QCHSC2024, Cairns

A quantum computing study of the static potential in (2+1)D QED

In collaboration with Arianna Crippa and Karl Jansen (DESY)

Enrico Rinaldi – 2024/08/21 – Lead Research Scientist at QUANTINUUM

A quantum computing study …

Quantum computing

For Lattice Gauge Theory

- A new paradigm for scientific computing (overview by Karl Jansen)
- Quantum algorithms work by manipulating quantum states in Hilbert space and measuring them
- Represent the full wavefunction of a quantum many-body system
- Can do unitary time evolution of such wavefunction
- Digital quantum computing implements unitary operators as sequence of gates

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$$U = e^{-iHt} \equiv \prod_i U_i$$

… of the static potential …

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The potential energy

Between two static charges

- In Path Integral Monte Carlo we extract this by computing Wilson Loops of various dimensions
- In quantum computing we have direct access to the Hamiltonian and the states of the system!
- By changing the distance between static charges we can study the force between them
- The potential $V(r)$ is the energy of the ground state with 2 opposite static charges

The potential energy

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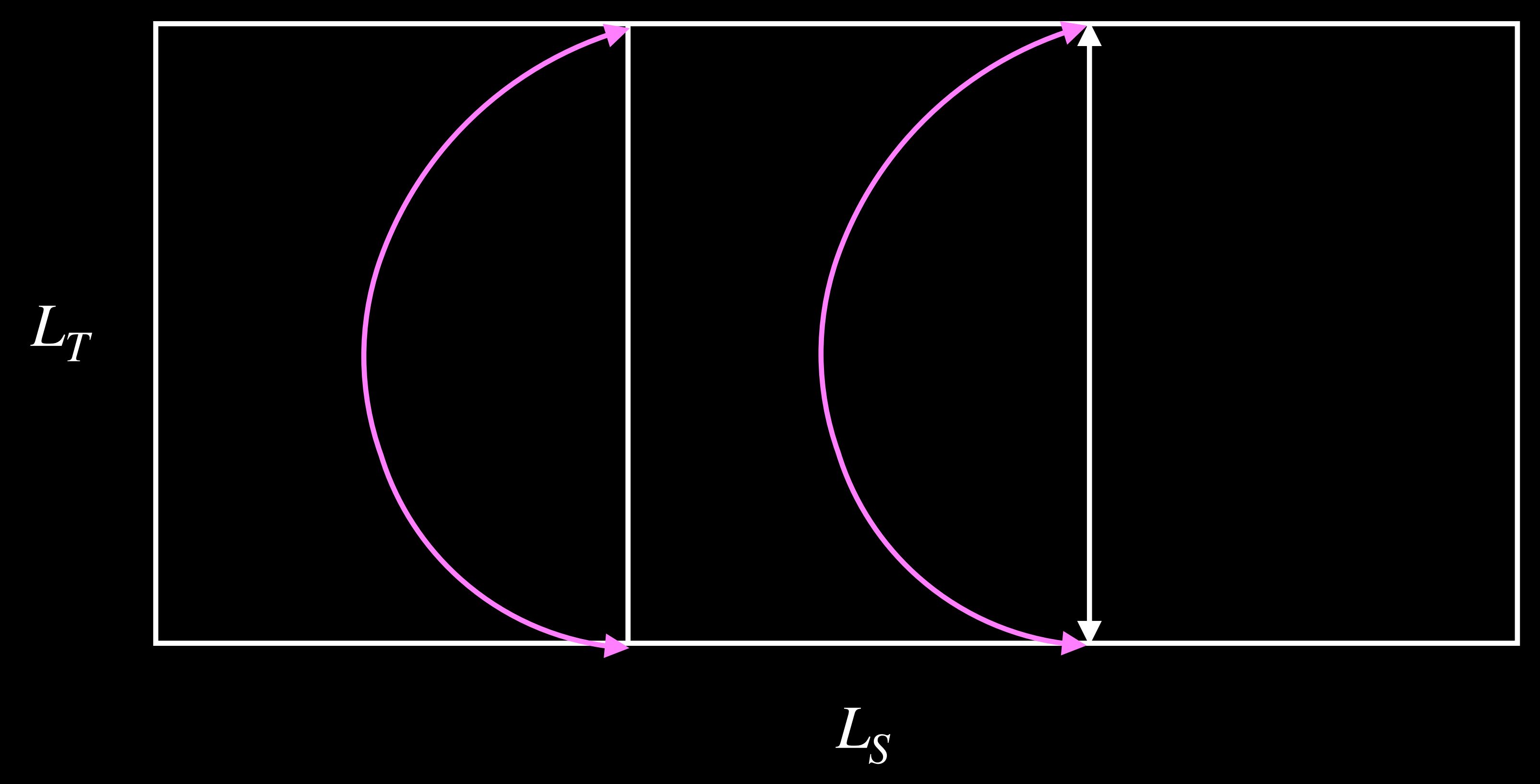

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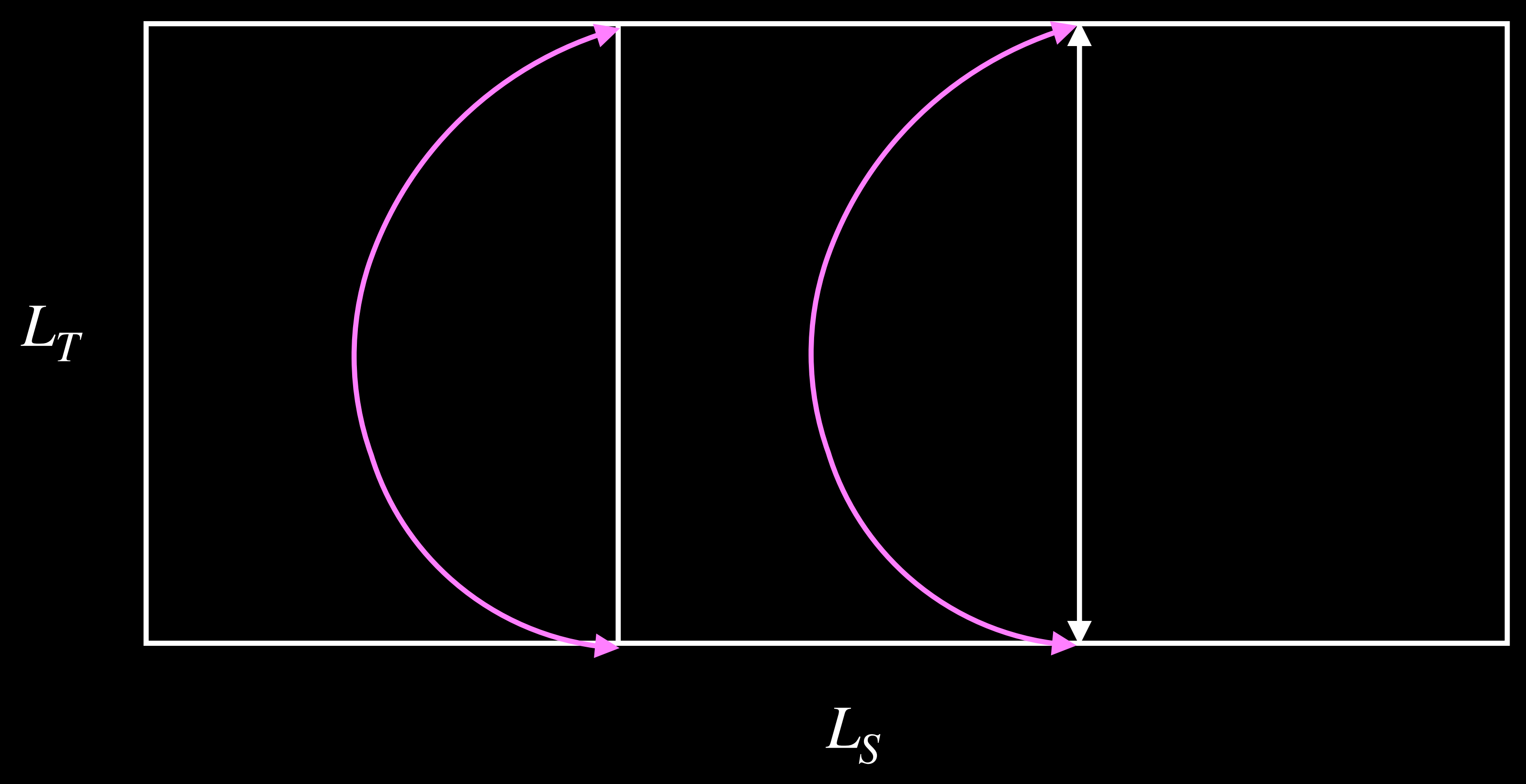

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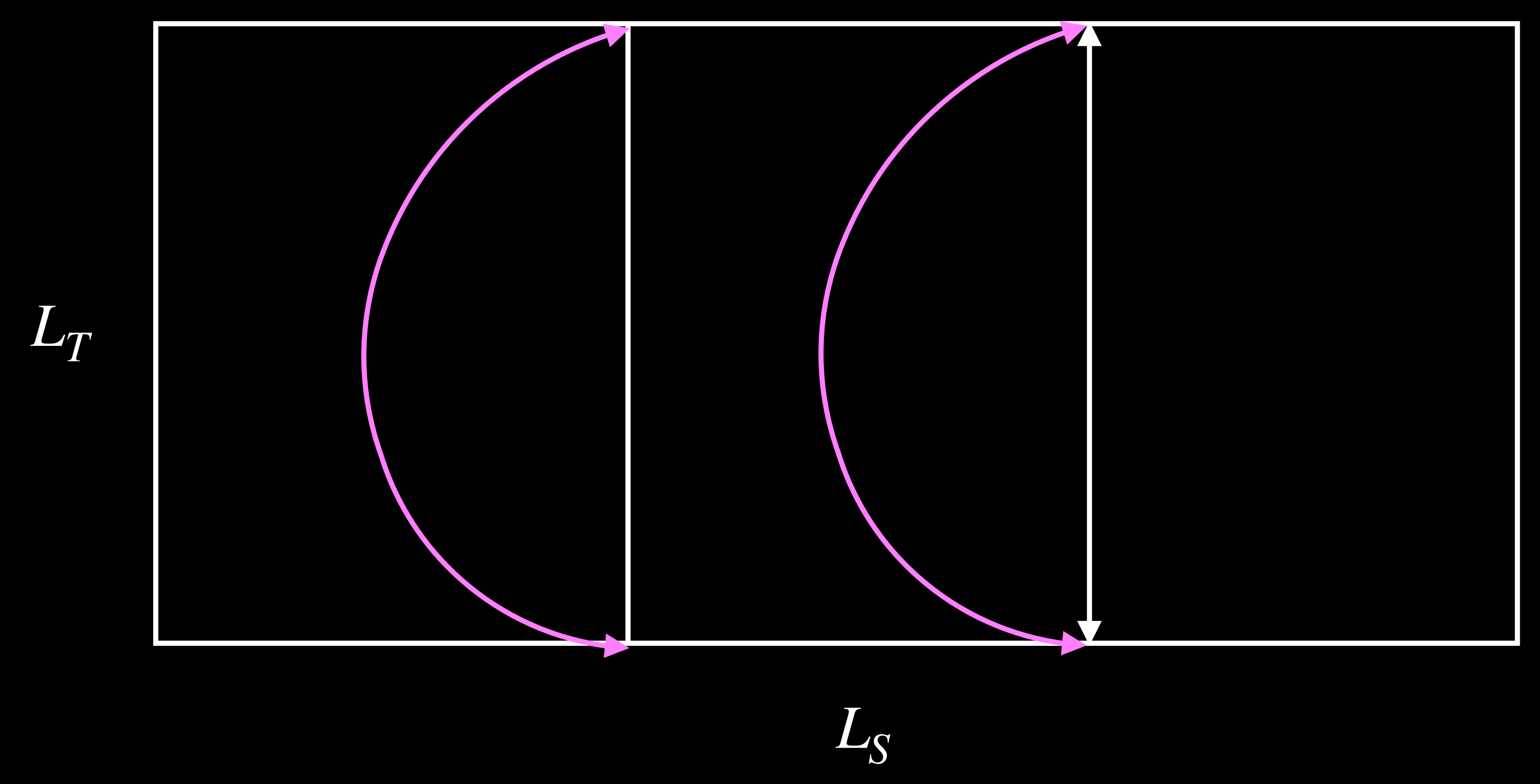


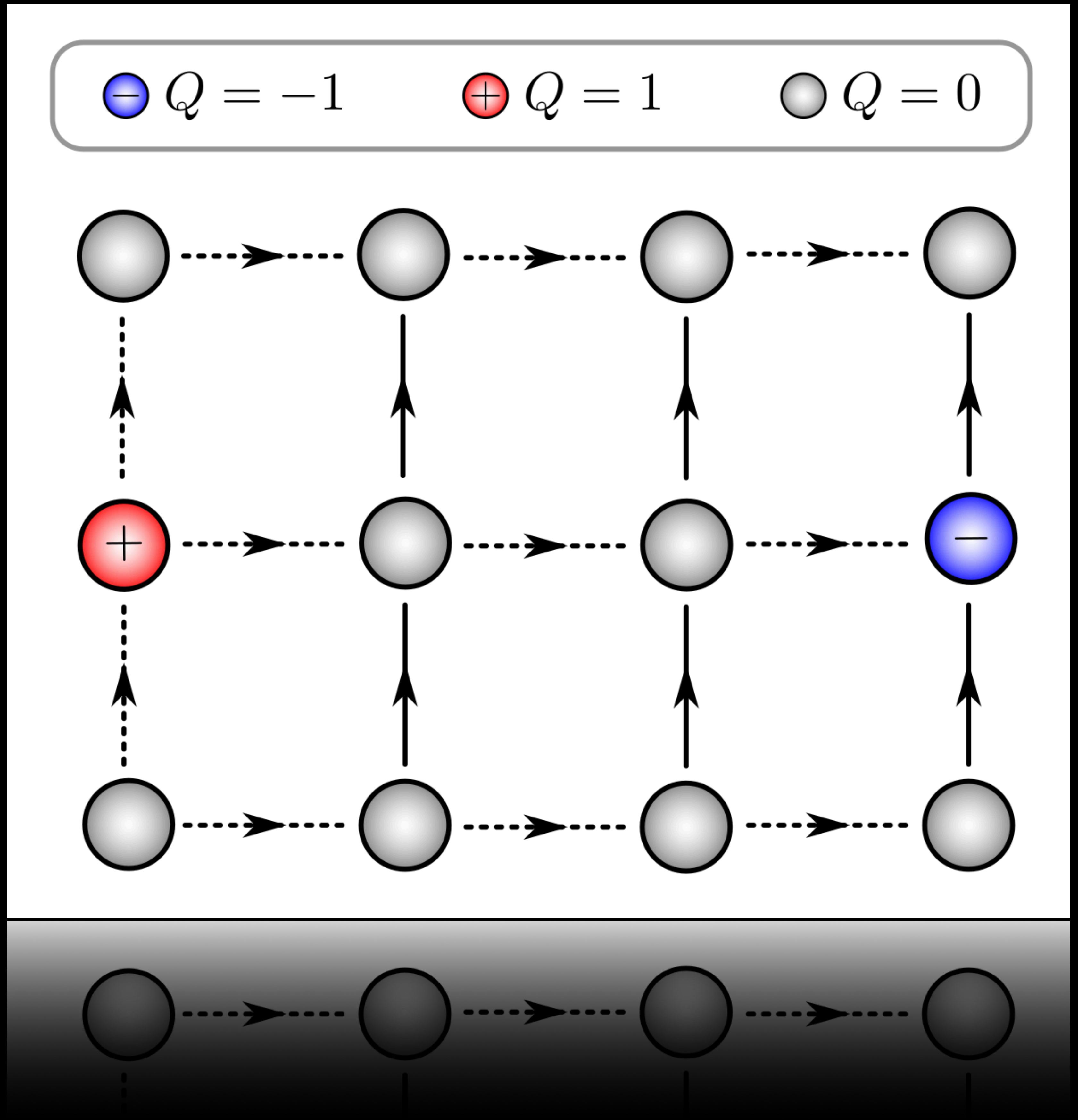
$$V(r) = \langle \Psi_0(r) | \hat{H} | \Psi_0(r) \rangle$$

… in (2+1)D QED

Hamiltonian Lattice QED

In 2 spatial dimensions

- We use the Kogut-Susskind Hamiltonian formalism of lattice gauge theory. Time is continuous.
- The Hilbert space is defined as the tensor product of the local Hilbert spaces of each degree of freedom on the lattice
- A state is a superposition of amplitudes for each possible configuration of degrees of freedom on the lattice
  - Site: fermion – Electron
  - Link: gauge – Electric field



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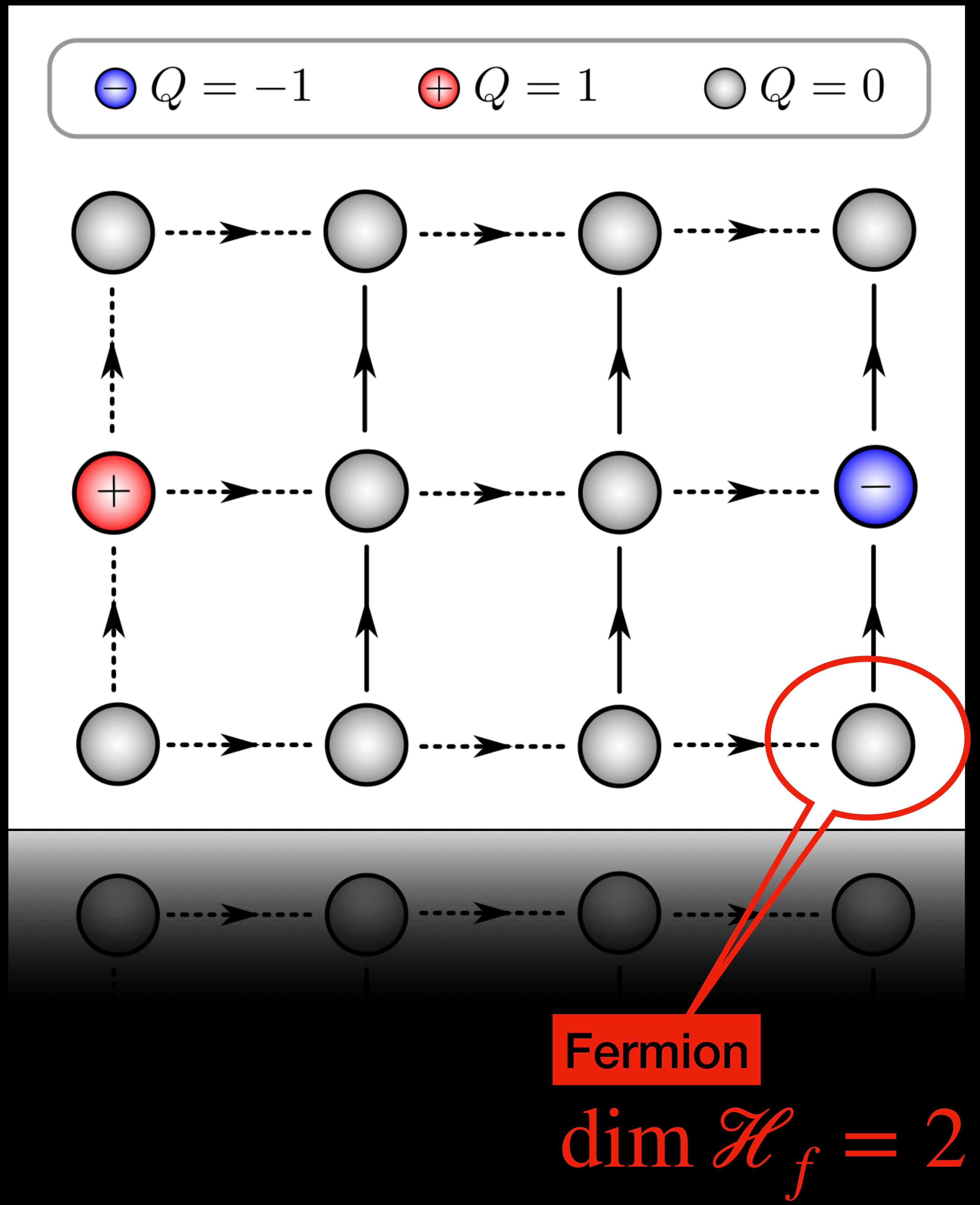

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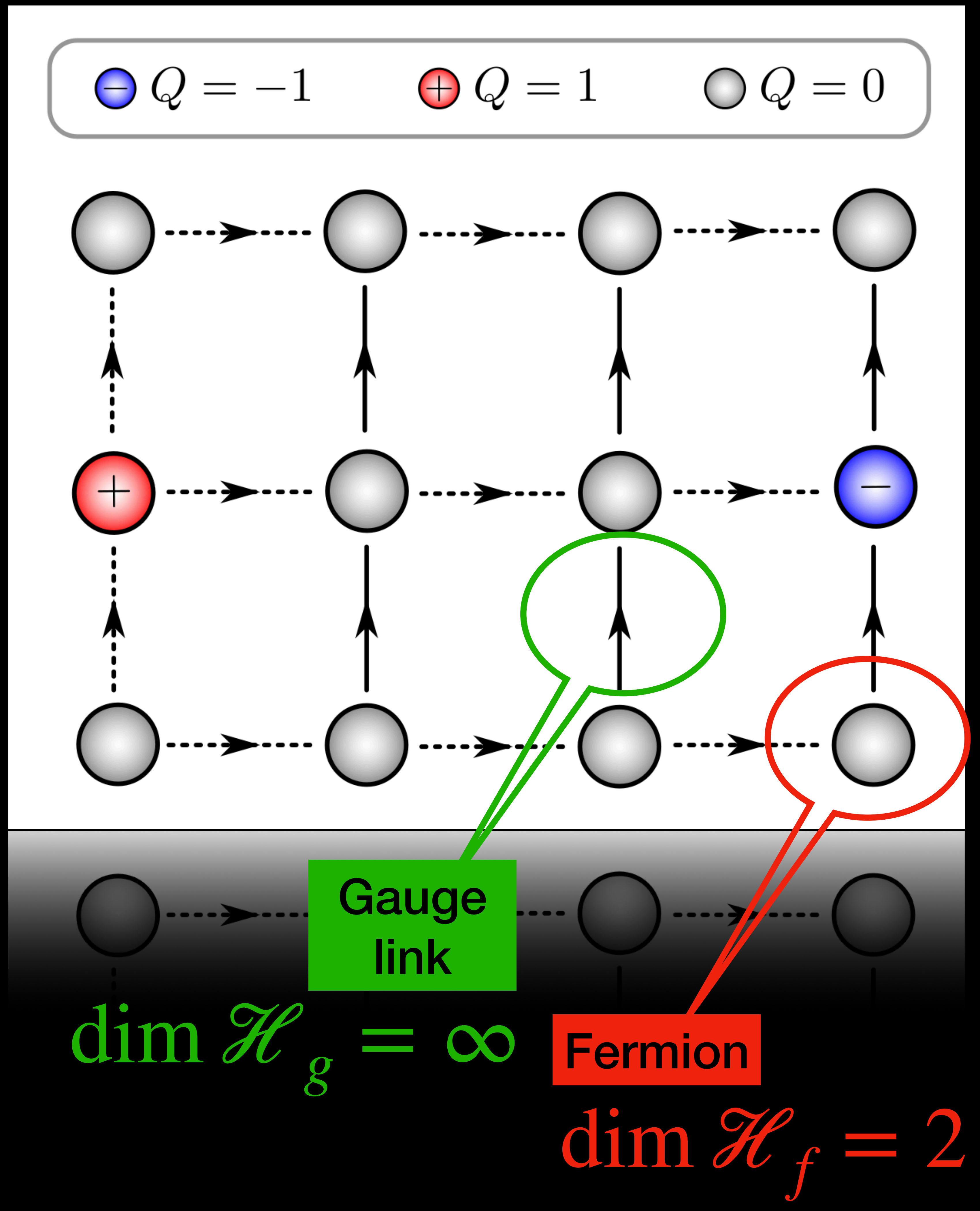

QED on qubits

Electric and Magnetic terms

$$\hat{H}_E = \frac{g^2}{2} \sum_{\vec{n}} \left(\hat{E}^2_{\vec{n},x} + \hat{E}^2_{\vec{n},y} \right)$$

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

$$\hat{H}_B = -\frac{1}{2g^2} \sum_{\vec{n}} \left(\hat{U}_{\vec{n},x} \hat{U}_{\vec{n}+x,y} \hat{U}^\dagger_{\vec{n}+y,x} \hat{U}^\dagger_{\vec{n},y} + \ldots \right)$$

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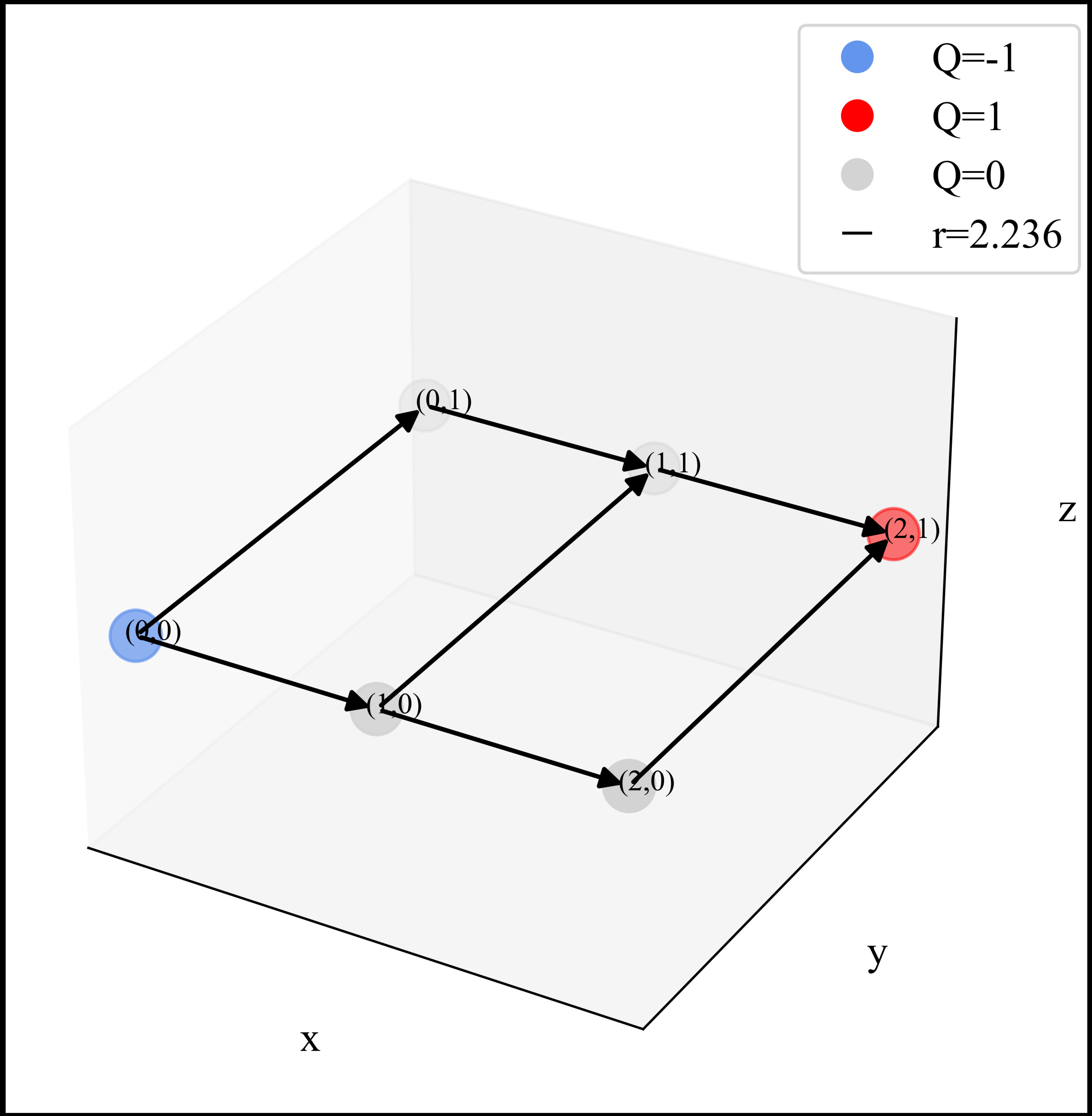

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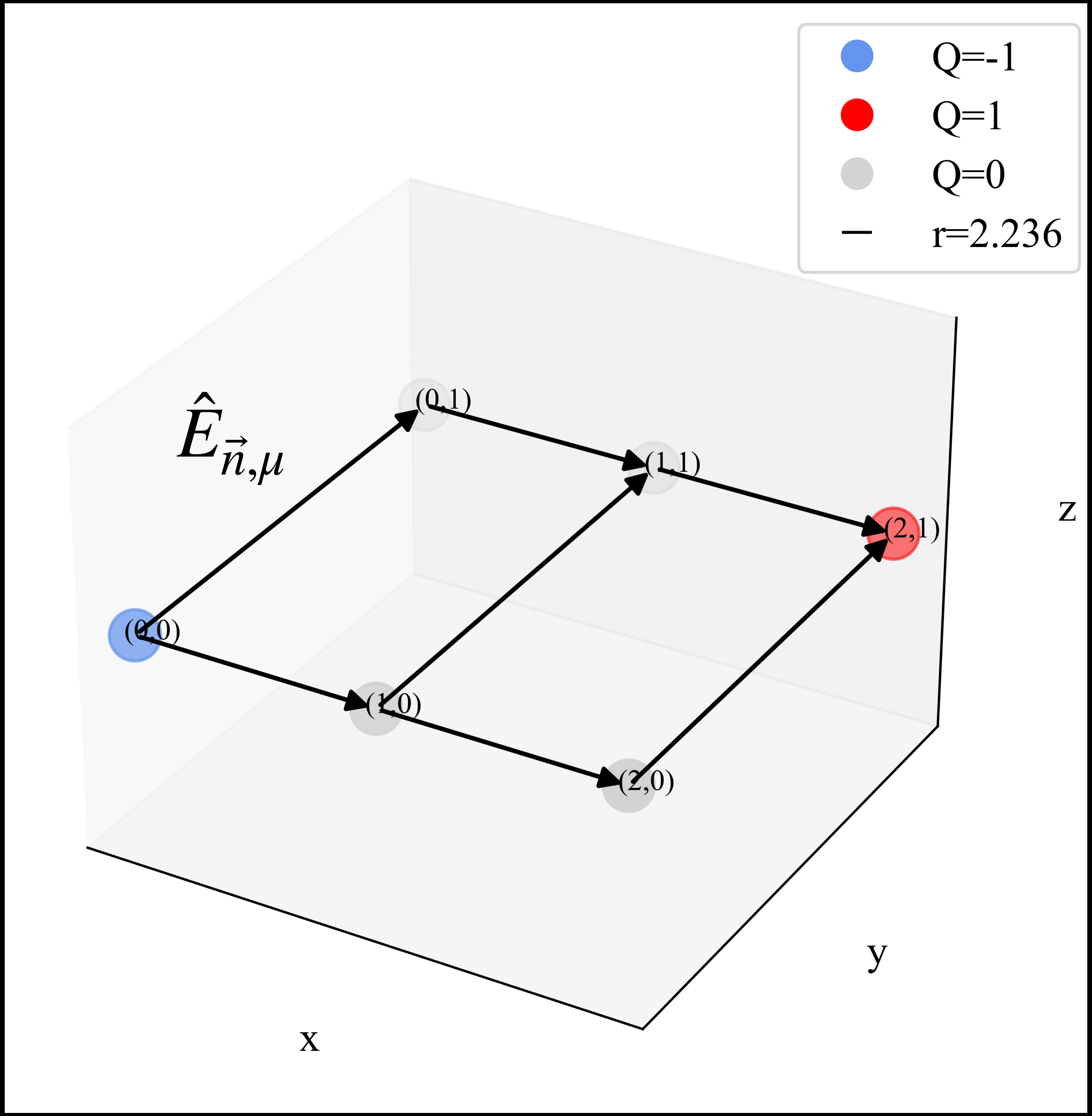

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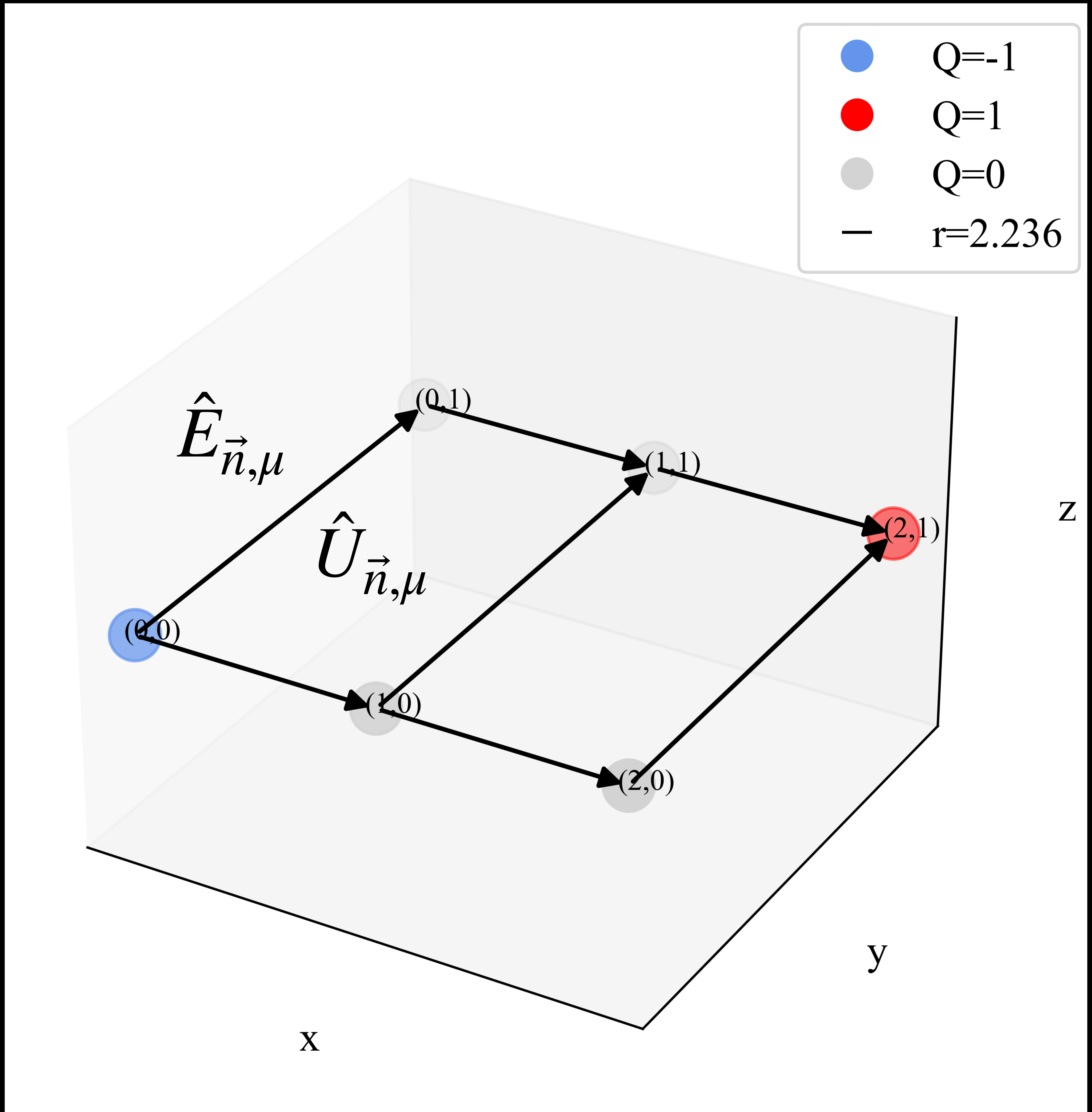

QED on qubits

Discretize: $U(1) \rightarrow \mathbb{Z}_{2l+1}$

$l = 1$

$i = +1$
$i = 0$
$i = -1$

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Encoding to qubits:
We need 2 qubits to represent 4 states. 1 state is "unphysical"

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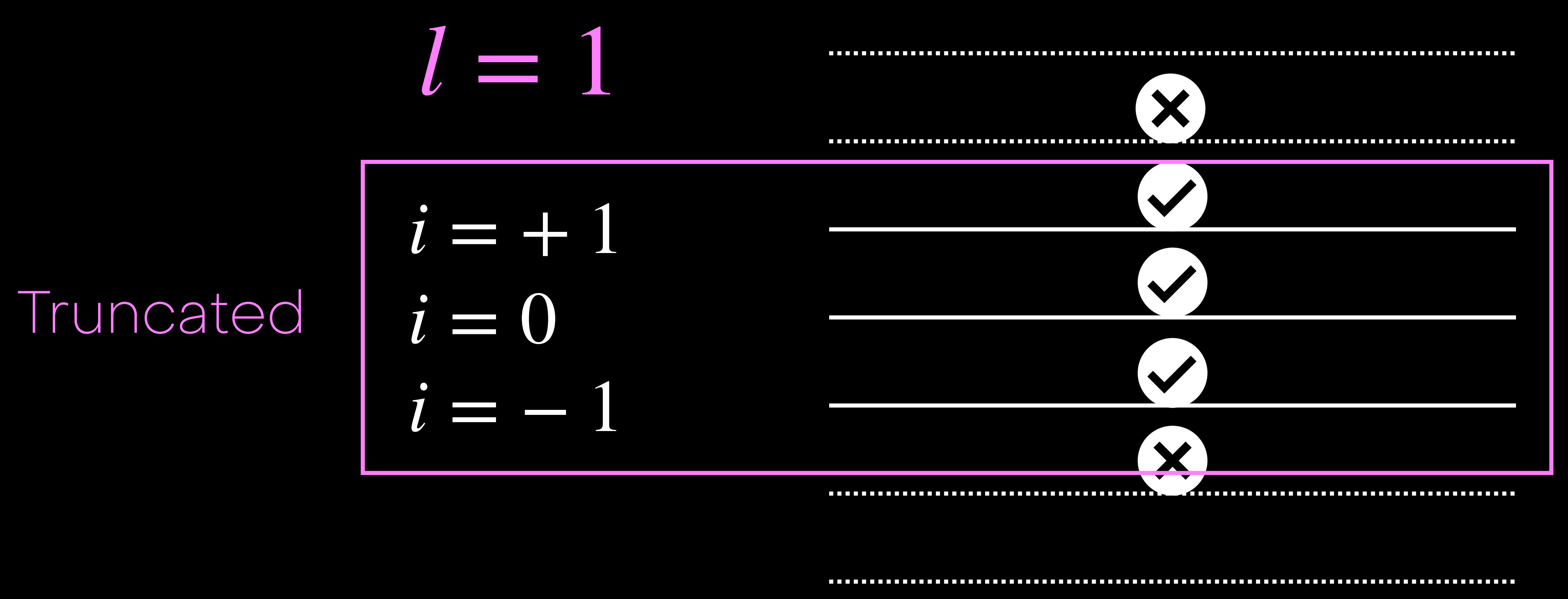

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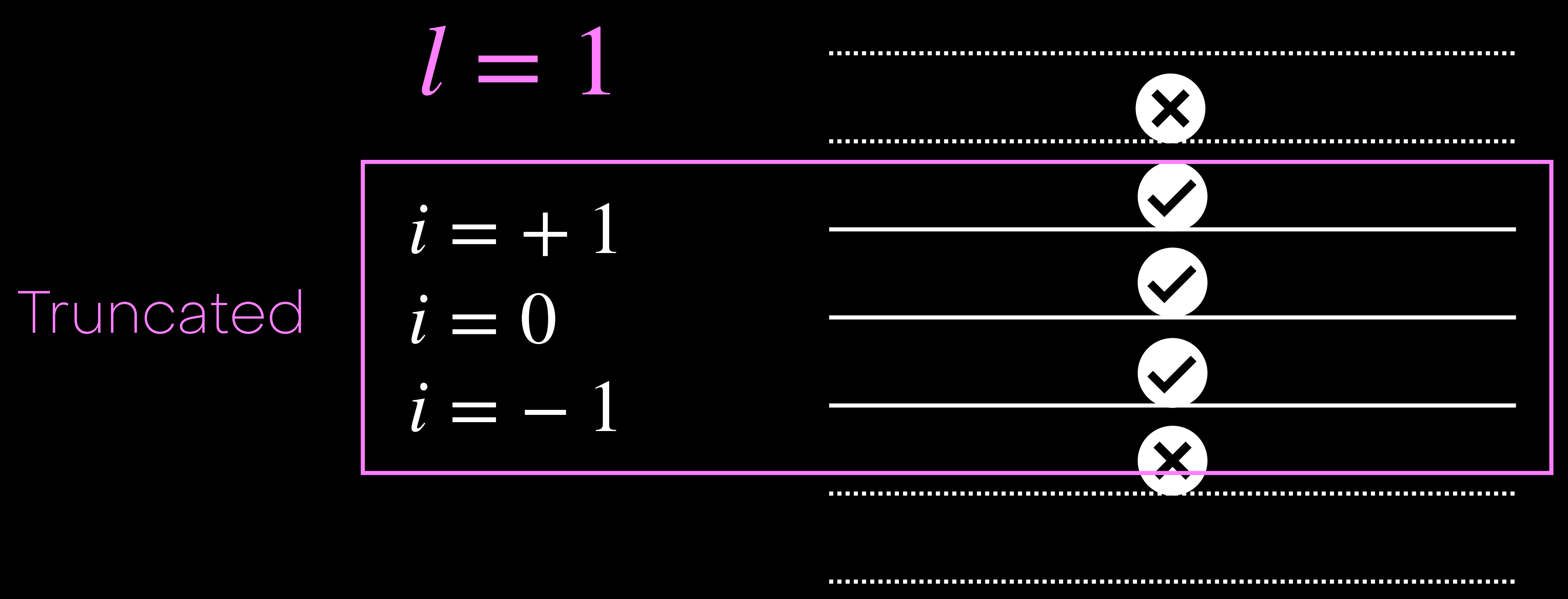

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Gray Encoding

$\|i\rangle_{\text{phys}}$	$\|i\rangle$
$\|-1\rangle_{\text{phys}}$	$\|00\rangle$
$\|0\rangle_{\text{phys}}$	$\|01\rangle$
$\|+1\rangle_{\text{phys}}$	$\|11\rangle$
Unphysical	$\|10\rangle$

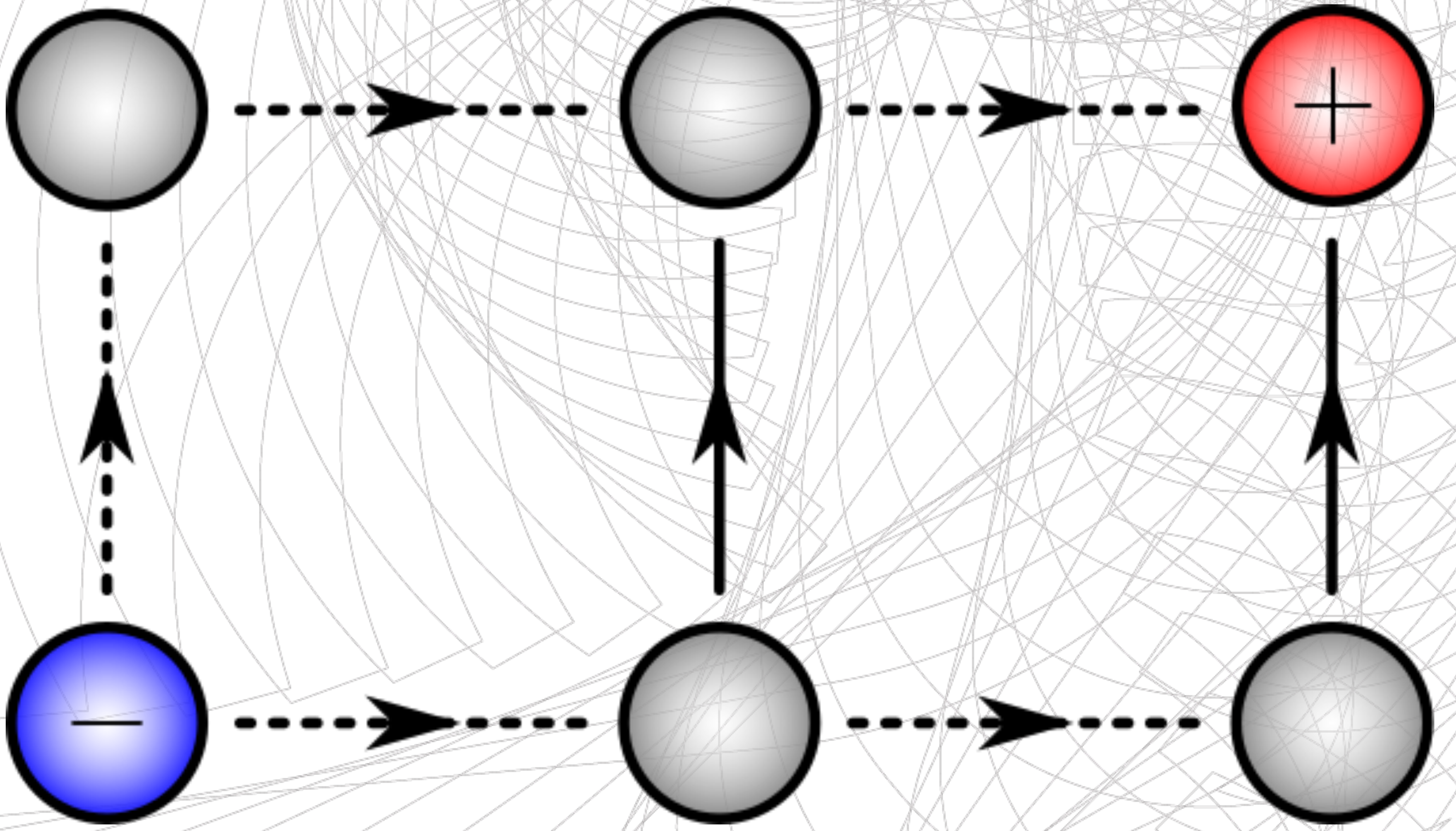
$l = 1$

Encoding to qubits:
We need 2 qubits to represent 4 states. 1 state is "unphysical"

Example on a 3×2 lattice

Gauss' law $\left[\sum_{\mu=x,y} \left(\hat{E}_{\vec{r},\mu} - \hat{E}_{\vec{r}-\mu,\mu} \right) - \hat{q}_{\vec{r}} - Q_{\vec{r}} \right] |\Phi\rangle = 0$

- Using Gauss' law we reduce the number of dynamical degrees of freedom: 6 sites, 2 links
- We use **1 qubit for each site**
- We use **2 qubits for each link**
- Any state of this lattice QED theory is defined on 10 qubits
- This classically requires manipulating a vector with $2^{10} = 1024$ complex components



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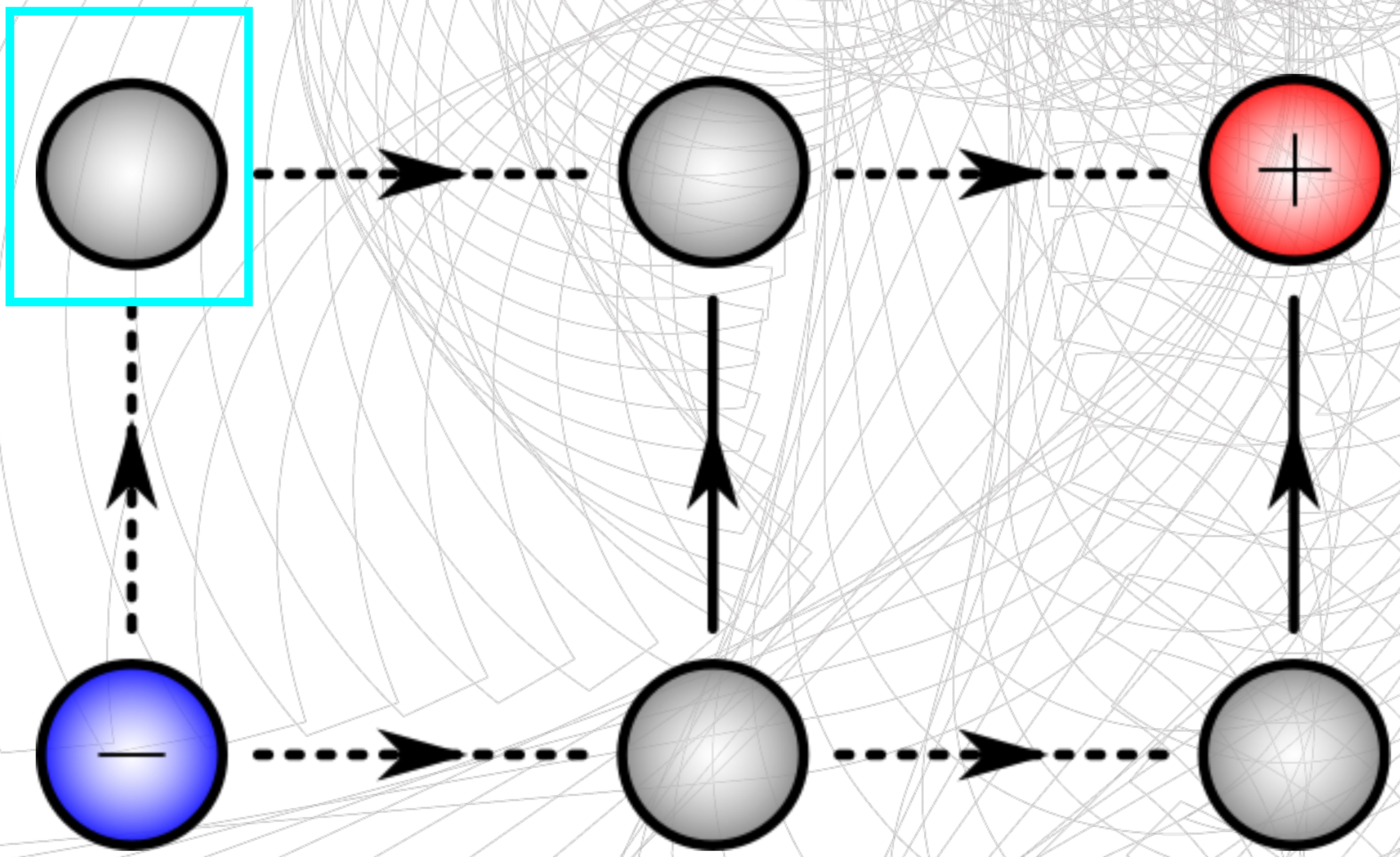

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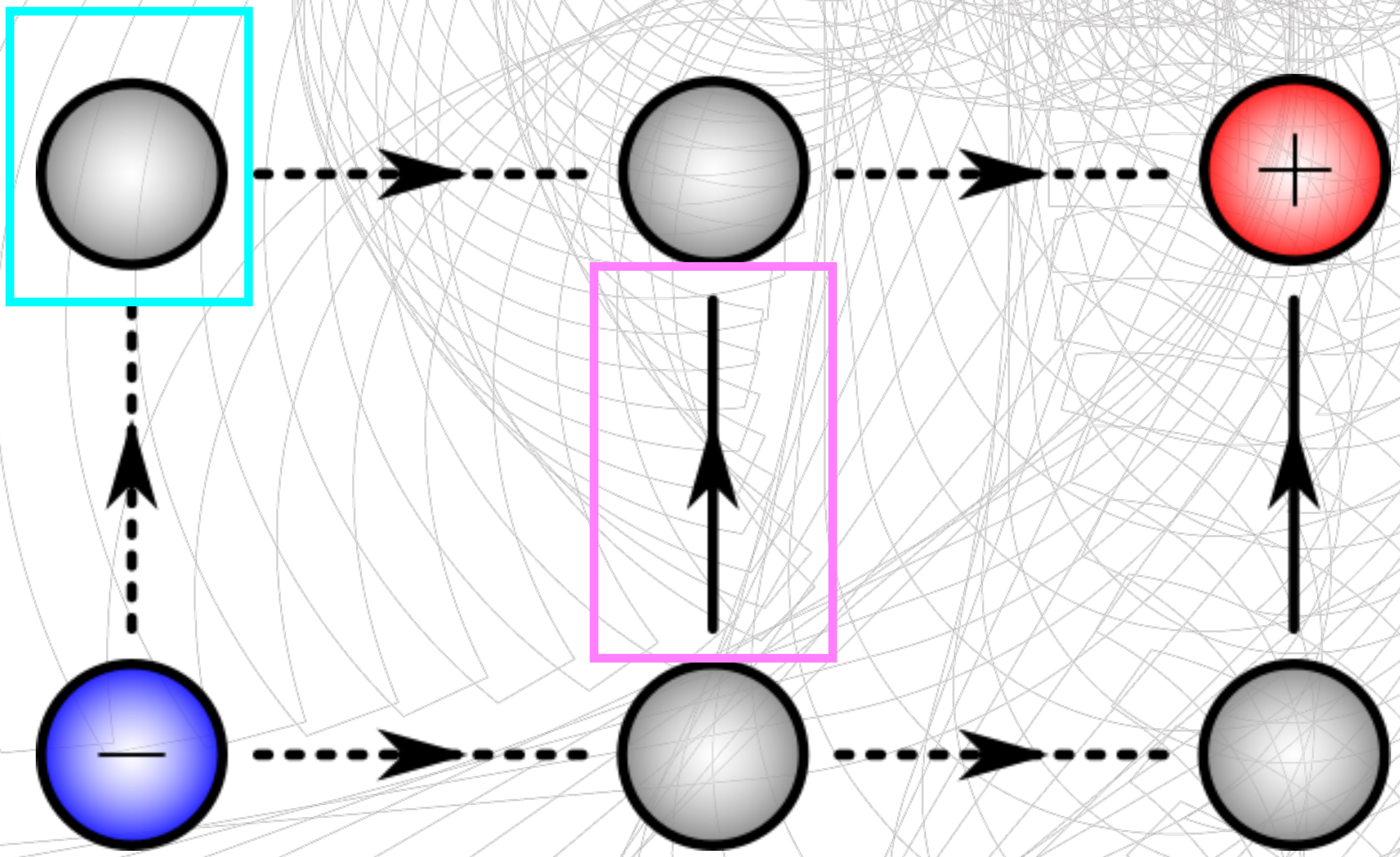

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Static Potential

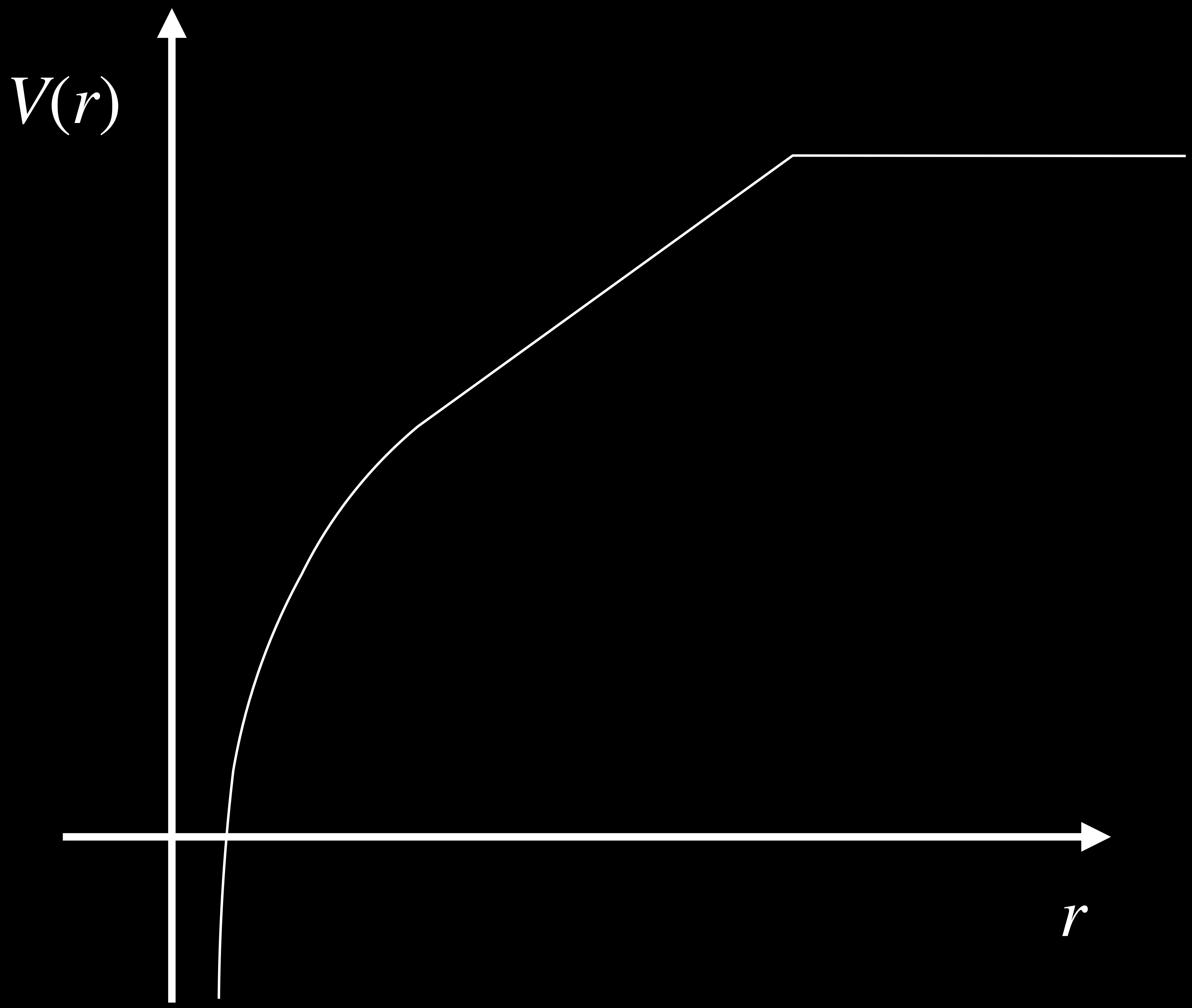
In (2+1)D QED

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

- On the lattice we can change r by changing the lattice spacing a

- The lattice spacing a depends non-perturbatively on the coupling constant g

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



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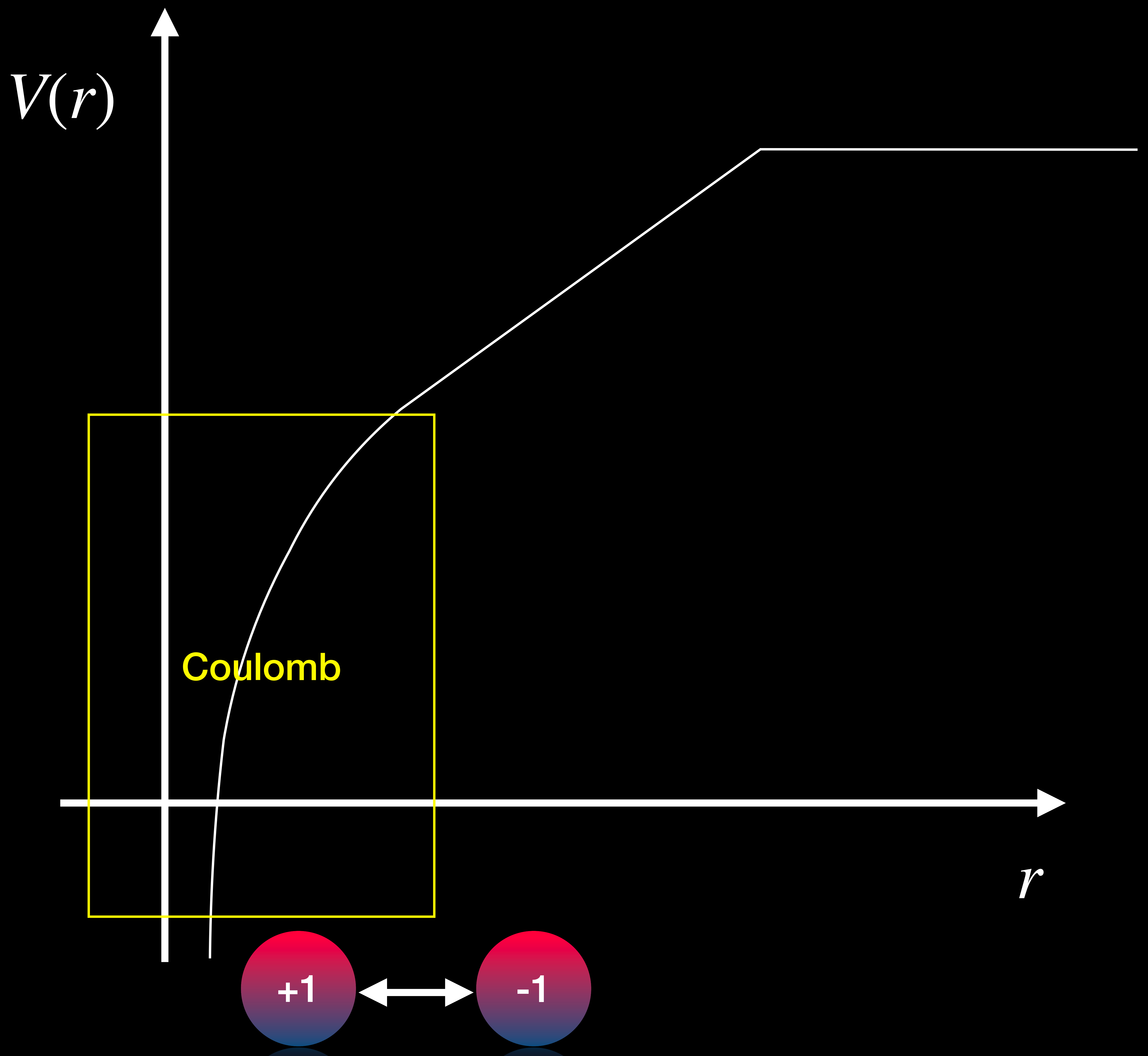

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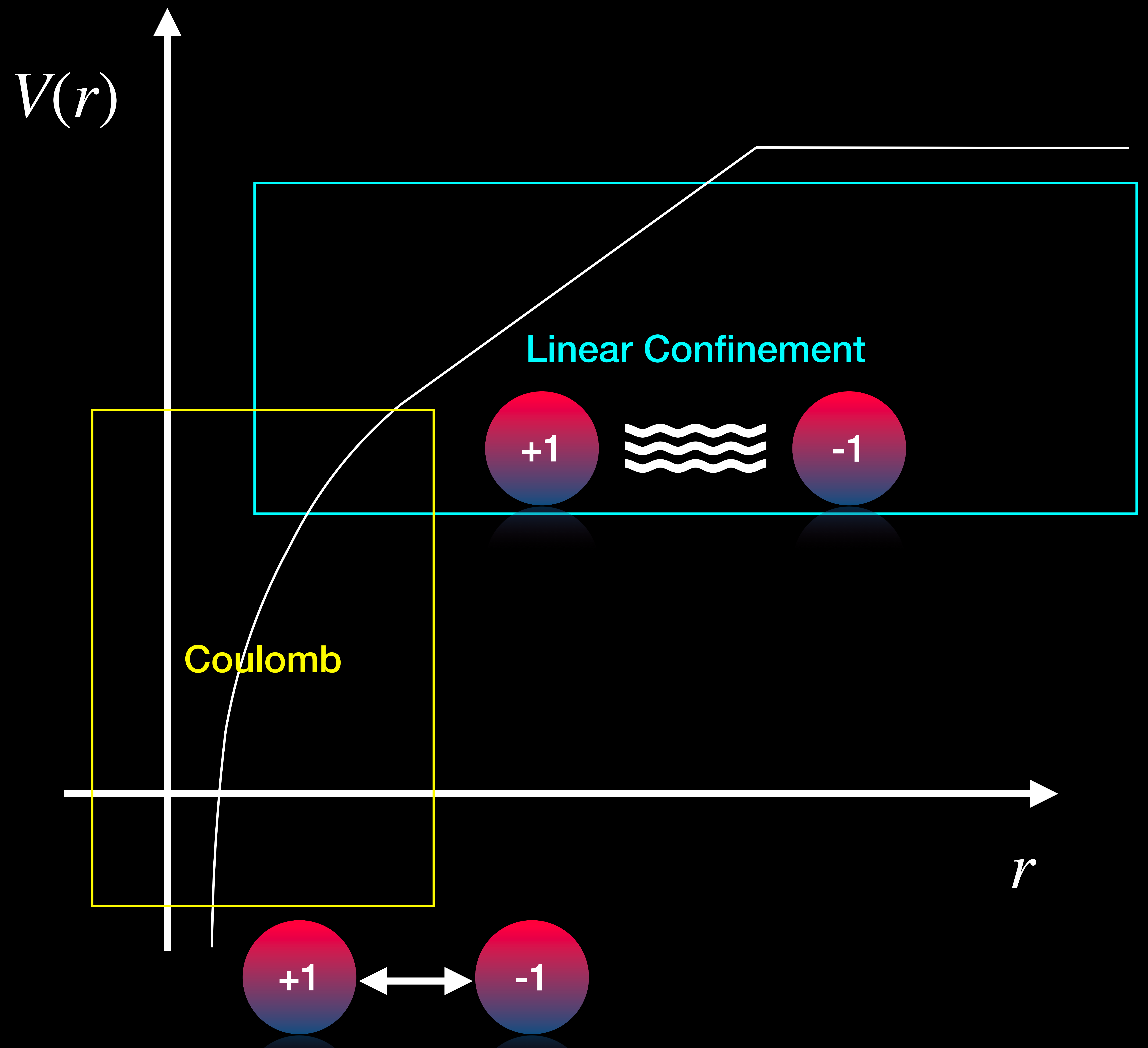

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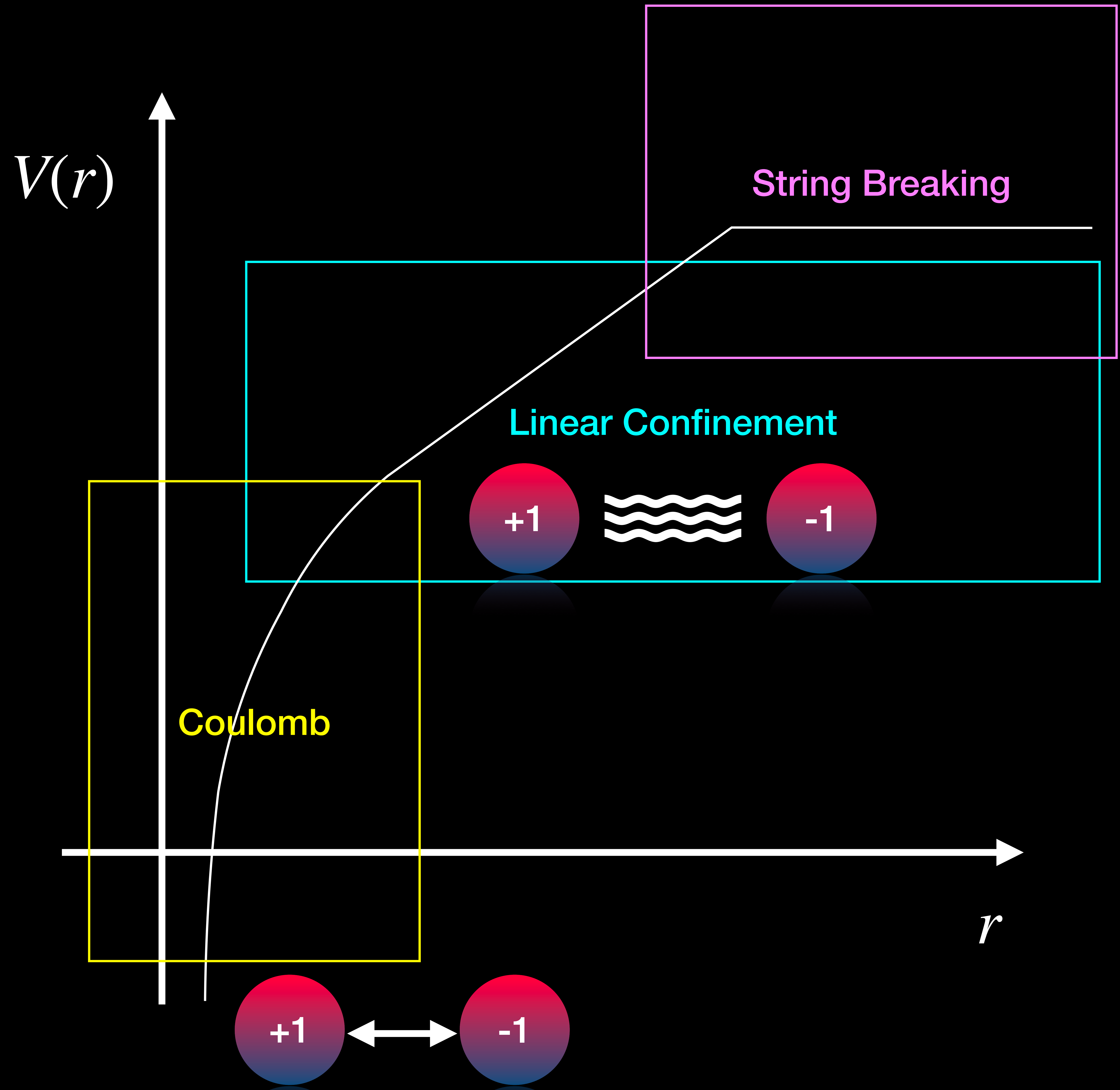

State Preparation

With variational methods

- The ground state is prepared using the variational quantum eigensolver (VQE)

- A trial state is obtained using a parametrized quantum circuit $C(\theta)$ acting on some initial state

  - $$|\Psi(\theta)\rangle = C(\theta)|\Psi_0\rangle$$

- The expectation value of the Hamiltonian is measured

- An optimizer updates the parameters towards the minimum of the energy landscape

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Initial State $|0\ldots0\rangle$

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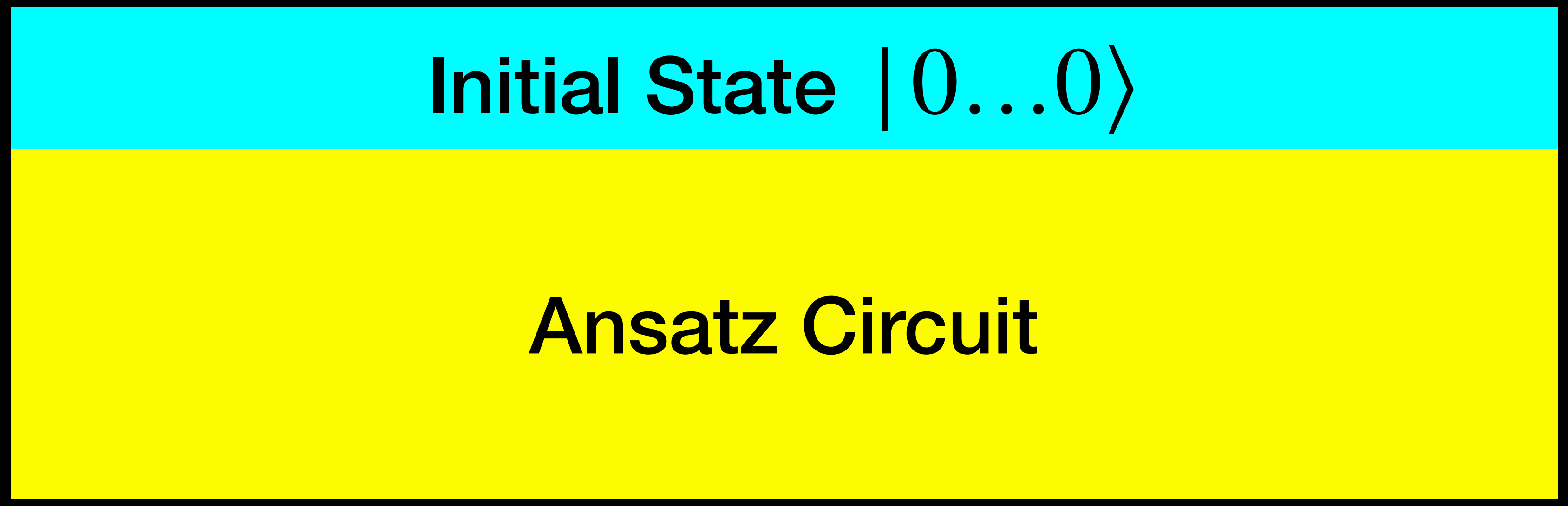

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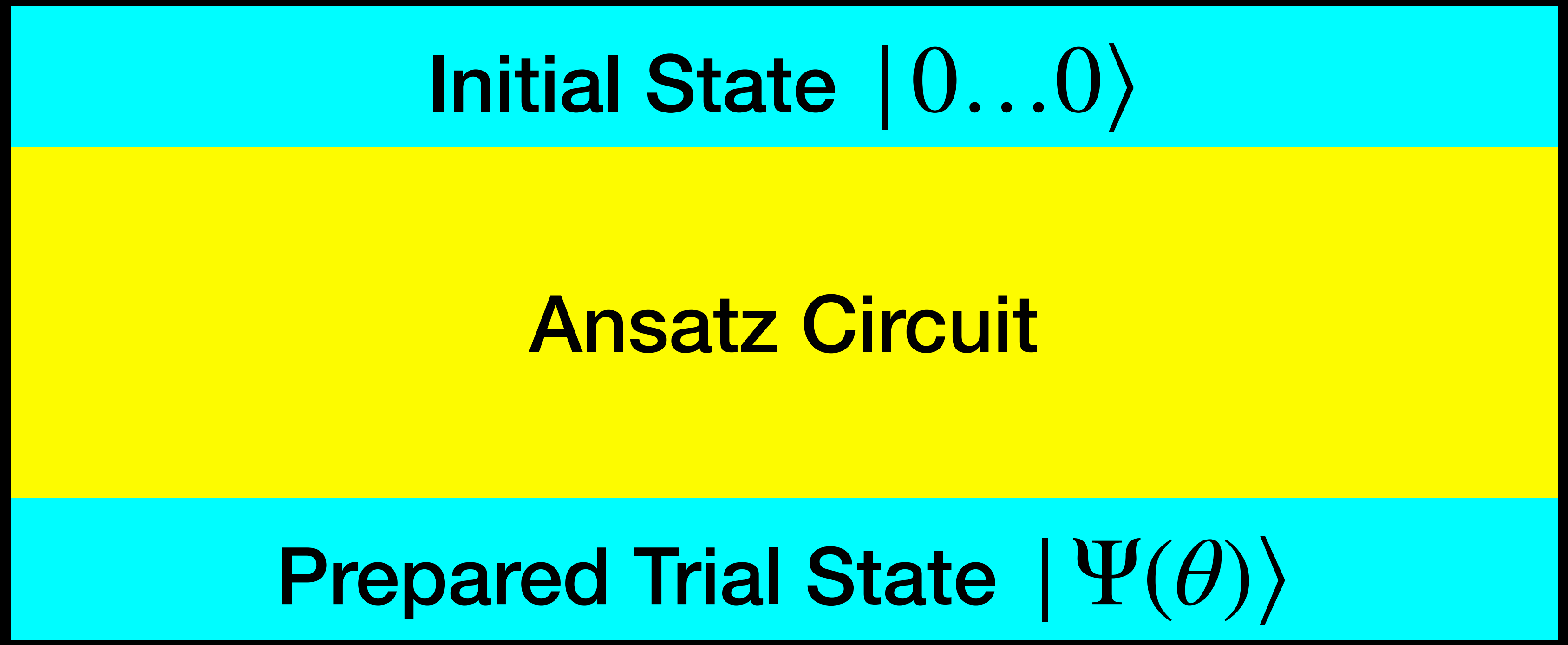

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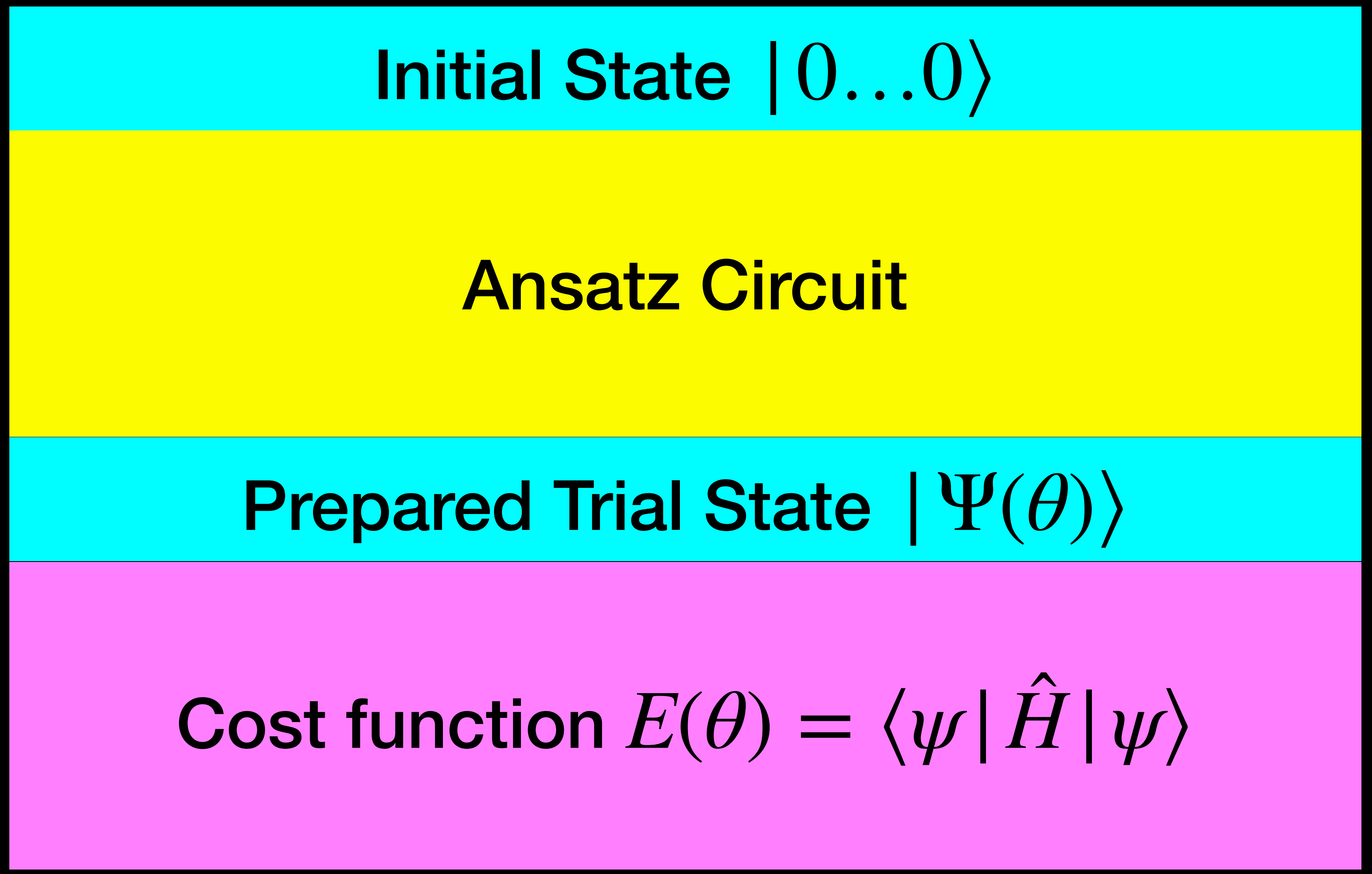

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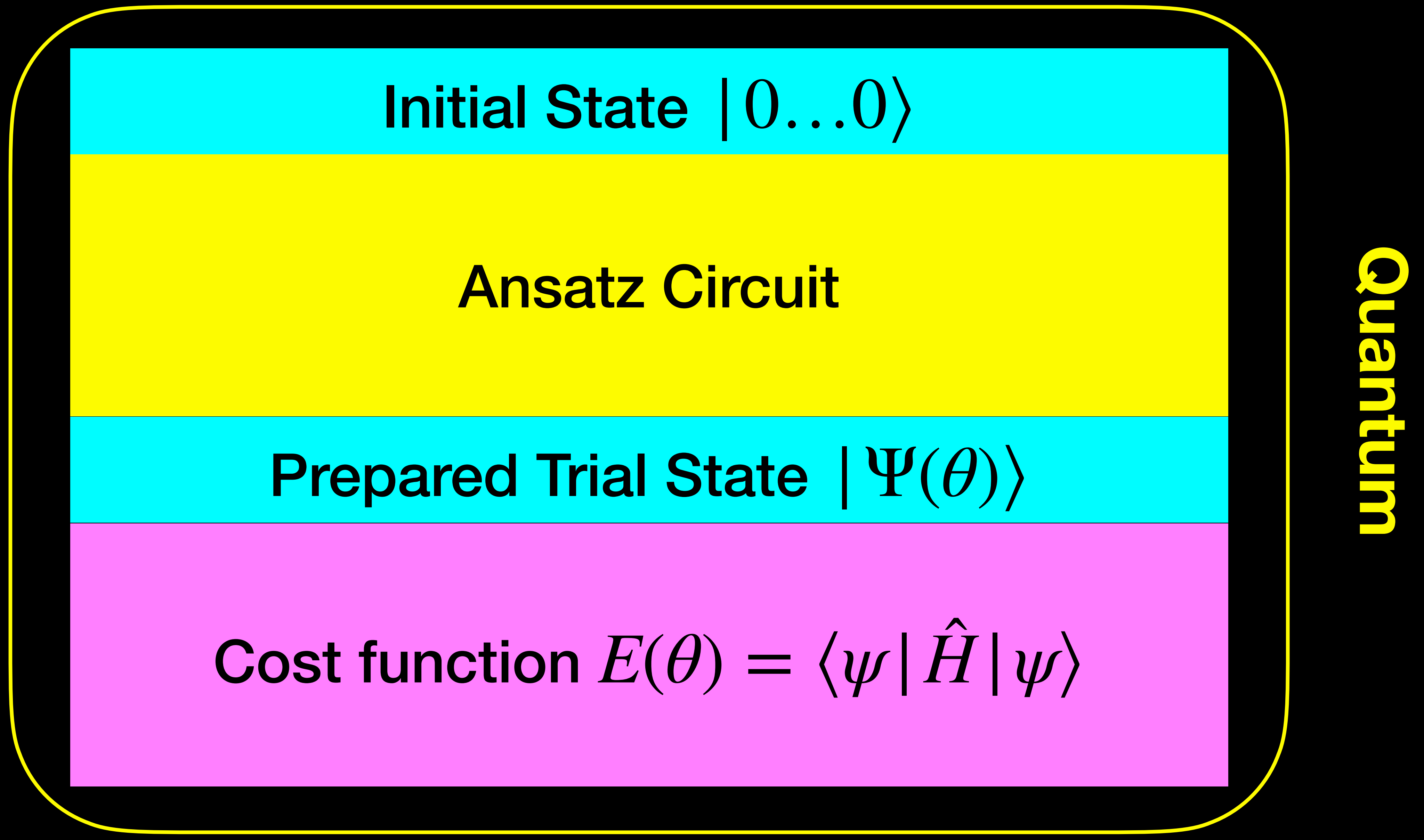

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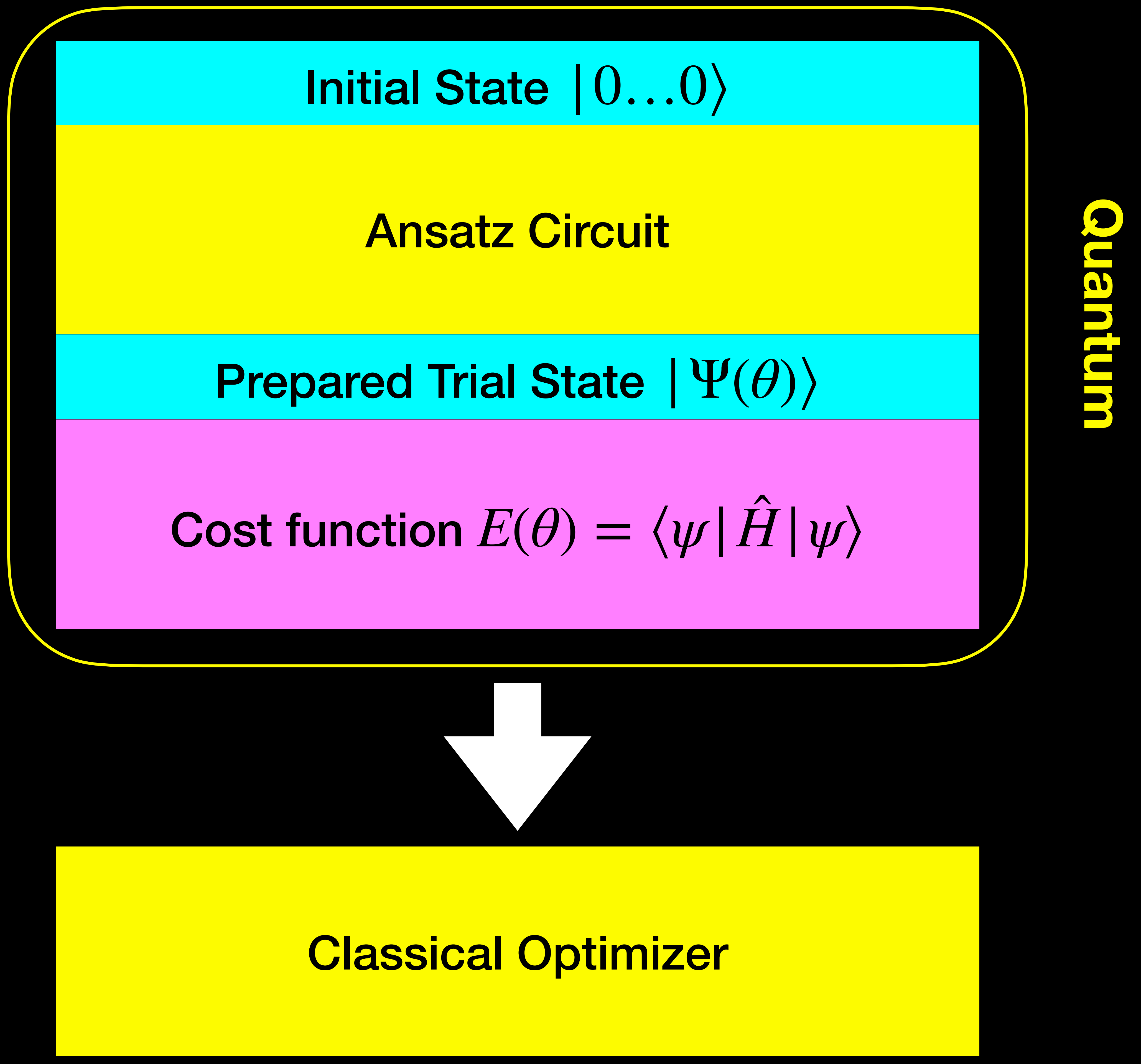

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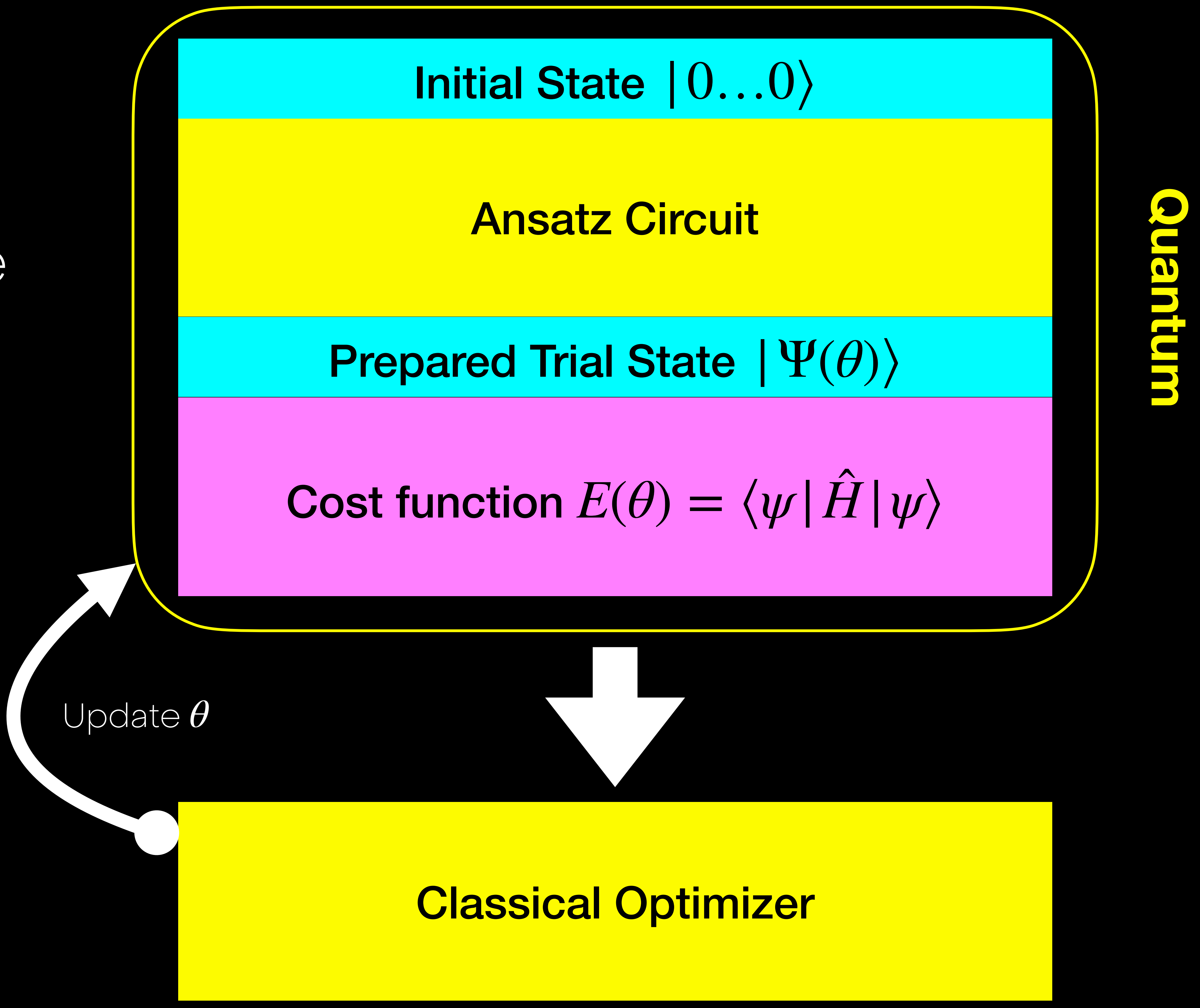

Example ansatz circuit

10 qubits, 30 parameters

$$\left|\Psi(\theta)\right\rangle = \left|\psi_{\text{sites}}\right\rangle \otimes \left|\psi_{links}\right\rangle = C(\theta)\left|\Psi_0\right\rangle$$

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$\Rightarrow$

$|1010100101\rangle$
$|1010100100\rangle$
$|1000110100\rangle$
$|1000110111\rangle$
...

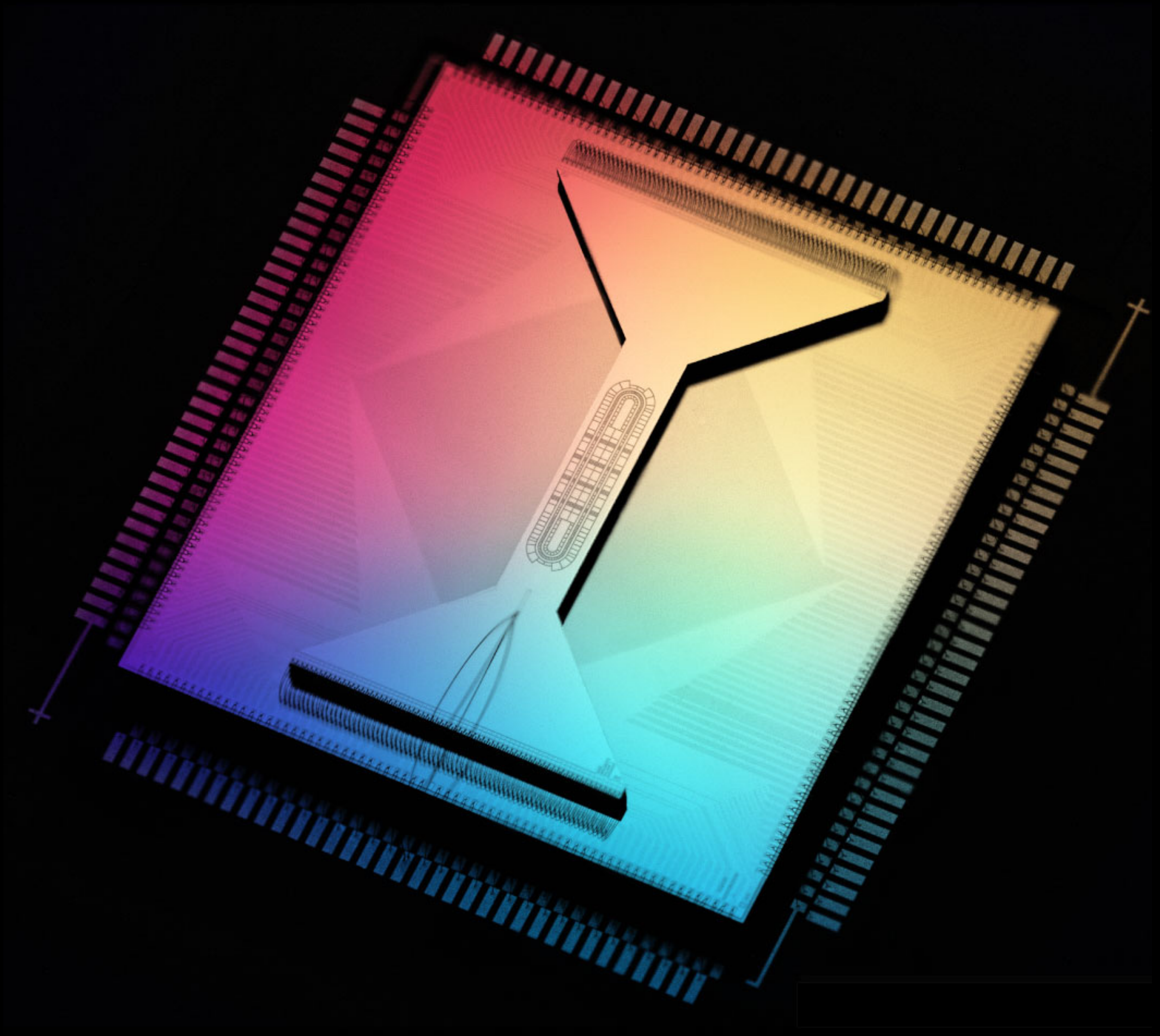
Quantinuum

H-series Quantum Hardware

Most benchmarked quantum computer

Lowest-error commercial quantum device

20 and 56 qubits on trapped ions



99.9979(3)%
single-qubit gate fidelity

99.914(3)%
two-qubit gate fidelity

Example of gate decomposition

{H, X, Rz, Rx, Ry, CNOT}: ≈ 115 2-qubit gates

H-series Native Gates: ≈ 80 2-qubit gates

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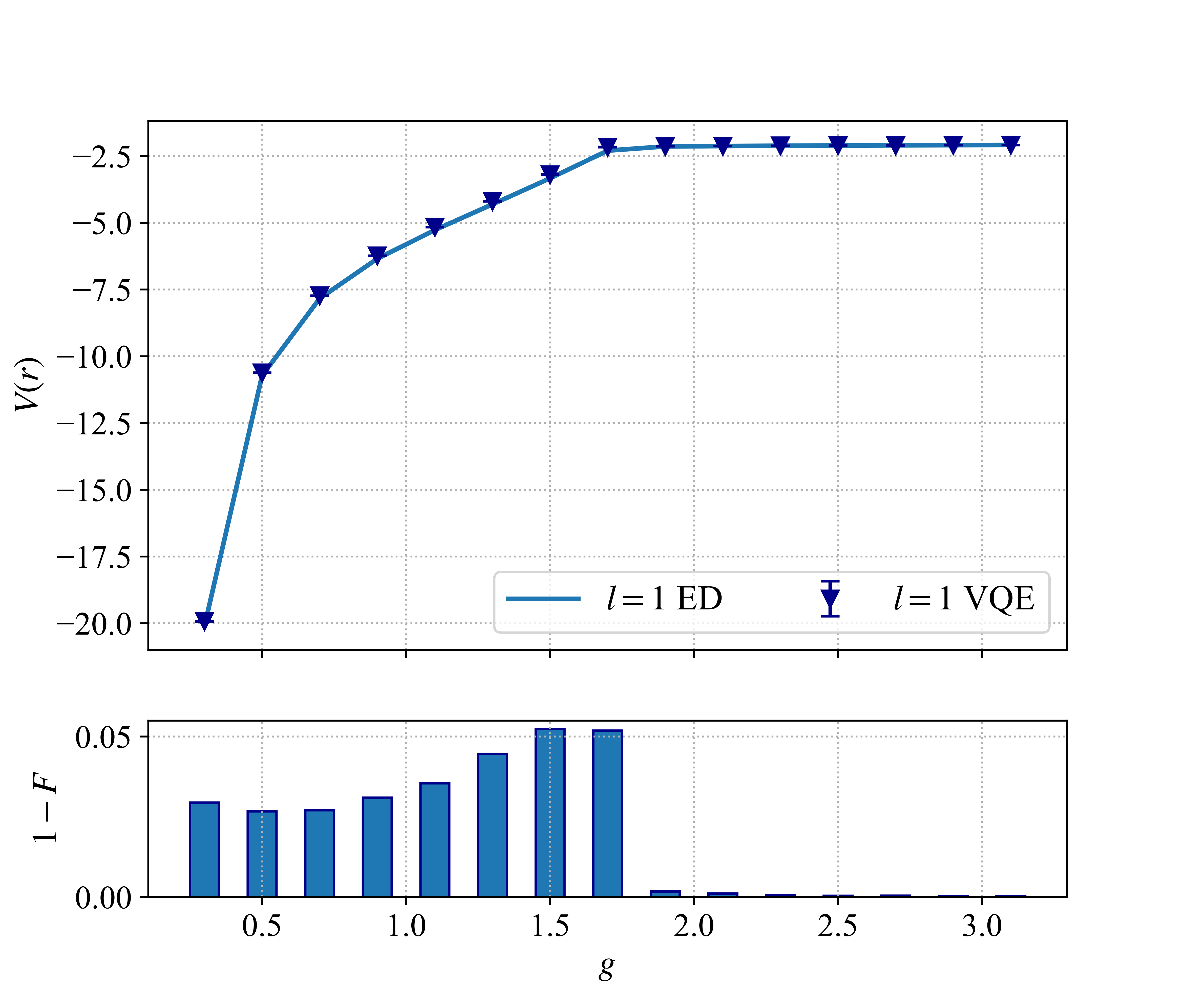
Results

Consistency checks

Benchmark quantum results against classical methods

- A quantum state of 10 qubits can be represented with classical memory on a laptop and the Hamiltonian can be easily written as a matrix
- Use exact diagonalization (ED) to find the ground state and its energy
- Use VQE to find the optimal parameters for the ground state circuit



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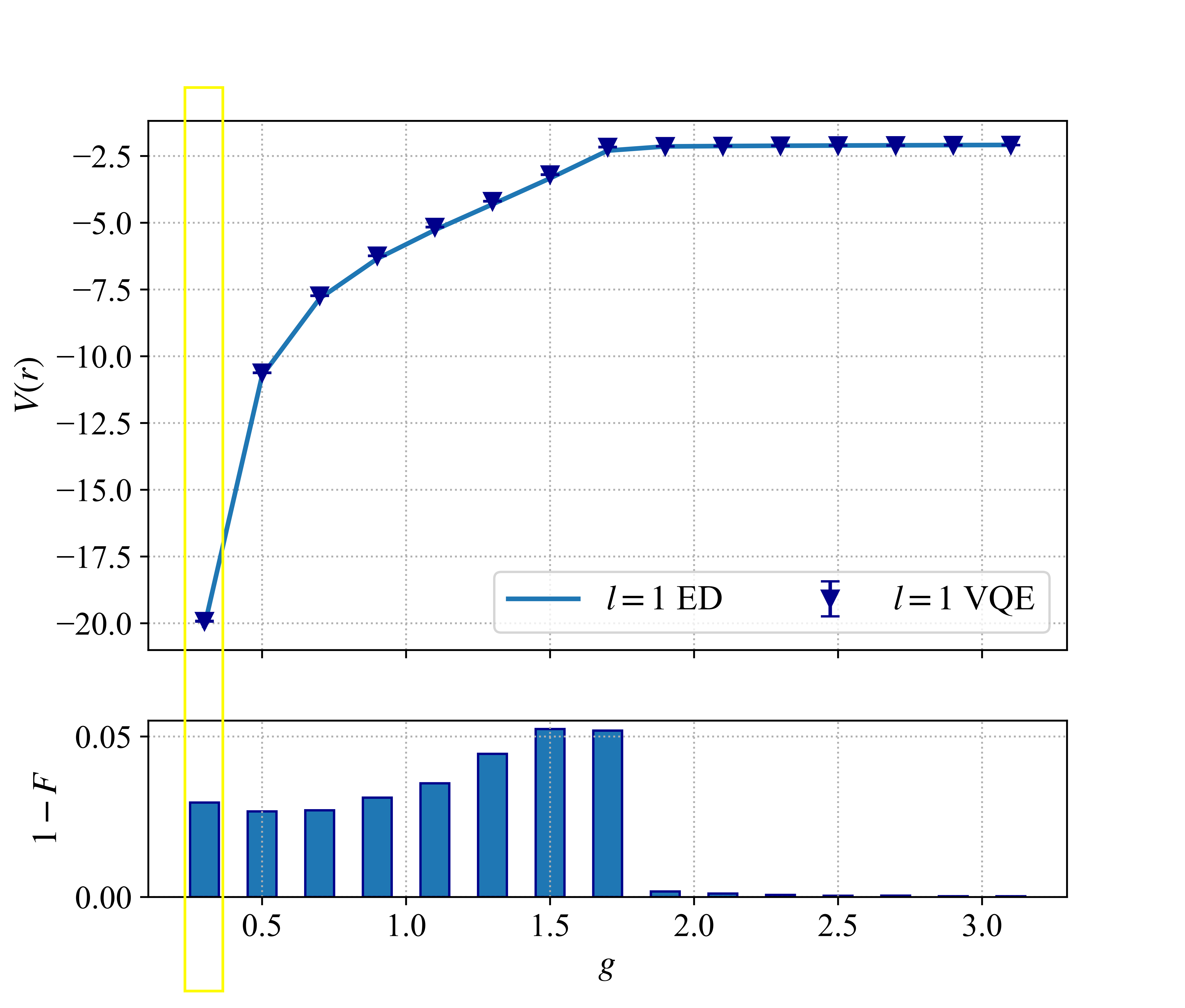

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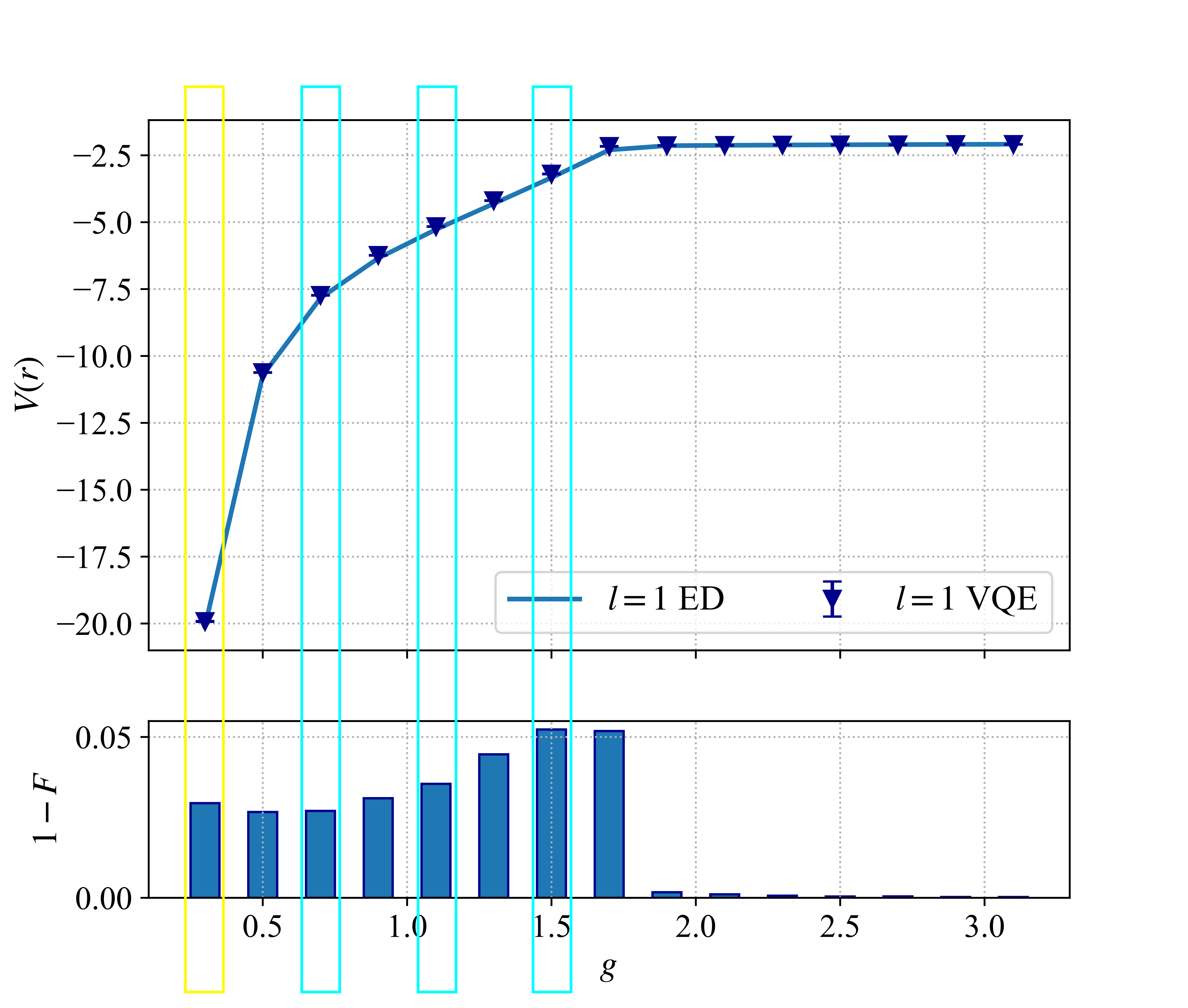
- Use exact diagonalization (ED) to find the ground state and its energy
- Use VQE to find the optimal parameters for the ground state circuit



Consistency checks

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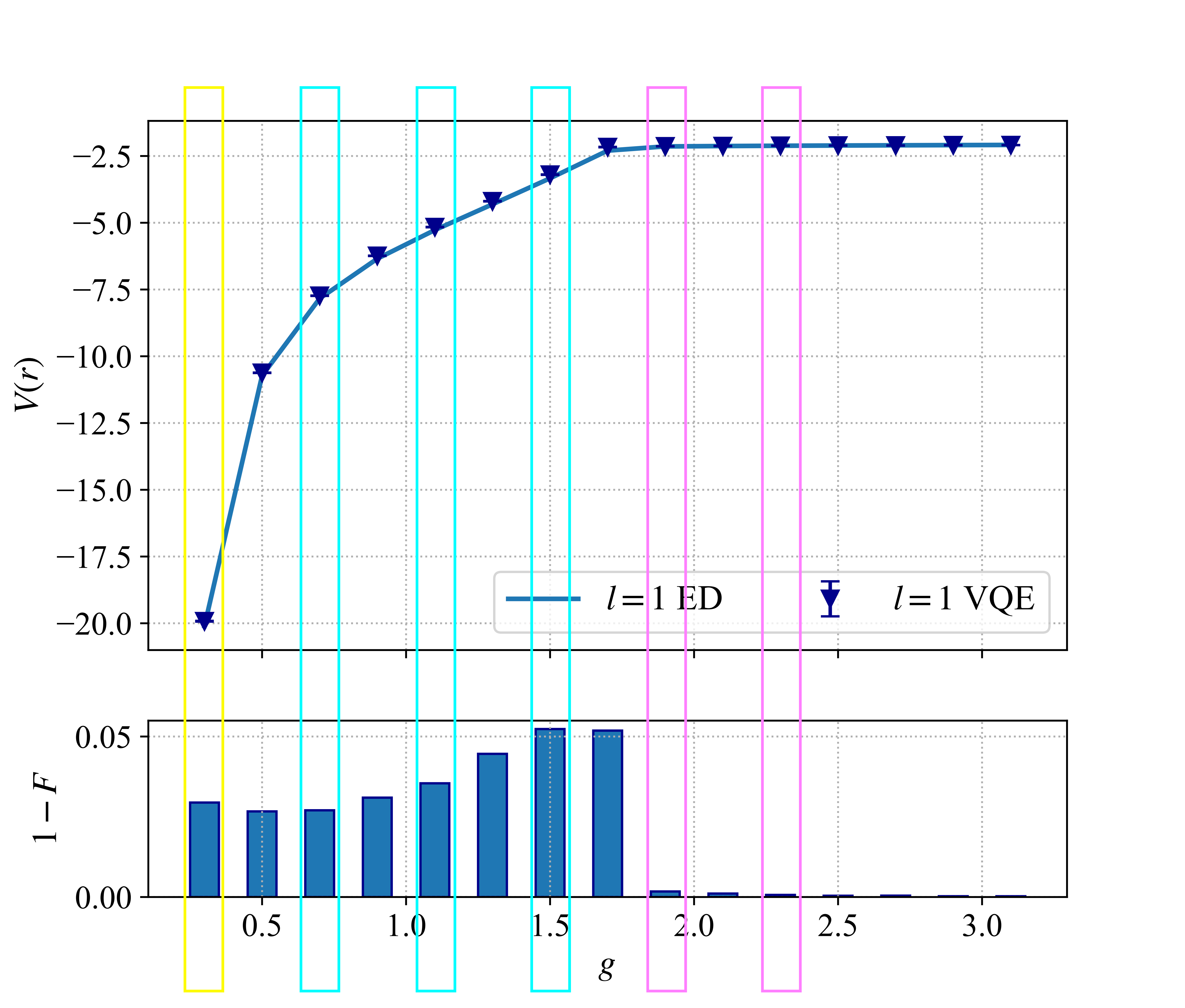

Simulation and Emulation

And real hardware experiments

- Given the optimal parameters for the ansatz circuit at each coupling we can:
  - Simulate the circuit classically without measuring
  - Simulate the circuit classically with measurements
  - Simulate the circuit classically with measurements and noisy operations
  - Emulate the circuit on a trapped ion device
  - Run the circuit on a trapped ion device

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H1-1E ↔ H1-1

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H1-1E ↔ H1-1

$$|\Psi_{GS}\rangle = \sum_{i}^{2^N} c_i |i\rangle \quad \Rightarrow \quad \mathrm{prob_i} = |c_i|^2 = |\langle i|\Psi_{GS}\rangle|^2$$

$$\text{prob}_{\text{i}} = |c_i|^2 = |\langle i | \Psi_{\text{GS}} \rangle|^2$$

Probabilities of the different states for each g value:AerStateBackend shots=None

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QUANTINUUM

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$|\Psi_{GS}\rangle = c_0|1010100101\rangle + c_1|1010101101\rangle + c_2|1010100111\rangle$

$|\Psi_{GS}\rangle = c_0|1000110101\rangle + \ldots$

Probabilities of the different states for each g value:AerBackend shots=100000

Small Noise Levels

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Large Noise Levels

Large Noise Levels

QUANTINUUM

Large Noise Levels

Remove unphysical states/bitstrings

H1-1E

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H1-1E

Remove unphysical states/bitstrings

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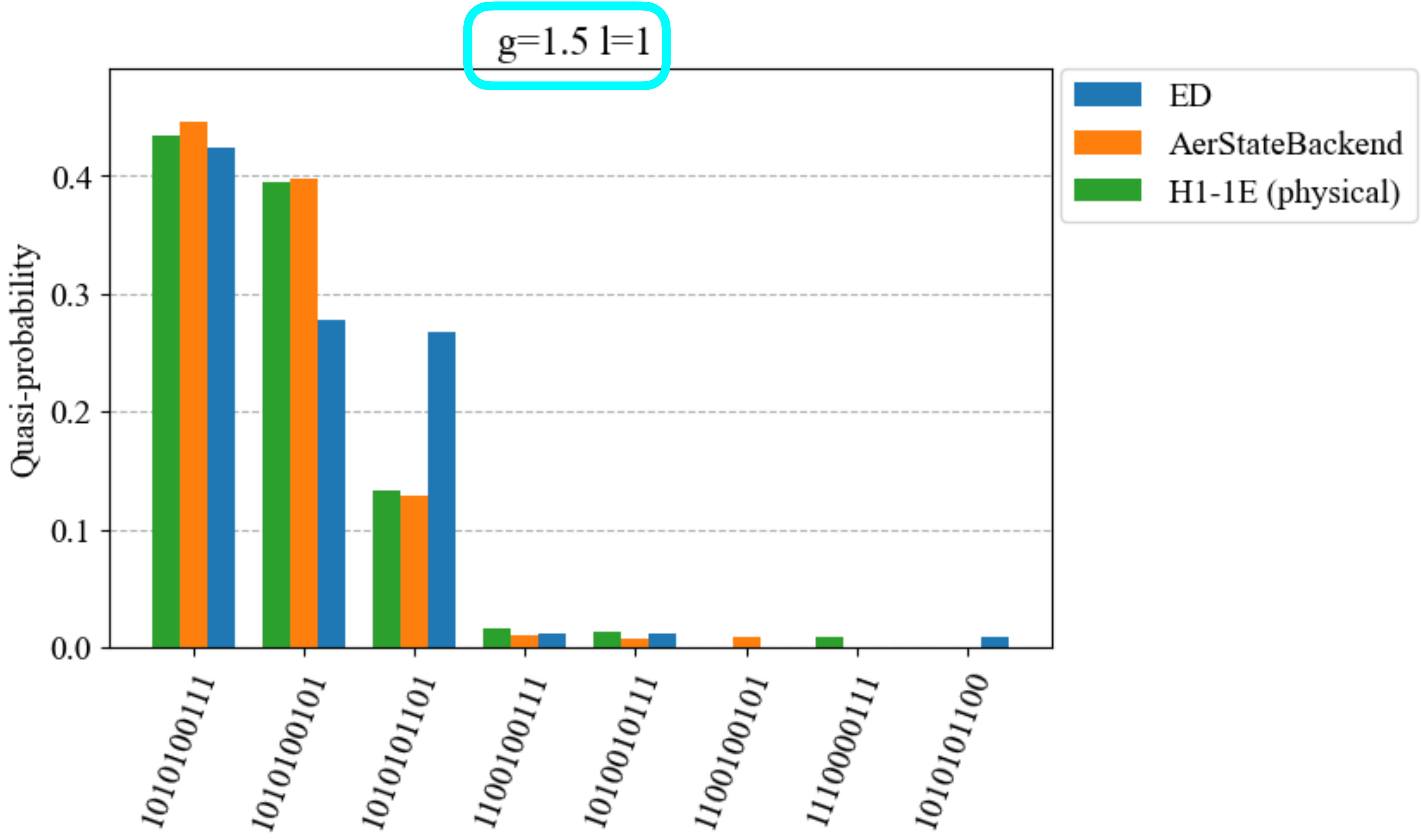
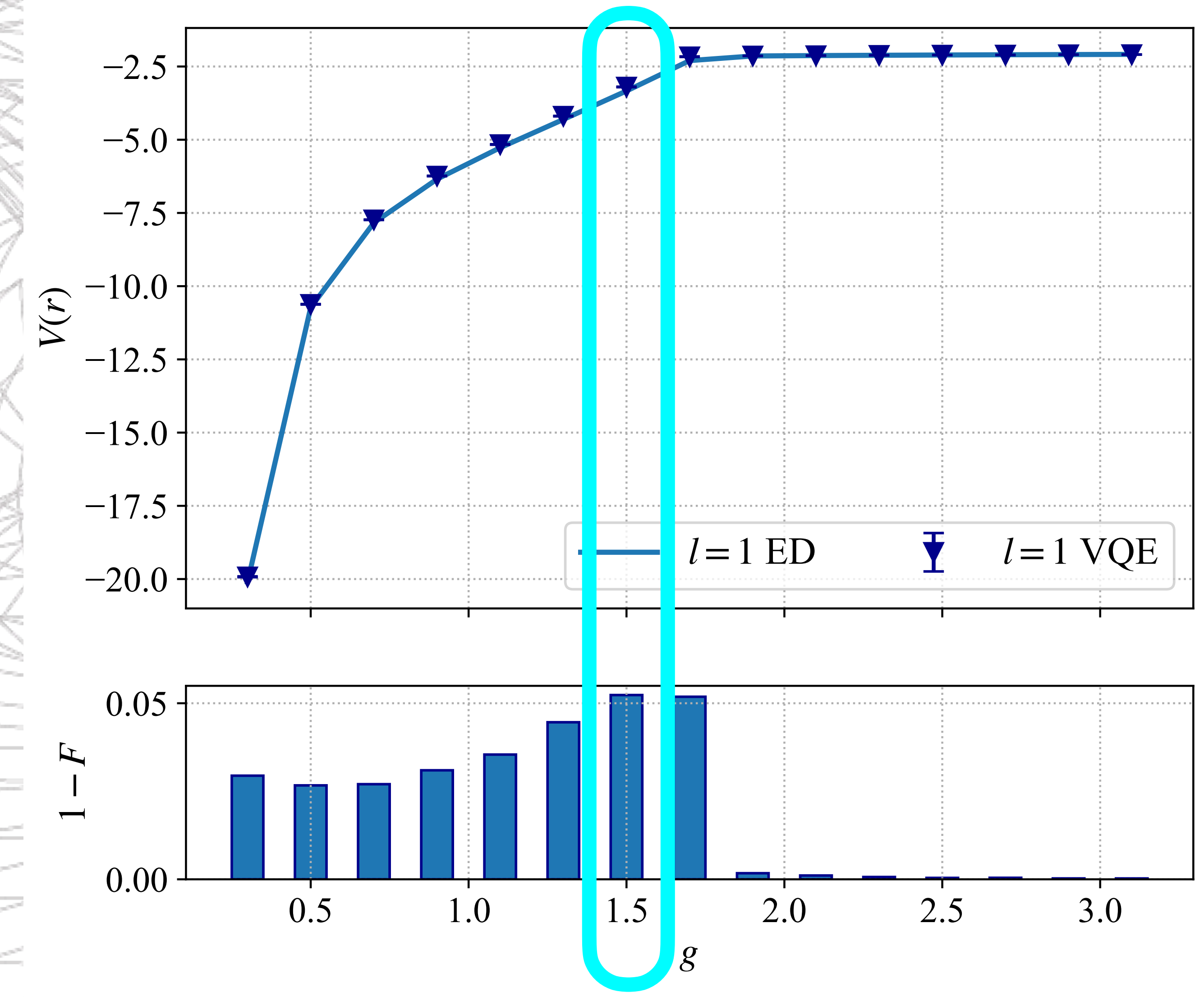
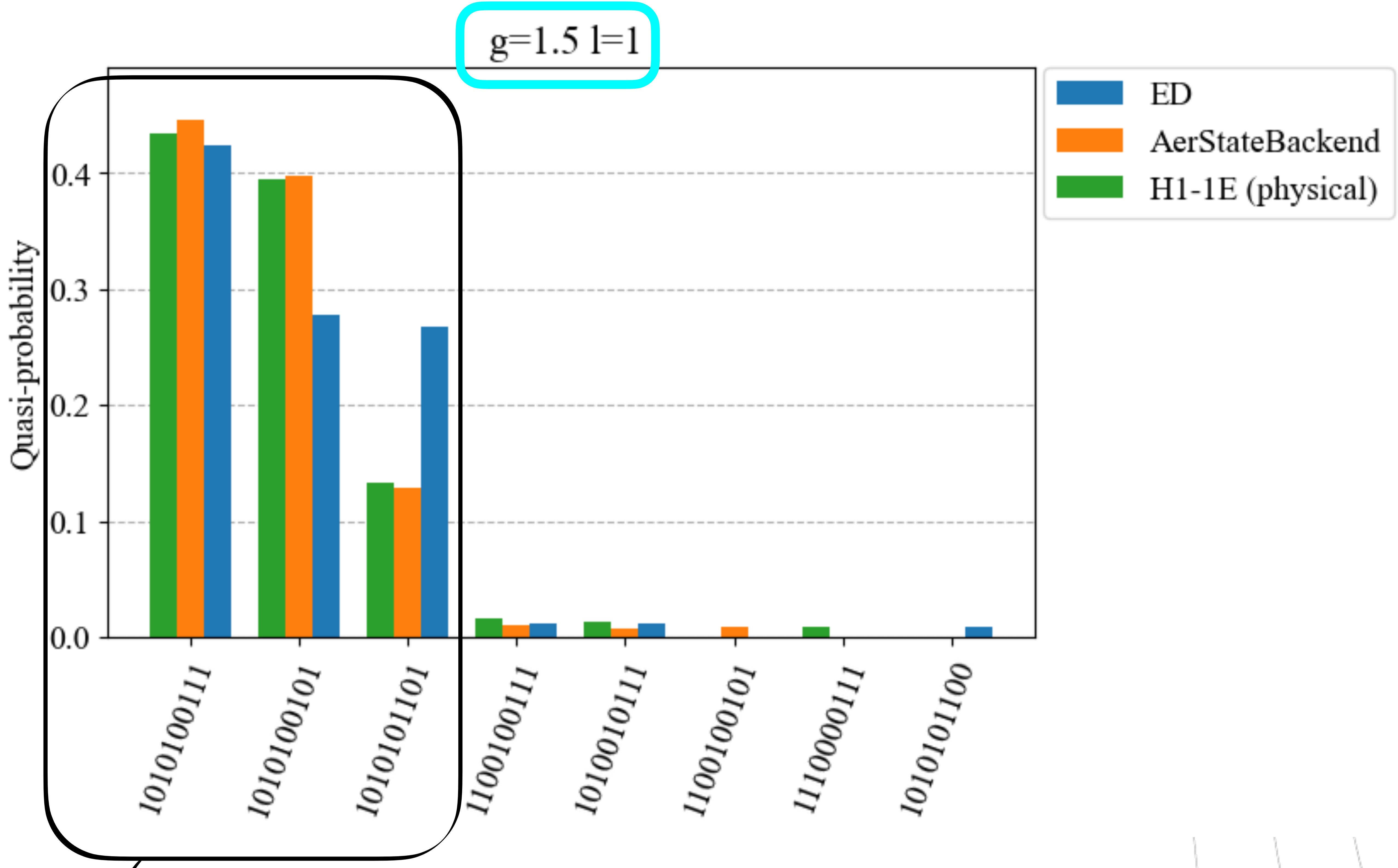
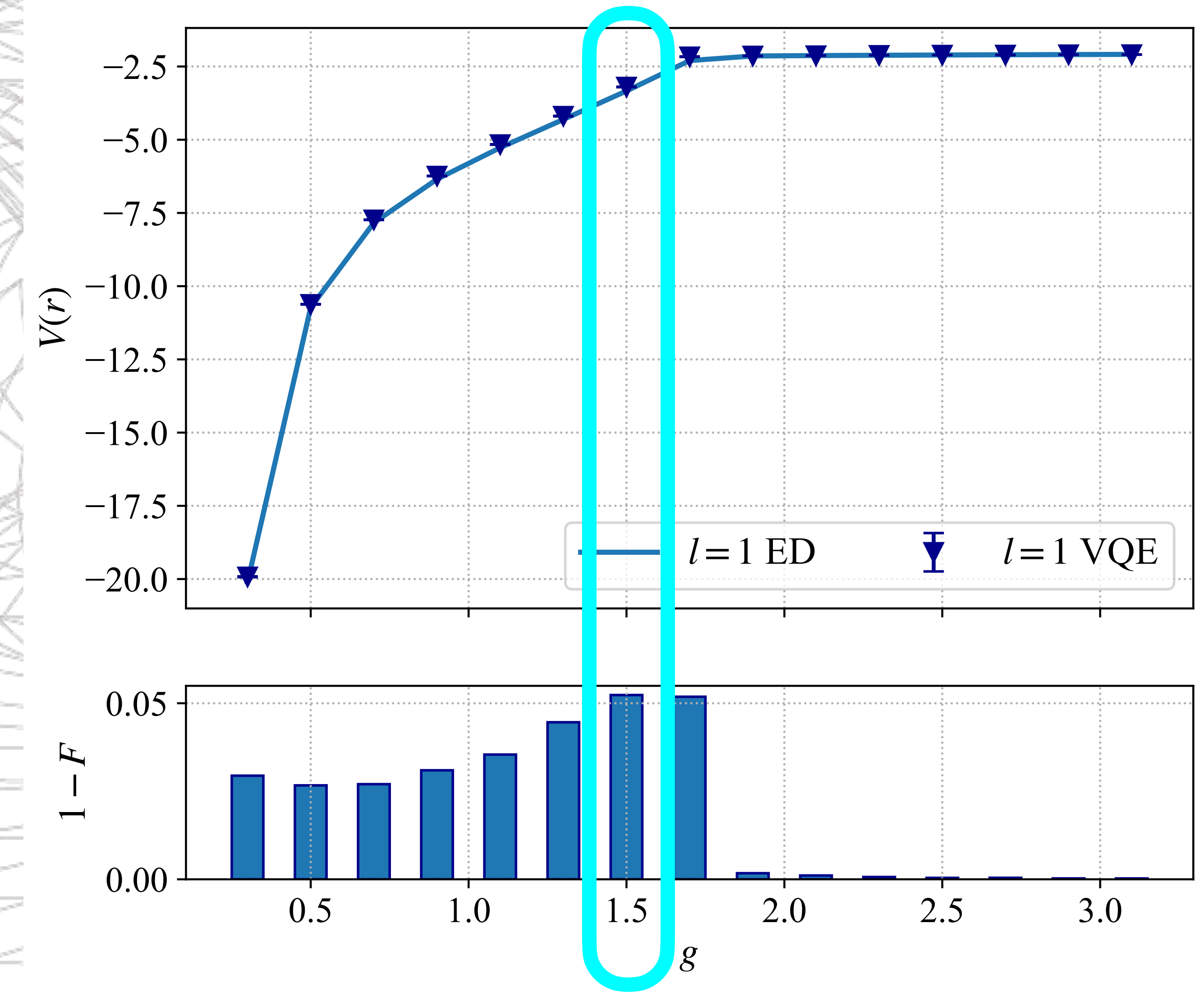
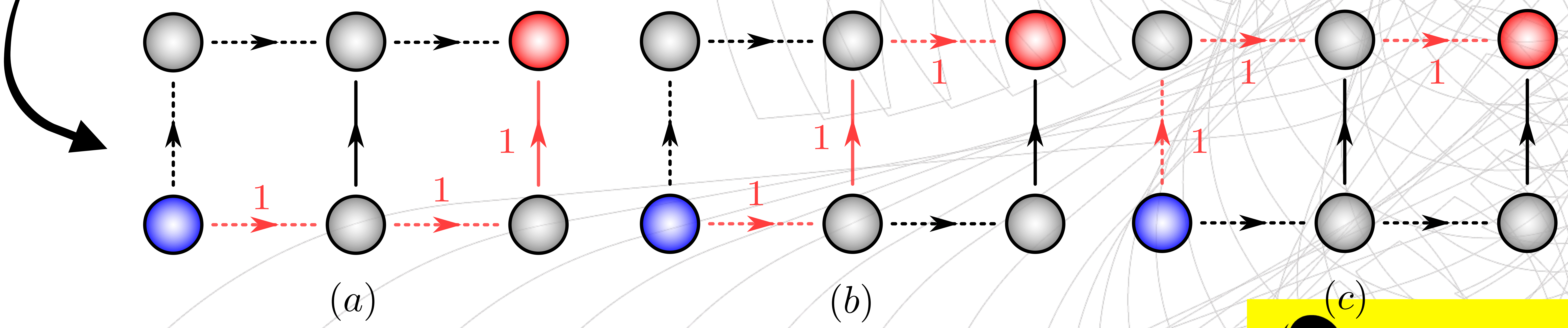

g=1.5 l=1
ED
AerStateBackend
H1-1E (physical)
Quasi-probability
0.0
0.1
0.2
0.3
0.4
1010100111
1010100101
1010101101
1100100111
1010010111
1100100101
1110000111
1010101100


V(r)
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
−20.0
l = 1 ED
l = 1 VQE
1 − F
0.05
0.00
0.5
1.0
1.5
2.0
2.5
3.0
g





Configurations with electric fluxes between static charges



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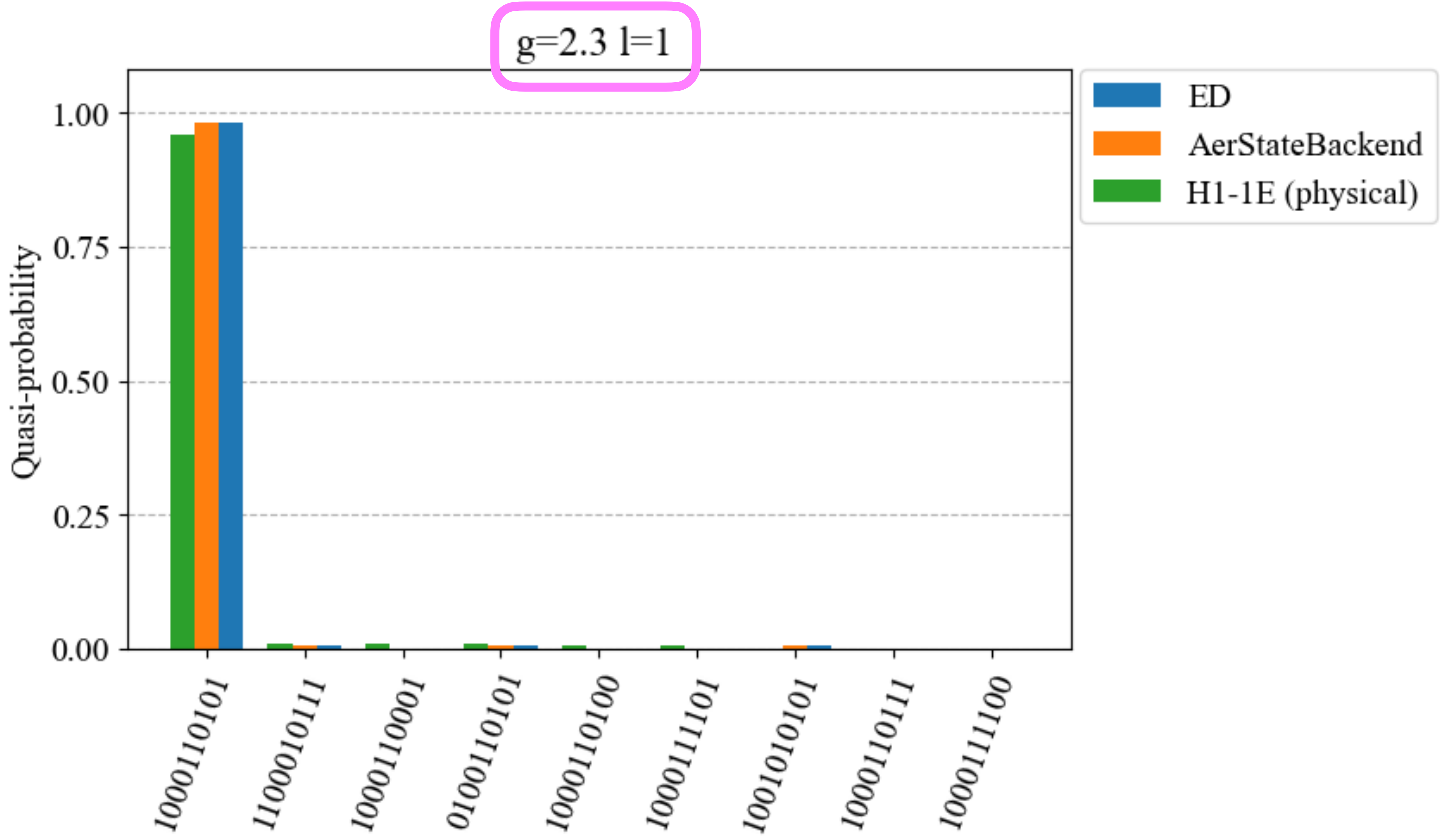
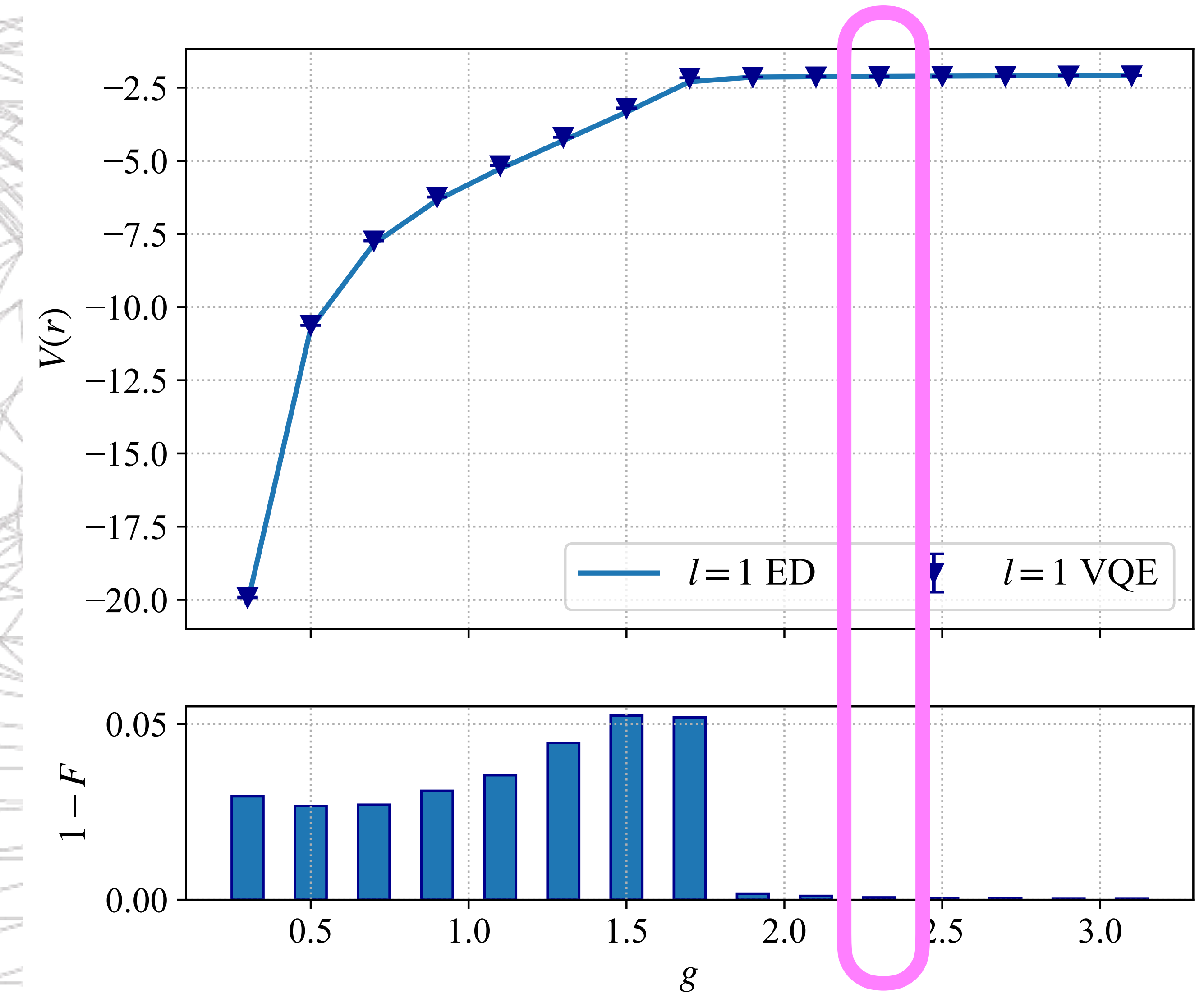
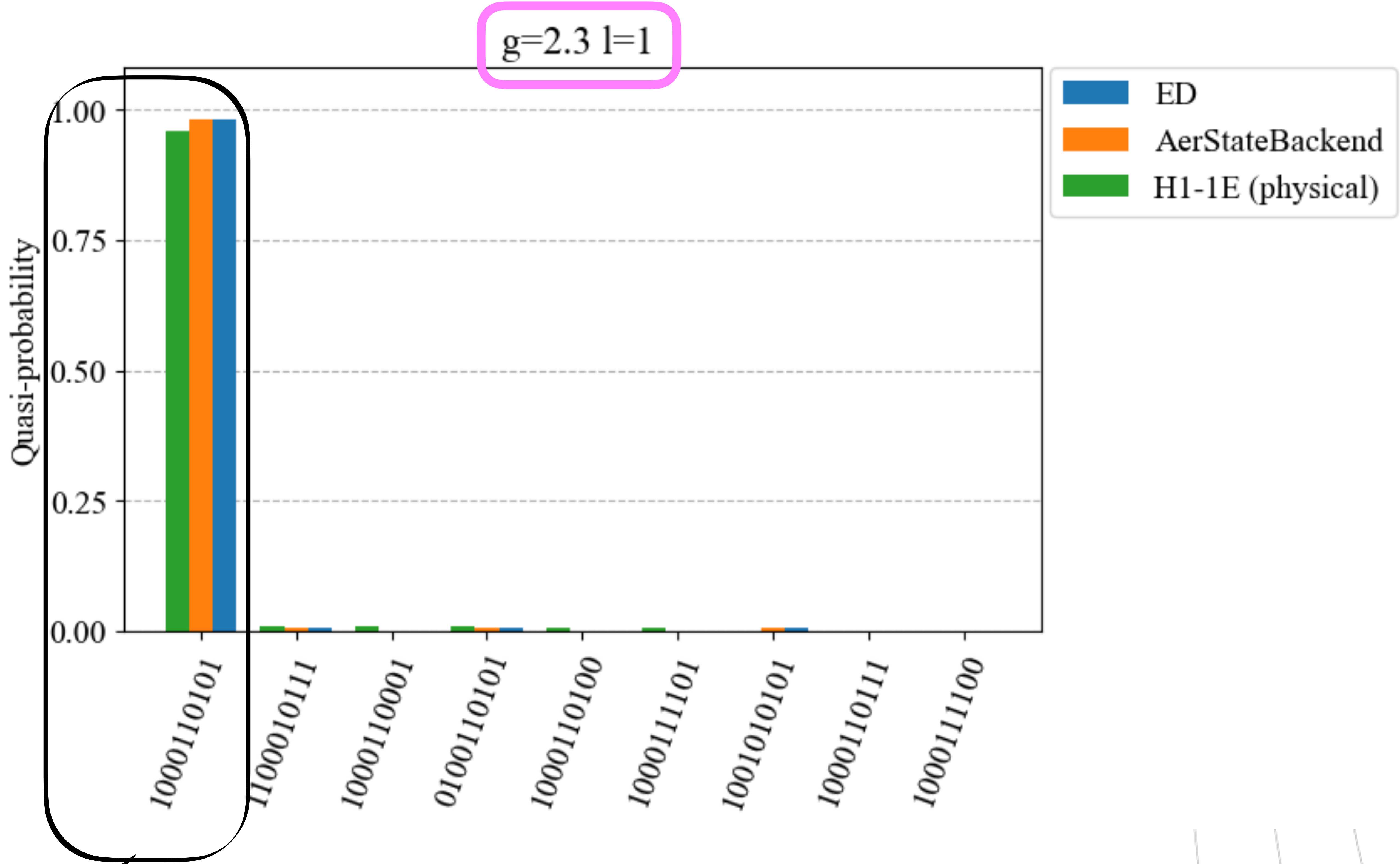
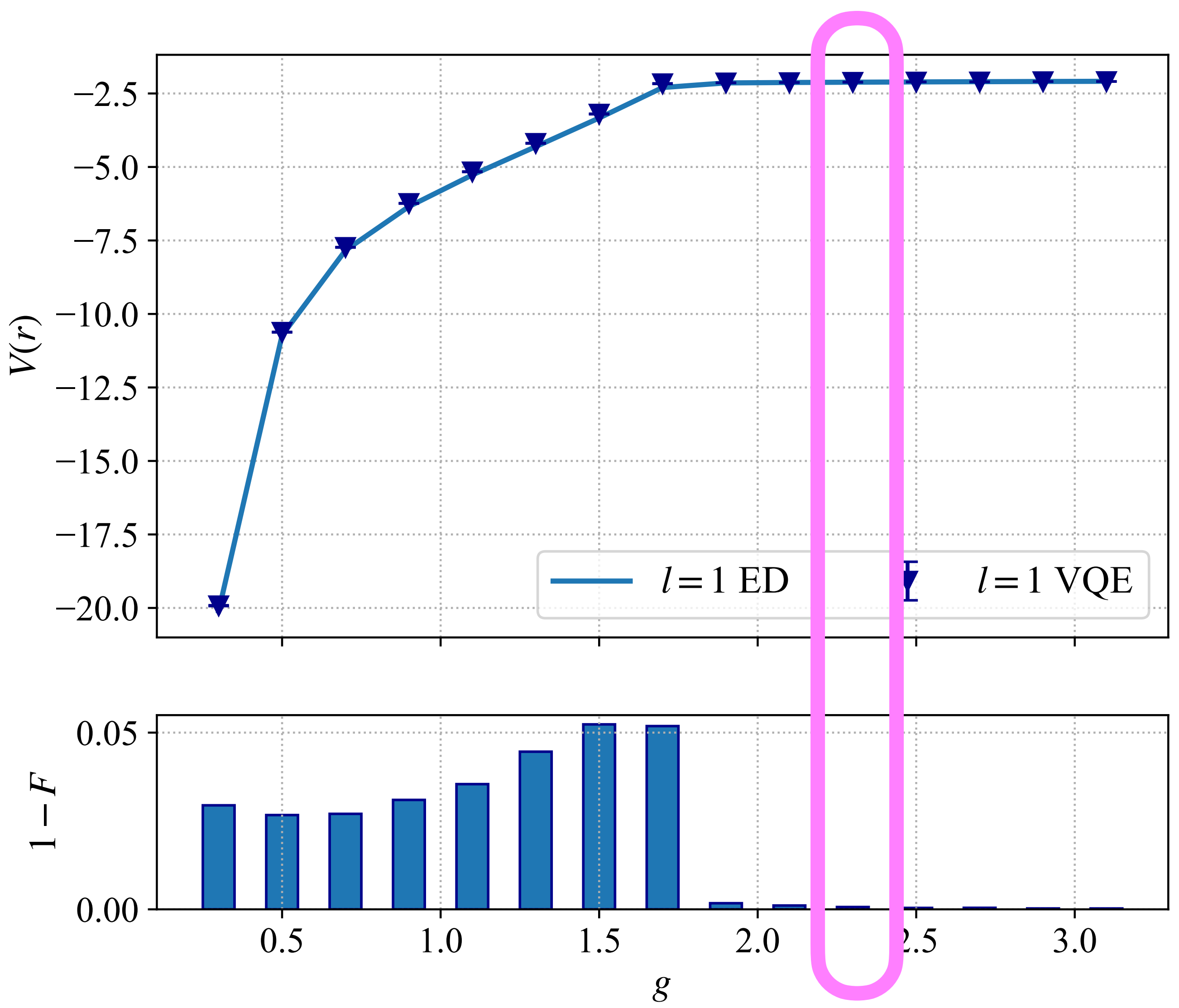
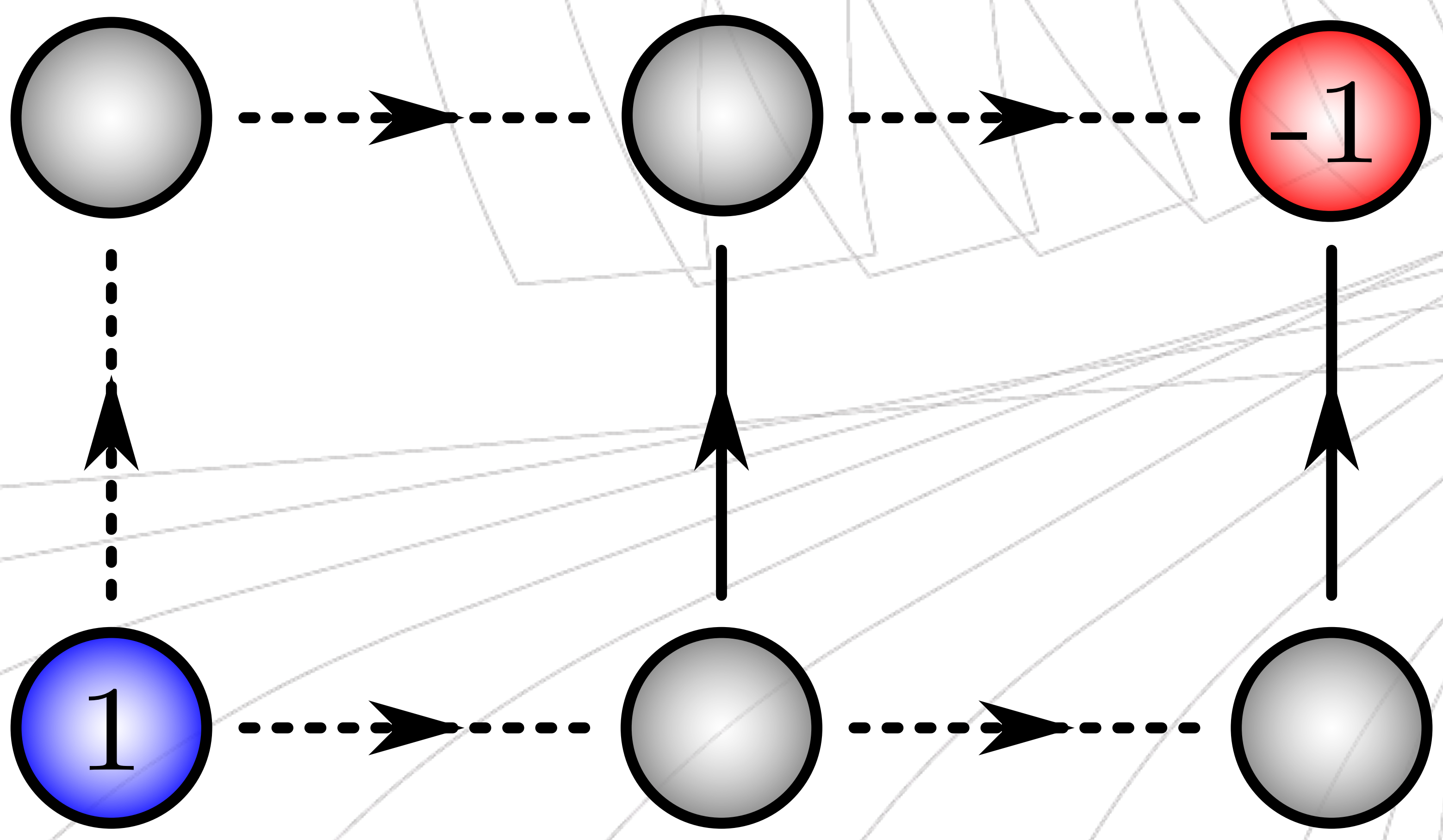

g=2.3 l=1
Quasi-probability
1.00
0.75
0.50
0.25
0.00
ED
AerStateBackend
H1-1E (physical)
1000110101
1100010111
1000110001
0100110101
1000110100
1000111101
1001010101
1000110111
1000111100


V(r)
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
−20.0
l = 1 ED
l = 1 VQE
1 − F
0.05
0.00
0.5
1.0
1.5
2.0
2.5
3.0
g





Configurations with string breaking: no flux and mesons

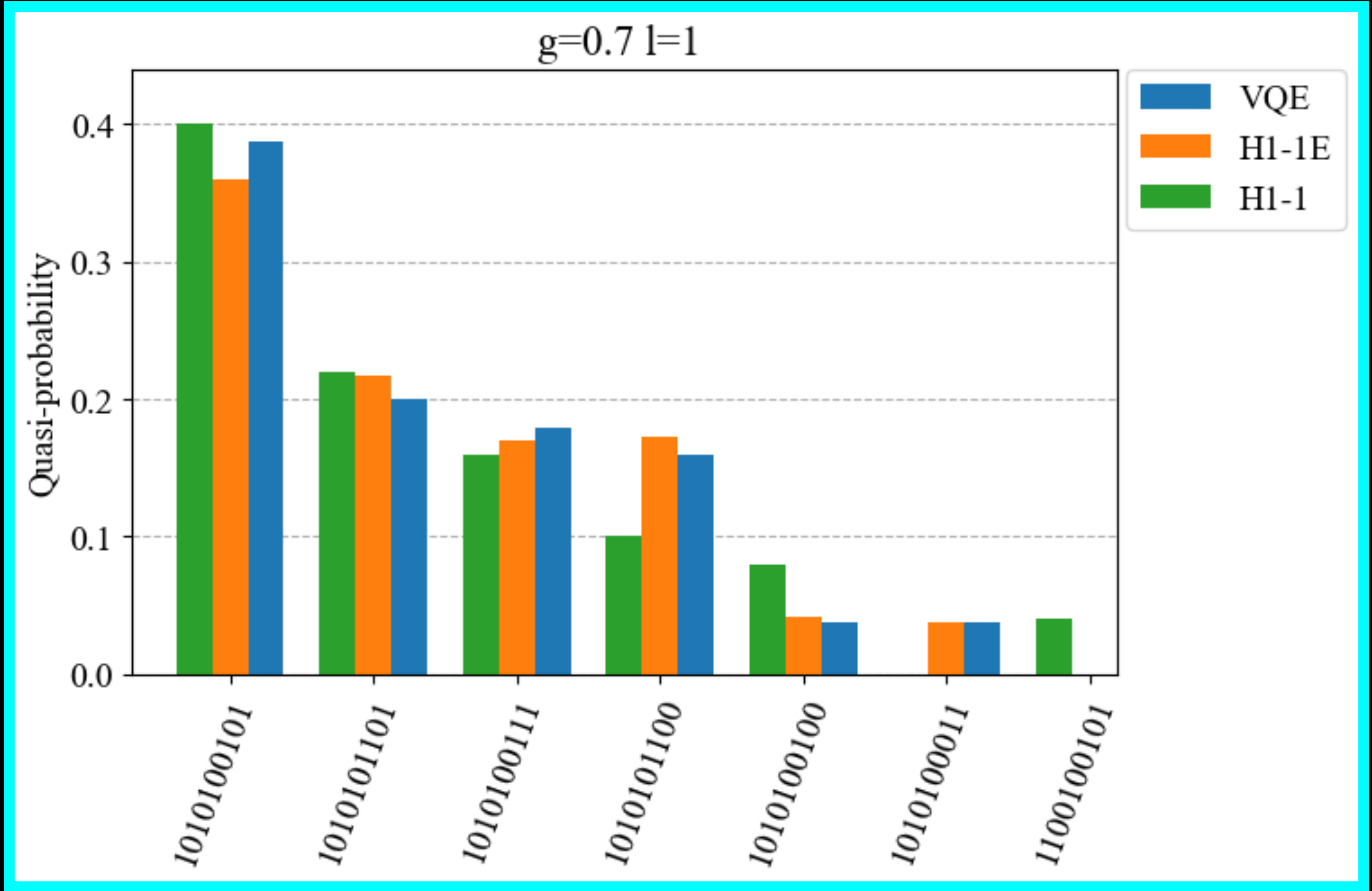


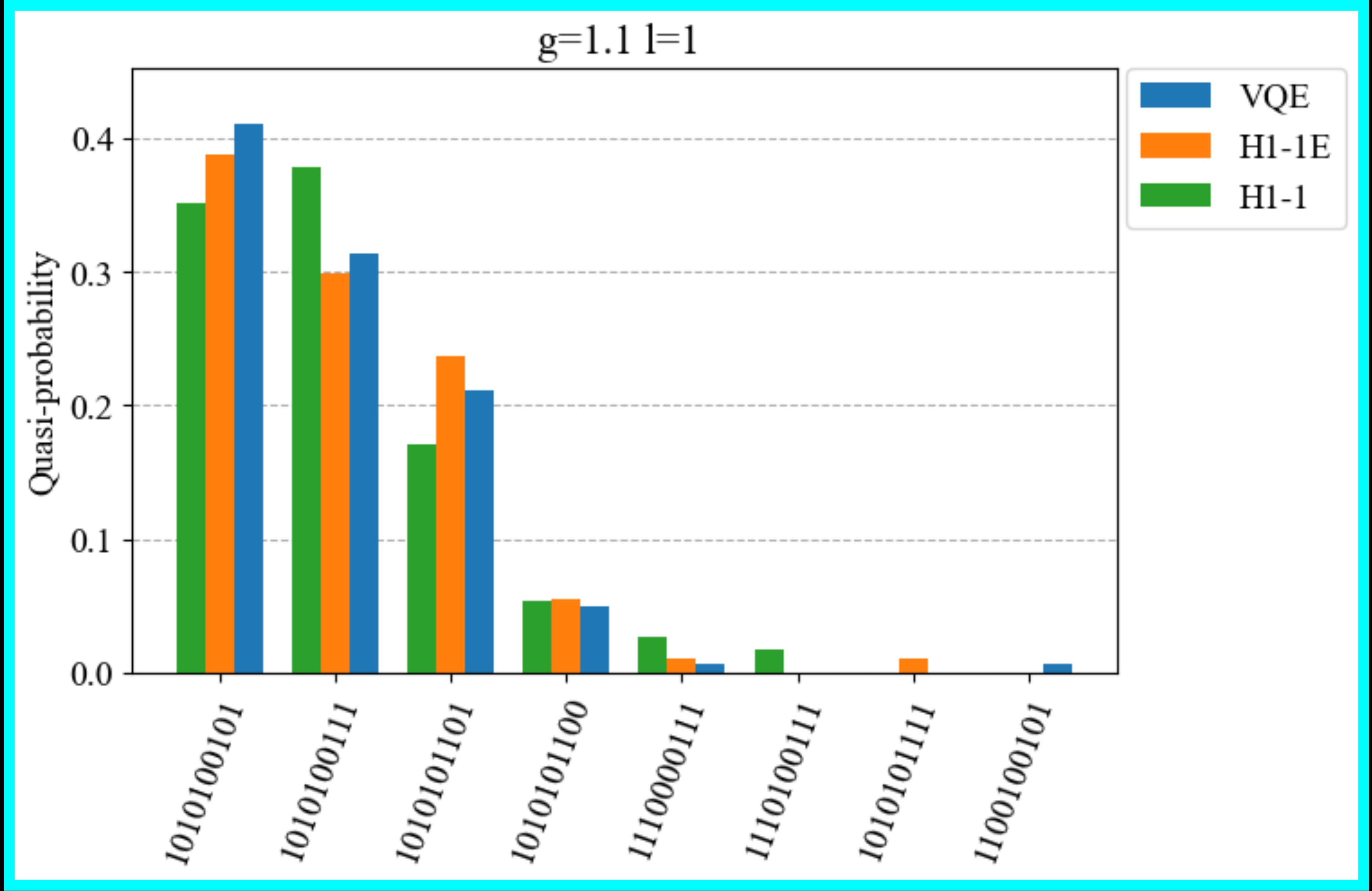
QUANTINUUM

Real Hardware

Results compared to Emulator

- 128 shots on H1-1
- No error mitigation!





Conclusions

And future directions

- We demonstrated on real quantum hardware a calculation of the confining potential of (2+1)D QED in the Hamiltonian formulation
- Access to the ground state, even in a variational sense, allows us to visualize the confining fluxes between static charges
- String breaking and the formation of “mesons” is observed
- Scaling up the quantum state preparation step is important to fully leverage the computational power of quantum hardware
- To get more details and see other applications of this method go see Karl Jansen’s poster at 18:30