Leveraging Quantum hardware for Fundamental Physics

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Rutherford Appleton Laboratory

Outline

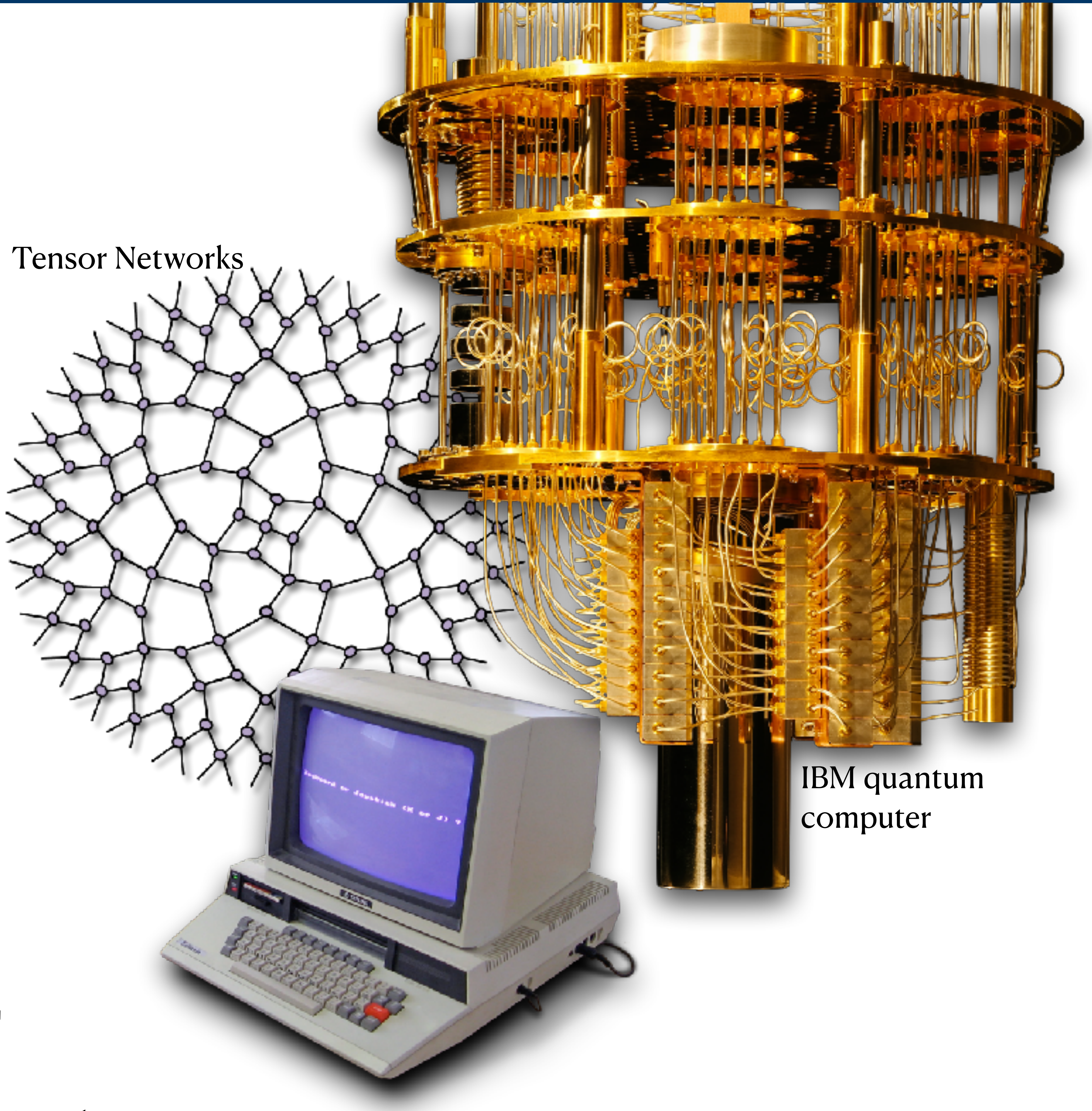
Digital Quantum Computing

- Superconducting QCs, à la IBM

Simulating
Fundamental Physics

Hybrid quantum systems
for quantum simulation

Quantum Optimal Control for
nearer-term quantum computing



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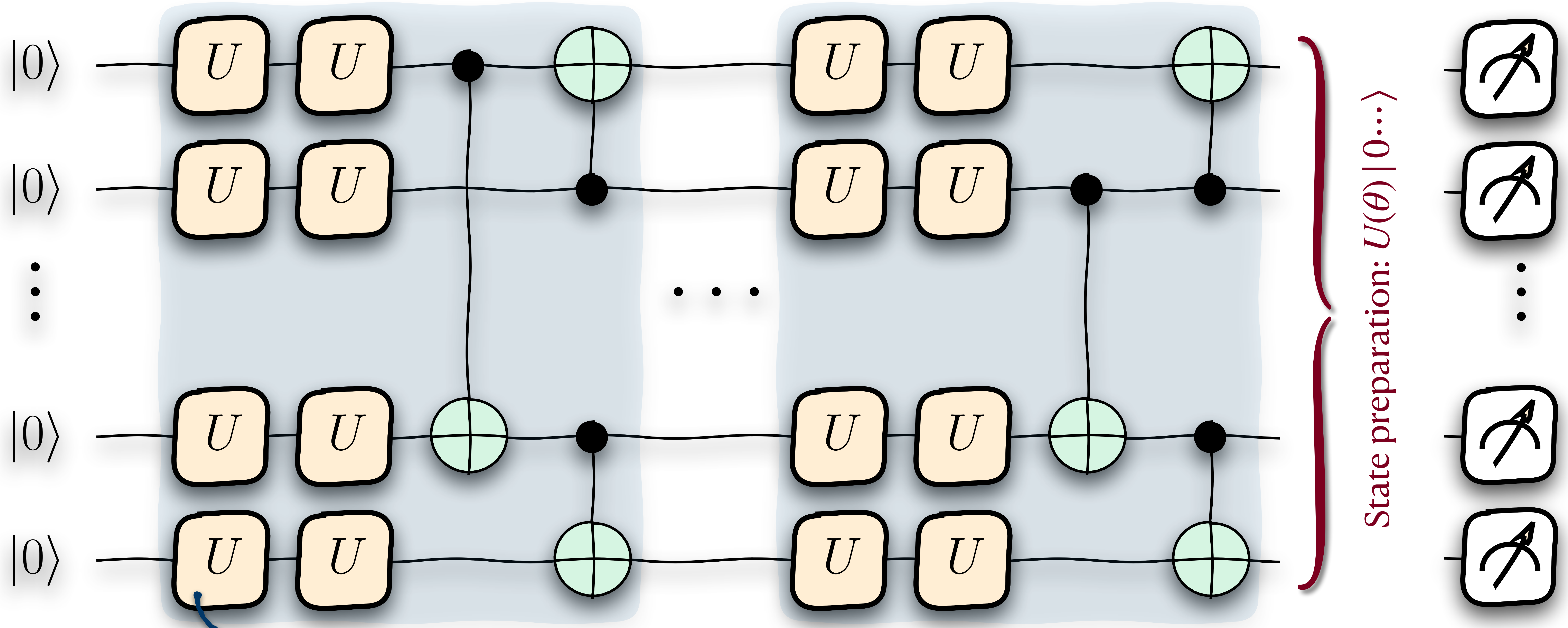
Digital Quantum Computing

How does the Quantum Computer work (theoretically)?

Read from left to right!

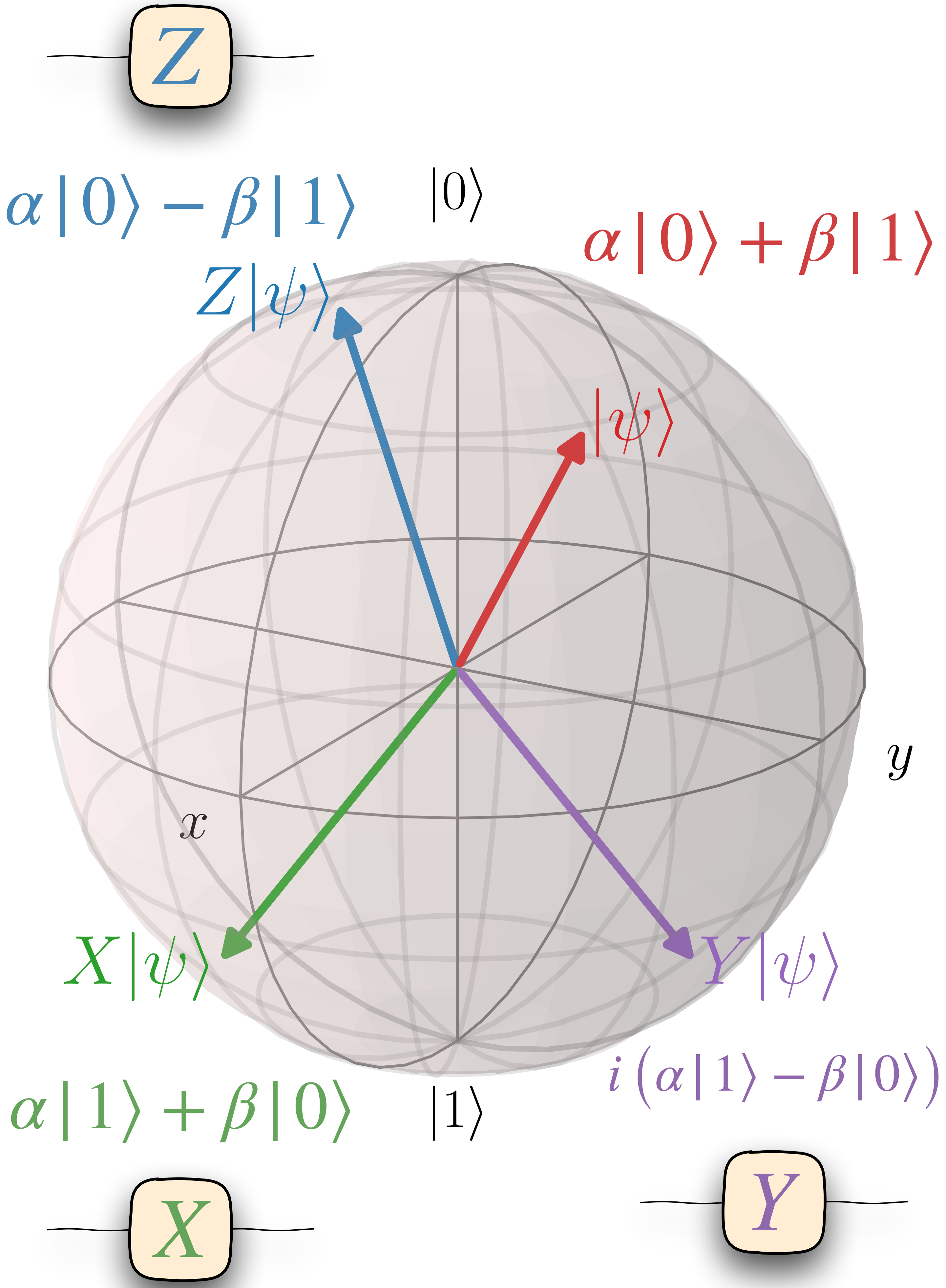


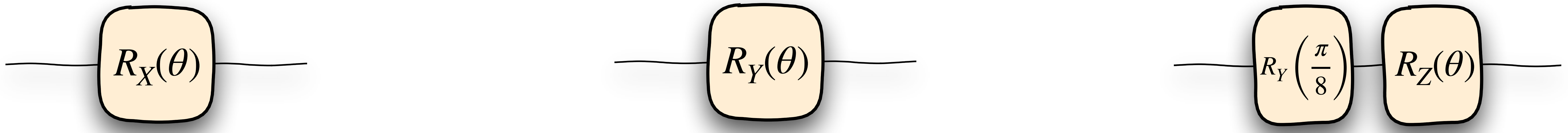
Initial state

Single Qubit Gates

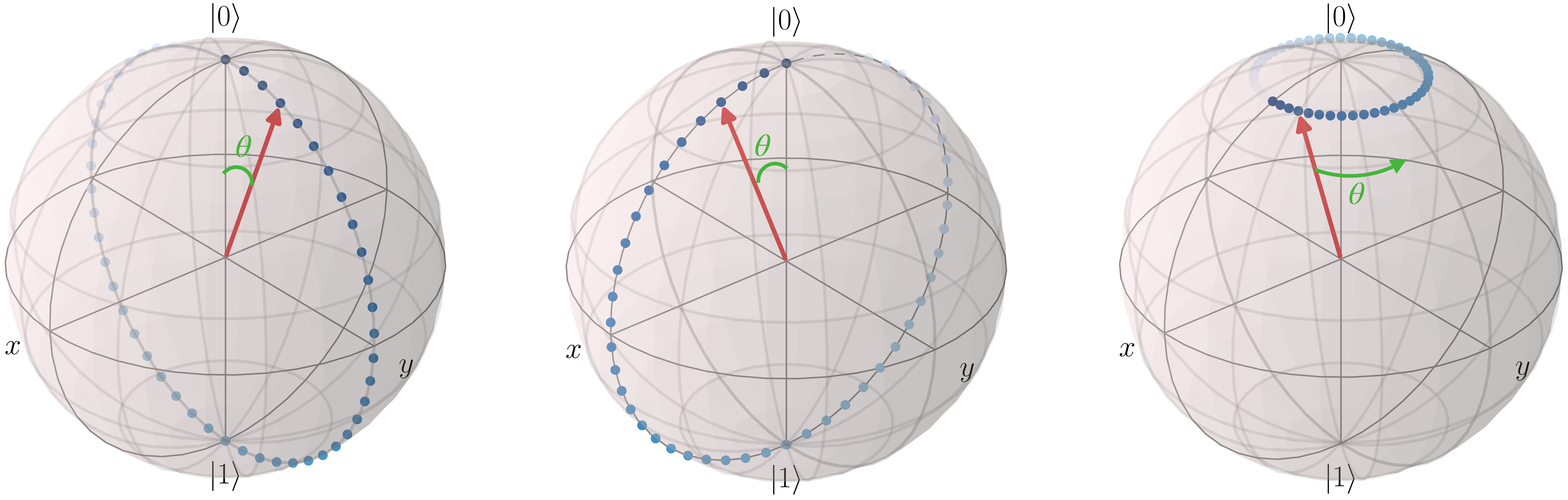
- U: unitary operators
- Pauli matrices: $X,\ Y,\ Z,\ I$

Pauli matrices are the letters of our alphabet (SU(2) generators)





$R_X(\theta)|0\rangle$ $R_Y(\theta)|0\rangle$ $R_Z(\theta)R_Y(\pi/8)|0\rangle$



Parametrised unitary gates

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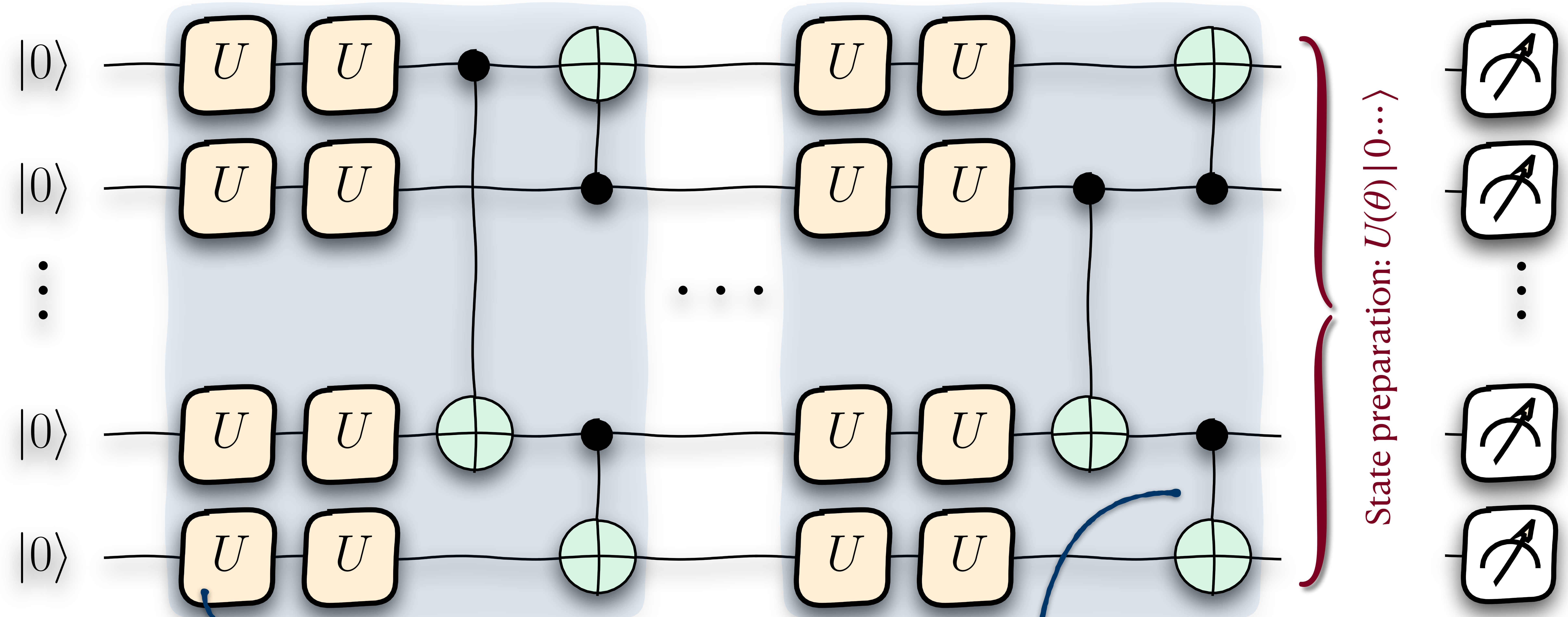

Initial state

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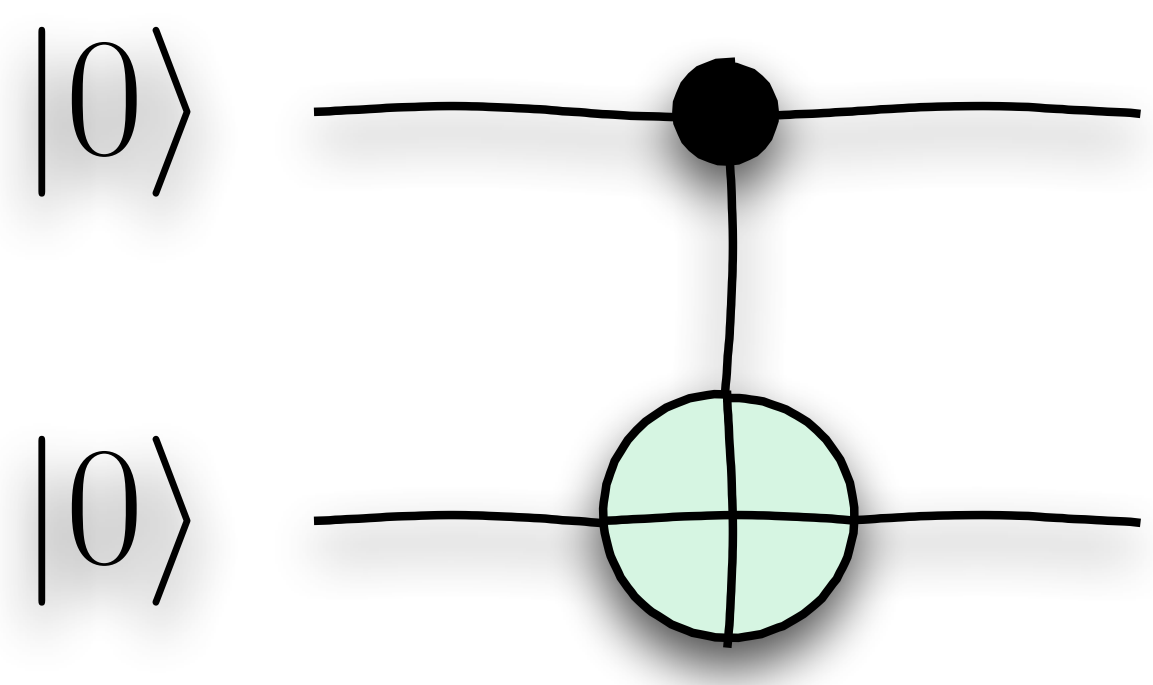
Two qubit gates

Two qubit gates



Is it
$|1\rangle$ or $|0\rangle$?

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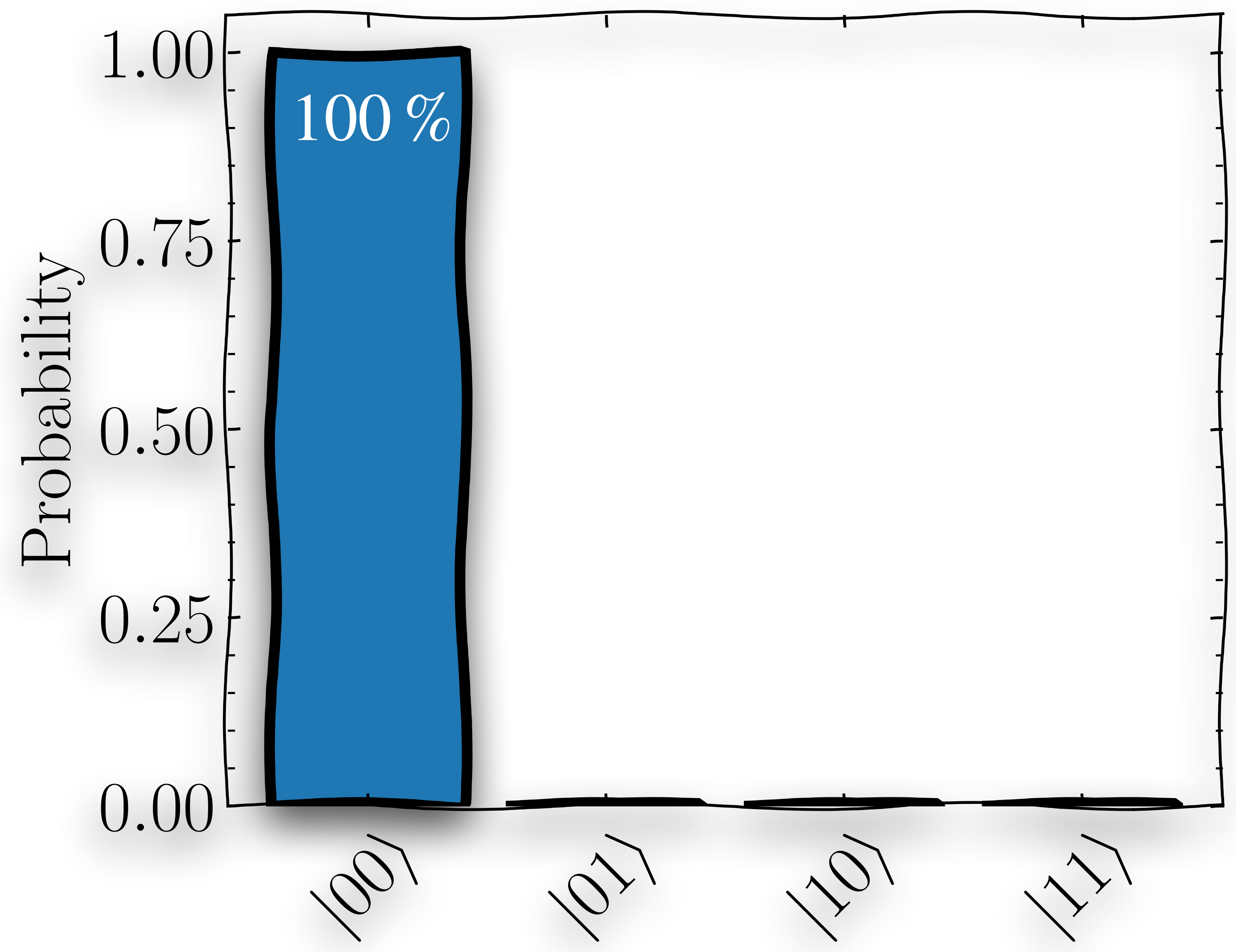

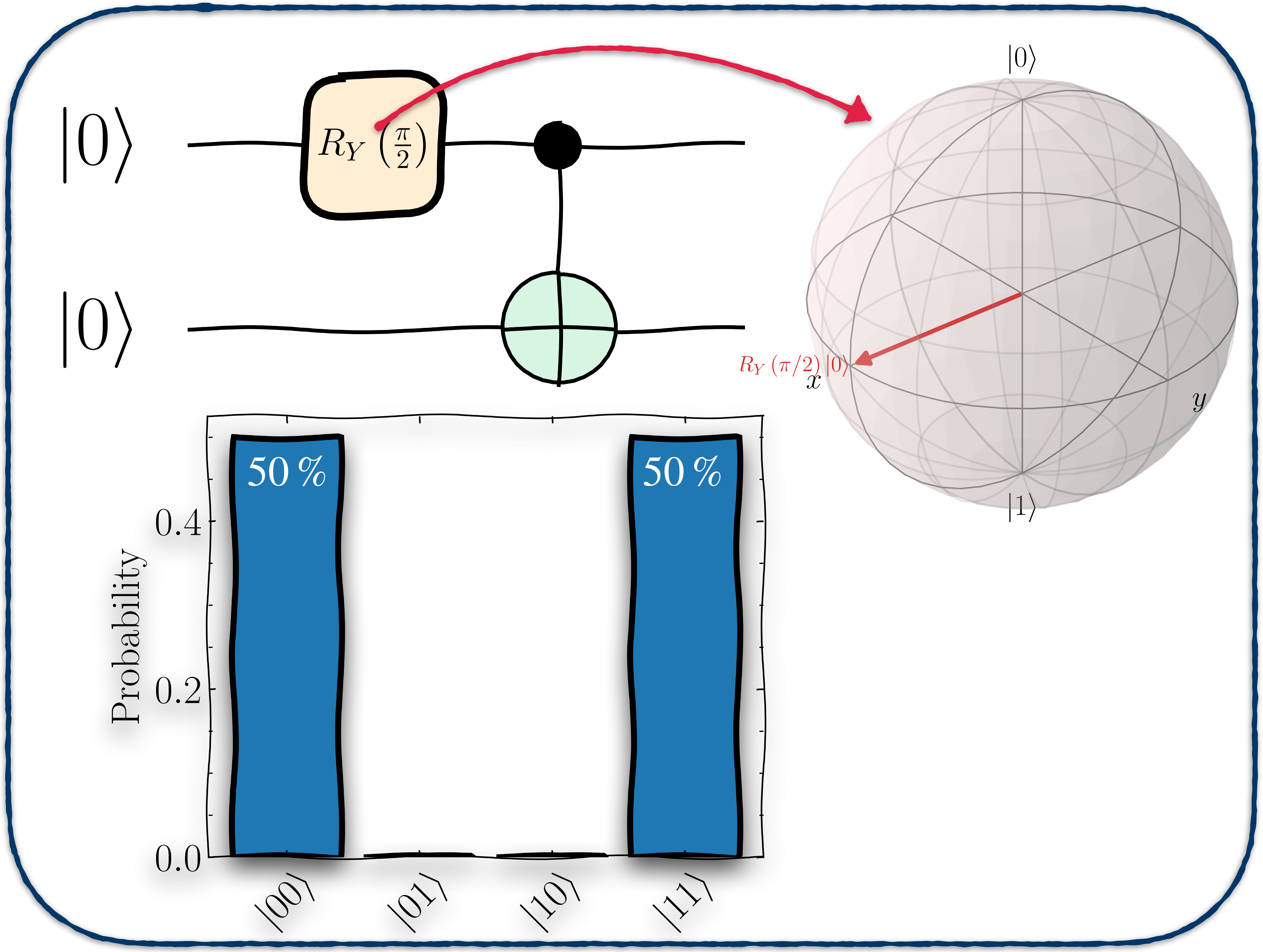

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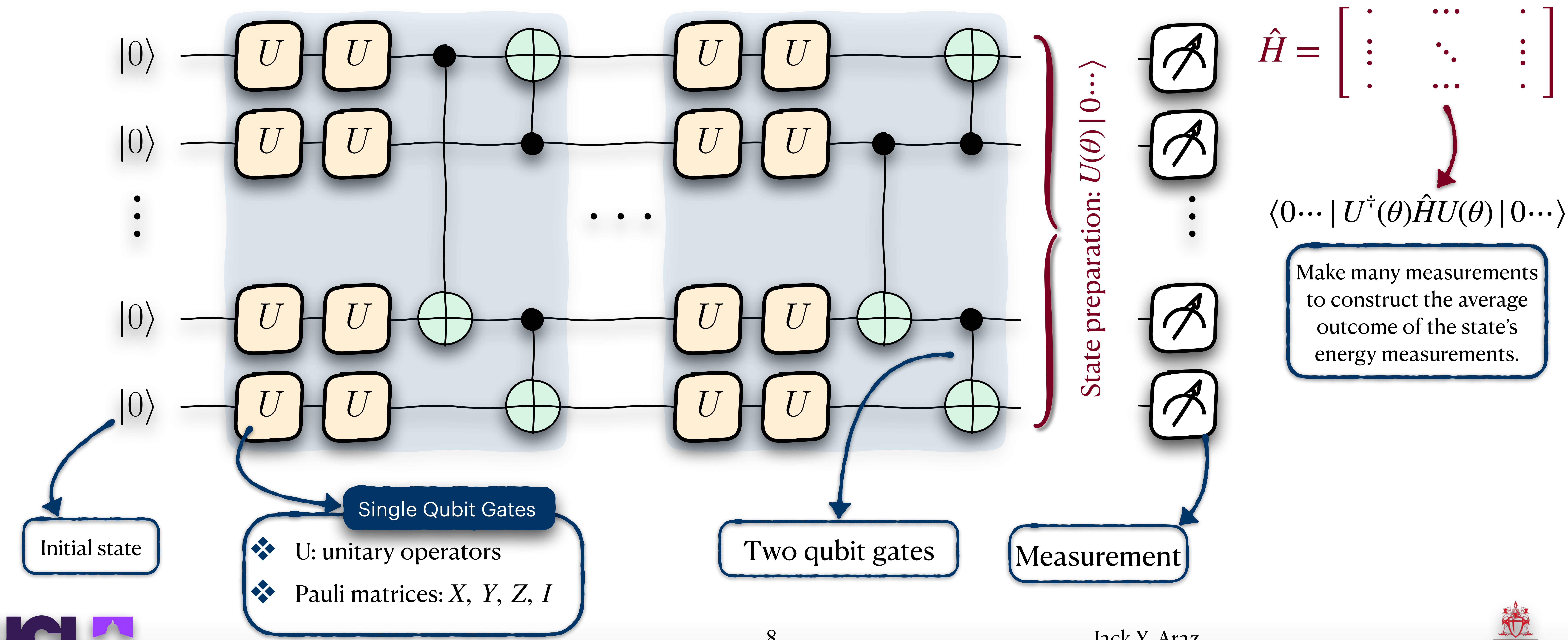


Simulating Fundamental Physics

Probing the fundamental structure of matter

Classical Methods

- Exact diagonalisation
- Monte Carlo
- Tensor Networks

- Condensed matter & quantum many-body systems
- Simulating atomic/molecular structure (chemistry)
- Understanding the structure of proton (i.e. QCD) (nuclear physics)

And many more...

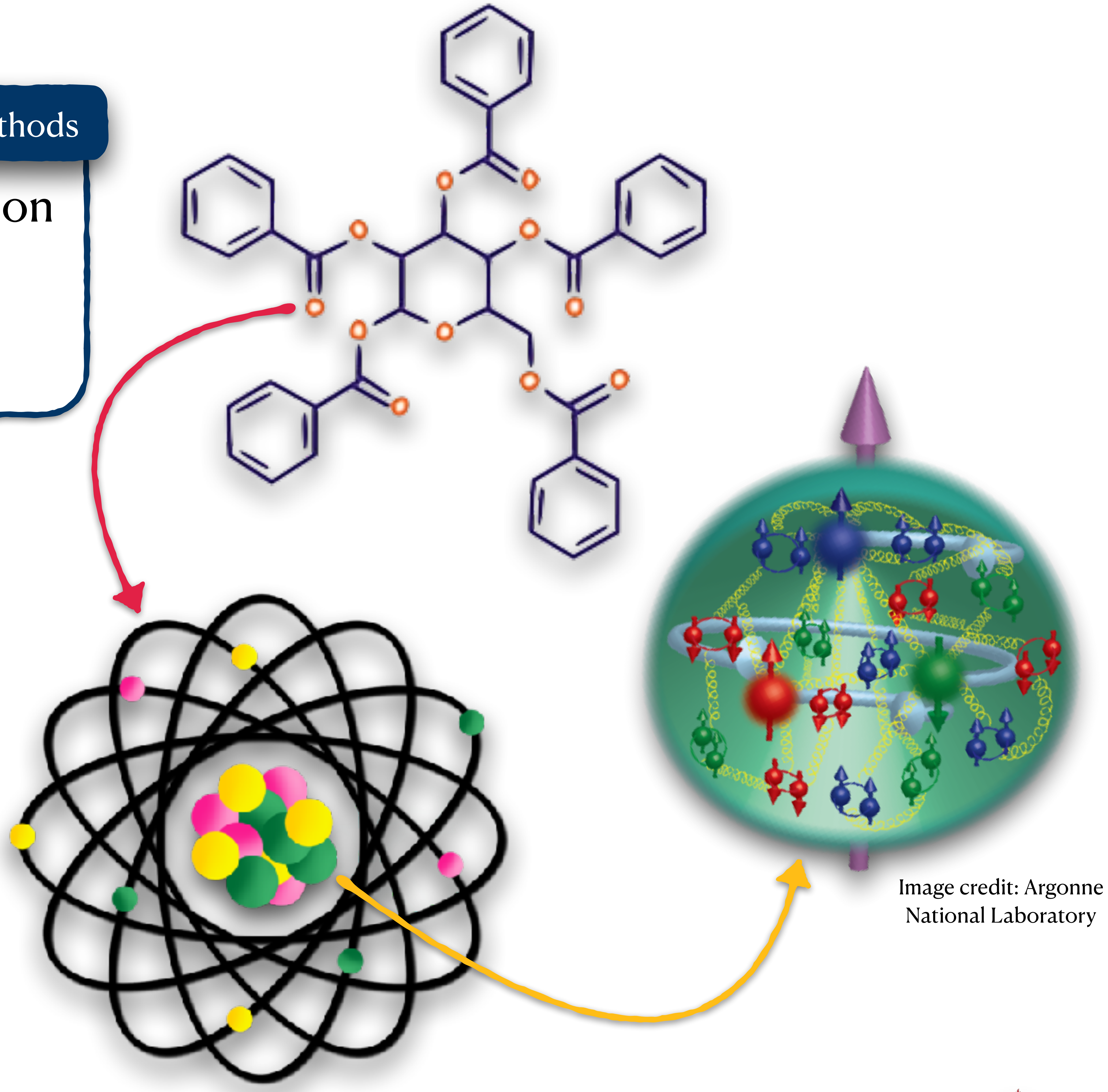
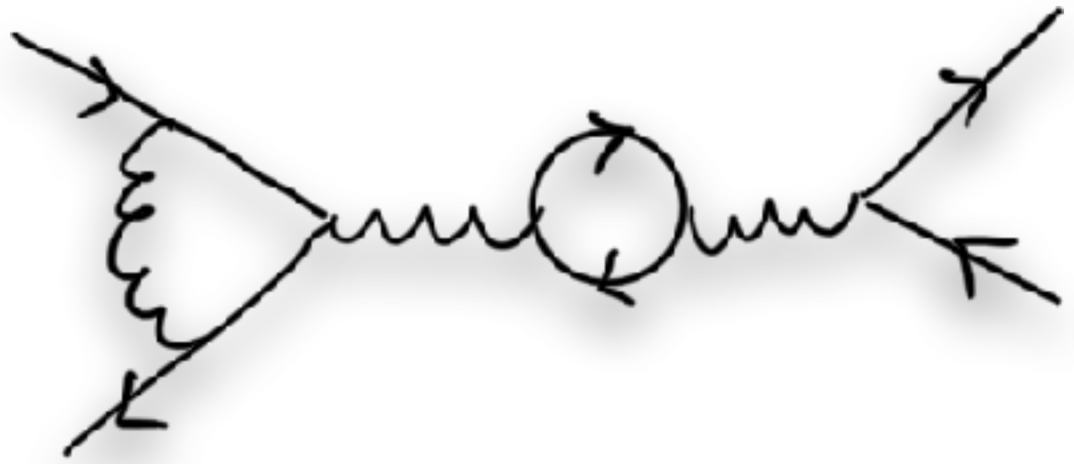


Image credit: Argonne National Laboratory

QCD from first principles

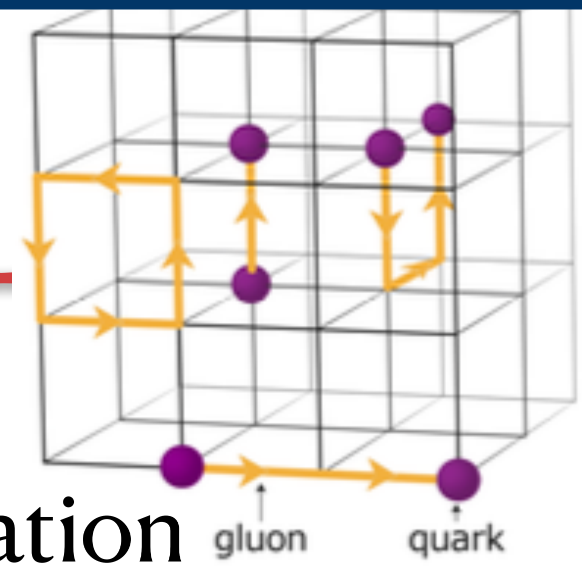
- Perturbative QCD at high energies

$$\sigma = \sigma^{(0)} + \alpha_s \sigma^{(1)} + \alpha_s^2 \sigma^{(2)} + \cdots$$



Not so much at low energies!!!

Lattice QCD



- Simulation via lattice discretisation
- Path integral vs Hamiltonian formulation
- Quantum computing for real-time dynamics

Wilson, Kogut, Susskind, 70's

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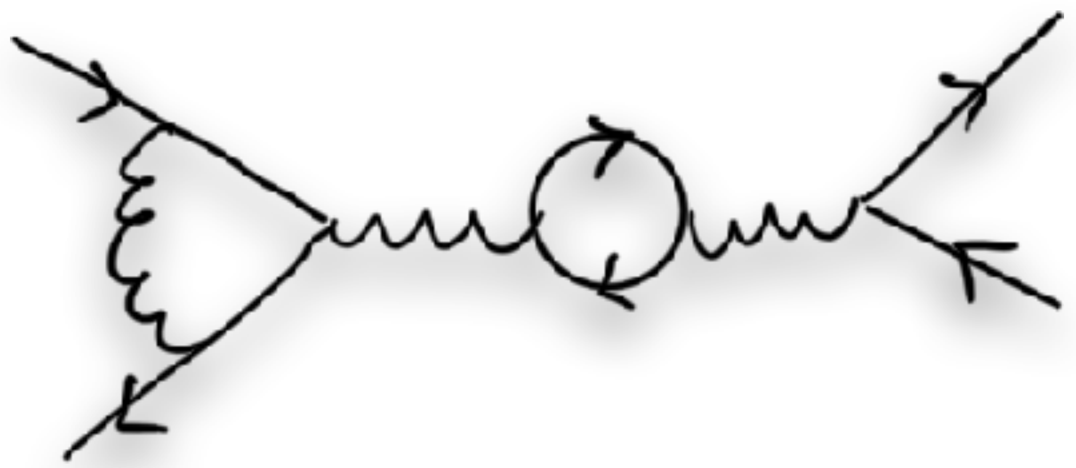

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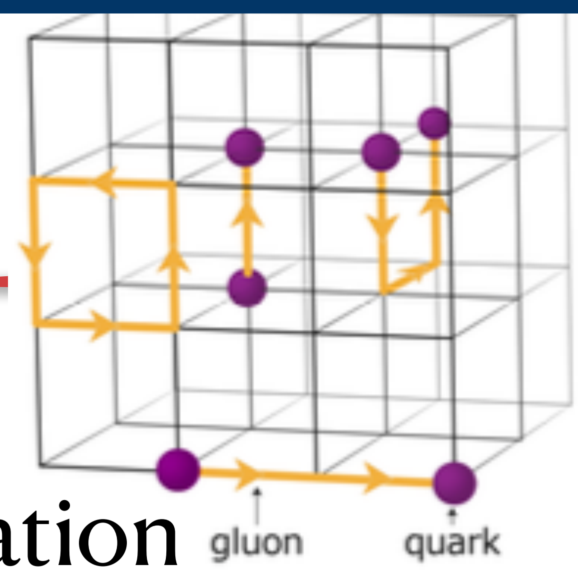

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Wilson, Kogut, Susskind, 70's

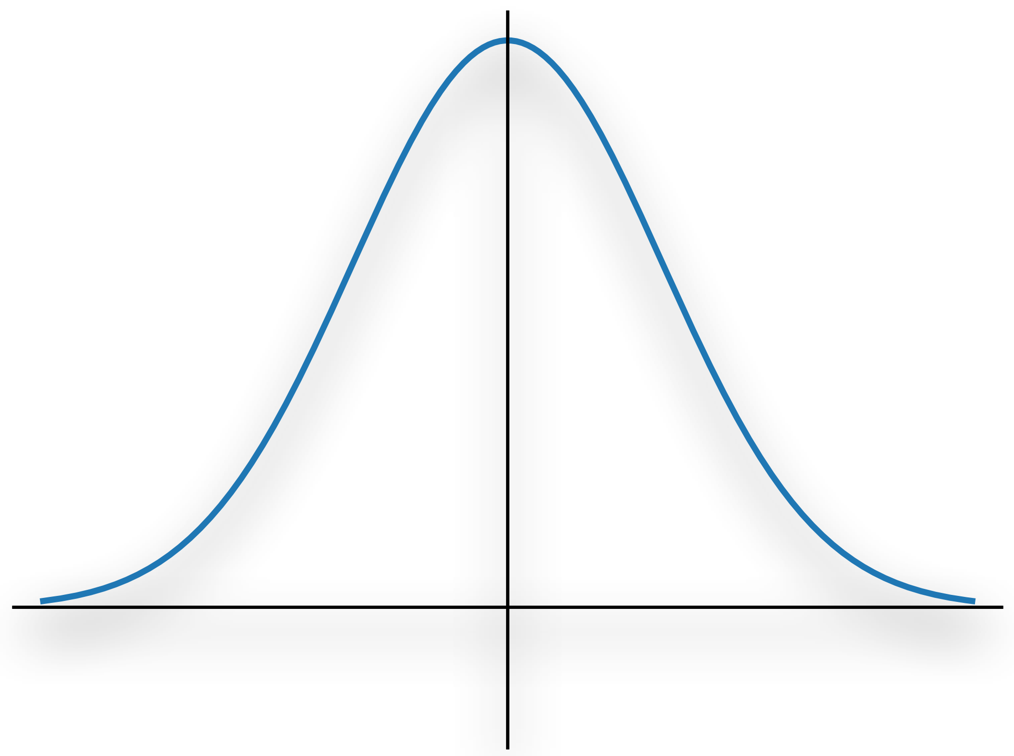
- Sign problem in Lattice QCD

$$\mathscr{L}_{QCD} \to \mathscr{L}_{QCD} + i\mu \sum_f \bar{q}_f \gamma_0 q_f$$

$$e^{-S} \to e^{-iS}$$

Chemical potential

$$\langle \mathcal{O} \rangle = \langle \mathcal{O} e^{-S} \rangle / \langle \sigma \rangle$$



QCD from first principles

- Perturbative QCD at high energies

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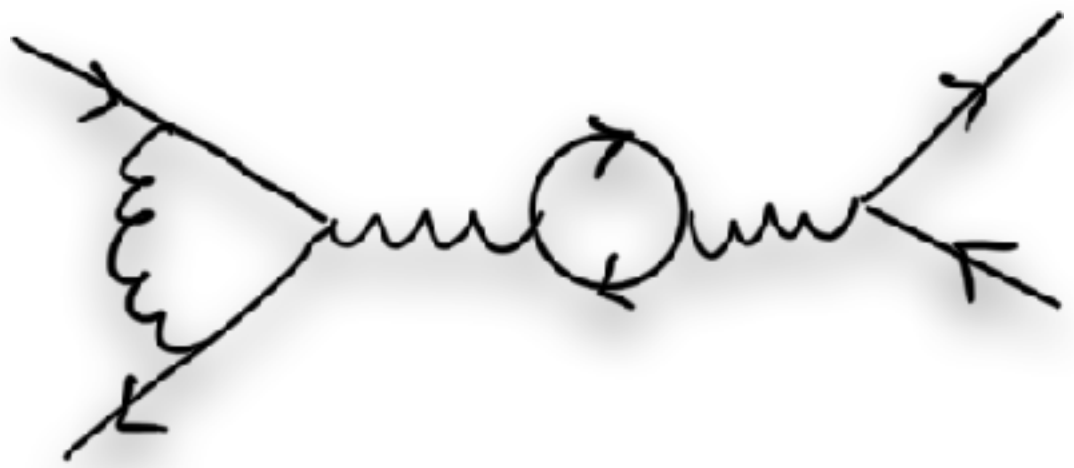

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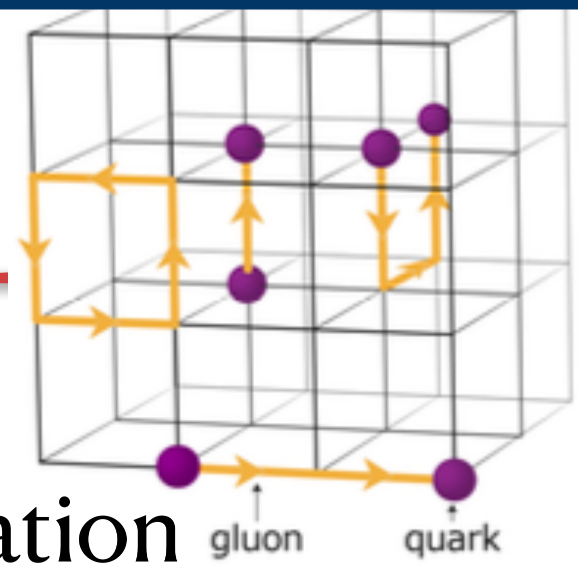

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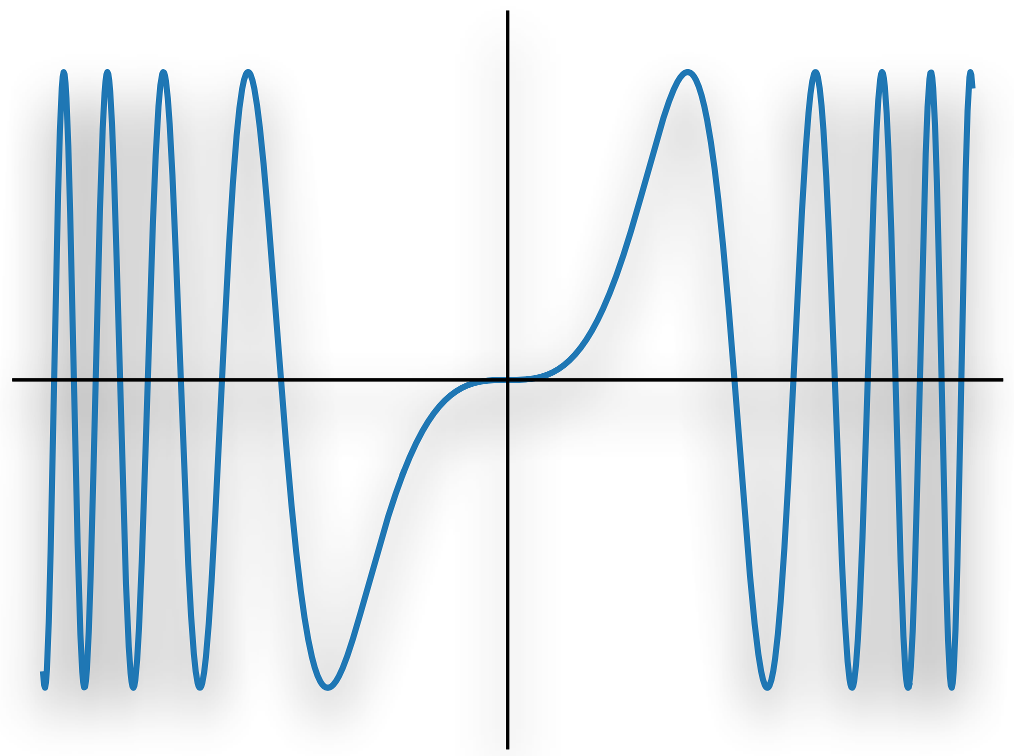


The problem

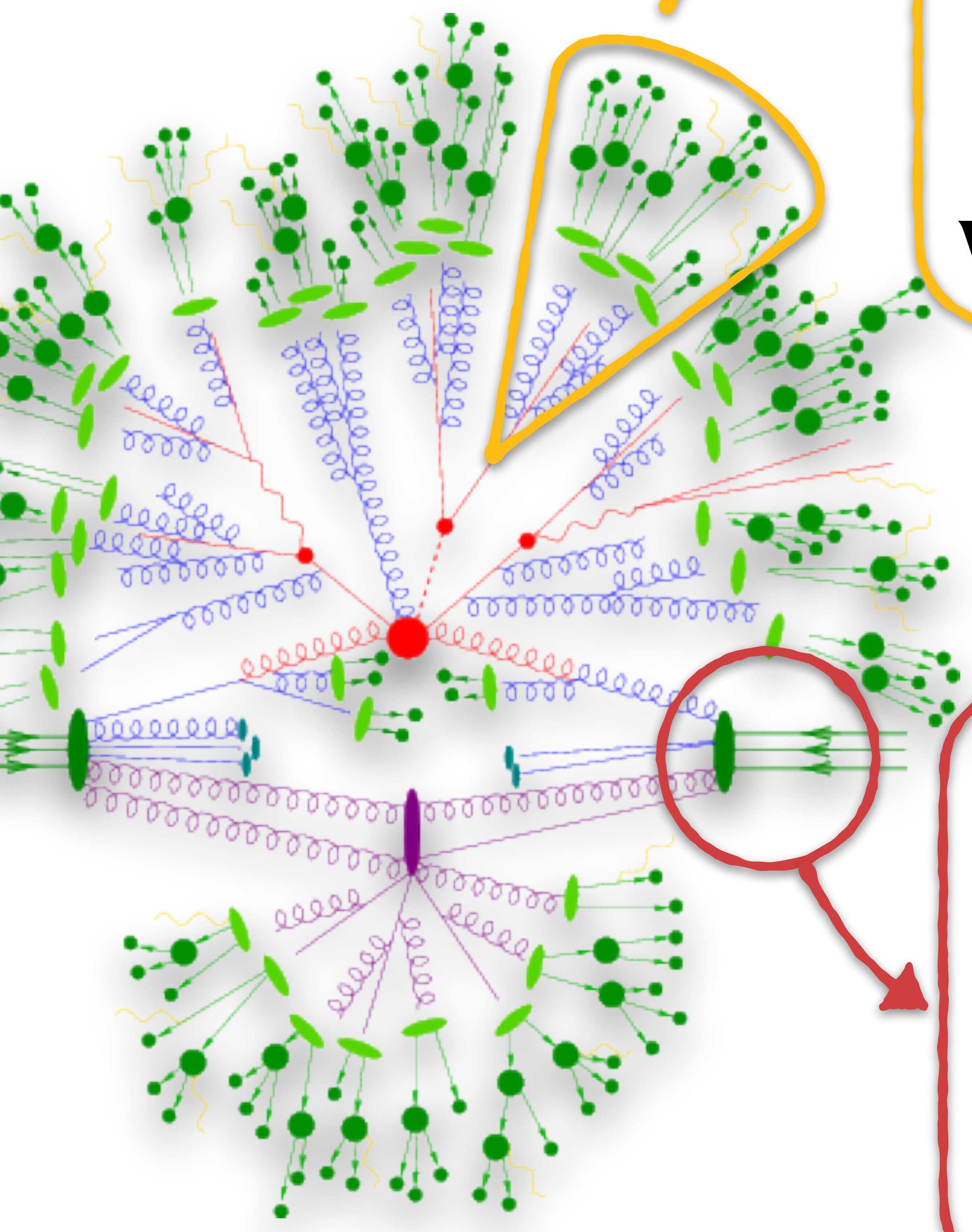
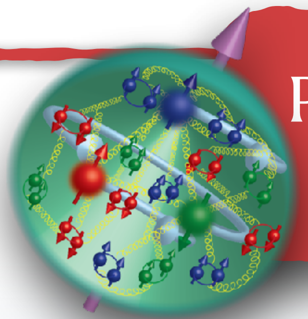


Image credit: Sherpa

How do the quarks and gluons evolve to become the particles we observe at the LHC?

Fragmentation Function (FF)

How a proton's momentum is distributed among quarks and gluons?



Parton Distribution Function (PDF)

The theory is well established, but impossible to solve even with the most powerful supercomputers.

Lattice QCD

- Can not access time-dependent observables
- PDF requires indirect extraction
- FF is largely inaccessible
- Computational cost scales exponentially

The problem

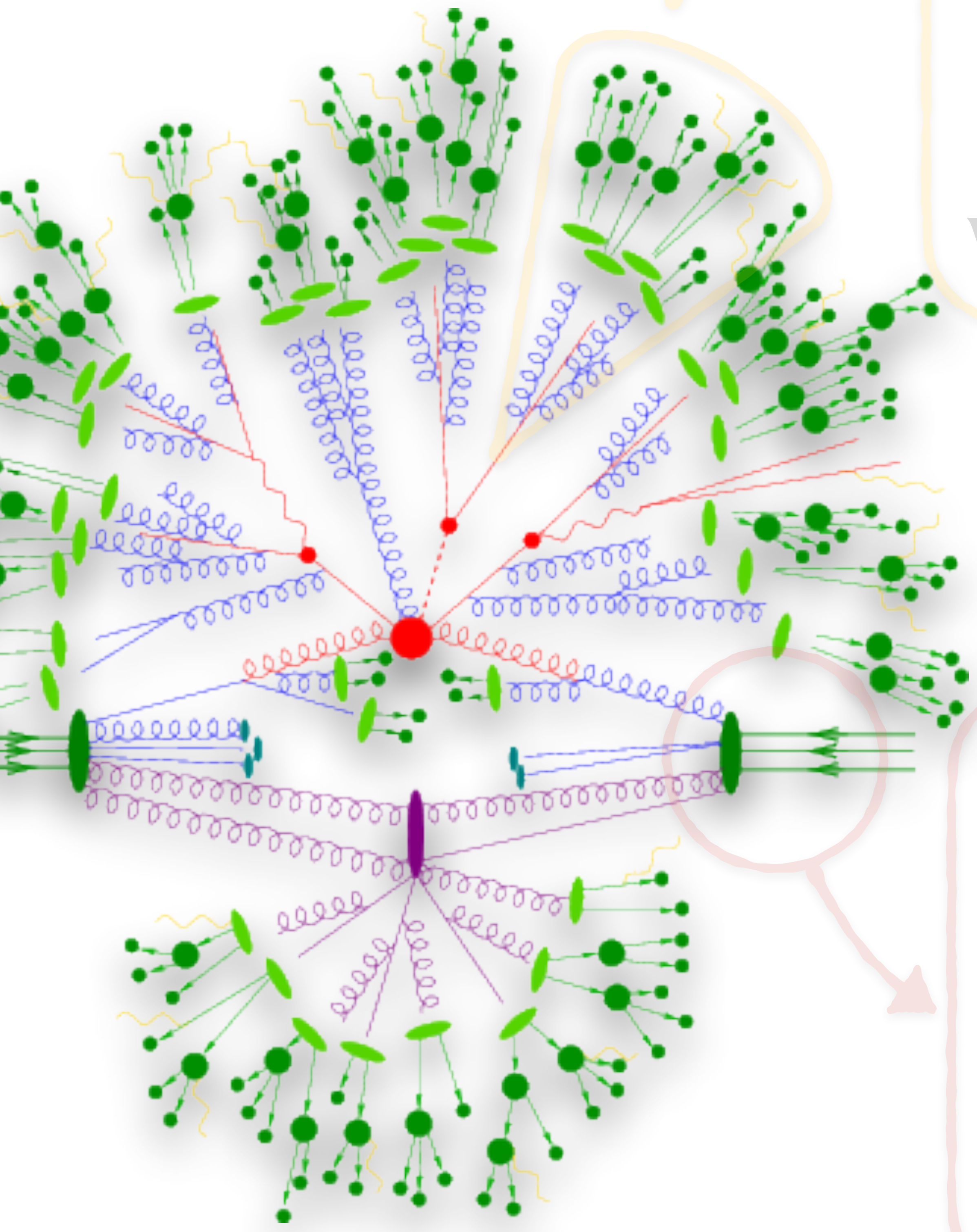


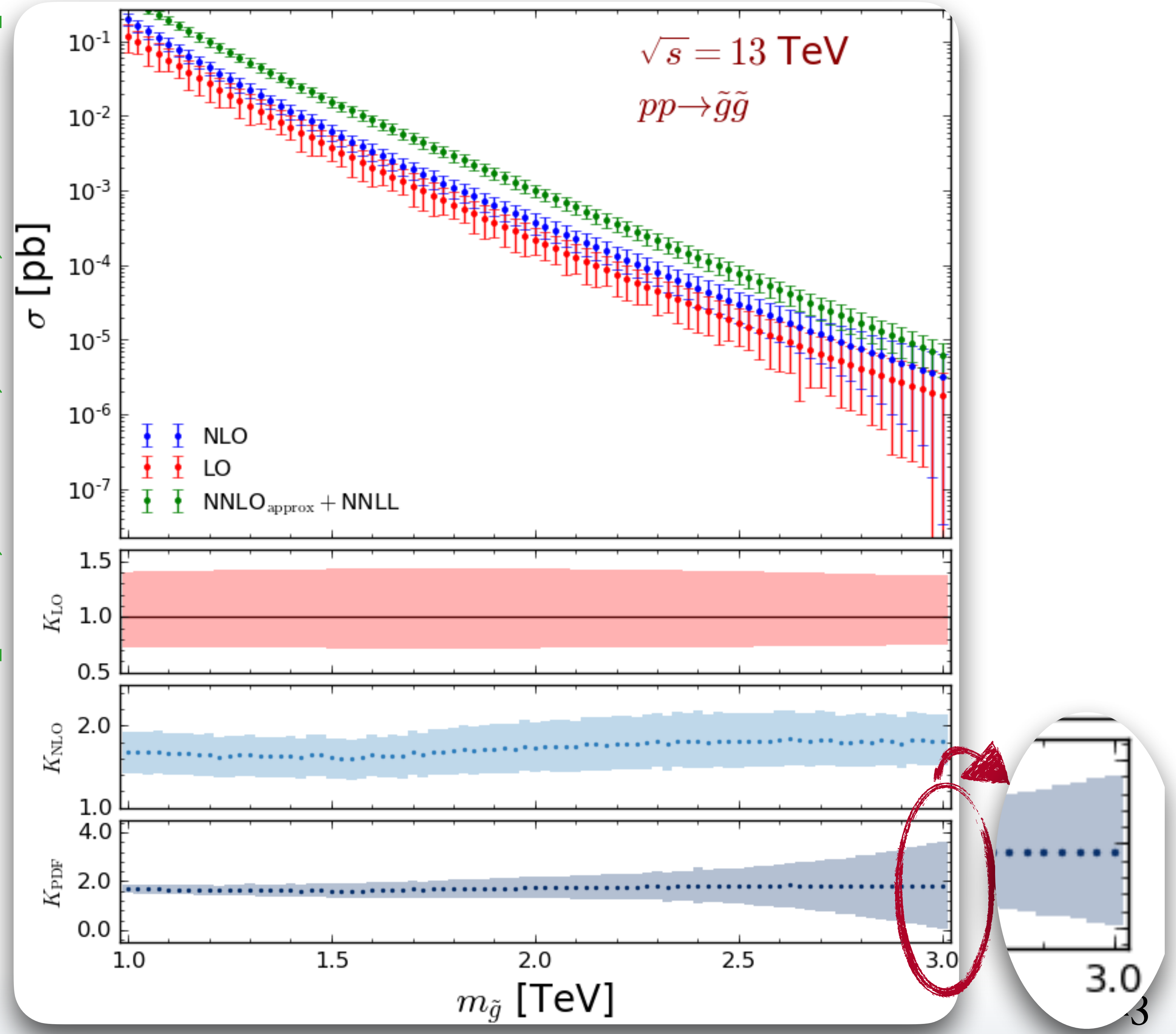
Image credit: Sherpa

How can we simulate time-dependent, non-perturbative phenomena?

Example: Why PDF?

- How quarks & gluons give rise to nucleons & pions?
  - Time-dependent → not amenable to calculation on an Euclidean lattice

[JYA, Frank, Fuks; EPJC '20]



Example: Why PDF?

- How quarks & gluons give rise to nucleons & pions?
  - Time-dependent → not amenable to calculation on an Euclidean lattice

In the hadron rest frame:

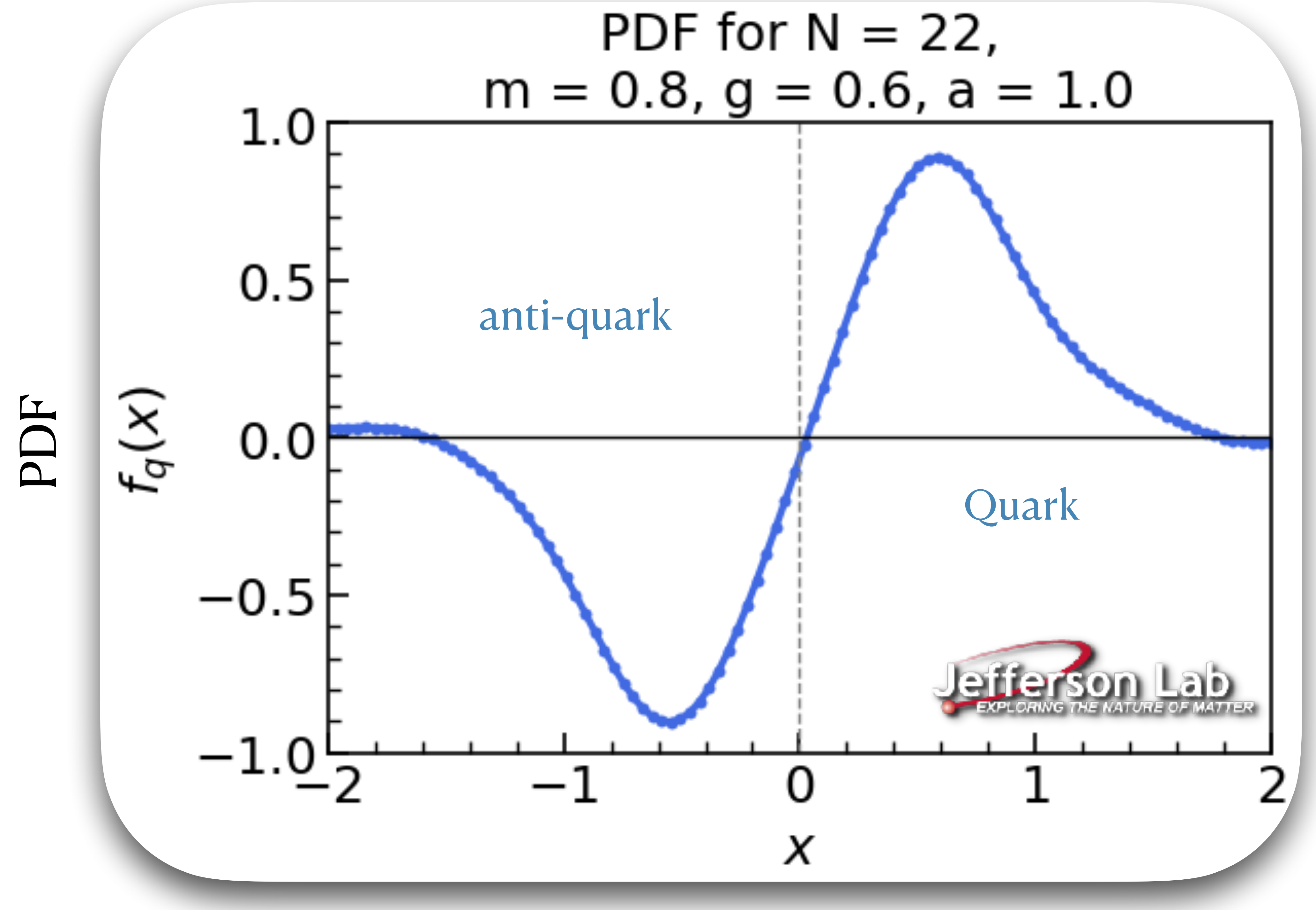
$$f_q(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \left[\langle h \,|\, e^{iHz} \bar{\psi}(0,-z) e^{-iHz} \psi(0,0) \,|\, h \rangle \right]$$

Quark field

Hadron state

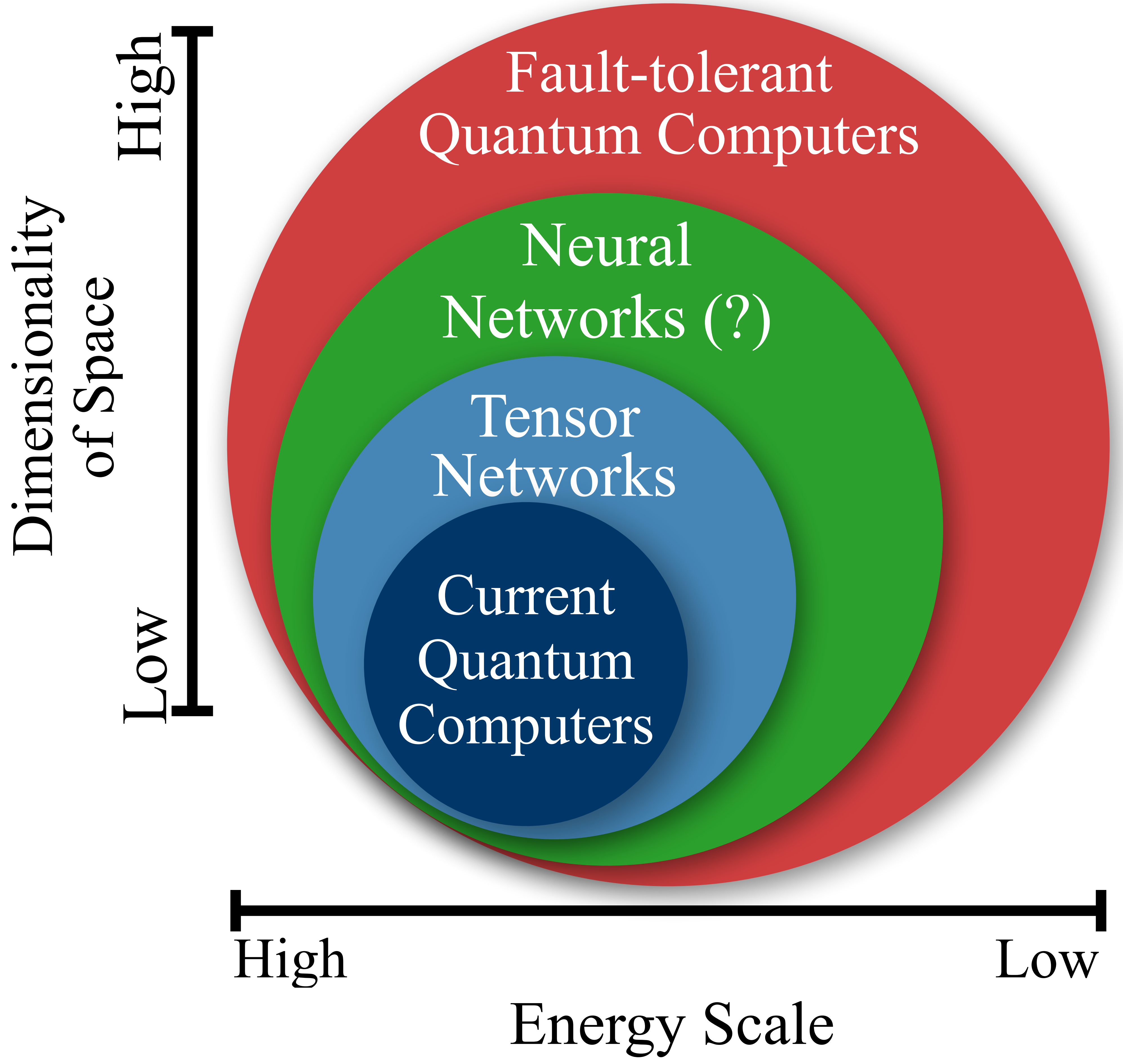
Time-dependent correlations can be computed in polynomial time on a Quantum Computer!

Very preliminary results:
[JYA, J. Qui, D. Richards, et. al.]



Momentum fraction

Towards quantum-enabled fundamental science



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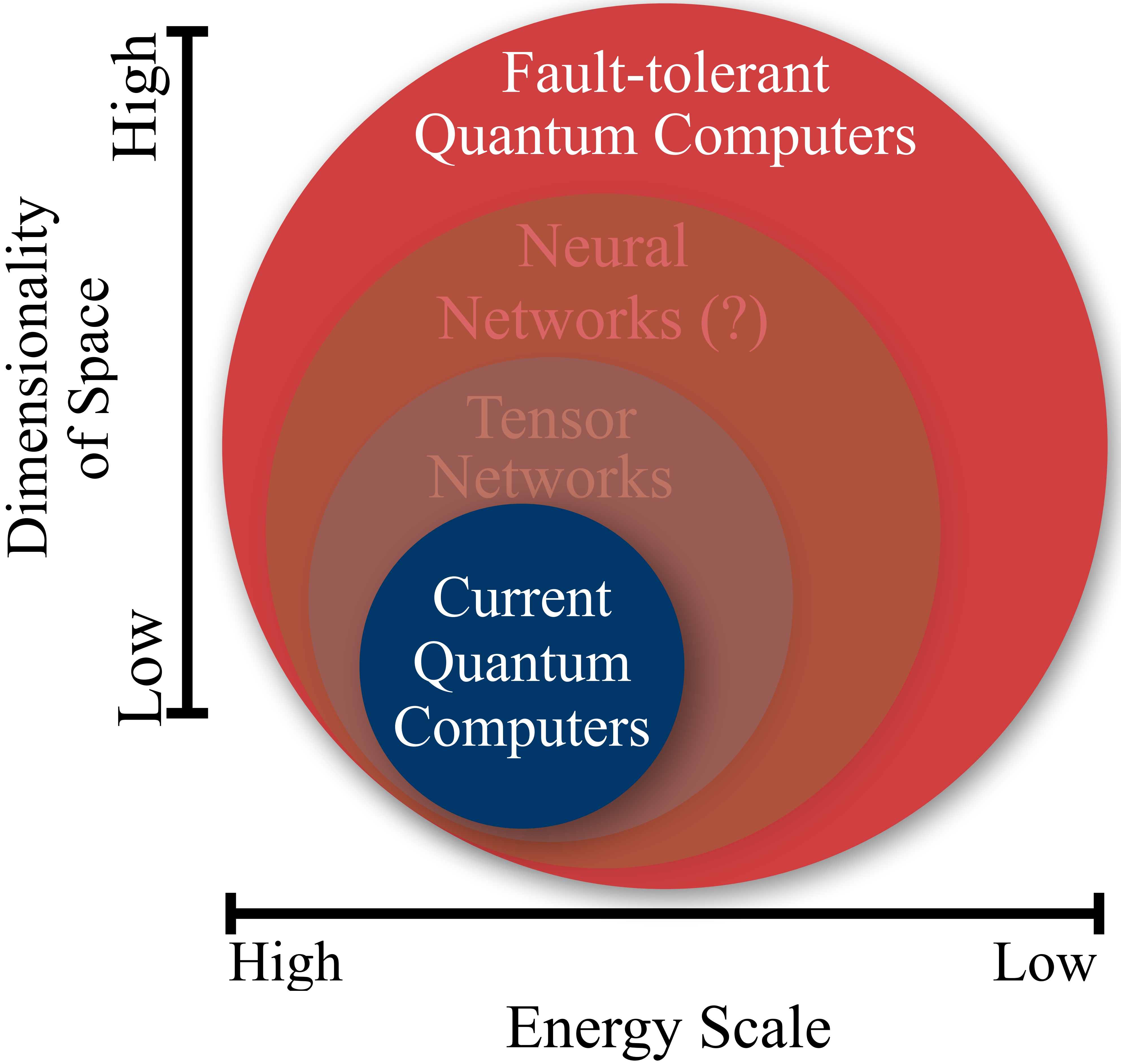
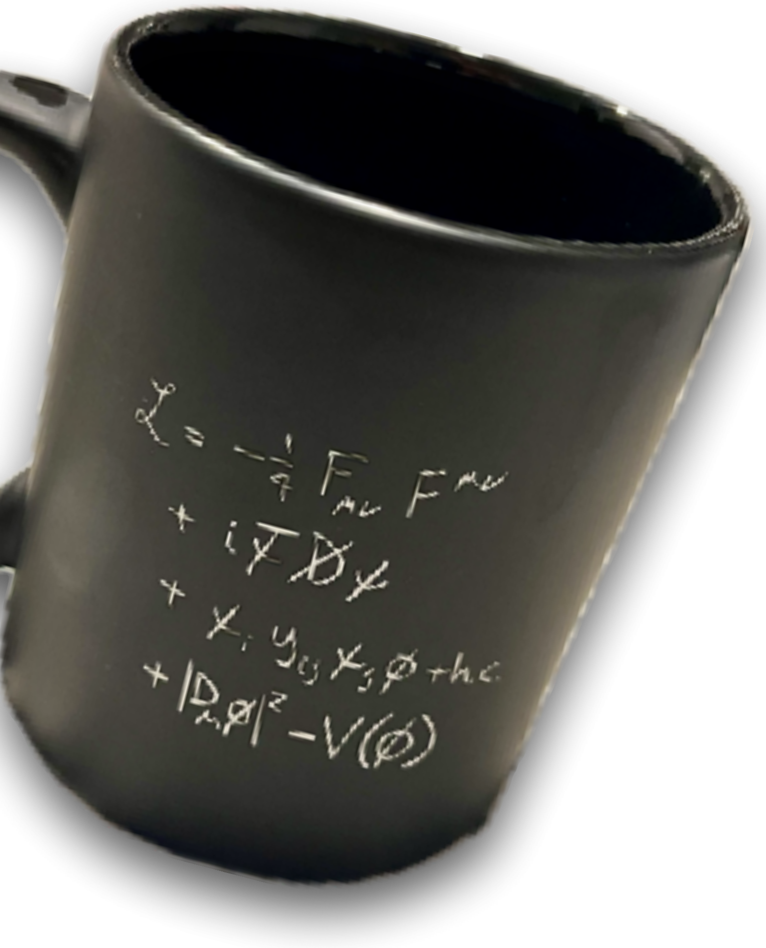
Towards quantum-enabled fundamental science



Which Quantum Hardware is the right one for the Standard Model?

Towards simulating QCD

$$\mathscr{L} = \bar{\psi}(i\partial^\mu\gamma_\mu - m)\psi$$



$$-\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

$$+g\bar{\psi}\gamma^\mu T_a \psi A^a_\mu$$

Towards simulating QCD

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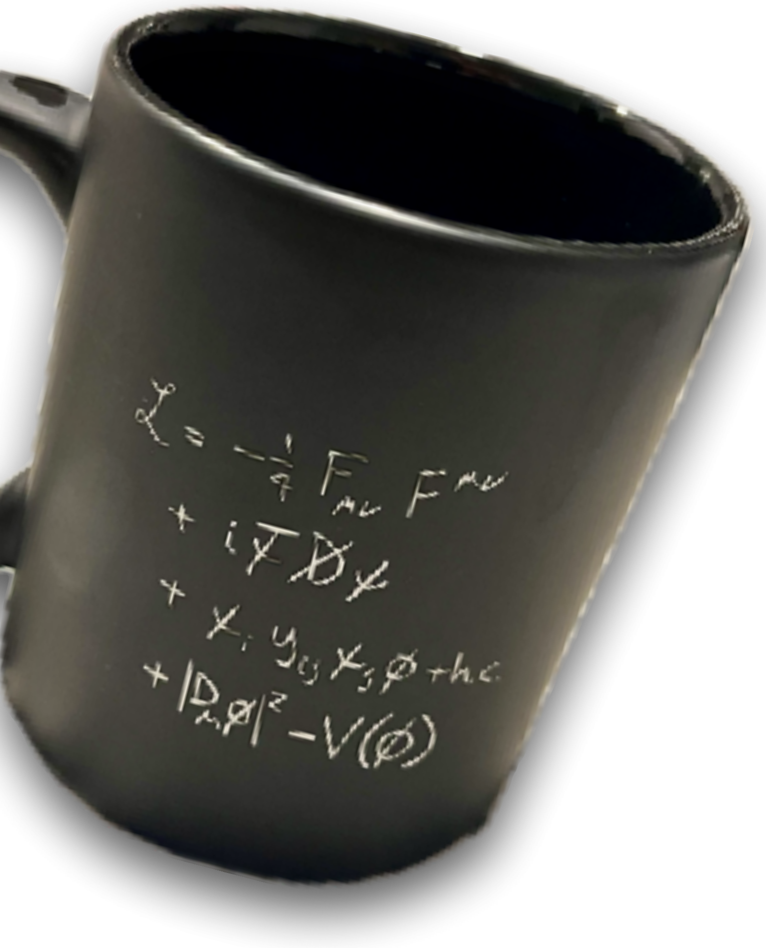

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DoF → ∞

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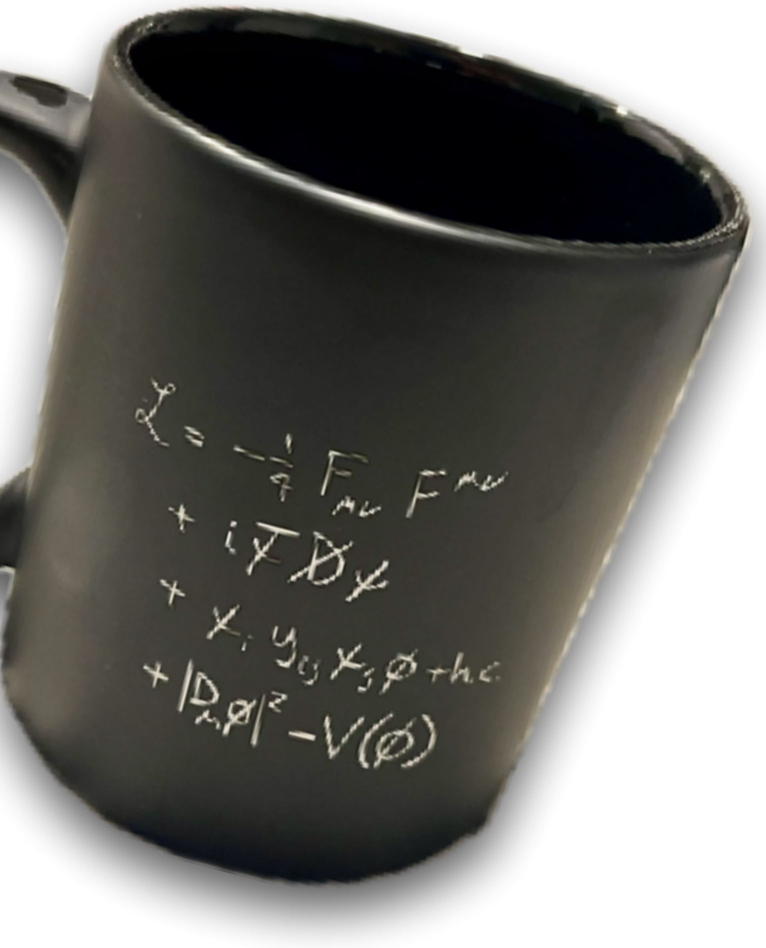

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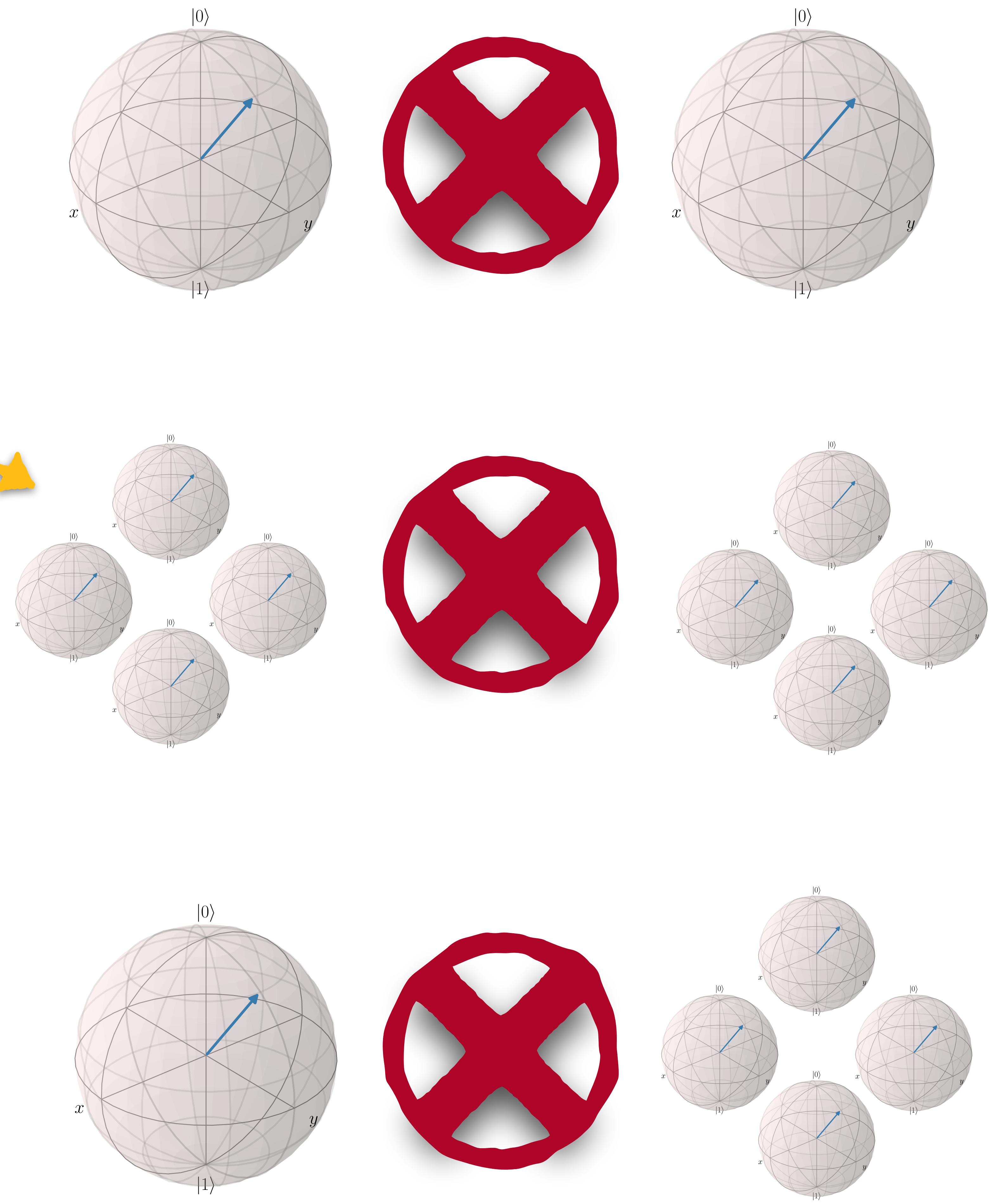

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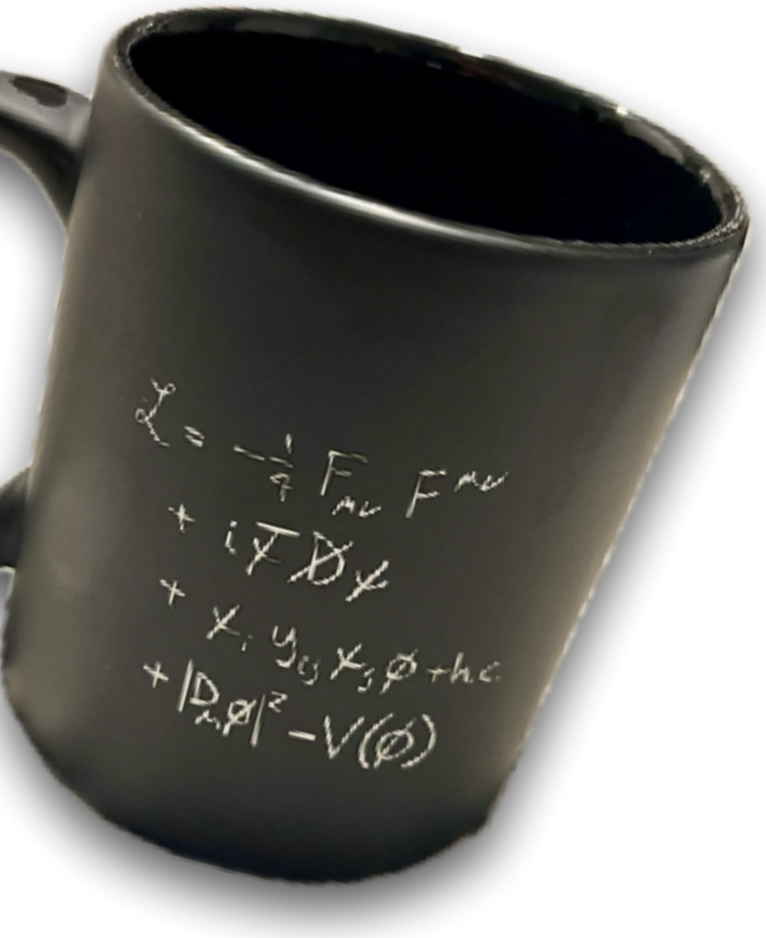


$$-\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

Qumodes or CV Quantum Computers

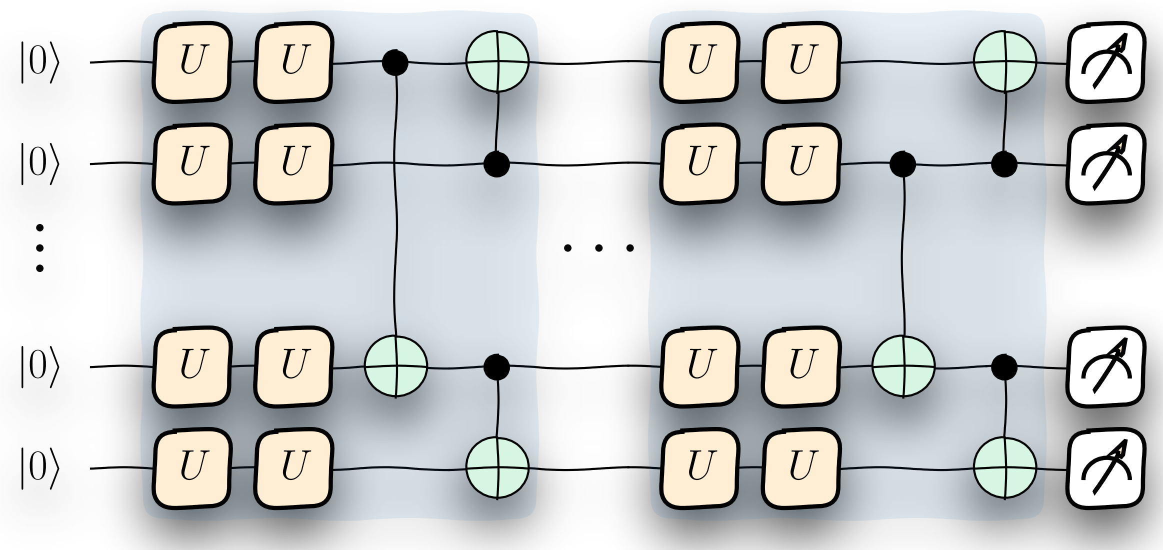
$$+g\bar{\psi}\gamma^{\mu}T_a\psi A^a_{\mu}$$

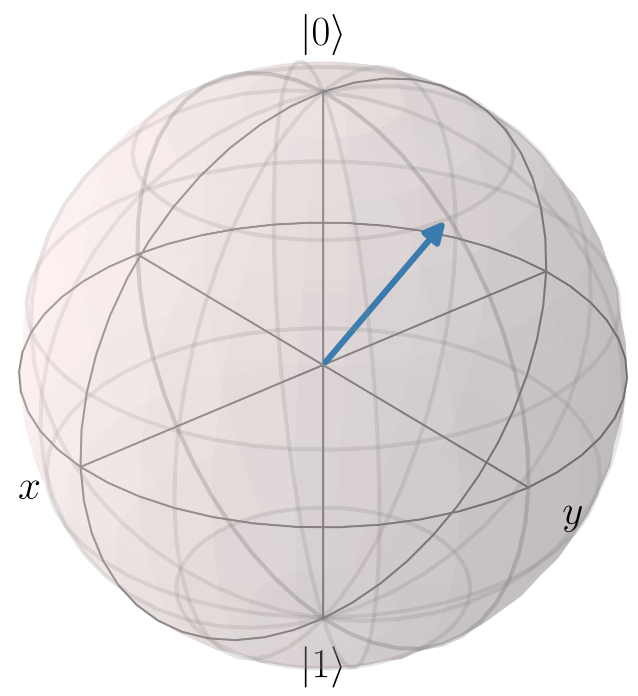
Qubit-Qumode Coupling

Qubits & Qumodes

Qubits

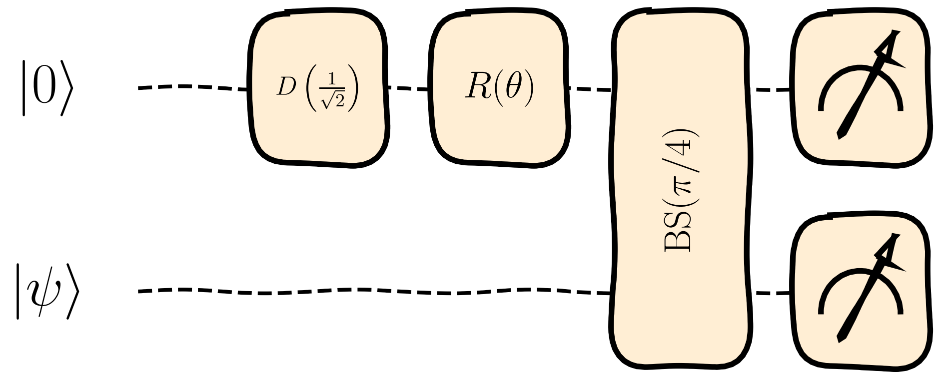
- Superconducting circuits, cold atoms, trapped ions, topological qubits
- Digital gate-based computing

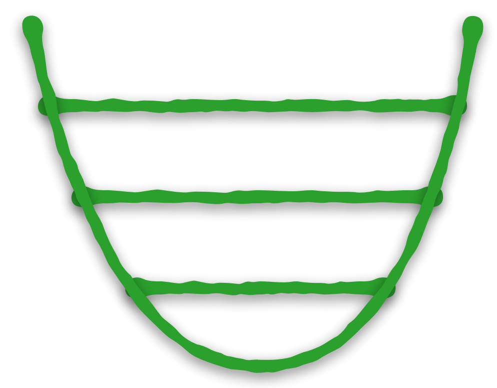




Qumodes

- Photonics, trapped ions, superconducting circuits
- Infinite-dimensional Hilbert space
- Gate-based BUT with continuous variables



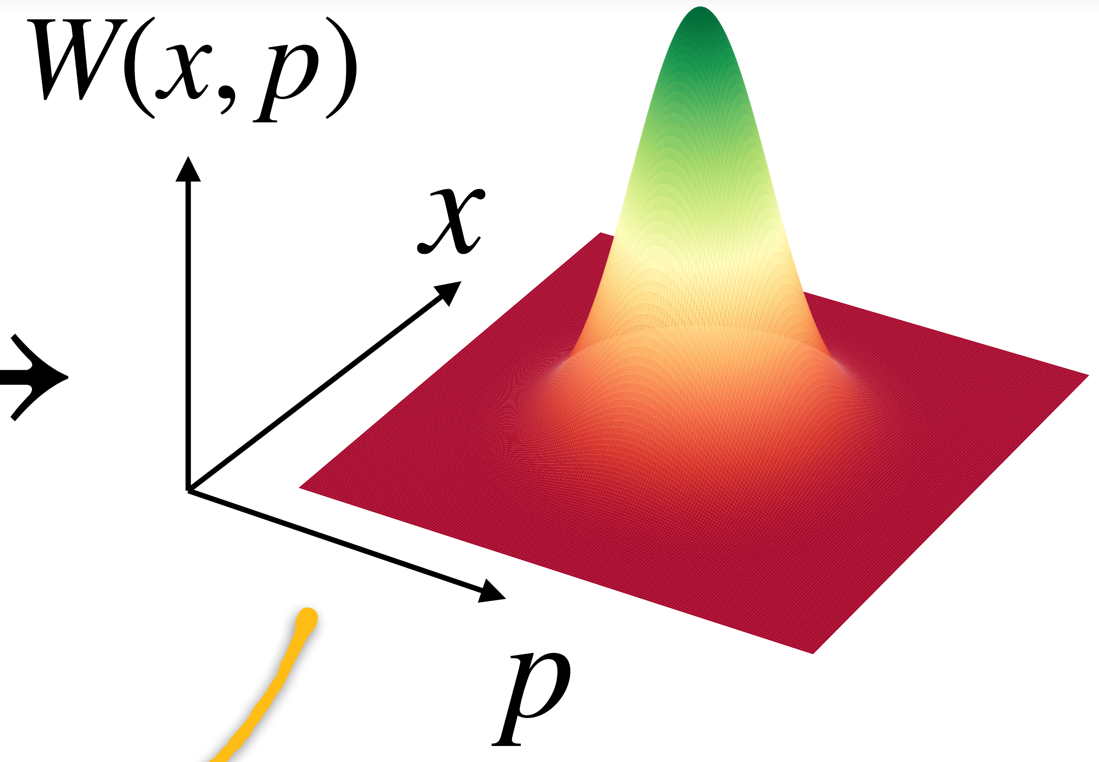


Quantum simulations with Qumodes

Llyod, Braunstein, '99

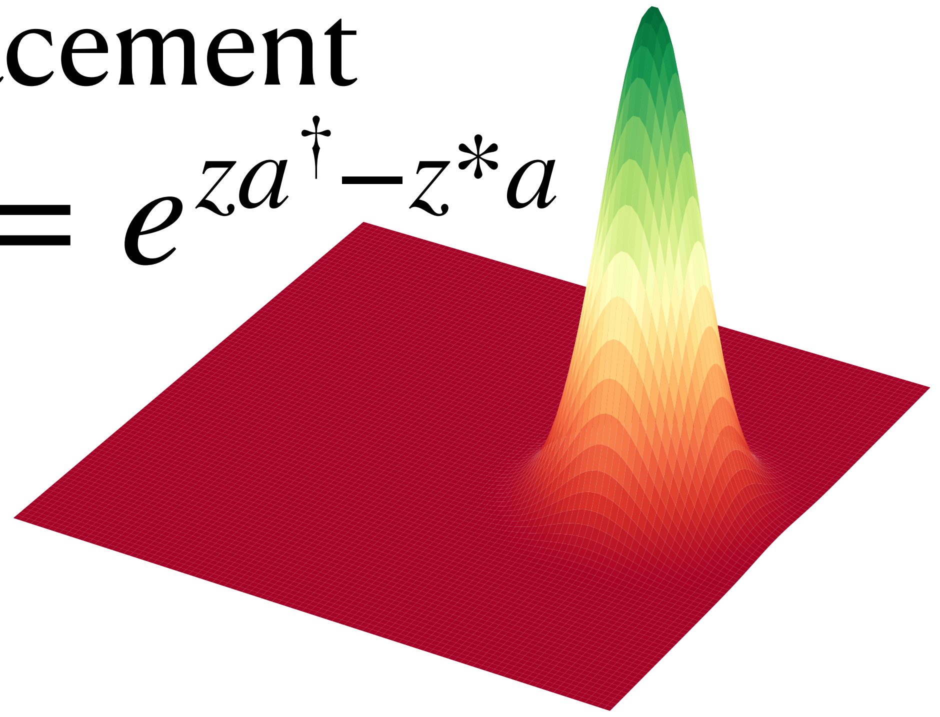
Universal gateset for Qumodes

$|0\rangle \rightarrow$

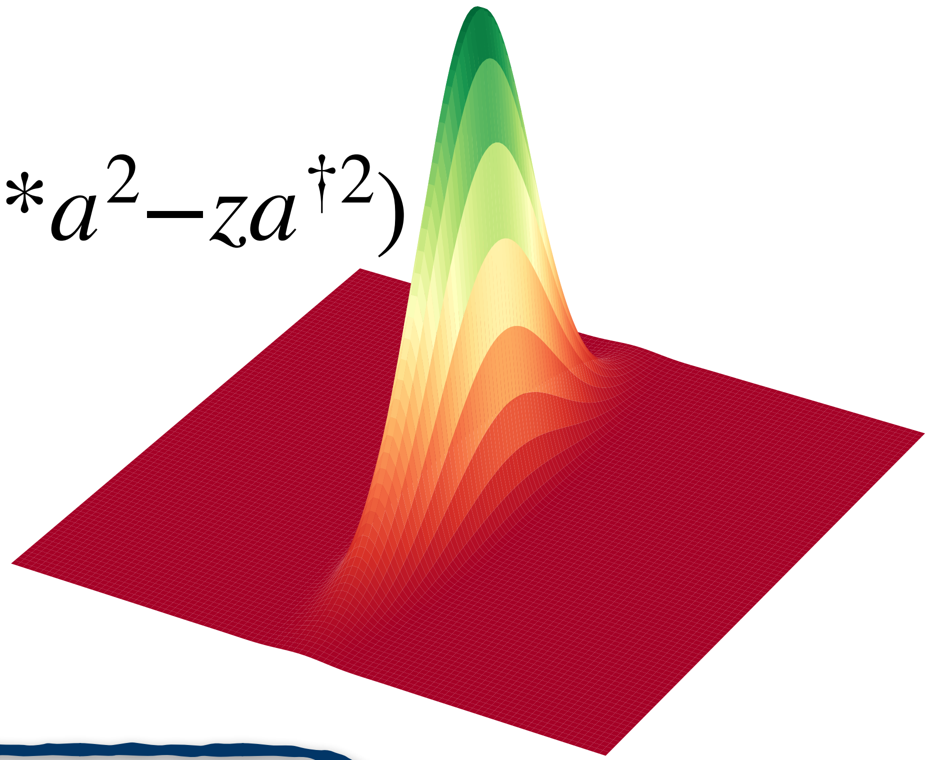


Wigner Function

- Displacement $D(z) = e^{za^\dagger - z^* a}$

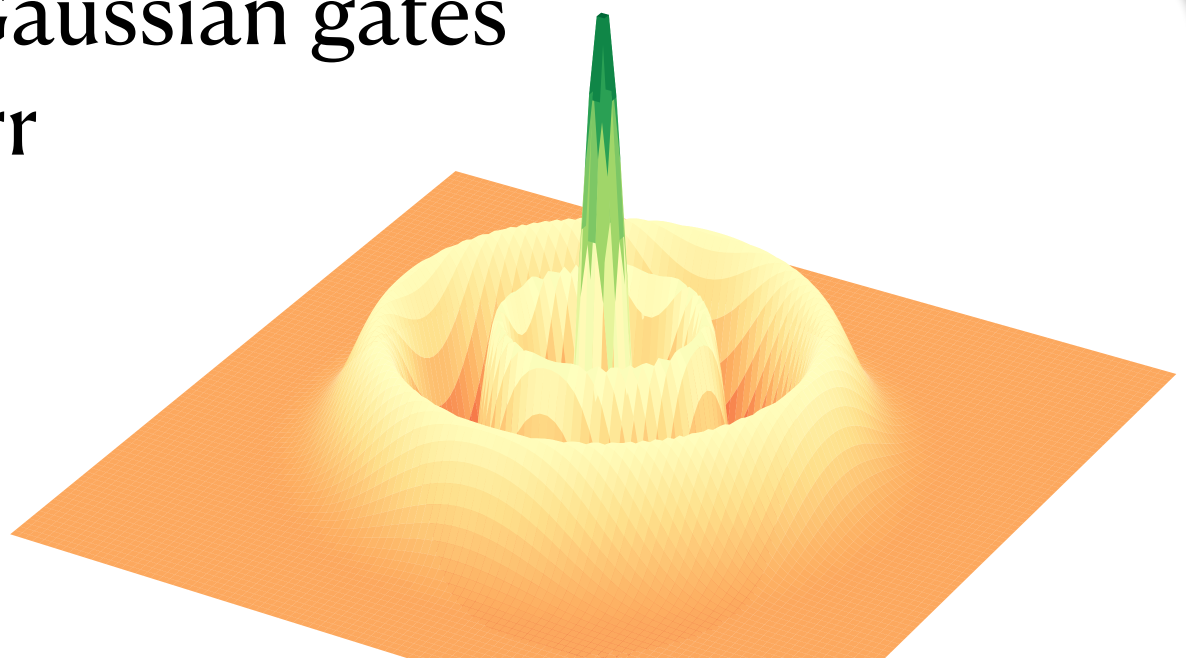


- Squeezing $S(z) = e^{\frac{1}{2}(z^* a^2 - z a^{\dagger 2})}$



- Rotation: $R(\theta) = e^{i\theta a^\dagger a}$
- Beam splitter: $BS(z) = e^{zab^\dagger - z^* a^\dagger b}$

Non-Gaussian gates
i.e. Kerr



Hybrid systems for quantum simulation

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Qubits & Qumodes with trapped ions

[JYA, Grau, Montgomery, Ringer; PRA '25]

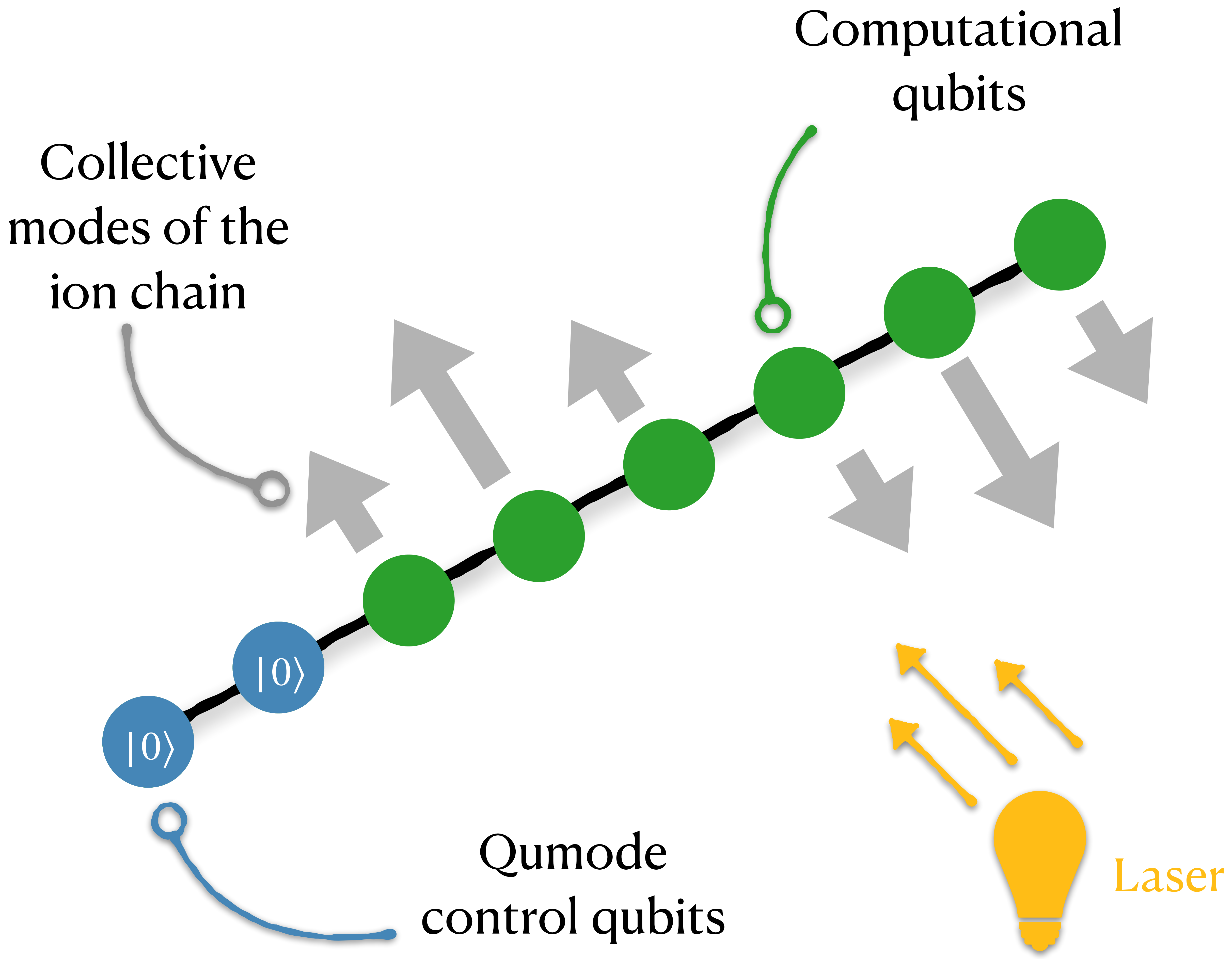
Qubits

Electronic states of the trapped ion

Qumodes

Collective vibrational modes of the ion chain (phonons)

✦ Need several qubits to control and readout qumodes



See also Girbin, Wiebe, et al. '22

Qubits & Qumodes with trapped ions

[JYA, Grau, Montgomery, Ringer; PRA '25]

Type	Operation	Short	Operator	Estimated fidelity
Qubit gates	Pauli operators		σ^i	99.999%
	Rotation	$R_i(\theta)$	$e^{i\theta\sigma^i/2}$	99.999%
	Controlled NOT	CNOT	$e^{i\frac{\pi}{4}(\mathbb{I}_1-\sigma_1^z)(\mathbb{I}_2-\sigma_2^x)}$	99.9%
Qumode gates	Rotation	$R(\theta)$	$e^{i\theta\hat{a}^\dagger\hat{a}}$	99%*
	Displacement	$D(z)$	$e^{z\hat{a}^\dagger-z^*\hat{a}}$	99%
	Single-mode squeezing	$S(z)$	$e^{(z^*\hat{a}\hat{a}-z\hat{a}^\dagger\hat{a}^\dagger)/2}$	98%
	Beam splitter	$BS(z)$	$e^{z\hat{a}^\dagger\hat{b}-z^*\hat{a}\hat{b}^\dagger}$	99%
	Kerr	$K(z)$	$e^{i\theta(\hat{a}^\dagger\hat{a})^2}$	95%*
	Cross-Kerr	$CK(z)$	$e^{i\theta\hat{a}^\dagger\hat{a}\hat{b}^\dagger\hat{b}}$	97%
Hybrid gates	Red sideband	$RSB(z)$	$e^{iz\hat{a}\sigma^+ + iz^*\hat{a}^\dagger\sigma^-}$	99.9%
	Blue sideband	$BSB(z)$	$e^{iz\hat{a}^\dagger\sigma^+ + iz^*\hat{a}\sigma^-}$	99.9%
	Controlled rotation	$CR(\theta)$	$e^{i\theta\sigma^z\hat{a}^\dagger\hat{a}}$	99%*
	Controlled displacement	$CD(z)$	$e^{\sigma^z(z\hat{a}^\dagger-z^*\hat{a})}$	95%*
	Controlled squeezing	$CS(z)$	$e^{\sigma^z(z^*\hat{a}\hat{a}-z\hat{a}^\dagger\hat{a}^\dagger)/2}$	99%*
	Controlled beam splitter	$CBS(z)$	$e^{\sigma^z(z\hat{a}^\dagger\hat{b}-z^*\hat{a}\hat{b}^\dagger)}$	99%
Measurements	Qubit Pauli strings		σ^i	99.99%
	Average phonon number		$\hat{N}$	97%
	Qumode PNR		$\|n\rangle\langle n\|$	99%
	Qumode homodyne		$\hat{X}, \hat{P}$	95%*
	Hybrid		$\sigma^i\hat{X},\ \sigma^i\hat{P}$	95%†

$^{171}Yb^+$ (ytterbium) ions in linear Paul trap

Qubits & Qumodes with trapped ions

[JYA, Grau, Montgomery, Ringer; PRA '25]

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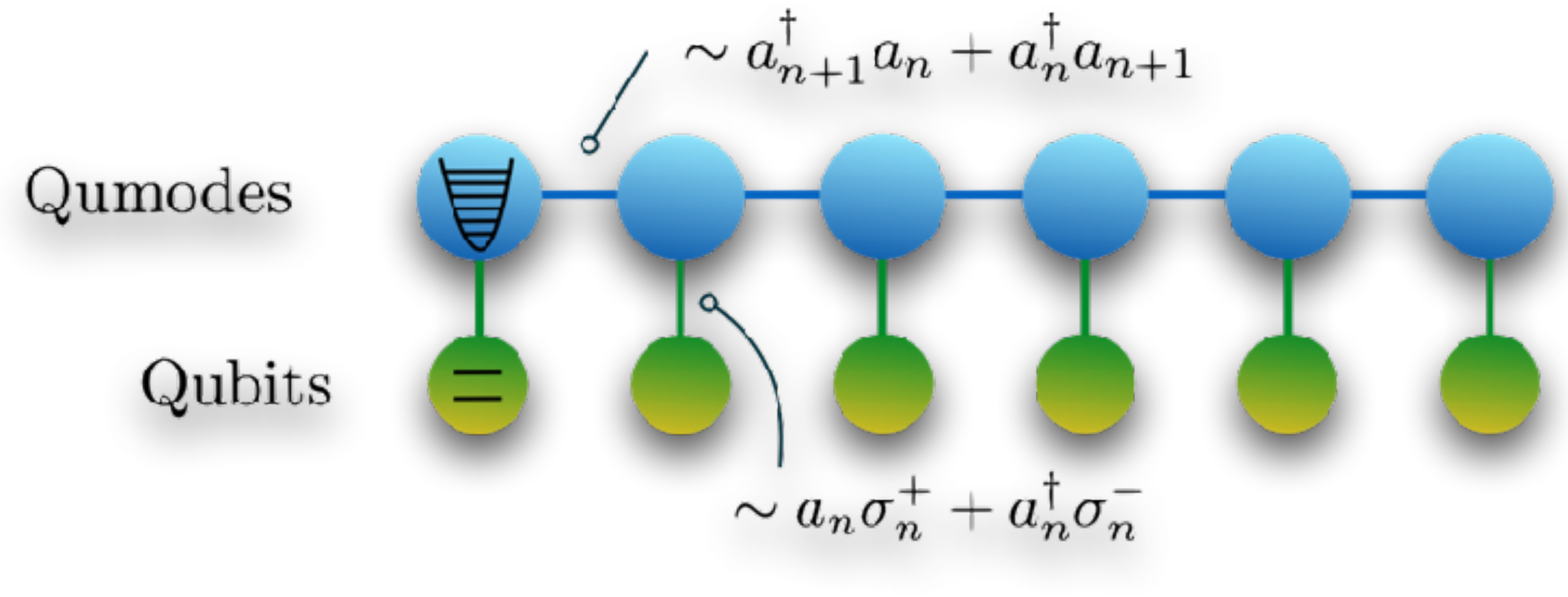
	Red sideband	RSB(z)	$e^{iz\hat{a}\sigma^+ + iz^*\hat{a}^\dagger\sigma^-}$	99.9%
	Blue sideband	BSB(z)	$e^{iz\hat{a}^\dagger\sigma^+ + iz^*\hat{a}\sigma^-}$	99.9%
	Controlled rotation	CR(θ)	$e^{i\theta\sigma^z\hat{a}^\dagger\hat{a}}$	99%*
	Controlled displacement	CD(z)	$e^{\sigma^z(z\hat{a}^\dagger - z^*\hat{a})}$	95%*
	Controlled squeezing	CS(z)	$e^{\sigma^z(z^*\hat{a}\hat{a} - z\hat{a}^\dagger\hat{a}^\dagger)/2}$	99%*
	Controlled beam splitter	CBS(z)	$e^{\sigma^z(z\hat{a}^\dagger\hat{b} - z^*\hat{a}\hat{b}^\dagger)}$	99%
	Qubit Pauli strings		[illegible]	[illegible]
Measurements	Average phonon number		$\hat{N}$	97%
	Qumode PNR		$\lvert n\rangle\langle n\rvert$	99%
	Qumode homodyne		$\hat{X}, \hat{P}$	95%*
	Hybrid		$\sigma^i\hat{X}, \sigma^i\hat{P}$	95%†

Jaynes-Cummings-Hubbard model

[JYA, Grau, Montgomery, Ringer; PRA '25]

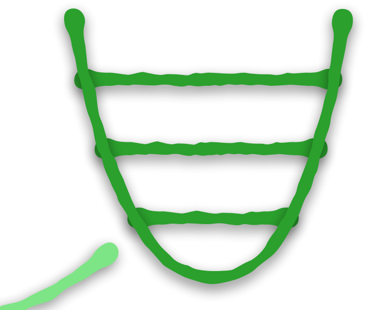
$$\hat{H} = \omega_c \sum_{n=1}^{M} \hat{a}_n^\dagger \hat{a}_n + \omega_a \sum_{n=1}^{M} \sigma_n^+ \sigma_n^- - \kappa \sum_{n=1}^{M} \left(\hat{a}_{n+1}^\dagger \hat{a}_n + \hat{a}_n^\dagger \hat{a}_{n+1} \right) + \eta \sum_{n=1}^{N} \left(\hat{a}_n \sigma_n^+ + \hat{a}_n^\dagger \sigma_n^- \right)$$

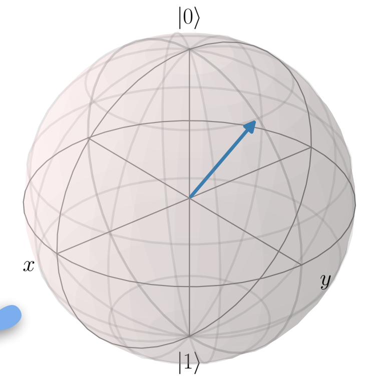


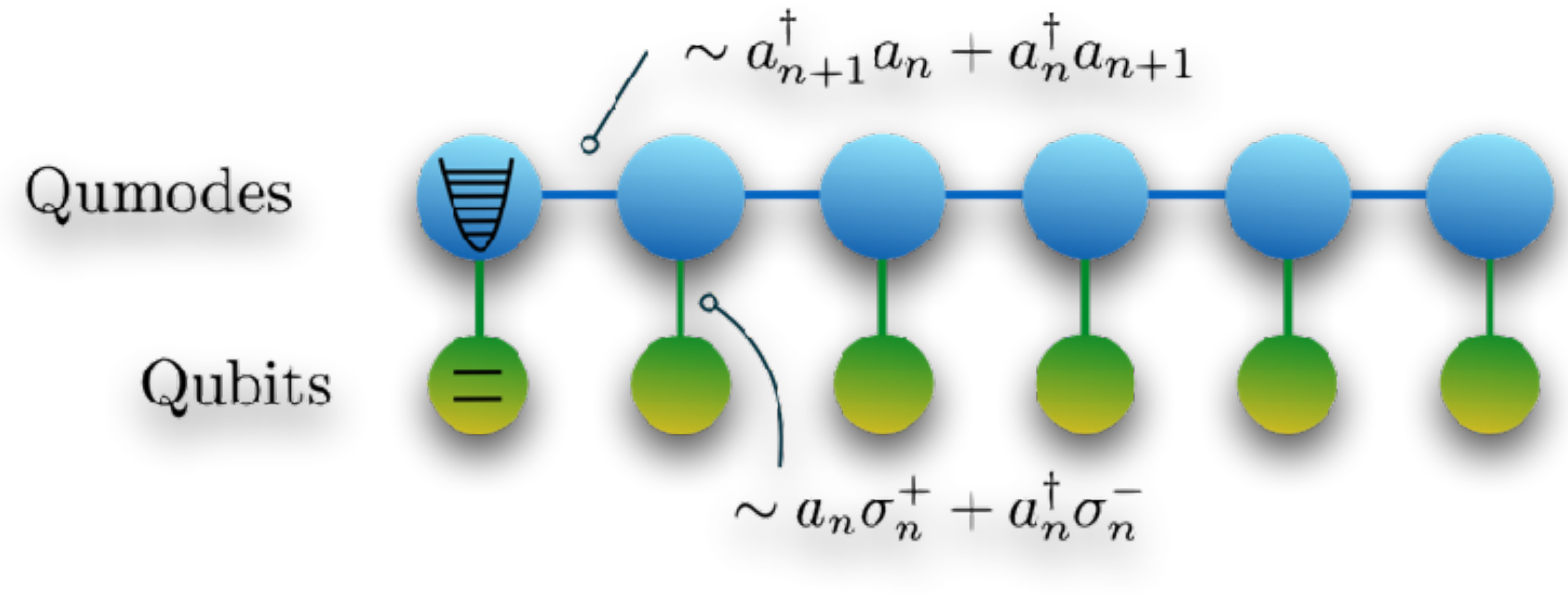
Jaynes-Cummings-Hubbard model

[JYA, Grau, Montgomery, Ringer; PRA '25]

$$\hat{H} = \omega_c \sum_{n=1}^{M} \hat{a}_n^\dagger \hat{a}_n + \omega_a \sum_{n=1}^{M} \sigma_n^+ \sigma_n^- - \kappa \sum_{n=1}^{M} \left(\hat{a}_{n+1}^\dagger \hat{a}_n + \hat{a}_n^\dagger \hat{a}_{n+1} \right) + \eta \sum_{n=1}^{N} \left(\hat{a}_n \sigma_n^+ + \hat{a}_n^\dagger \sigma_n^- \right)$$





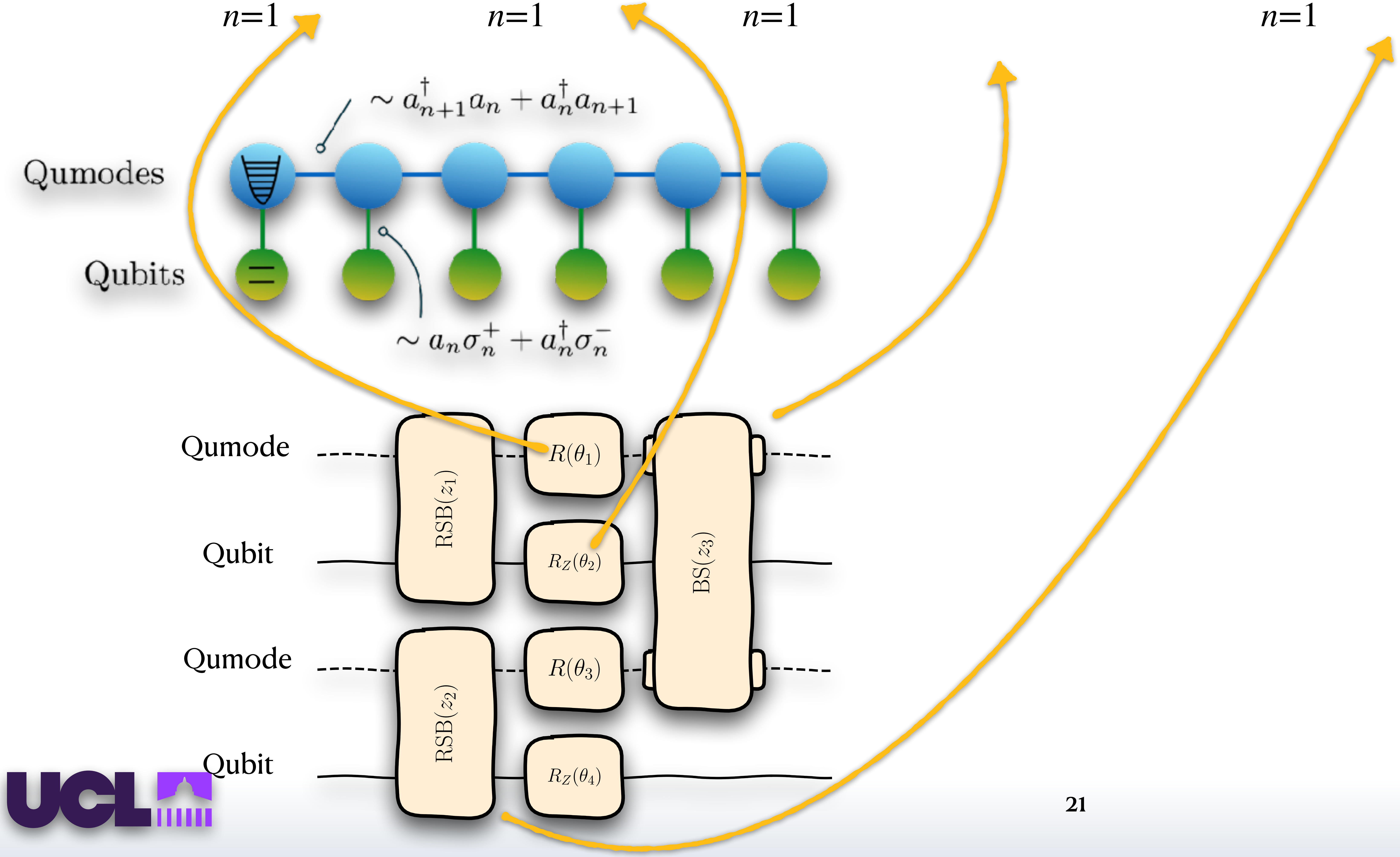


Jack Y. Araz

Jaynes-Cummings-Hubbard model

[JYA, Grau, Montgomery, Ringer; PRA '25]

$$\hat{H} = \omega_c \sum_{n=1}^{M} \hat{a}_n^\dagger \hat{a}_n + \omega_a \sum_{n=1}^{M} \sigma_n^+ \sigma_n^- - \kappa \sum_{n=1}^{M} \left(\hat{a}_{n+1}^\dagger \hat{a}_n + \hat{a}_n^\dagger \hat{a}_{n+1} \right) + \eta \sum_{n=1}^{N} \left(\hat{a}_n \sigma_n^+ + \hat{a}_n^\dagger \sigma_n^- \right)$$



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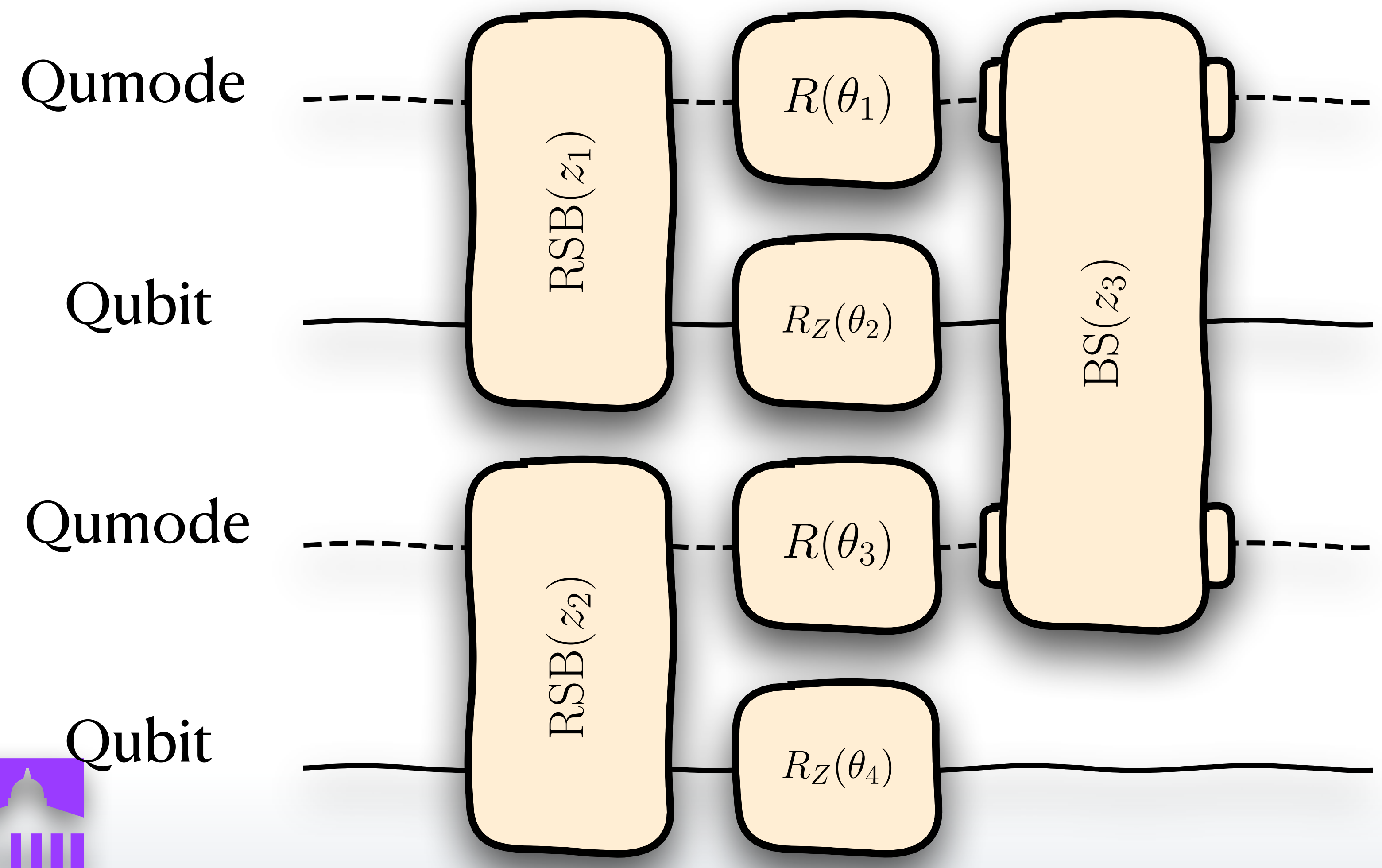

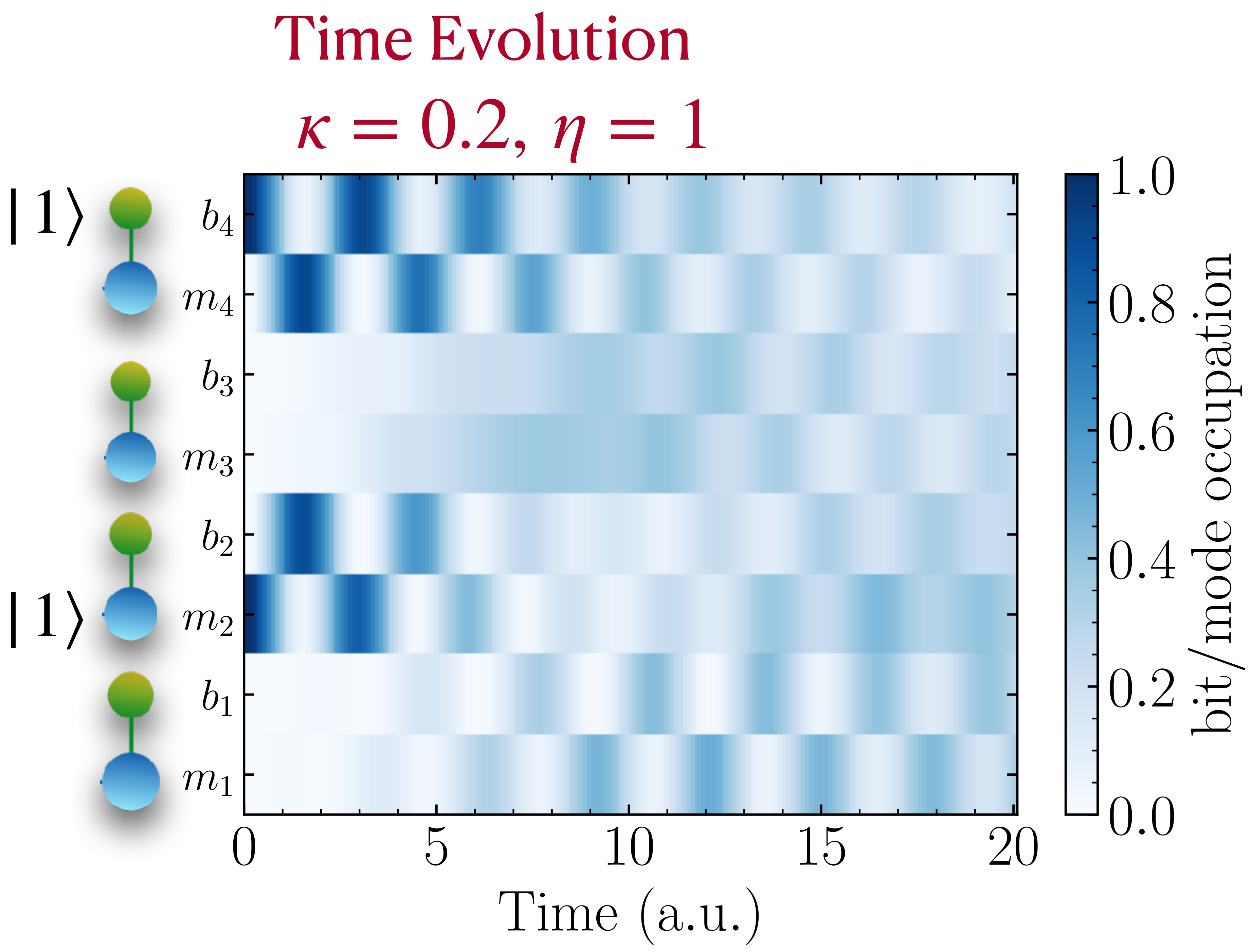

Jaynes-Cummings-Hubbard model

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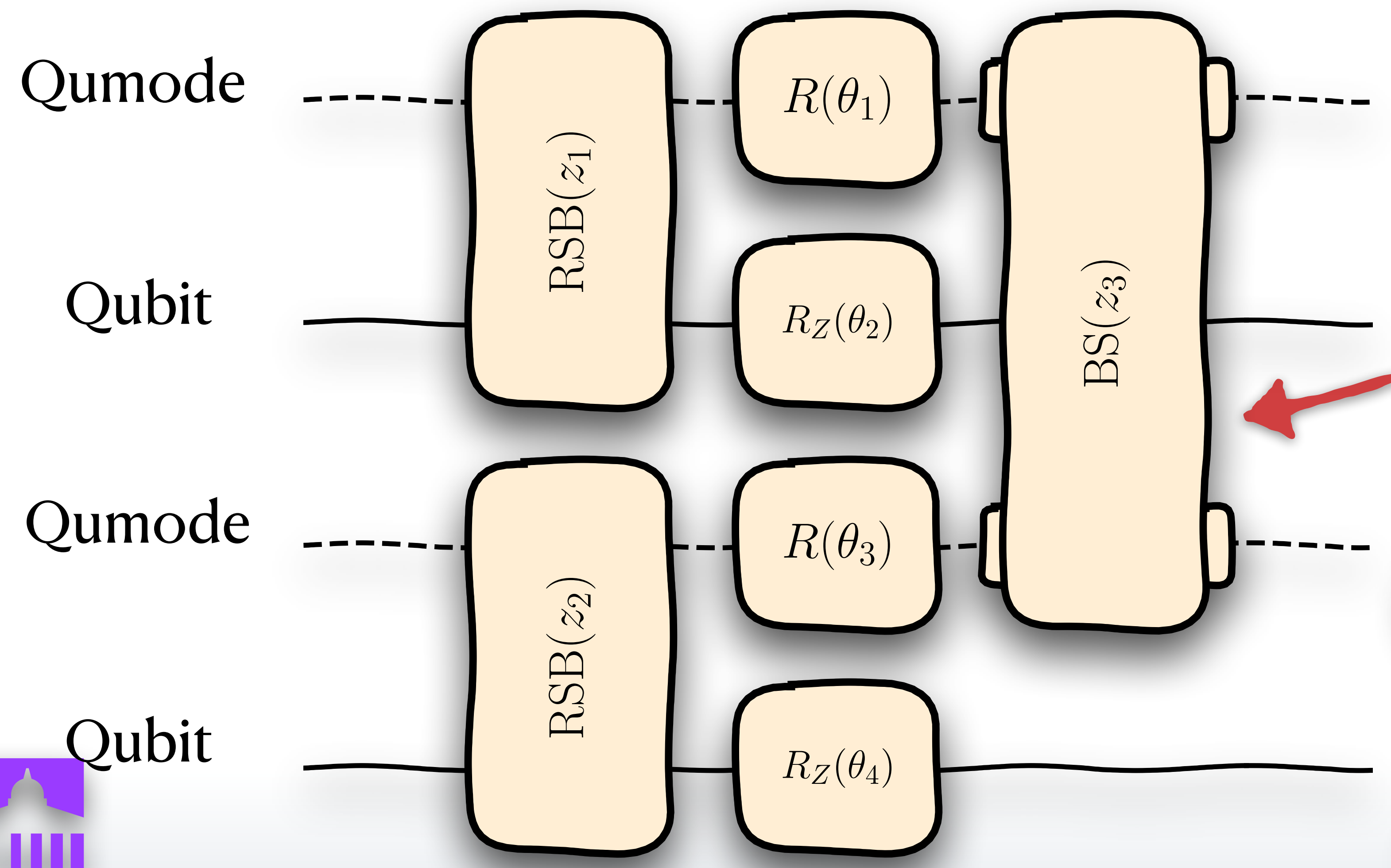
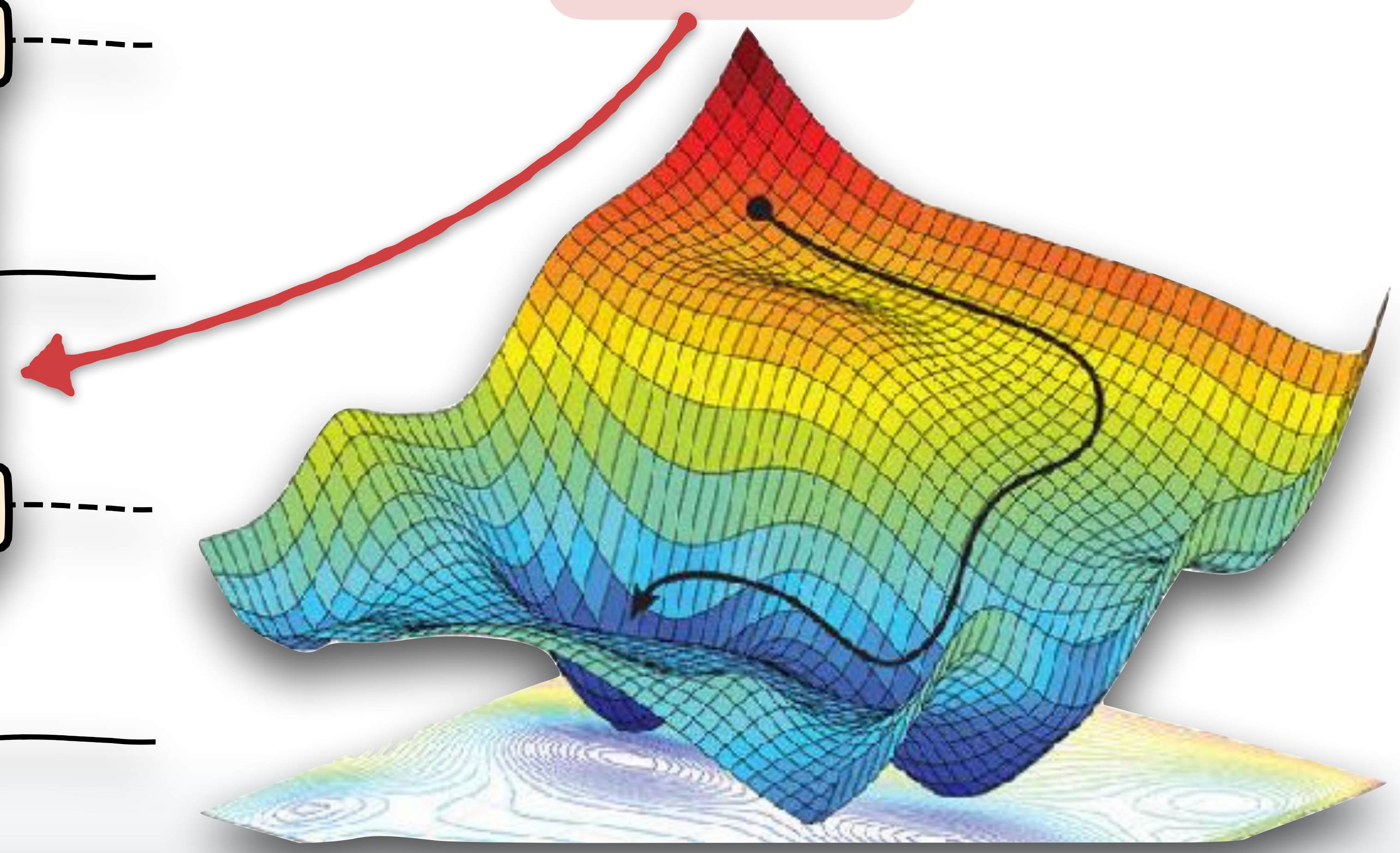


$$\text{Loss} = \langle 0 | U^\dagger(\theta) \hat{H} U^\dagger(\theta) | 0 \rangle$$



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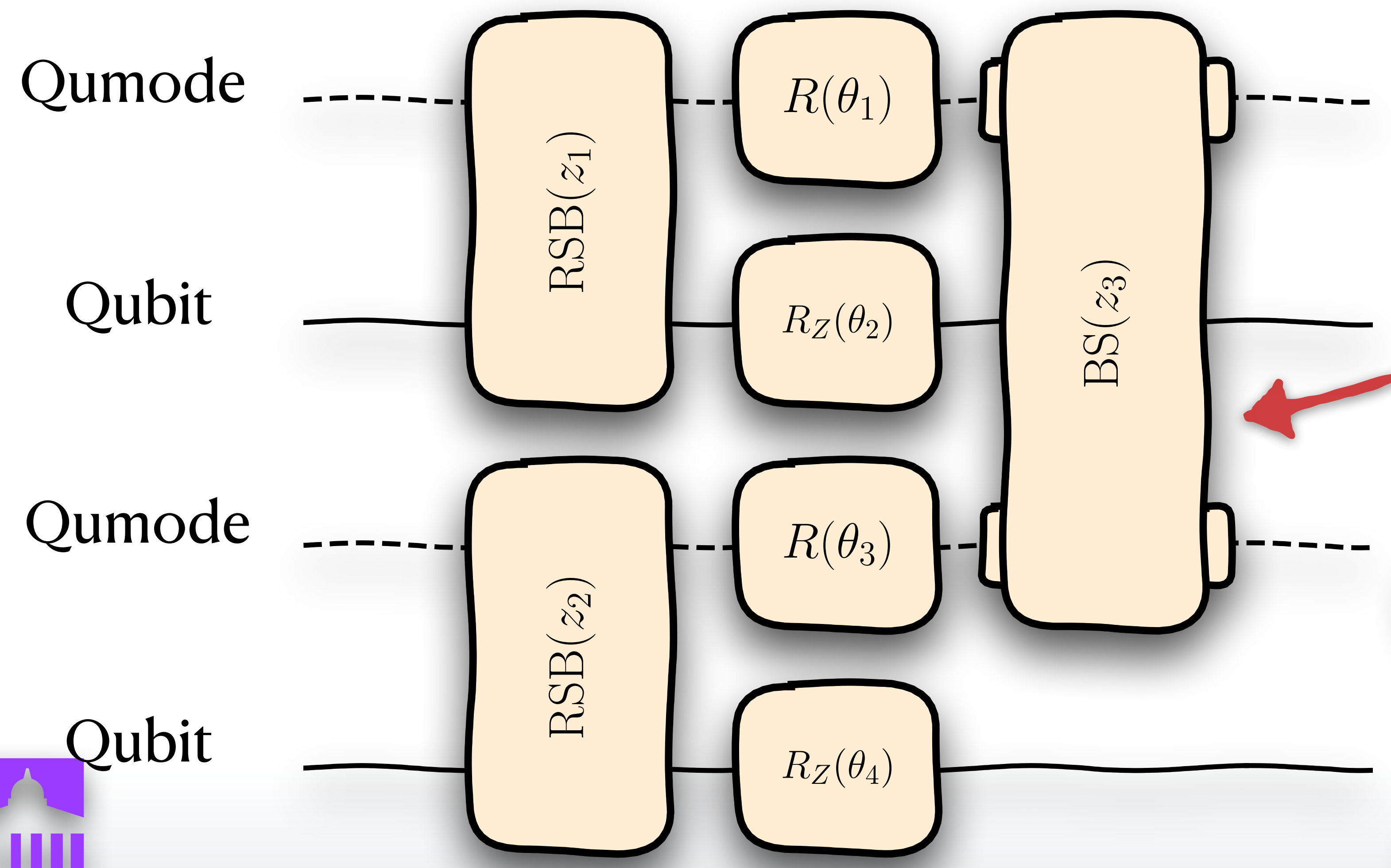

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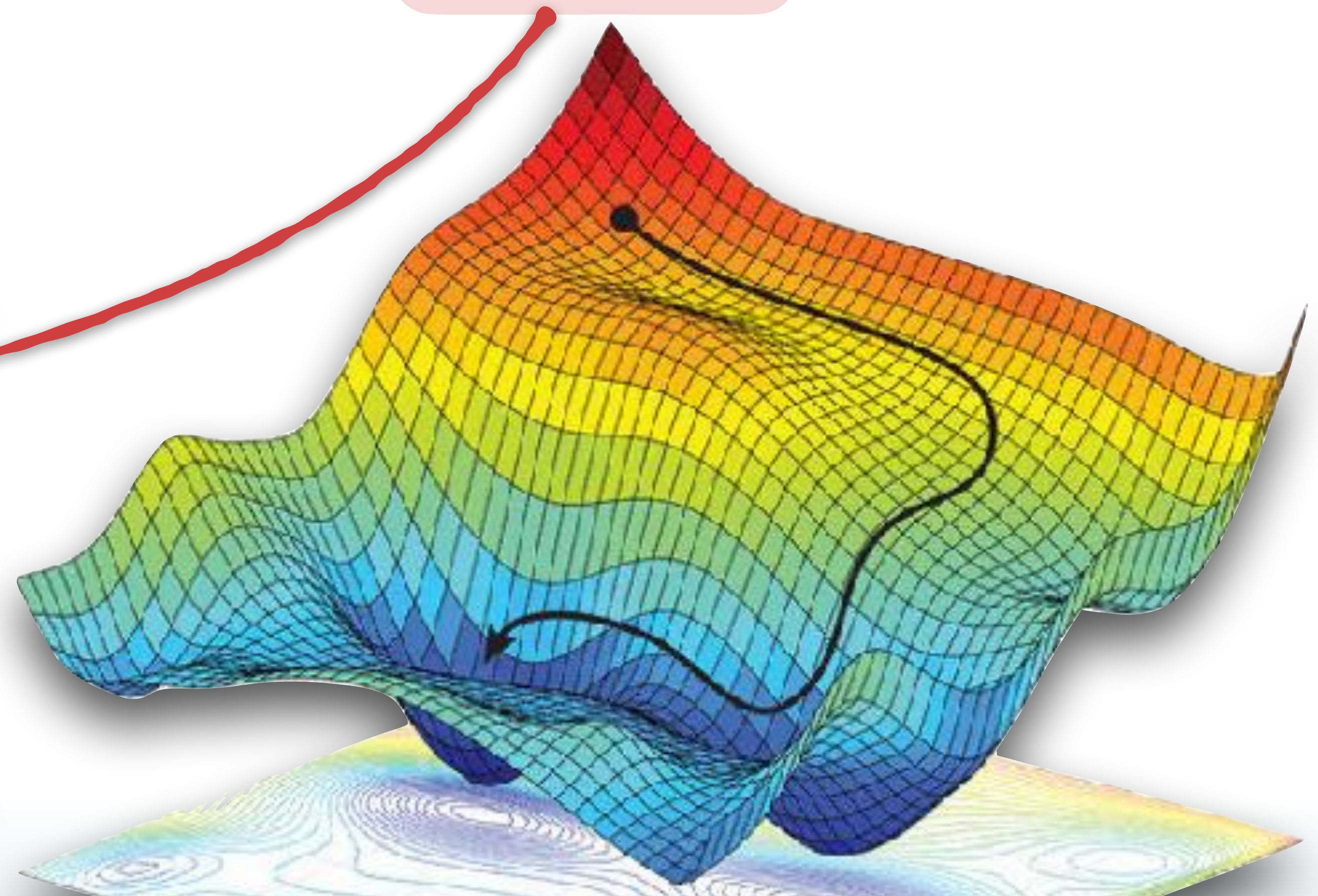
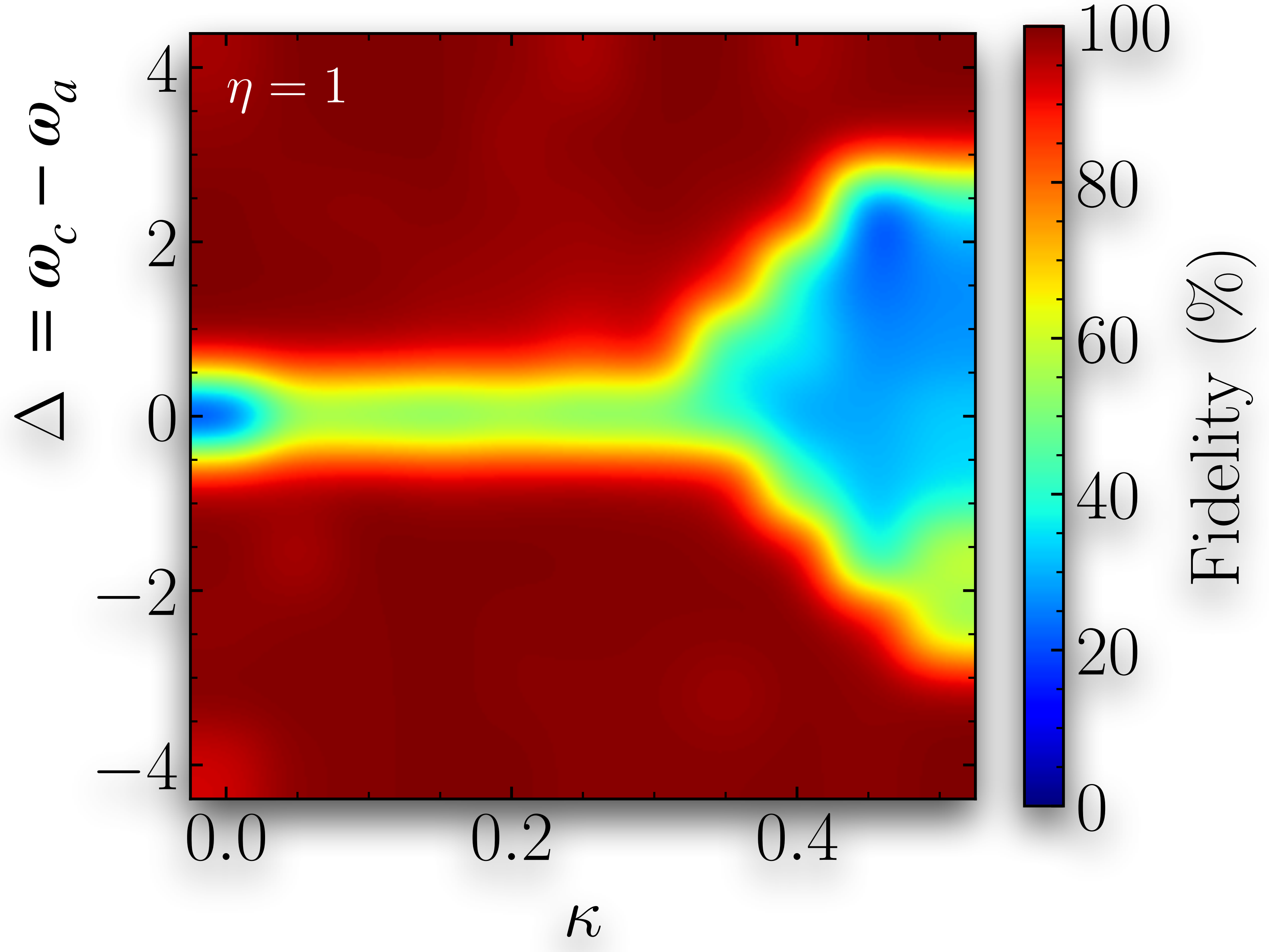
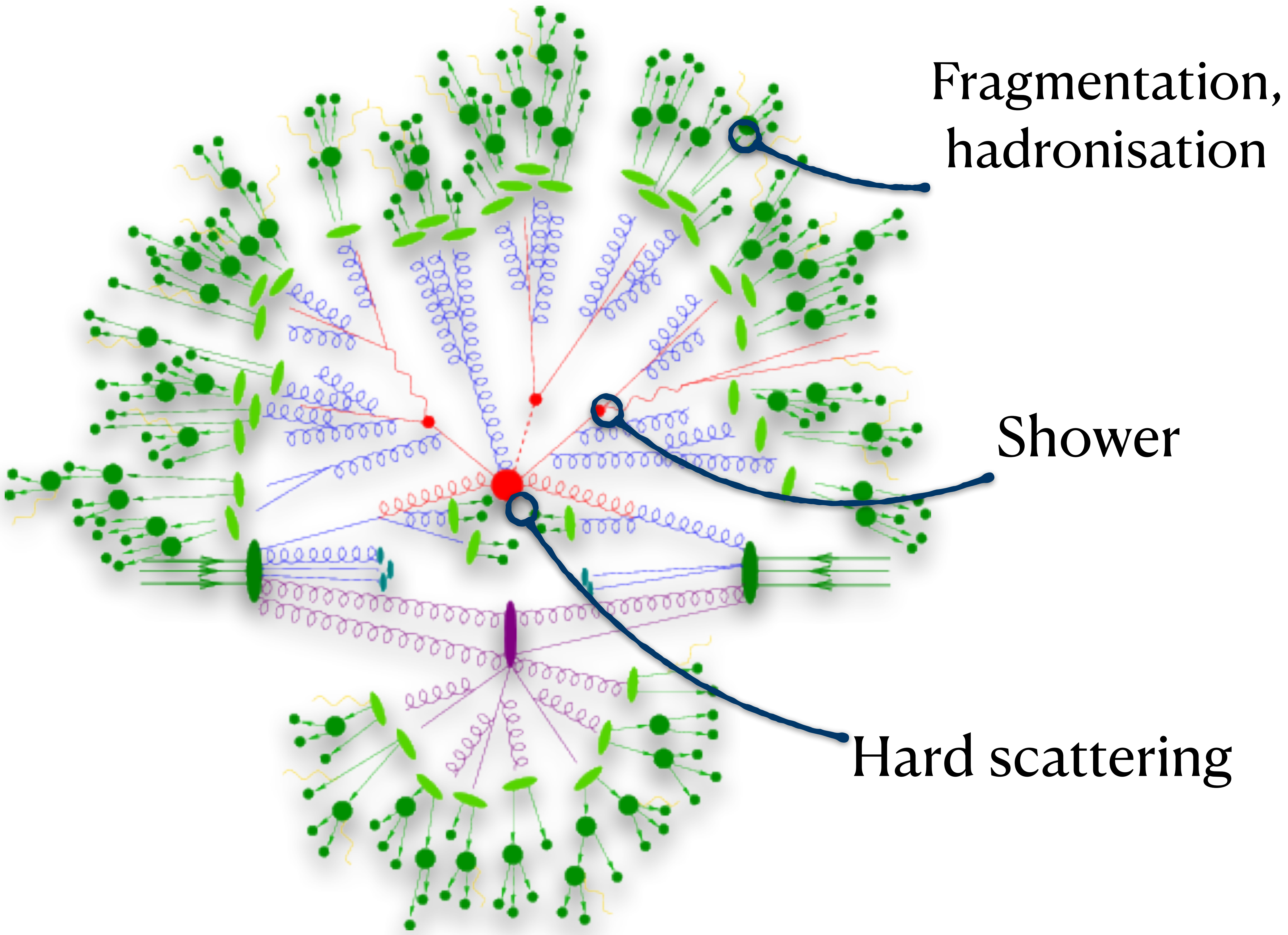


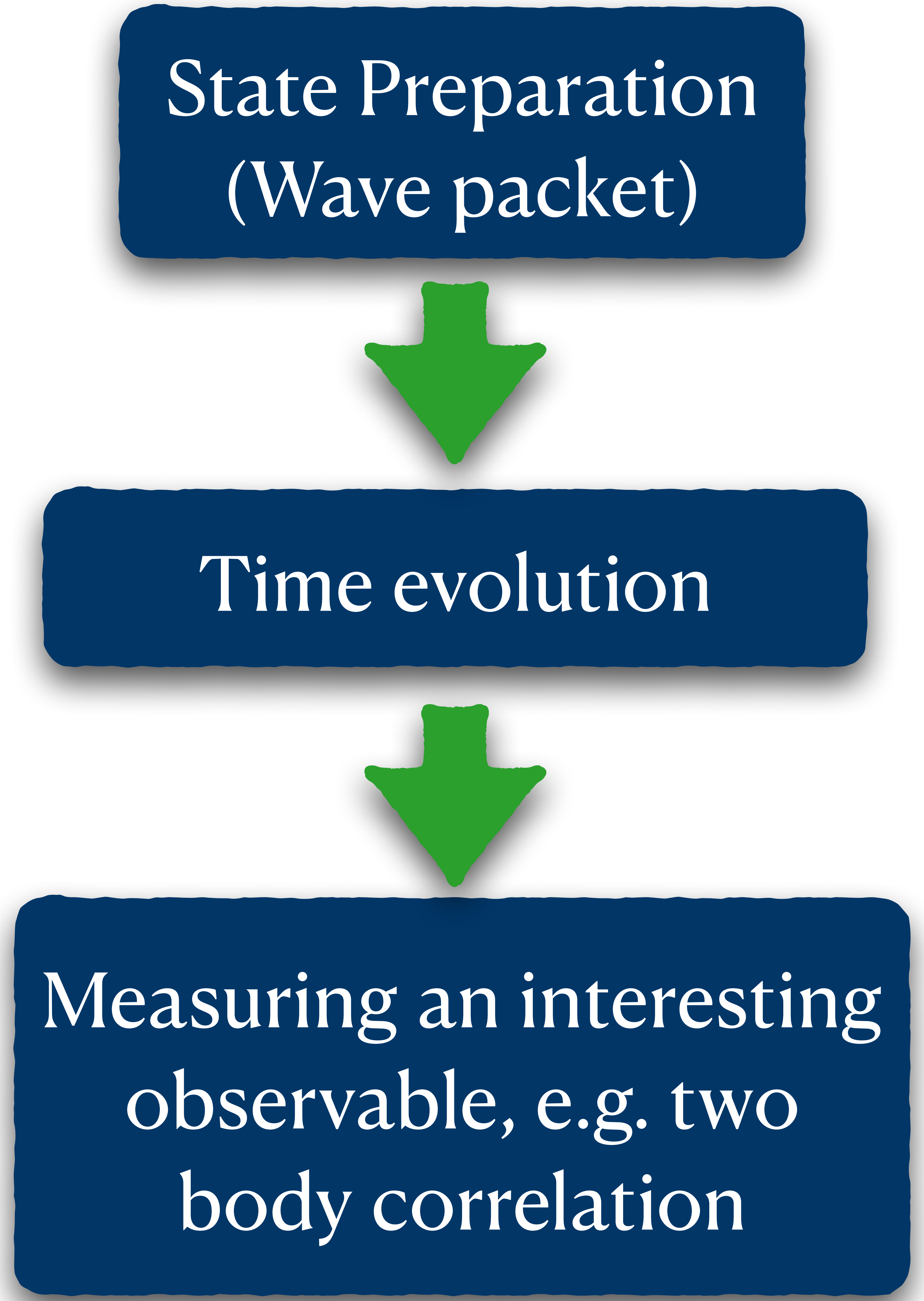
Variational State Preparation



Jack Y. Araz

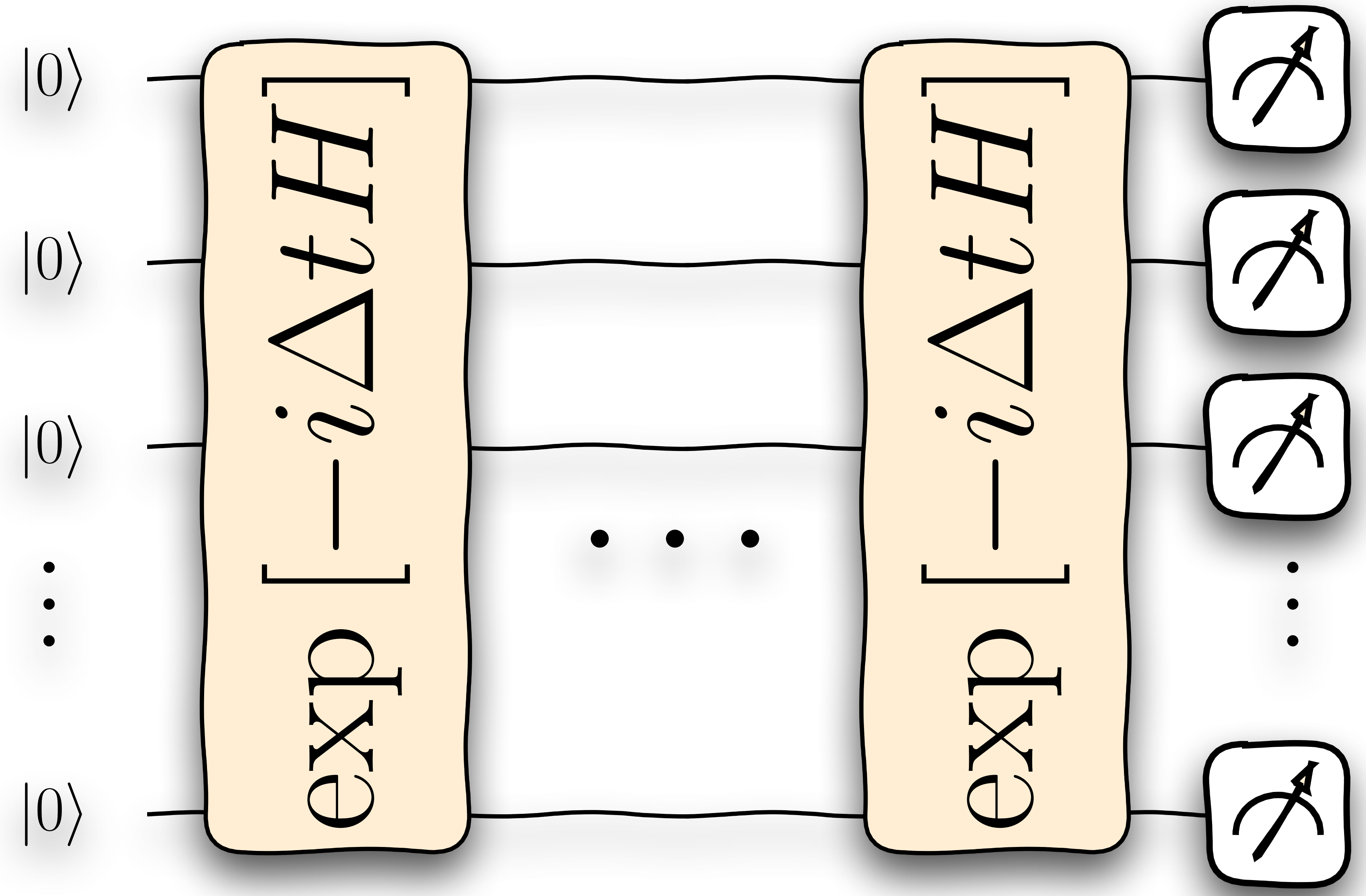
Towards simulating the scattering process





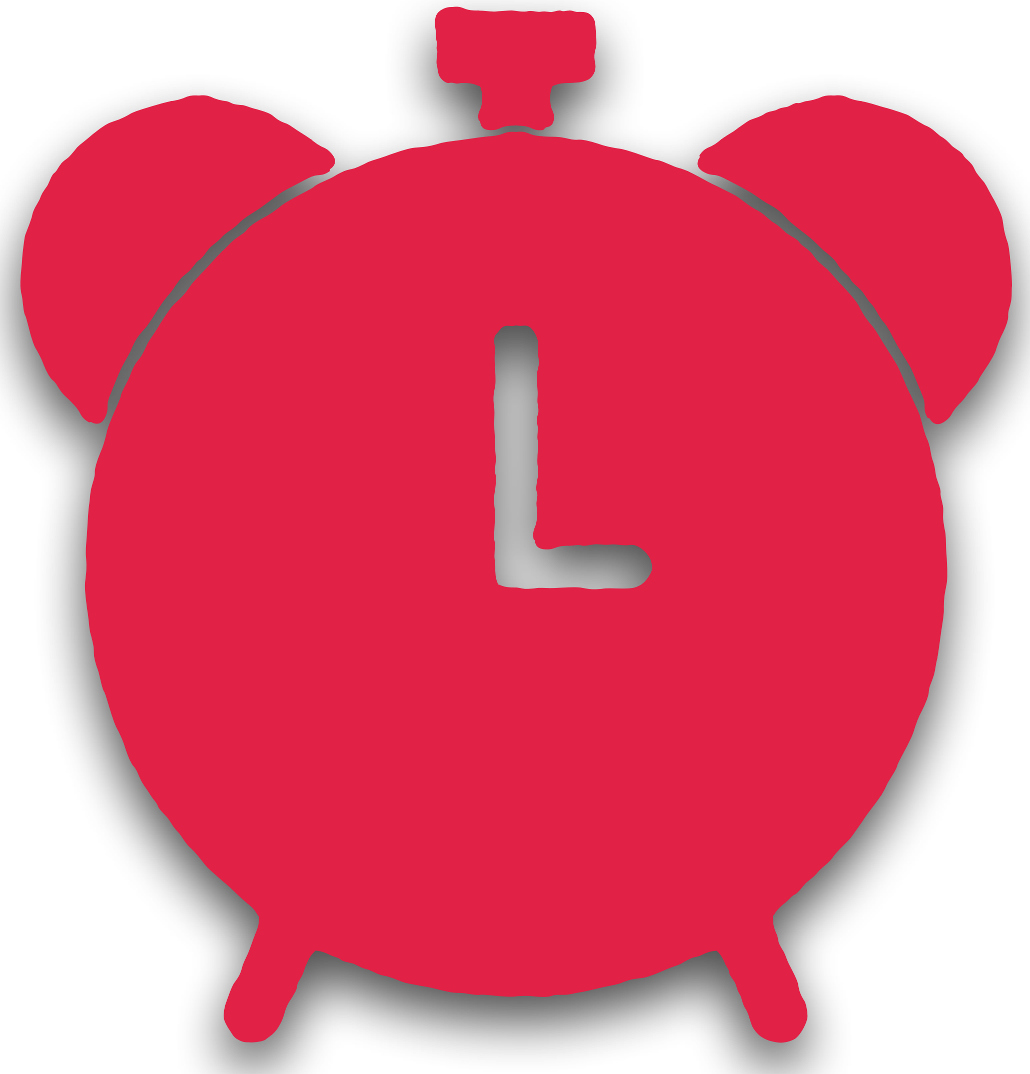
But...

Time Evolution or Adiabatic State Preparation

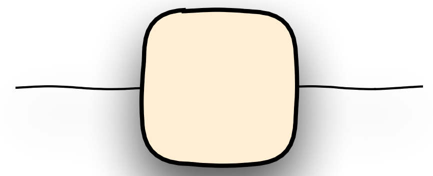


$$e^{-iTH} \simeq \prod^{N} e^{-i\Delta t H}$$

Short Coherence Time

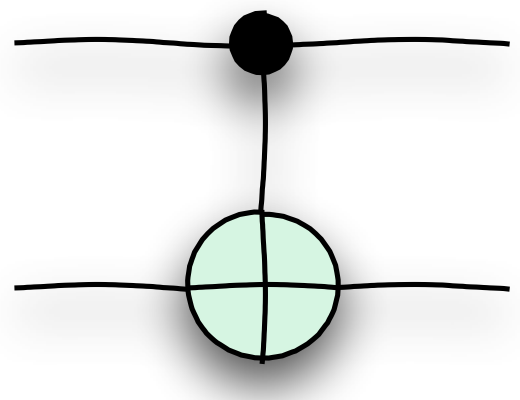


Typical coherence time for an IBM superconducting qubit is 50 to 100 microsecond



$\simeq 71$ ns

Limit: ~1408 single qubit gates

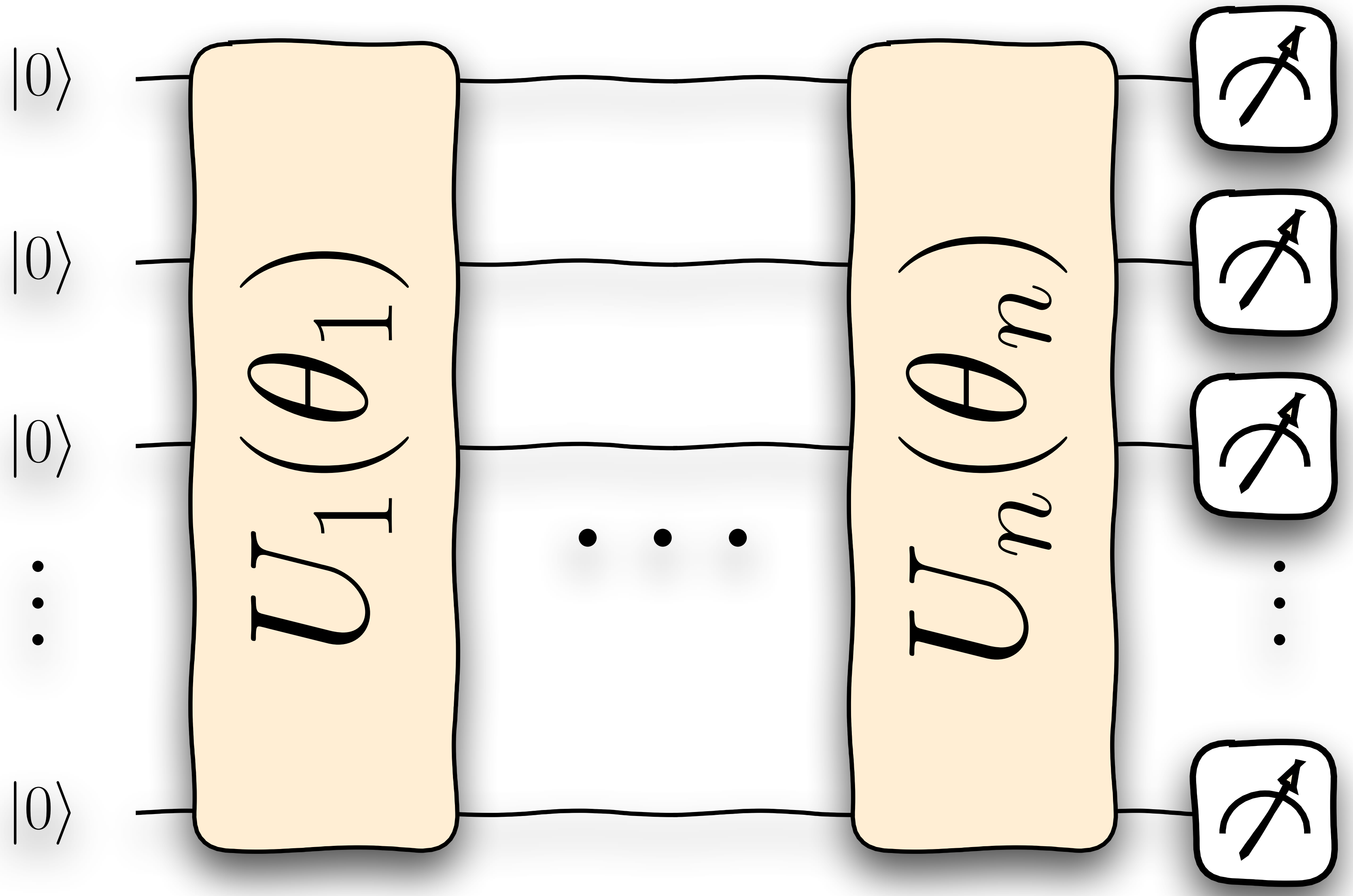


$\simeq 600$ ns

Limit: ~166 CNOT gates

But...

State Preparation with VQE



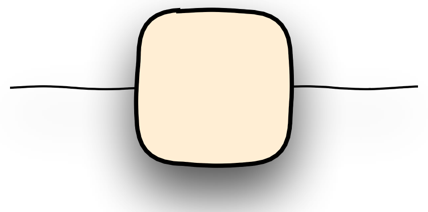
$$\langle 0 | U(\theta) H U^\dagger(\theta) | 0 \rangle \geq E_{gs}$$

Barren Plateaus

August 2021, taken after getting lost for 4h

How can we go beyond the limitations?

I'll build my own gates, thank you very much!



$\simeq 71$ ns

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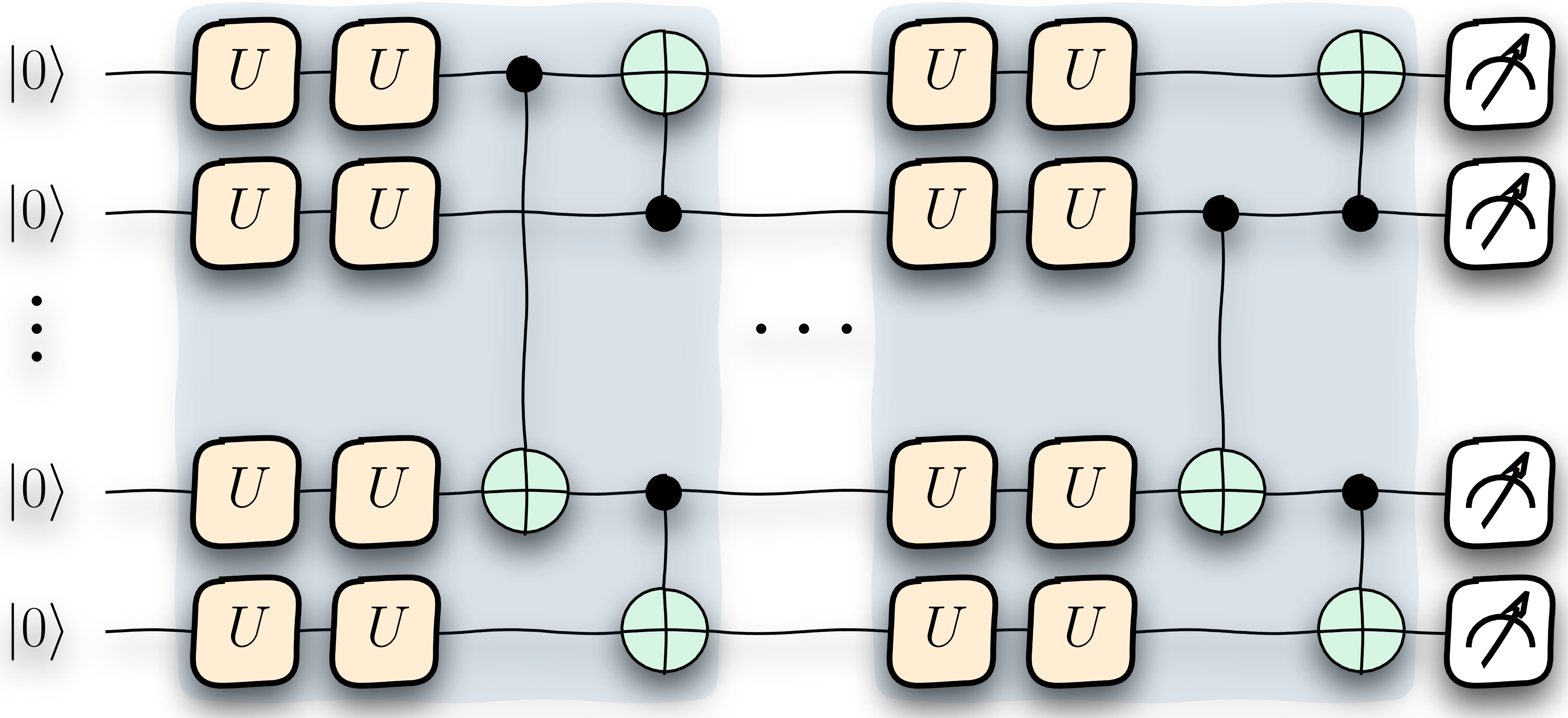

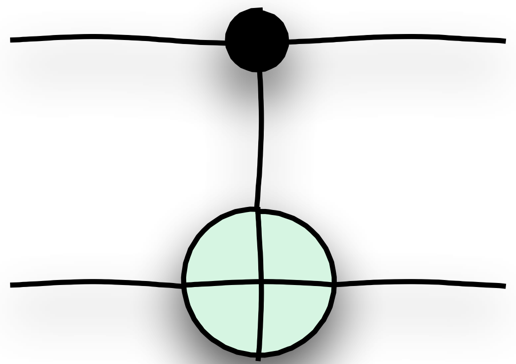

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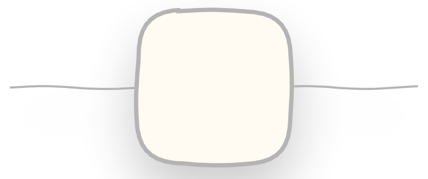

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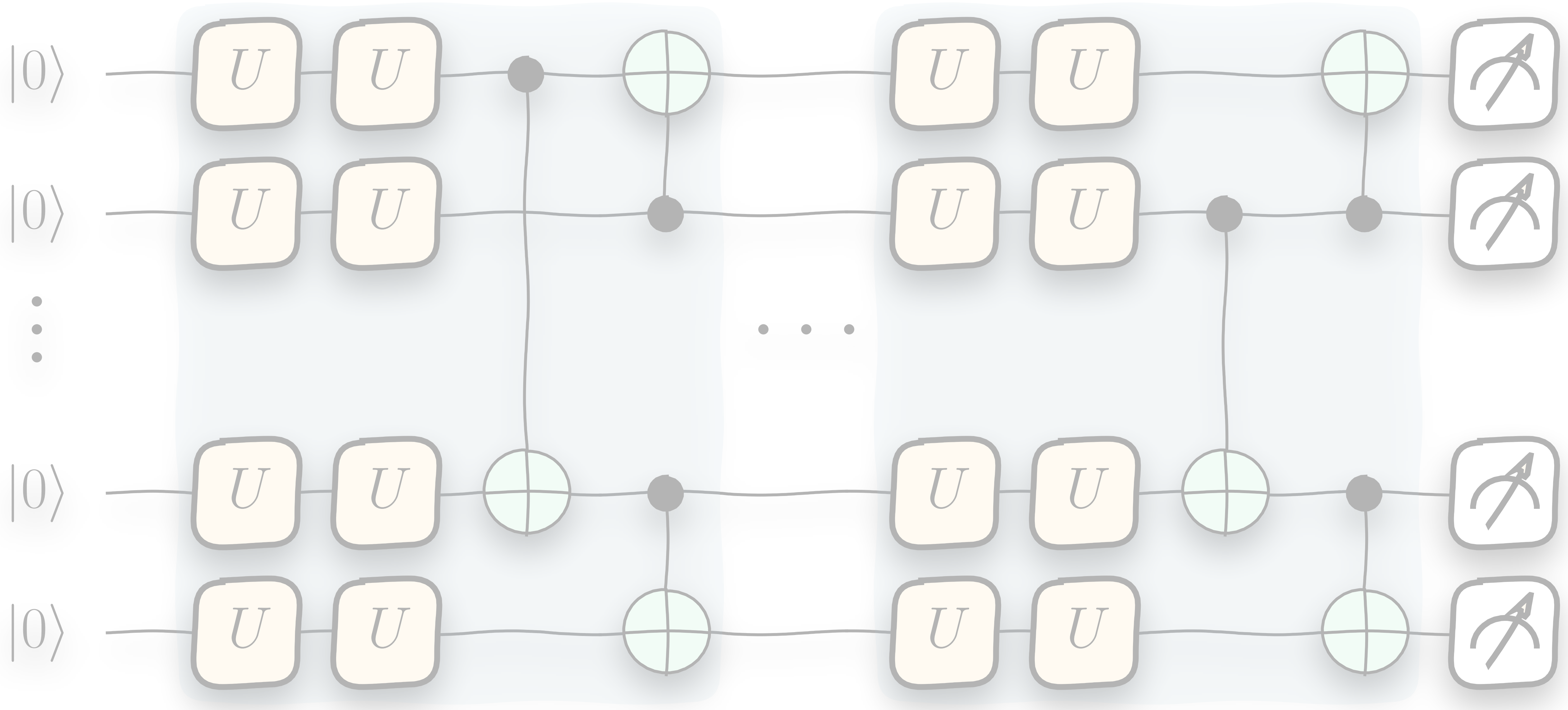

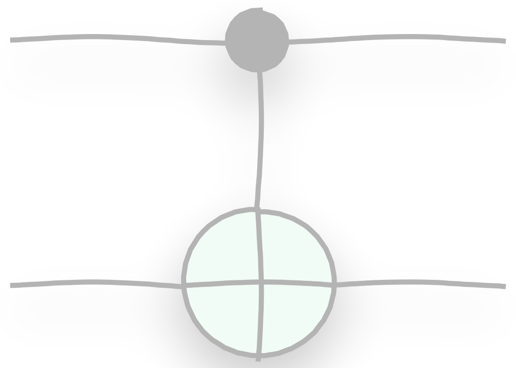

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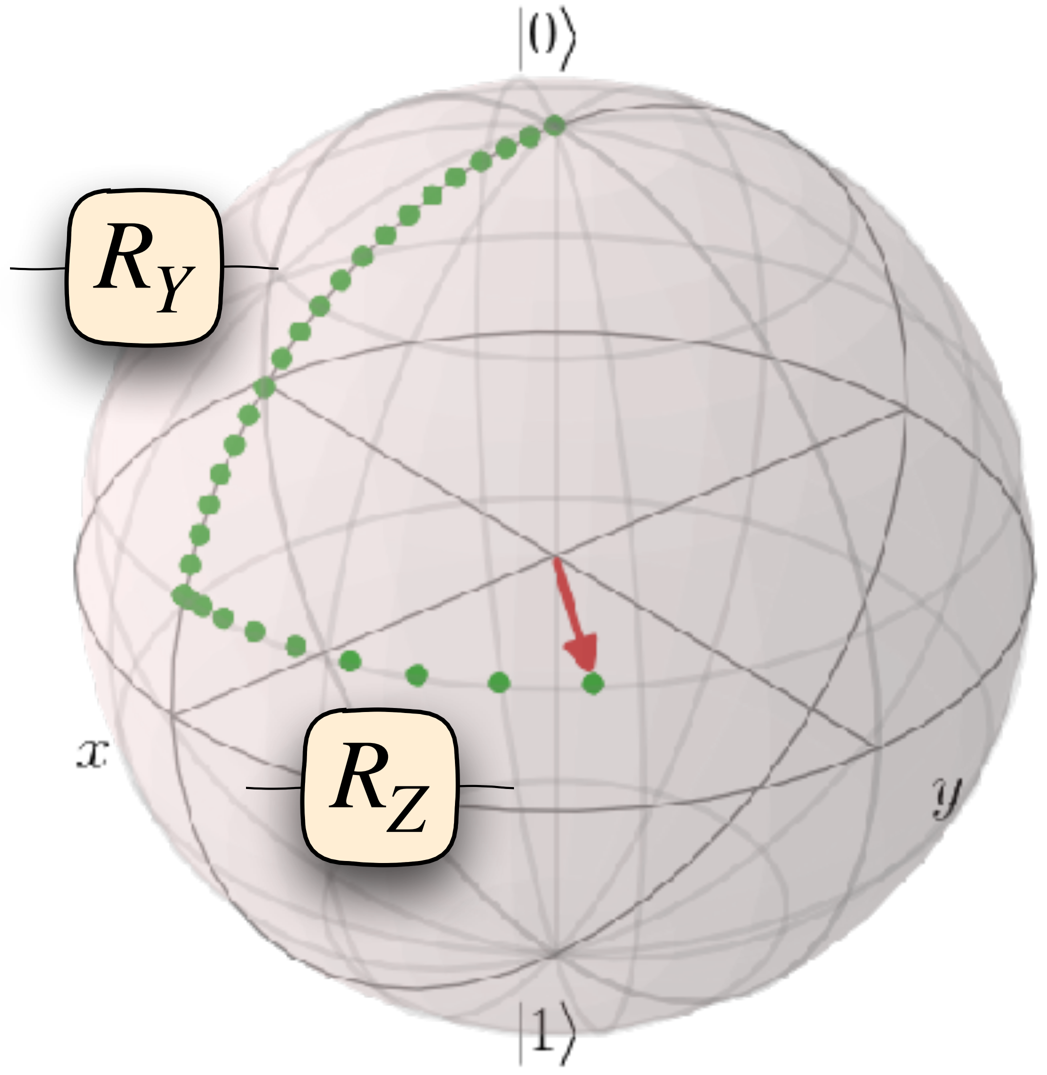

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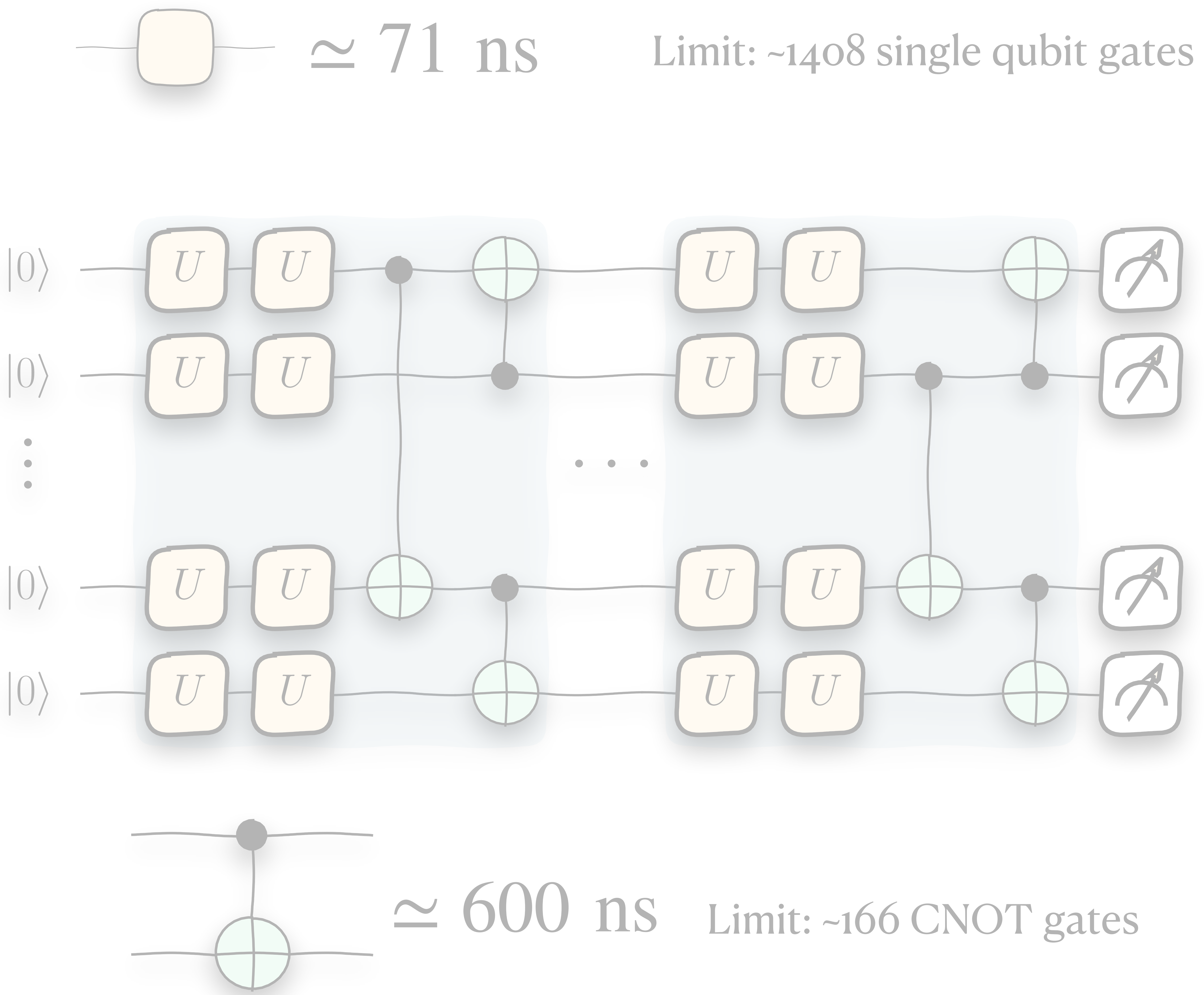

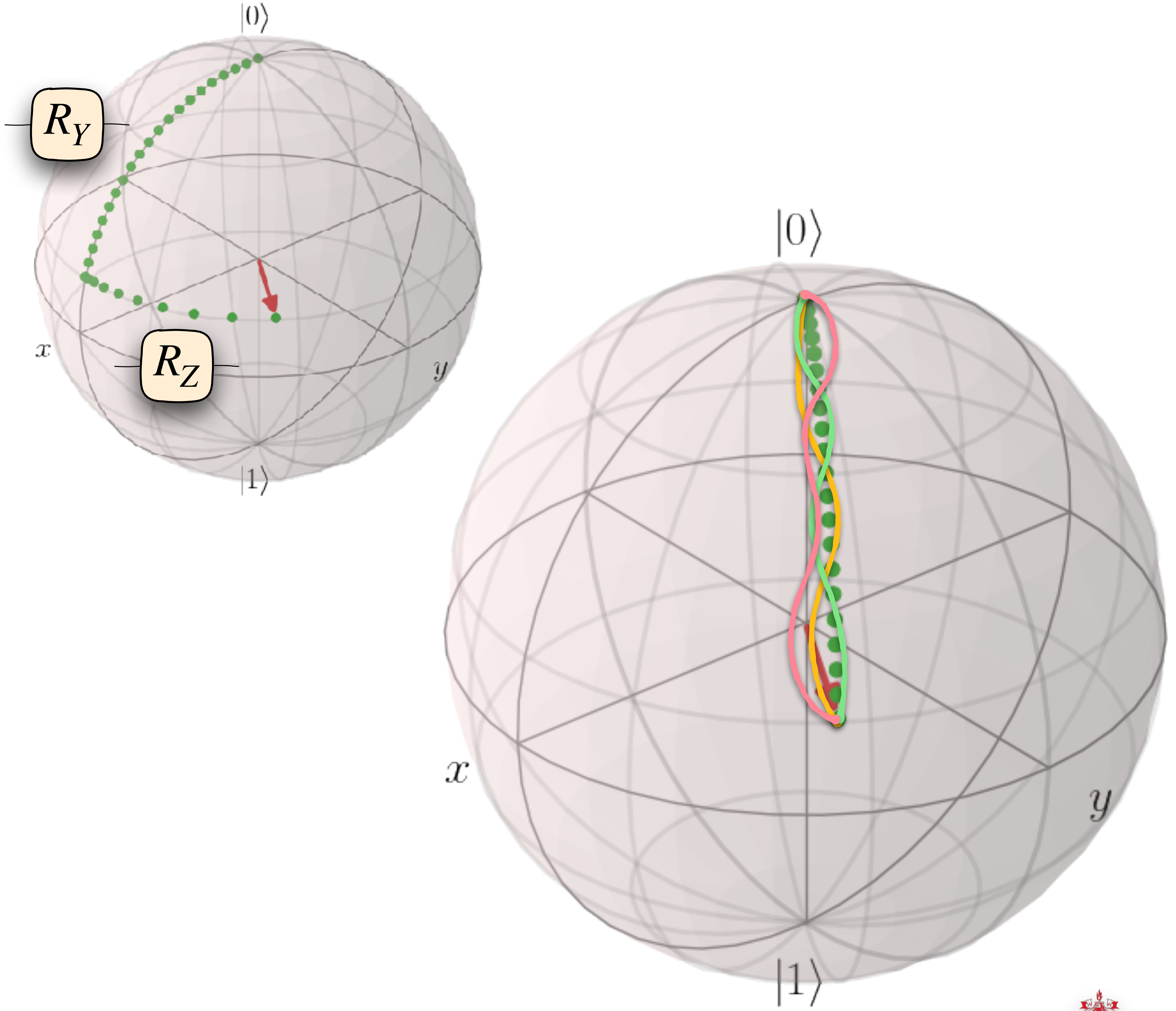

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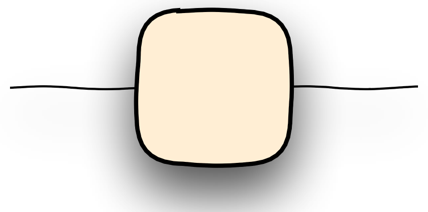

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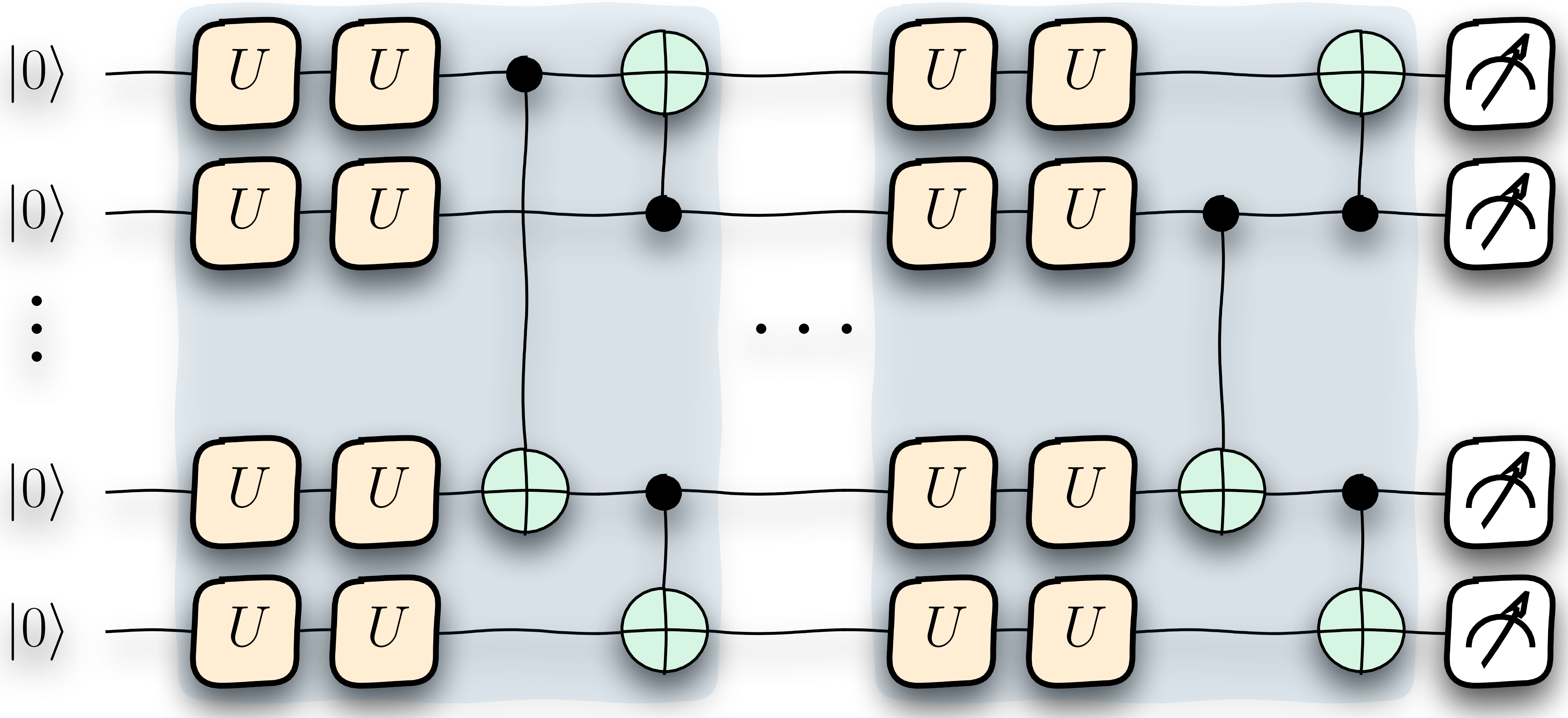
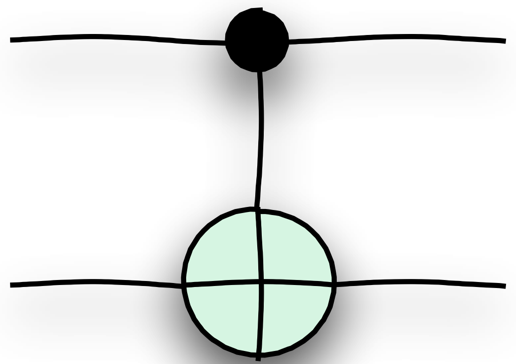
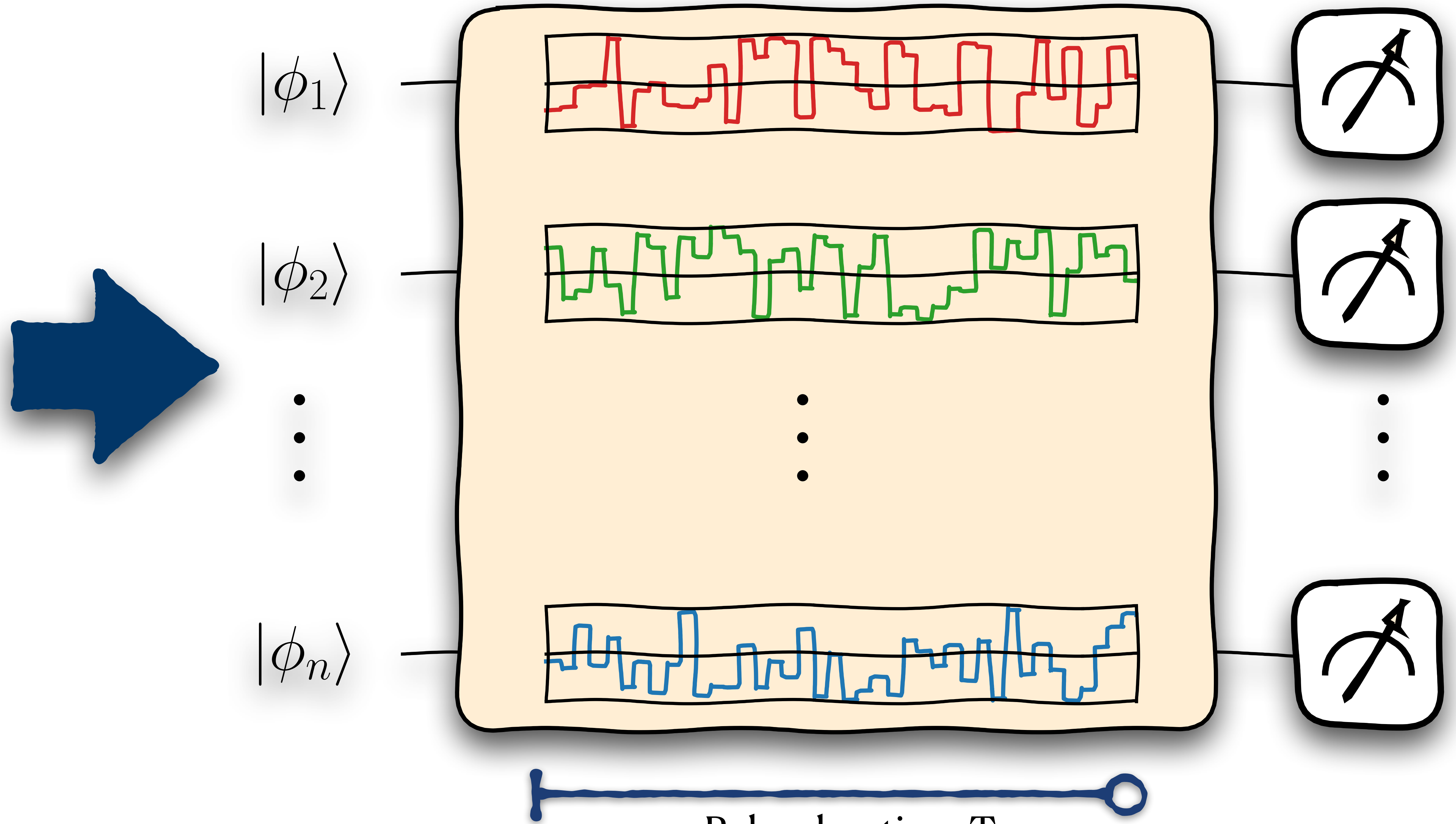




$\simeq 600$ ns

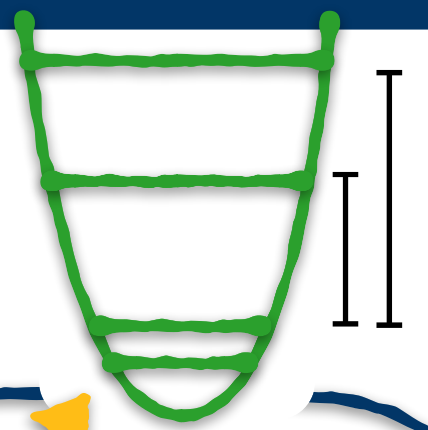
Limit: ~166 CNOT gates

$$\exp\left[-i\int_0^T H(t)dt\right]|\phi_{\text{init}}\rangle$$



Pulse duration, T

Quantum Optimal Control: Transmon Hamiltonian



Drive Hamiltonian

$$H_D = \sum_i \omega_i a_i^\dagger a_i - \sum_i \frac{\delta_i}{2} a_i^\dagger a_i^\dagger a_i a_i + \sum_{i,j} g_{ij} a_i^\dagger a_j$$

- First term: $|0\rangle \leftrightarrow |1\rangle$
- Second term: Separate higher-order states, i.e. $|n > 1\rangle$
- Third term: Qubit architecture

ω : Transition frequency, $\mathcal{O}(4.5)$ GHz$/2\pi$
δ : Anharmonicity, $\mathcal{O}(0.3)$ GHz$/2\pi$
g : two-qubit coupling, $\mathcal{O}(0.02)$ GHz$/2\pi$

Limits from IBM, machine dependent

Control Hamiltonian

$$H_C(t) = \sum_i \Omega_i(t) \left(e^{i\nu_i t} a_i + e^{-i\nu_i t} a_i^\dagger \right)$$

$\Omega(t)$: Pulse amplitude, $-20 \leq \Omega(t) \leq 20$ MHz
ν : Phase, $|\nu_i - \omega_i| \leq 1$ GHz

$$H(t) = H_D + H_C(t)$$

$$|\Psi(T)\rangle = \mathcal{T} e^{-i\int_0^T H(t)dt} |\psi(0)\rangle$$

Our new ansatz ($\mathcal{T} e^{-i\int_0^T H(t)dt}$)

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

And more…

Quantum Optimal Control: Transmon Hamiltonian

Why bother?

- Short execution time is needed to avoid decoherence. This will allow more time to play with the state!
- If enough time is given, this method is free from the local minima. Russel et al. arXiv:1608.06198
- Lack of barren plateaus (coming up)

Control Hamiltonian

$$H_C(t) = \sum_i \Omega_i(t)\left(e^{i\nu_i t}a_i + e^{-i\nu_i t}a_i^\dagger\right)$$

$\Omega(t)$: Pulse amplitude, $-20 \leq \Omega(t) \leq 20$ MHz

ν : Phase, $|\nu_i - \omega_i| \leq 1$ GHz

$$H(t) = H_D + H_C(t)$$

$$|\Psi(T)\rangle = \underbrace{\mathcal{T} e^{-i\int_0^T H(t)dt}}_{\text{Our new ansatz}} |\psi(0)\rangle$$

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

Schwinger Model

Schwinger Model with topological term

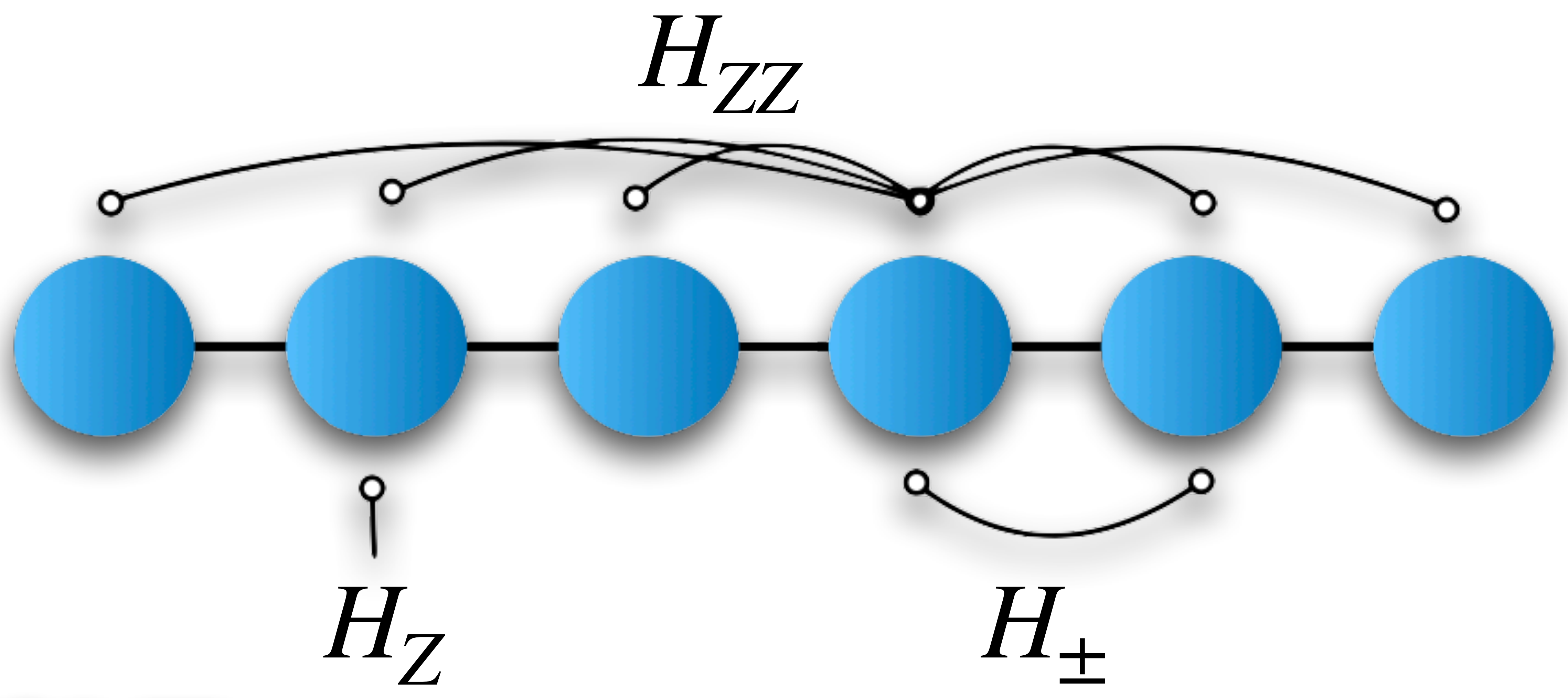
Simple QED

1+1 dimensional $U(1)$ gauge theory coupled to a Dirac fermion

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}(\partial_{\mu} + igA_{\mu})\psi - m\underbrace{\bar{\psi}e^{i\theta\gamma^5}}_{\text{Chiral rotation}}\psi$$

Gauss law: $\partial_1 \dot{A}^1 + g\bar{\psi}\gamma^0\psi = 0$

Use the staggered fermion discretisation of the electron field and apply JW transformation with open boundaries!



$$H_\pm = \frac{1}{2}\sum_i^{N-1}\left(\frac{1}{2a} - (-1)^i\frac{m}{2}\sin\theta\right)\left[X_iX_{i+1} + Y_iY_{i+1}\right]$$

$$H_Z = \frac{m\cos\theta}{2}\sum_i^{N}(-1)^n Z_n - \frac{g^2a}{2}\sum_i^{N-1}(i \bmod 2)\sum_l^{i} Z_l$$

$$H_{ZZ} = \frac{g^2a}{4}\sum_{i=2}^{N-1}\sum_{1\leq k<l\leq i} Z_kZ_l$$

a : lattice spacing
m : fermion mass
g : gauge coupling
θ : topological angle

Chakraborty et al. arXiv: 2001.00485

Without θ : Farrell et al. arXiv: 2308.04481

Trotterised Schwinger Hamiltonian: $e^{-i\Delta t H}$

$$\sim 11\ \mu s$$

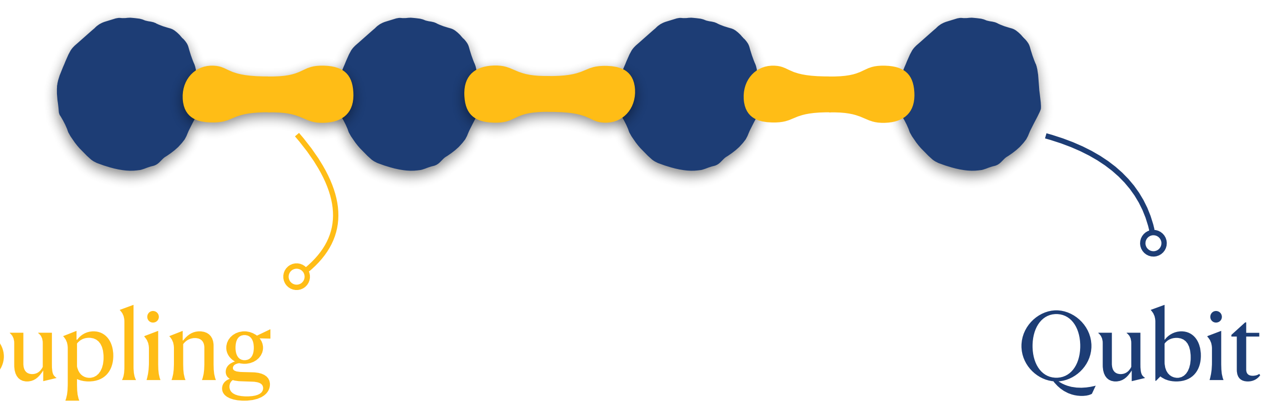
Limit: ~9 trotter steps

[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

The Schwinger Gate!

[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

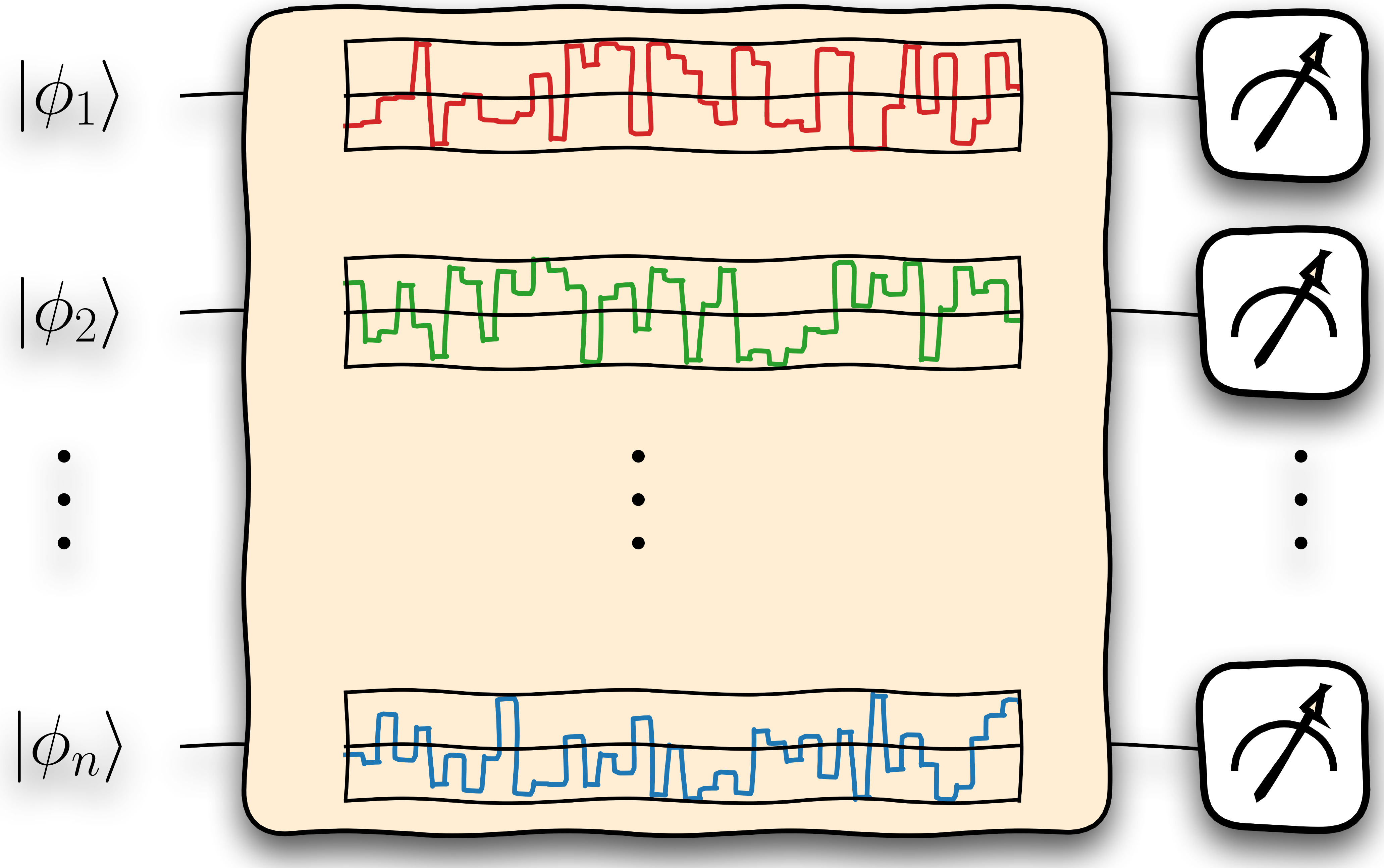
Quantum Computer:

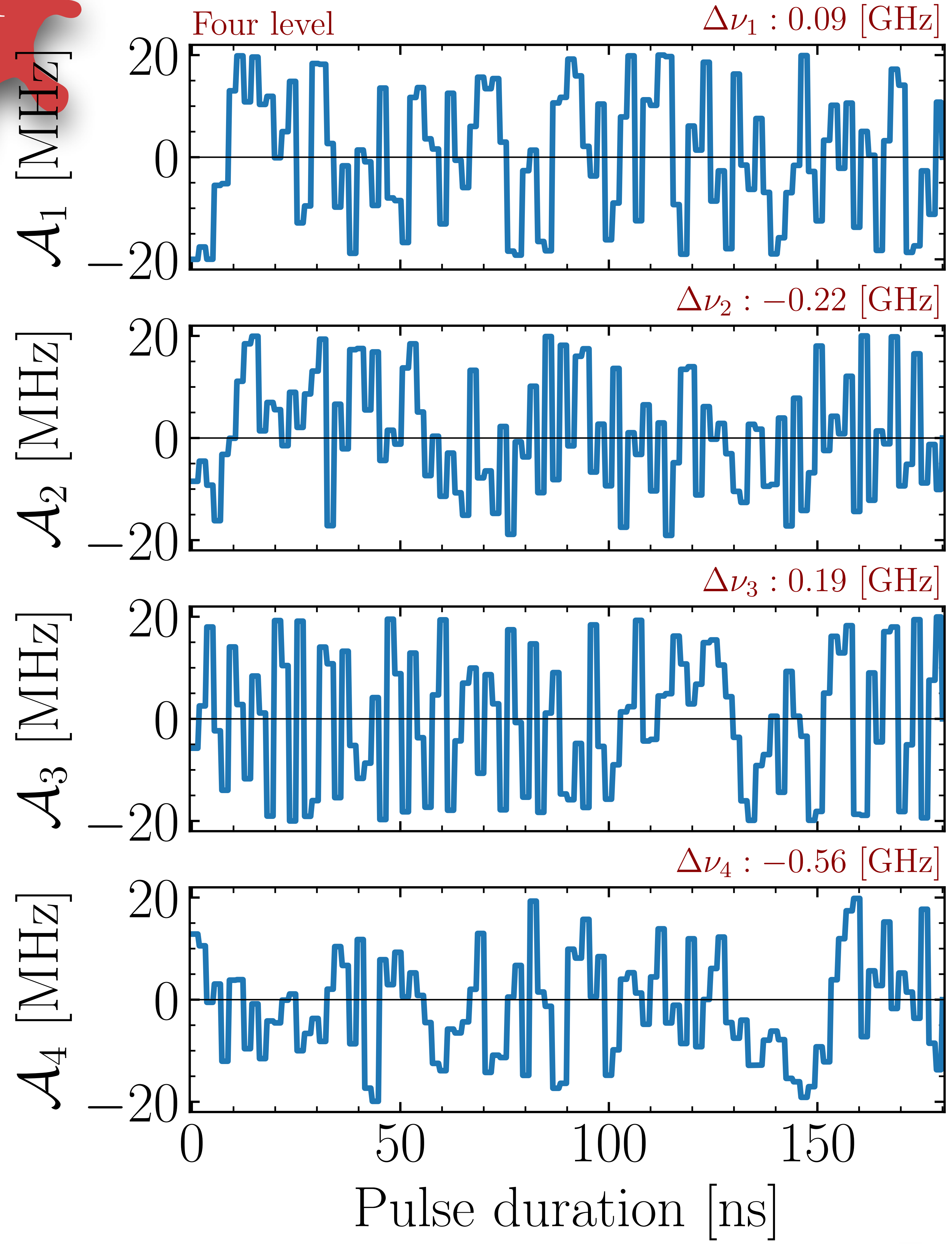


$\times 61$

180 ns

$\Delta E \sim 5 \times 10^{-3}$





The Schwinger Gate!

[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

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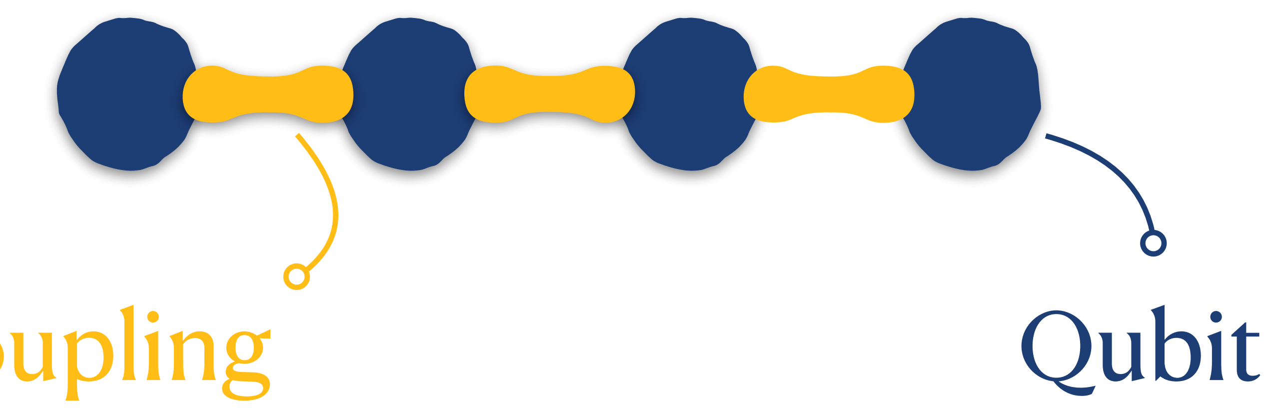

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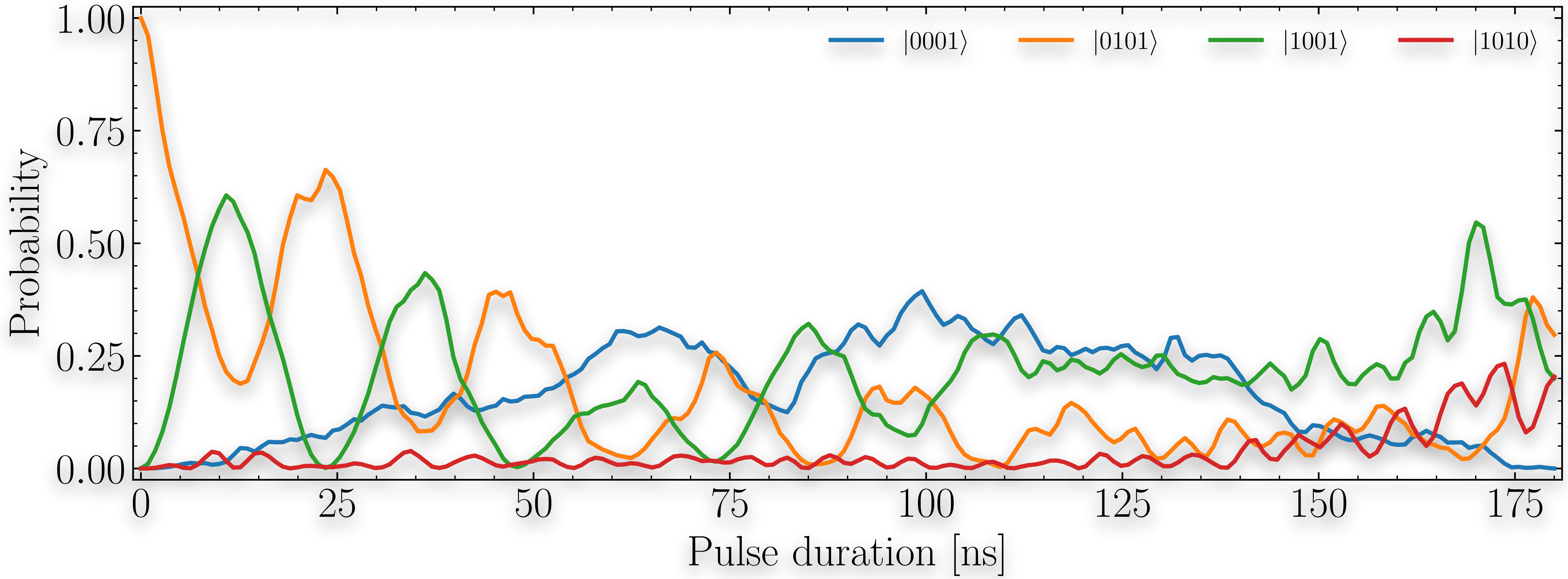
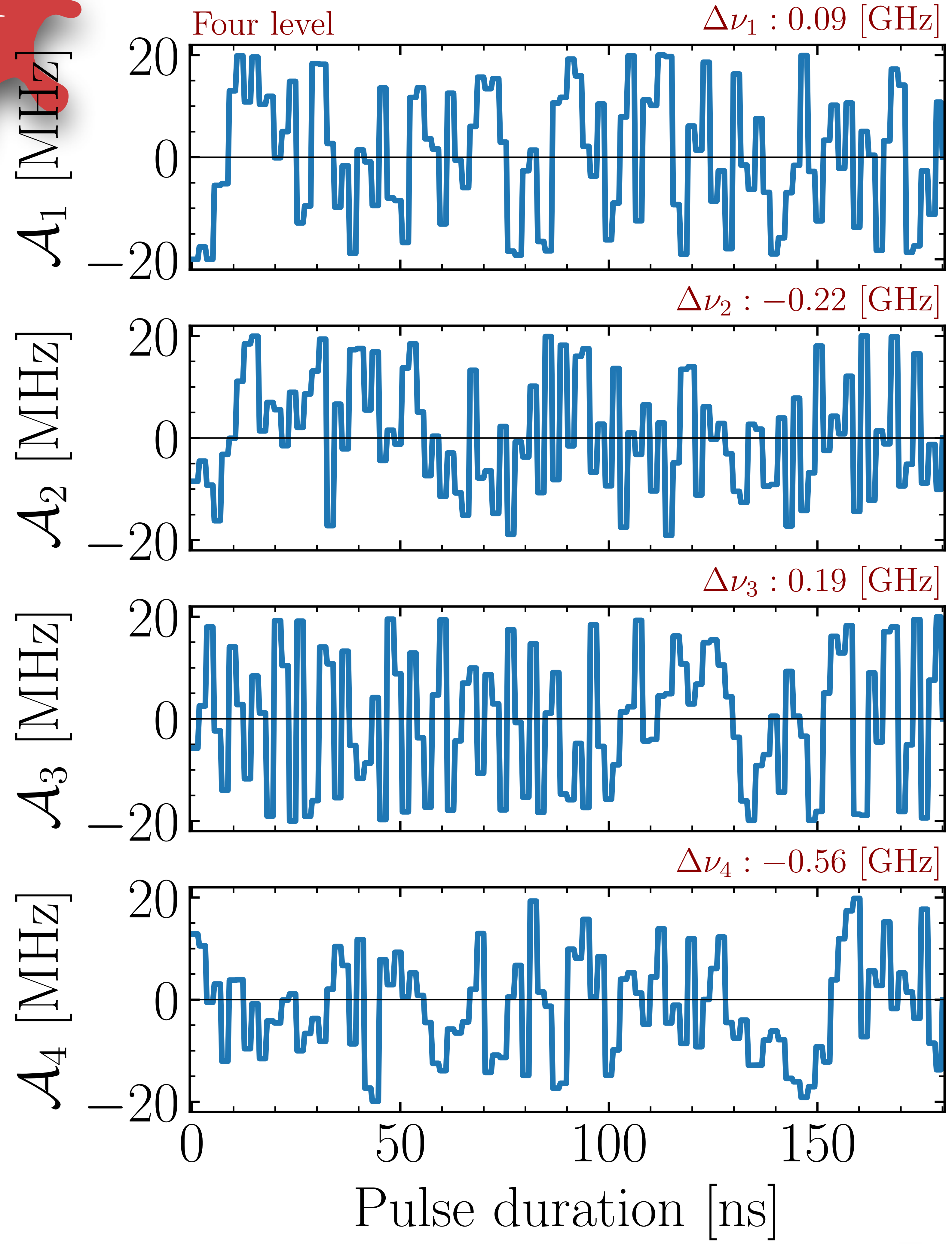




The Schwinger Gate!

[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

Quantum Computer:

180 ns

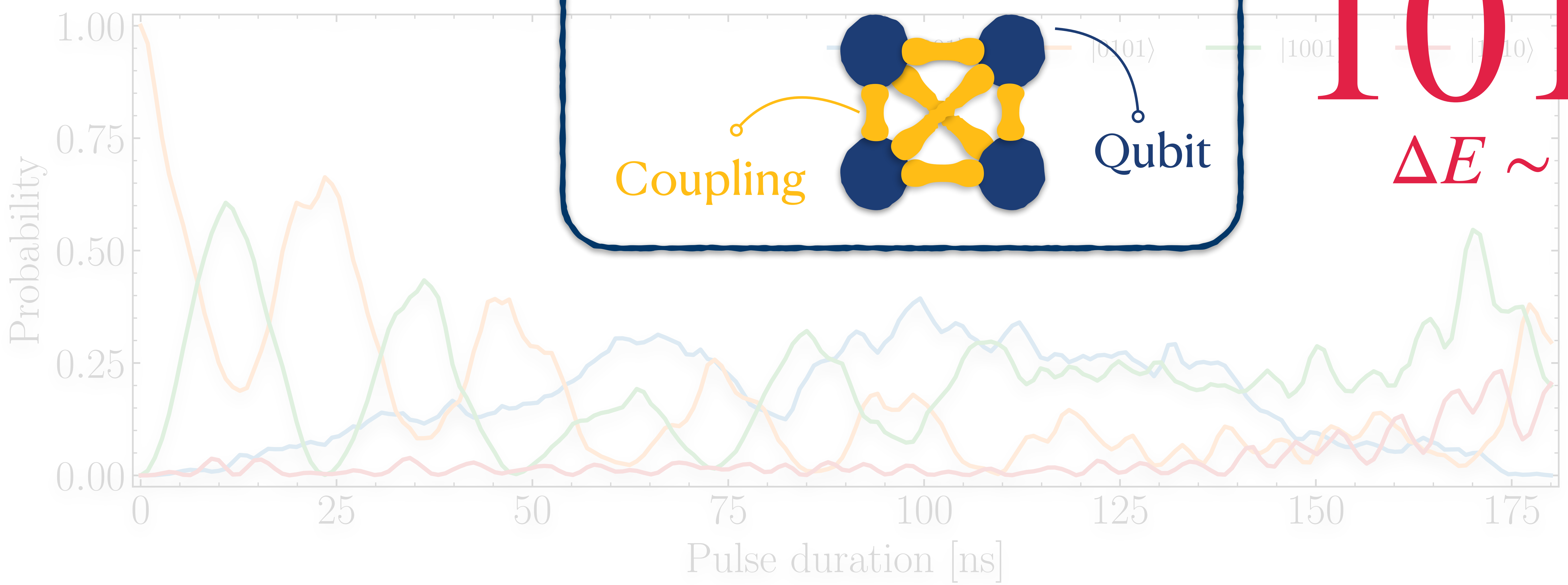
$\Delta E \sim 5 \times 10^{-3}$

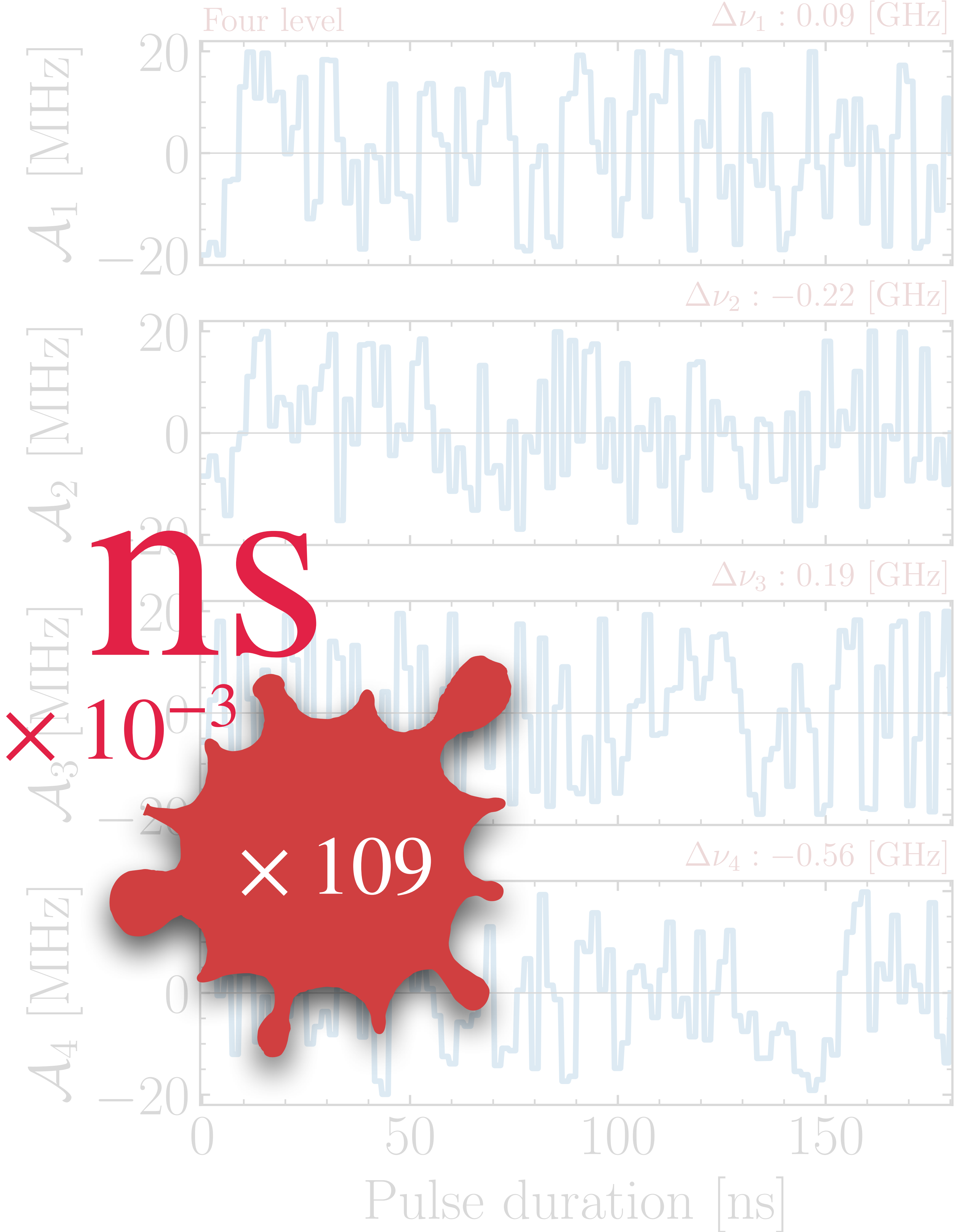
Quantum Computer:

101 ns

$\Delta E \sim 5 \times 10^{-3}$

$\times\, 109$

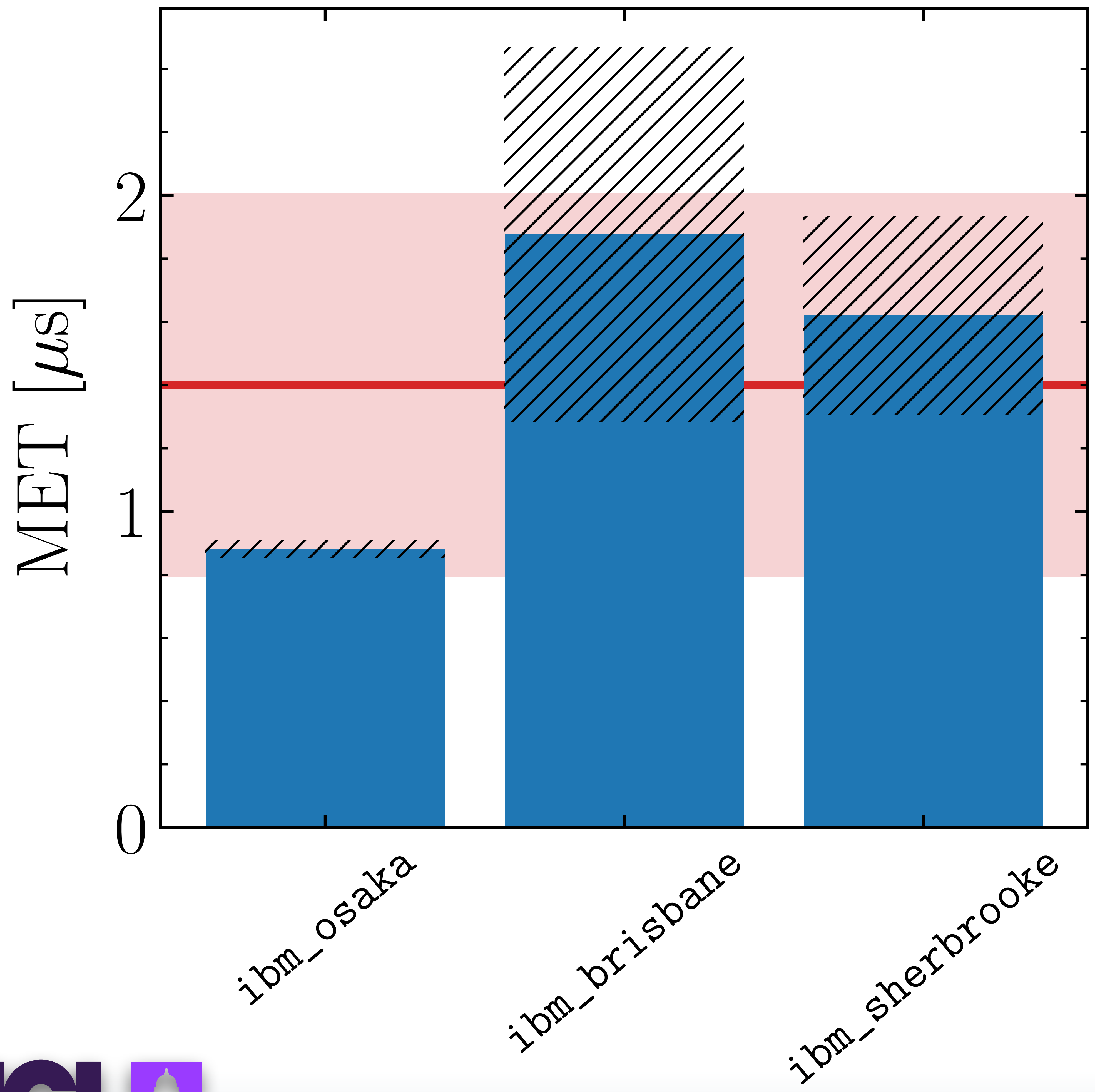




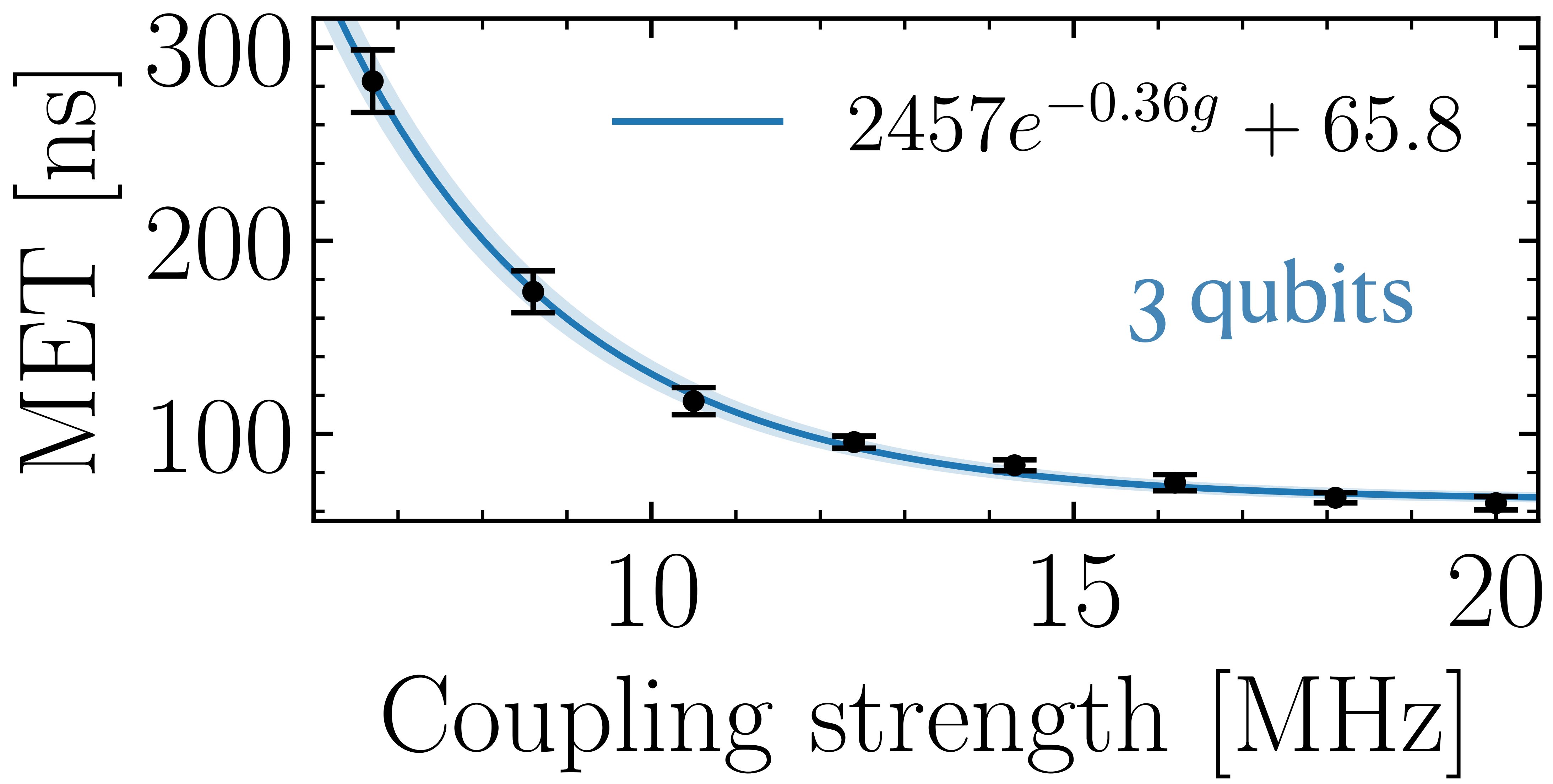
Can we improve the quantum device?

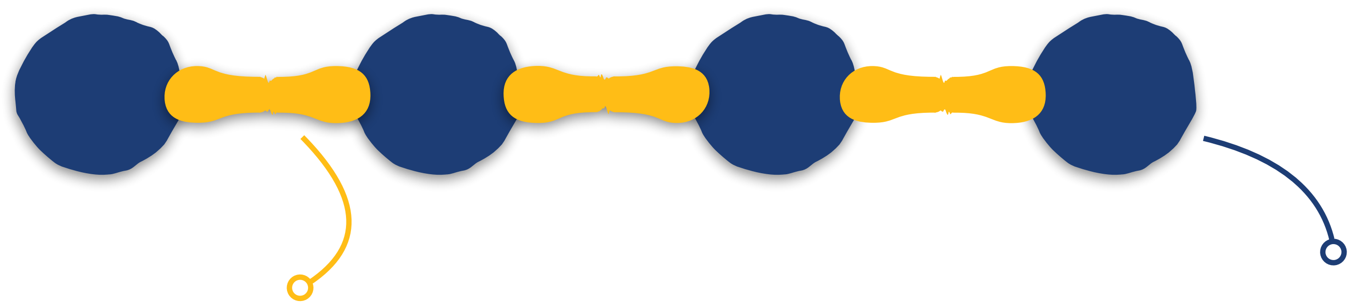
[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

Coupling strength: 2 MHz



- What if we can improve the Josephson junction to have a better-entangled state?



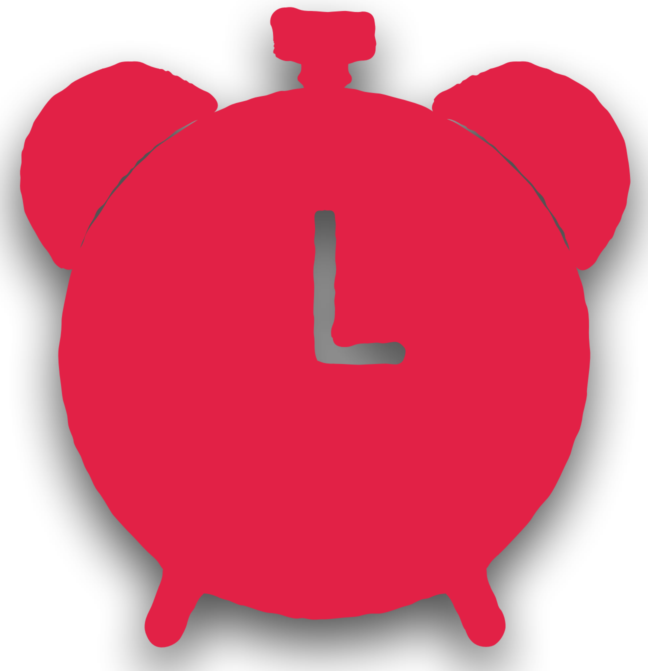


Towards simulating the Standard Model

$$\mathscr{L} = \bar{\psi}(i\partial^{\mu}\gamma_{\mu} - m)\psi$$

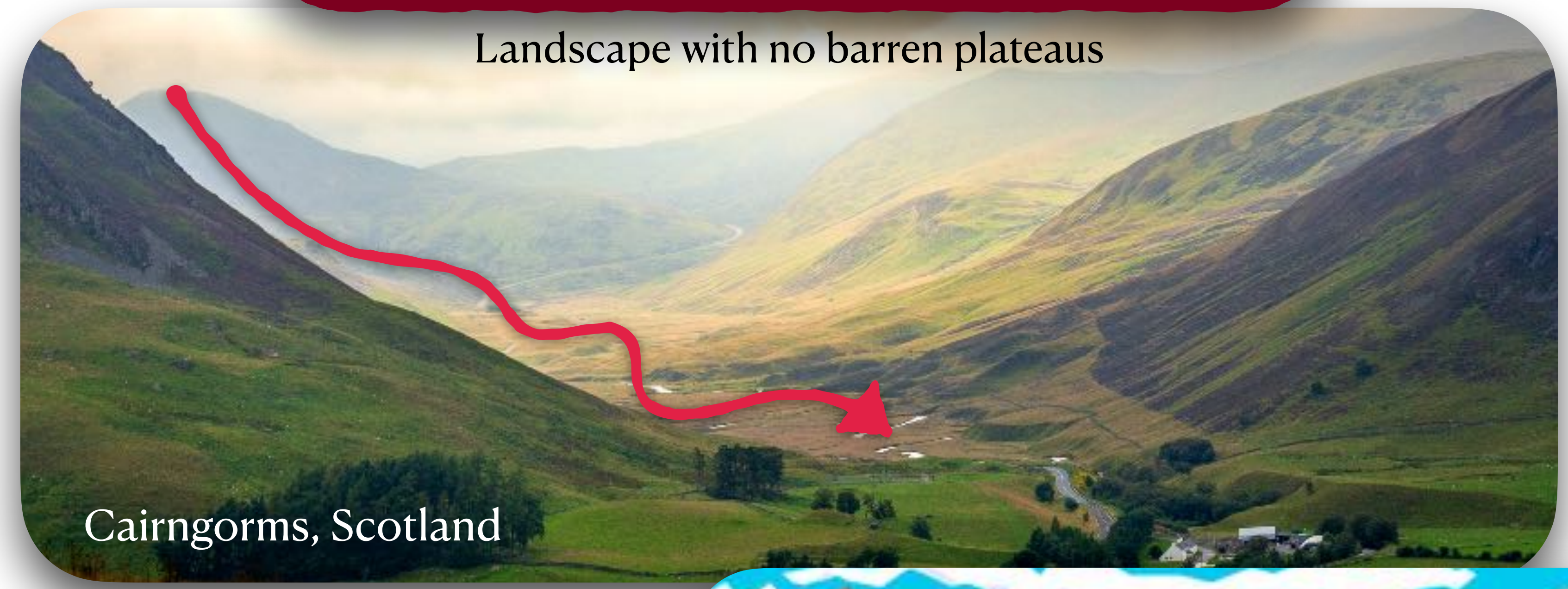
Qubits

Short Coherence Time



Typical coherence time for an IBM superconducting qubit is 50 to 100 microsecond

Barren Plateaus



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Qubits

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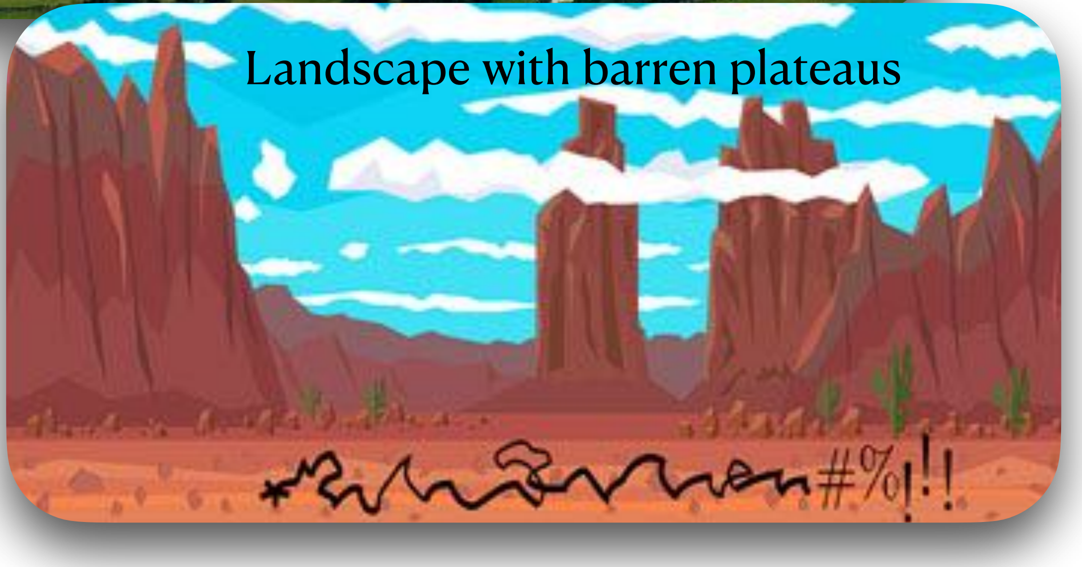


Jack Y. Araz

No more barren plateaus!

[JYA, Bhowmick, Grau, McEntire, Ringer; PRD ’25]

Larger duration per pulse improves the variance of the loss!

The behaviour of the loss function with gradient descent

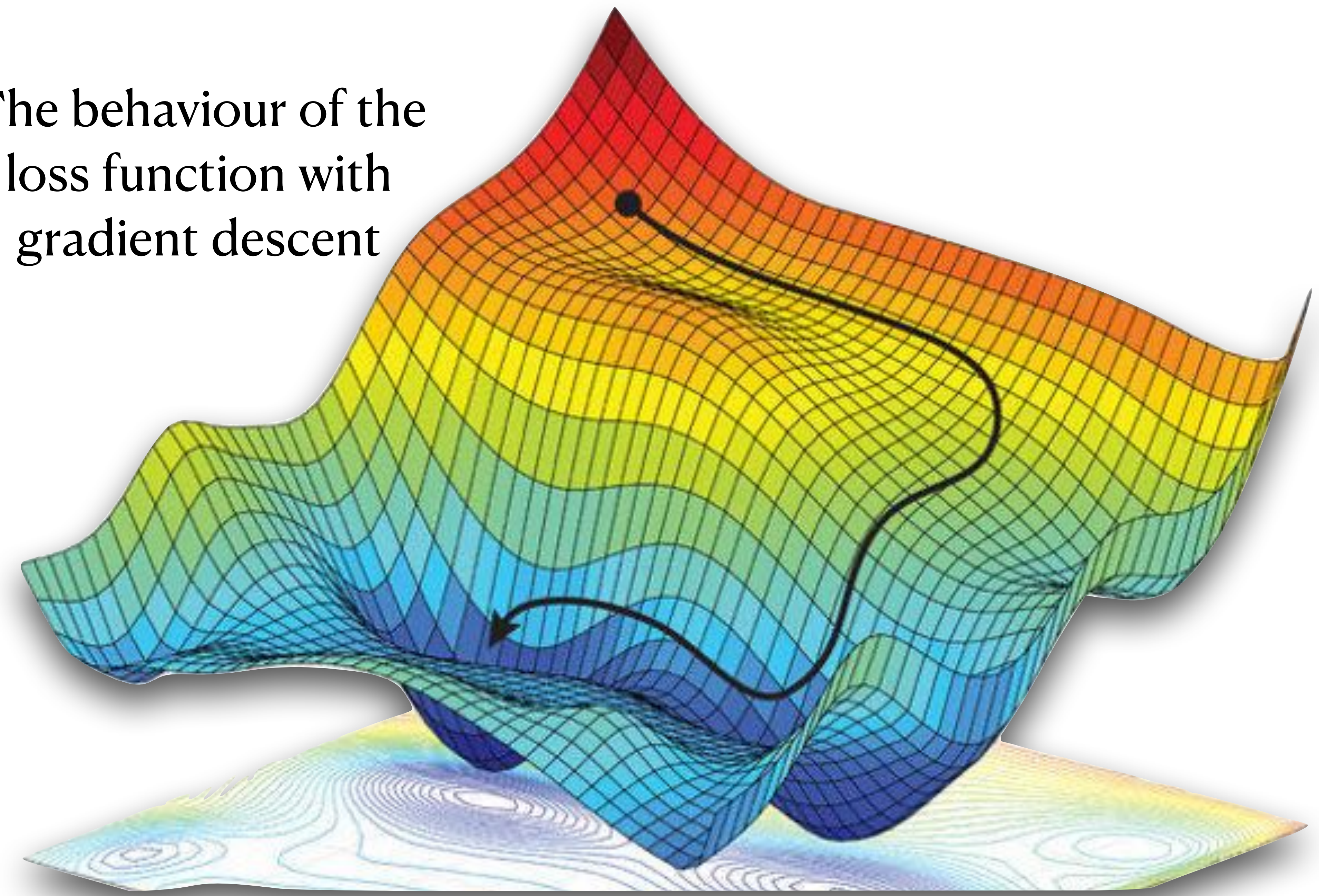
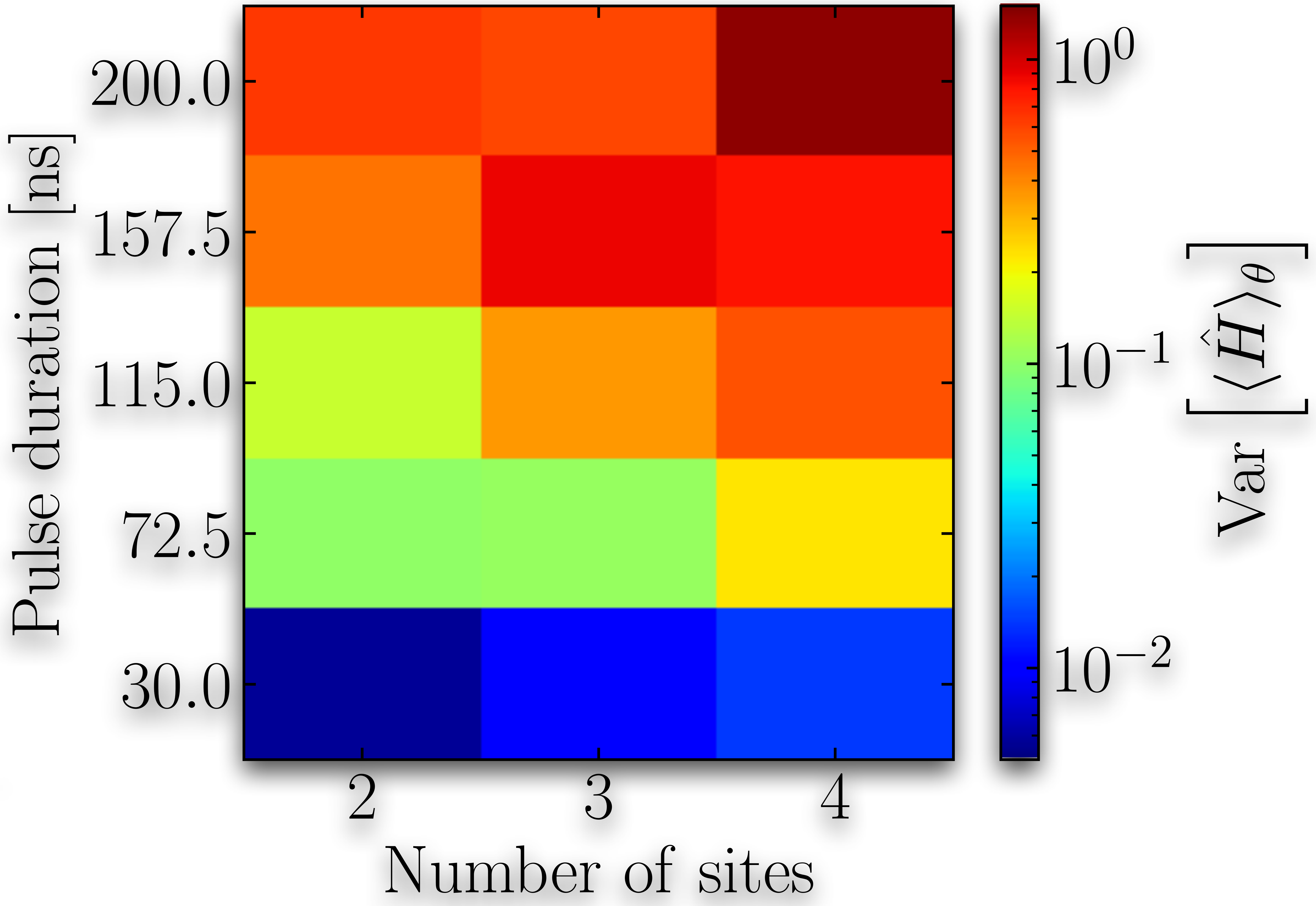


Image credit: Francisco Lima



Conclusion & Outlook

Conclusion & Outlook

- Combining different technologies may be the best way to simulate the SM.
- Custom gates can allow us to create more efficient algorithms for LGT.

Sponsors

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Conclusion & Outlook

- Combining different technologies may be the best way to simulate the SM.
- Custom gates can allow us to create more efficient algorithms for LGT.

- How do we simulate scattering in a hybrid system?
- How do we embed gauge links in a hybrid system?
- Can we tune hybrid gates with QOC?
- Can we fill the gap between Tensor Networks & future quantum computers?

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