Towards simulating fundamental physics with near-term quantum computers

Jack Y. Araz

STONY BROOK UNIVERSITY

Jan. 13th, 2025
QIS on the Intersections of Nuclear and AMO Physics

Jefferson Lab EXPLORING THE NATURE OF MATTER · U.S. DEPARTMENT OF ENERGY | Office of Science · MCnet · Stony Brook University

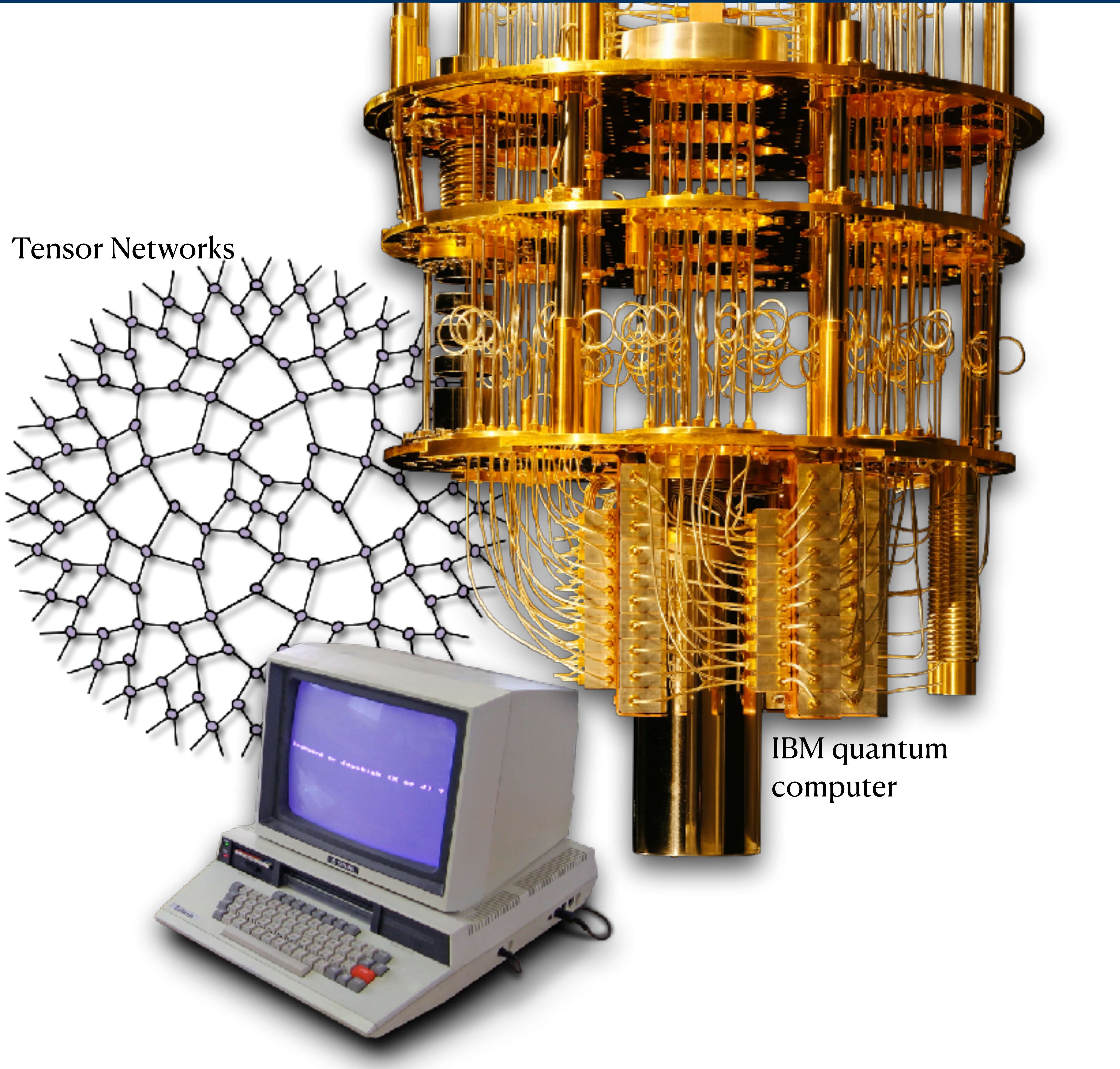
Outline

Simulating the Fundamental Physics

Limitations of Quantum Computing

And how to avoid them

(just one of the options for this talk)



Simulating the Quantum Nature

Simulating the Quantum Nature

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

And many more…

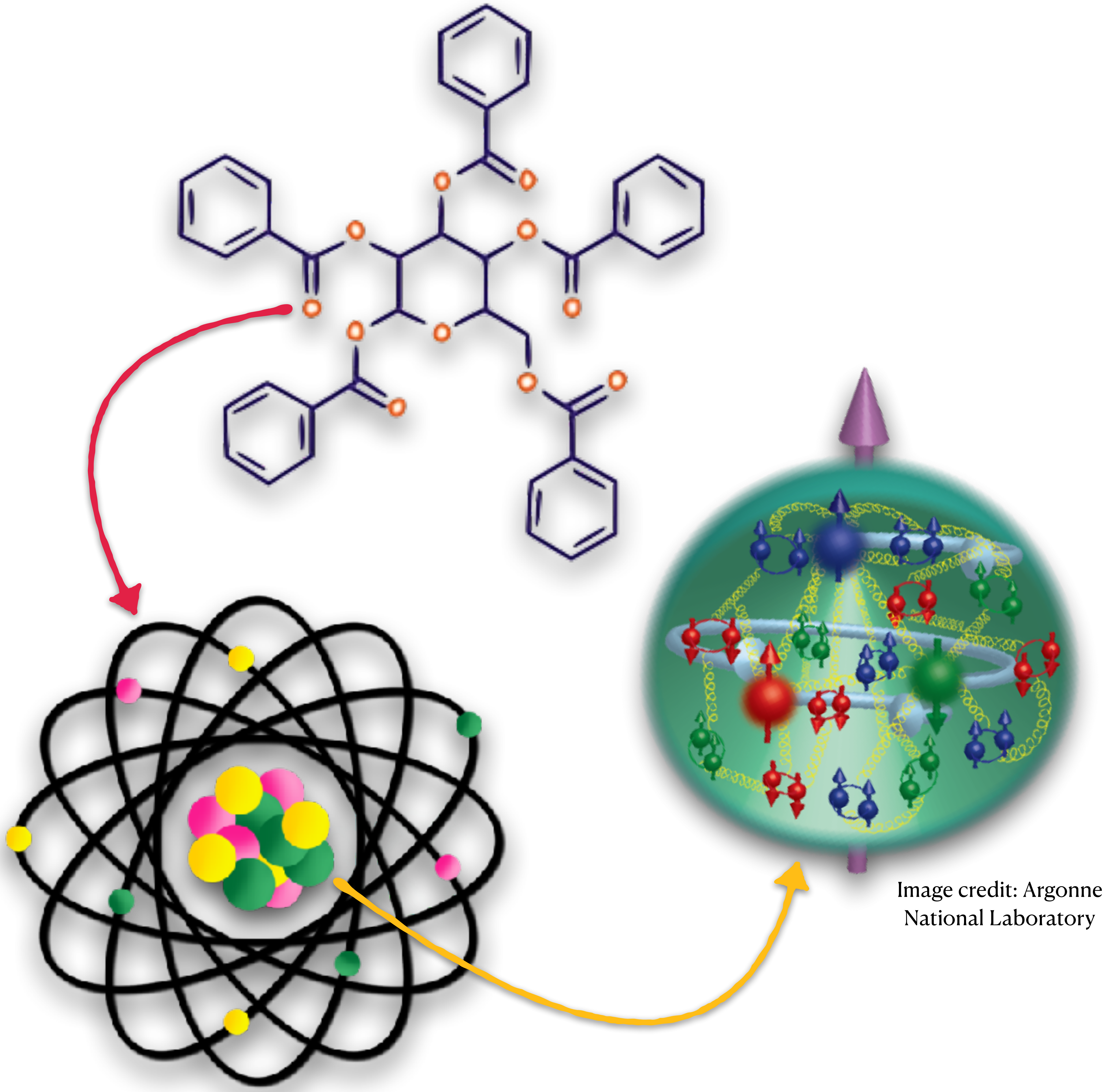


Image credit: Argonne National Laboratory

Simulating the Quantum Nature

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

And many more…

Classical Methods

- Exact diagonalisation
- Monte Carlo
- Tensor Networks

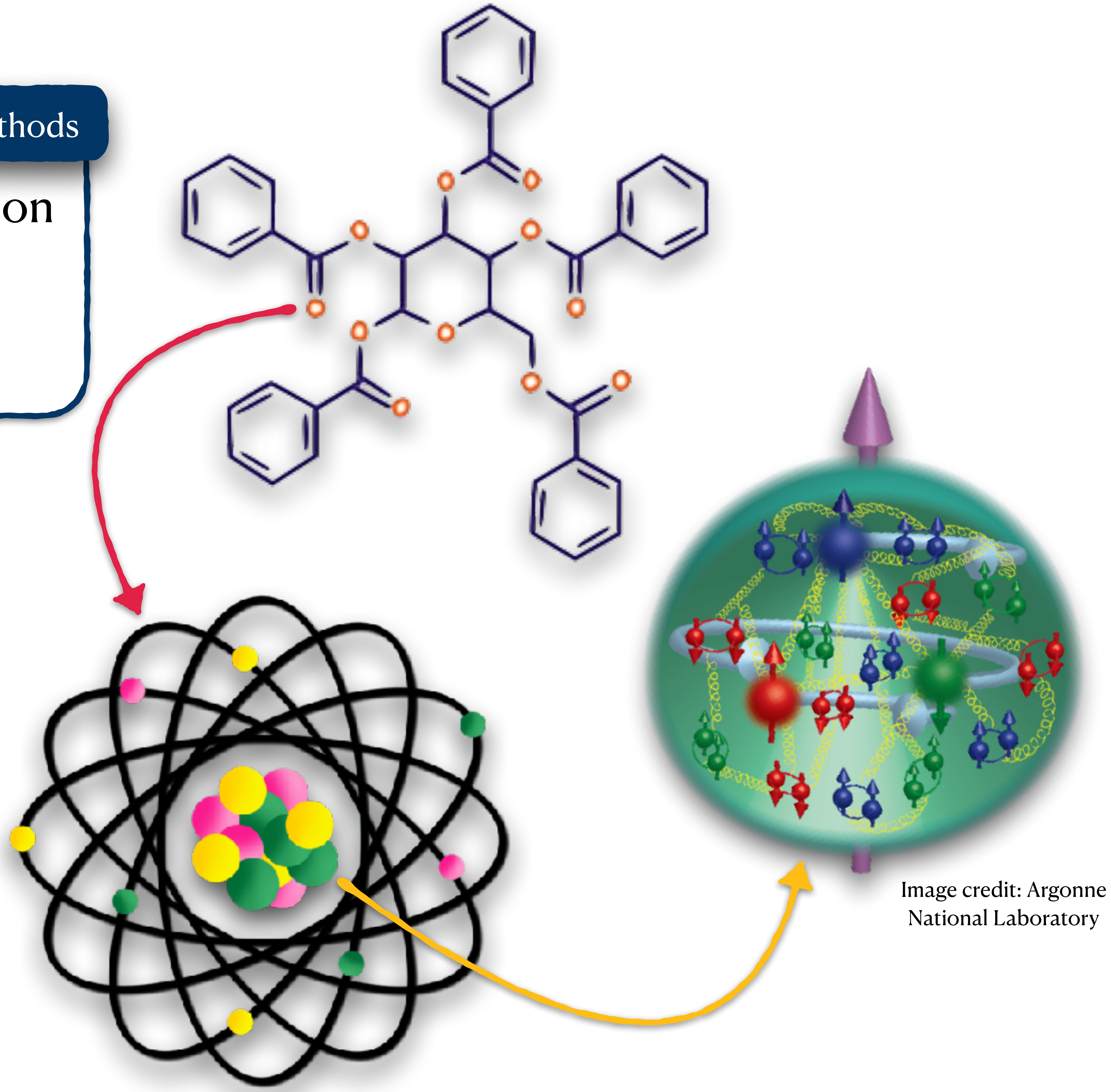


Image credit: Argonne National Laboratory

Simulating the Quantum Nature

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

And many more...

Classical Methods

- Exact diagonalisation
- Monte Carlo
- Tensor Networks

Why Quantum?

- The main goal is to study physics
- Efficient way of simulating quantum systems

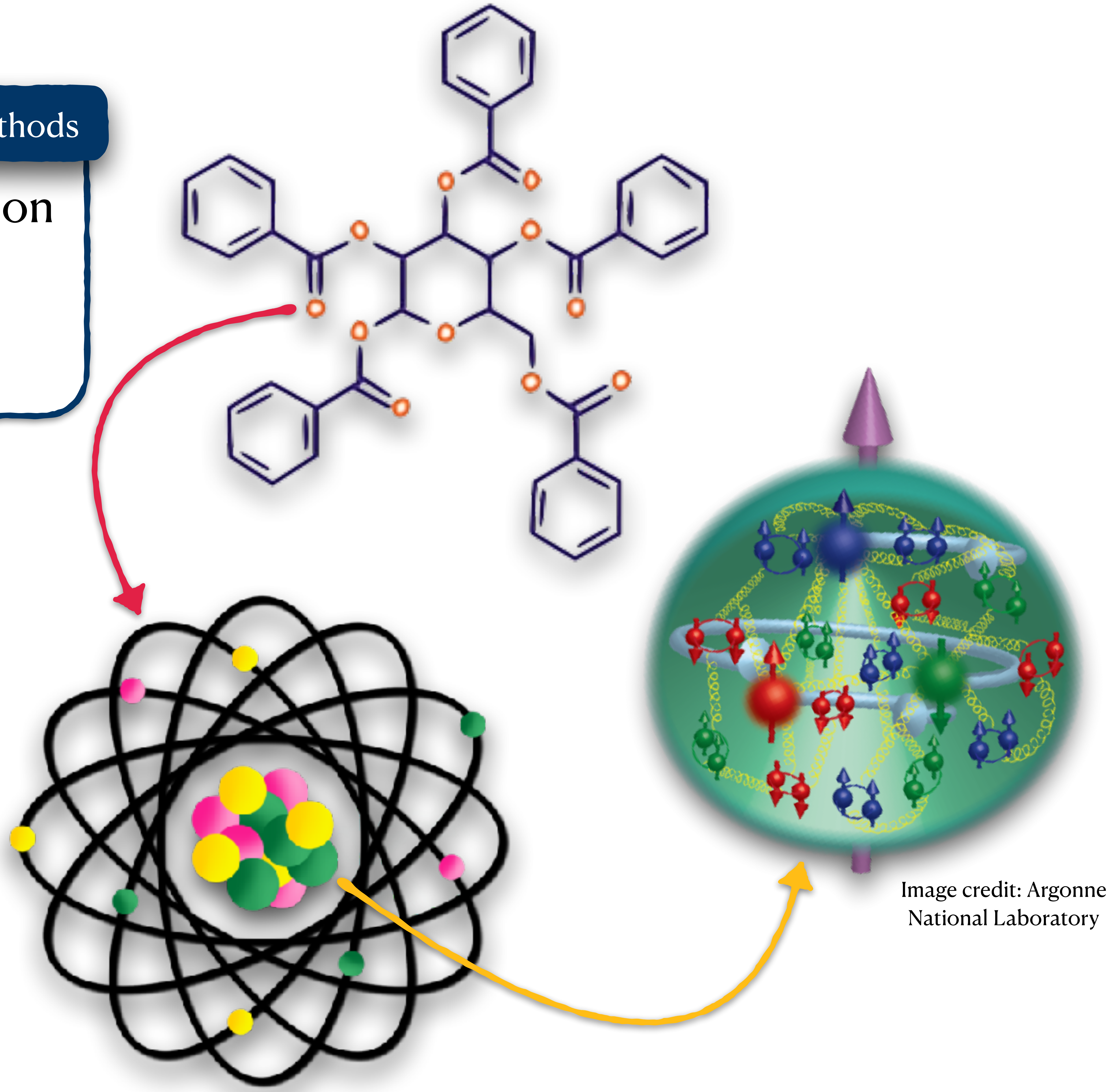
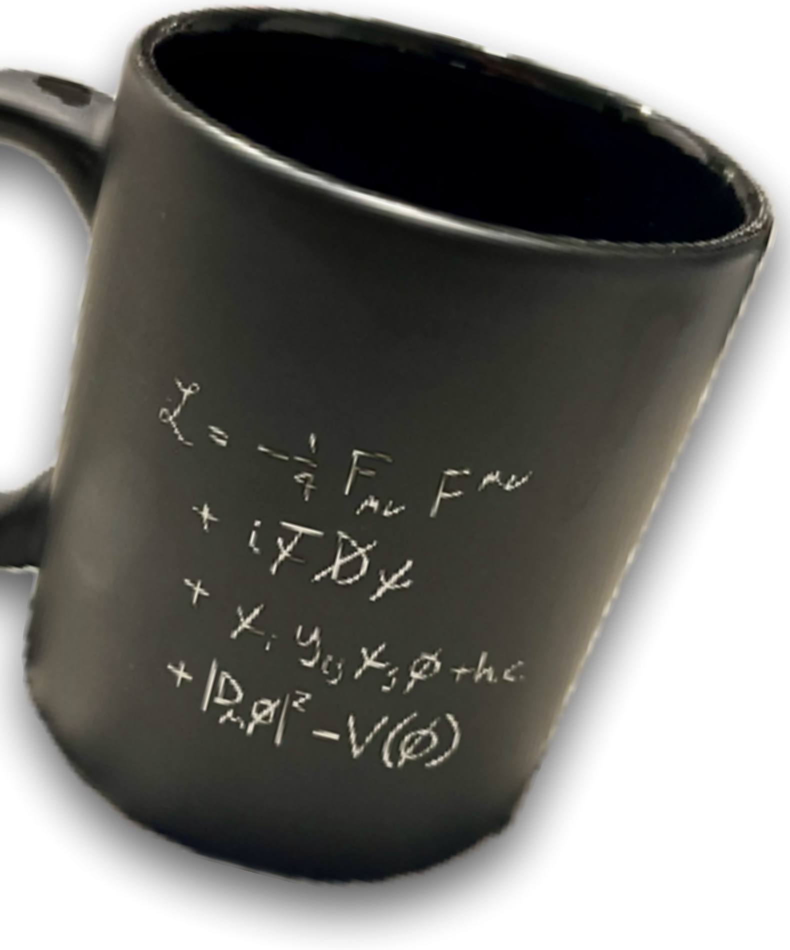


Image credit: Argonne National Laboratory

Towards simulating the Standard Model

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

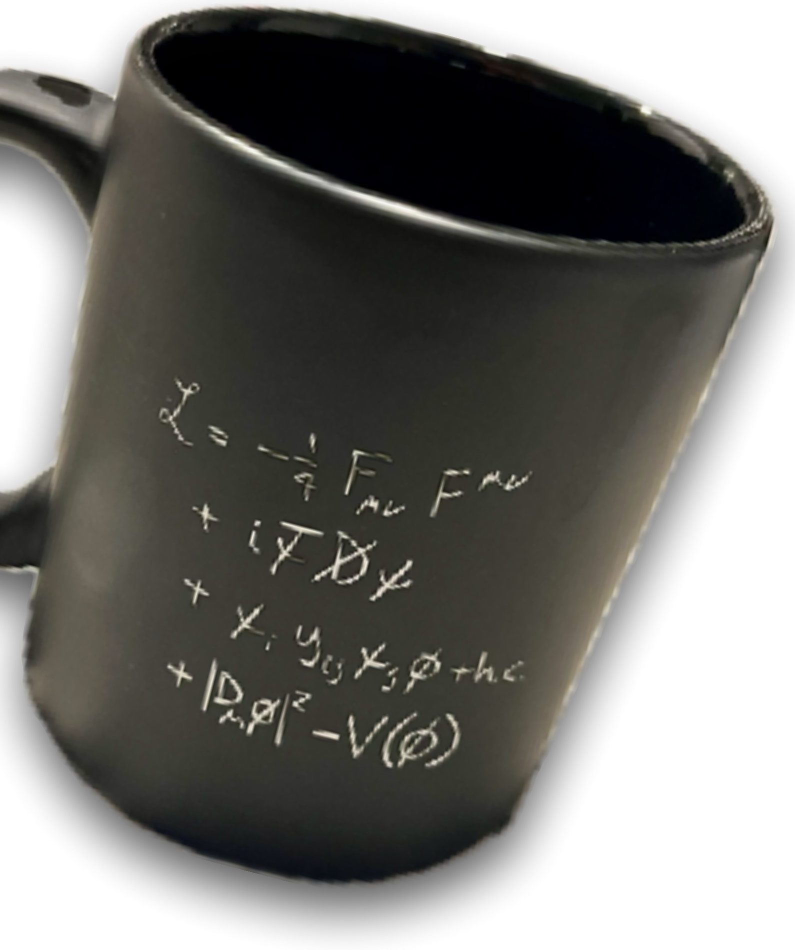


$$-\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

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

Towards simulating the Standard Model

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



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

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

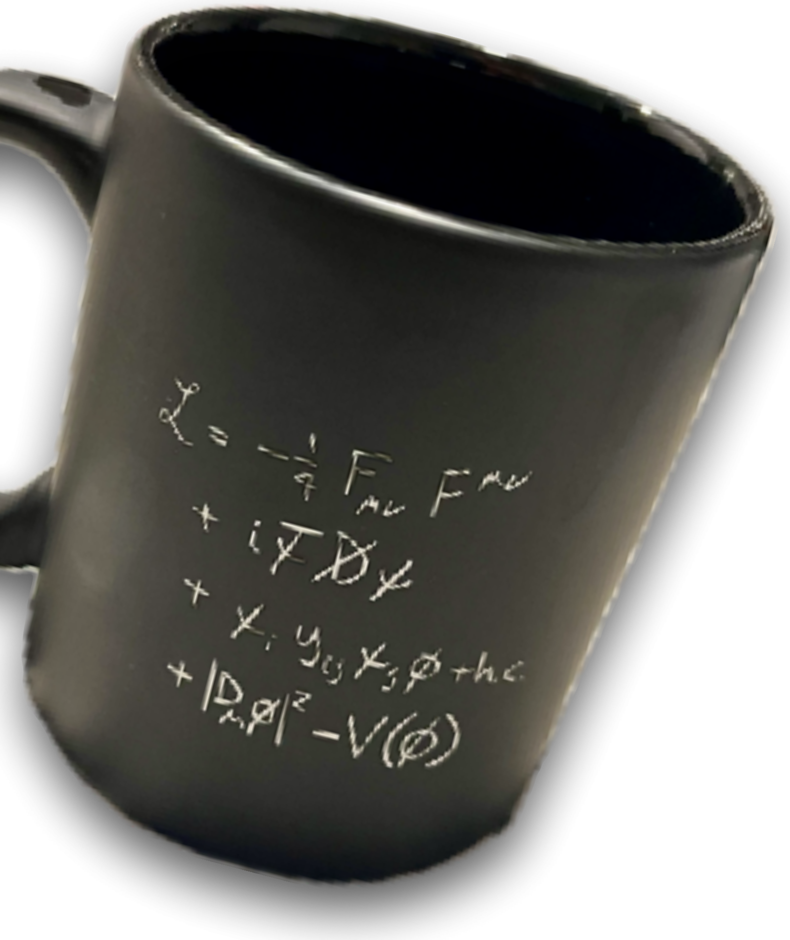
Jack Y. Araz

Jefferson Lab EXPLORING THE NATURE OF MATTER

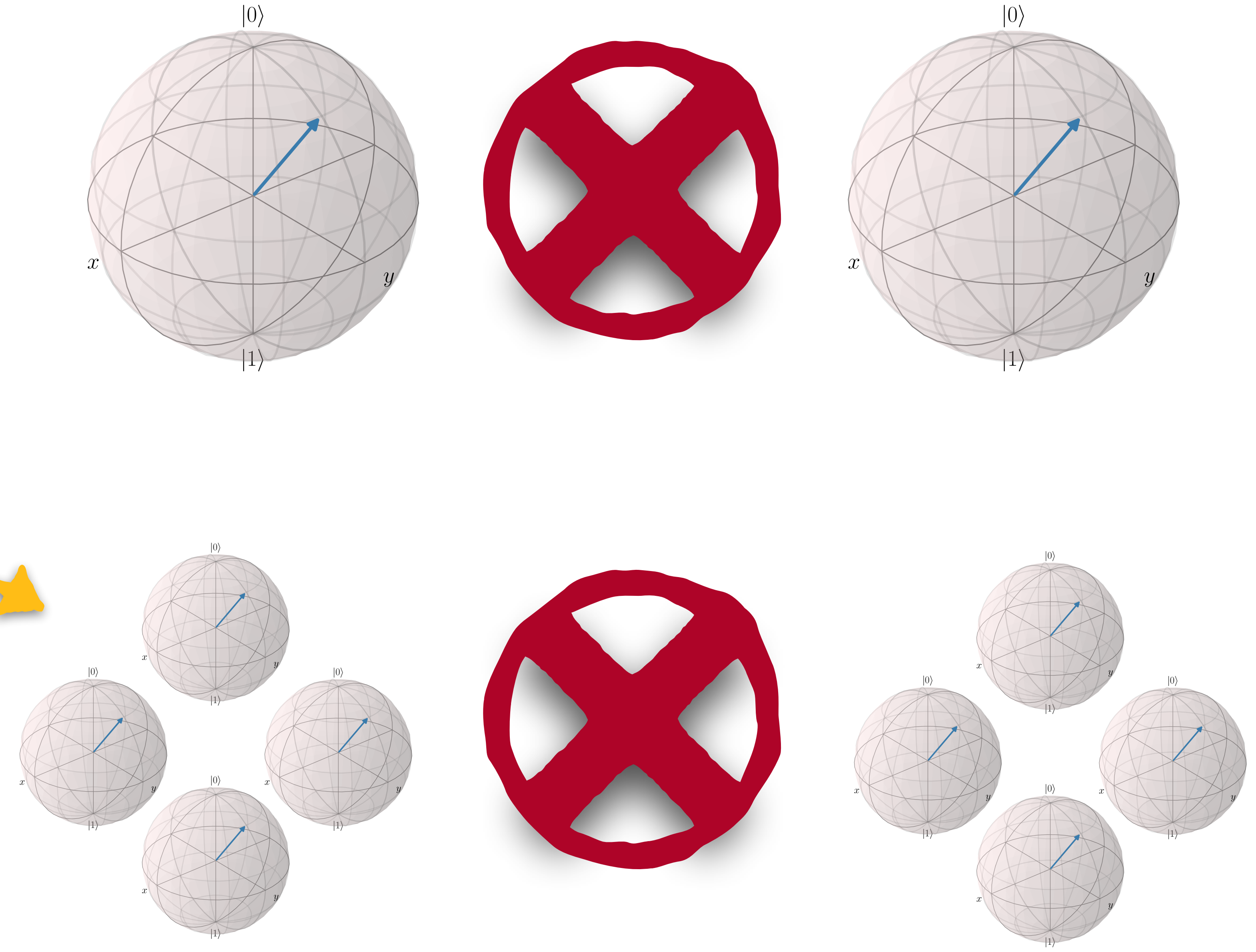
Stony Brook University

Towards simulating the Standard Model

$$\mathscr{L} = \bar{\psi}(i\partial^{\mu}\gamma_{\mu} - m)\psi - \frac{1}{4}F_{a}^{\mu\nu}F^{a}_{\mu\nu} + g\bar{\psi}\gamma^{\mu}T_{a}\psi A^{a}_{\mu}$$

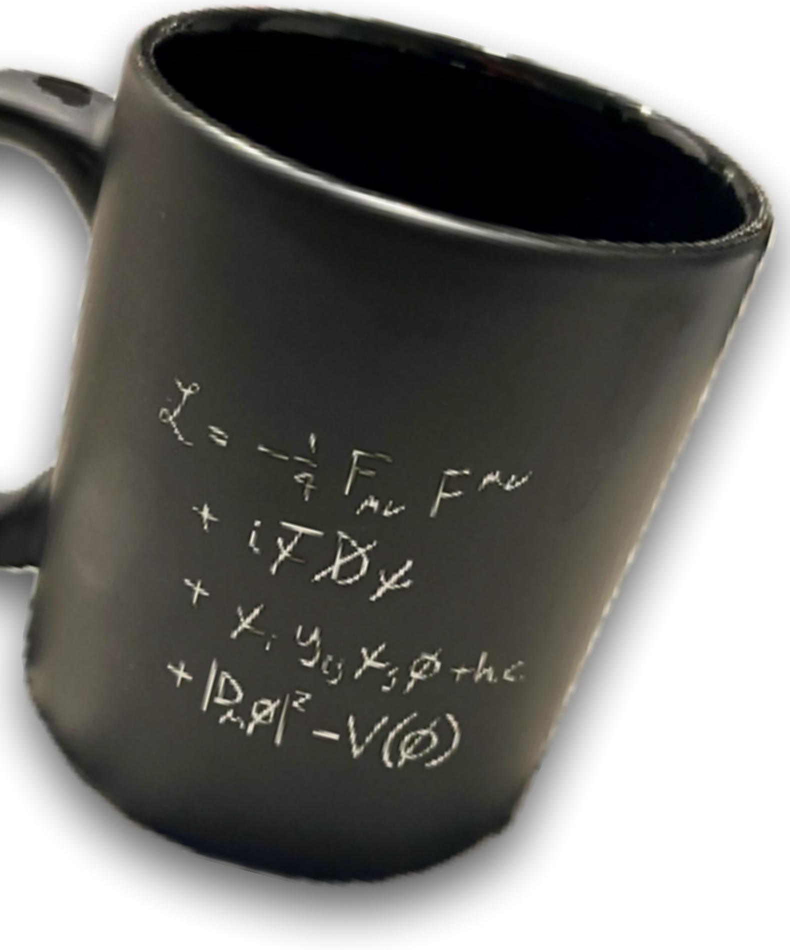


DoF $\to \infty$



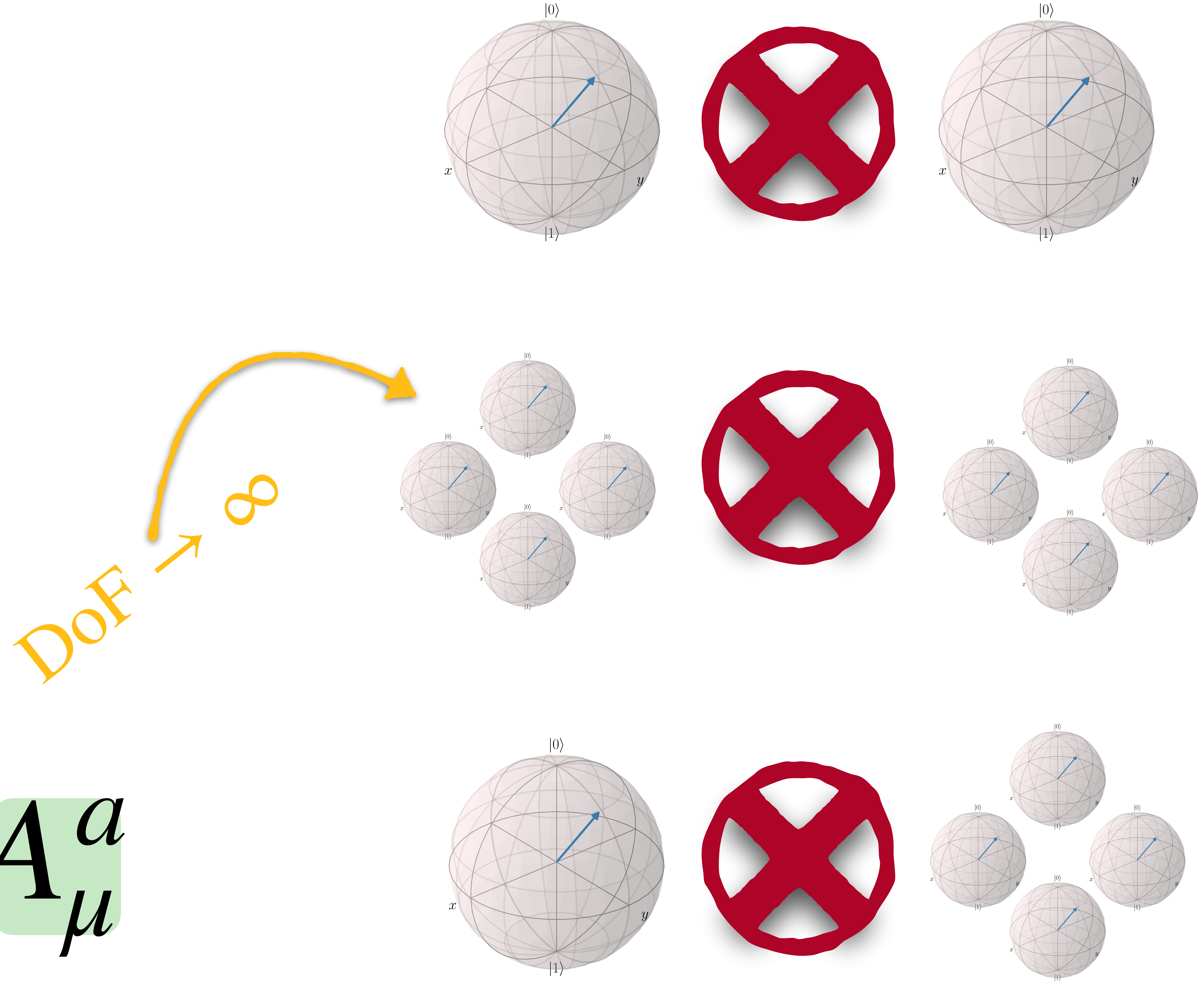
Towards simulating the Standard Model

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



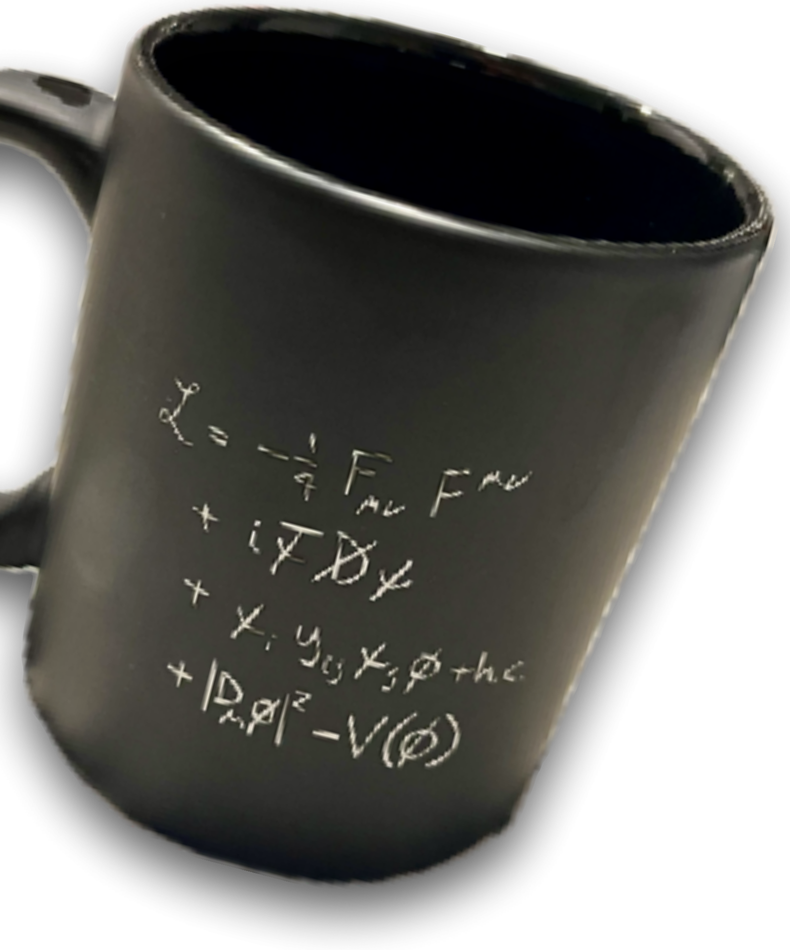
$$-\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

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



Towards simulating the Standard Model

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



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

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

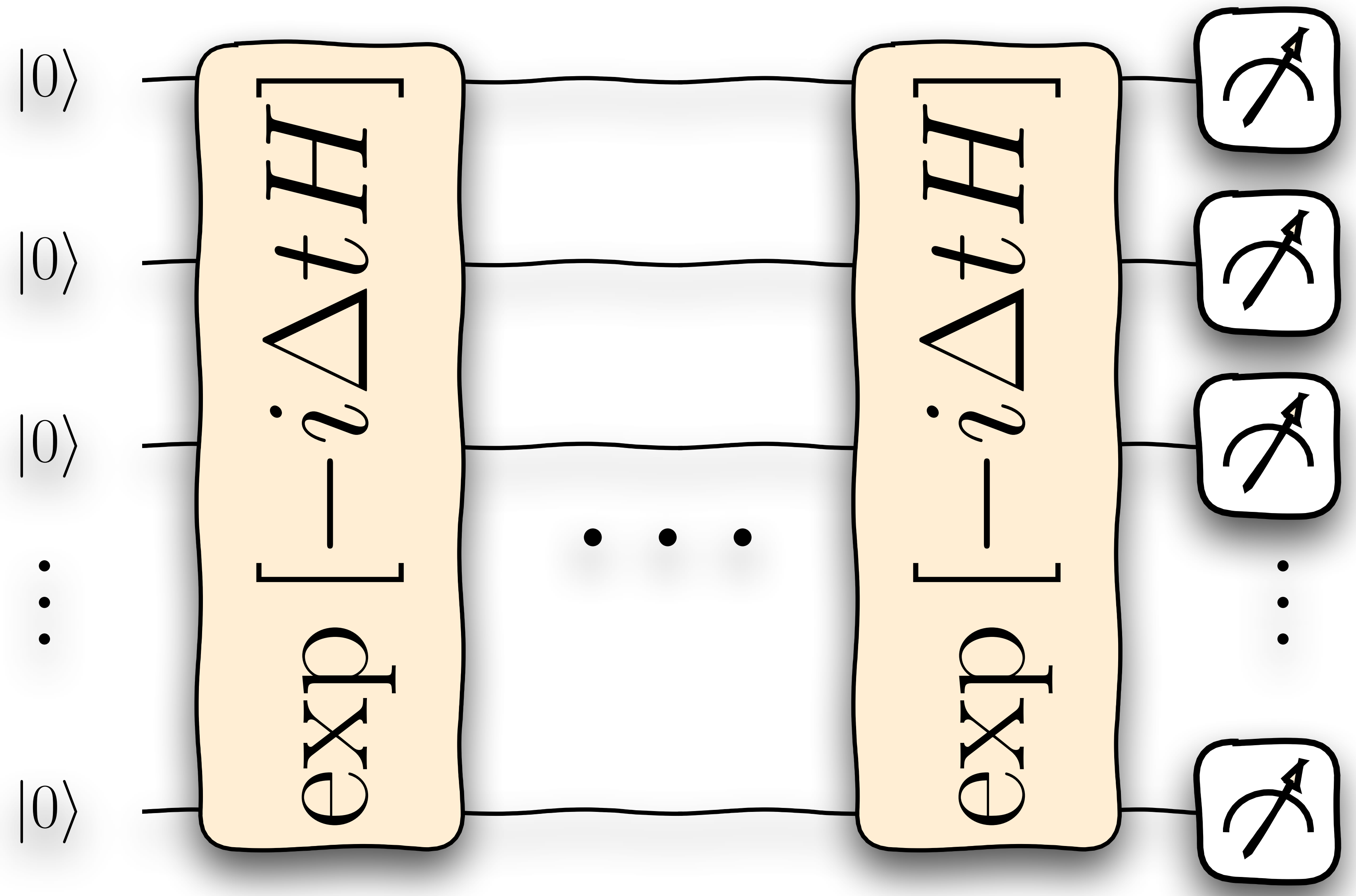
See Kenneth's talk today & Felix's talk tomorrow

Qumodes or CV Quantum Computers

Qubit-Qumode Coupling

Quantum Computing for Fundamental Physics

Time Evolution or Adiabatic State Preparation

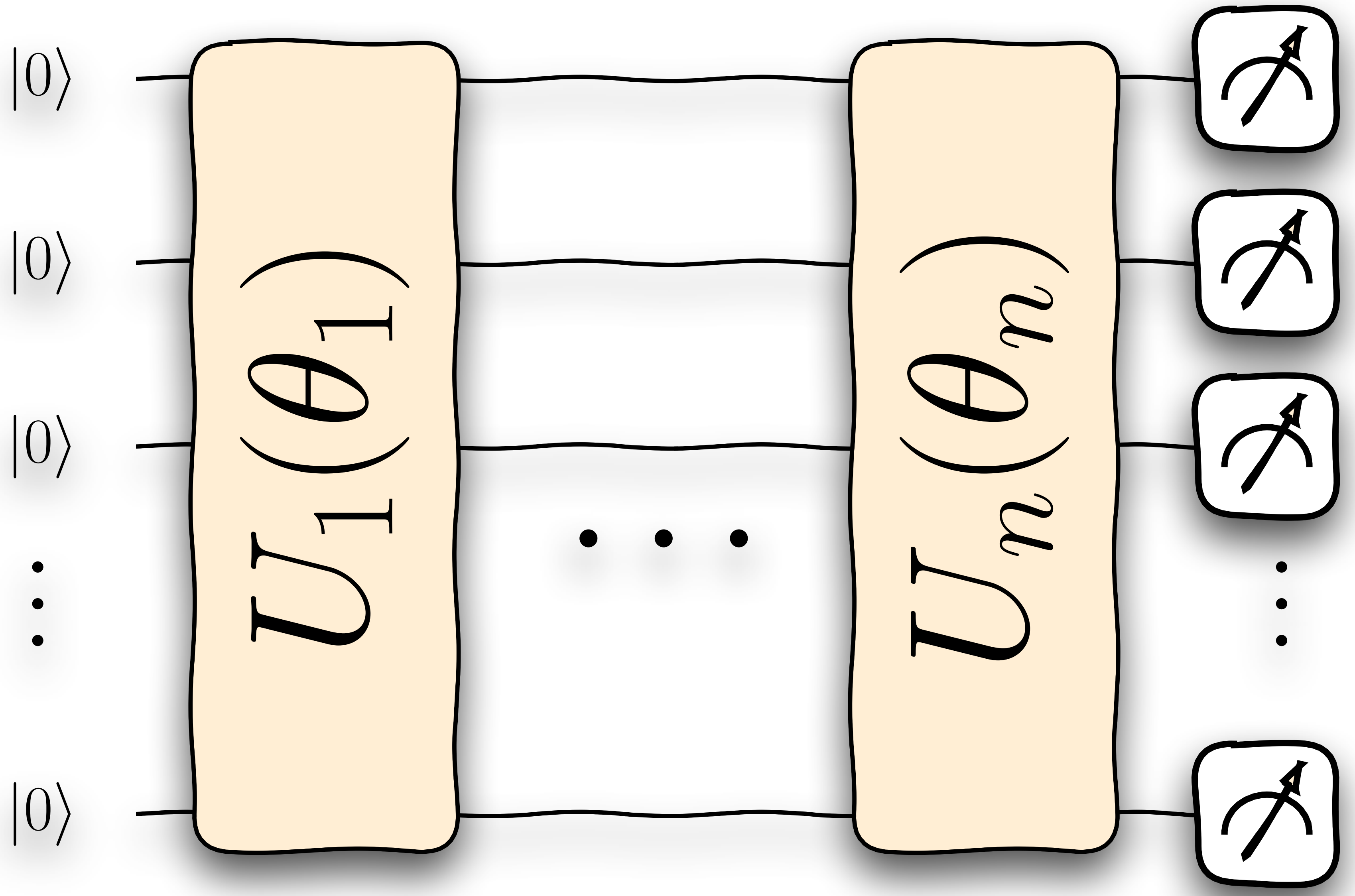


$$e^{-iTH} \simeq \prod^{N} e^{-i\Delta t H}$$

Quantum Computing for Fundamental Physics

Time Evolution or Adiabatic State Preparation

State Preparation with VQE



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

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

Quantum Computing for Fundamental Physics

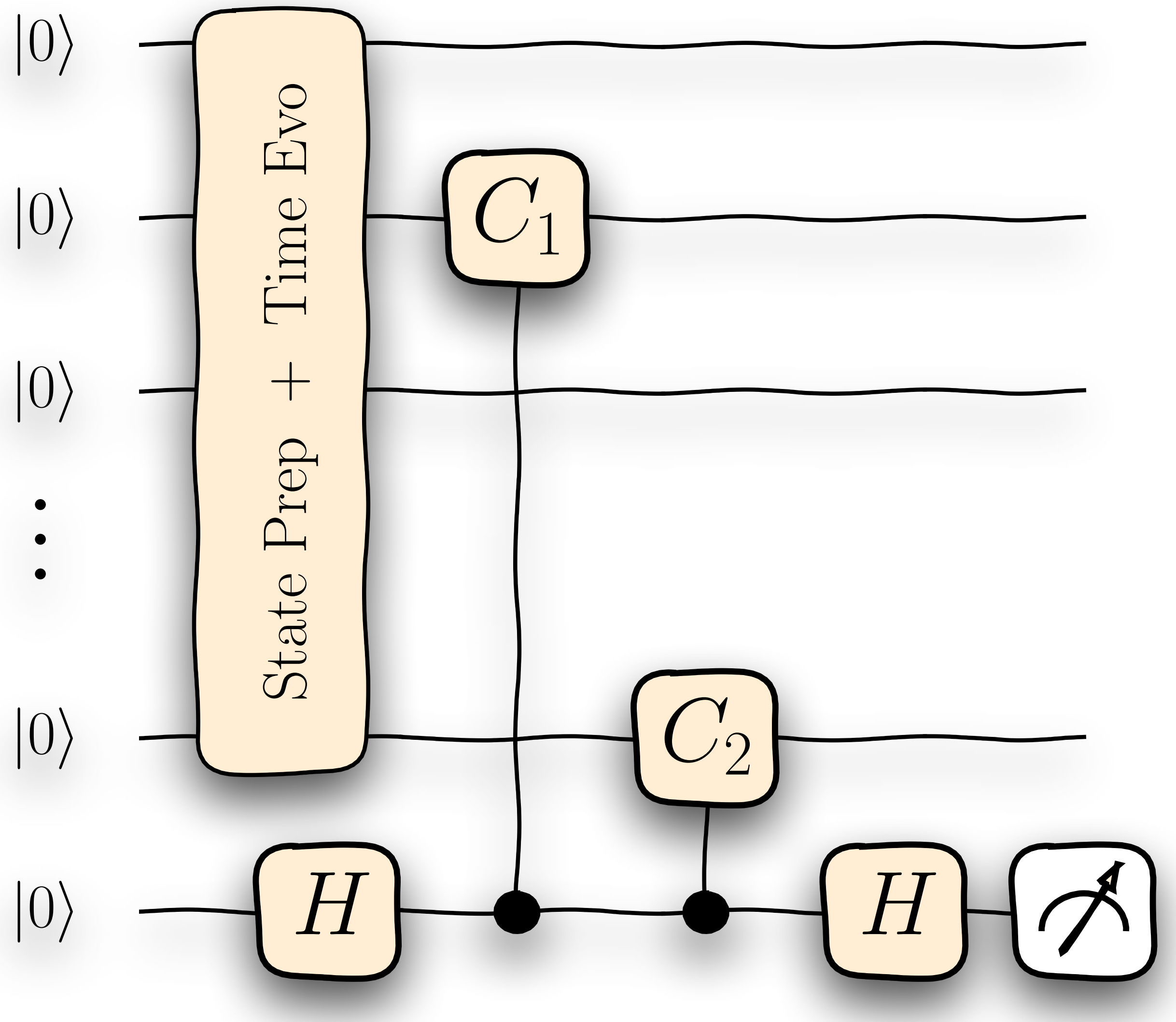
Time Evolution or Adiabatic State Preparation

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

State Preparation with VQE

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

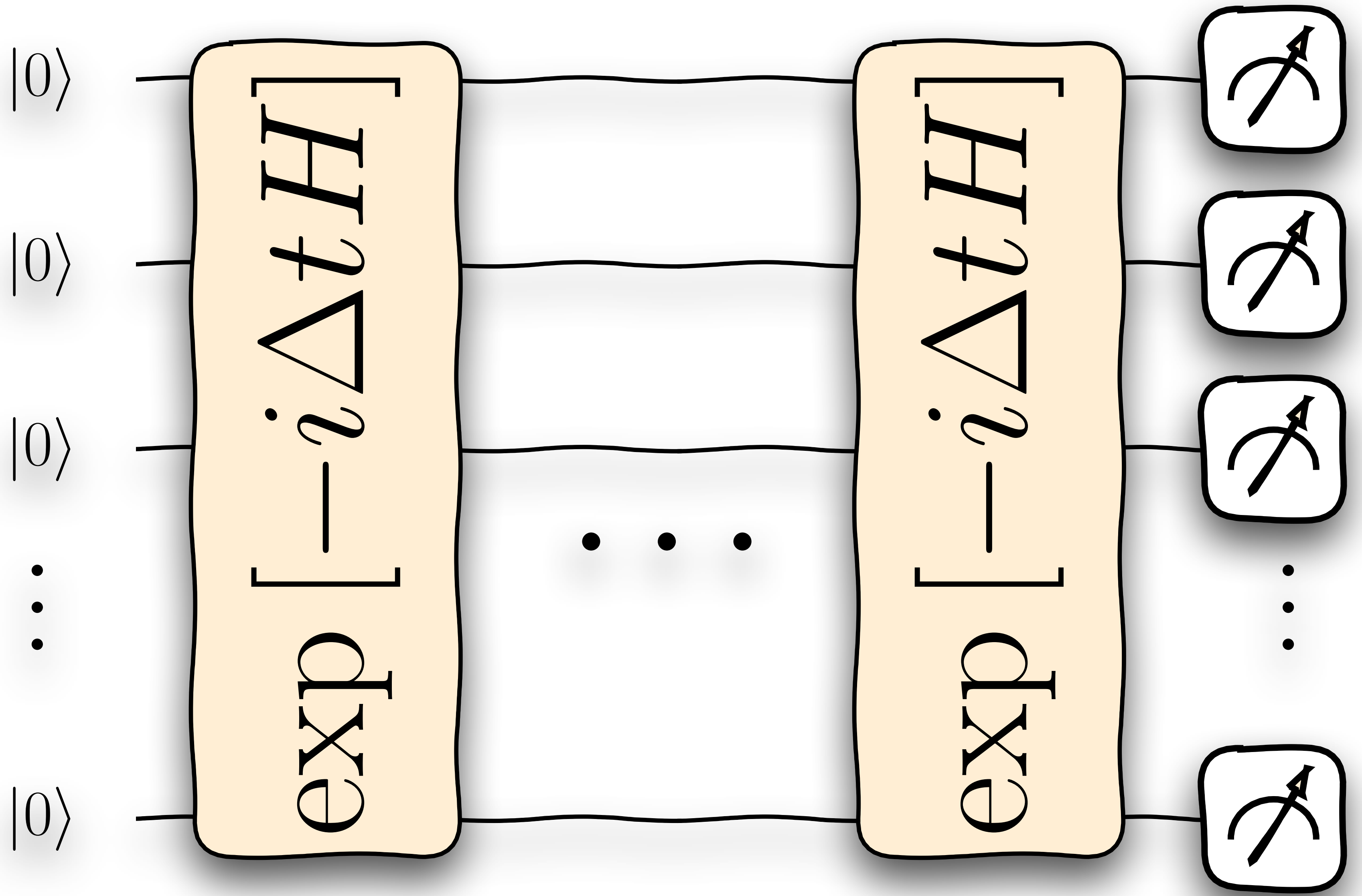
Computing interesting observables



Jack Y. Araz

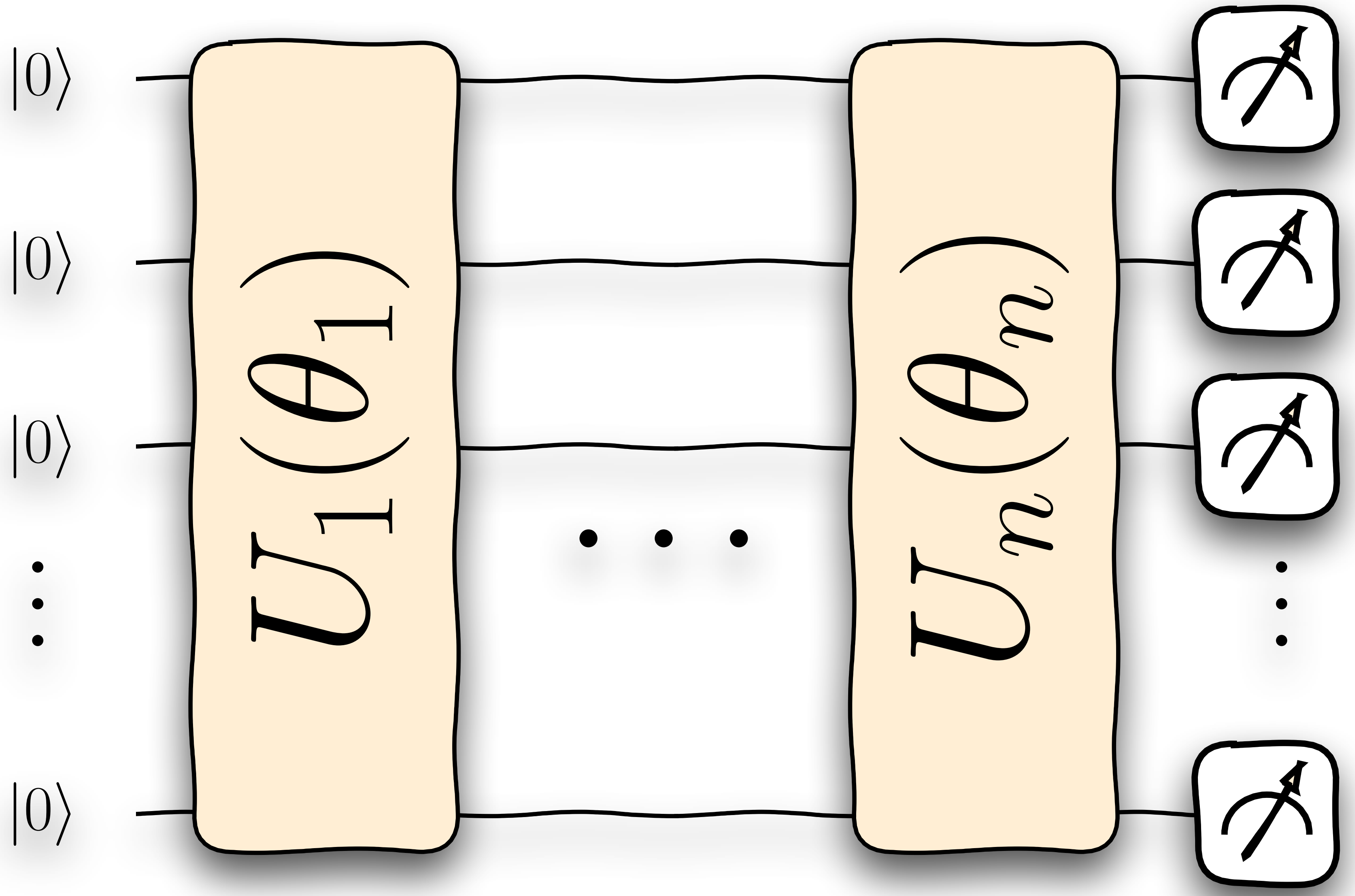
Quantum Computing for Fundamental Physics

Time Evolution or Adiabatic State Preparation



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

State Preparation with VQE

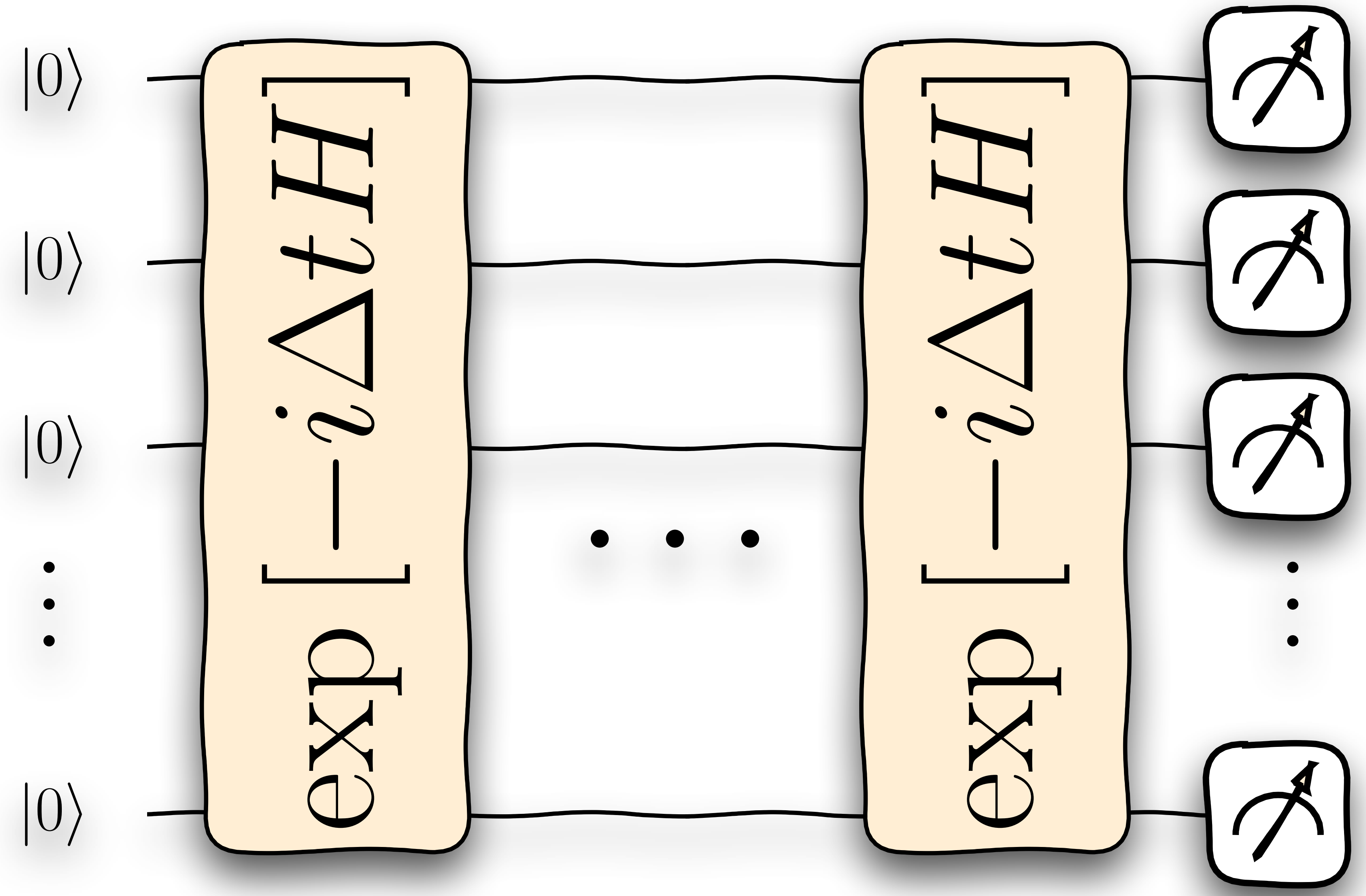


$$\langle 0 | U(\theta) H U^{\dagger}(\theta) | 0 \rangle \geq E_{gs}$$

Computing interesting observables

But, there is no free lunch…

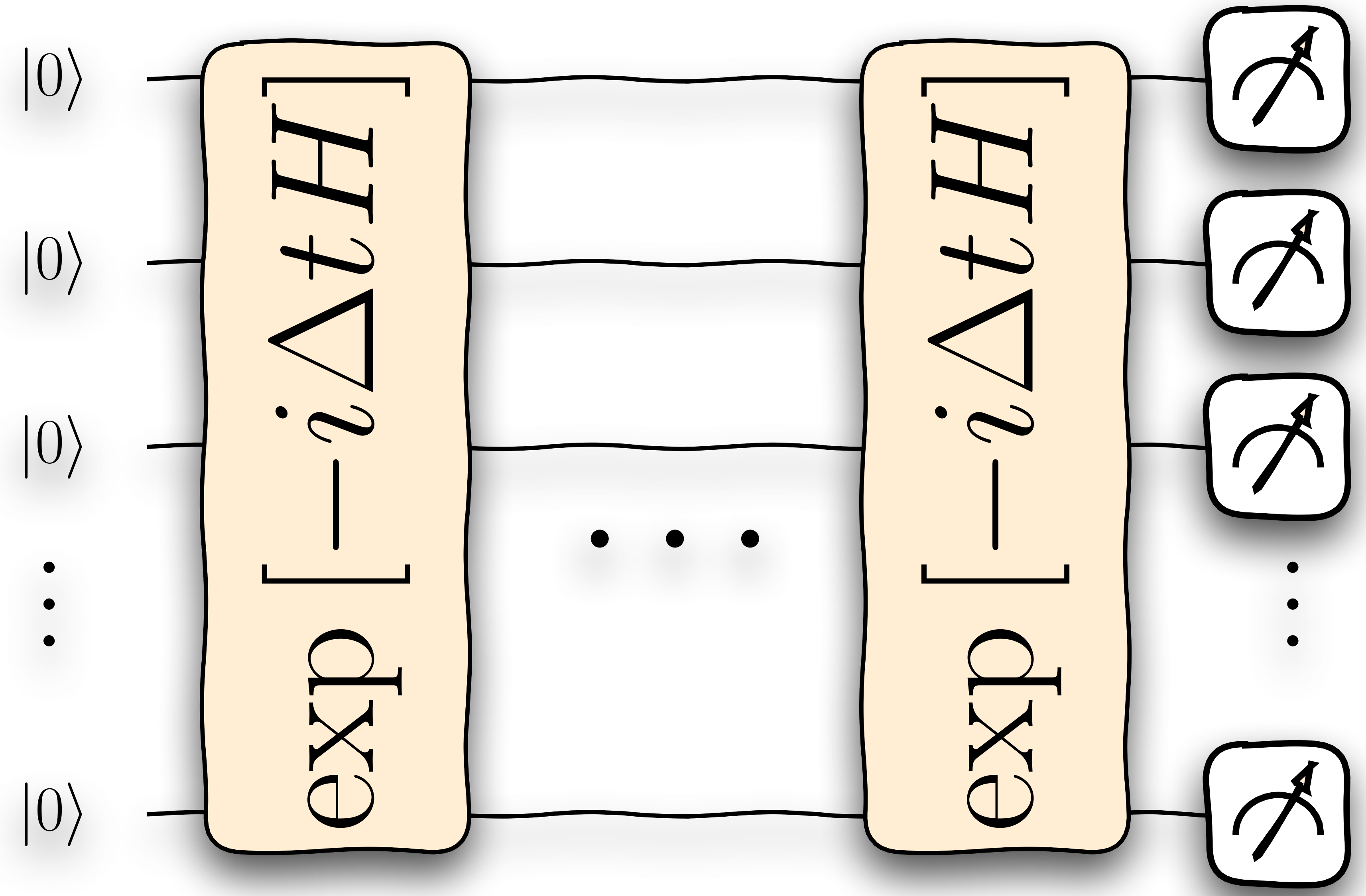
Time Evolution or Adiabatic State Preparation



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

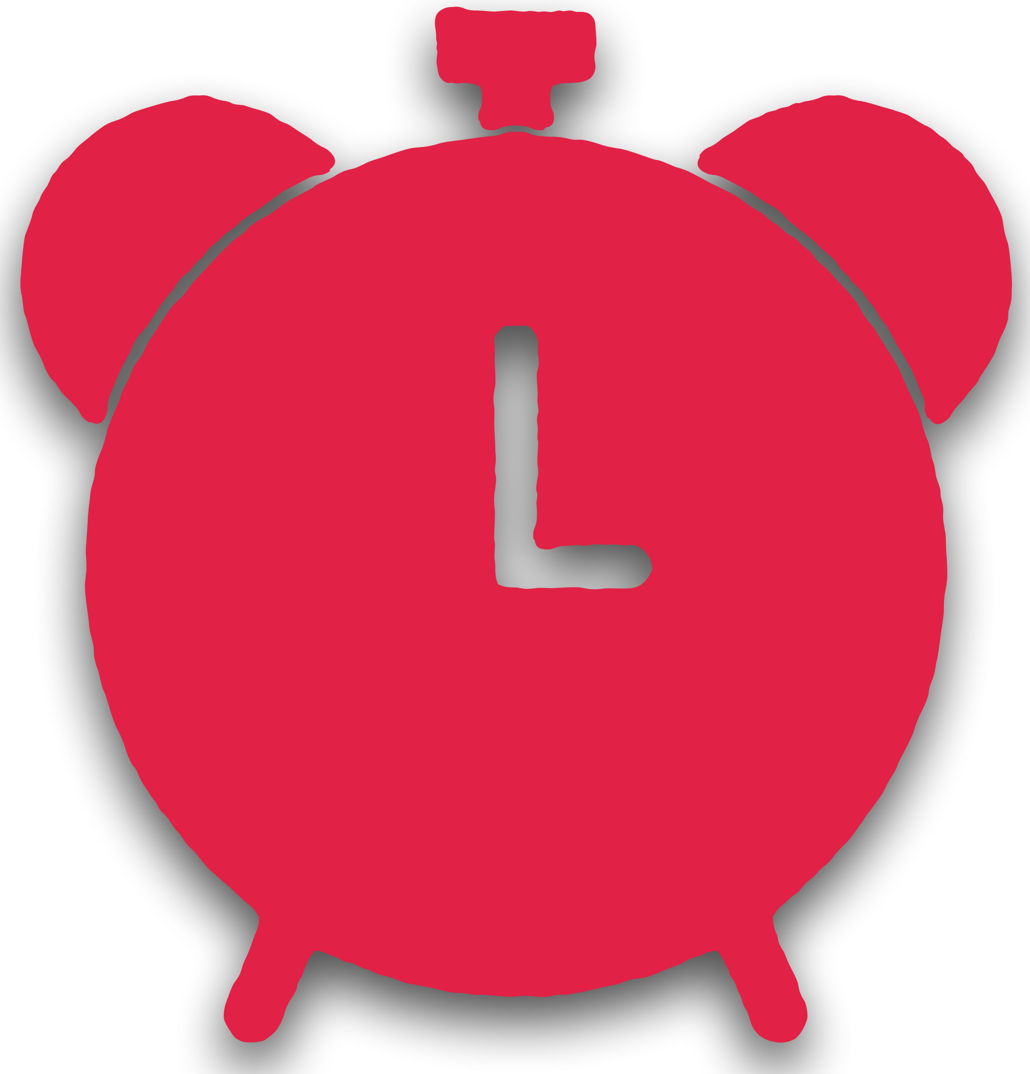
But, there is no free lunch…

Time Evolution or Adiabatic State Preparation

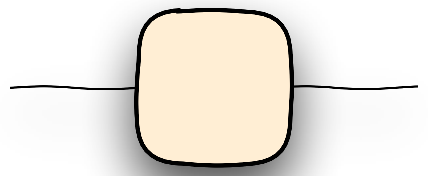


$$e^{-iTH} \simeq \prod^{N} e^{-i\Delta t H}$$

Short Coherence Time

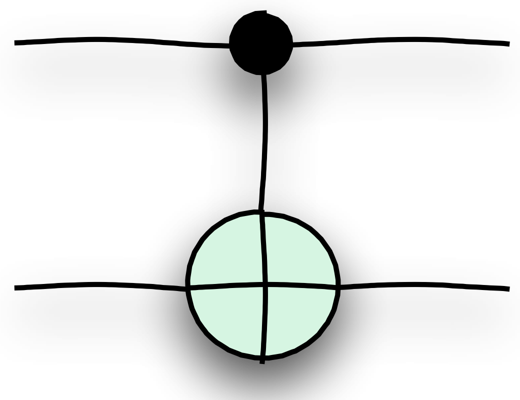


Typical coherence time for an IBM superconducting qubit is 50 to 100 microsecond



$\simeq 71$ ns

Limit: ~1408 single qubit gates

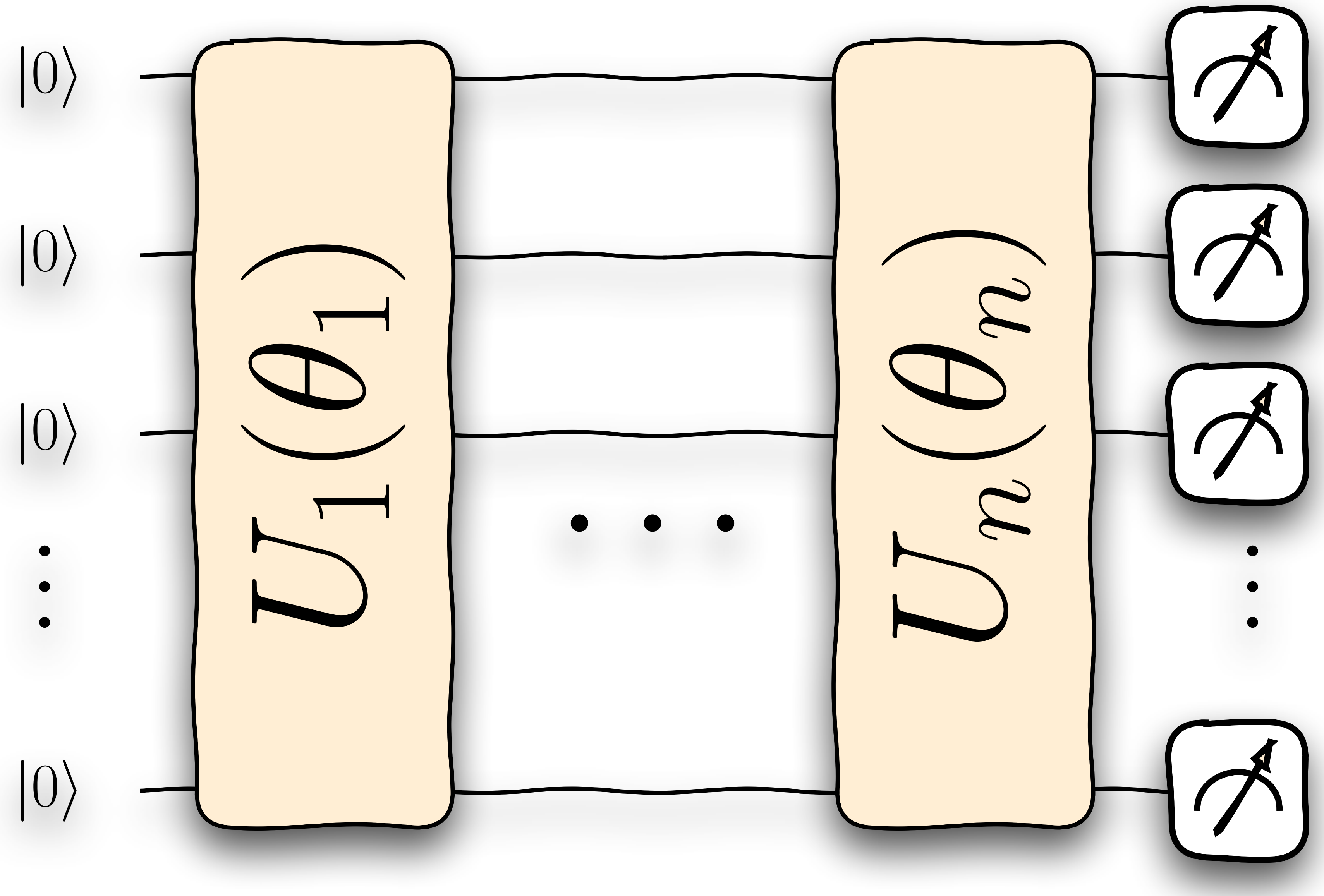


$\simeq 600$ ns

Limit: ~166 CNOT gates

But, there is no free lunch…

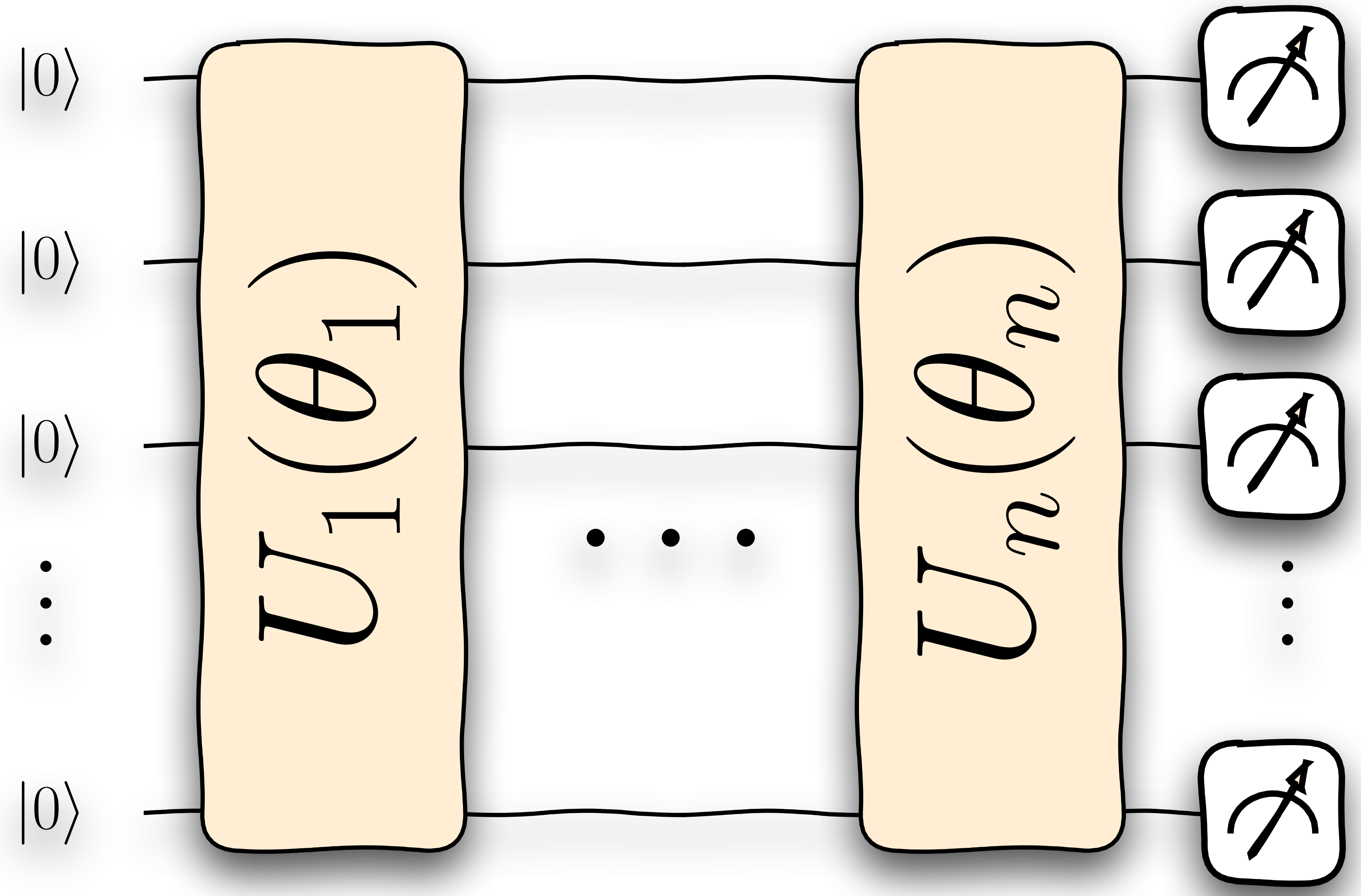
State Preparation with VQE



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

But, there is no free lunch...

State Preparation with VQE



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

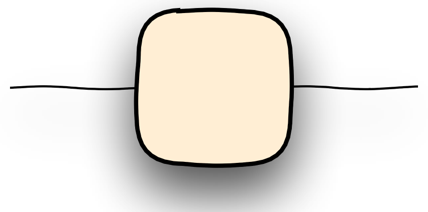
Barren Plateaus

August 2021, taken after getting lost for 4h

Jack Y. Araz

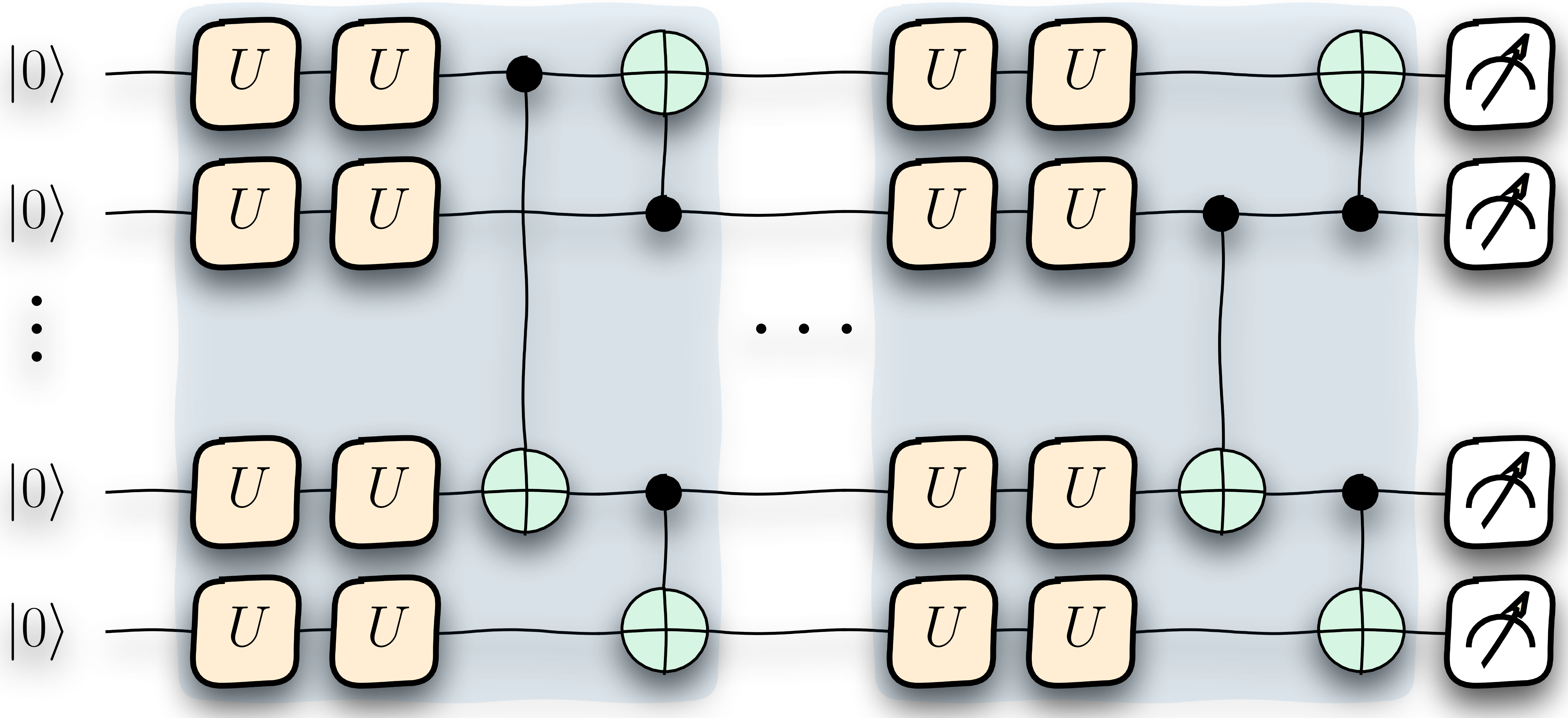
How can we go beyond the limitations?

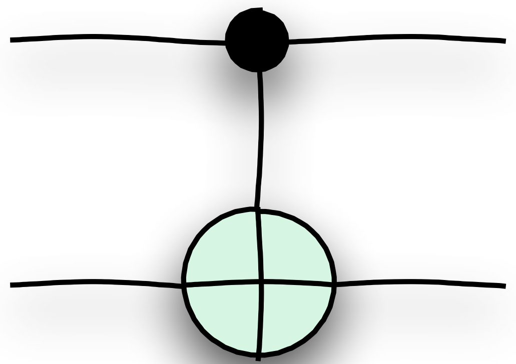
I'll build my own gates, thank you very much!



$\simeq 71$ ns

Limit: ~1408 single qubit gates

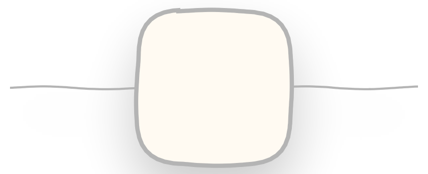




$\simeq 600$ ns

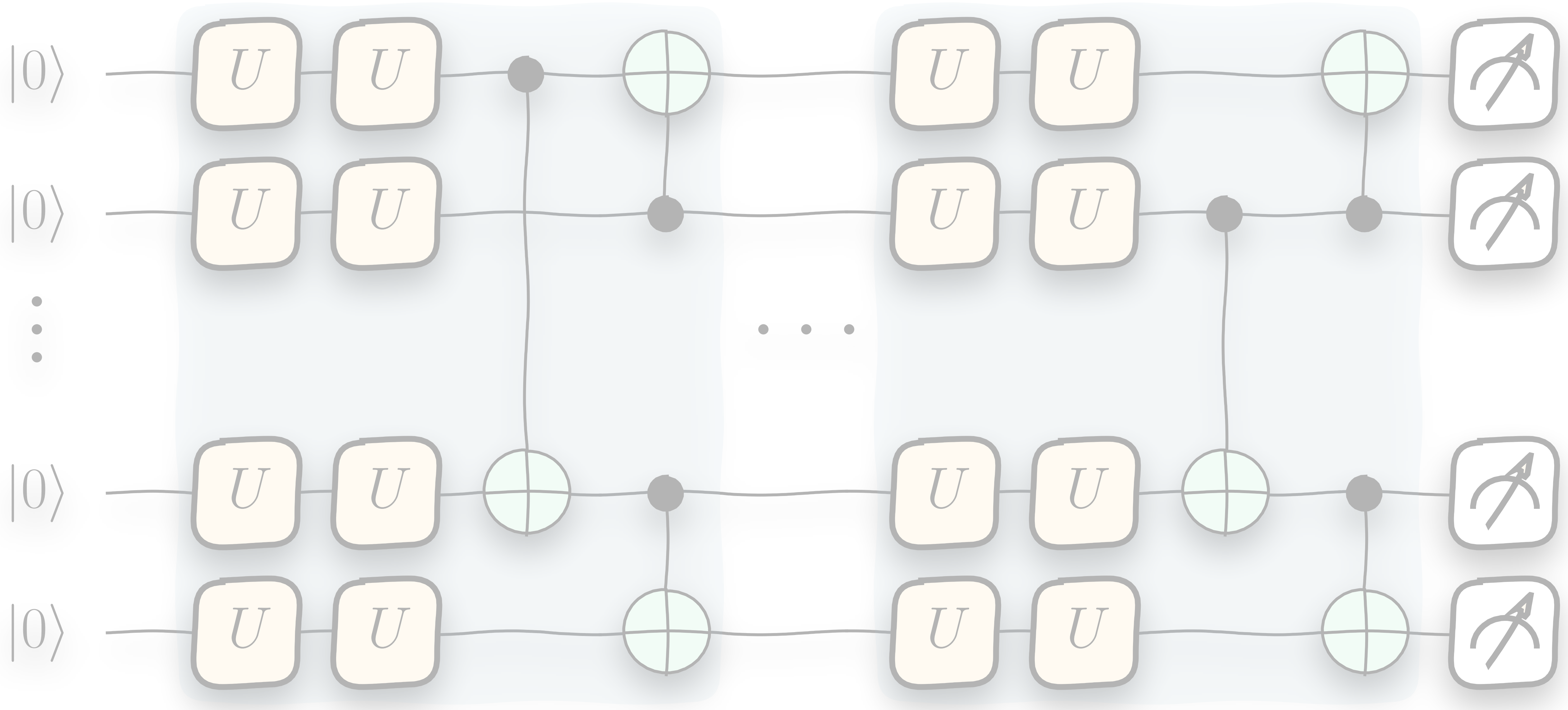
Limit: ~166 CNOT gates

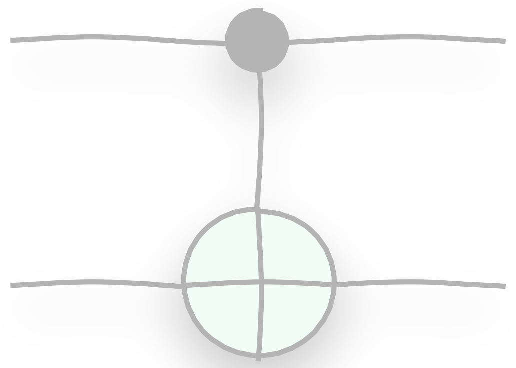
I’ll build my own gates, thank you very much!



$\simeq 71$ ns

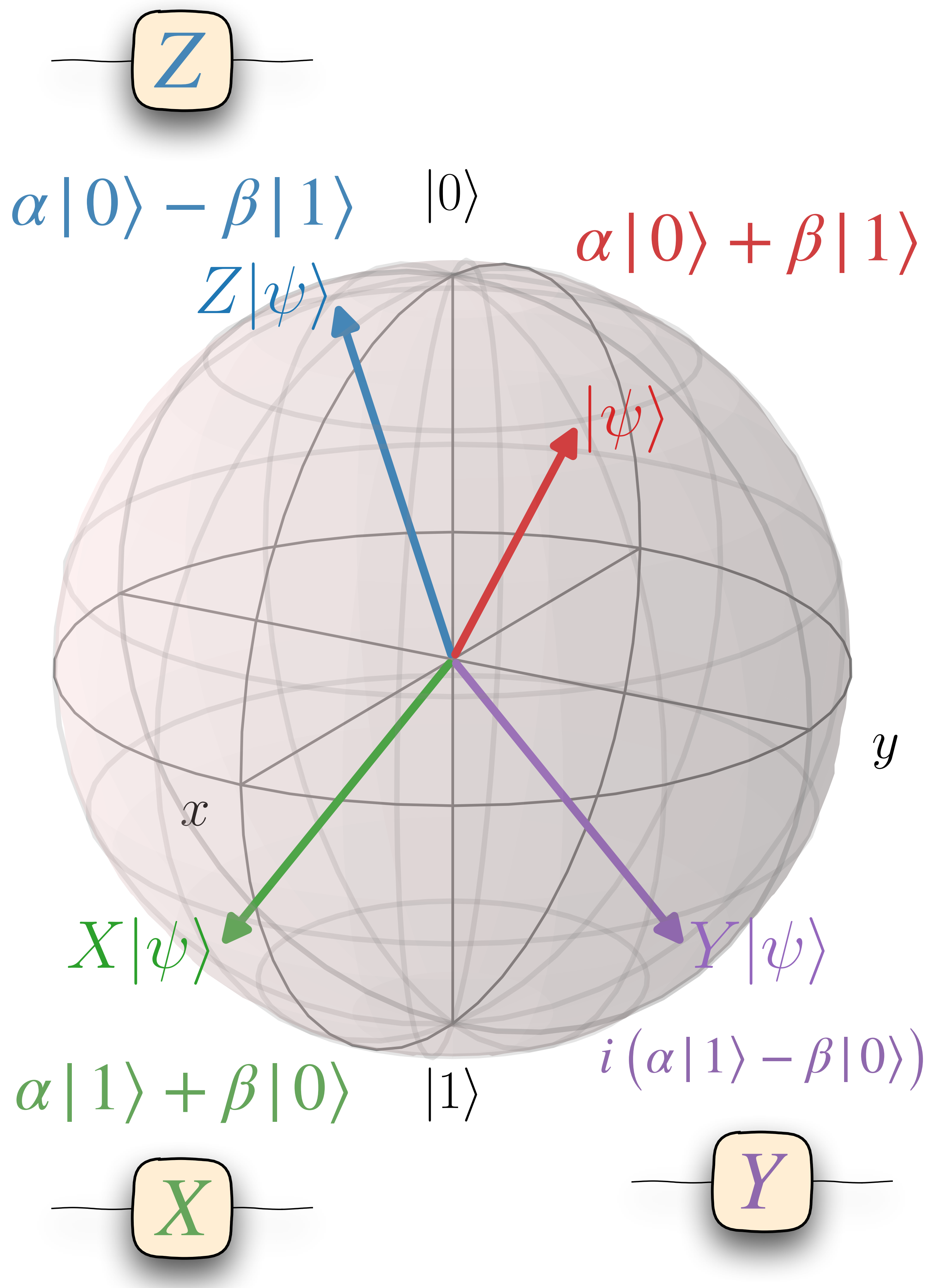
Limit: ~1408 single qubit gates



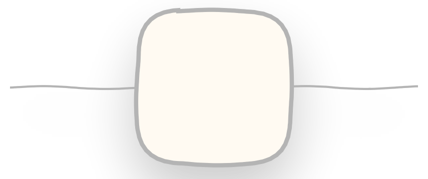


$\simeq 600$ ns

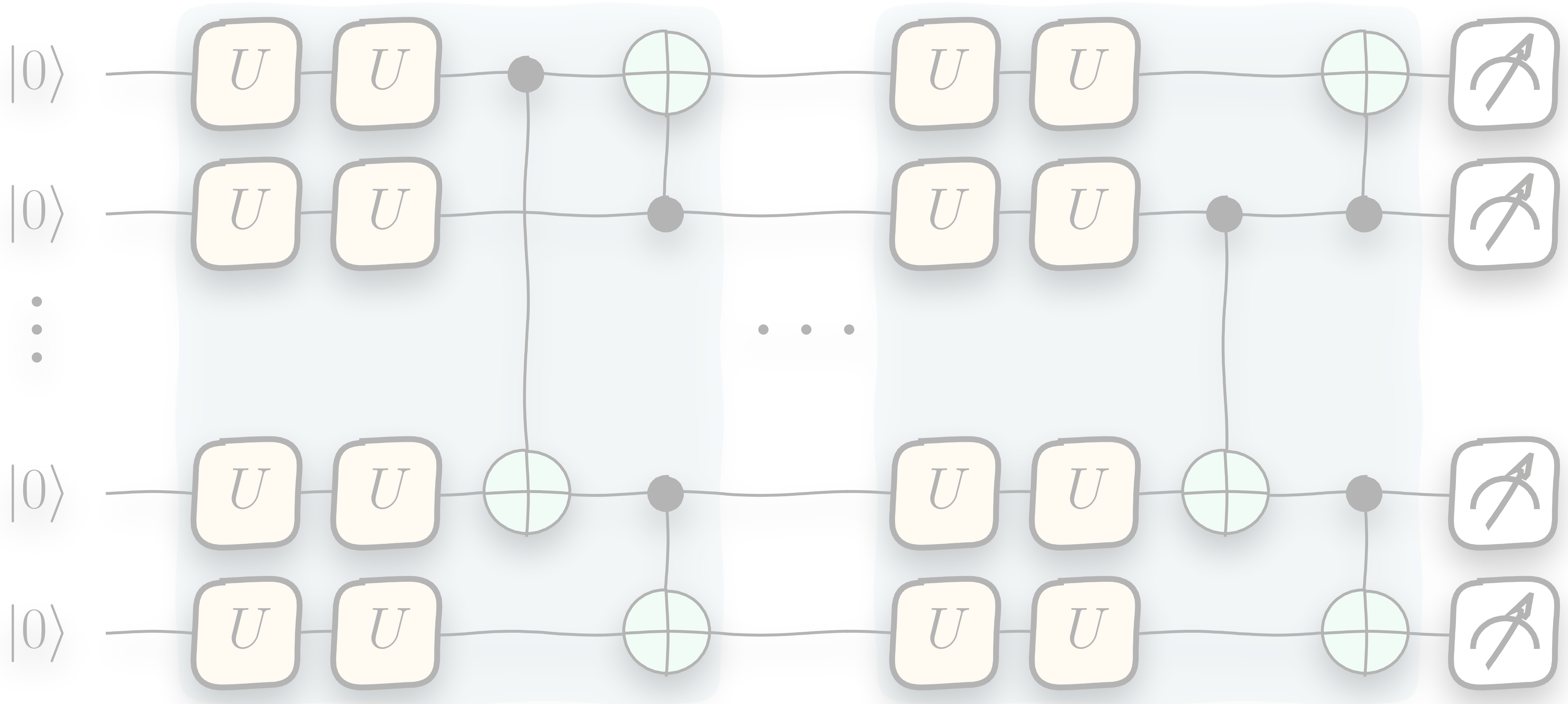
Limit: ~166 CNOT gates

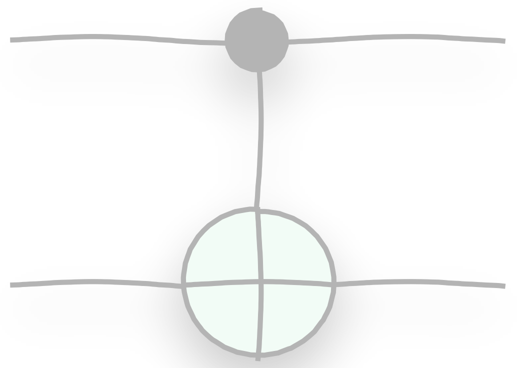


I'll build my own gates, thank you very much!

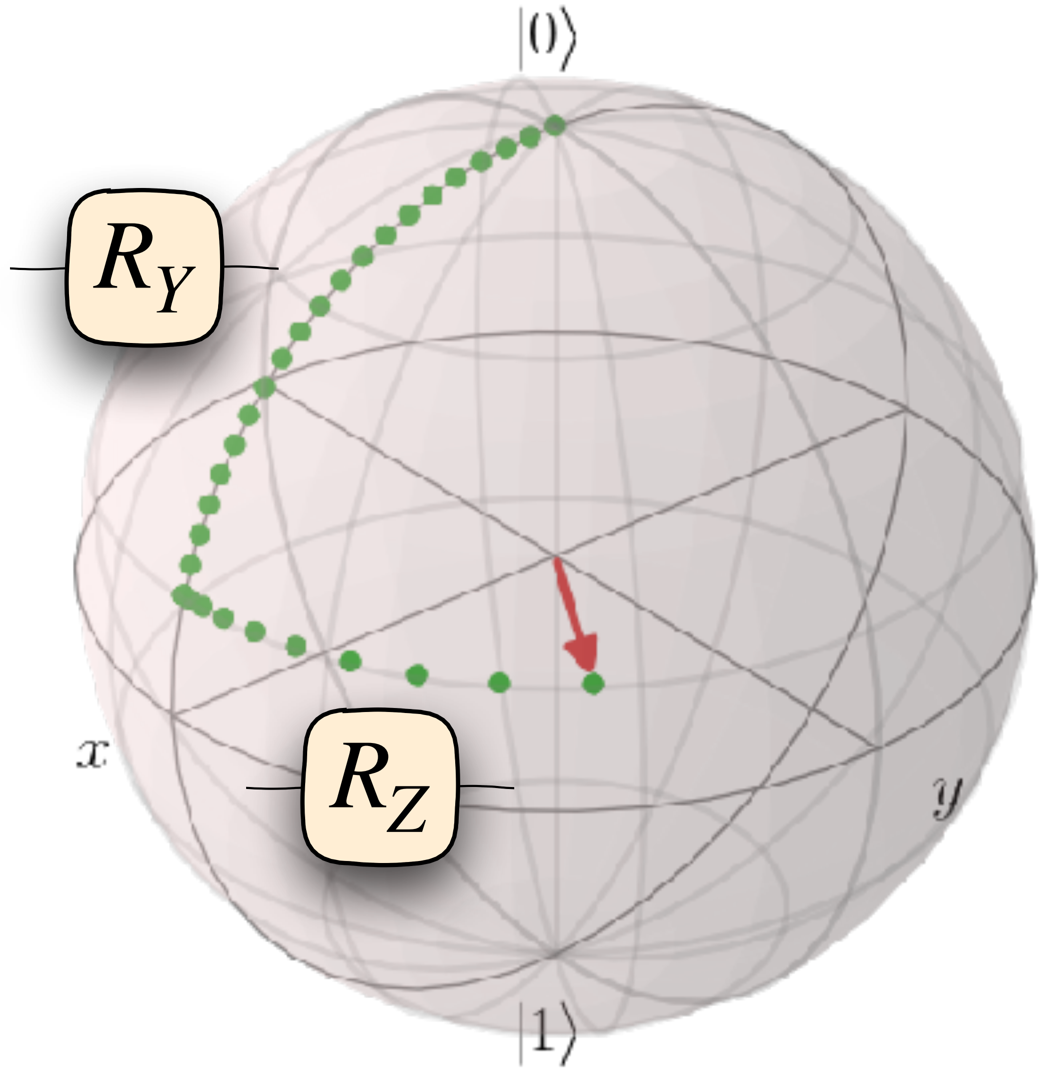


$\simeq$ 71 ns   Limit: ~1408 single qubit gates

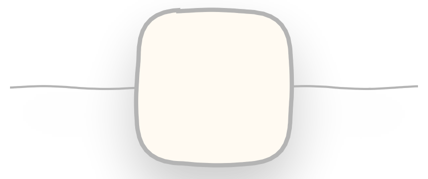




$\simeq$ 600 ns   Limit: ~166 CNOT gates

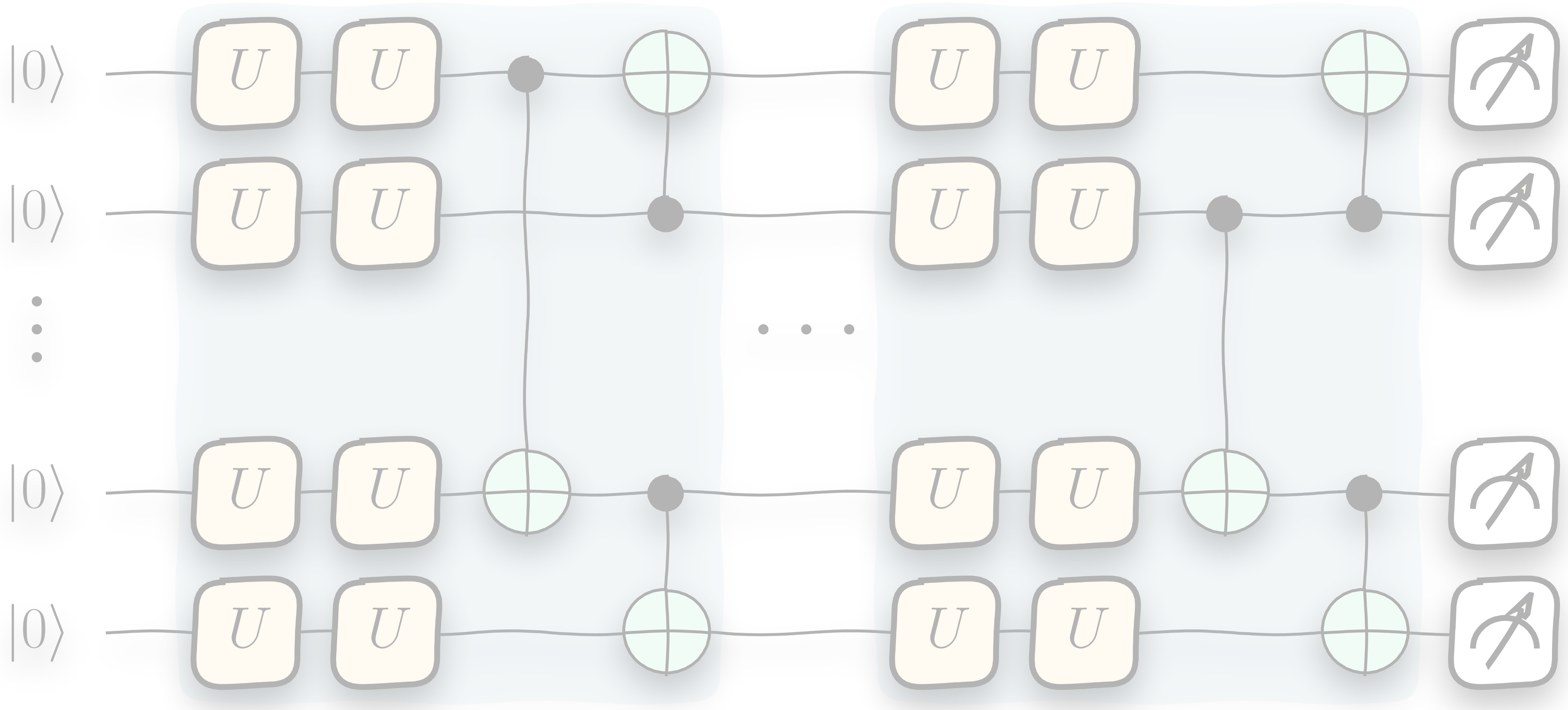


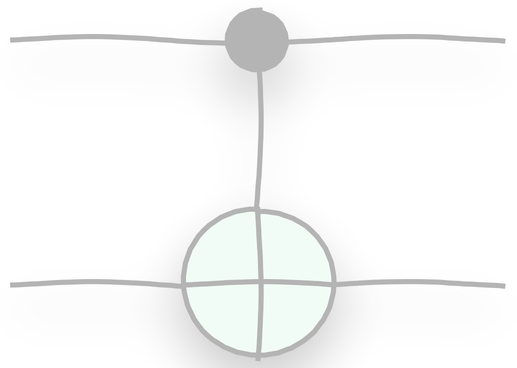
I’ll build my own gates, thank you very much!



$\simeq 71$ ns

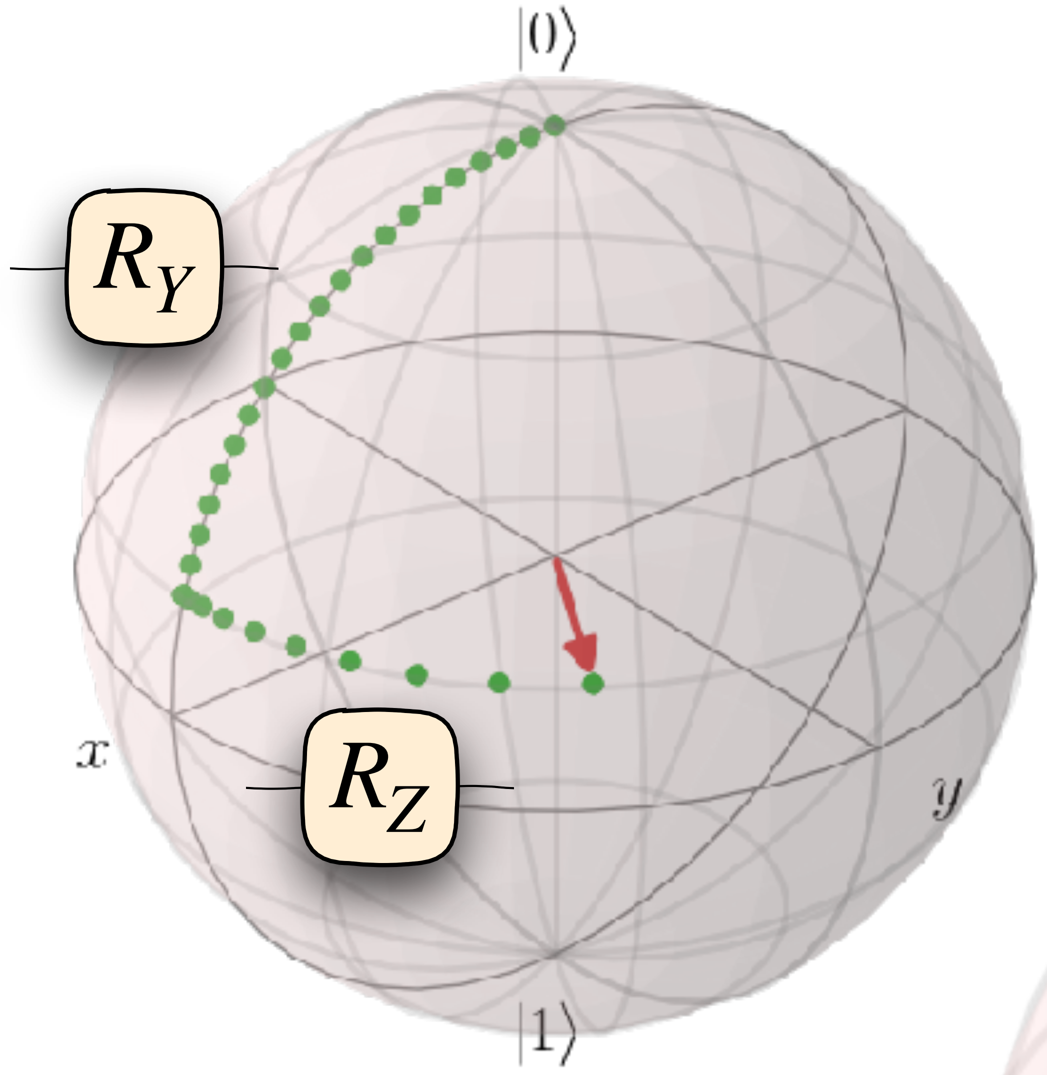
Limit: ~1408 single qubit gates

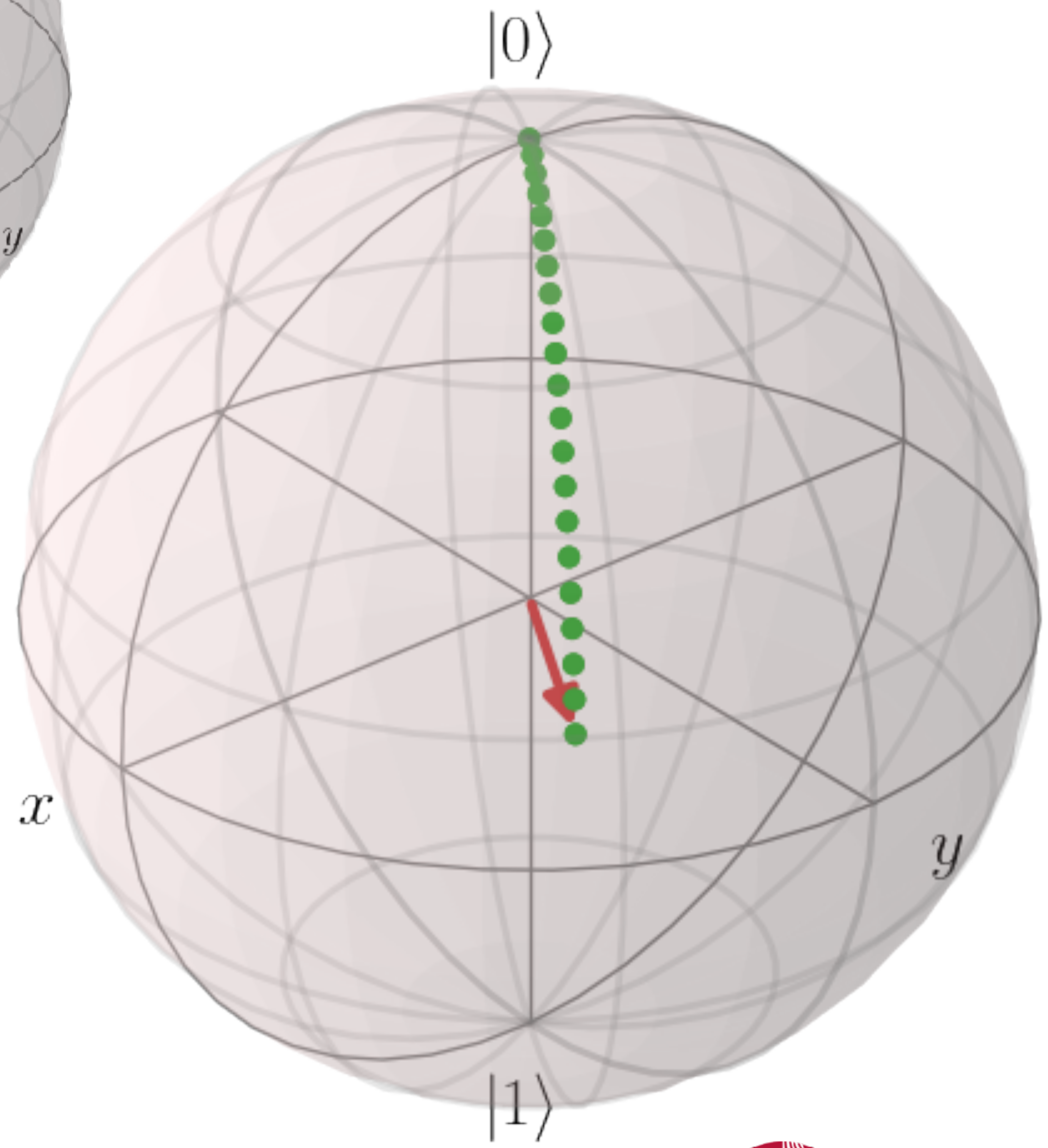




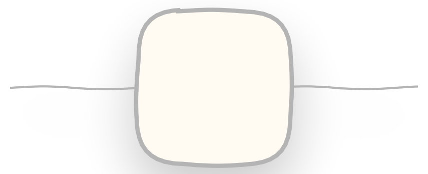
$\simeq 600$ ns

Limit: ~166 CNOT gates

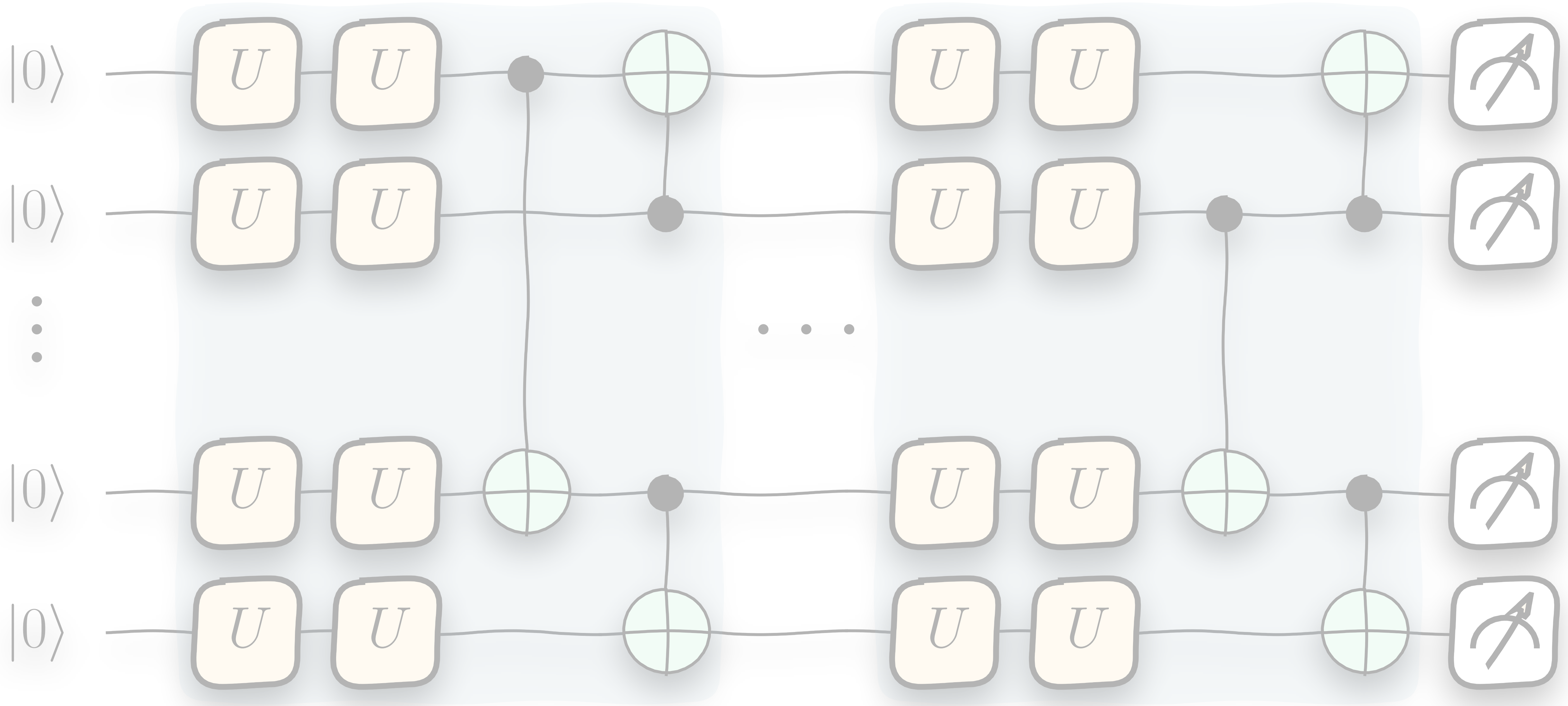


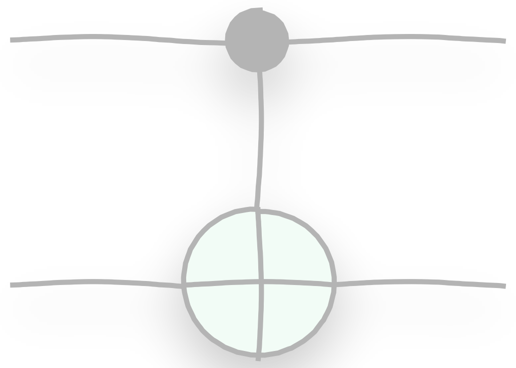


I'll build my own gates, thank you very much!

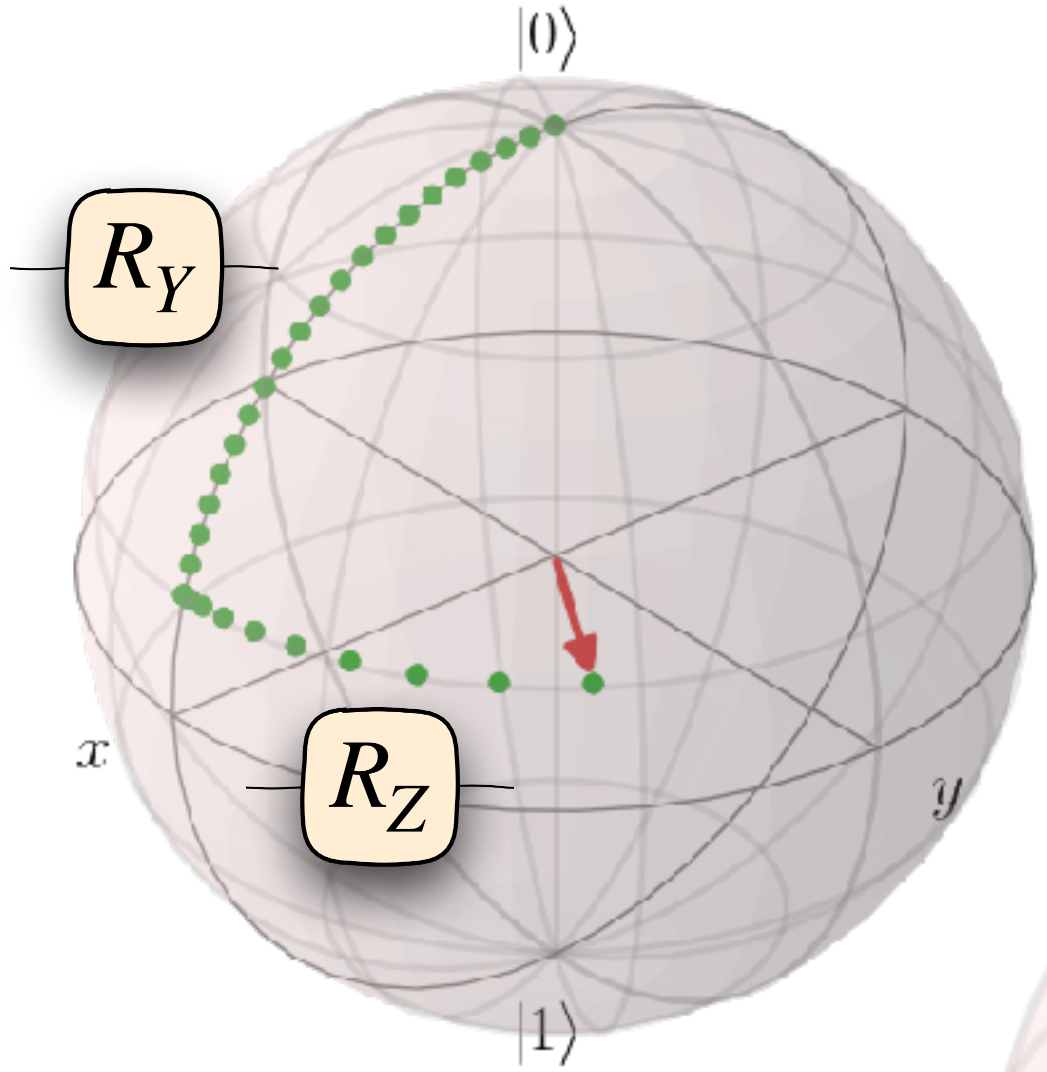


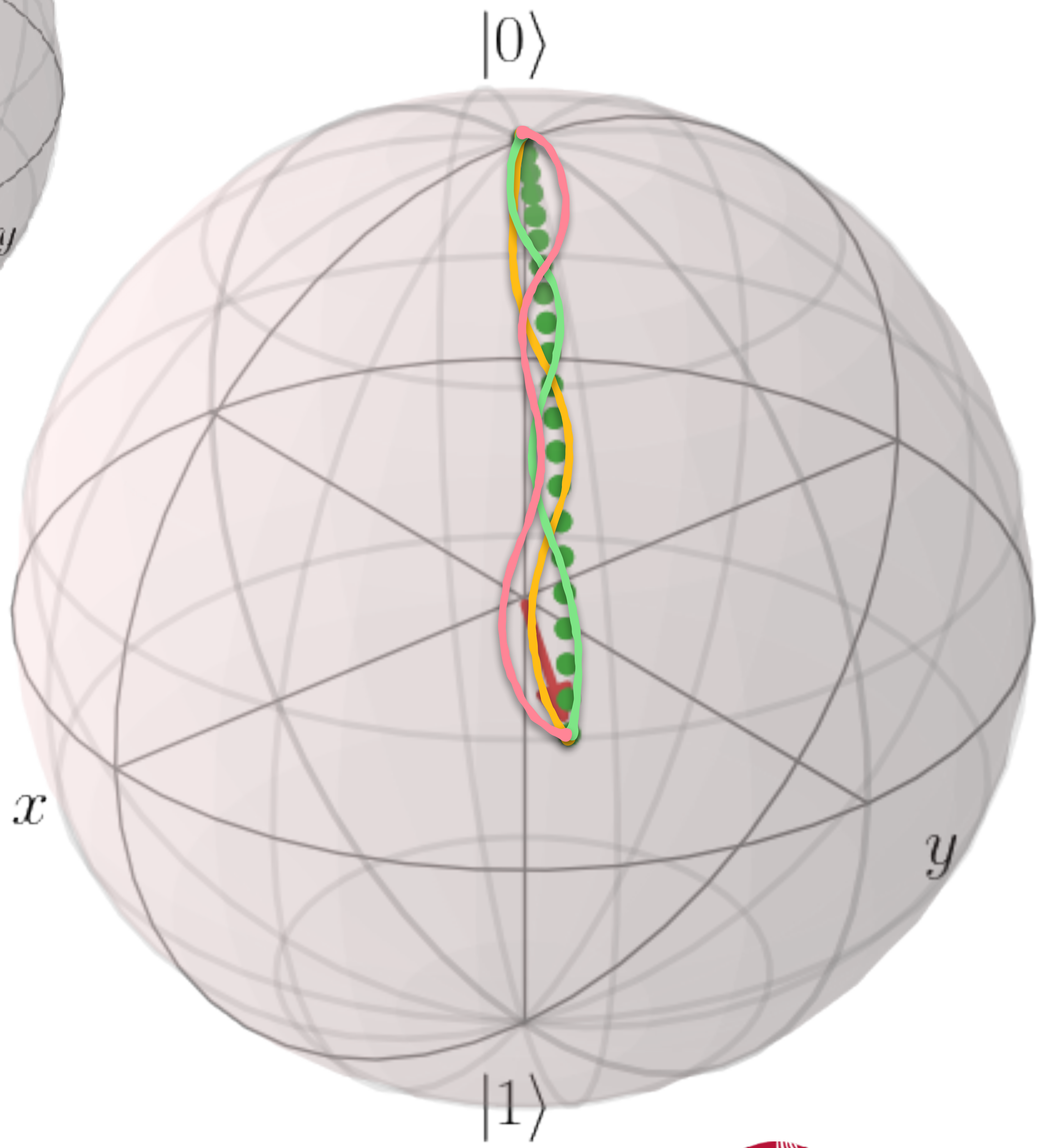
$\simeq$ 71 ns Limit: ~1408 single qubit gates



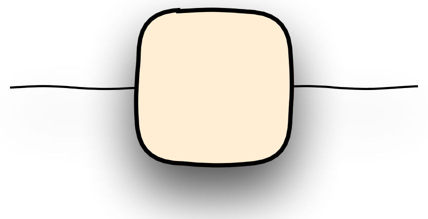


$\simeq$ 600 ns Limit: ~166 CNOT gates

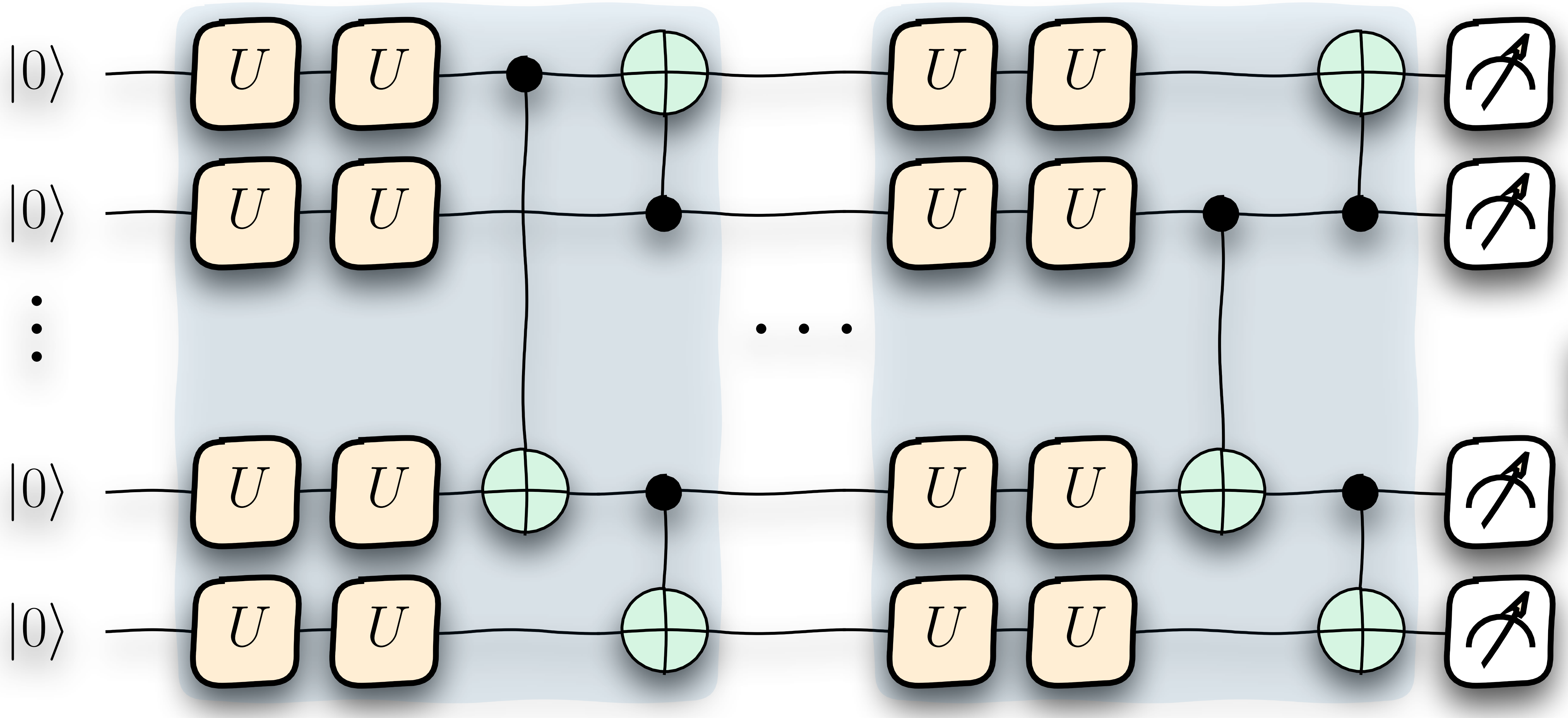


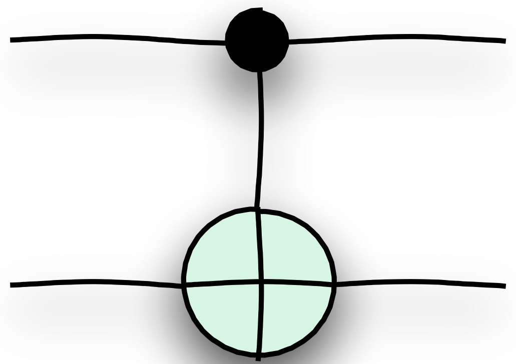


I'll build my own gates, thank you very much!



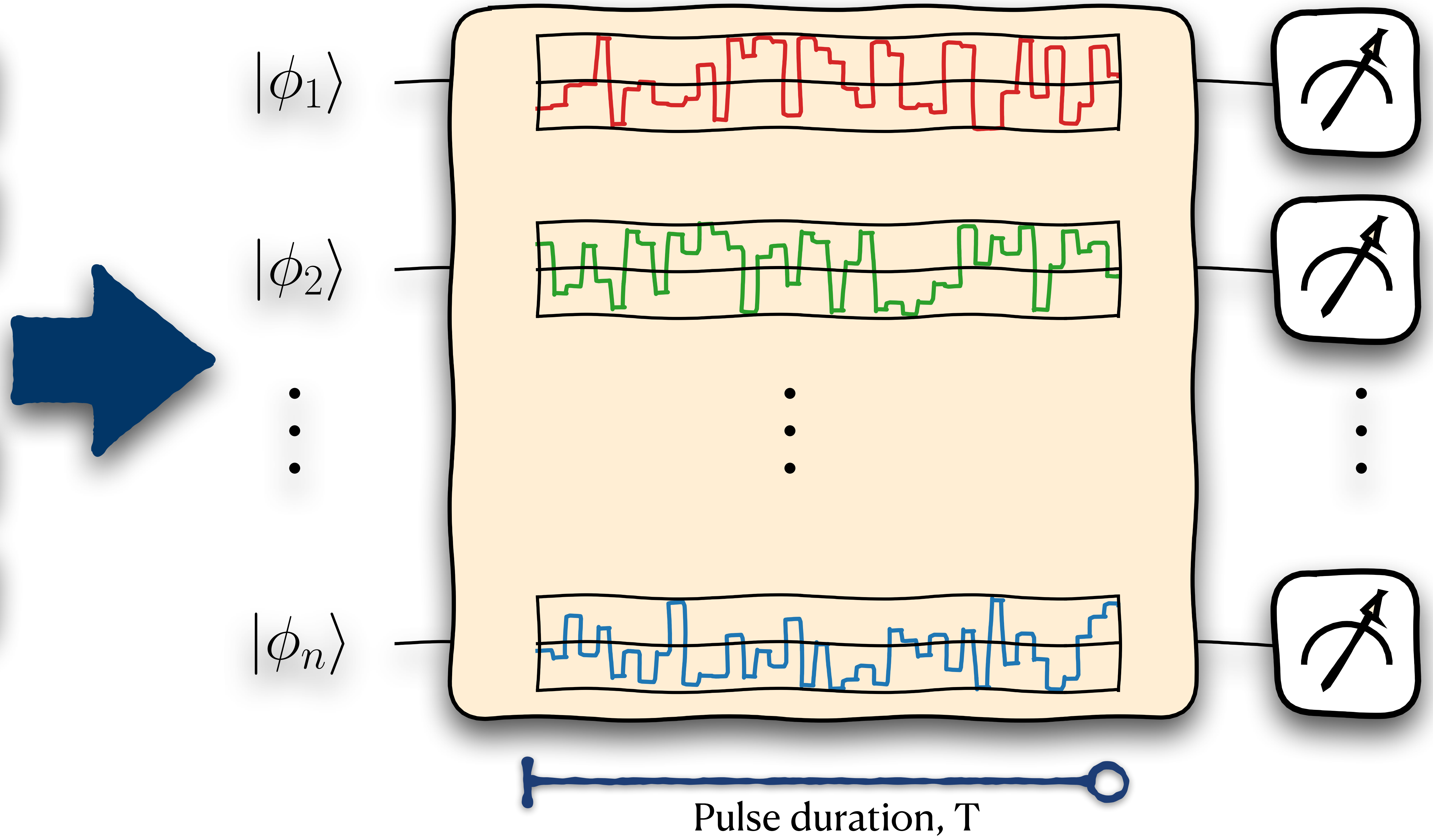
$\simeq 71$ ns   Limit: ~1408 single qubit gates





$\simeq 600$ ns   Limit: ~166 CNOT gates

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



Quantum Optimal Control: Transmon Hamiltonian

Drive Hamiltonian

$$H_D = \underbrace{\sum_i \omega_i a_i^\dagger a_i}_{|0\rangle \leftrightarrow |1\rangle} - \underbrace{\sum_i \frac{\delta_i}{2} a_i^\dagger a_i^\dagger a_i a_i}_{\text{Separate higher-order states, i.e. } |n>1\rangle} + \underbrace{\sum_{i,j} g_{ij} a_i^\dagger a_j}_{\text{Qubit architecture}}$$

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

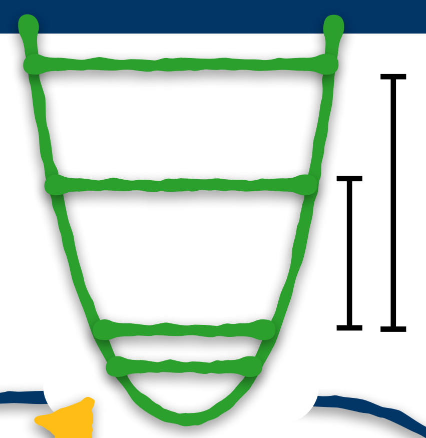
Limits from IBM, machine dependent

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

And more...

Quantum Optimal Control: Transmon Hamiltonian



Drive Hamiltonian

$$H_D = \underbrace{\sum_i \omega_i a_i^\dagger a_i}_{|0\rangle \leftrightarrow |1\rangle} - \underbrace{\sum_i \frac{\delta_i}{2} a_i^\dagger a_i^\dagger a_i a_i}_{\text{Separate higher-order states, i.e. } |n > 1\rangle} + \underbrace{\sum_{i,j} g_{ij} a_i^\dagger a_j}_{\text{Qubit architecture}}$$

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

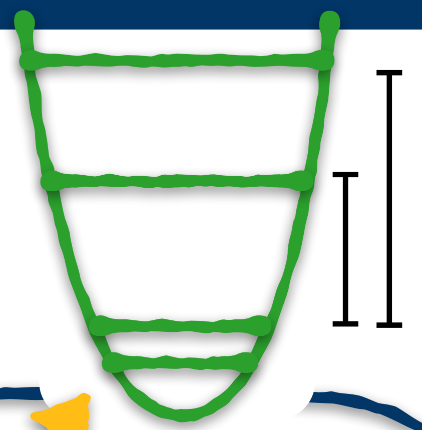
Limits from IBM, machine dependent

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

And more...

Quantum Optimal Control: Transmon Hamiltonian



Drive Hamiltonian

$$H_D = \underbrace{\sum_i \omega_i a_i^\dagger a_i}_{|0\rangle \leftrightarrow |1\rangle} - \underbrace{\sum_i \frac{\delta_i}{2} a_i^\dagger a_i^\dagger a_i a_i}_{\text{Separate higher-order states, i.e. } |n>1\rangle} + \underbrace{\sum_{i,j} g_{ij} a_i^\dagger a_j}_{\text{Qubit architecture}}$$

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

Limits from IBM, machine dependent

Control Hamiltonian

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

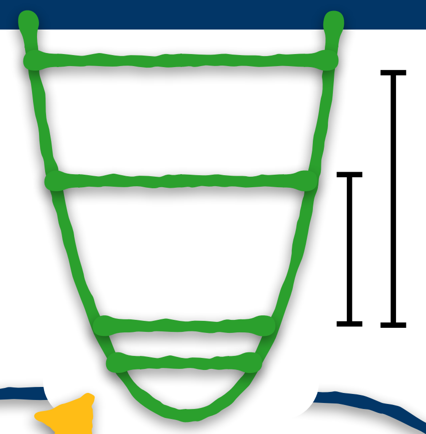
$\Omega(t)$: Pulse amplitude, $-20 \leq \Omega(t) \leq 20$ MHz
ν : Phase, $|\nu_i - \omega_i| \leq 1$ GHz

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

And more...

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/2π
δ : Anharmonicity, $\mathcal{O}(0.3)$ GHz/2π
g : two-qubit coupling, $\mathcal{O}(0.02)$ GHz/2π

Limits from IBM, machine dependent

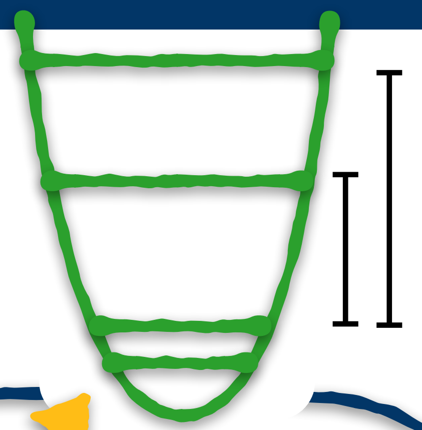
Control Hamiltonian

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

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

Asthana et. al. arXiv:2203.06818
Meitei et. al. arXiv:2008.04302
And more...

Quantum Optimal Control: Transmon Hamiltonian



Drive Hamiltonian

$$H_D = \underbrace{\sum_i \omega_i a_i^\dagger a_i}_{|0\rangle \leftrightarrow |1\rangle} - \underbrace{\sum_i \frac{\delta_i}{2} a_i^\dagger a_i^\dagger a_i a_i}_{\text{Separate higher-order states, i.e. } |n>1\rangle} + \underbrace{\sum_{i,j} g_{ij} a_i^\dagger a_j}_{\text{Qubit architecture}}$$

ω : Transition frequency, $\mathcal{O}(4.5)$ GHz/2π

δ : Anharmonicity, $\mathcal{O}(0.3)$ GHz/2π

g : two-qubit coupling, $\mathcal{O}(0.02)$ GHz/2π

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, $-20 \le \Omega(t) \le 20$ MHz

ν : Phase, $|\nu_i - \omega_i| \le 1$ 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

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

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

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

Our new ansatz

Asthana et. al. arXiv:2203.06818

Meitei et. al. arXiv:2008.04302

Jefferson Lab EXPLORING THE NATURE OF MATTER

Schwinger Model

Schwinger Model with topological term

Simple QED

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

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

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

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

Schwinger Model with topological term

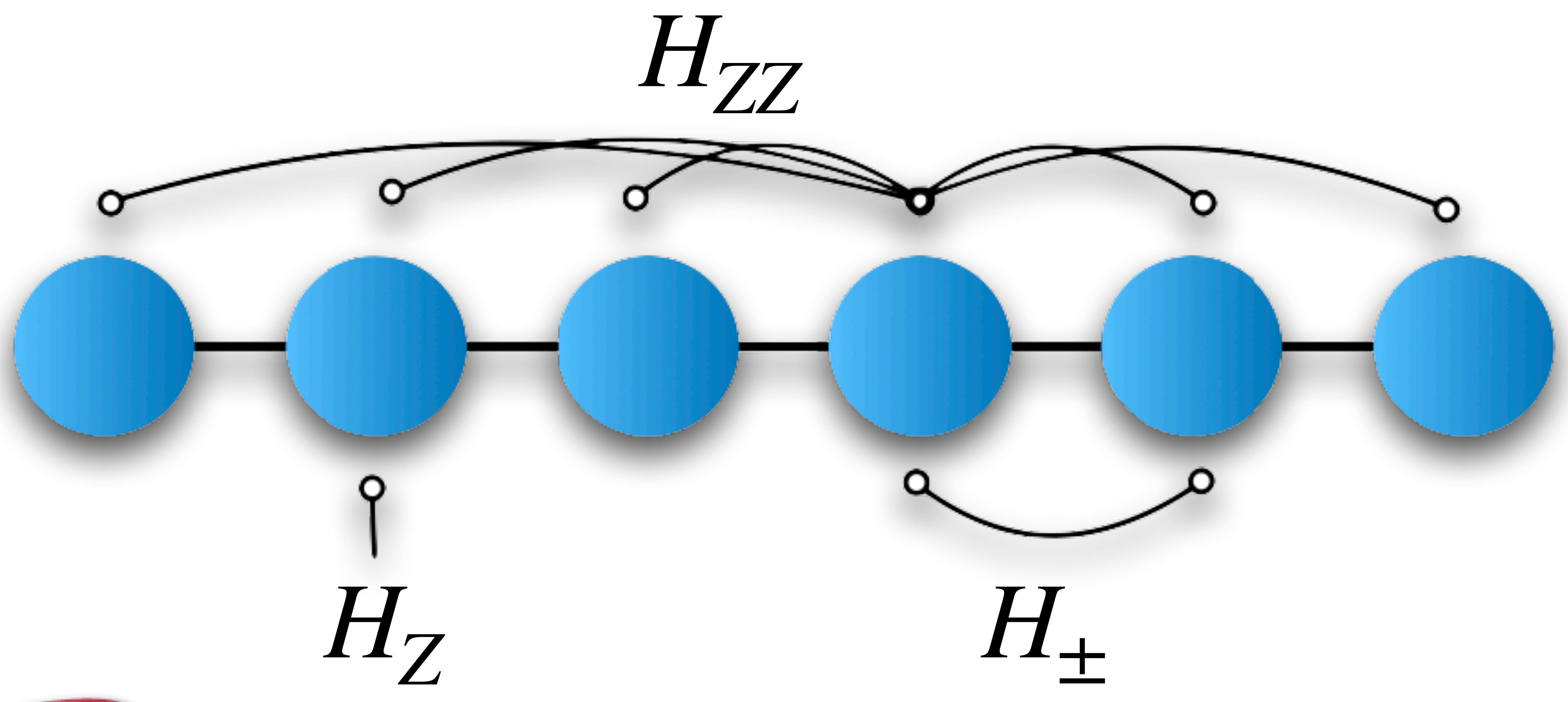
Simple QED

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

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

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!



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

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

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

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

$\sim 11\ \mu s$

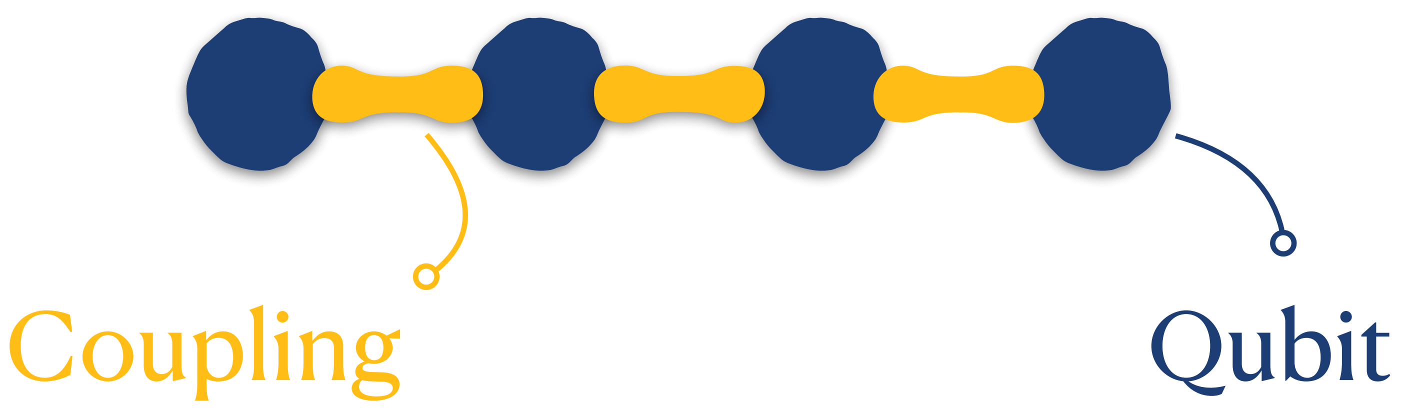
Limit: ~9 trotter steps

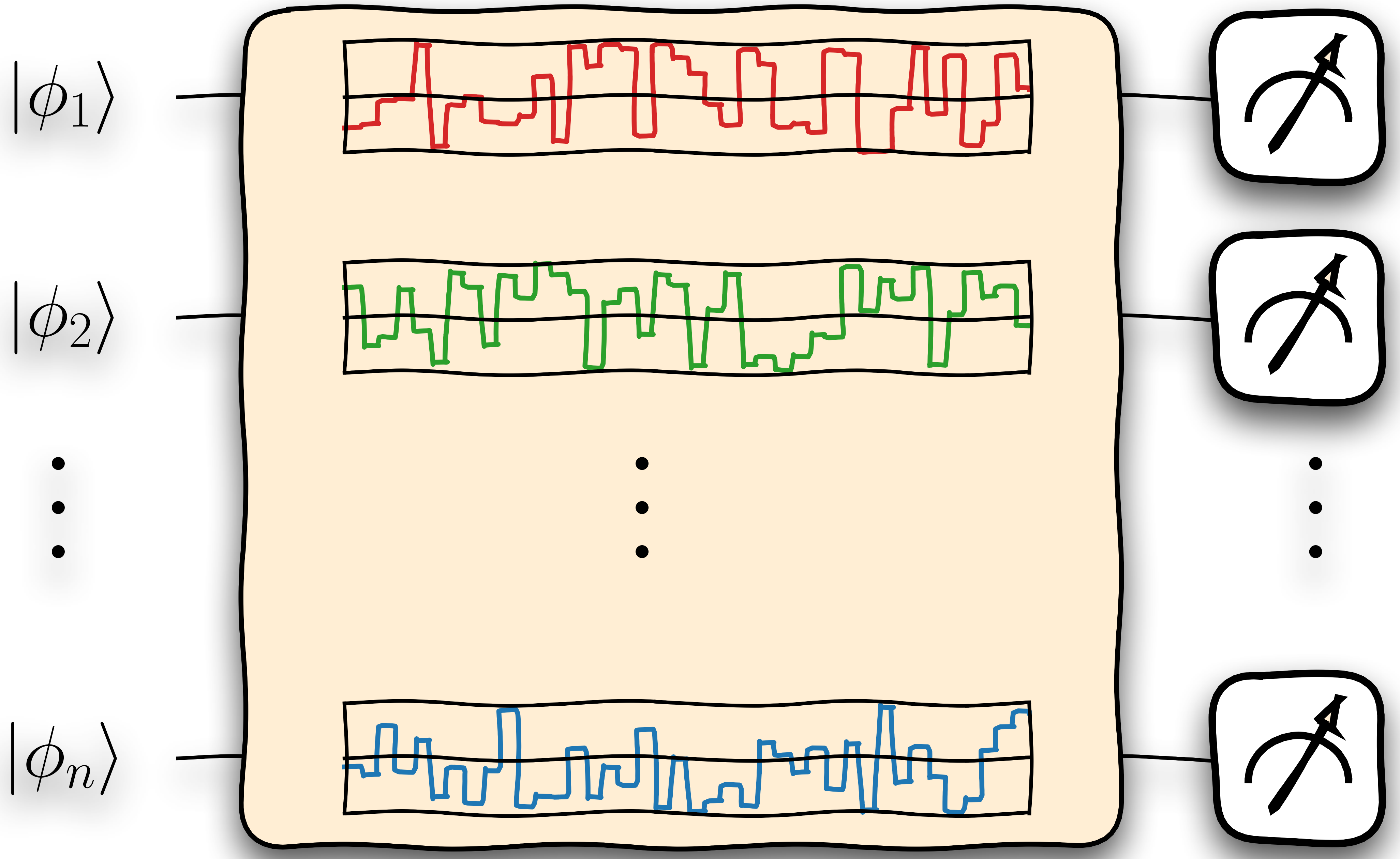
JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

Quantum Computer:

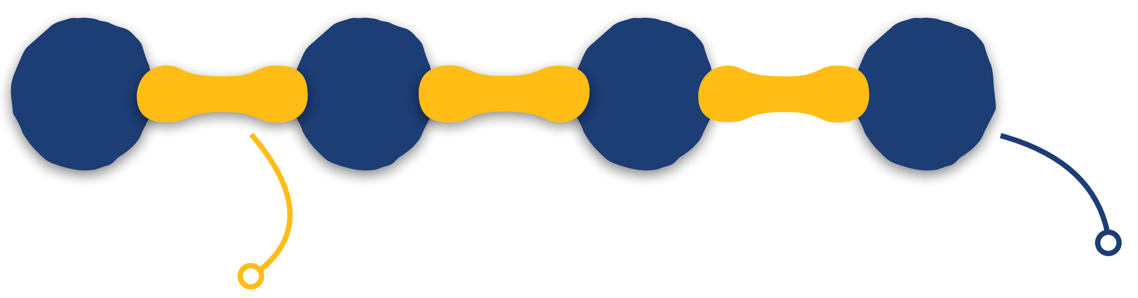




The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

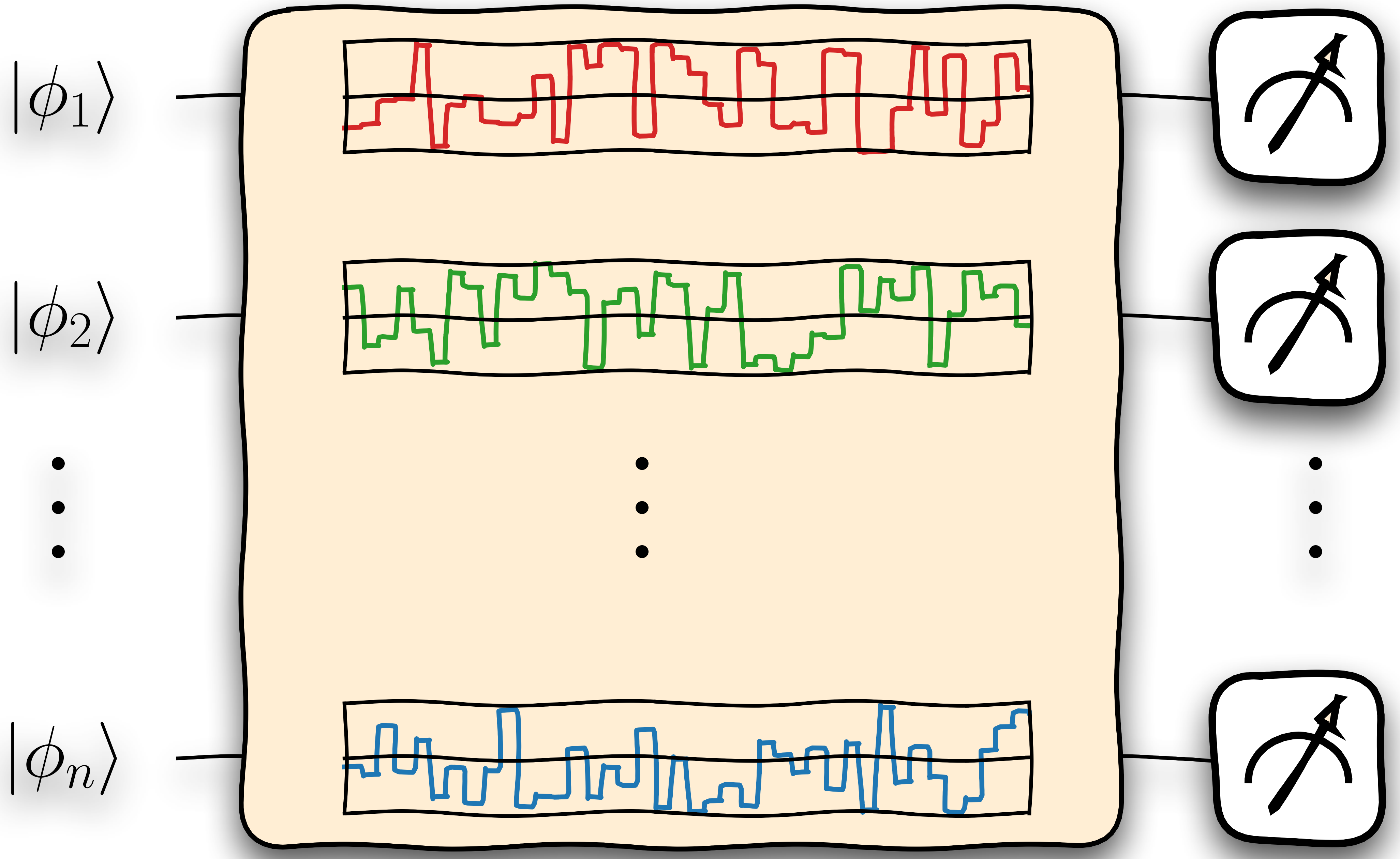
Quantum Computer:

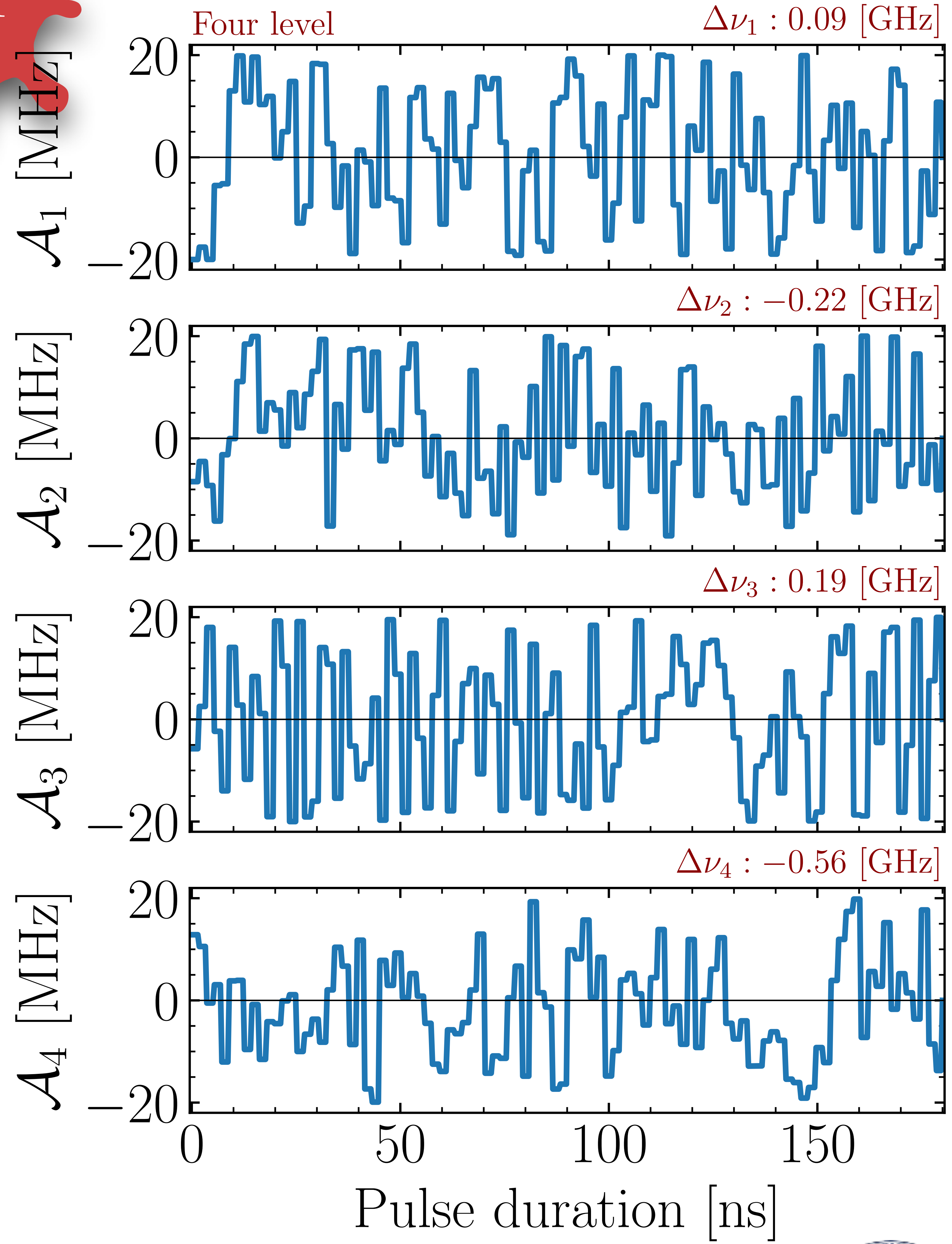


$\times 61$

180 ns

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

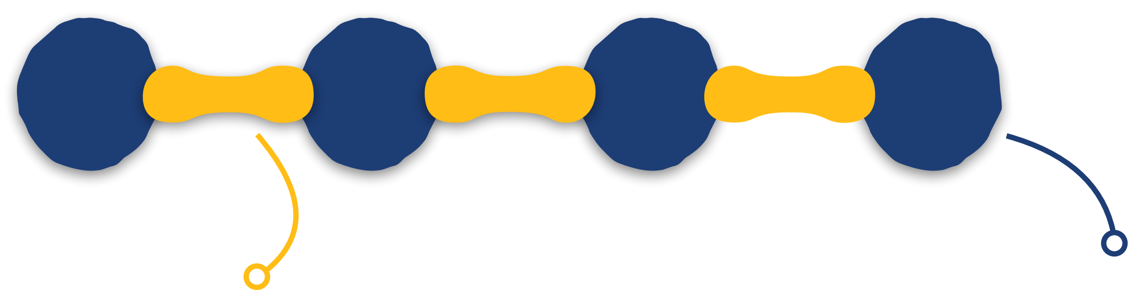




The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

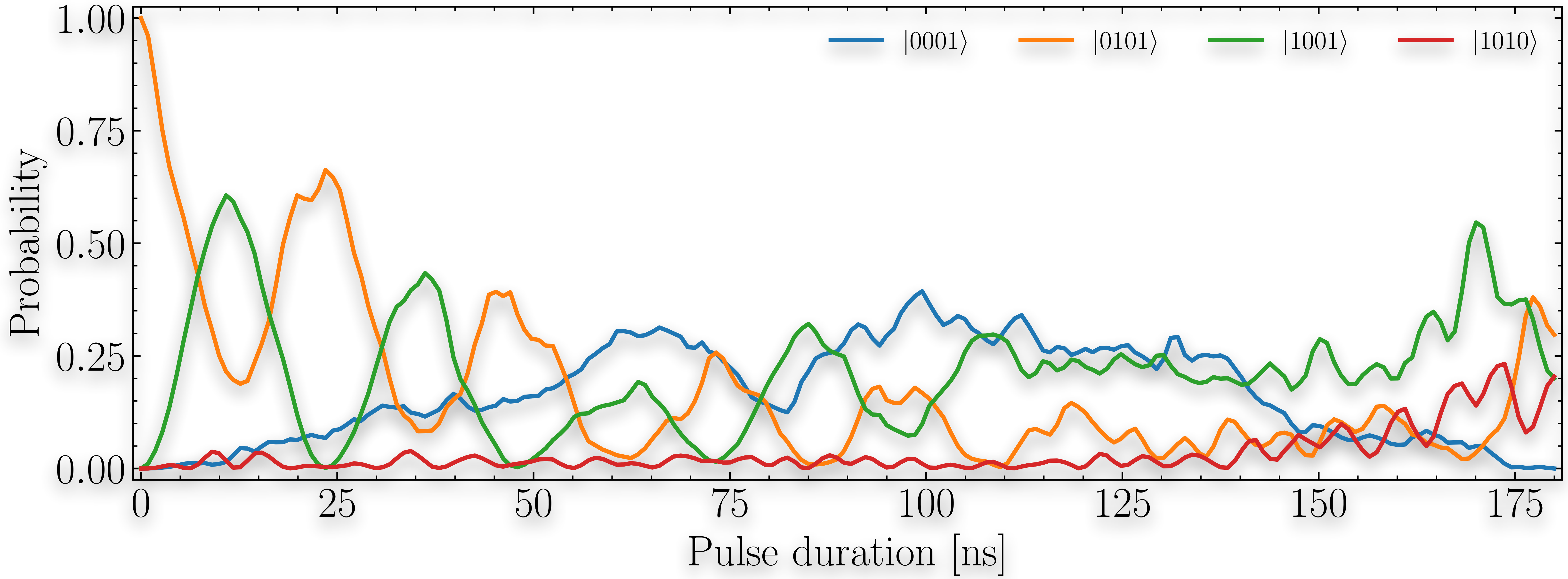
Quantum Computer:

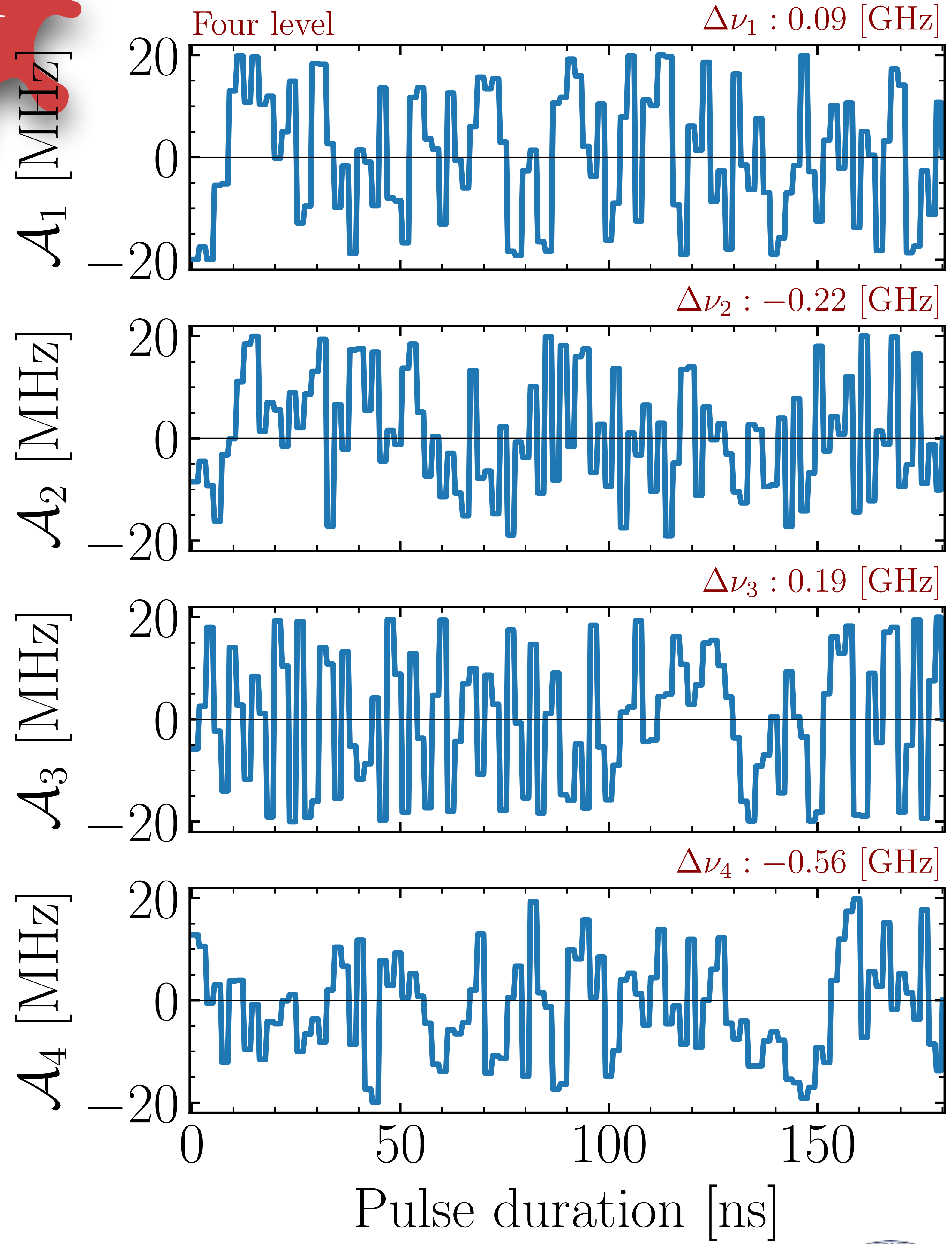


$\times 61$

180 ns

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

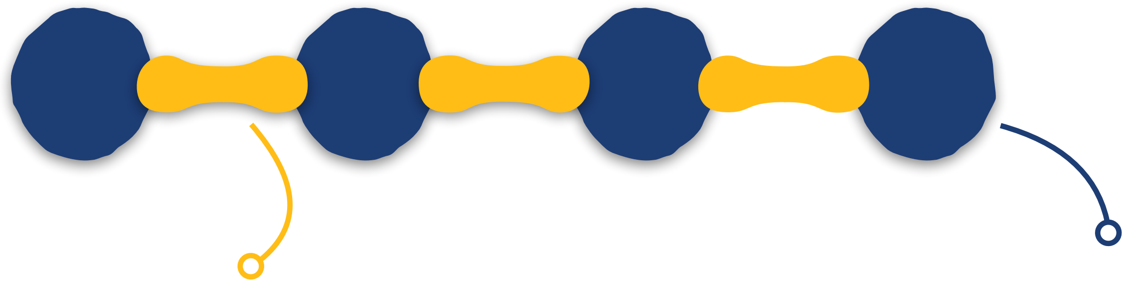




The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

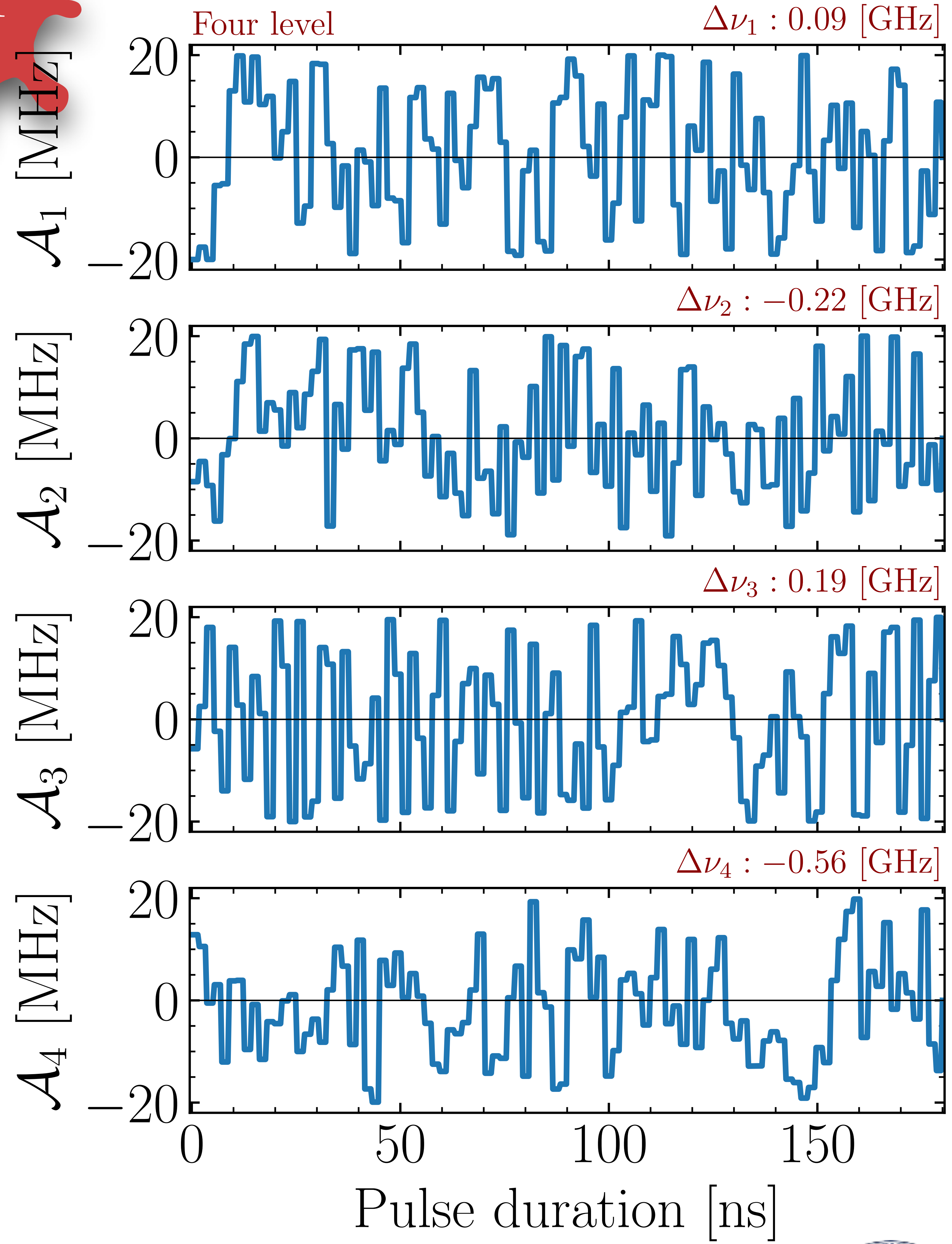
Quantum Computer:

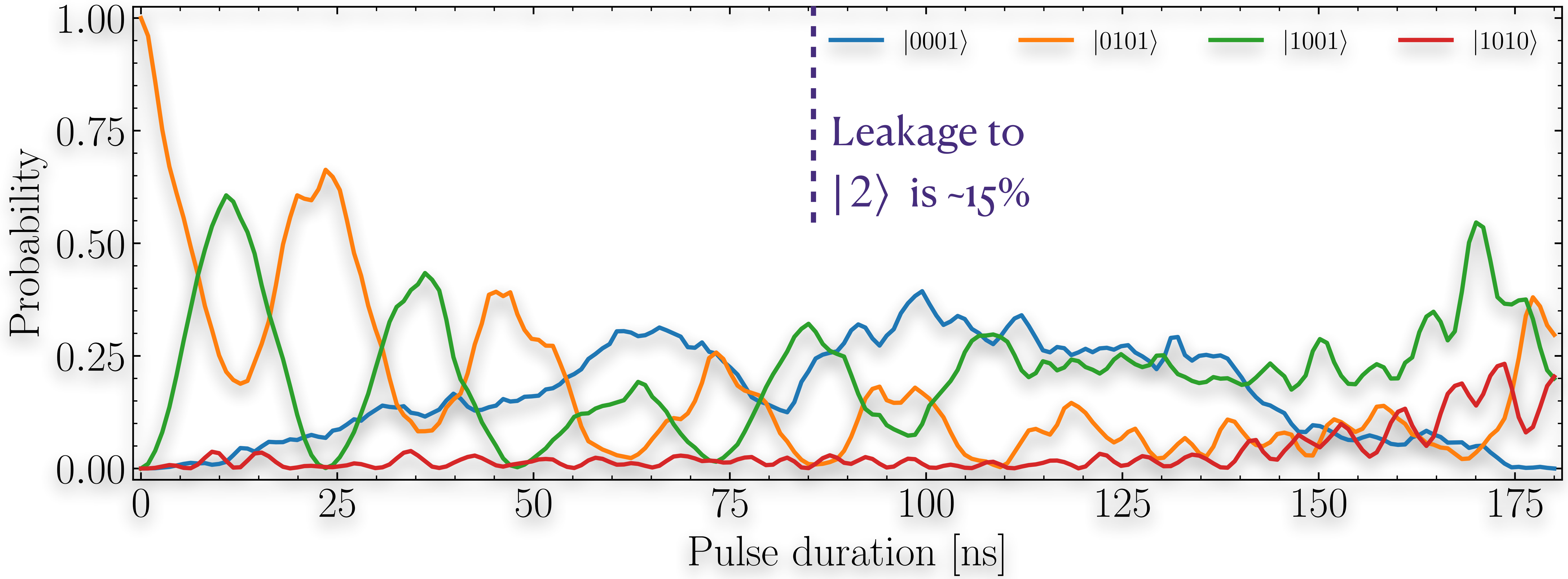


180 ns

× 61

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

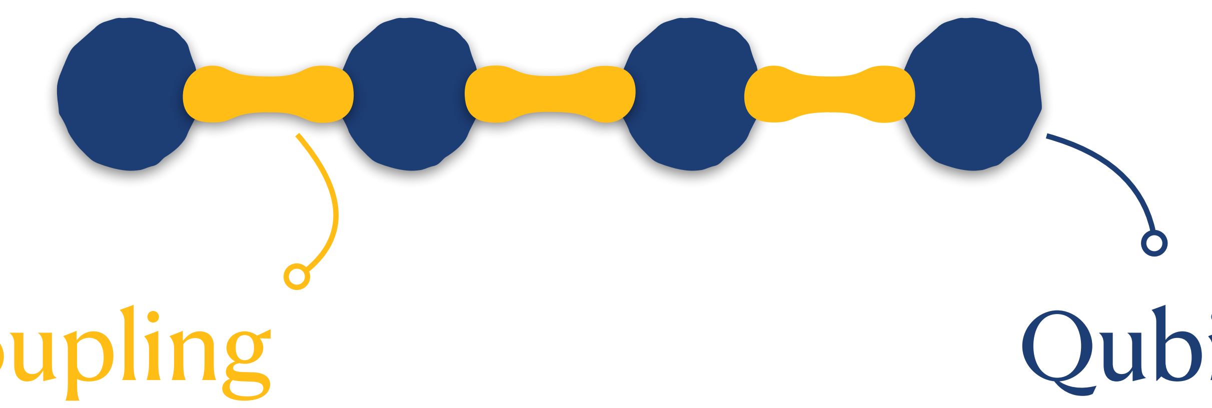




The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

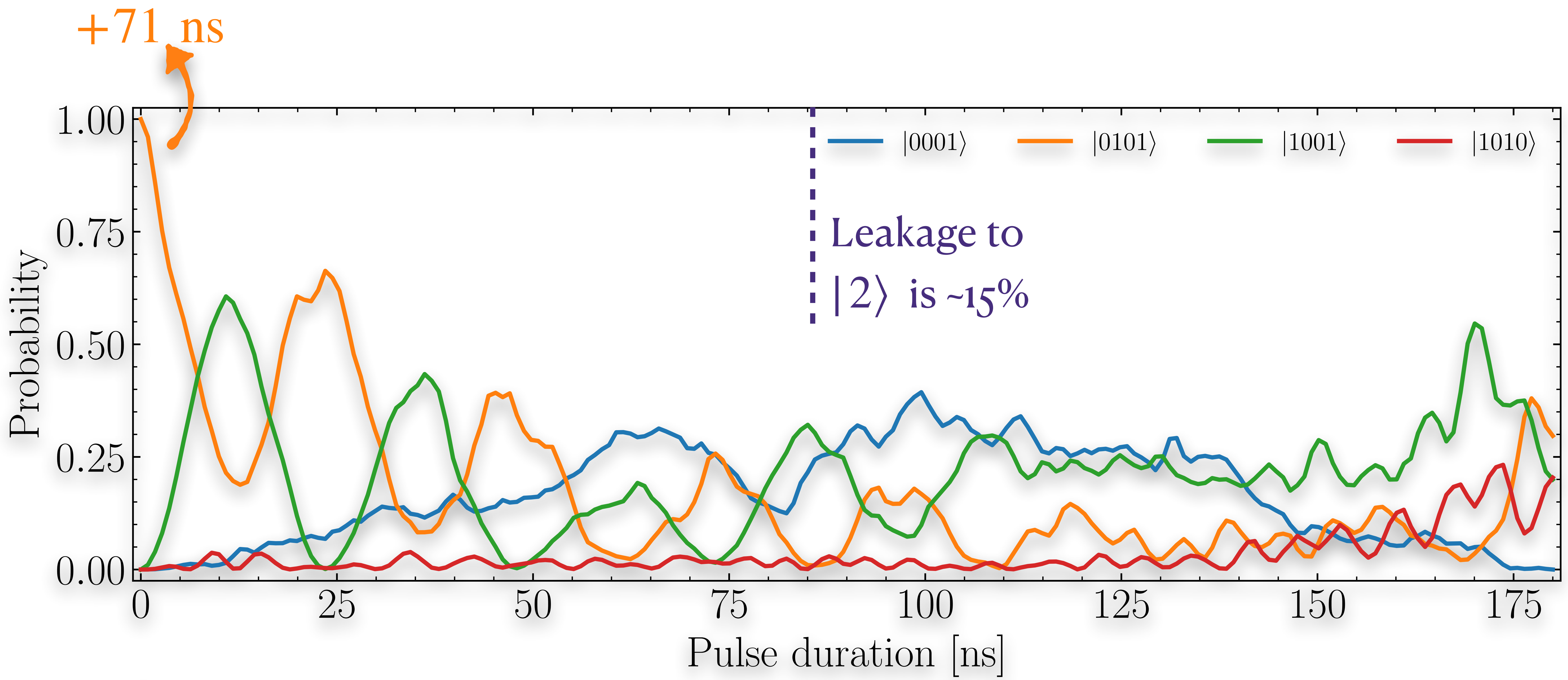
Quantum Computer:

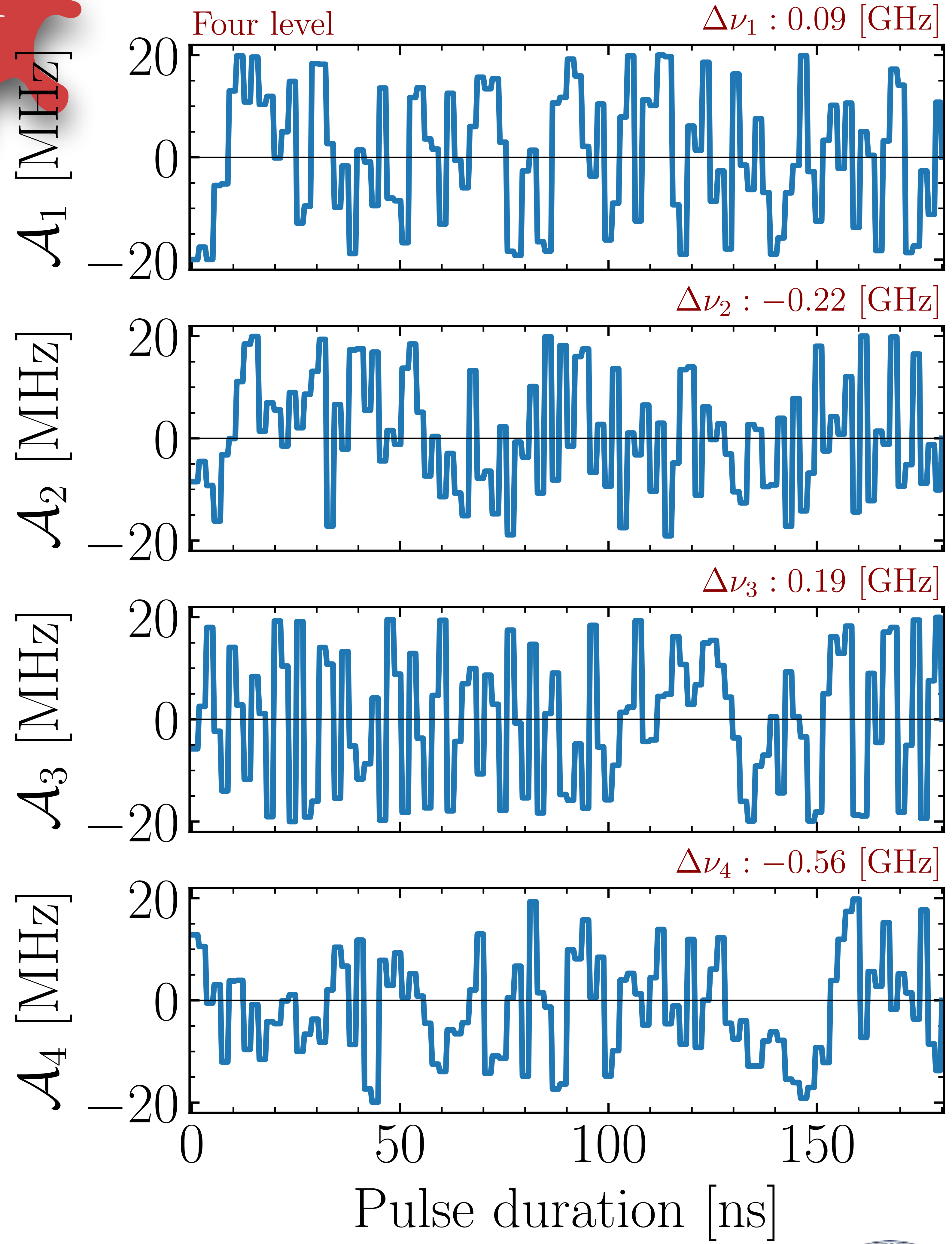


180 ns

$\times 61$

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





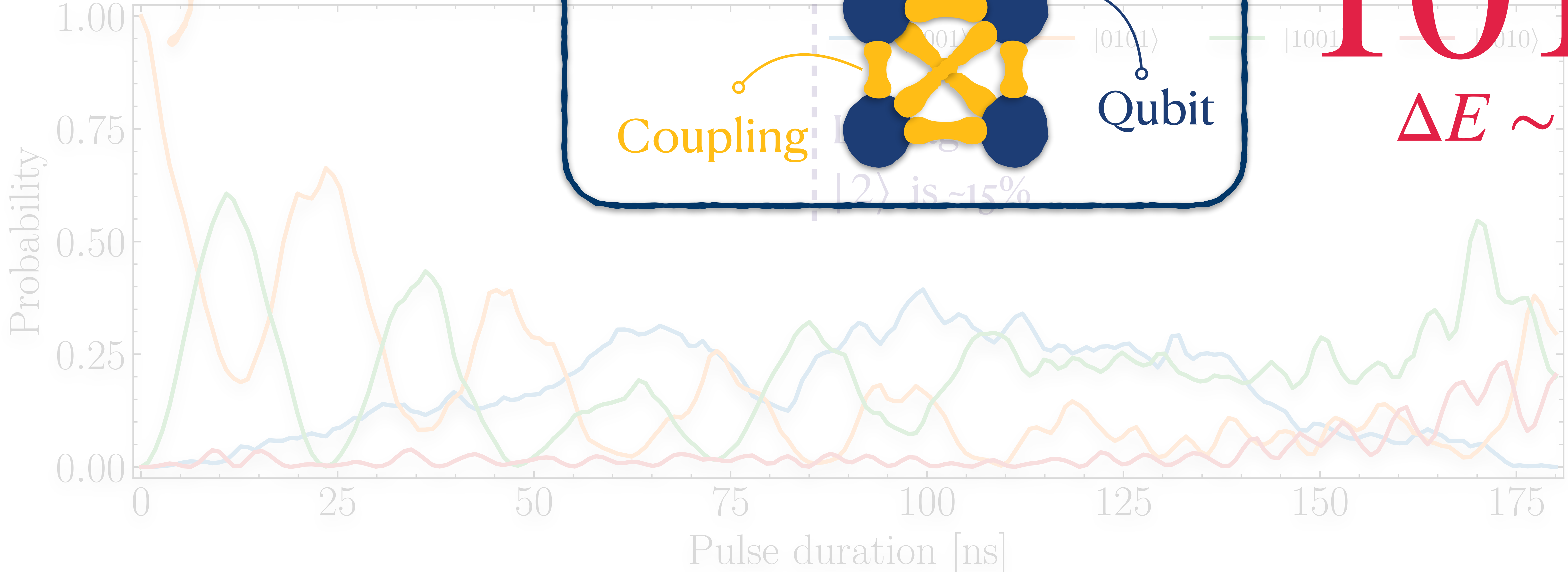
The Schwinger Gate!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

Quantum Computer:

180 ns

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



Quantum Computer:

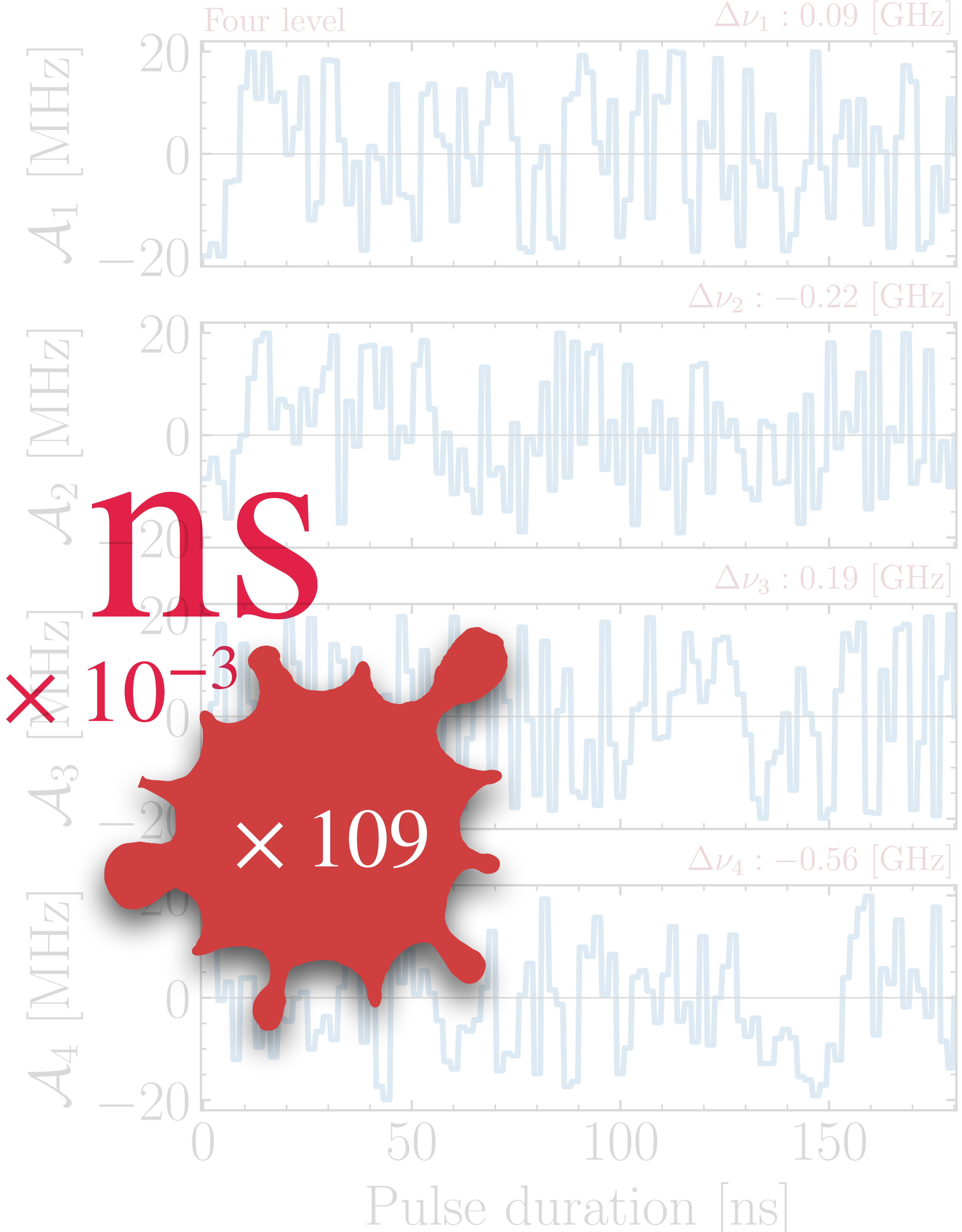
Coupling

Qubit

101 ns

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

× 109

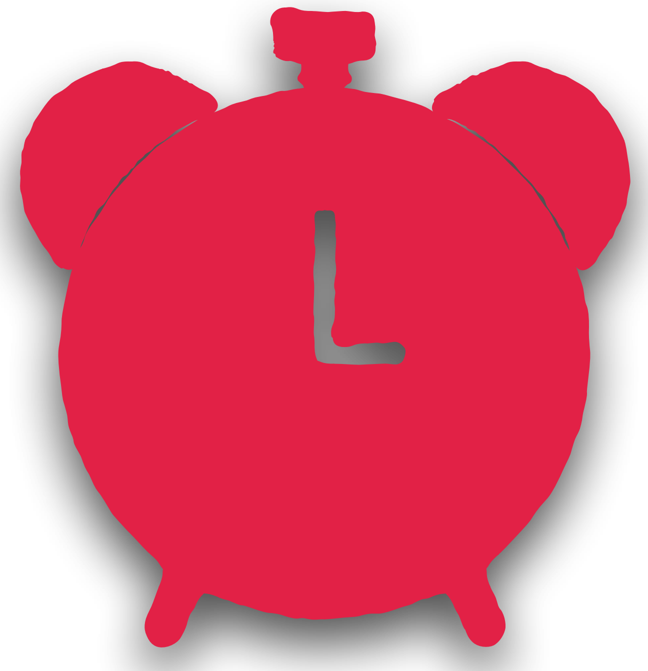


Towards simulating the Standard Model

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

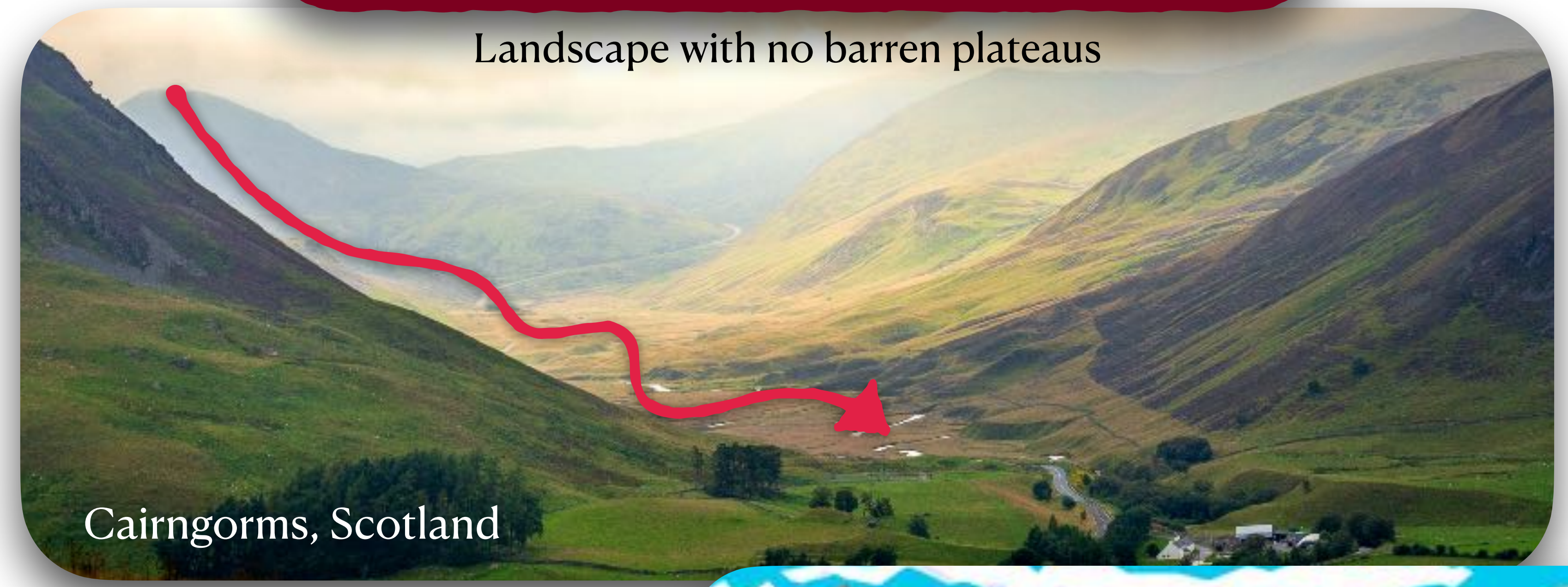
Qubits

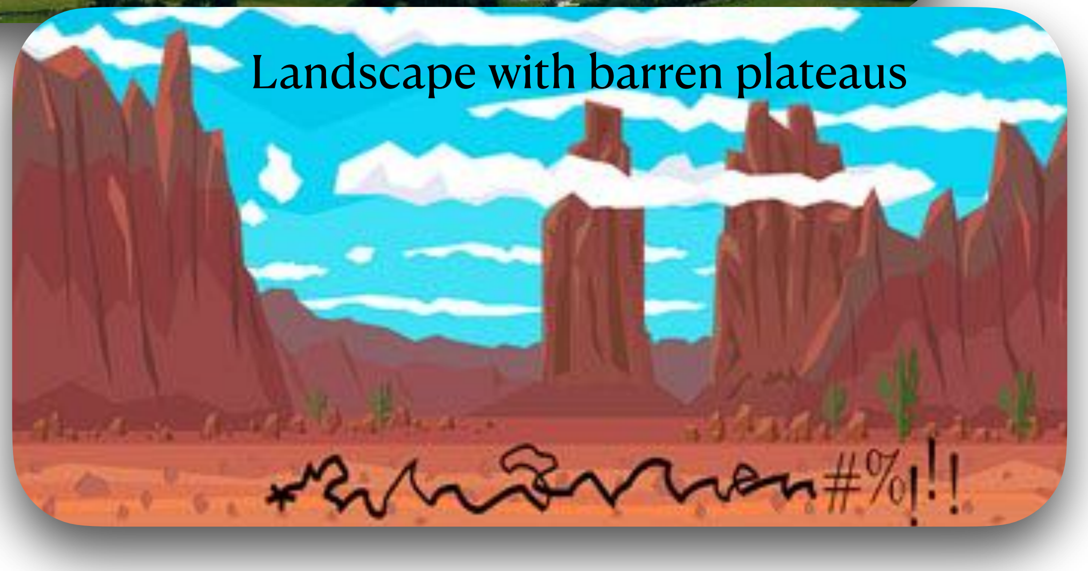
Short Coherence Time



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

Barren Plateaus





Jack Y. Araz

Towards simulating the Standard Model

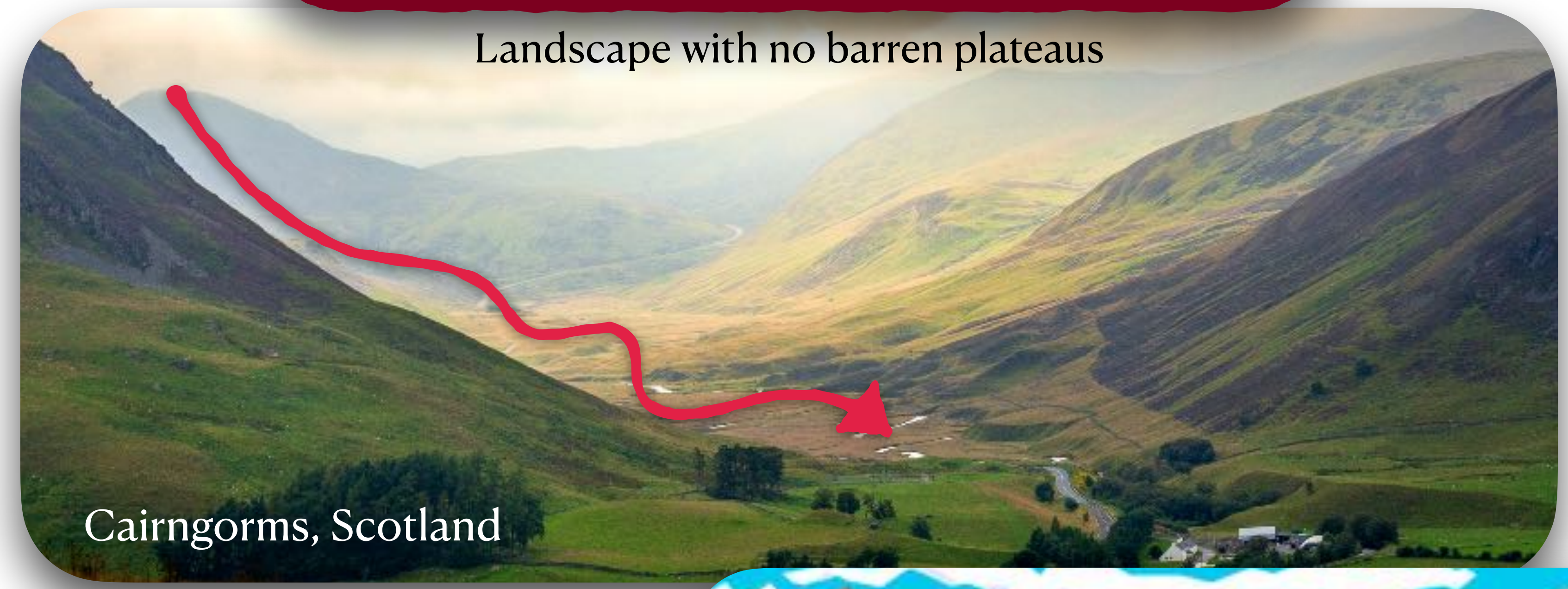
$$\mathscr{L} = \bar{\psi}(i\partial^{\mu}\gamma_{\mu} - m)\psi$$

Qubits

Short Coherence Time

Ty[illegible]erence time for an IBM superconducting qubit is 50 to 100 microsecond

Barren Plateaus



No more barren plateaus!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

The behaviour of the loss function with gradient descent

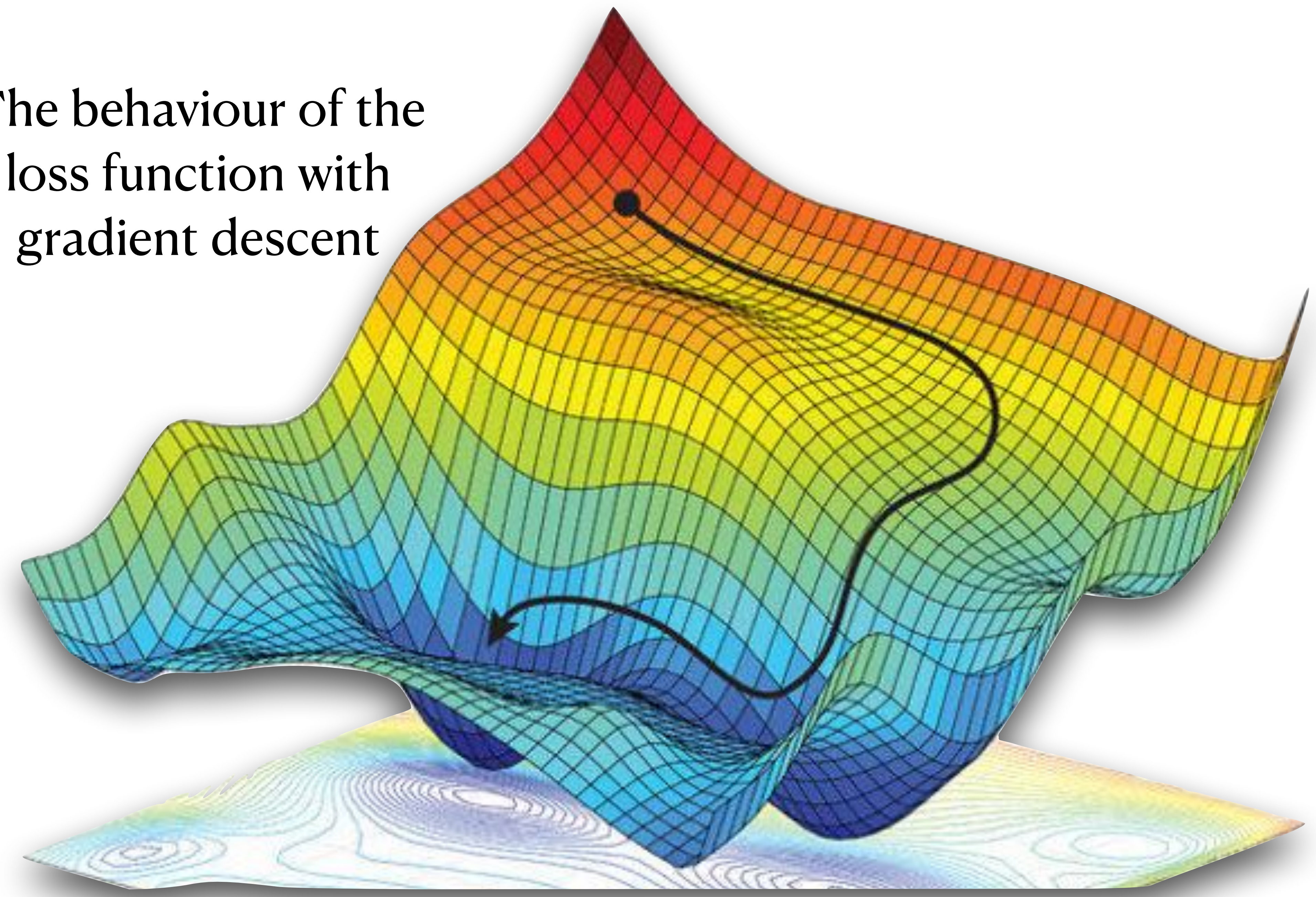


Image credit: Francisco Lima

No more barren plateaus!

JYA, Bhowmick, Grau, McEntire, Ringer; 2406.15545

Larger duration per pulse improves the variance of the loss!

The behaviour of the loss function with gradient descent

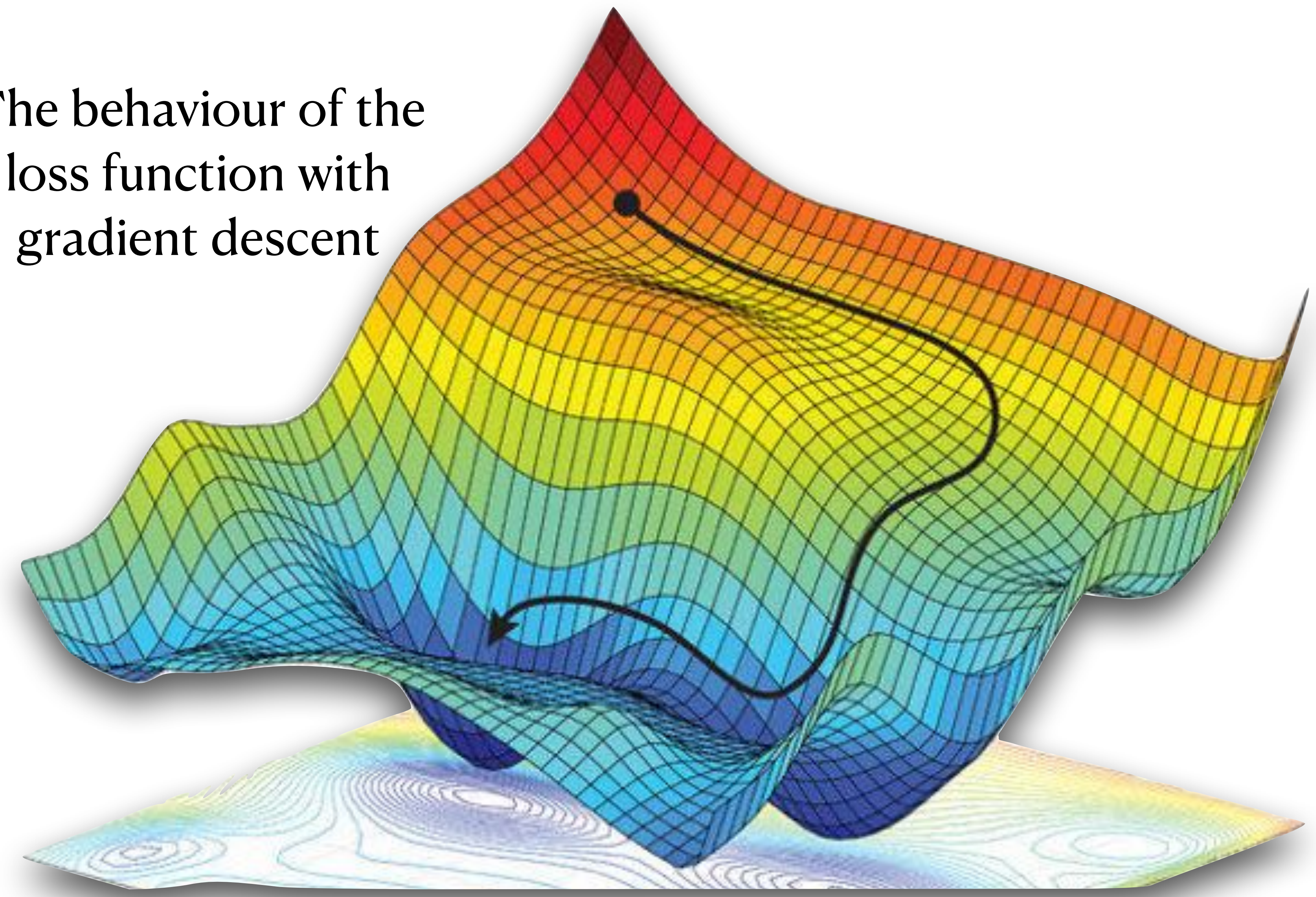
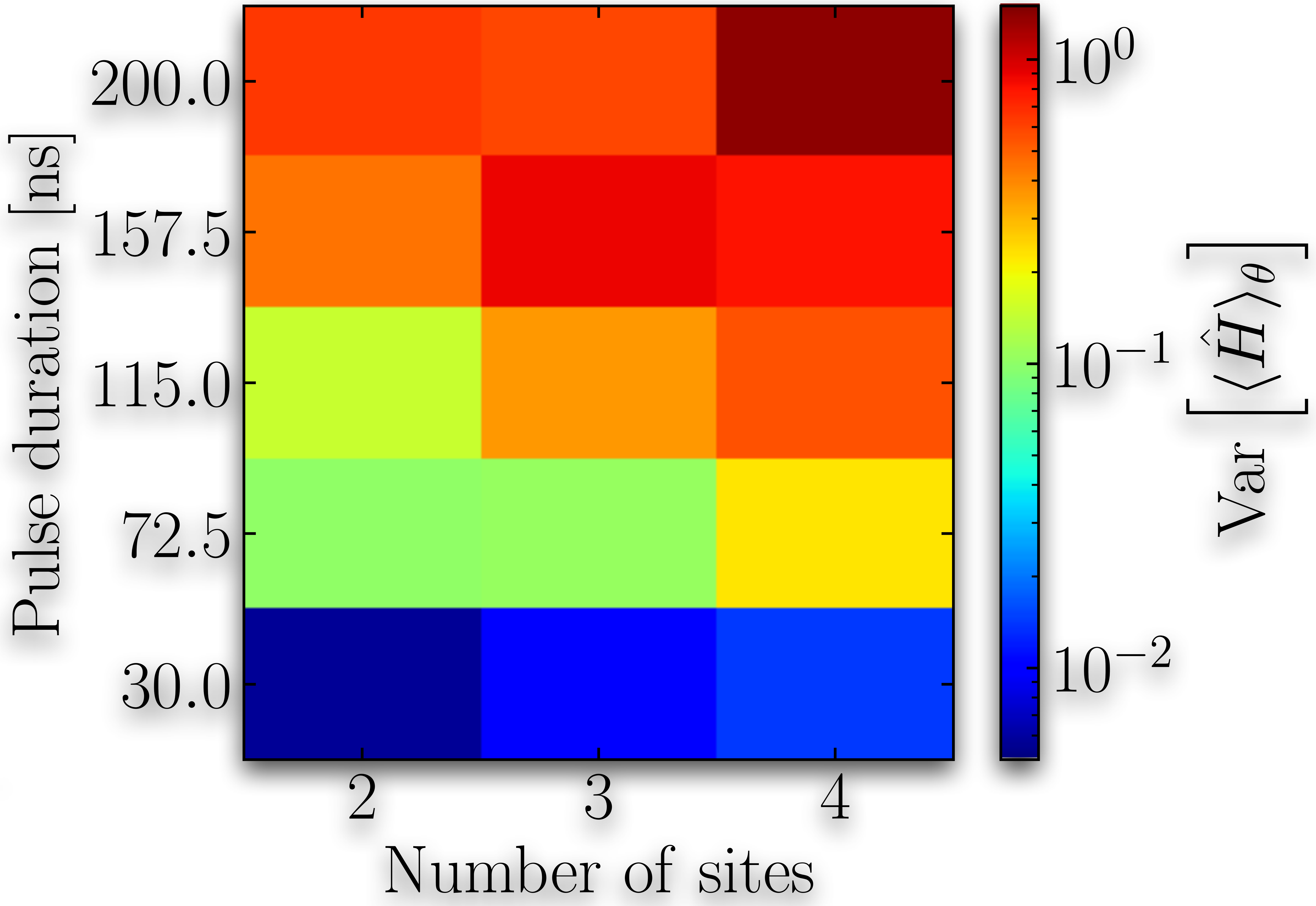


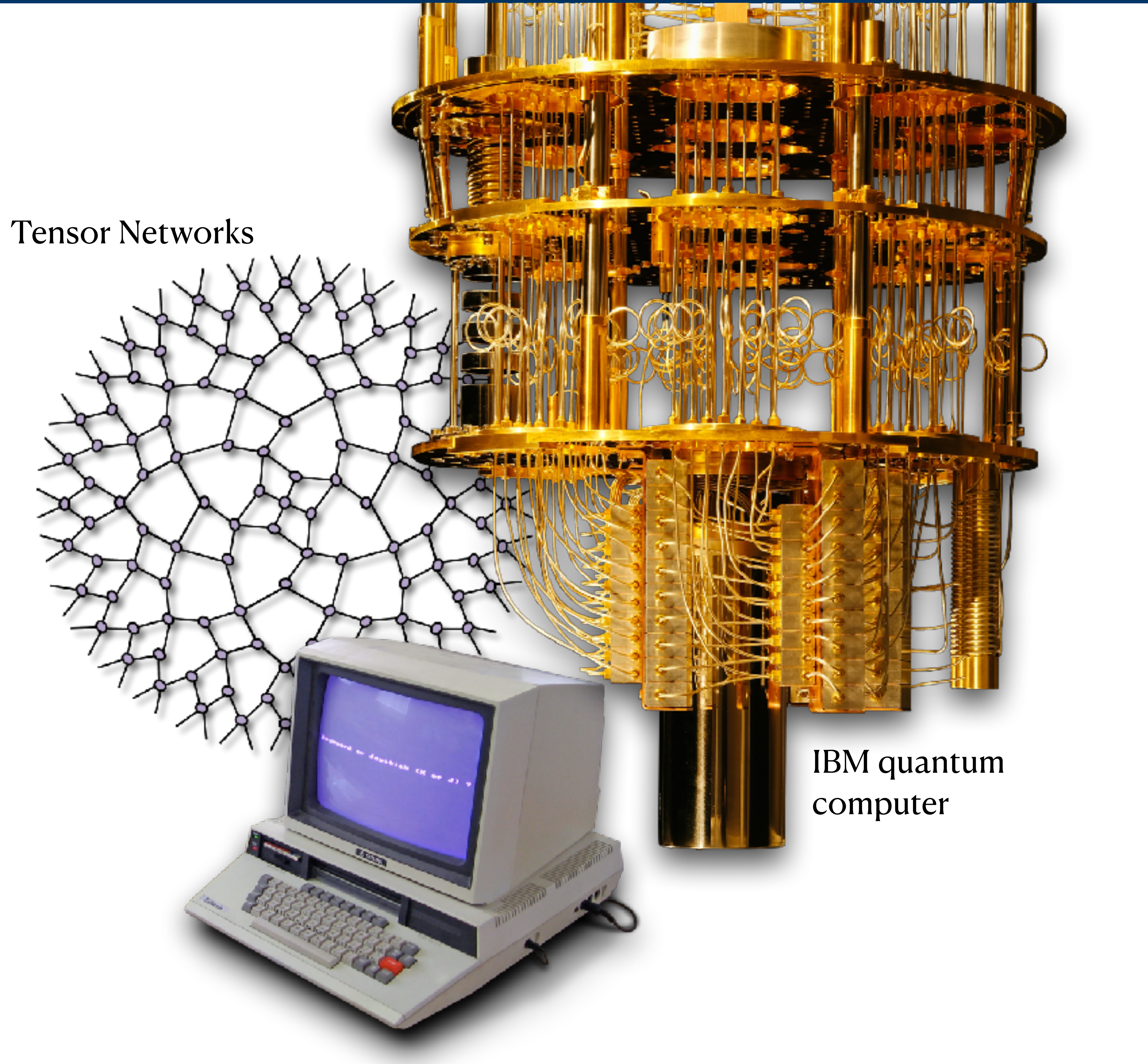
Image credit: Francisco Lima



Conclusion

Conclusion

- QOC can assist in creating more efficient algorithms.
- Allows to avoid decoherence.
- No barren plateaus.



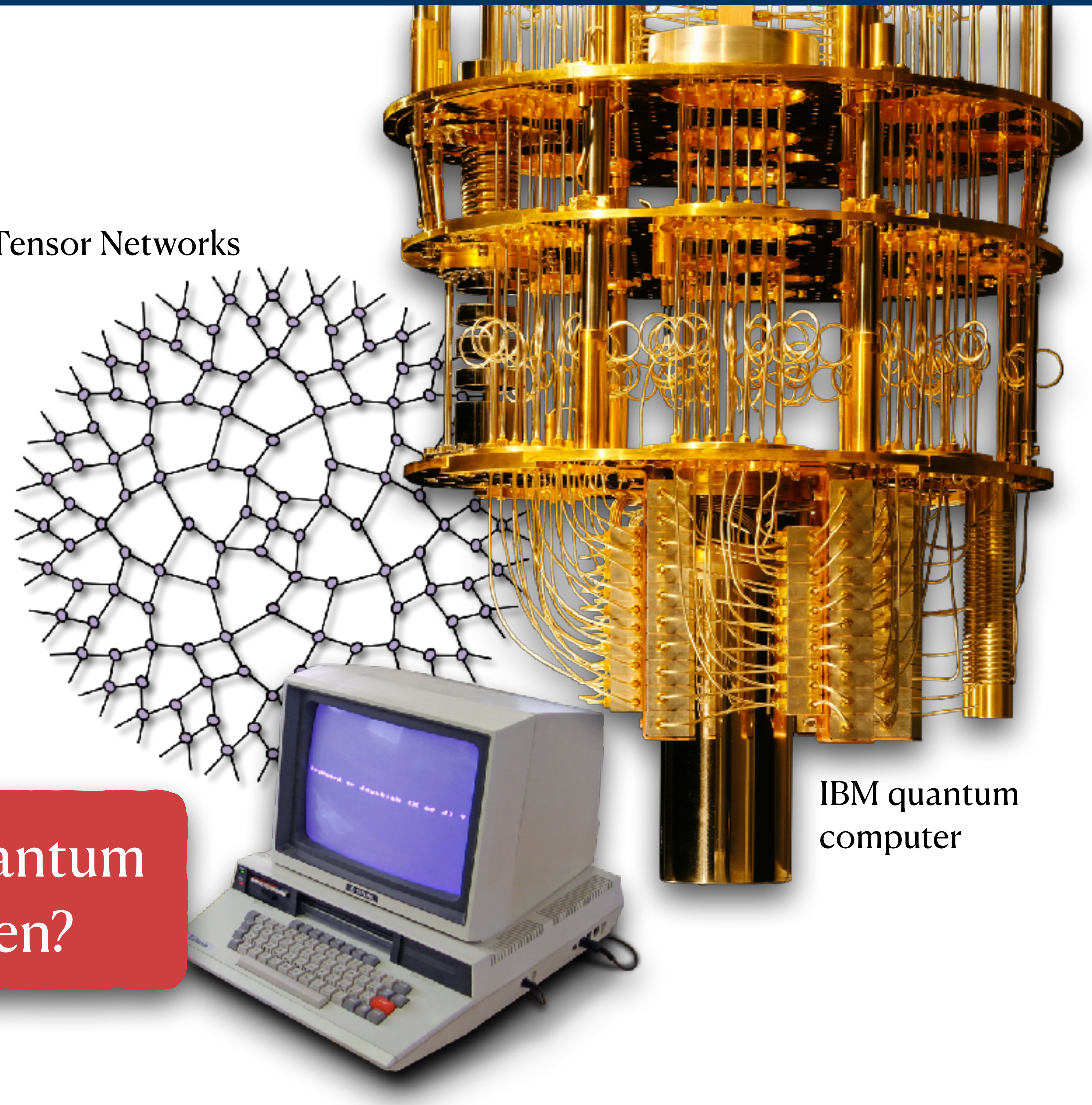
Conclusion

- QOC can assist in creating more efficient algorithms.
- Allows to avoid decoherence.
- No barren plateaus.

- QOC is very sensitive to device config.
- It is classically hard to scale.
- Can we use it as a foundation model?
- How to do error mitigation?

Where is the quantum advantage then?

Tensor Networks



IBM quantum computer