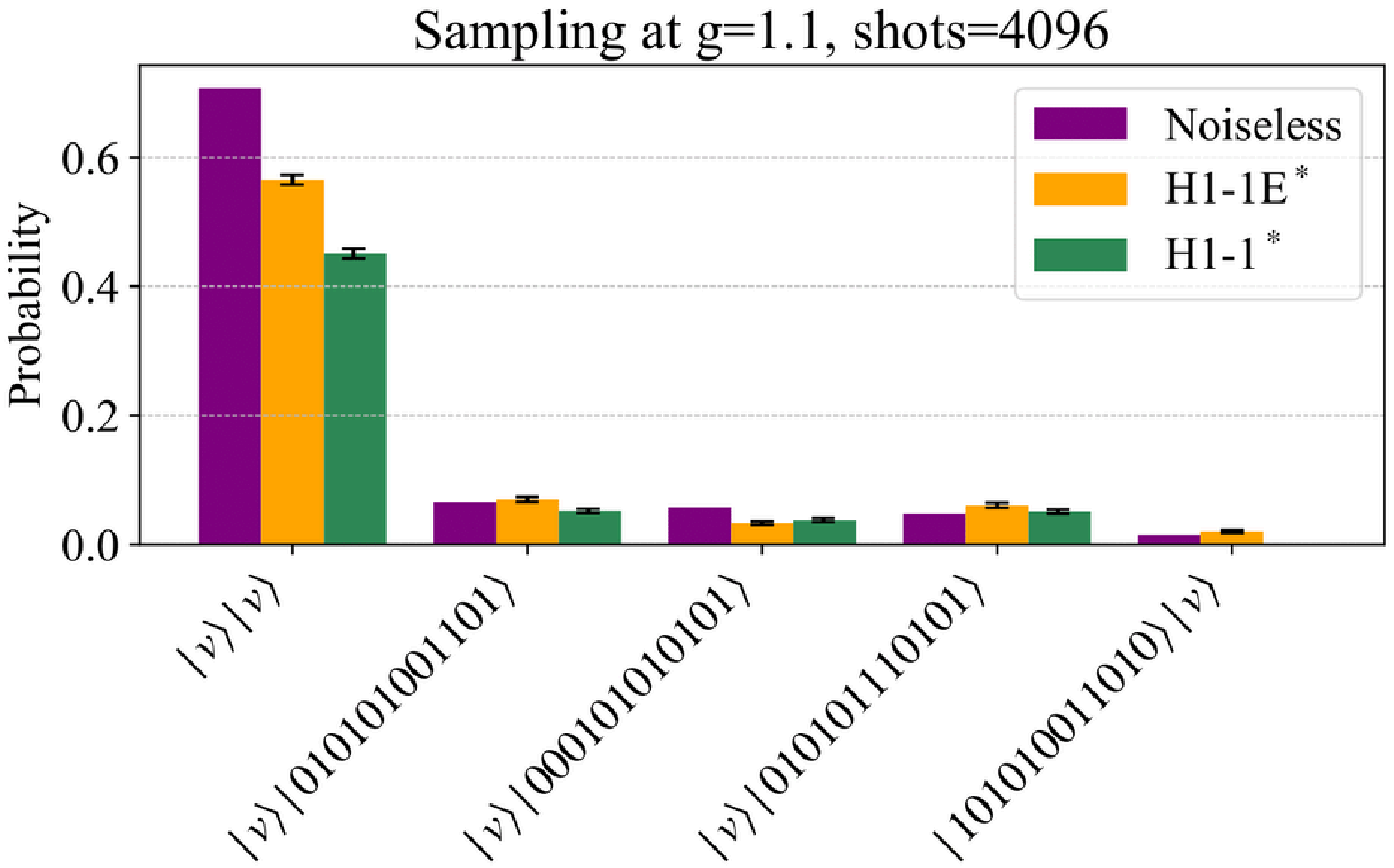
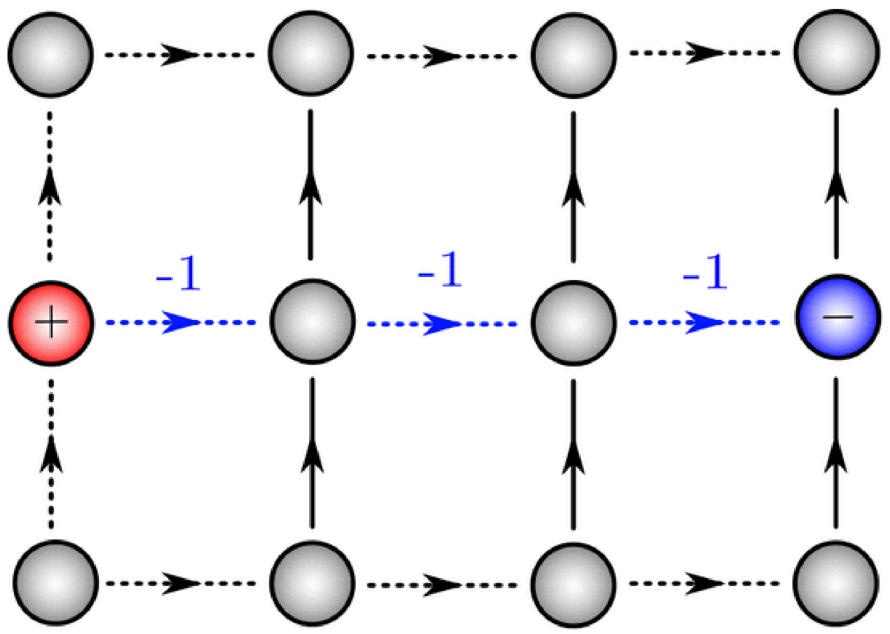
Quantum Hardware Results

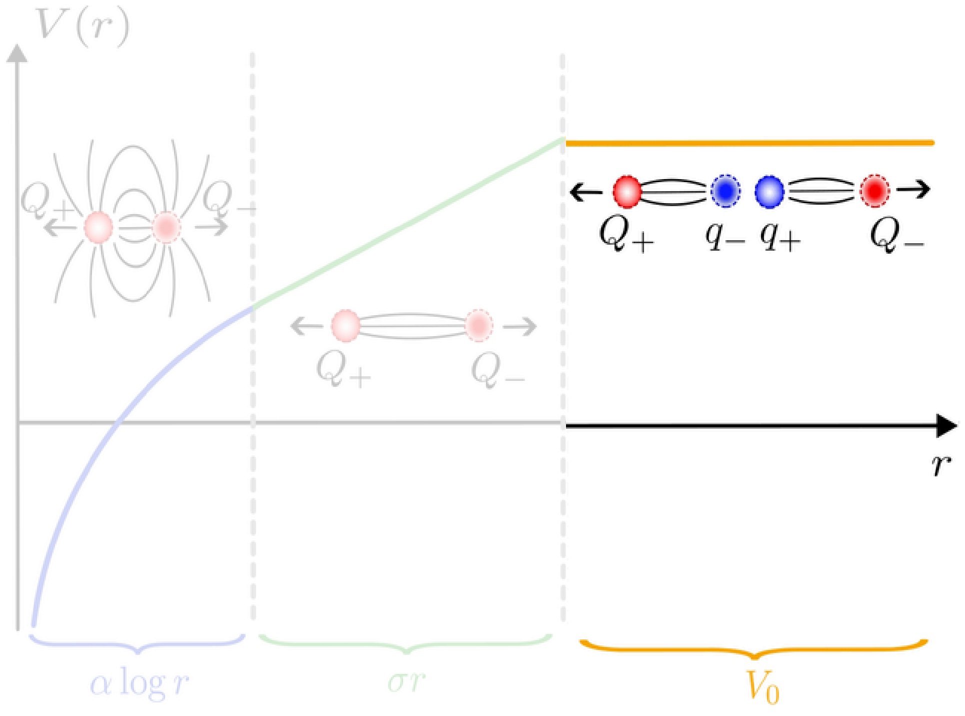






A. Crippa, K. Jansen, E. Rinaldi, arXiv:2411.05628

Quantum Hardware Results



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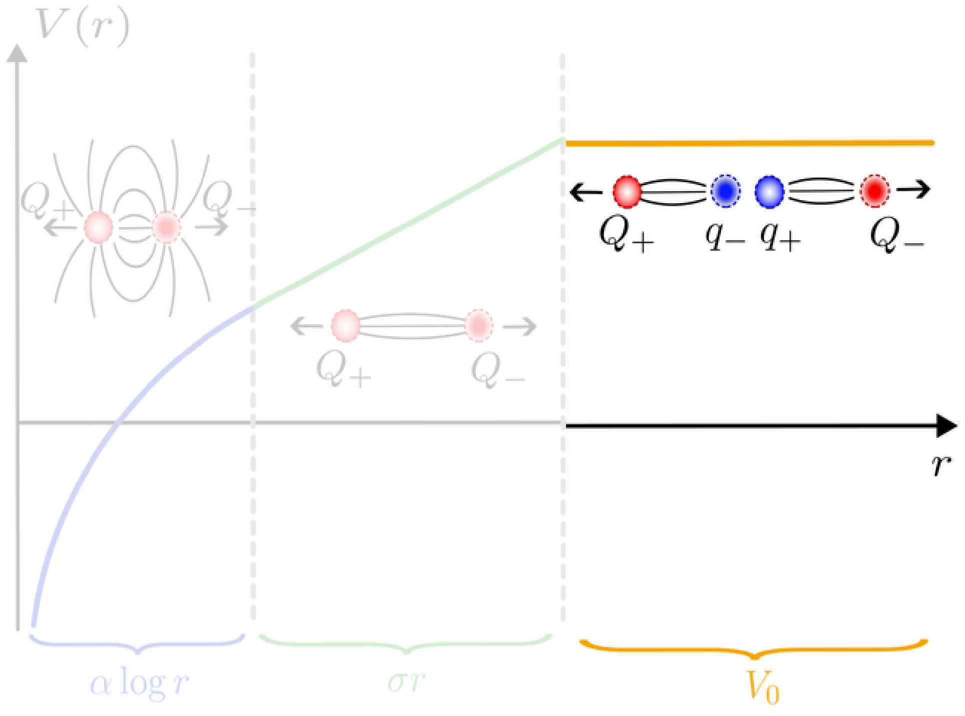

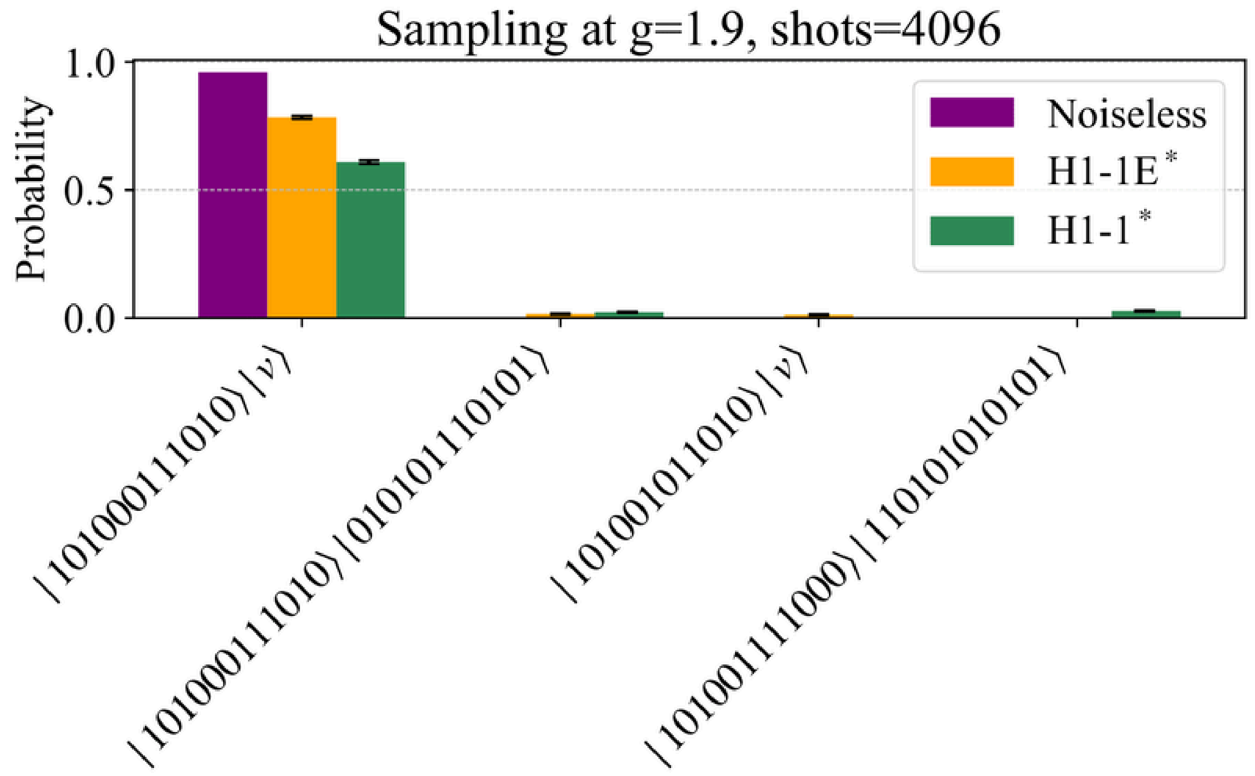

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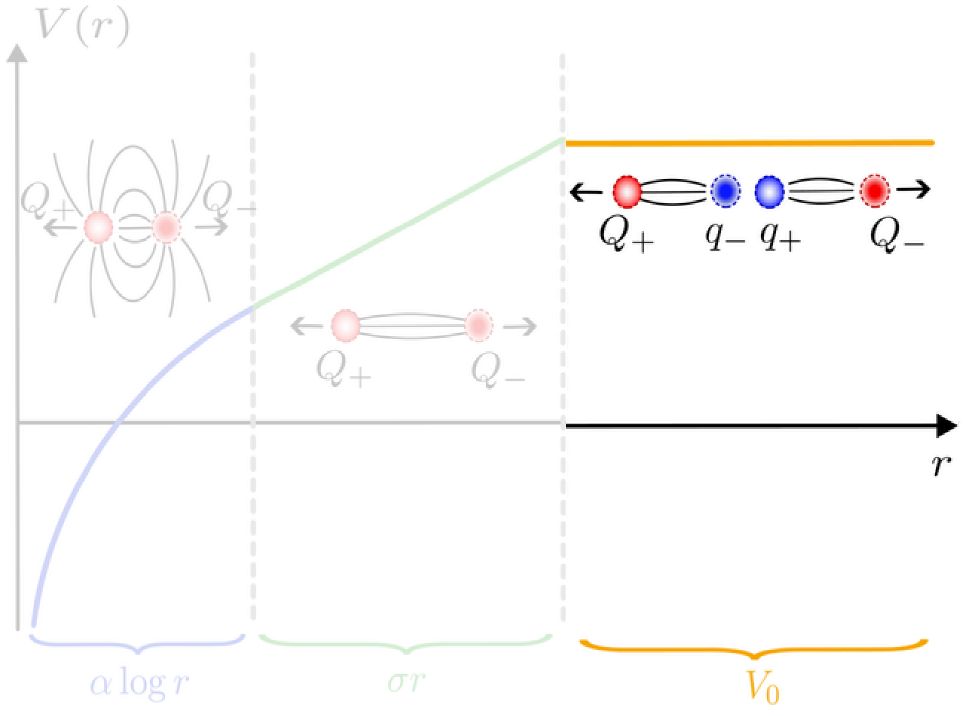

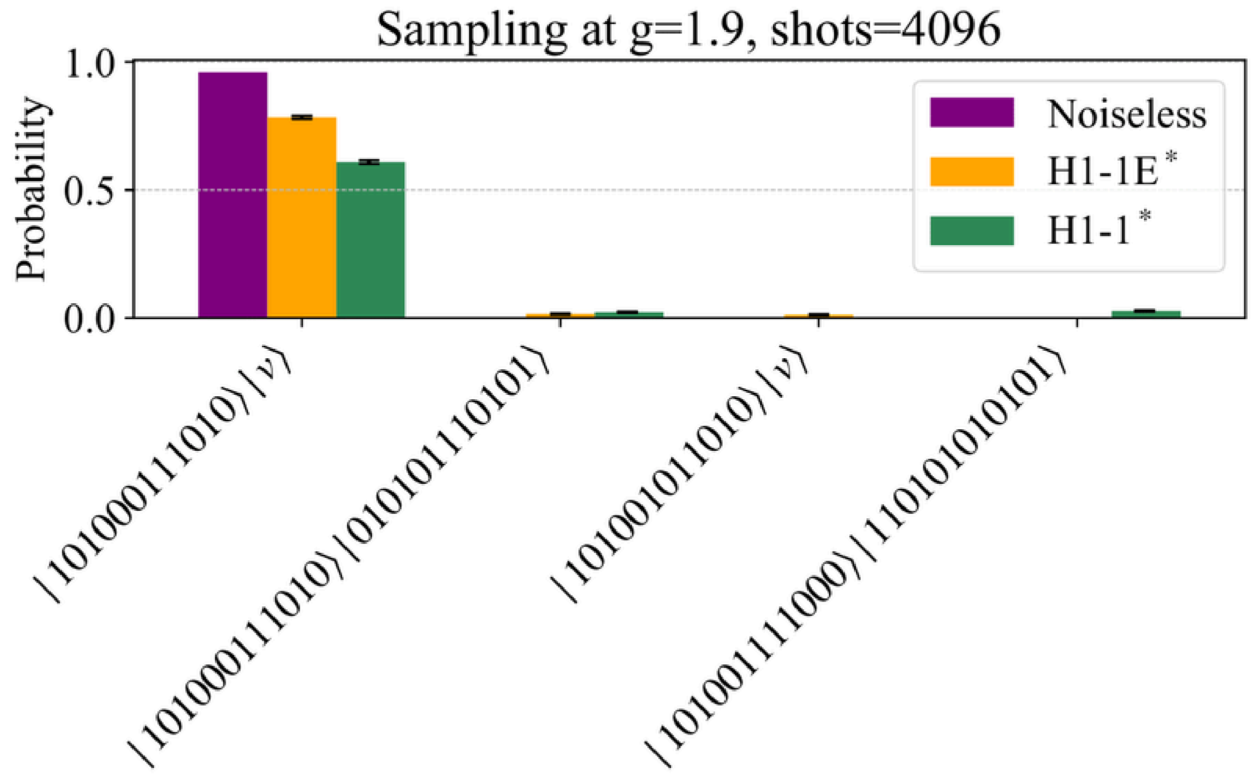

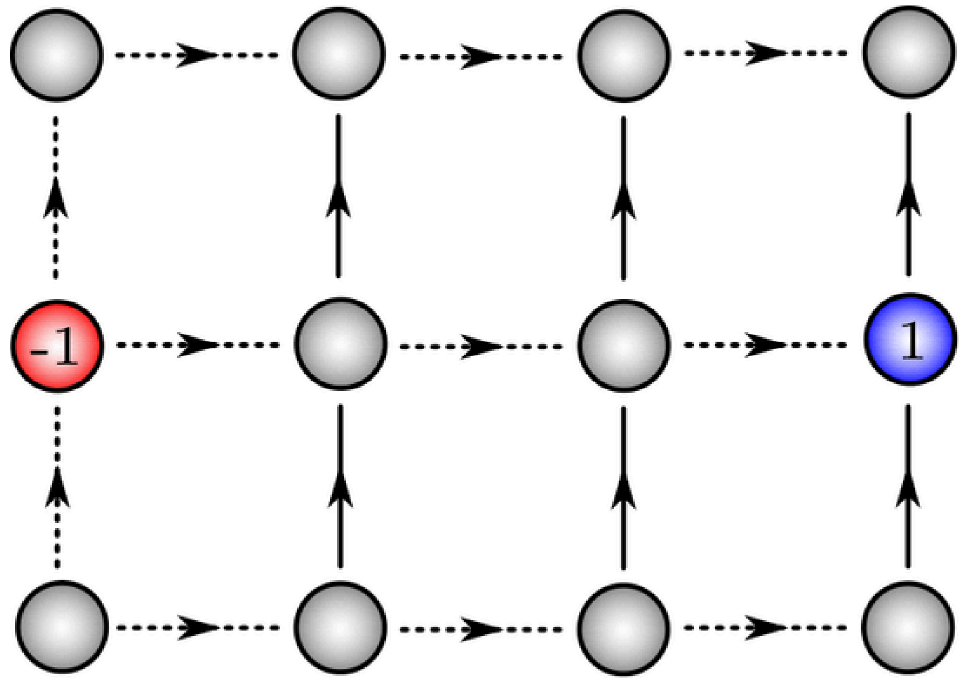

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Conclusions

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- Visualize confining electric fluxes and string breaking.
- Develop expressive Ansaetze describing the system, using mutual information.
- Results with real quantum hardwares.

Thank you for your attention!

BACKUP SLIDES

Encoding

Gauge fields

Map with Gray encoding

$$\hat{E} \mapsto -|00\rangle\langle 00| + |11\rangle\langle 11| = -\frac{1}{2}[\sigma_0^z + \sigma_1^z]$$

$$\hat{U}^\dagger \mapsto |00\rangle\langle 01| + |01\rangle\langle 11| = \frac{1}{2}\left[\sigma_0^-(I_1 + \sigma_1^z) + \sigma_1^-(I_0 - \sigma_0^z)\right]$$

Fermions

Map to spins with **Jordan-Wigner** transformation

$$\hat{\phi}_j^\dagger = \left[\prod_{k<j}(i\sigma_k^z)\right]\sigma_j^- \qquad \hat{\phi}_j = \left[\prod_{k<j}(-i\sigma_k^z)\right]\sigma_j^+$$

U operator

Example l=2 U(lowering)

$$U_{\text{ladder}} = \begin{pmatrix} 0 & & & & \\ 1 & 0 & & & \\ & 1 & 0 & & \\ & & 1 & 0 & \\ & & & 1 & 0 \end{pmatrix}$$

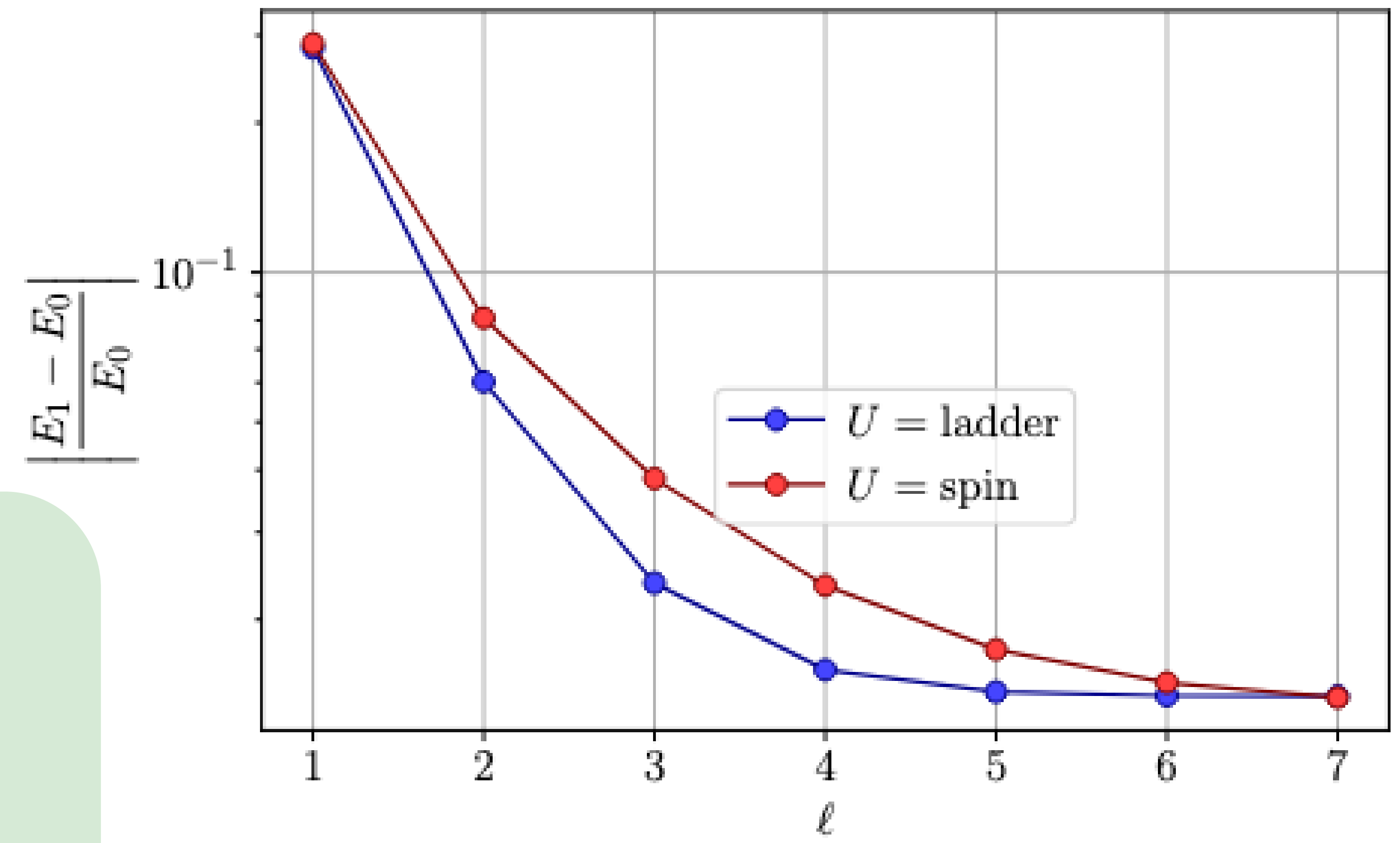
$$U_{\text{spin}} = \frac{S^-}{\ell} = \frac{1}{2} \begin{pmatrix} 0 & & & & \\ 2 & 0 & & & \\ & \sqrt{6} & 0 & & \\ & & \sqrt{6} & 0 & \\ & & & 2 & 0 \end{pmatrix}$$

$$U_{\text{spin}} = \frac{1}{\ell}\sqrt{\ell(\ell+1) - m(m-1)}\delta_{m,m-1}$$

$$U^\dagger_{\text{spin}} = \frac{1}{\ell}\sqrt{\ell(\ell+1) - m(m+1)}\delta_{m,m+1}$$

$$E_{\text{spin}} = S^z = m\delta_{m,m} \qquad m \in [-l, l]$$

Energy gap convergence



Mutual Information Ansatz

$$I(X;Y) = S(X) + S(Y) - S(X,Y)$$

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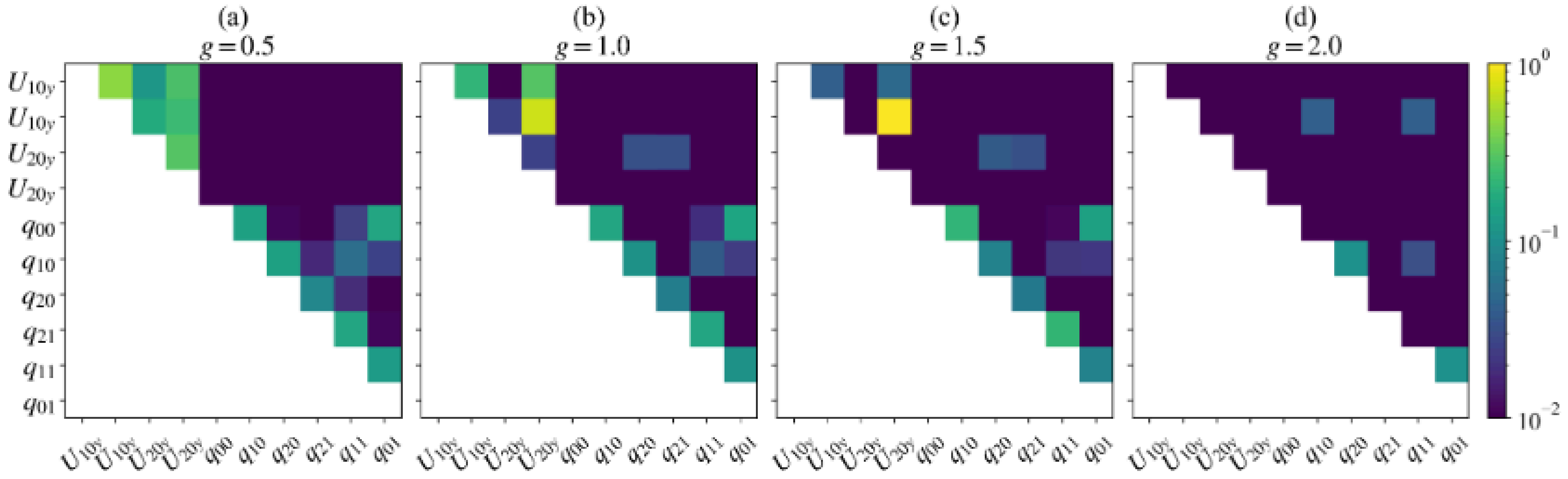

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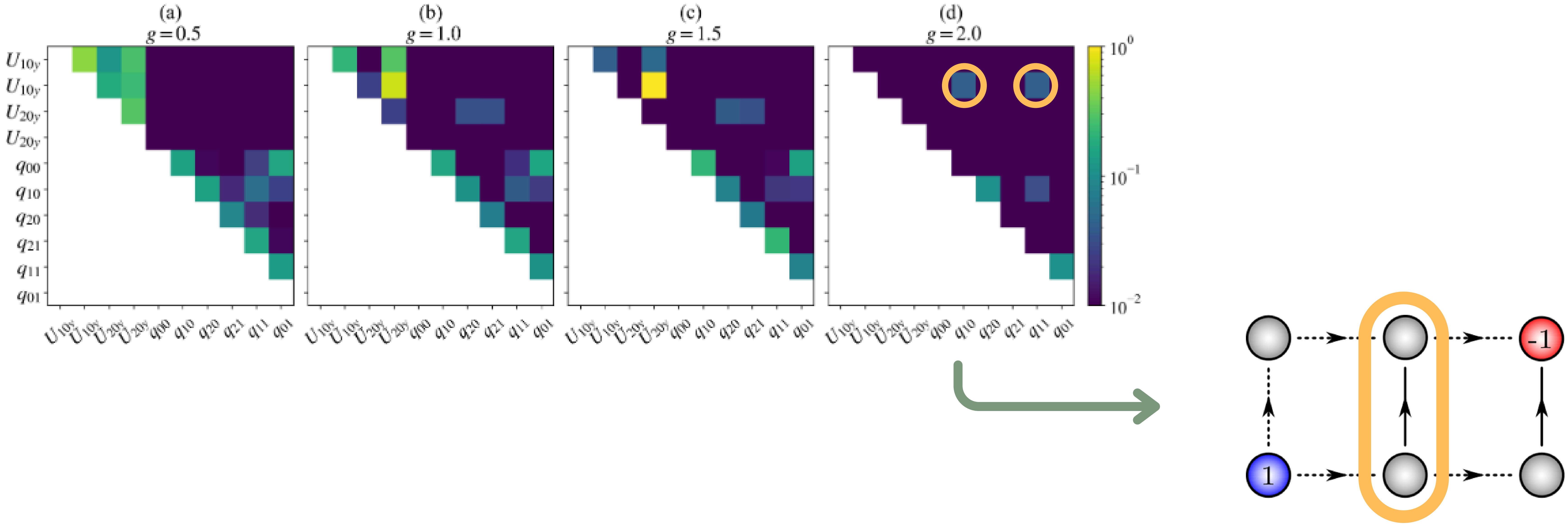

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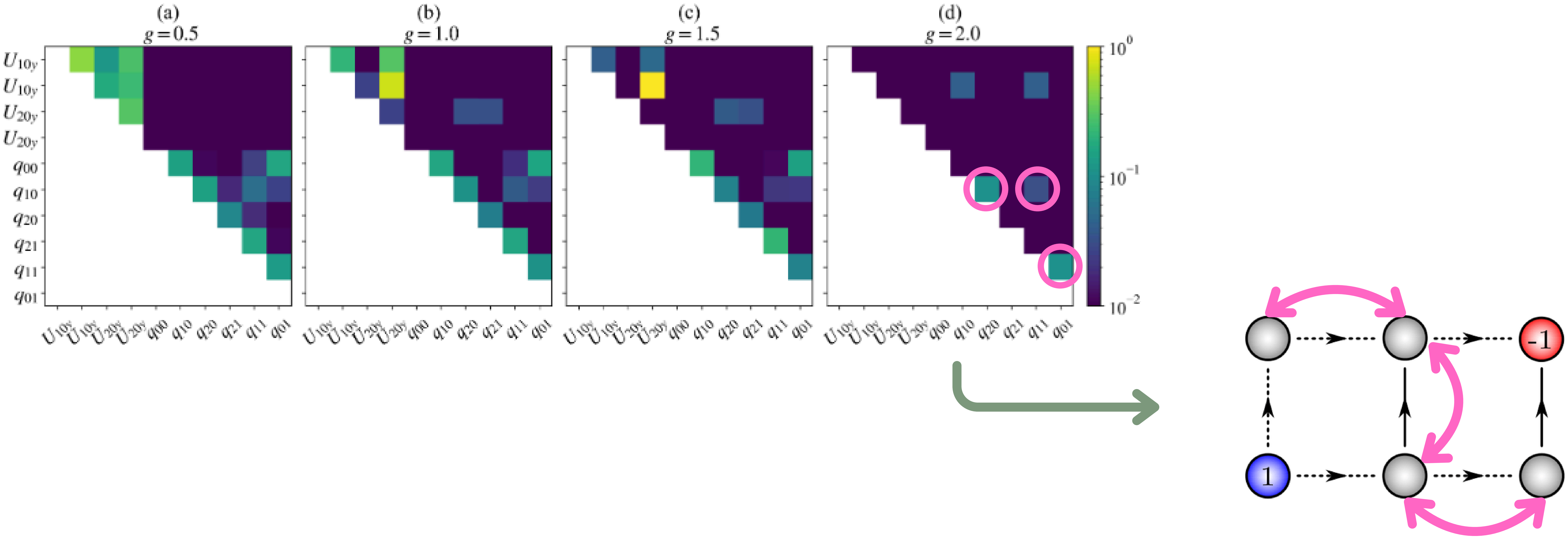

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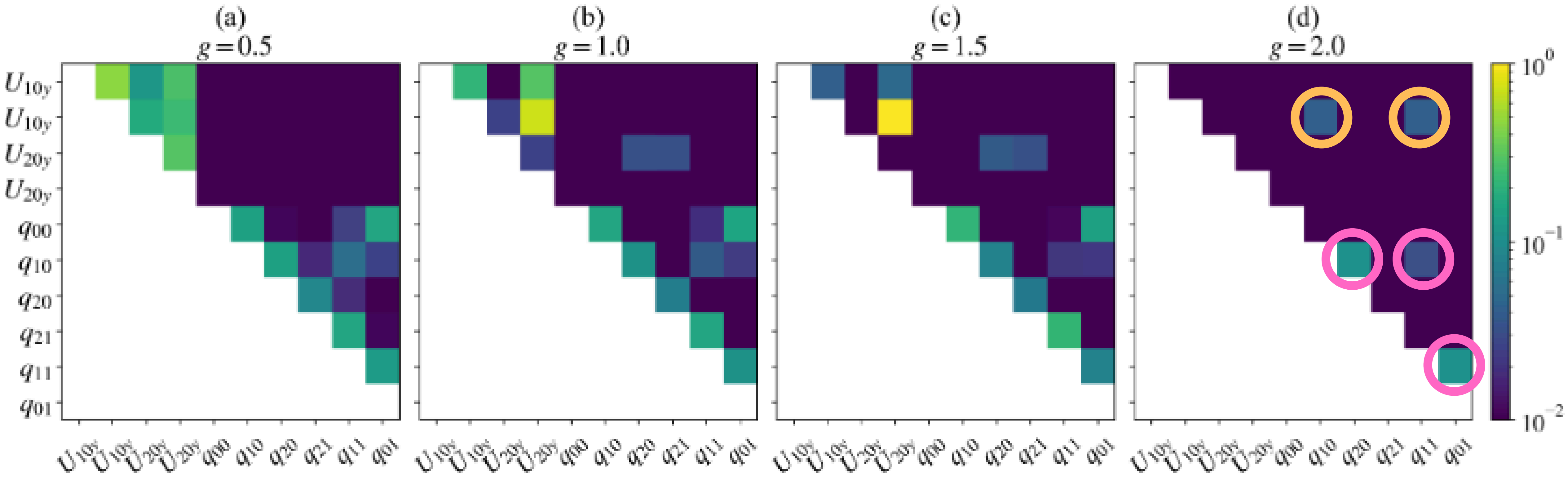
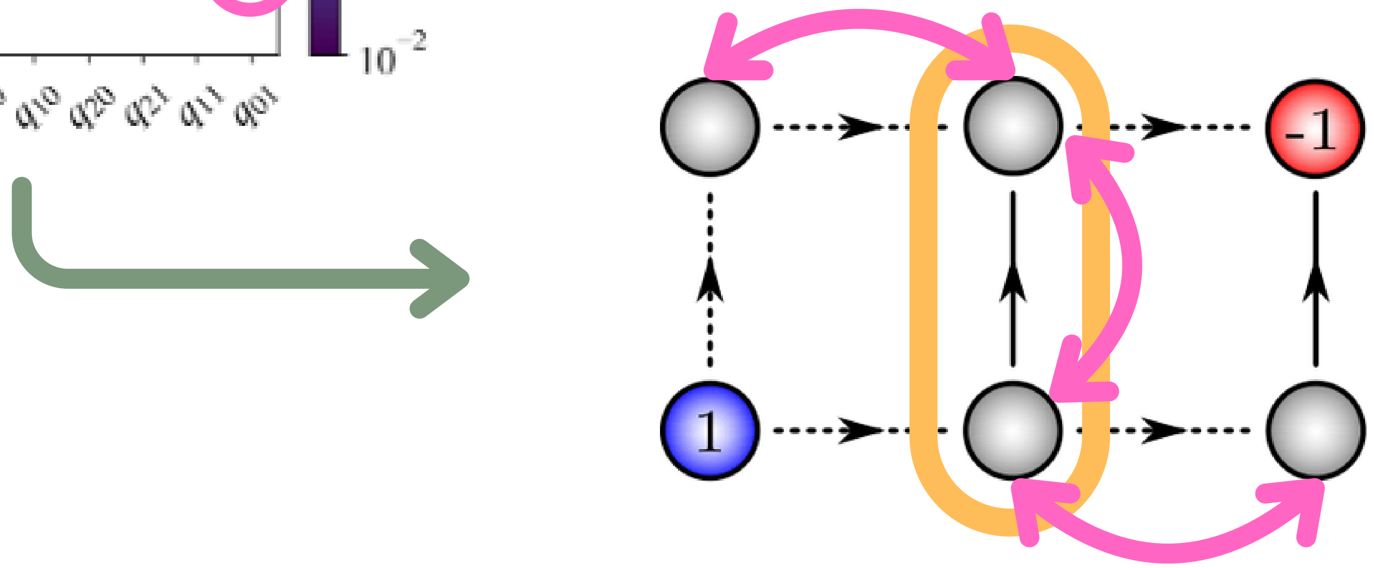
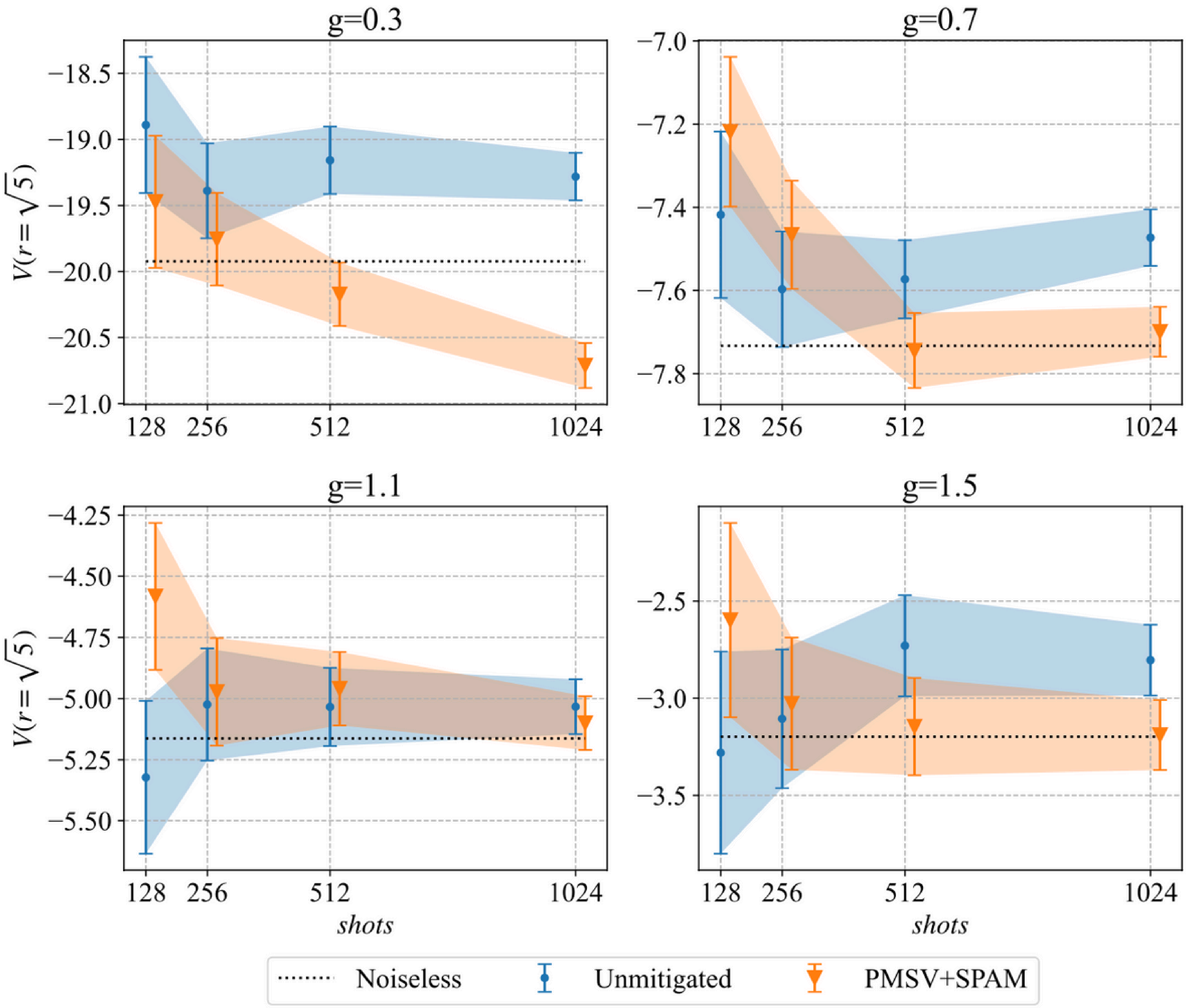


Dynamical charges+
static charges
are isolated.



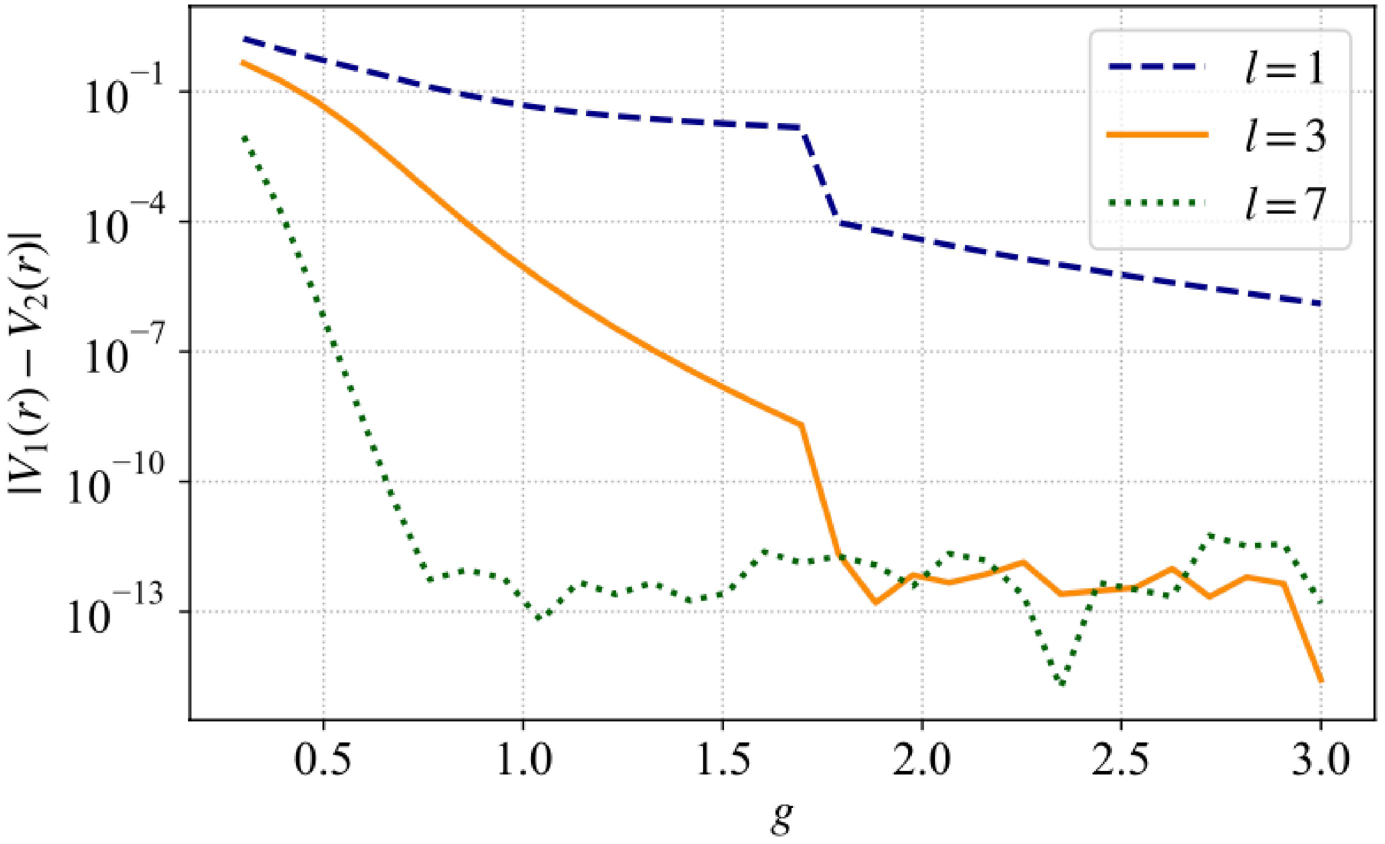
H1-1E

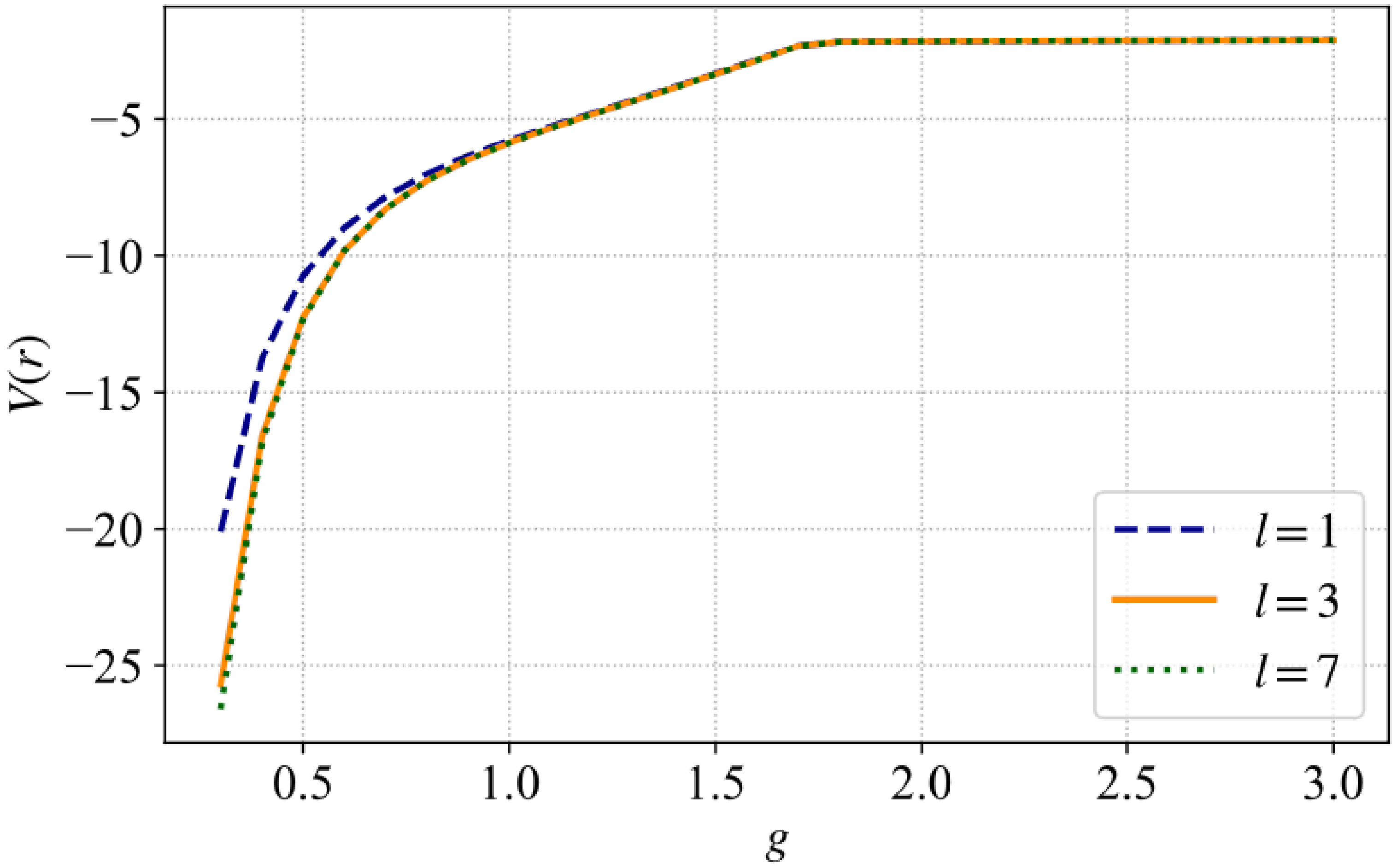
Study of the number of shots at four values of the coupling.



Truncation and Gauss's law

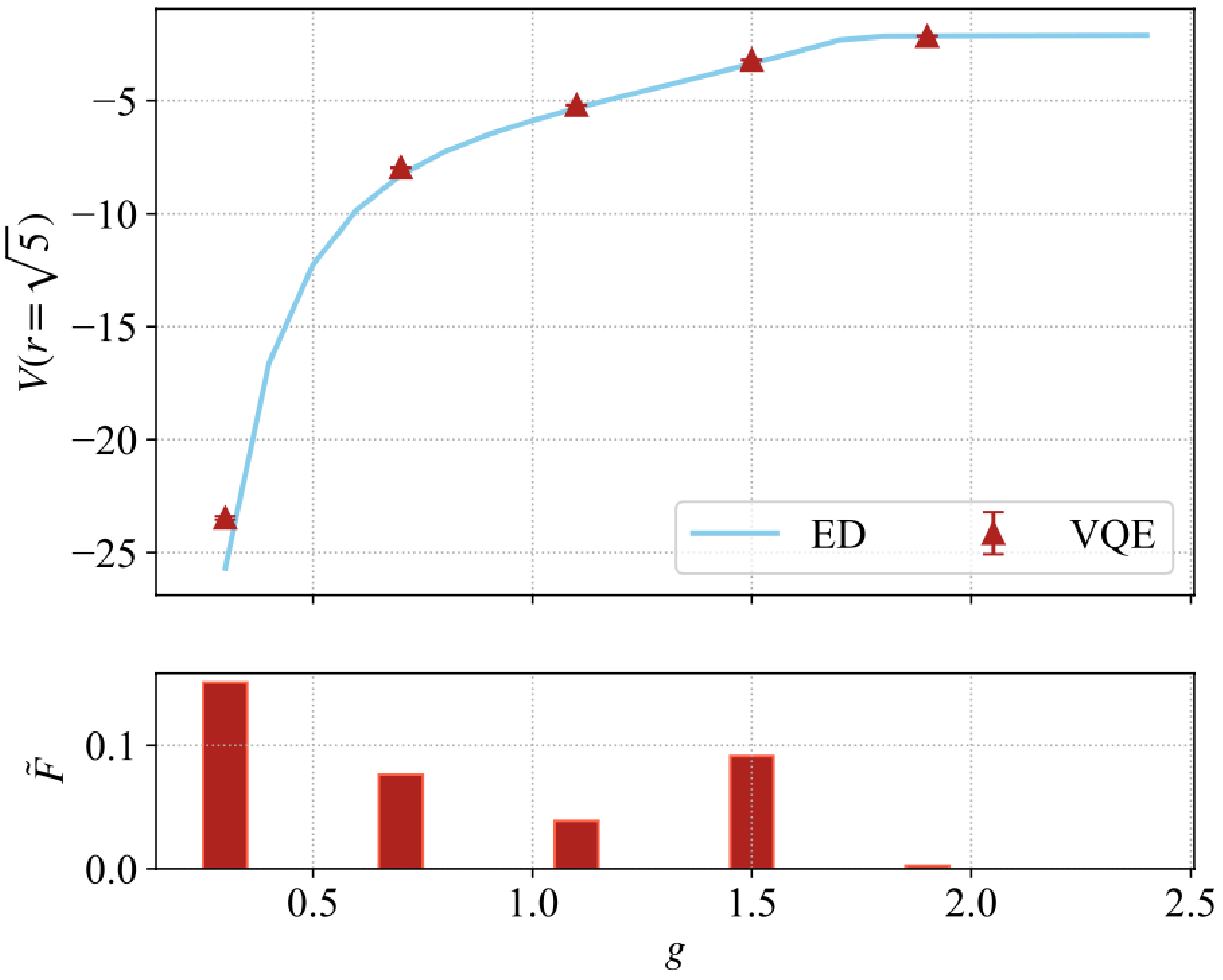
$$V_1(r) \to \{E_{10y}, E_{20y}\}$$
$$V_2(r) \to \{E_{00y}, E_{20y}\}$$





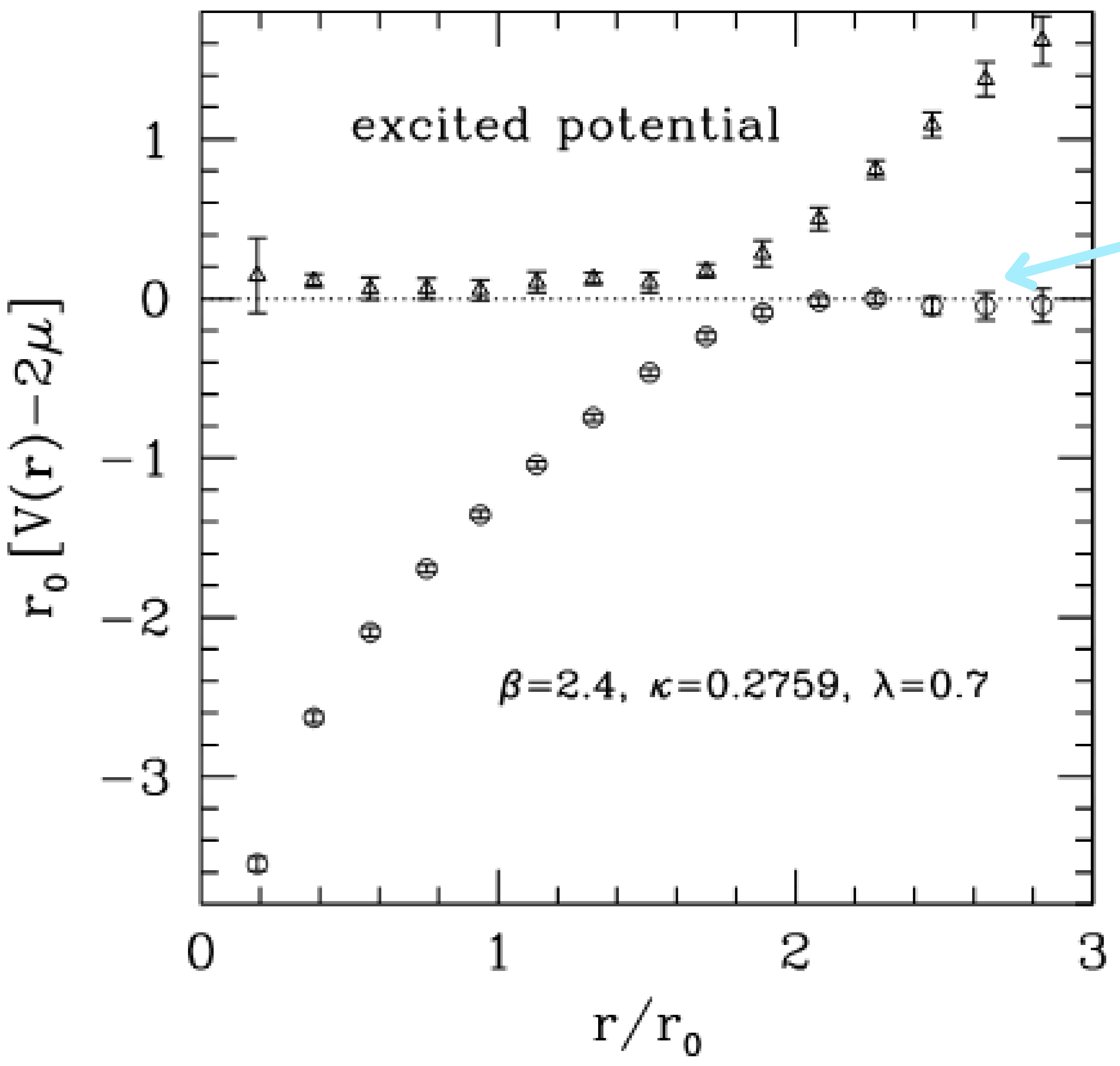
Static potential with different truncation values.

VQE Results with l=3



Noiseless variational quantum results 3x2 system.
(NFT and 10^4 shots)

V(r) with MC



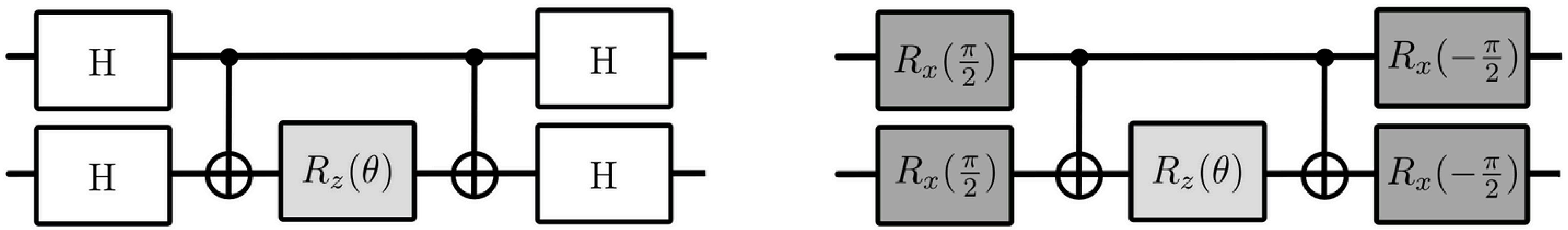
Large distances the potential approaches the asymptotic value 2μ

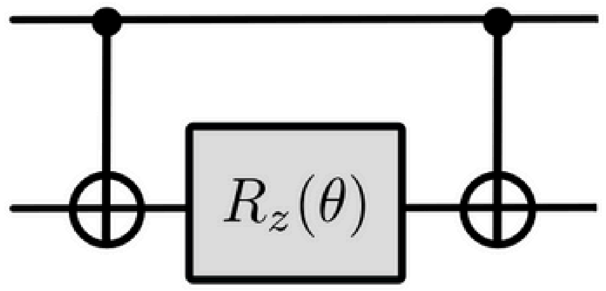
Ground state and first excited state static potentials as functions of static quark separation. Simulations of SU(2).

ALPHA Collaboration, 0005021

iSWAP gates

(a) $R_{xx}(\theta)$ (b) $R_{yy}(\theta)$





(c) $R_{zz}(\theta)$

Added for NFT optimizer

Quantum Hardware

Qubit Type	Pros	Cons	Examples
Superconducting	• High gate **speeds** and **fidelities**. • Established technology.	• Requires cryogenic **cooling**. • Short **coherence** times.	Google IBM Q IQM
Trapped Ions	• Extremely high gate **fidelities**. • Long **coherence** times • **No** extreme cryogenic **cooling** needed.	• **Slow** gate times and operations. • Difficulty in aligning and scaling **lasers**. • Ion charges may limit **scalability**.	AG Quantum Optics and Spectroscopy QUANTINUUM

Error mitigations

Partition Measurement Symmetry Verification (PMSV)

Measurements of specific Pauli strings that encode the system’s known **symmetries** (e.g. fermionic *zero-charge* sector).

Measurement outcomes not satisfying the symmetry are **discarded.**

State Preparation And Measurement error mitigation (SPAM)

Uses a **calibration matrix** that characterizes the **noise** profile of the quantum device.

The **inverse** of this matrix is applied to correct the measured expectation values.

Error mitigations

R-state selection

$$\langle\psi|\hat{H}|\psi\rangle = \sum_{m,n=0}^{2^N-1} \langle\psi|m\rangle\langle m|\hat{H}|n\rangle\langle n|\psi\rangle$$

$$= \sum_{m,n}{}' |\langle m|\psi\rangle|^2 |\langle n|\psi\rangle|^2 \frac{\langle m|\hat{H}|n\rangle}{\langle m|\psi\rangle\langle\psi|n\rangle}$$

with

$$|\psi\rangle = \sum_{n=0}^{2^N-1} \langle n|\psi\rangle|n\rangle$$

Kohda, M. et al. Phys. Rev. Res. 4, 033173

1. Sample state in computational basis.

2. Select R computational basis states (highest probability $|\langle n|\psi\rangle|^2$). Avoid noise from other states.

3. Calculate transition matrix elements classically,

$$\langle m|\hat{H}|n\rangle = \sum_{i=1}^{M} c_i \langle m|P_i|n\rangle,$$

(diag.=energy of R-th state).

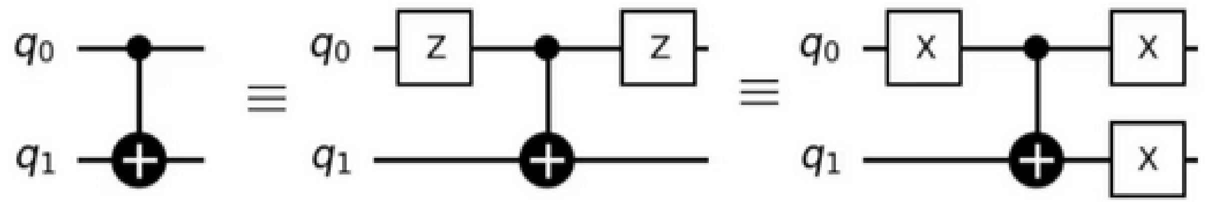
4. Calculate other terms.

5. Estimate final expectation value.

Error mitigations

PAULI TWIRLING

Transforms complex quantum noise into Pauli noise.



Random applications of **Pauli** gates before and after a gate.

Now stochastic errors, improved by **averaging** more.

READOUT ERROR MITIGATION

$$C := \begin{pmatrix} 1 - \Pr(0|1) & \Pr(0|1) \\ \Pr(1|0) & 1 - \Pr(1|0) \end{pmatrix}$$

$\Pr(\text{detected } j | \text{prepared } i)$

$$CP = P_{\text{noisy}}$$