

Leveraging Quantum hardware for Fundamental Physics

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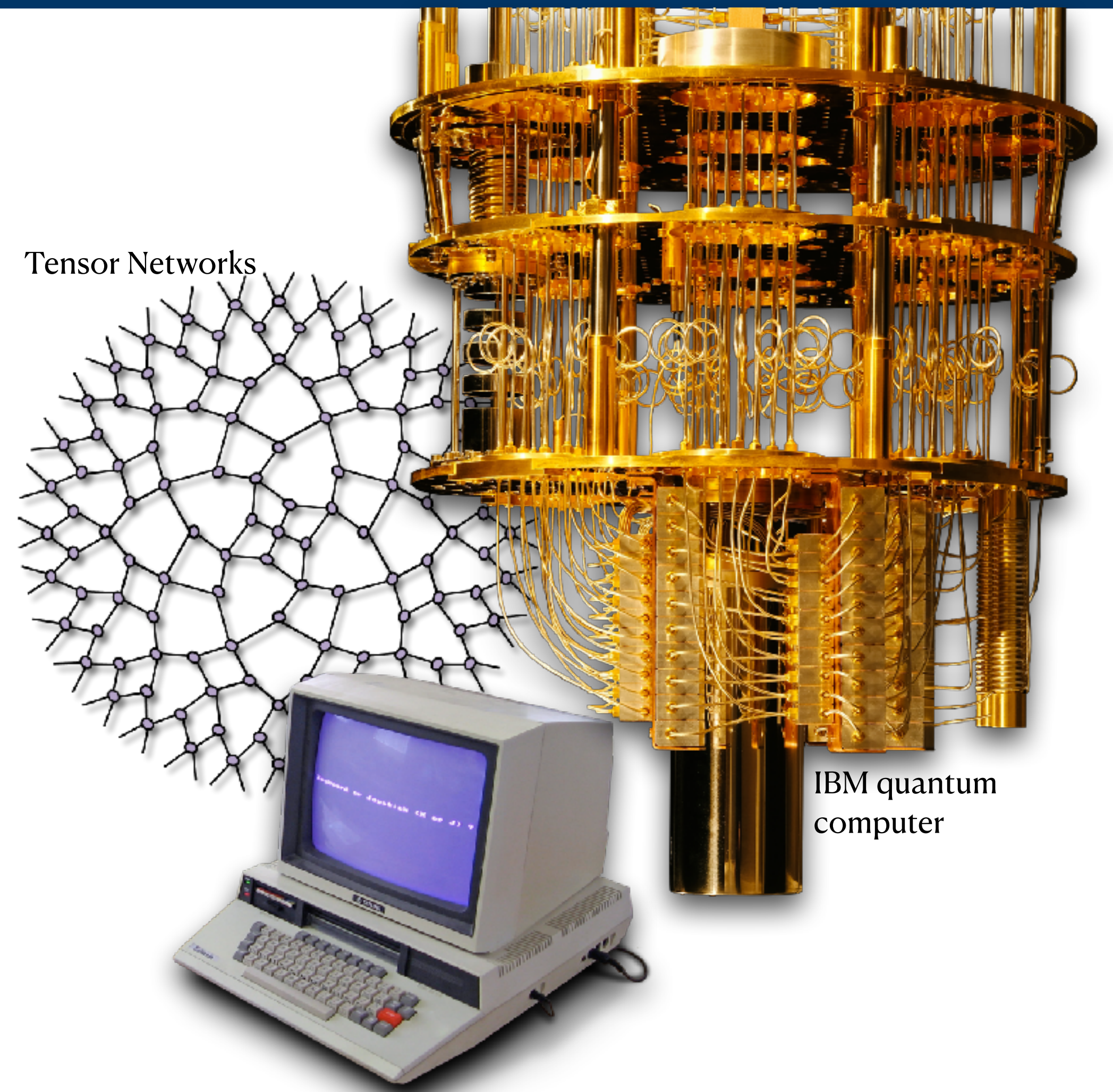


Outline

Simulating
Fundamental Physics

Hybrid quantum systems
for quantum simulation

Quantum Optimal Control for
nearer-term quantum computing



Simulating Fundamental Physics

Probing the fundamental structure of matter

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

Classical Methods

- ◆ Exact diagonalisation
- ◆ Monte Carlo
- ◆ Tensor Networks

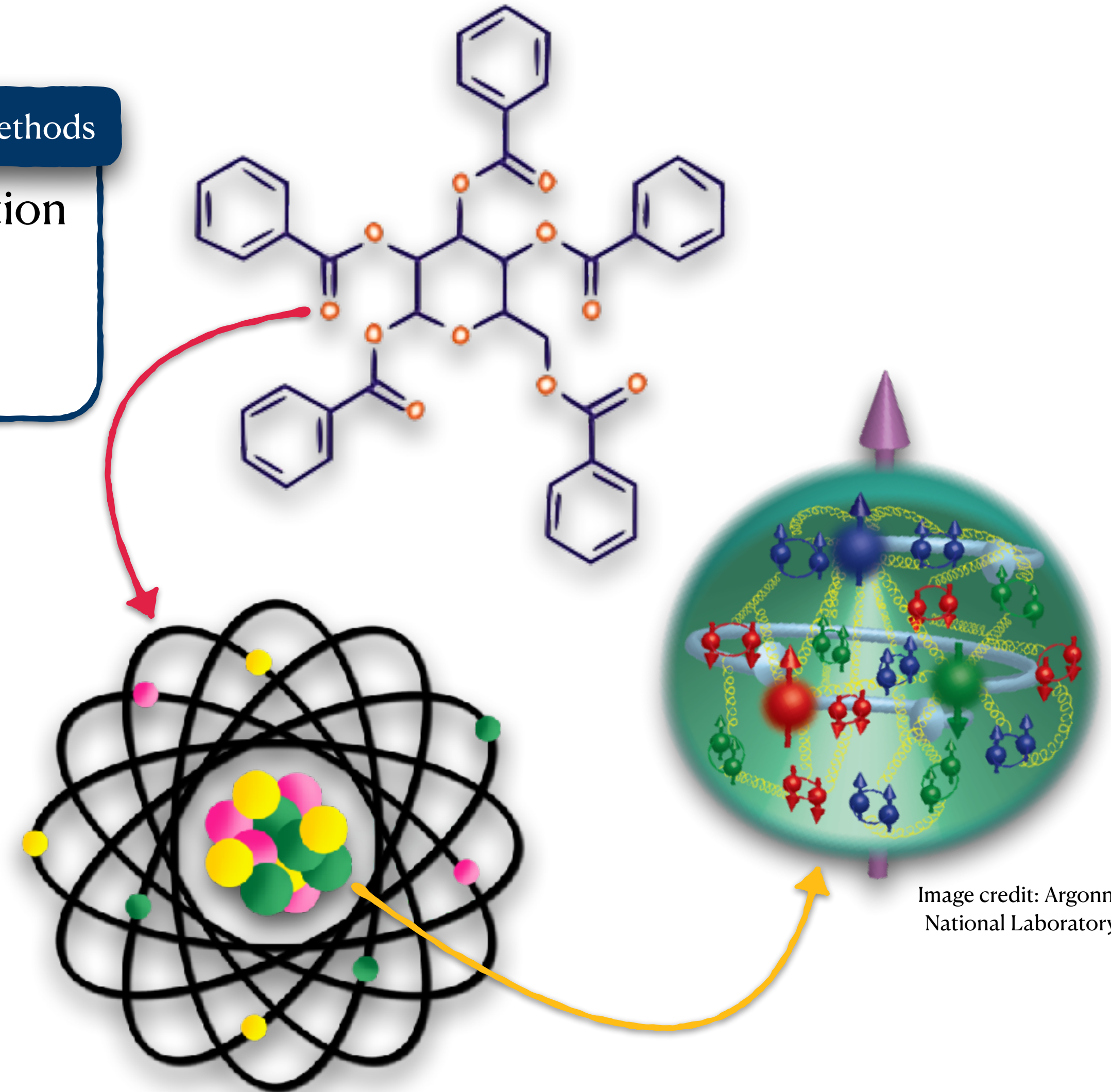


Image credit: Argonne National Laboratory

QCD from first principles

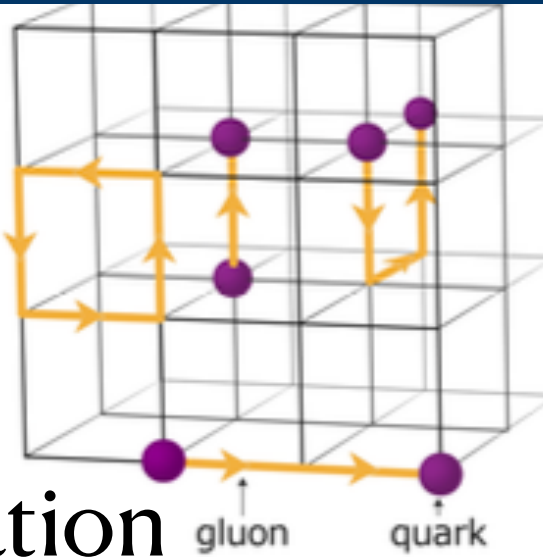
❖ Perturbative QCD at high energies

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



Not so much at
low energies!!!

Lattice QCD

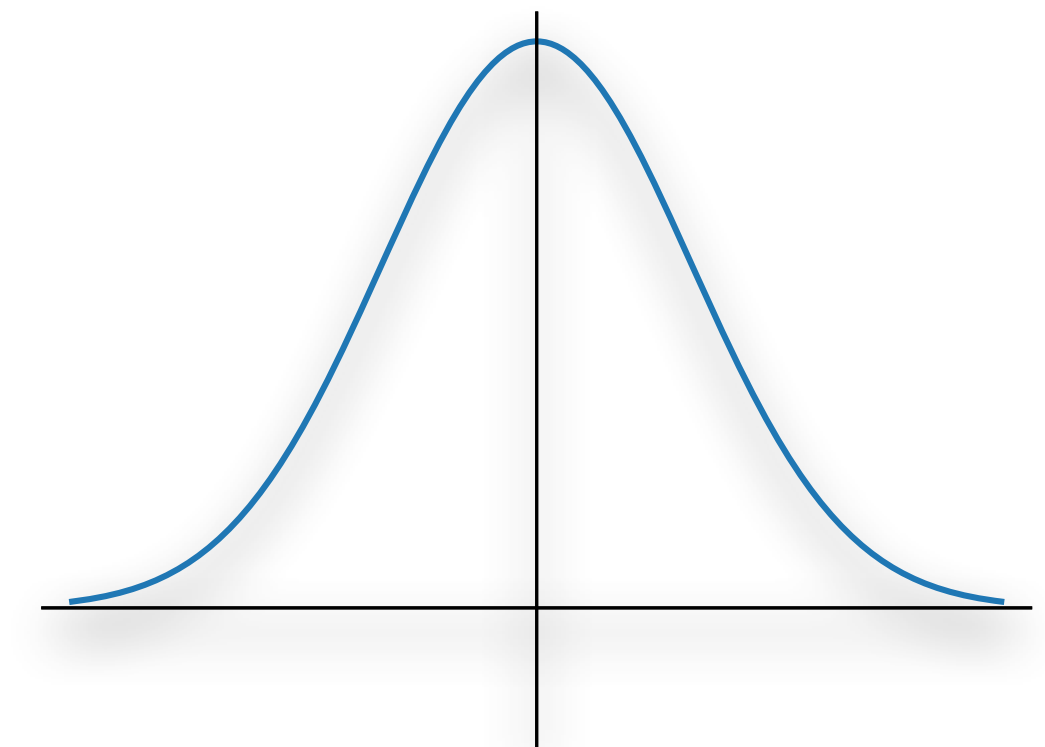


- ◆ Simulation via lattice discretisation
- ◆ Path integral vs Hamiltonian formulation
- ◆ Quantum computing for real-time dynamics

Wilson, Kogut, Susskind, 70's

❖ Sign problem in Lattice QCD

$$\left. \begin{aligned} \mathcal{L}_{QCD} &\rightarrow \mathcal{L}_{QCD} + i\mu \sum_f \bar{q}_f \gamma_0 q_f \\ e^{-S} &\rightarrow e^{-iS} \end{aligned} \right\} \text{Chemical potential} \quad \langle \mathcal{O} \rangle = \langle \mathcal{O} e^{-S} \rangle / \langle \sigma \rangle$$



QCD from first principles

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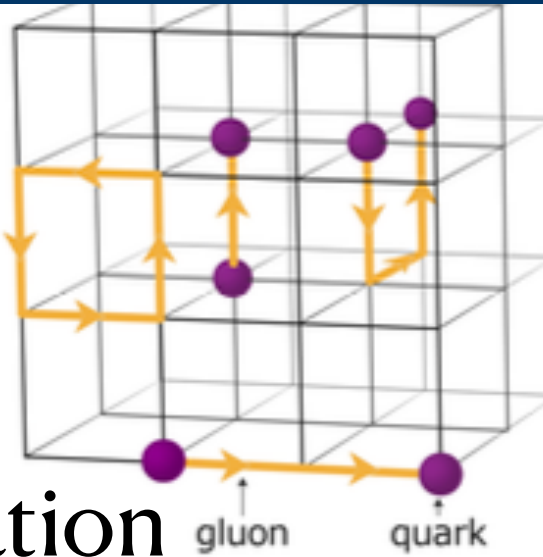
❖ Sign problem in Lattice QCD

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$e^{-S} \rightarrow e^{-iS}$ ← Chemical potential

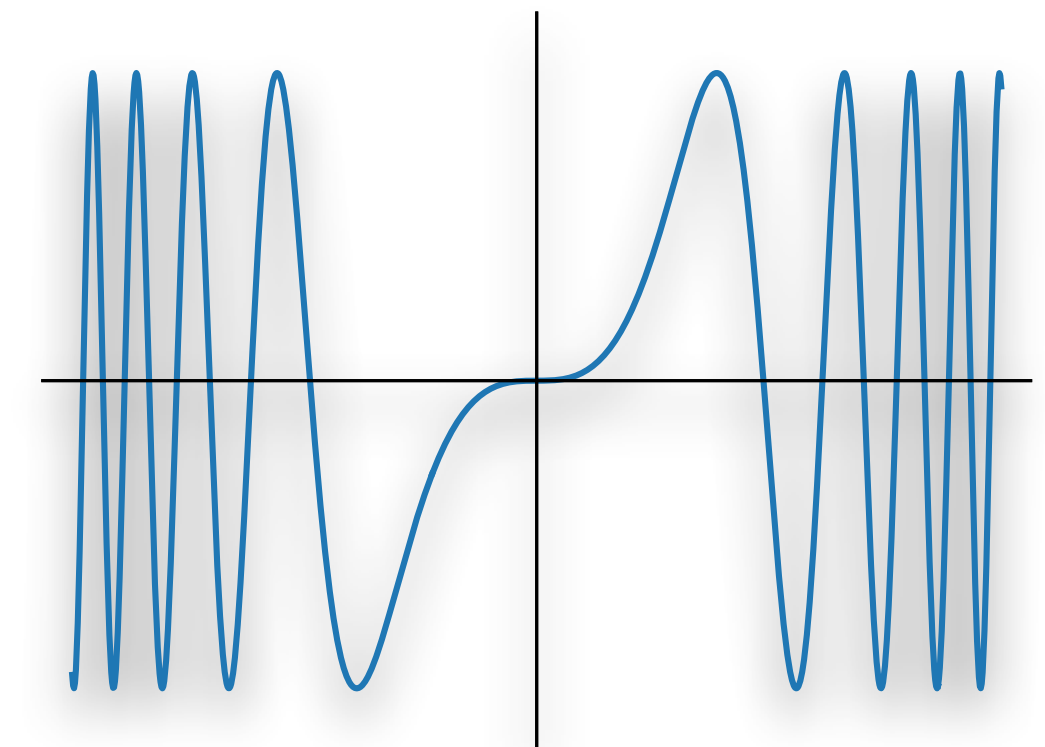
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Lattice QCD

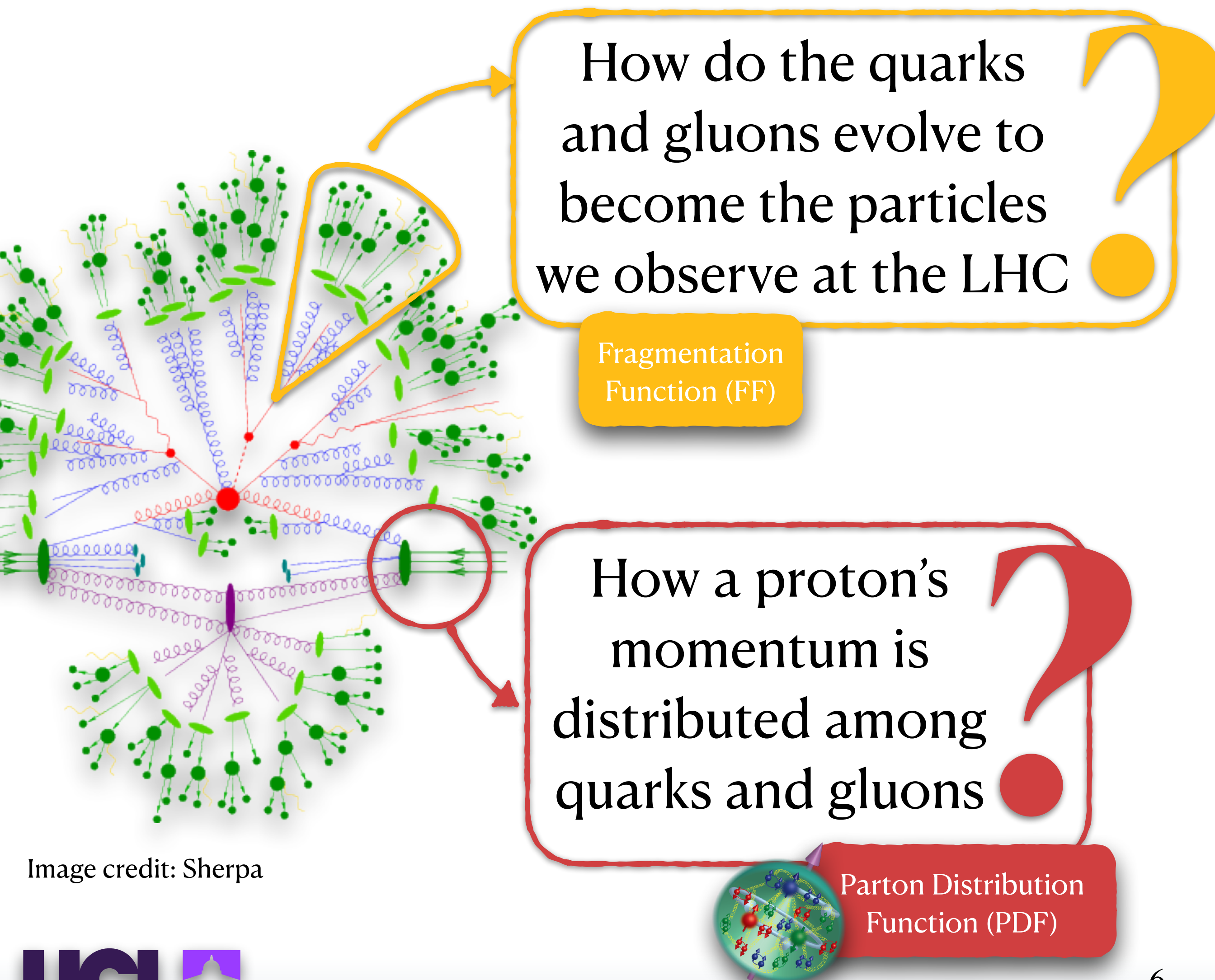


- ♦ Simulation via lattice discretisation
- ♦ Path integral vs Hamiltonian formulation
- ♦ Quantum computing for real-time dynamics

Wilson, Kogut, Susskind, 70's



The problem



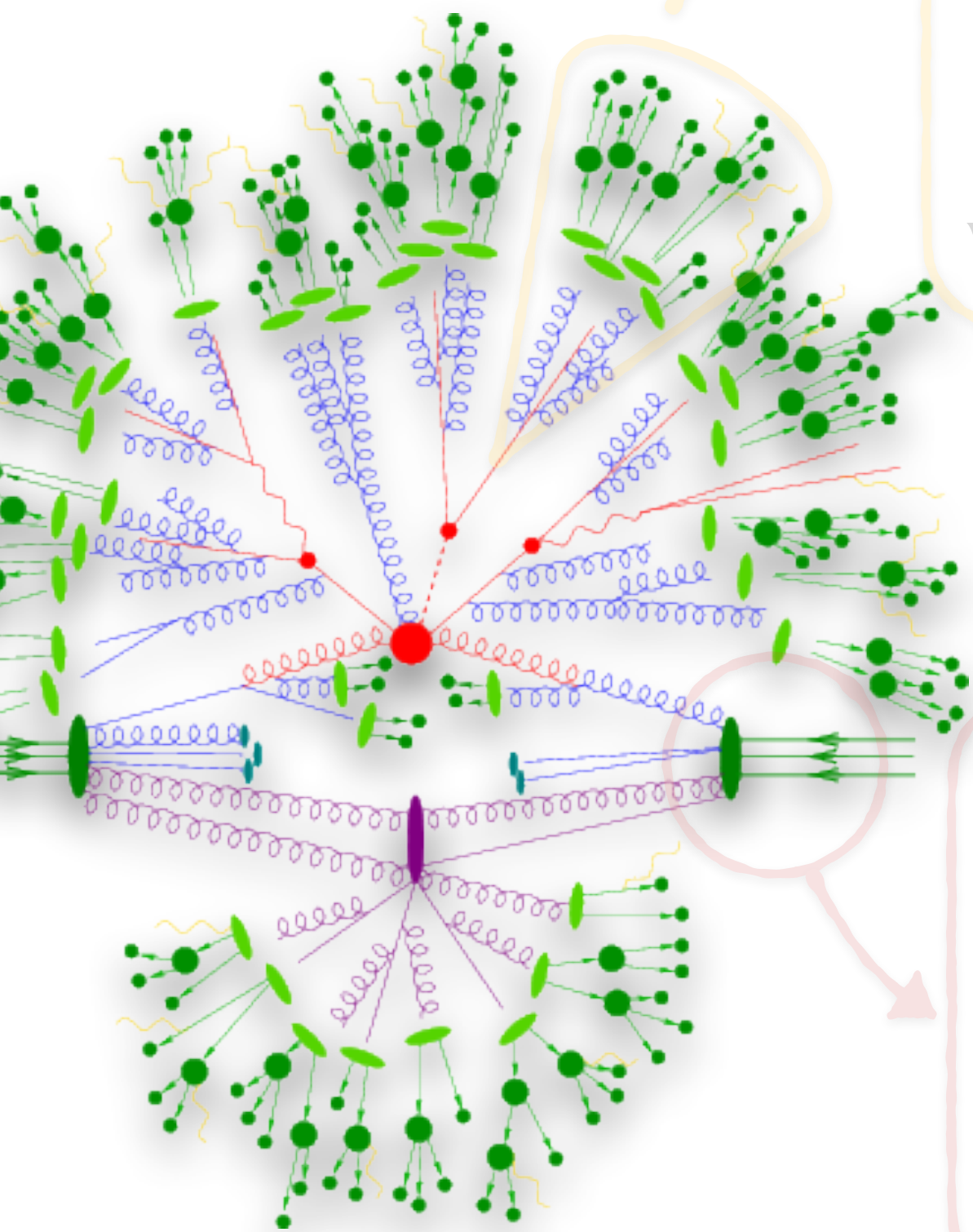
The theory is well established, but **impossible** to solve even with the most powerful supercomputers.

Lattice QCD

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

Image credit: Sherpa

The problem



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

The theory is well established, but

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

How is the energy distributed among quarks and gluons?

❖ Computational cost scales exponentially

Parton Distribution Function (PDF)

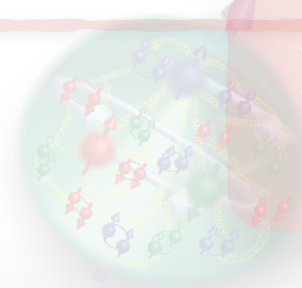
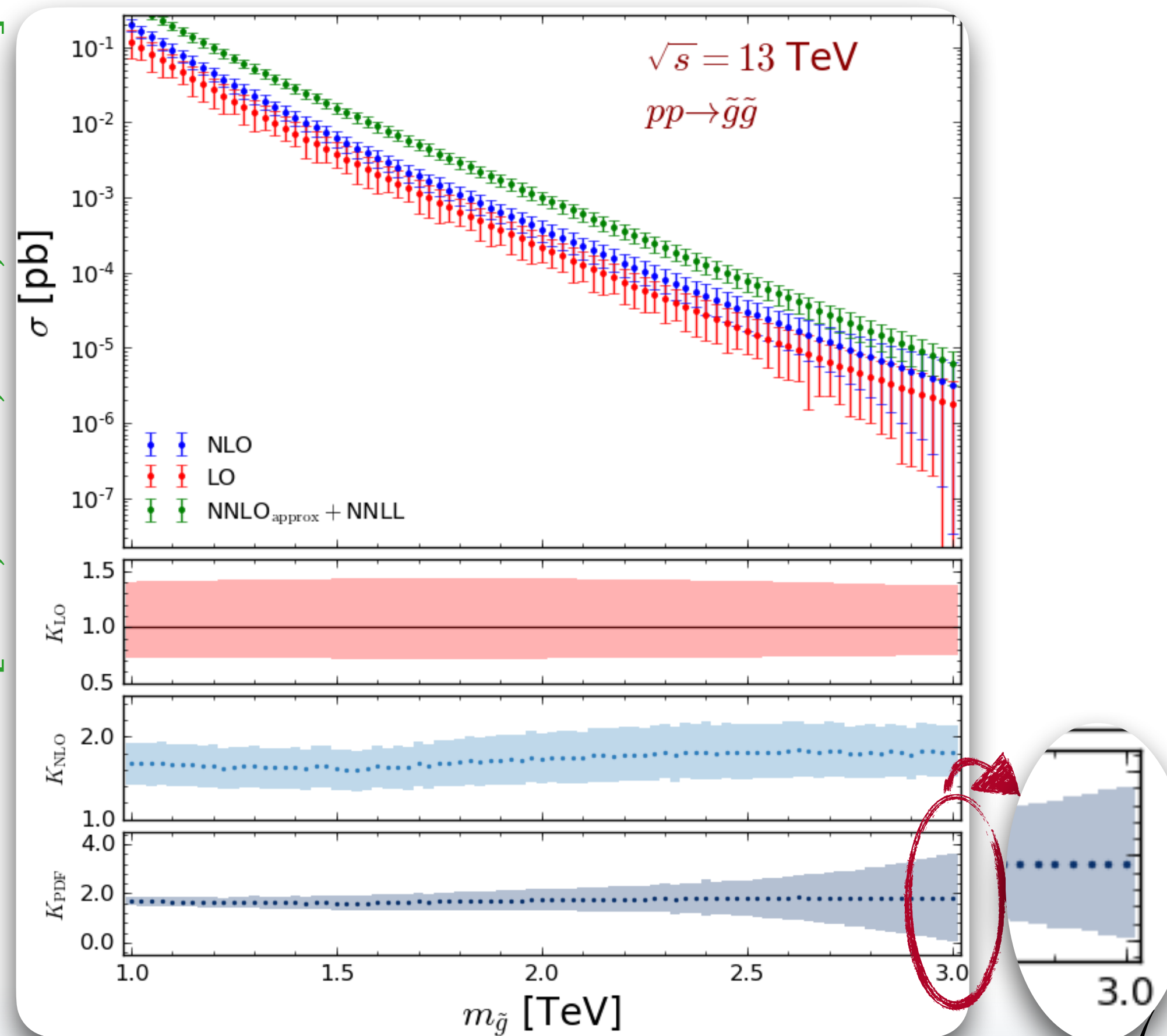


Image credit: Sherpa

Example: Why PDF?

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

[JYA, Frank, Fuchs; EPJC '20]



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Example: Why PDF?

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

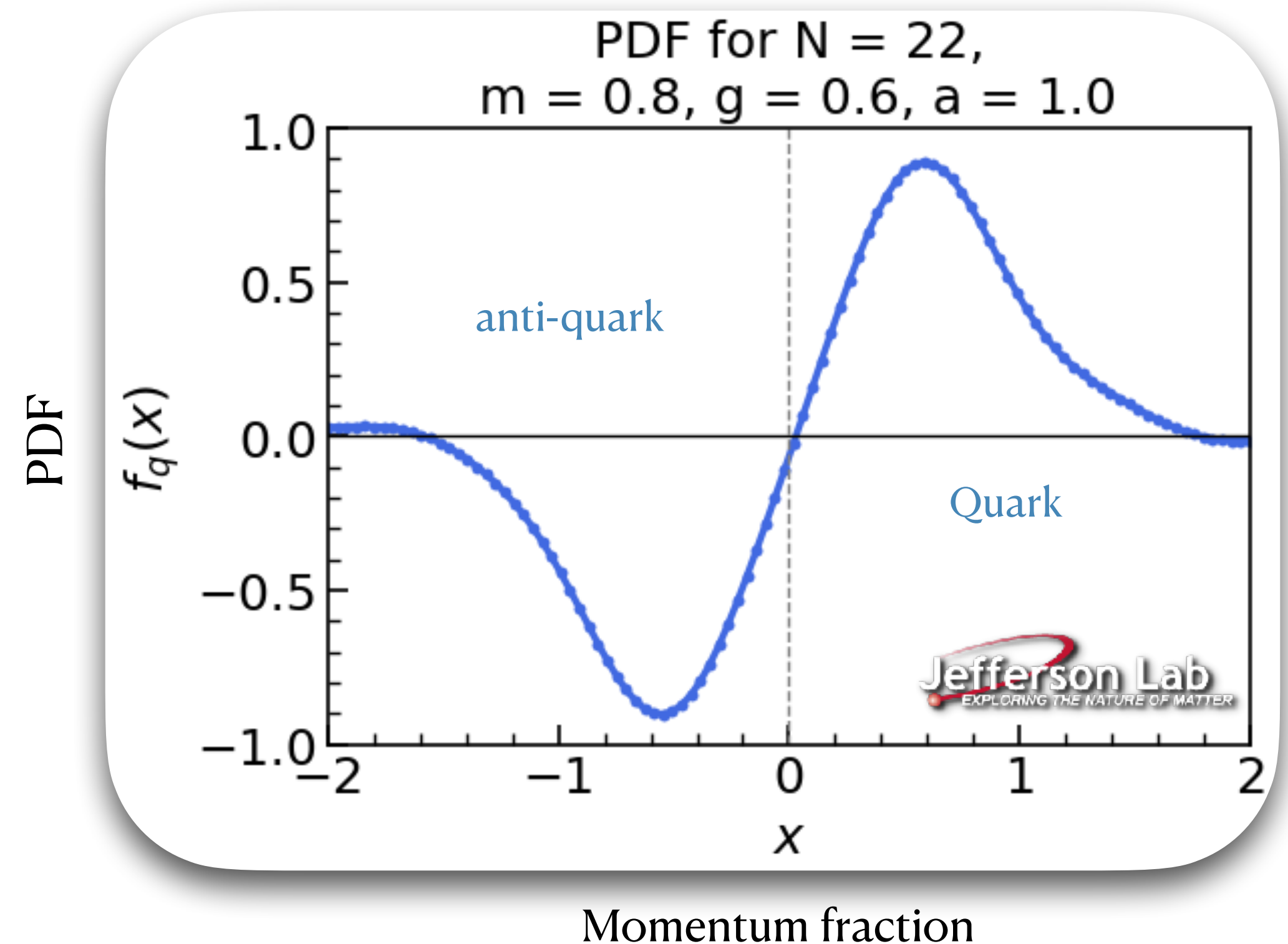
In the hadron rest frame:

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

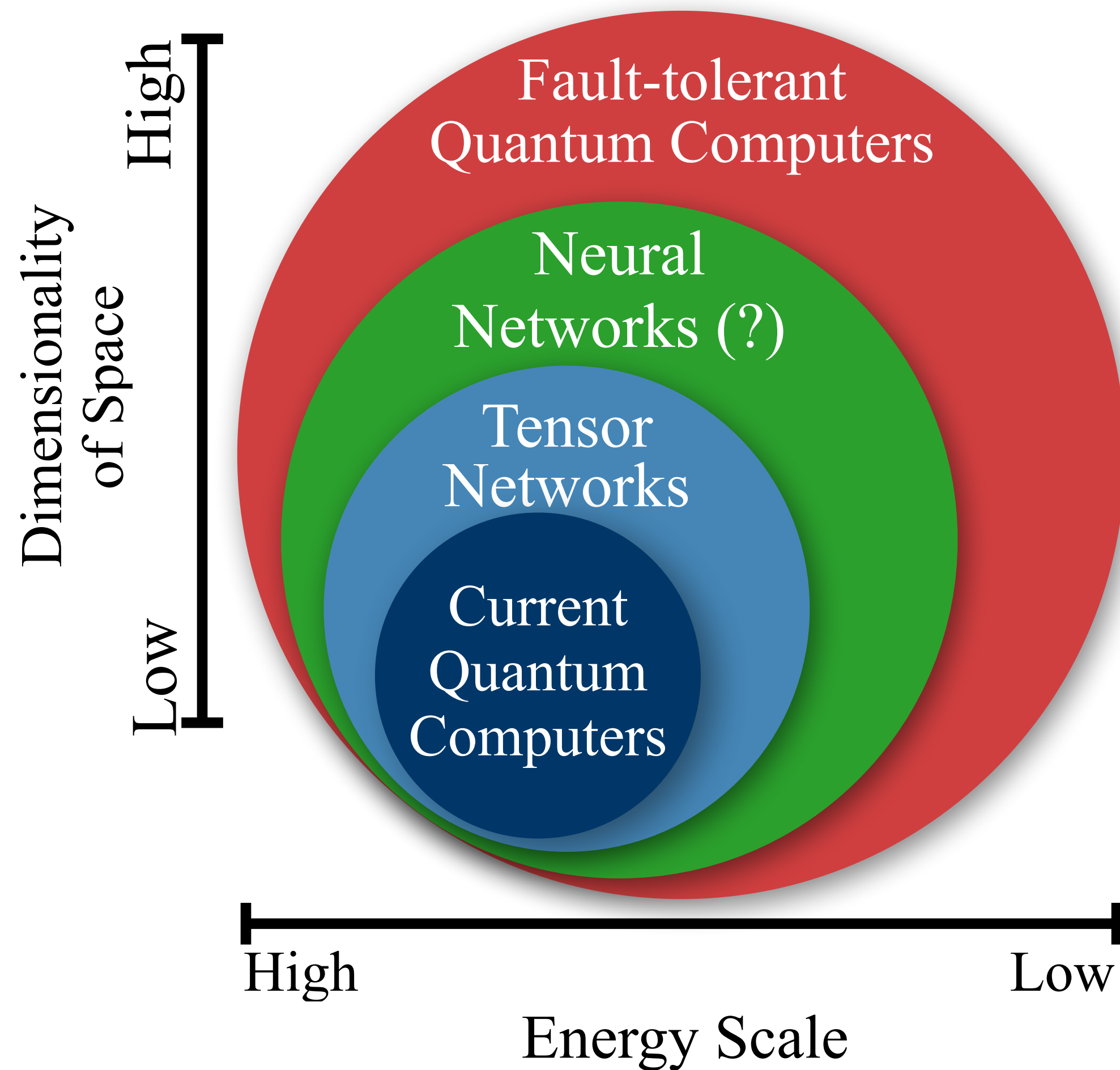
Quark
field

Hadron
state

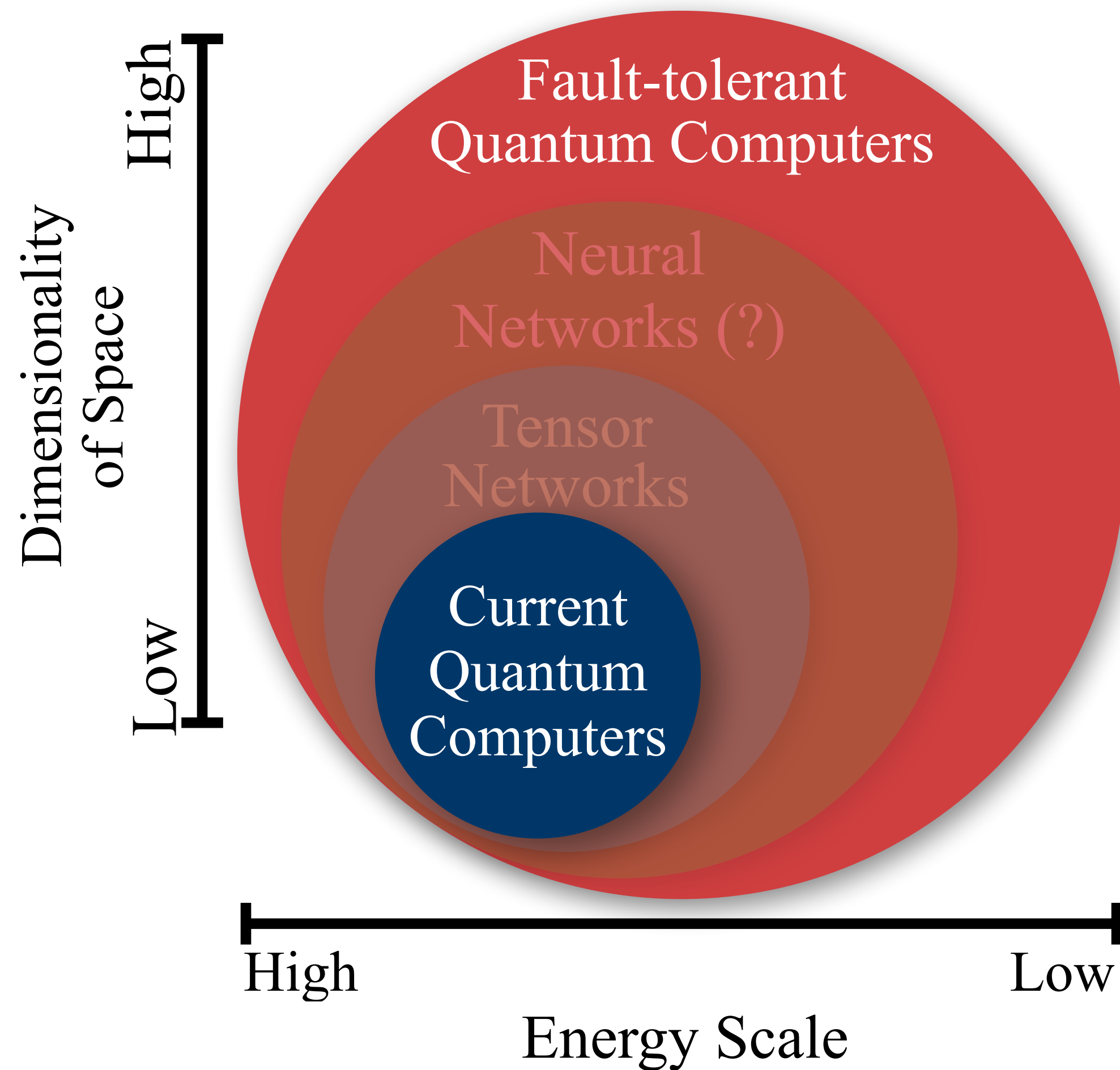
Time-dependent correlations can be
computed in polynomial time on a
Quantum Computer!



Towards quantum-enabled fundamental science



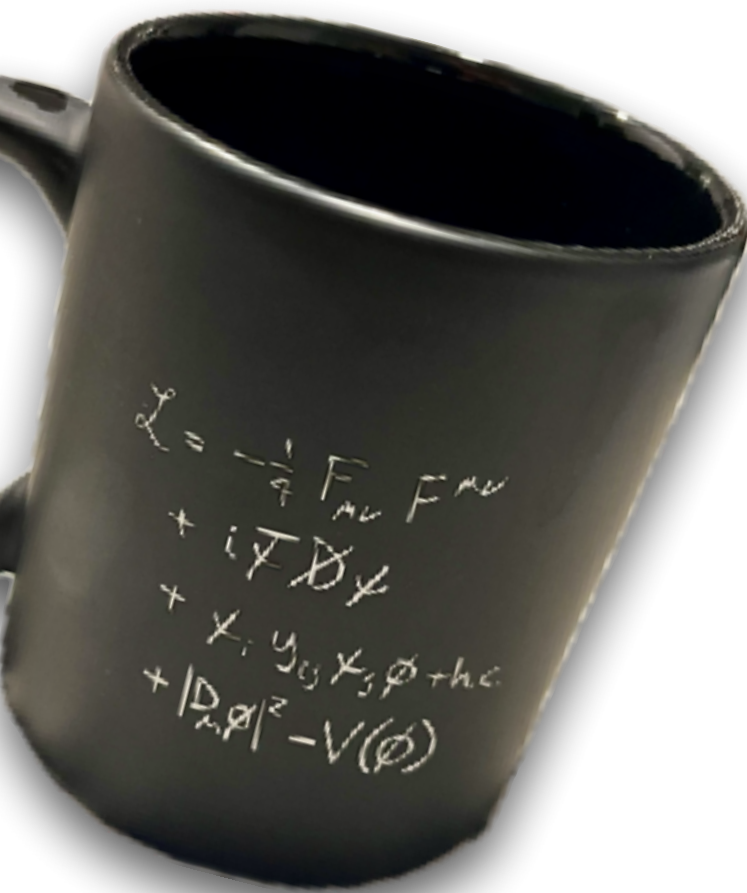
Towards quantum-enabled fundamental science



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

Towards simulating QCD

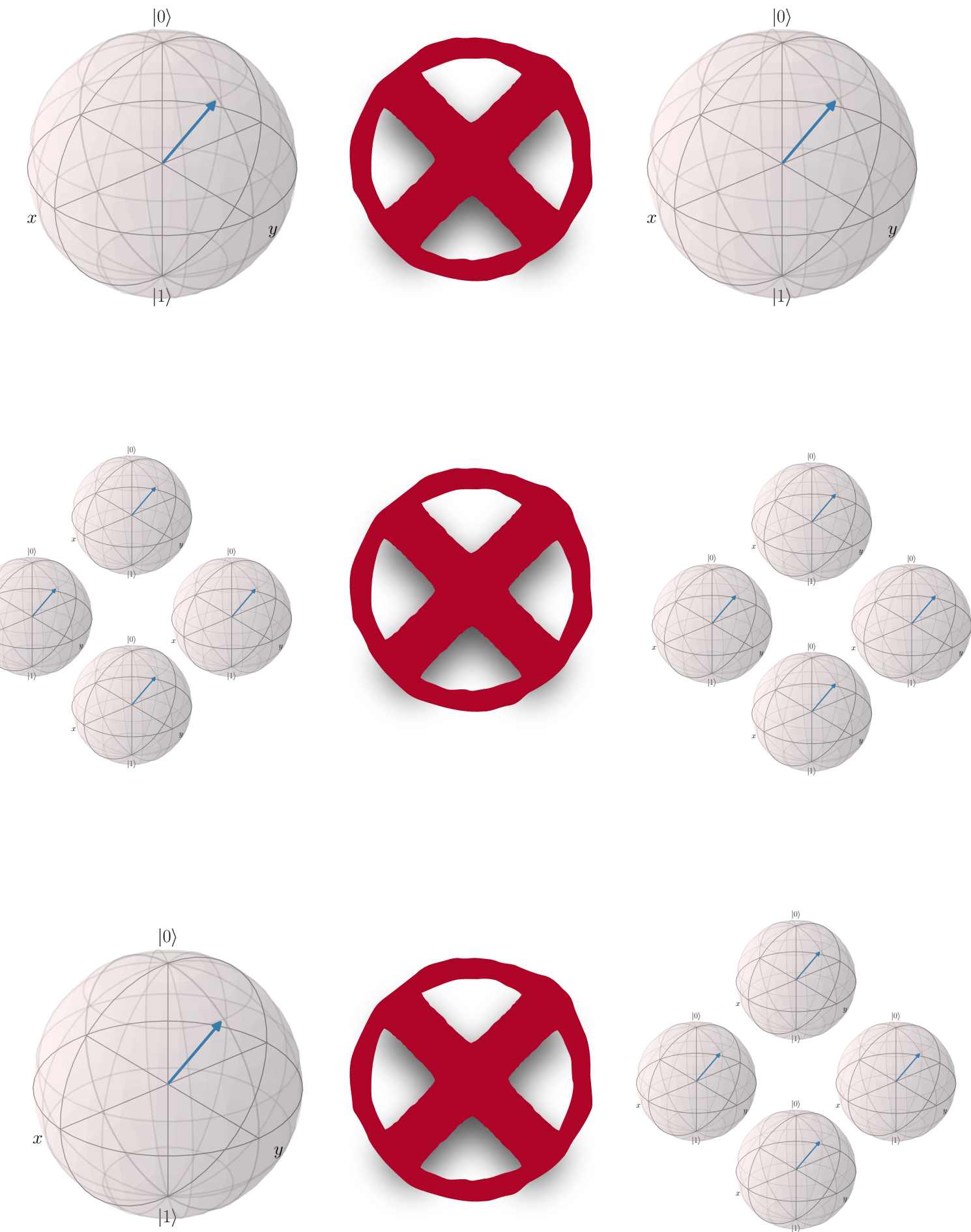
$$\mathcal{L} = \bar{\psi}(i\partial^\mu\gamma_\mu - m)\psi$$



$$-\frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a$$

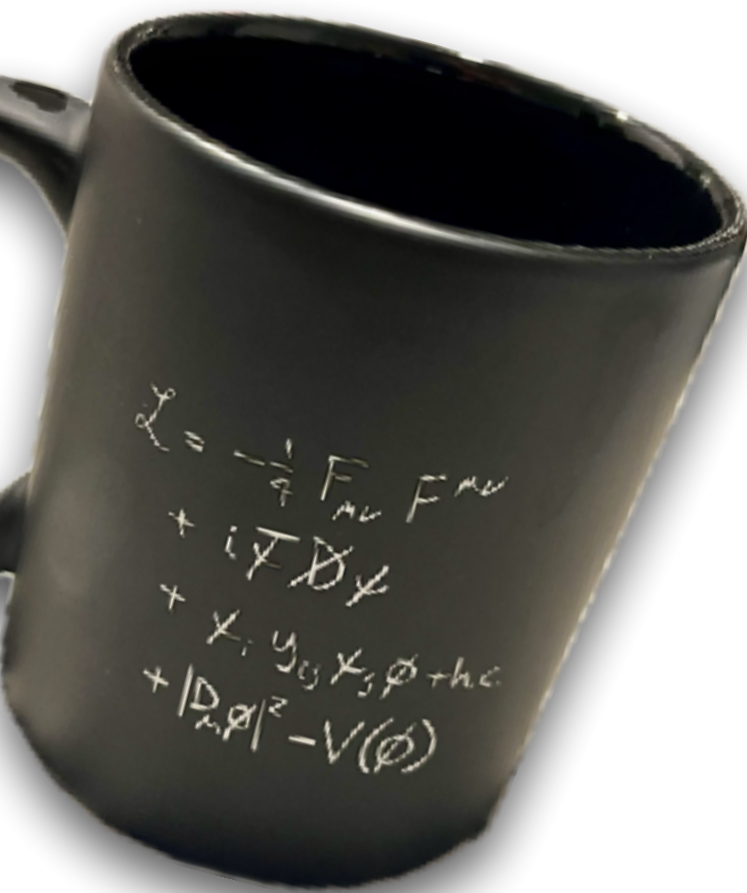
$$+ g\bar{\psi}\gamma^\mu T_a\psi A_\mu^a$$

DoF $\rightarrow \infty$



Towards simulating QCD

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



$$-\frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a$$

$$+g\bar{\psi}\gamma^\mu T_a\psi A_\mu^a$$



Qumodes or CV Quantum Computers

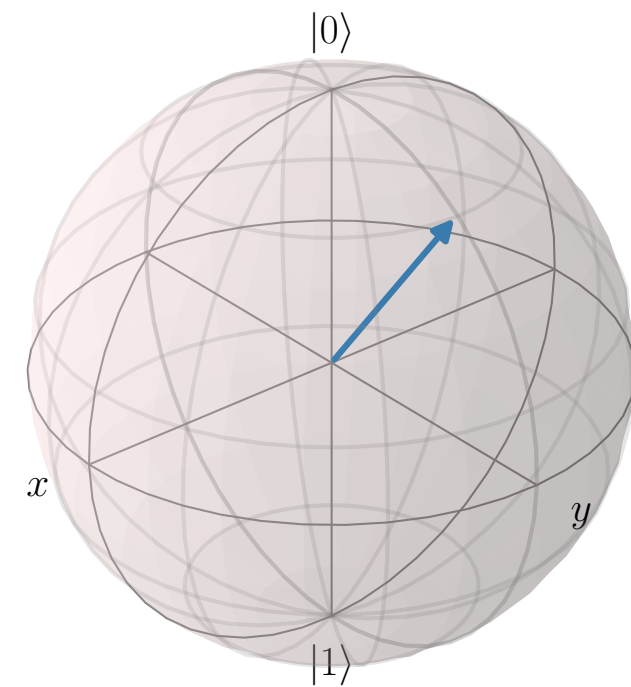
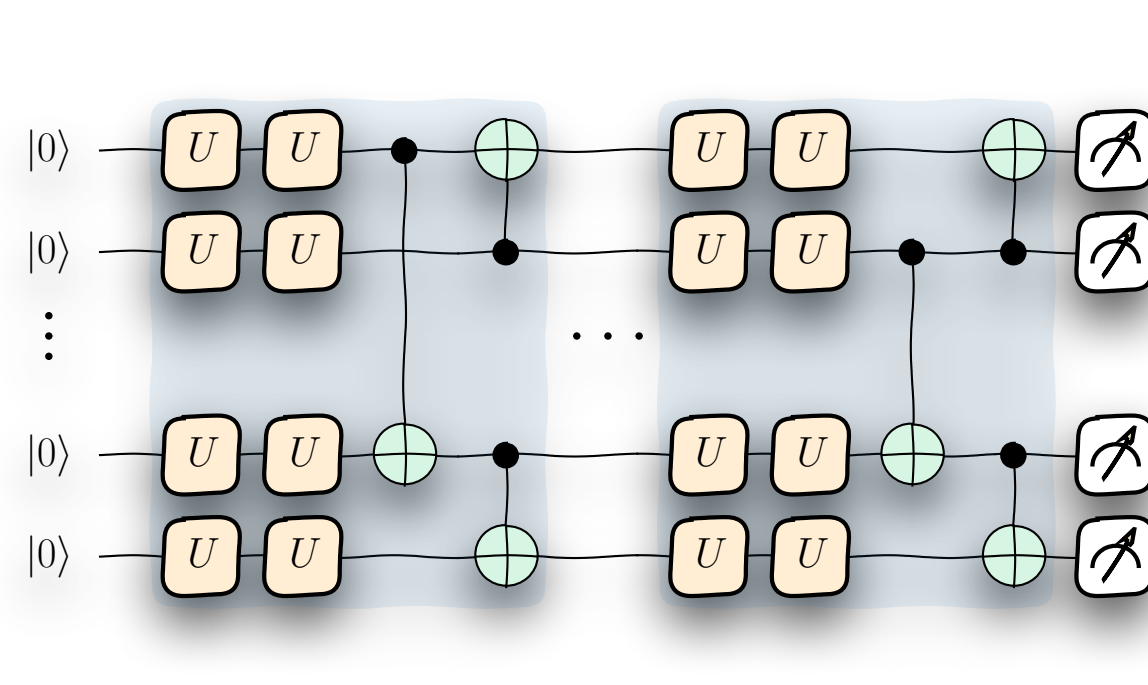


Qubit-Qumode Coupling

Qubits & Qumodes

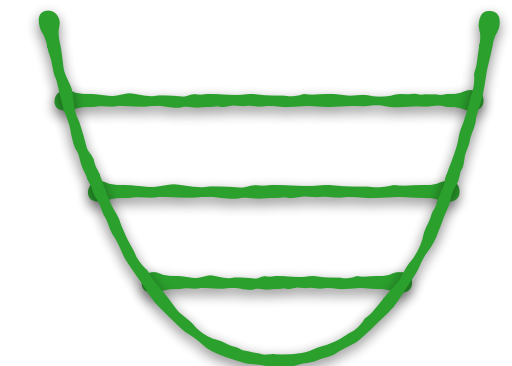
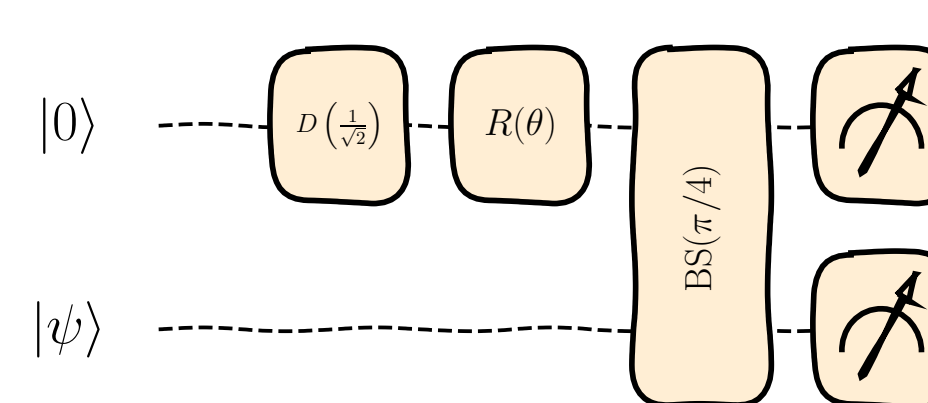
Qubits

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



Qumodes

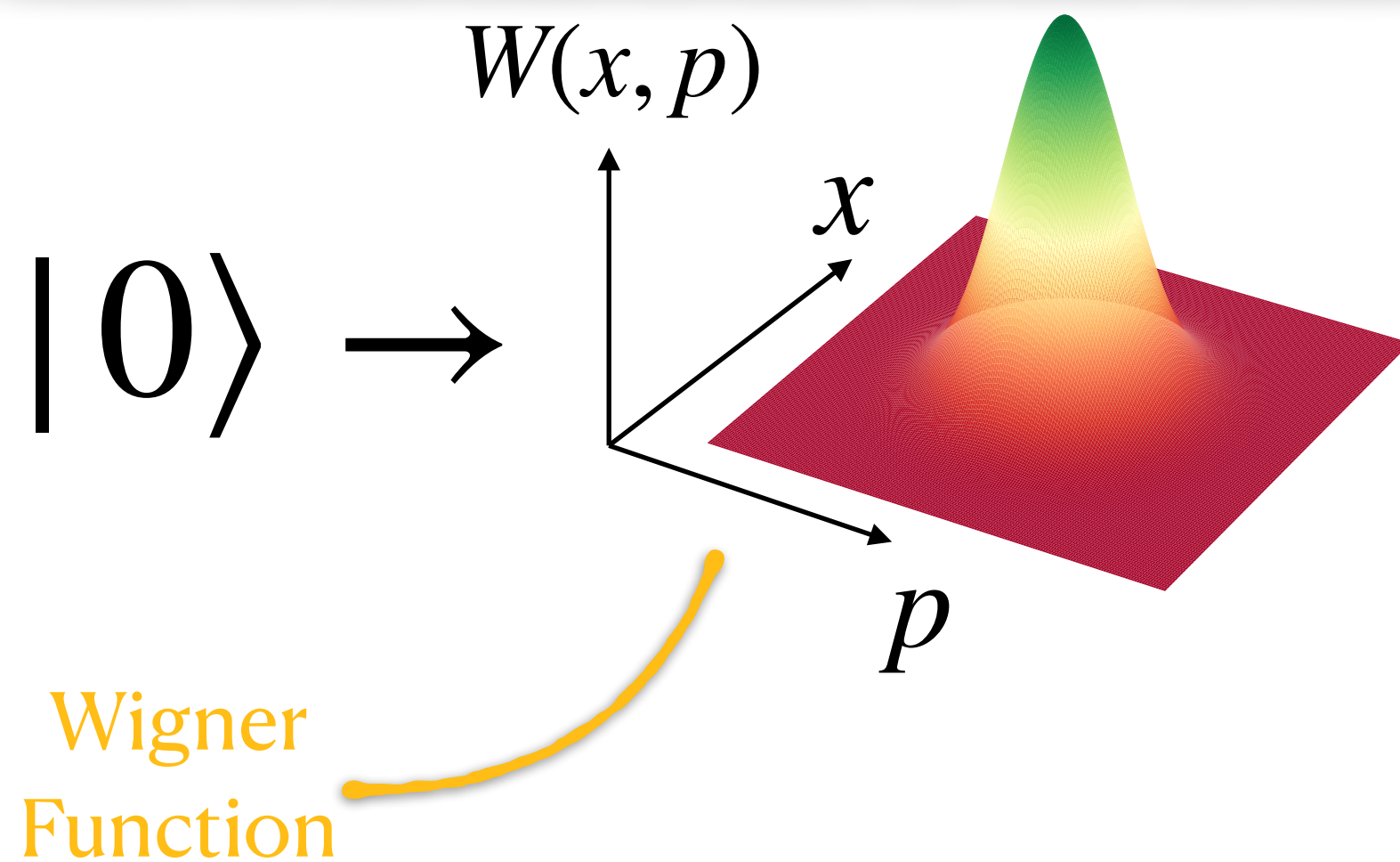
- ❖ Photonics, trapped ions, superconducting circuits
- ❖ Infinite-dimensional Hilbert space
- ❖ Gate-based BUT with continuous variables



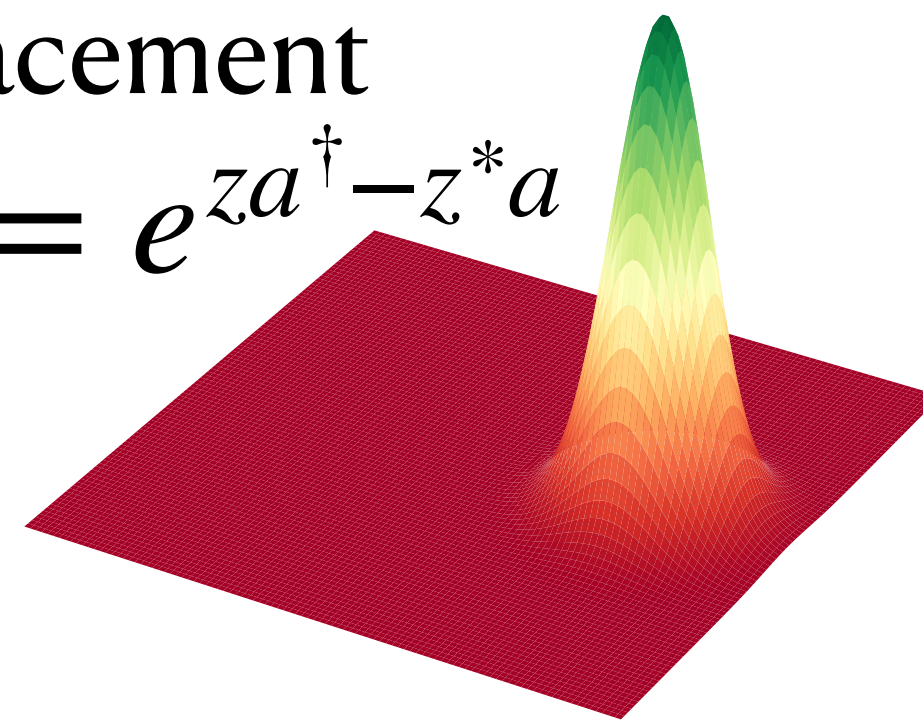
Quantum simulations with Qumodes

Llyod, Braunstein, '99

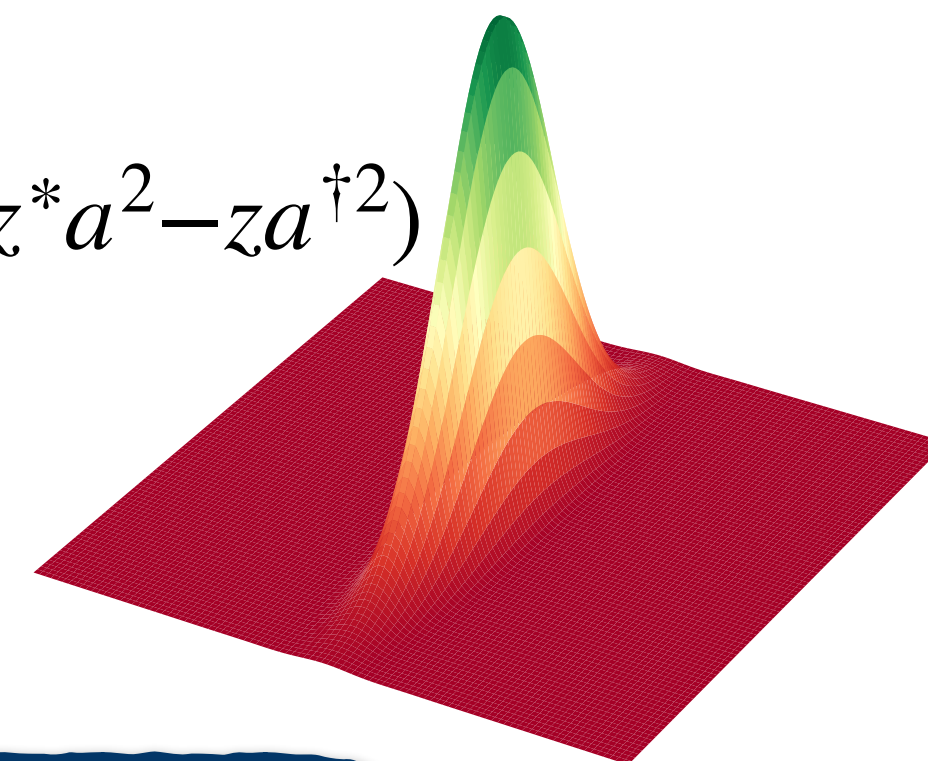
Universal gateset for Qumodes



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



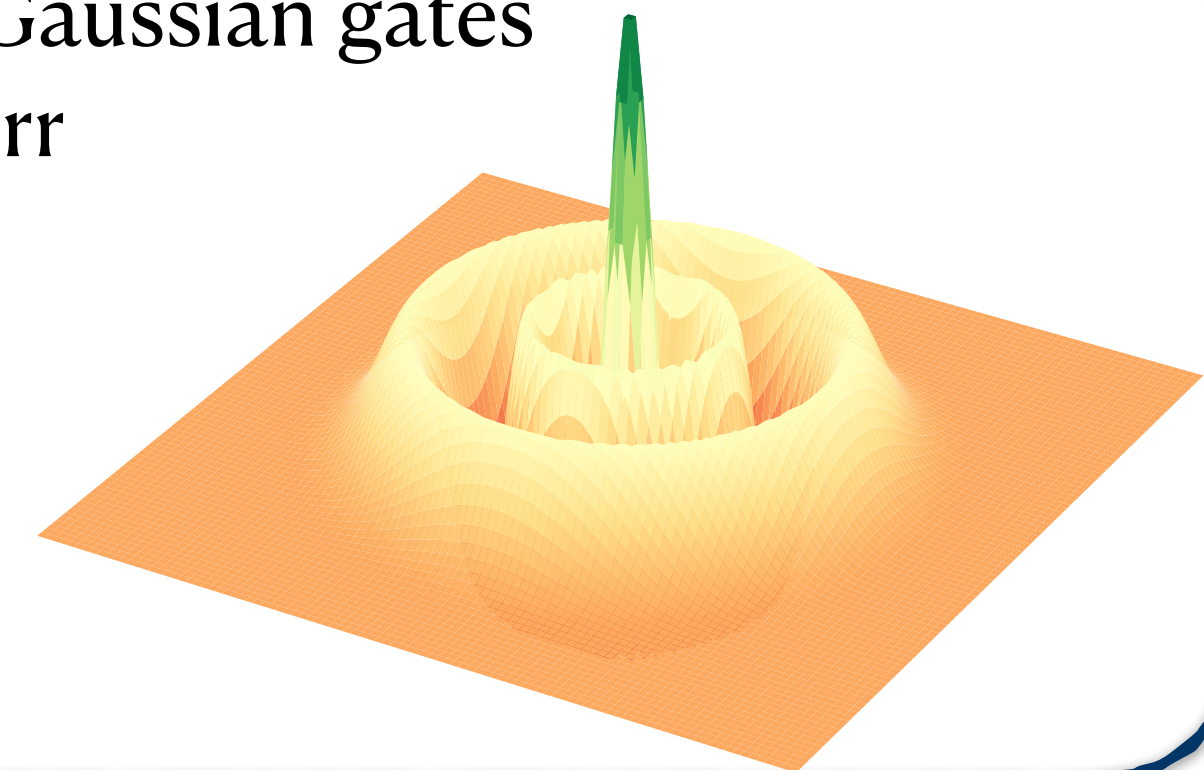
❖ Squeezing
 $S(z) = e^{\frac{1}{2}(z^*a^2 - za^{\dagger 2})}$



❖ 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

Qubits & Qumodes with trapped ions

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

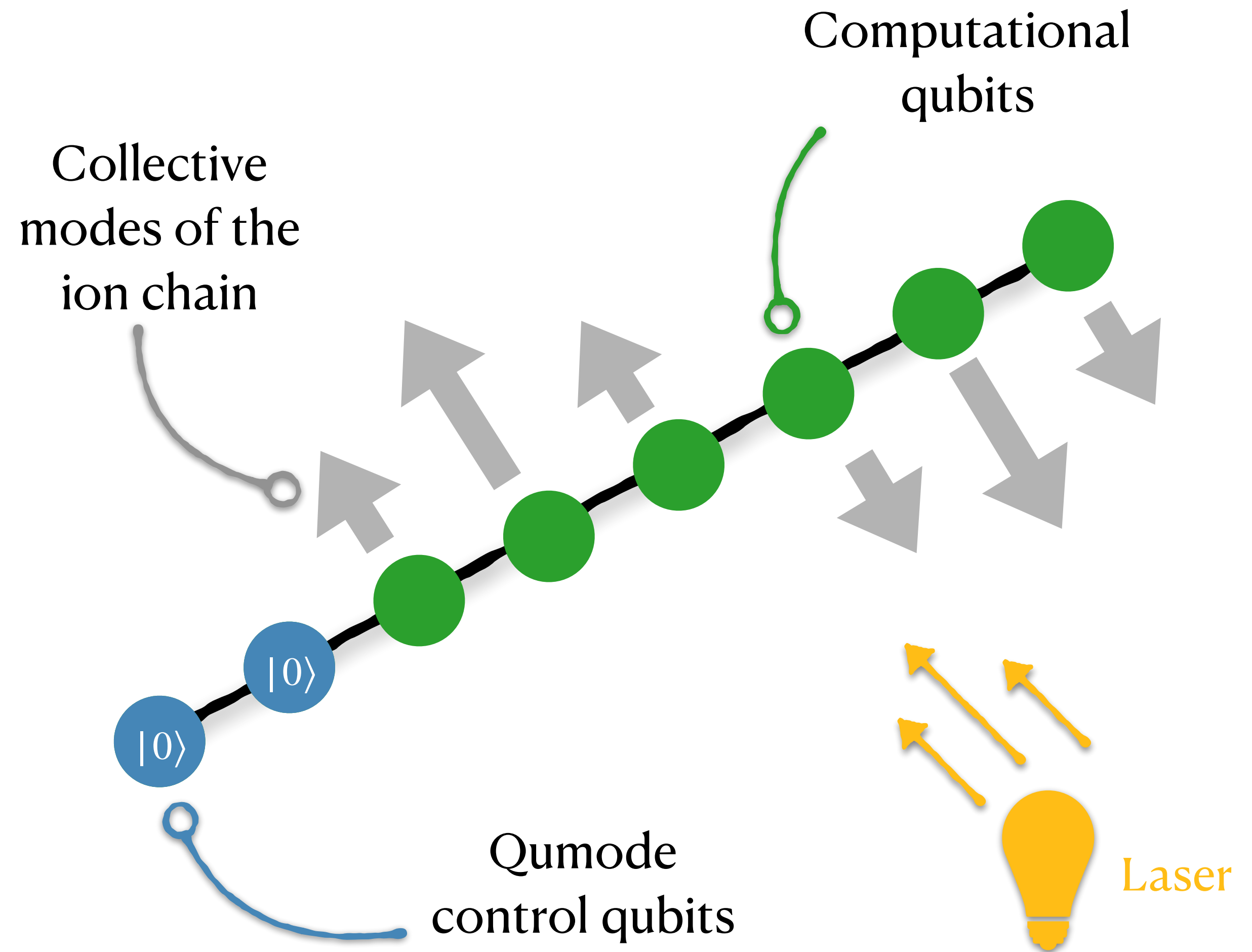
Qubits

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

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Qubits & Qumodes with trapped ions

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

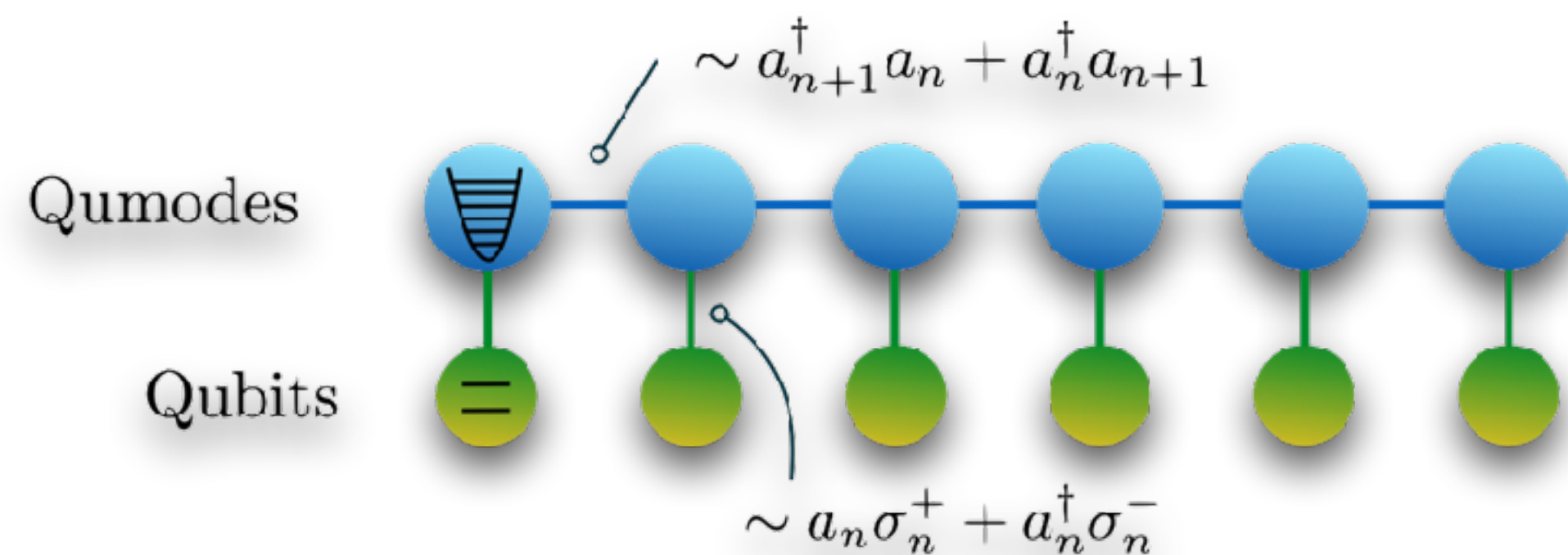
Type	Operation	Short	Operator	Estimated fidelity
Qubit gates	Pauli operators		σ^i	99.999%
	Rotation	$R_i(\theta)$	$e^{i\theta\sigma^i/2}$	99.999%
	Controlled NOT	CNOT	$e^{i\frac{\pi}{4}(\mathbb{I}_1 - \sigma_1^z)(\mathbb{I}_2 - \sigma_2^x)}$	99.9%
Qumode gates	Rotation	$R(\theta)$	$e^{i\theta\hat{a}^\dagger\hat{a}}$	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%†

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

Jaynes-Cummings-Hubbard model

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

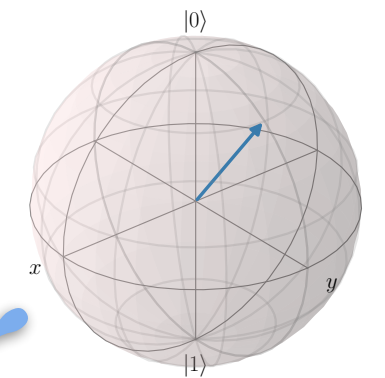
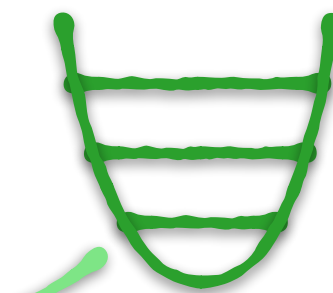
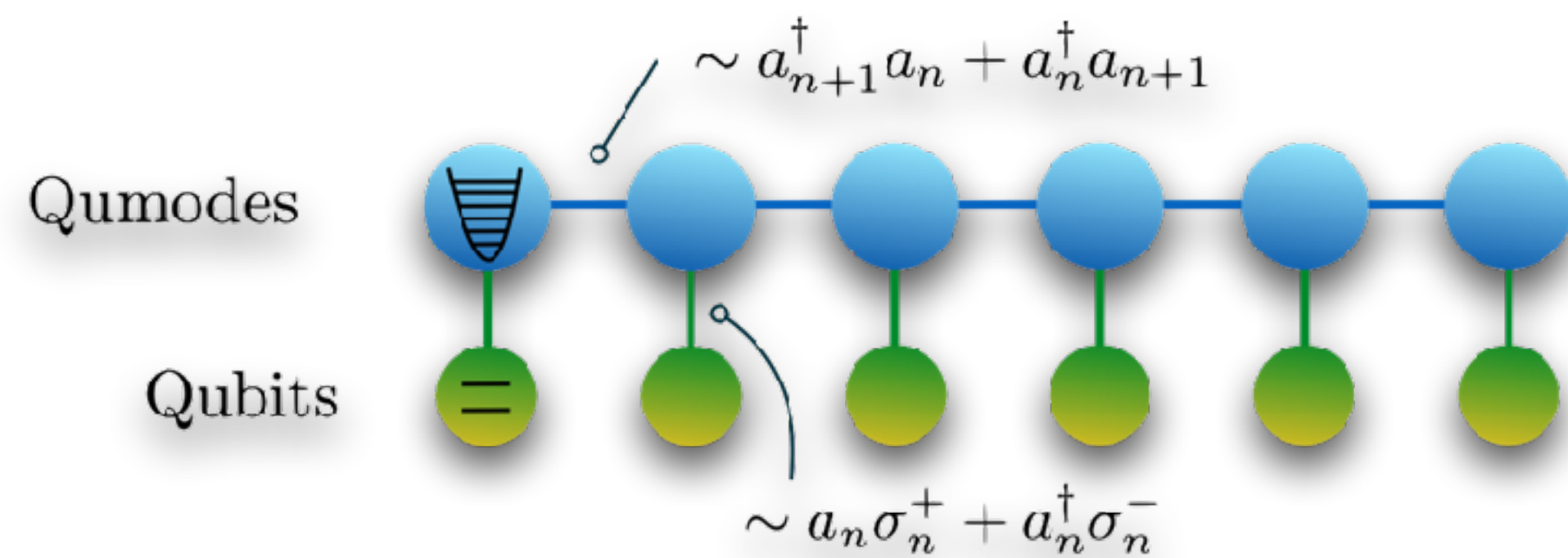
$$\hat{H} = \omega_c \sum_{n=1}^M \hat{a}_n^\dagger \hat{a}_n + \omega_a \sum_{n=1}^M \sigma_n^+ \sigma_n^- - \kappa \sum_{n=1}^M \left(\hat{a}_{n+1}^\dagger \hat{a}_n + \hat{a}_n^\dagger \hat{a}_{n+1} \right) + \eta \sum_{n=1}^N \left(\hat{a}_n \sigma_n^+ + \hat{a}_n^\dagger \sigma_n^- \right)$$



Jaynes-Cummings-Hubbard model

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

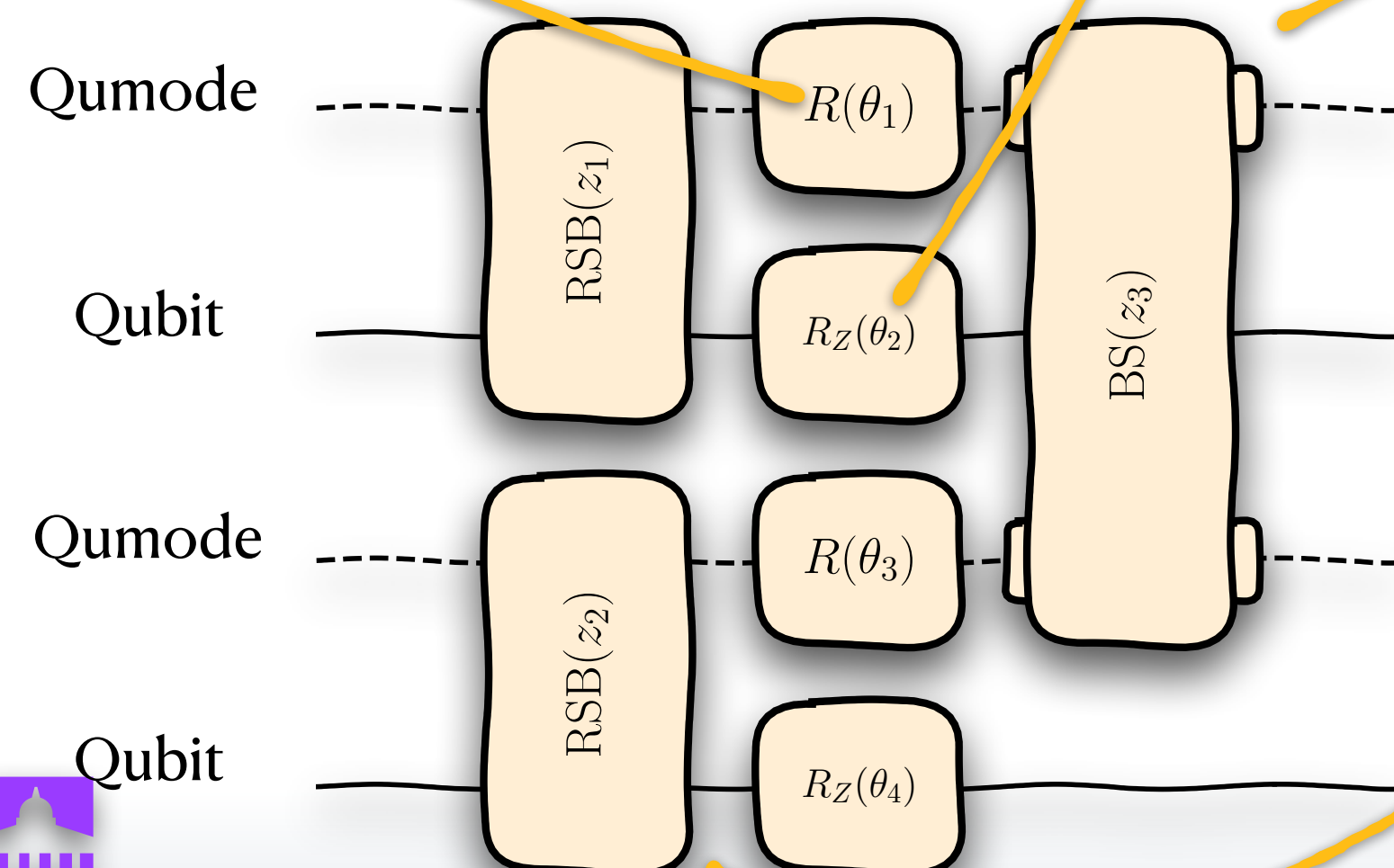
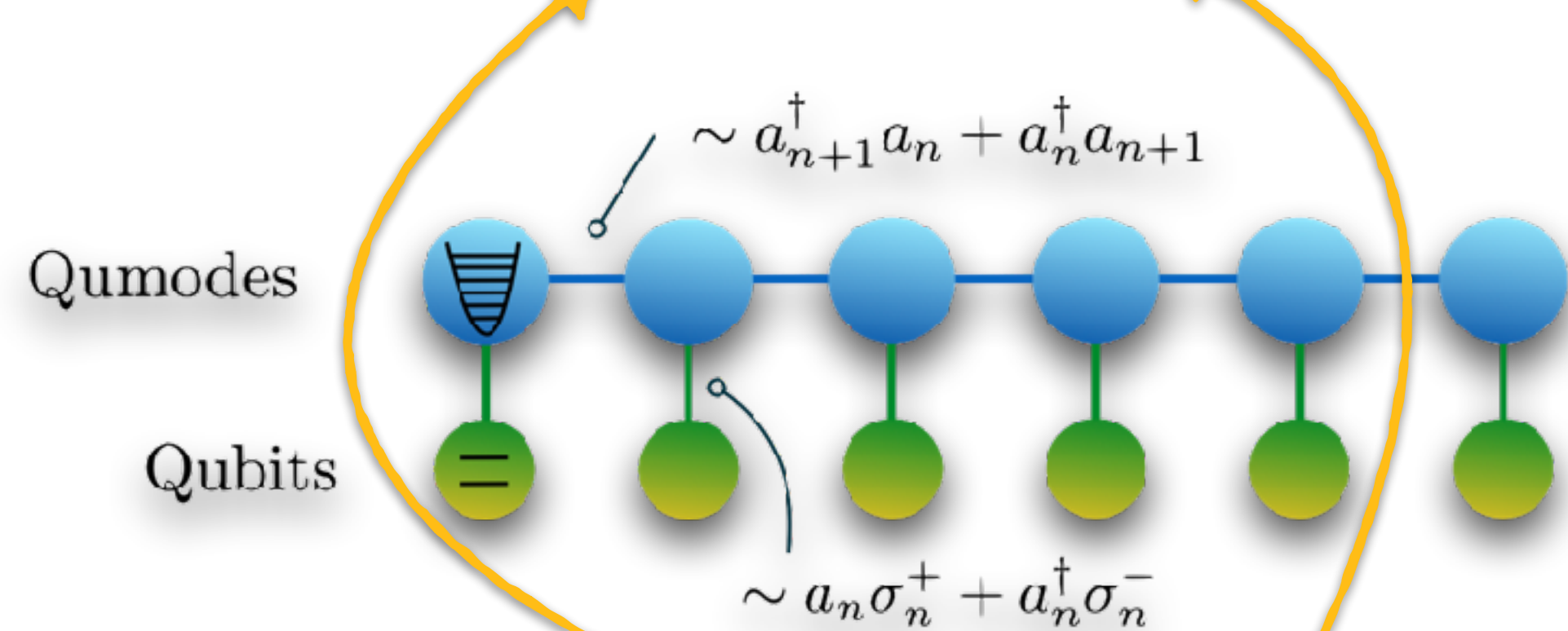
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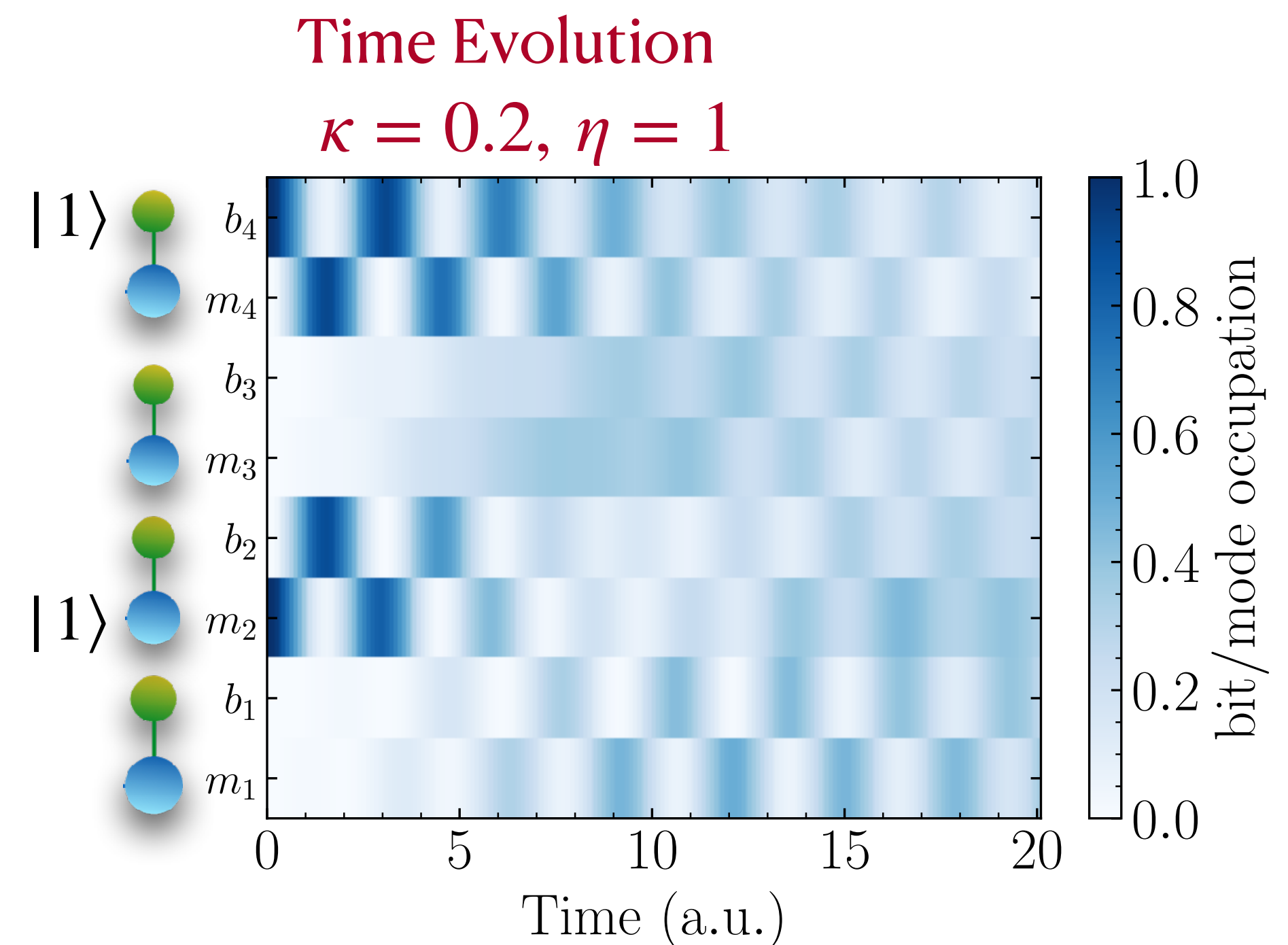
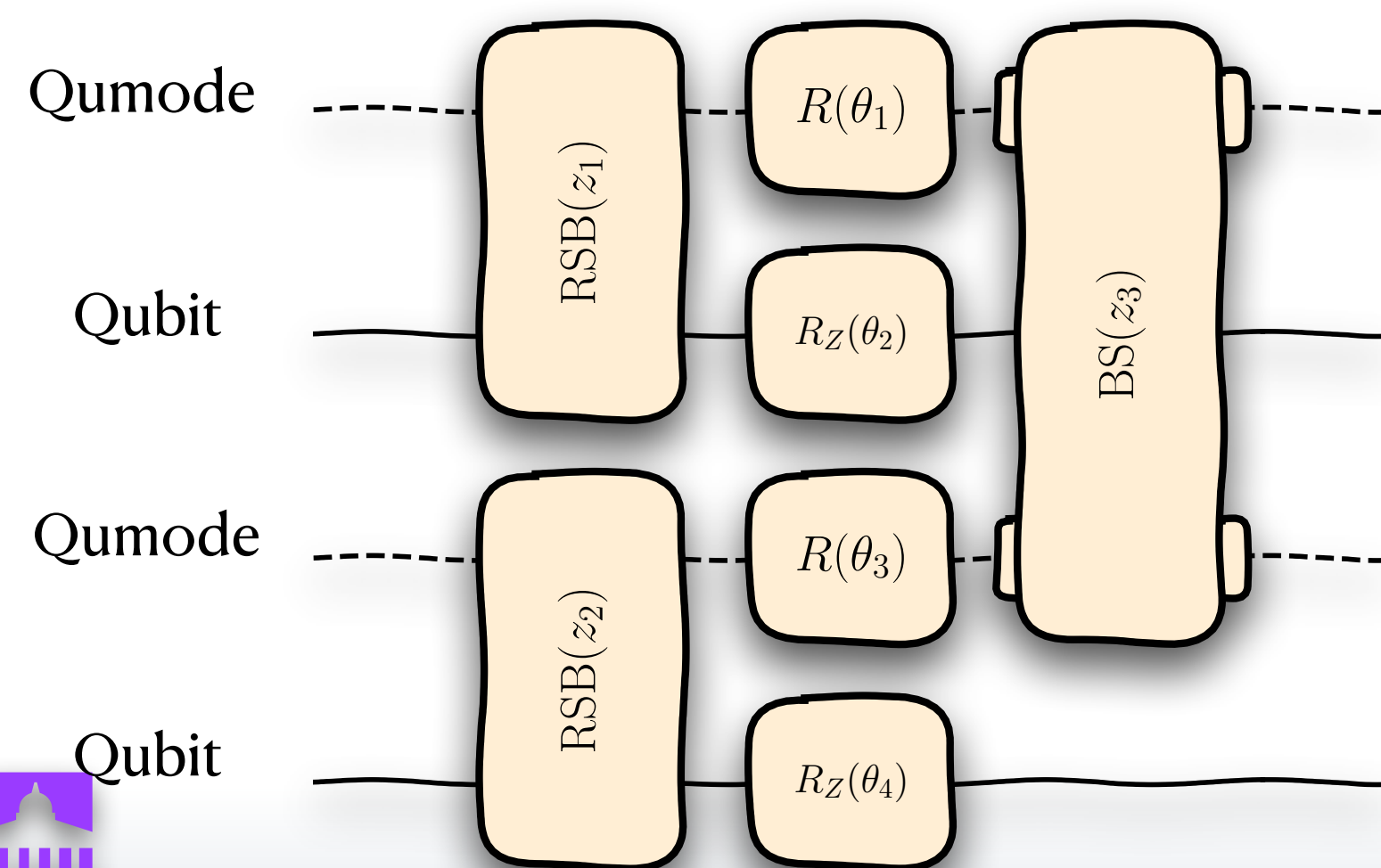
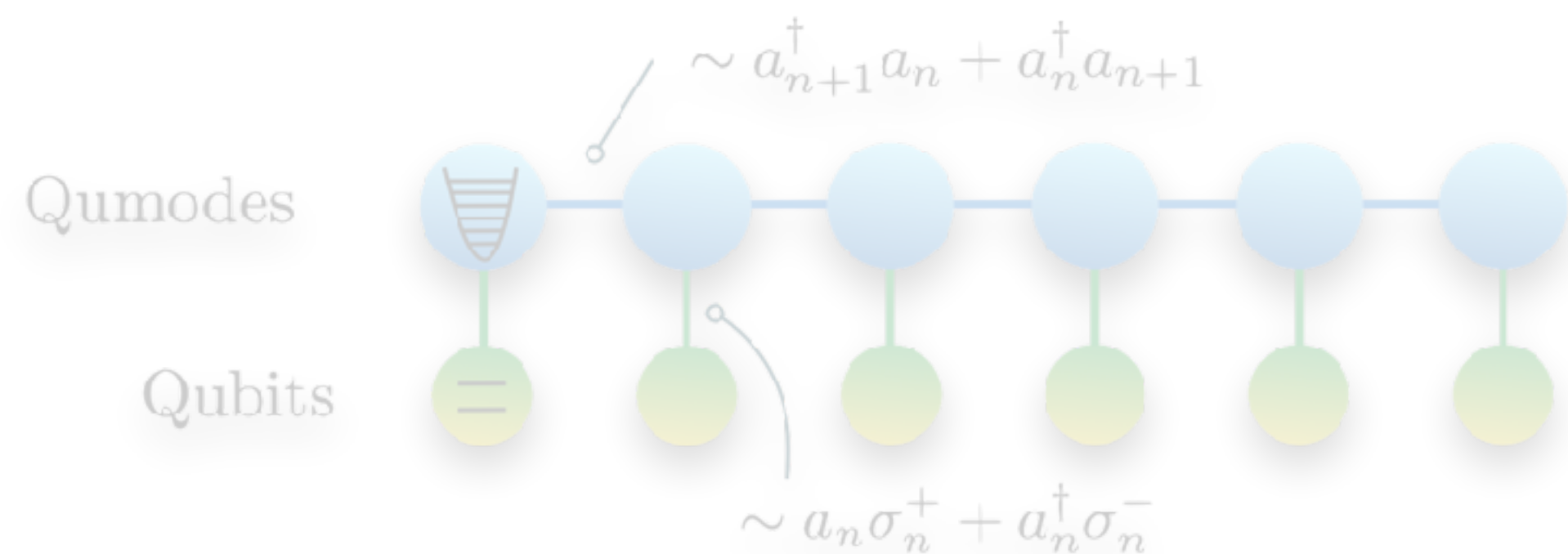
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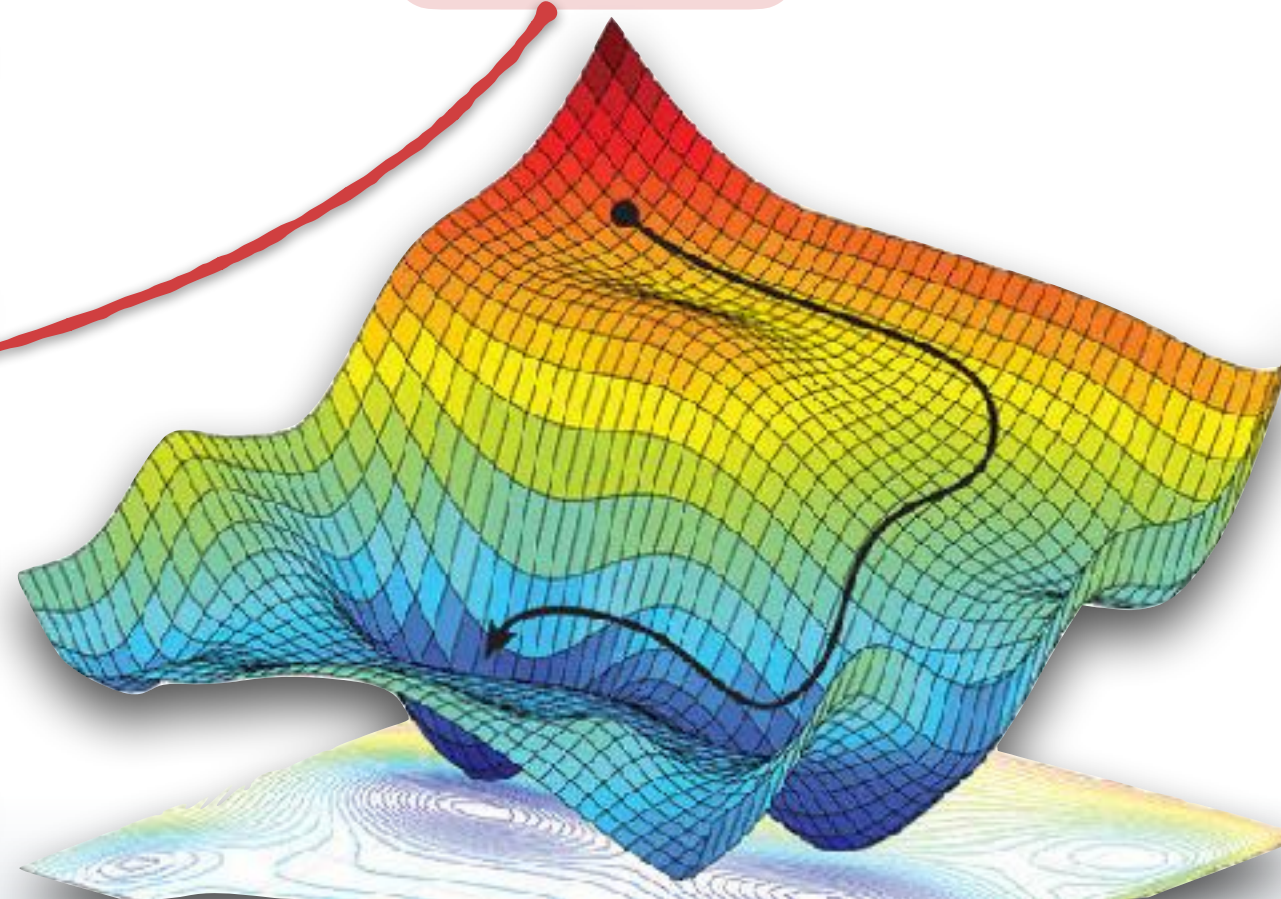
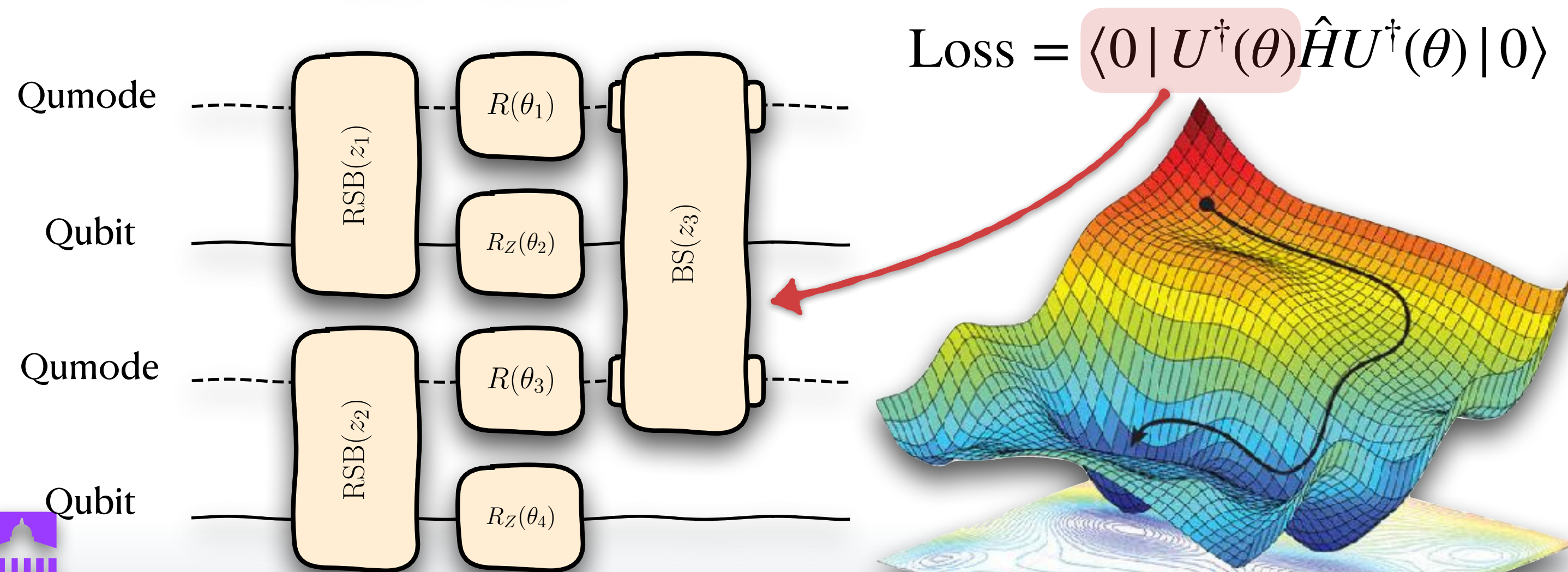
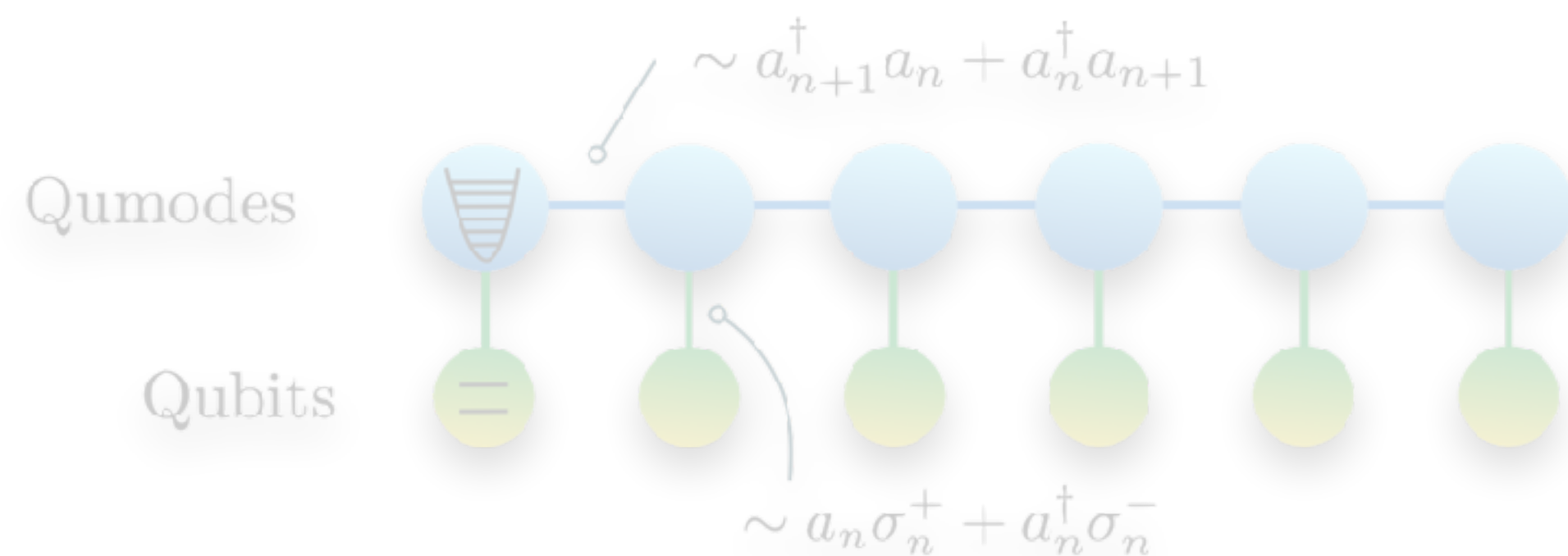
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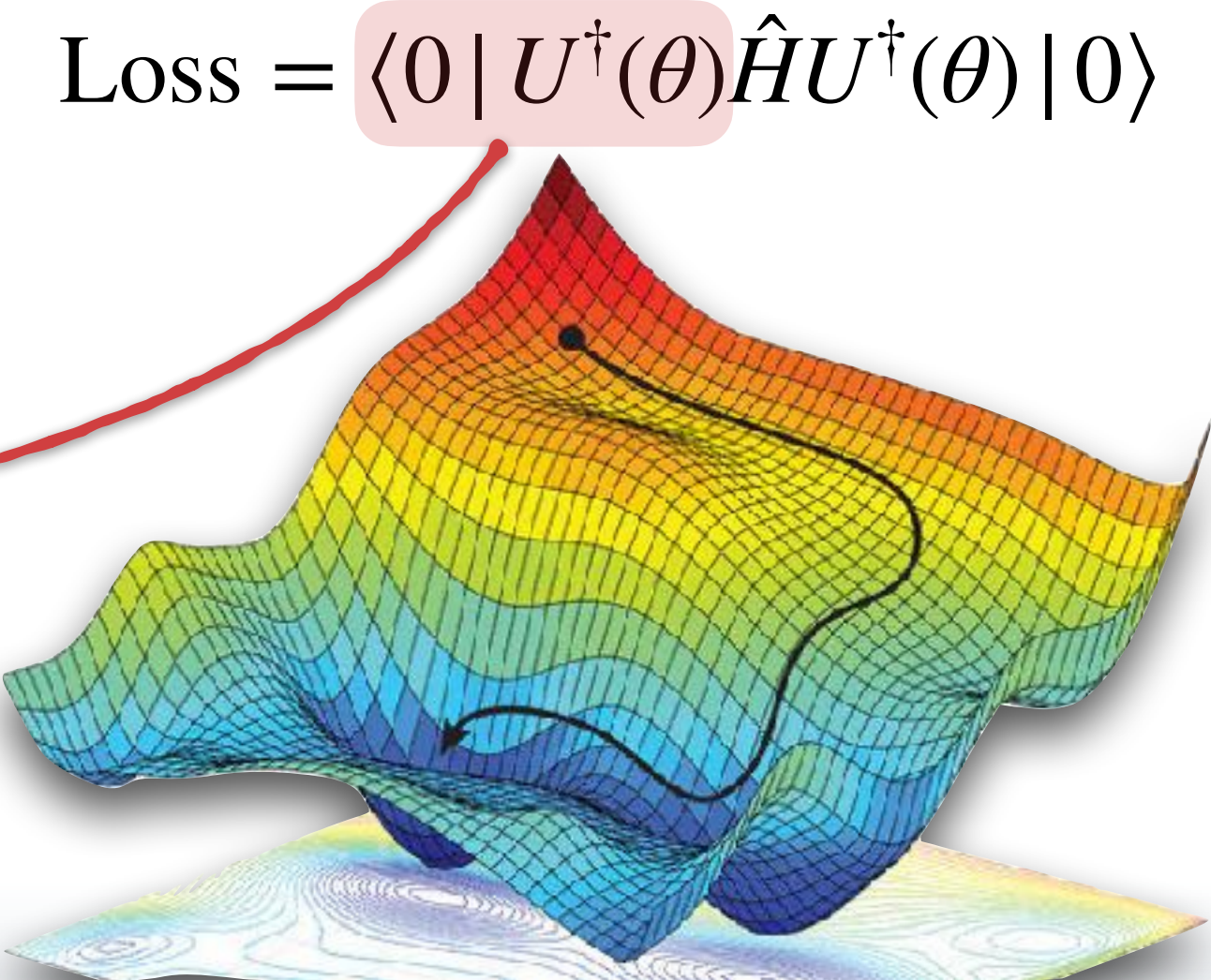
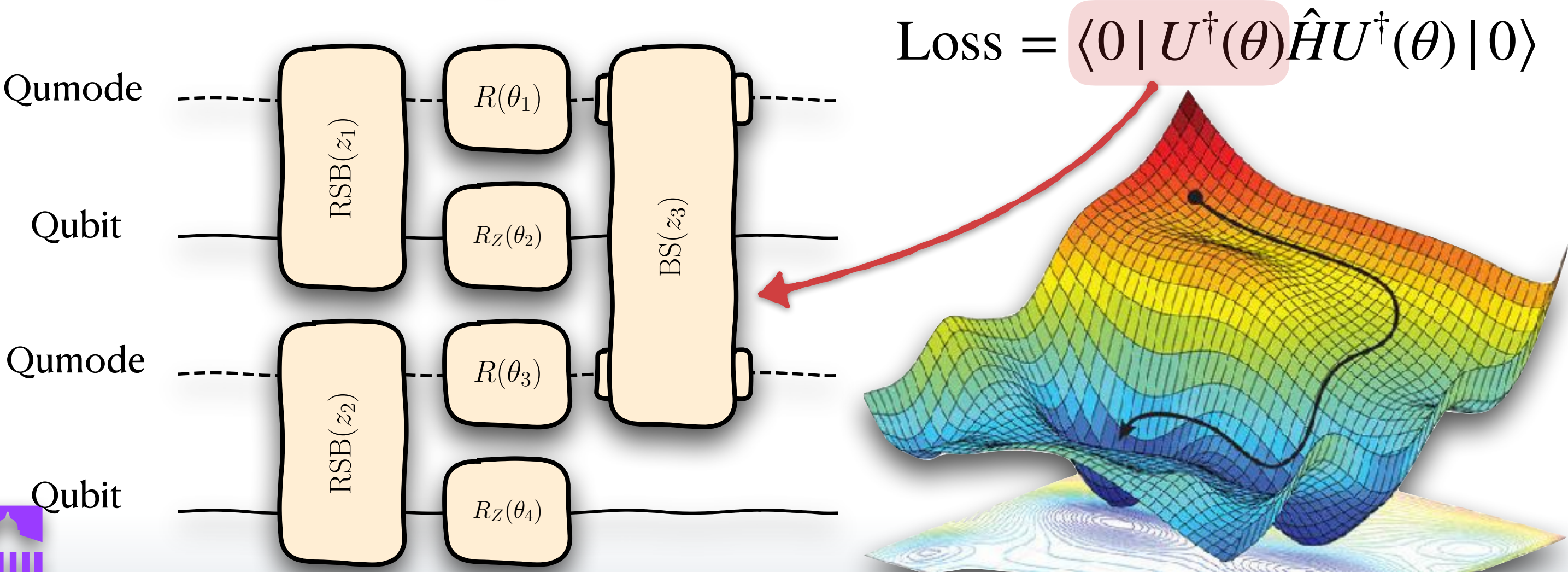
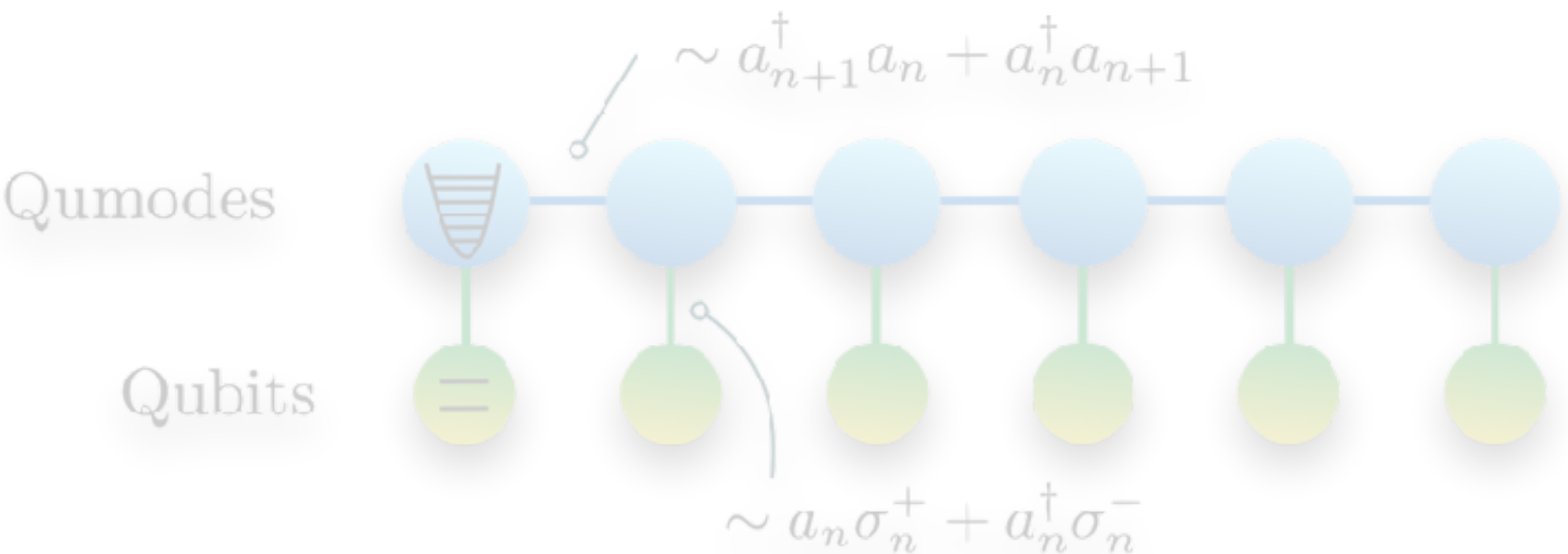


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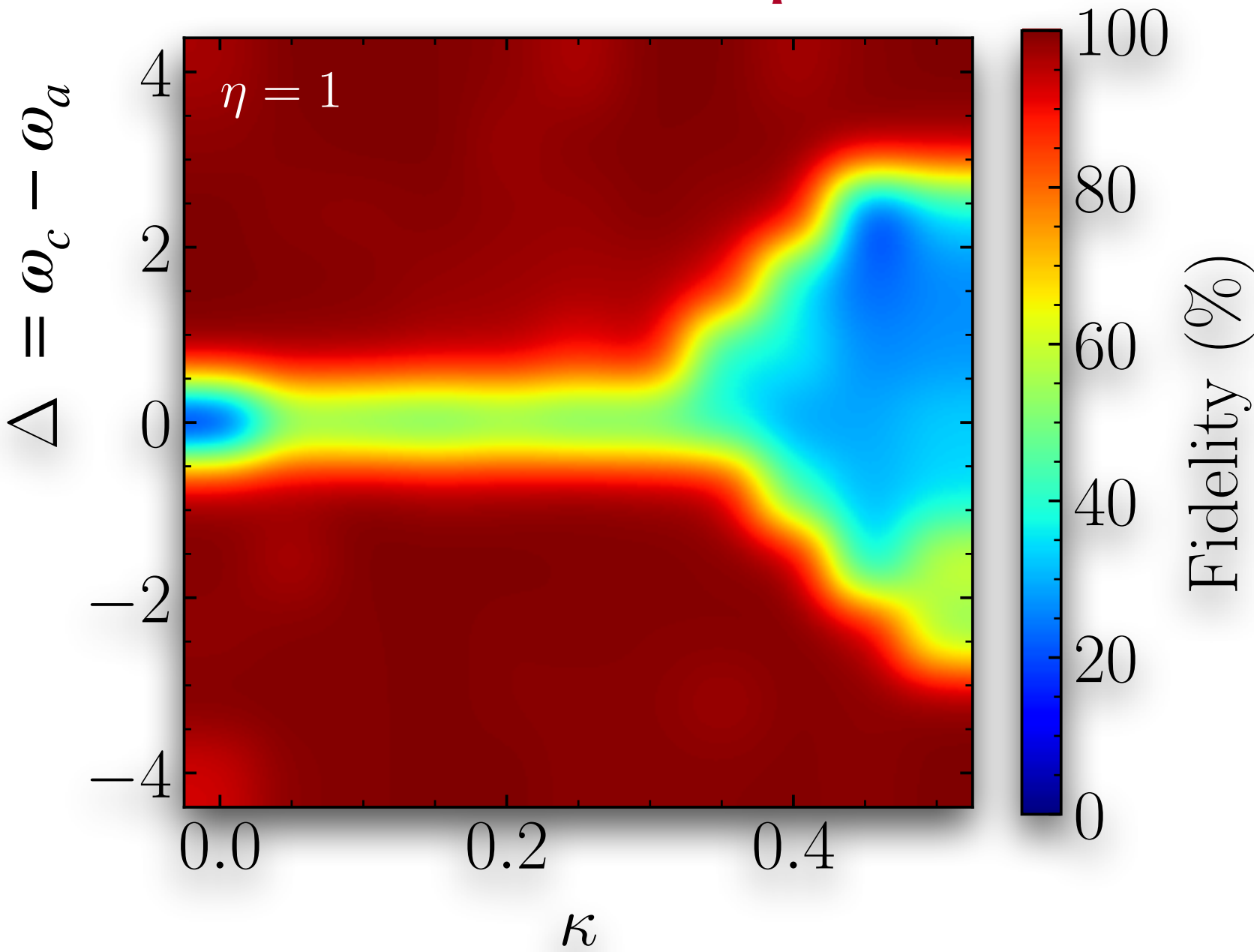
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Variational State Preparation



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Do we really need qumodes? Spoiler: YES!

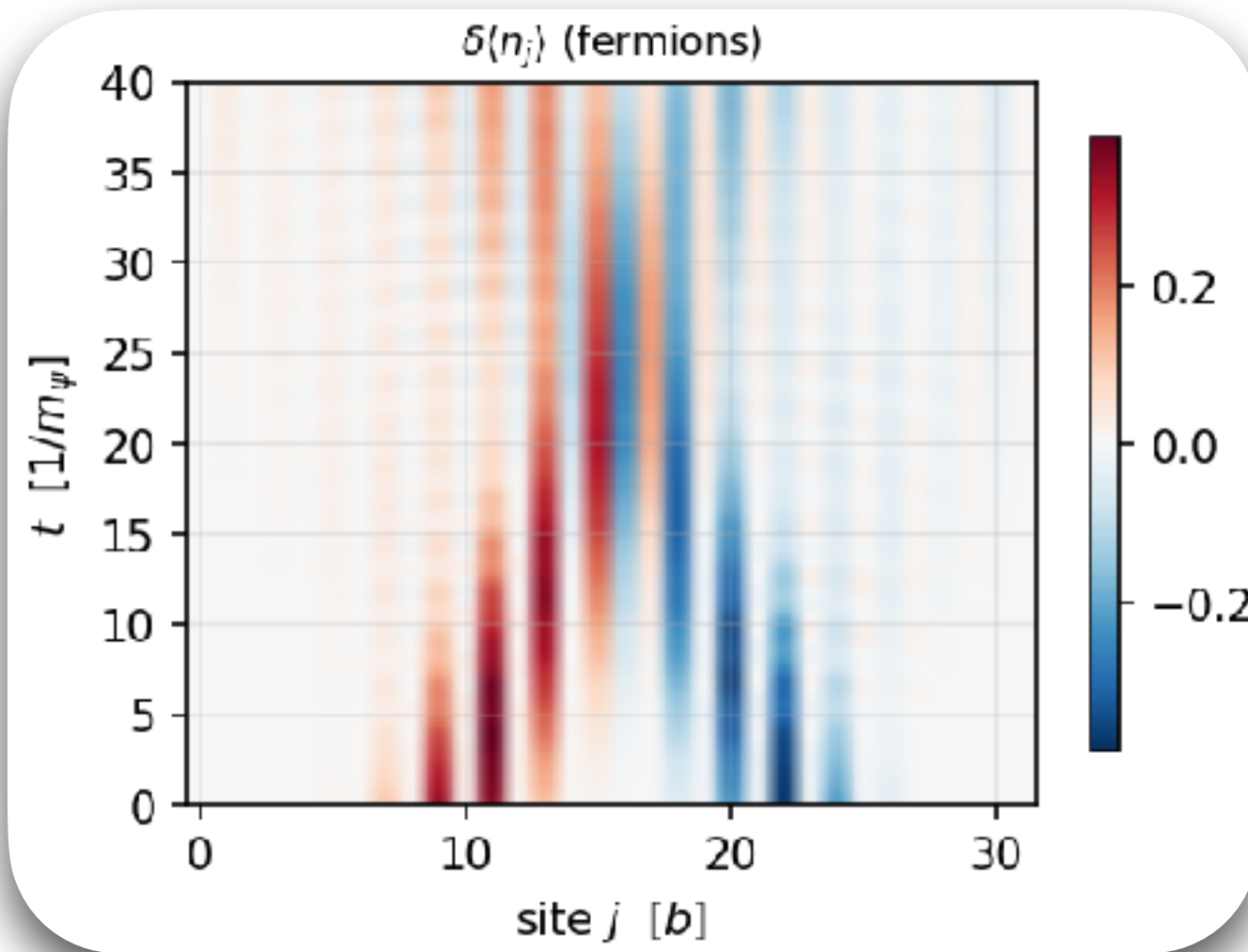
$$H_{\text{Yuk}} = \underbrace{\sum_{j=1}^N \left[\frac{i}{2b} (\psi_j^\dagger \psi_{j+1} - \psi_{j+1}^\dagger \psi_j) + m_\psi (-1)^j \psi_j^\dagger \psi_j \right]}_{\text{Fermions}} + \underbrace{b \sum_{j=1}^N \left[\frac{\Pi_j^2}{2} + \frac{(\nabla \varphi_j)^2}{2} + \frac{m_\varphi^2}{2} \varphi_j^2 \right]}_{\text{Scalar field}} + \underbrace{gb \sum_{j=1}^N \psi_j^\dagger \varphi_j \psi_j}_{\text{Fermion-Scalar Interaction}}$$

[JYA, Forshaw, Jenkinson; in prep.]

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Scalar field
Fermion-Scalar Interaction



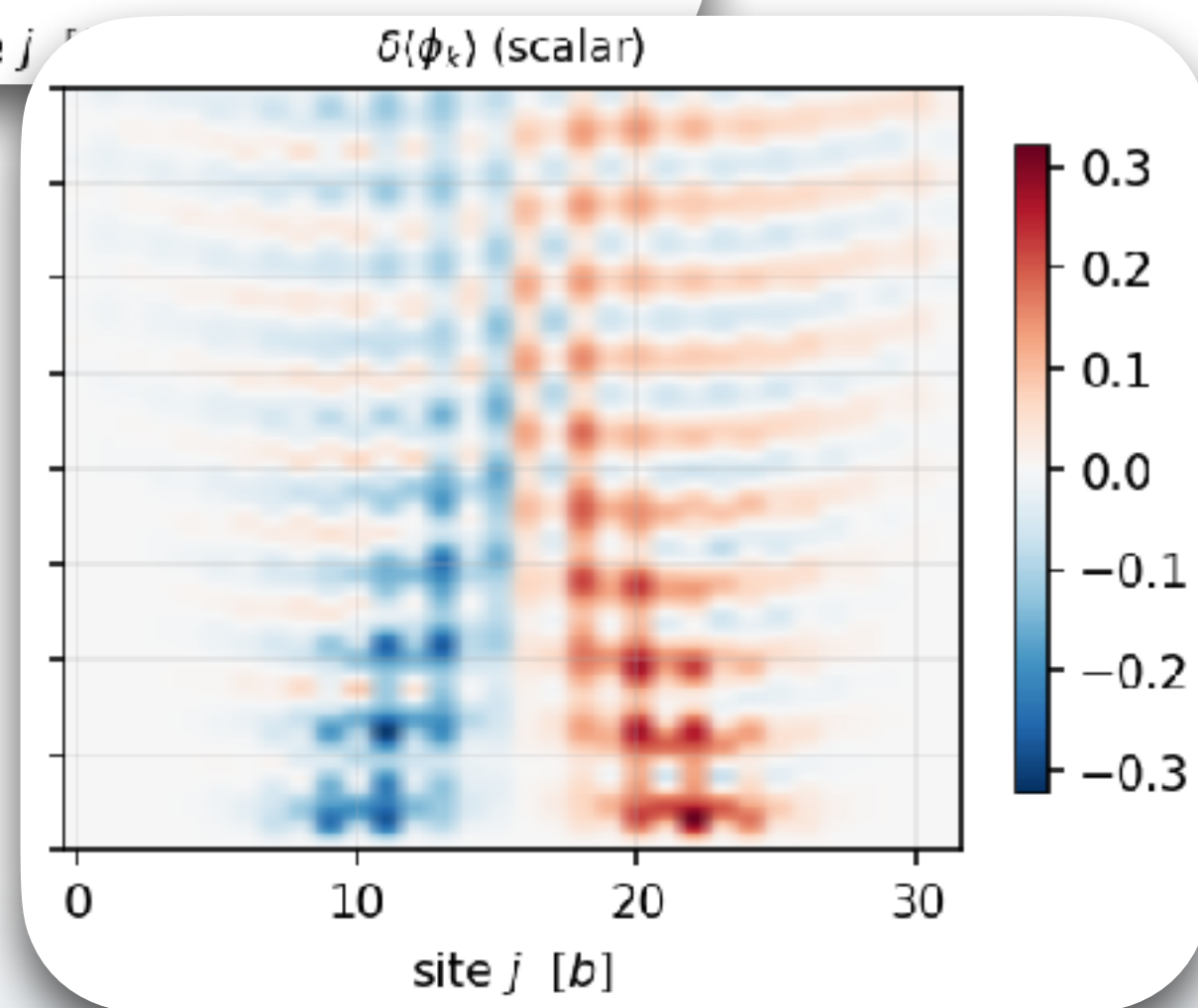
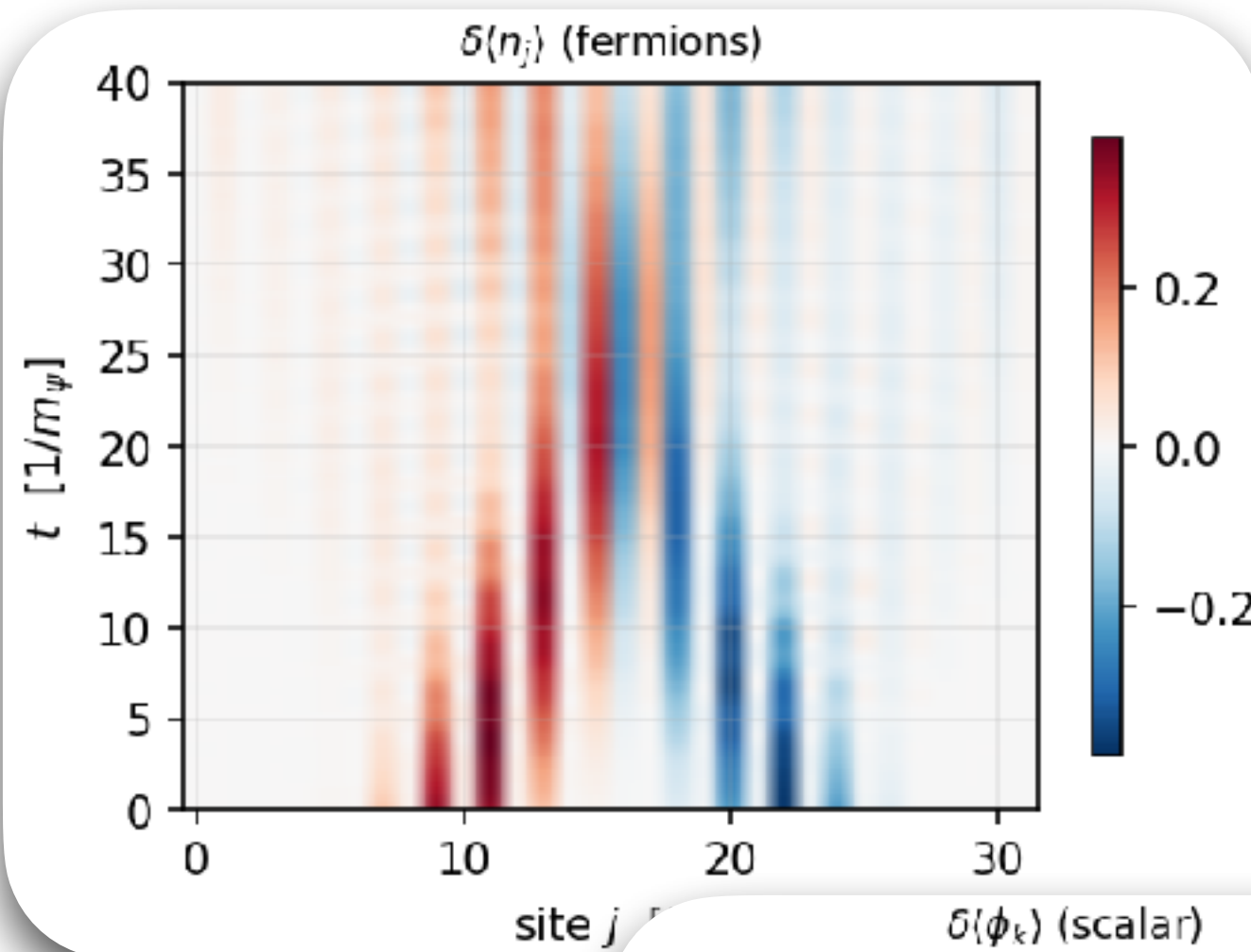
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Scalar field
Fermion-Scalar Interaction

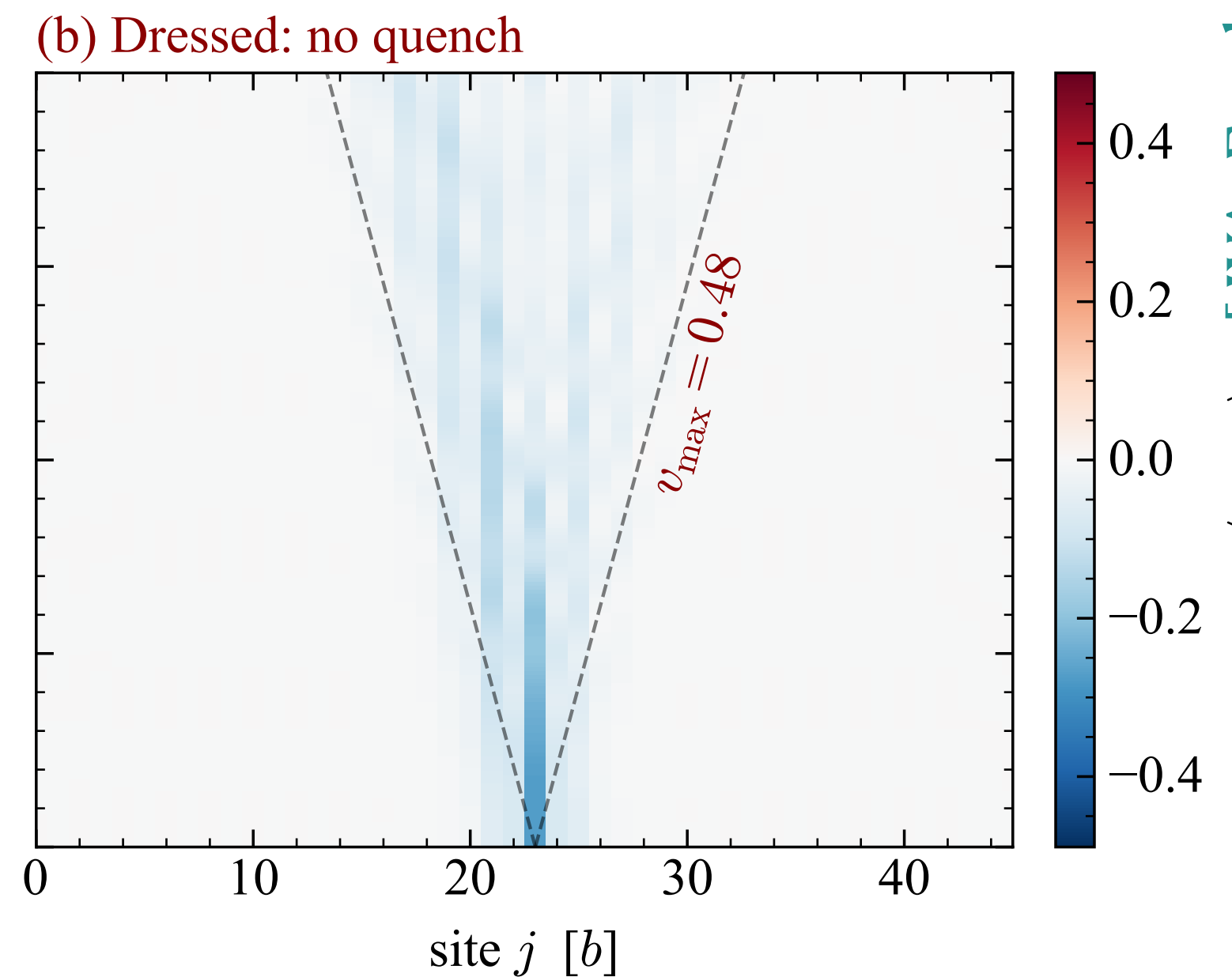
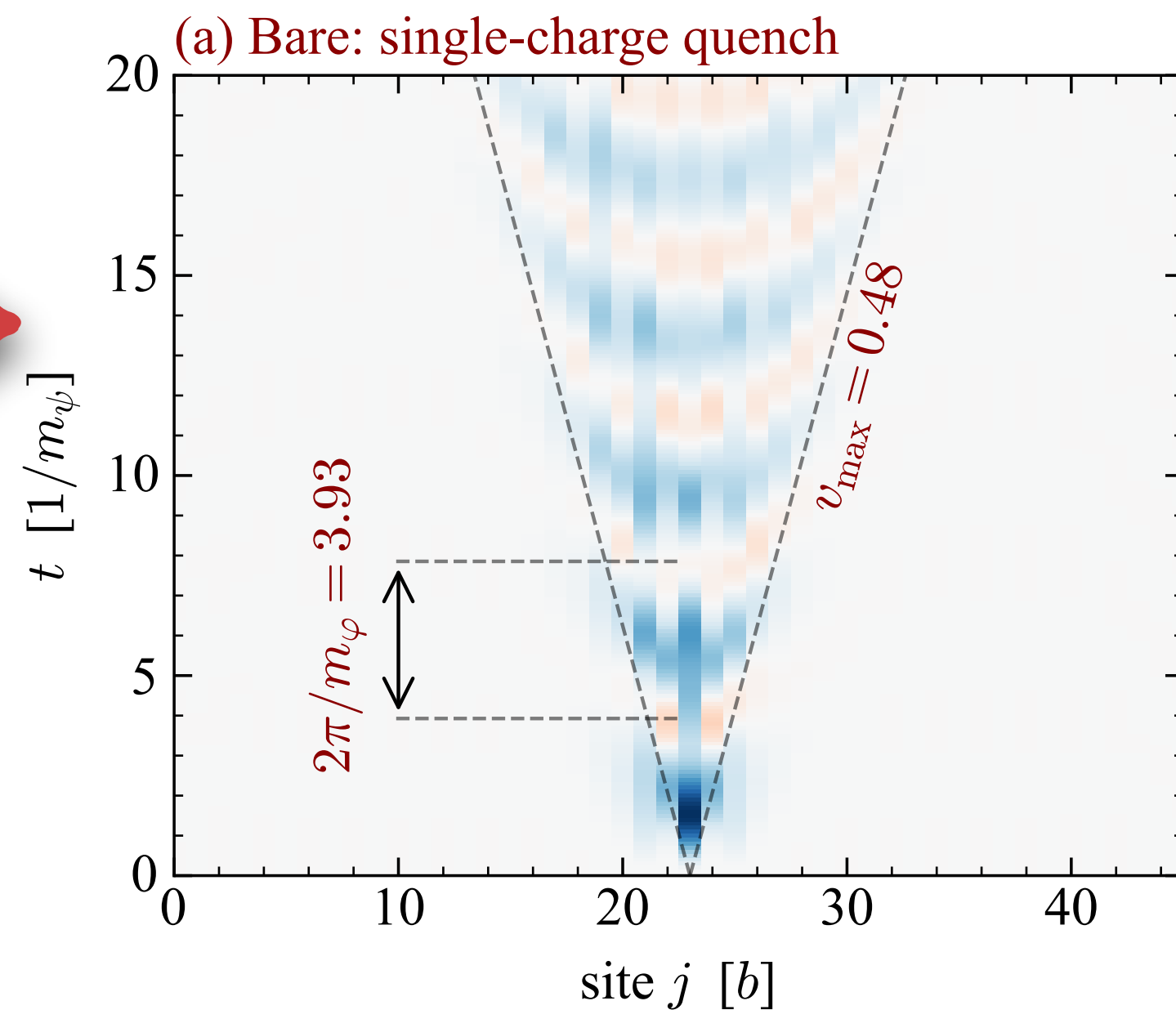
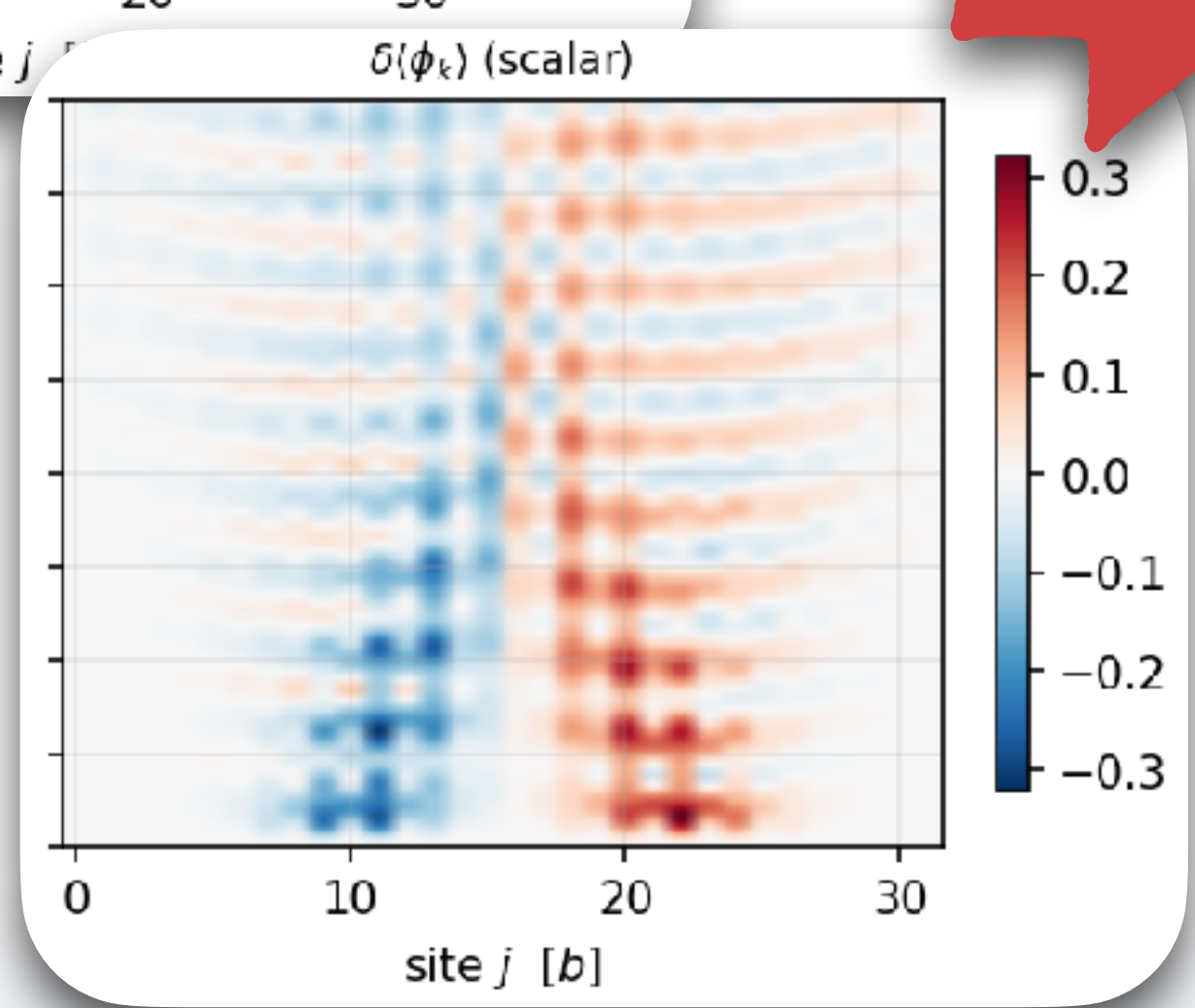
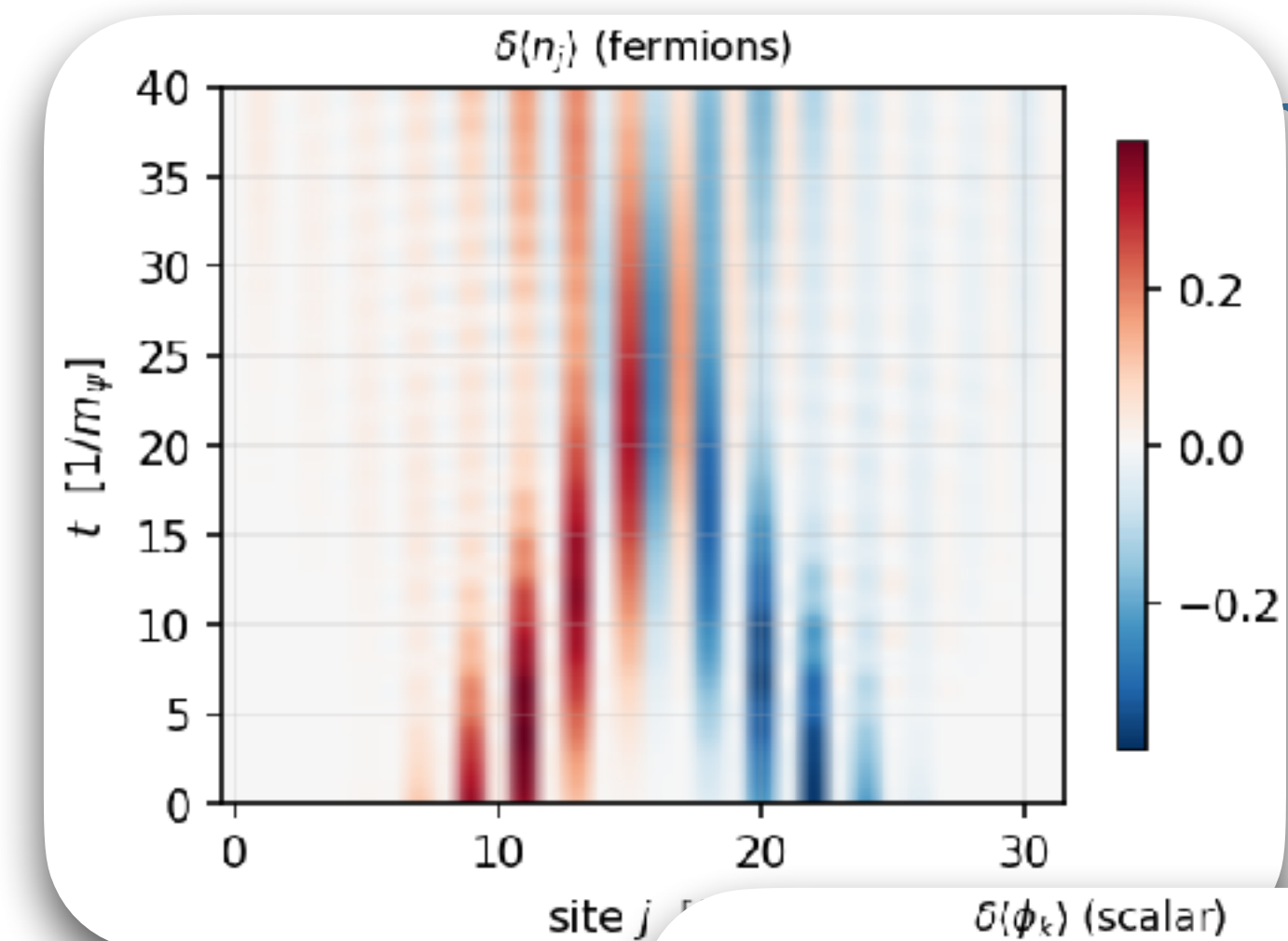
[JYA, Forshaw, Jenkinson; in prep.]



Do we really need qumodes? Spoiler: YES!

$$H_{\text{Yuk}} = \sum_{j=1}^N \left[\frac{i}{2b} (\psi_j^\dagger \psi_{j+1} - \psi_{j+1}^\dagger \psi_j) + m_\psi (-1)^j \psi_j^\dagger \psi_j \right] + b \sum_{j=1}^N \left[\frac{\Pi_j^2}{2} + \frac{(\nabla \phi_j)^2}{2} + \frac{m_\phi^2}{2} \phi_j^2 \right] + gb \sum_{j=1}^N \psi_j^\dagger \phi_j \psi_j$$

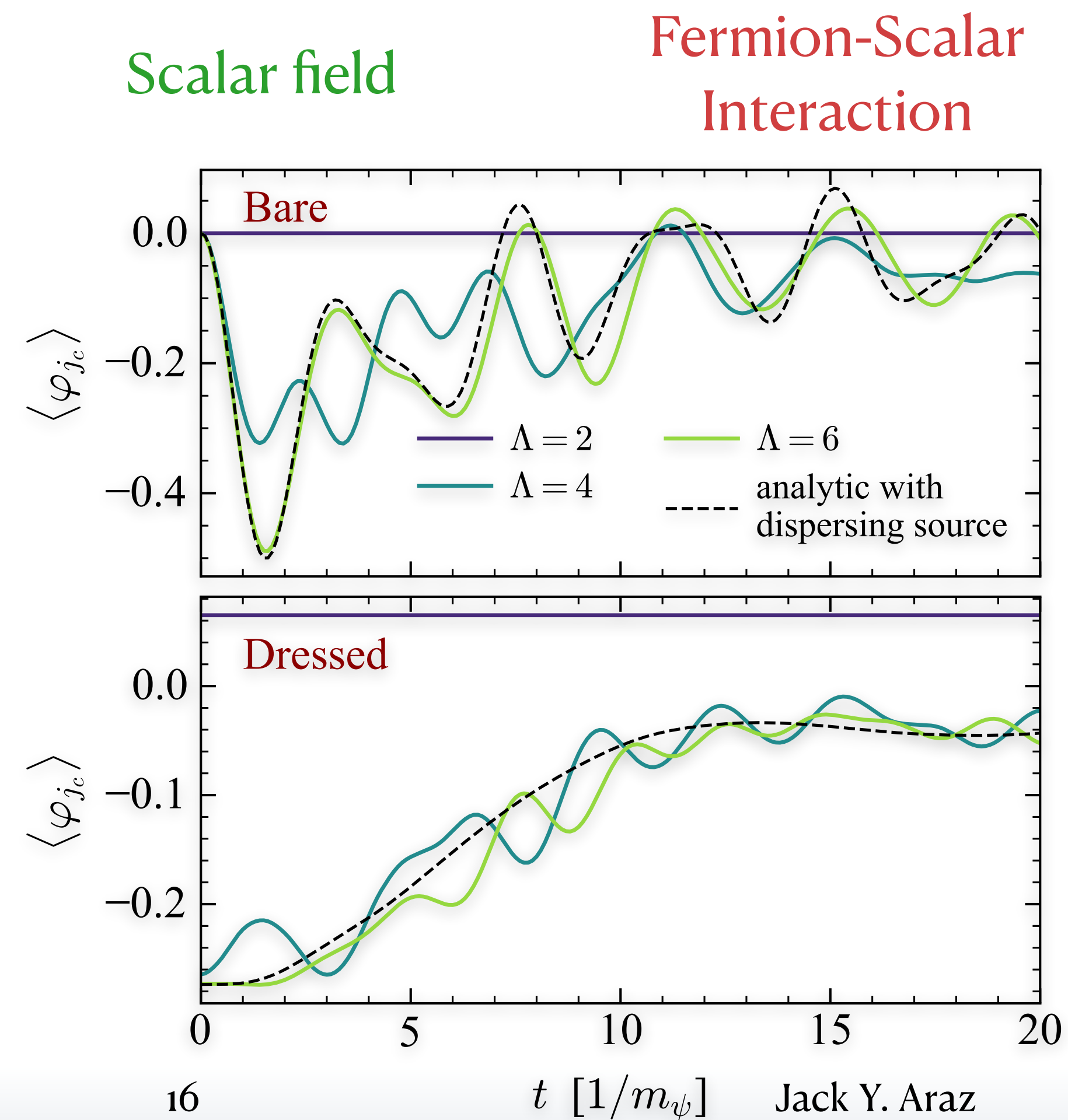
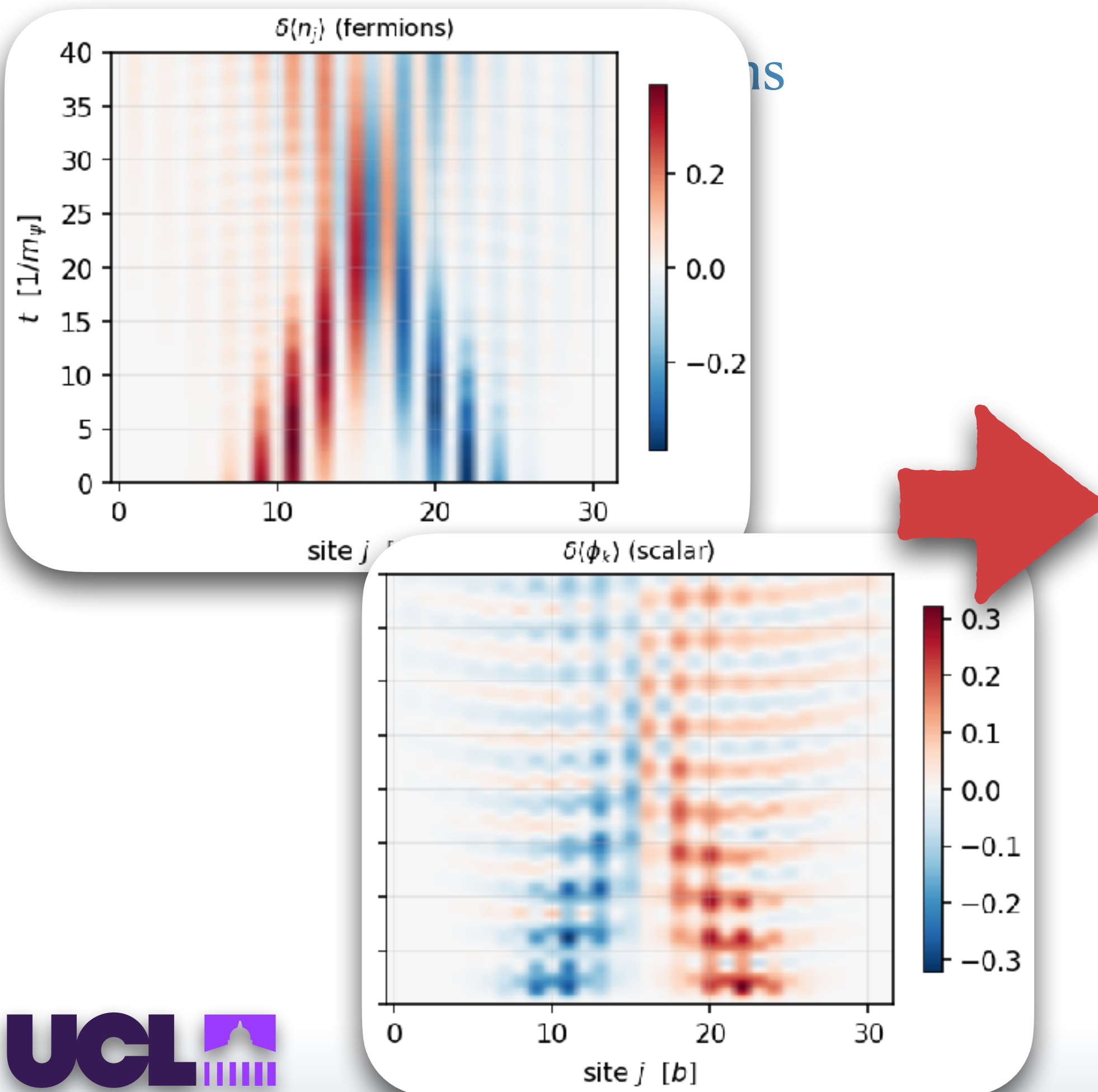
Scalar field
Fermion-Scalar Interaction



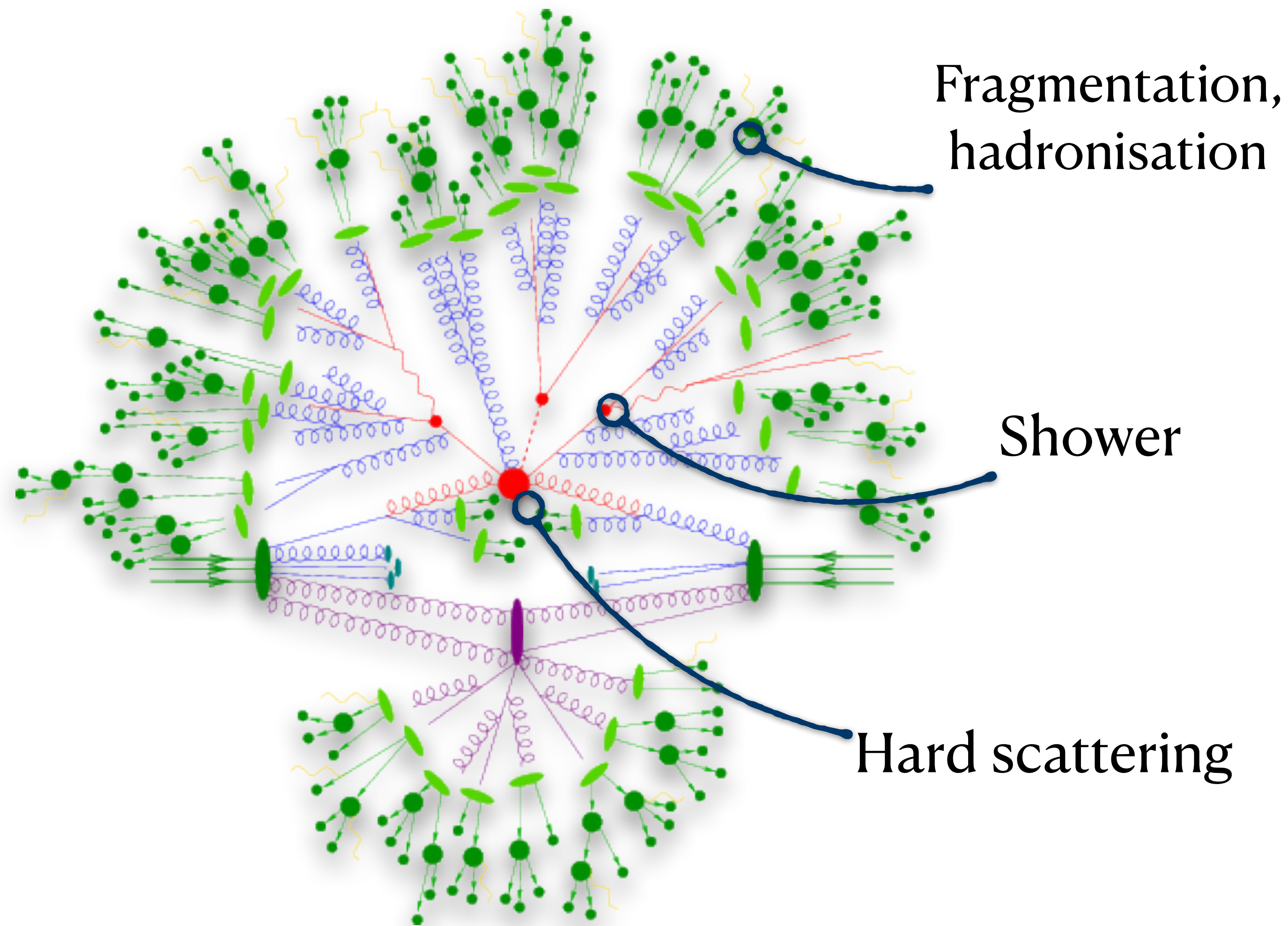
[JYA, Forshaw, Jenkinson; in prep.]

Do we really need qumodes? Spoiler: YES!

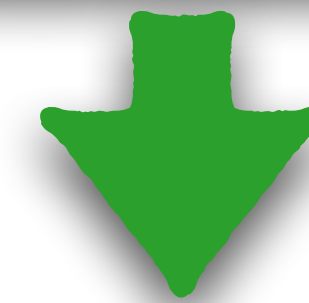
$$H_{\text{Yuk}} = \sum_{j=1}^N \left[\frac{i}{2b} (\psi_j^\dagger \psi_{j+1} - \psi_{j+1}^\dagger \psi_j) + m_\psi (-1)^j \psi_j^\dagger \psi_j \right] + b \sum_{j=1}^N \left[\frac{\Pi_j^2}{2} + \frac{(\nabla \phi_j)^2}{2} + \frac{m_\phi^2}{2} \phi_j^2 \right] + gb \sum_{j=1}^N \psi_j^\dagger \phi_j \psi_j$$



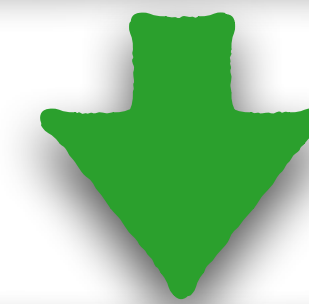
Towards simulating the scattering process



State Preparation
(Wave packet)



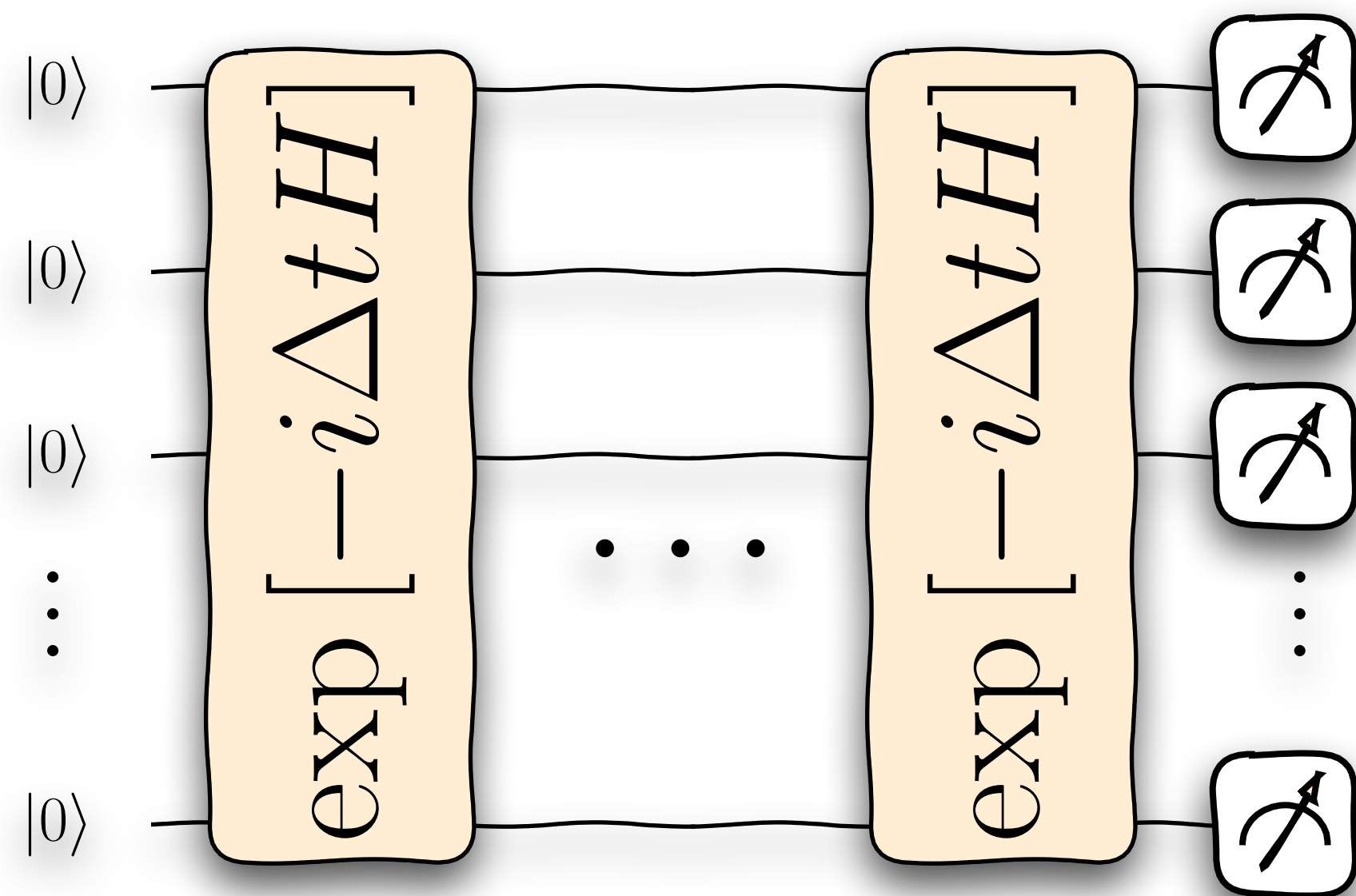
Time evolution



Measuring an interesting
observable, e.g. two
body correlation

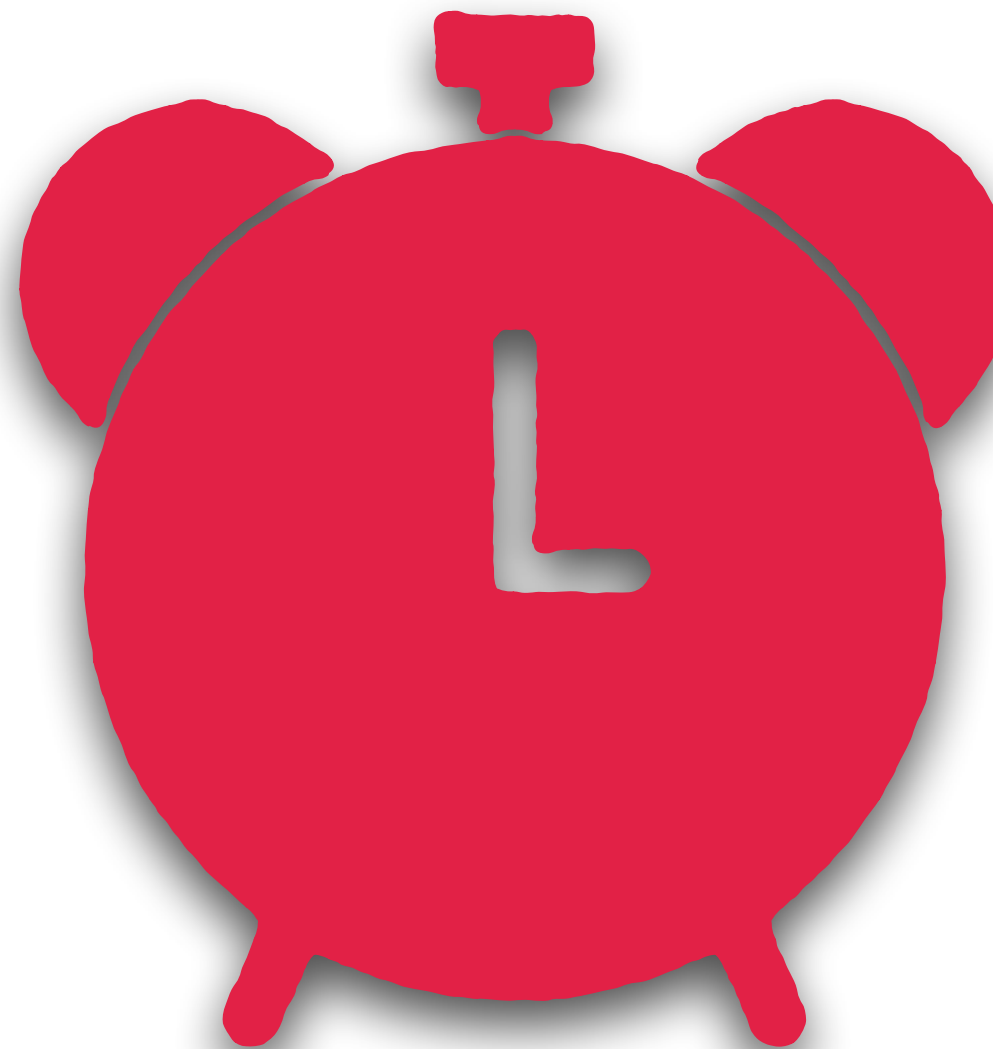
But...

Time Evolution or Adiabatic
State Preparation

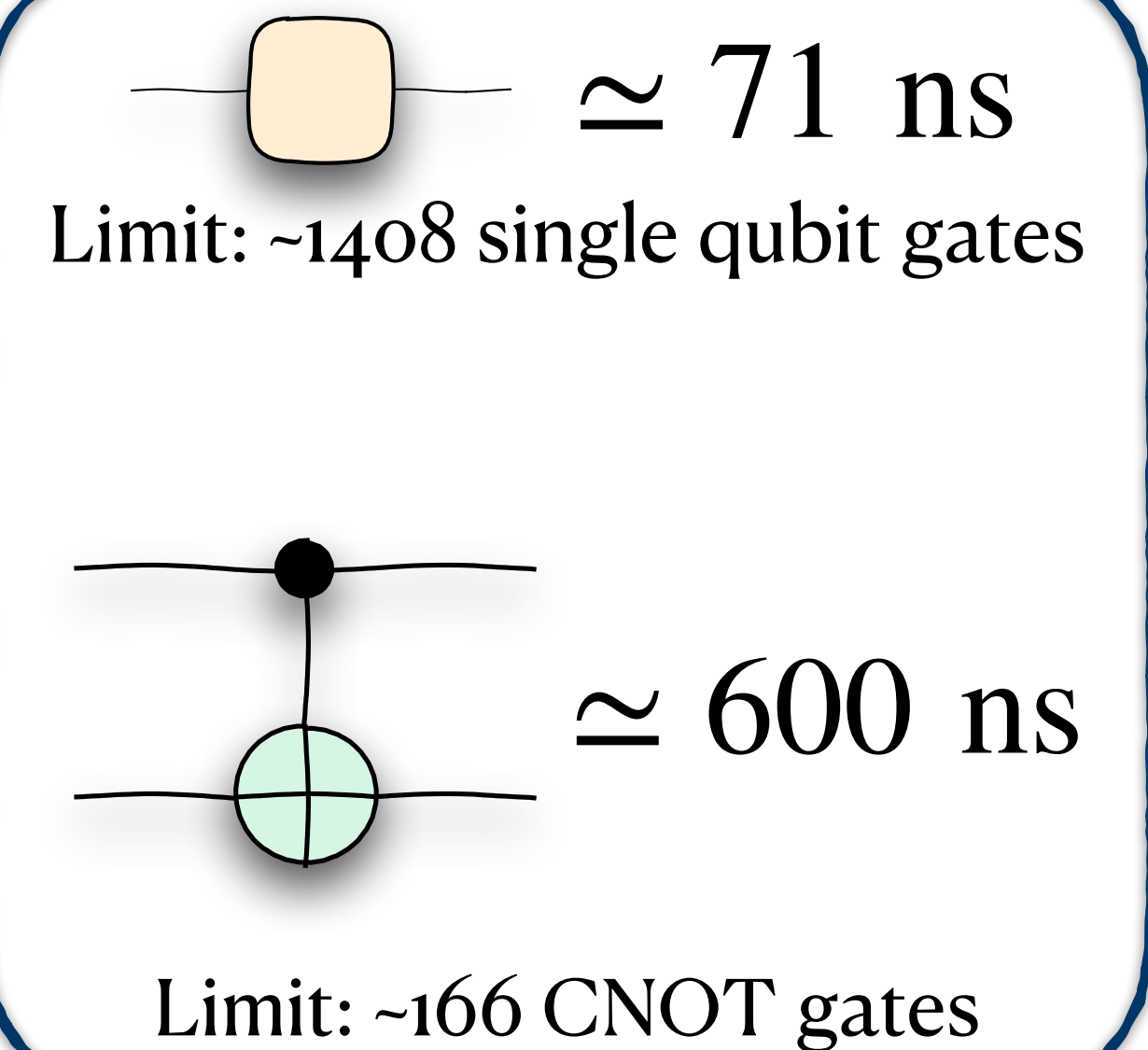


$$e^{-iTH} \simeq \prod^N e^{-i\Delta t H}$$

Short Coherence Time

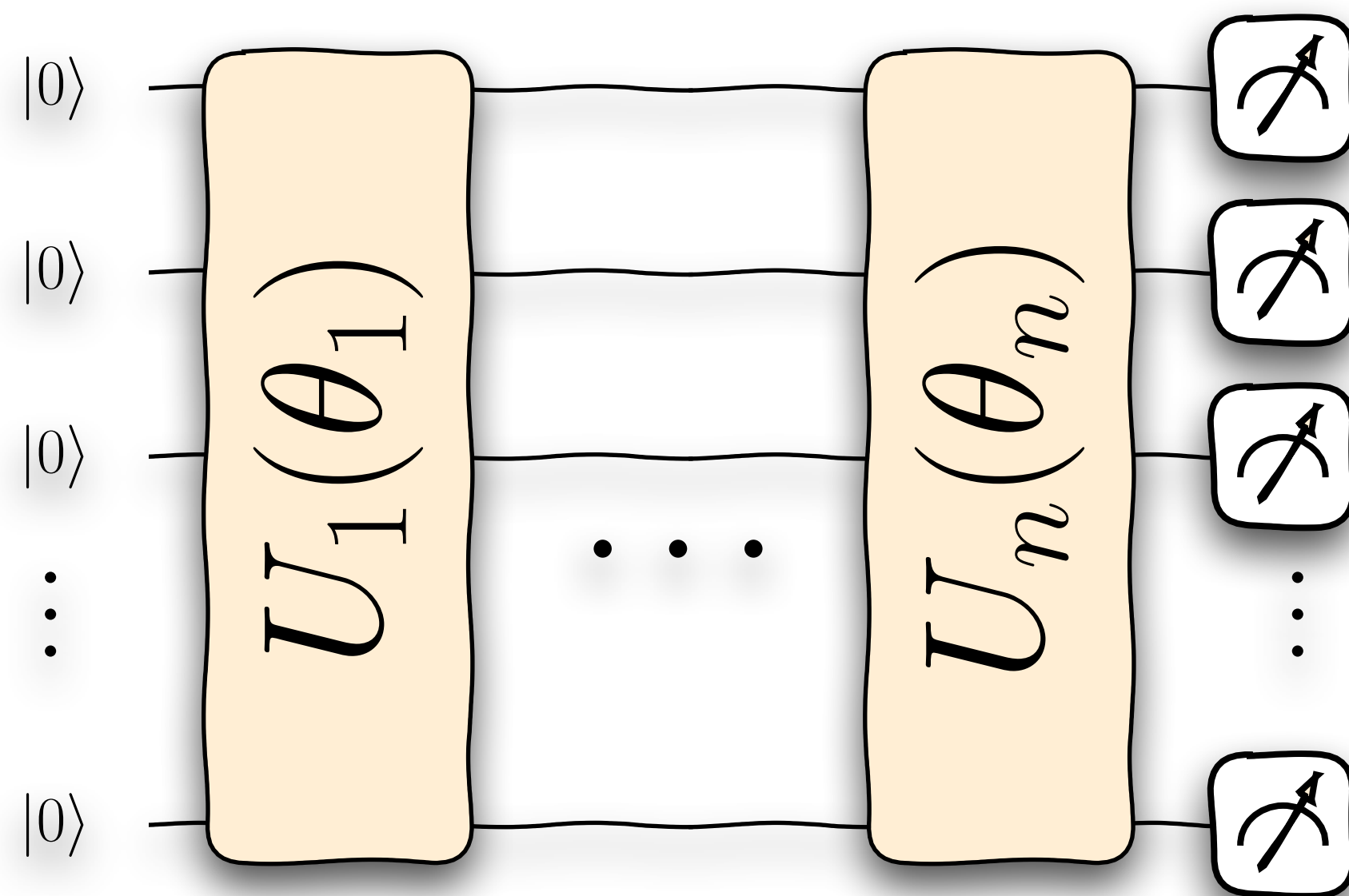


Typical coherence time for an IBM
superconducting qubit is 50 to 100
microsecond



But...

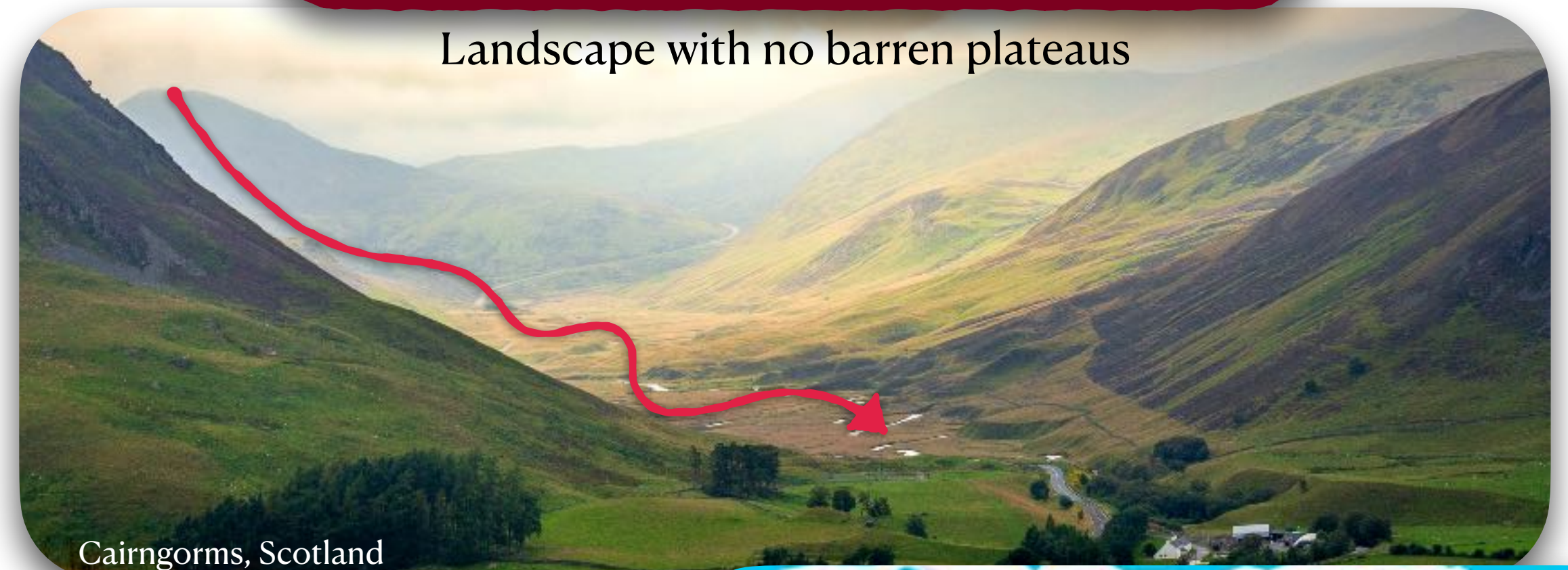
State Preparation with VQE



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

Barren Plateaus

Landscape with no barren plateaus



Cairngorms, Scotland

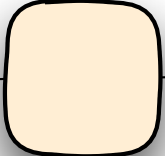
August 2021, taken after
getting lost for 4h

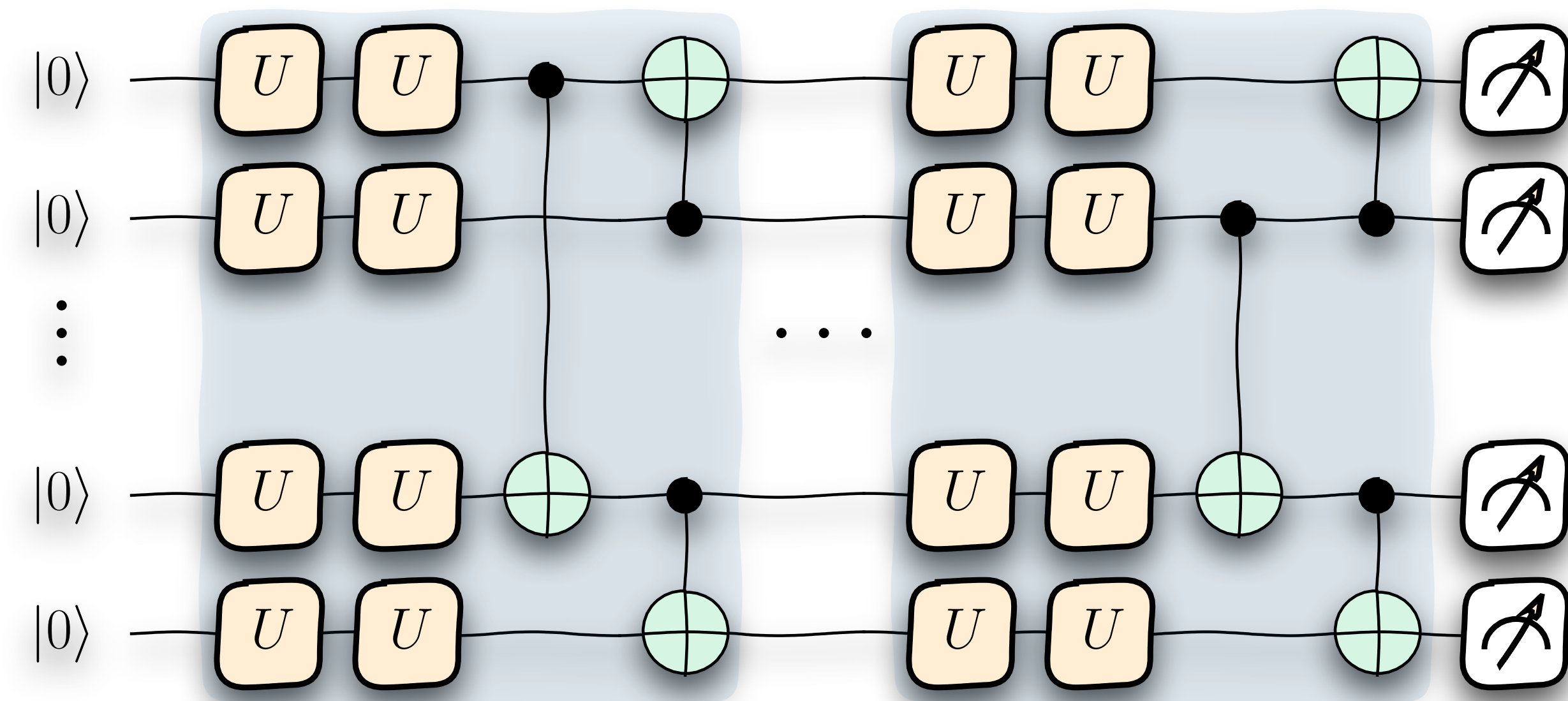
Landscape with barren plateaus

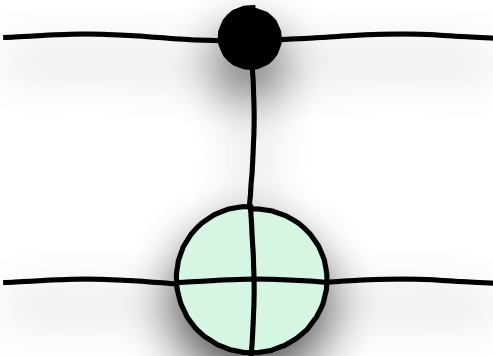


How can we go beyond the limitations?

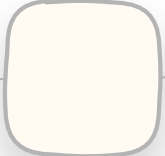
I'll build my own gates, thank you very much!

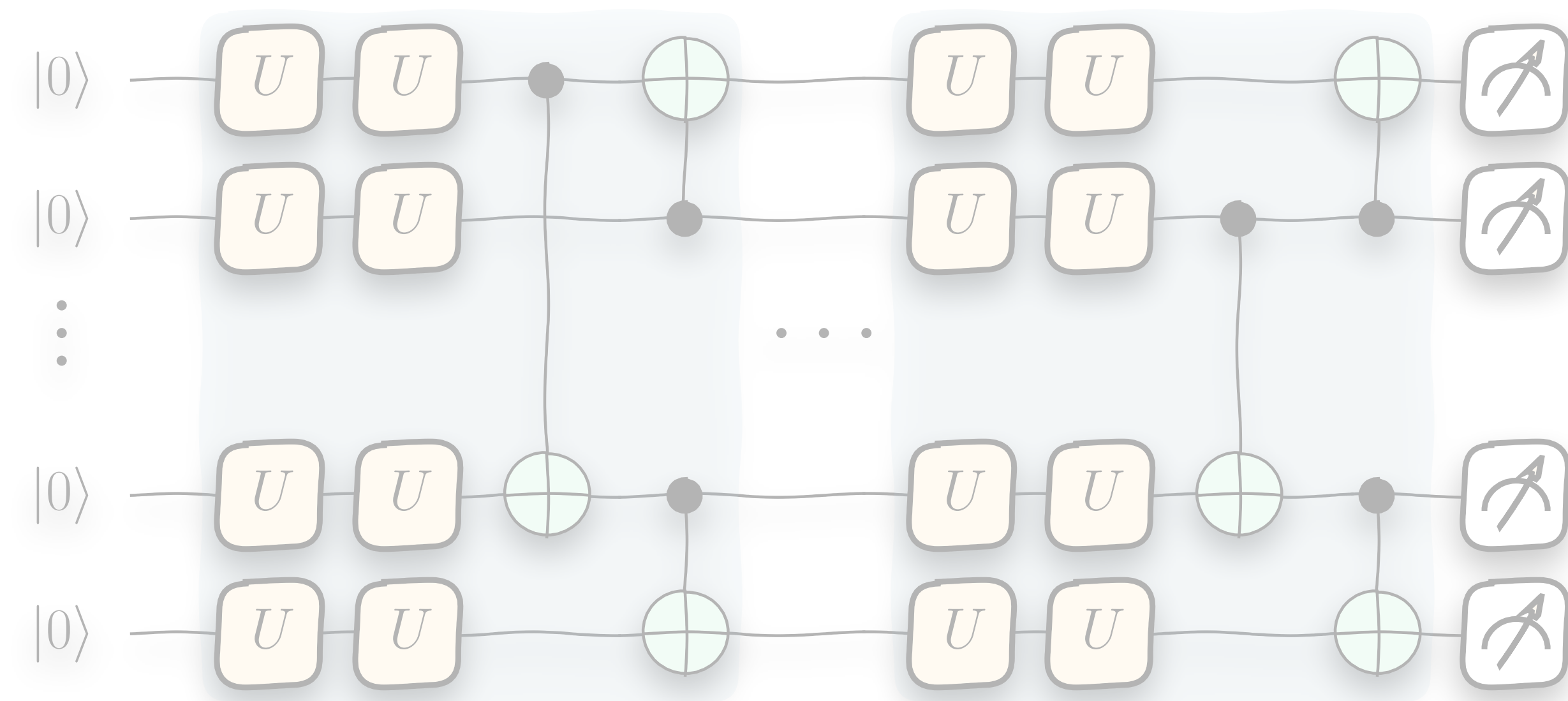
 $\simeq 71 \text{ ns}$ Limit: ~ 1408 single qubit gates

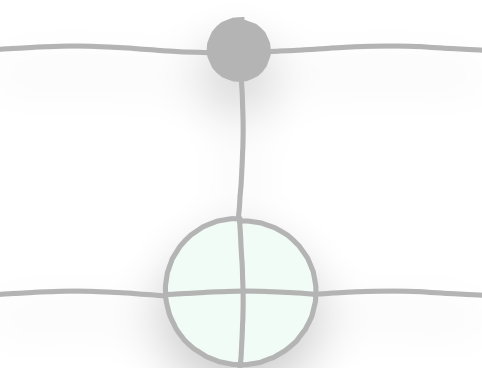


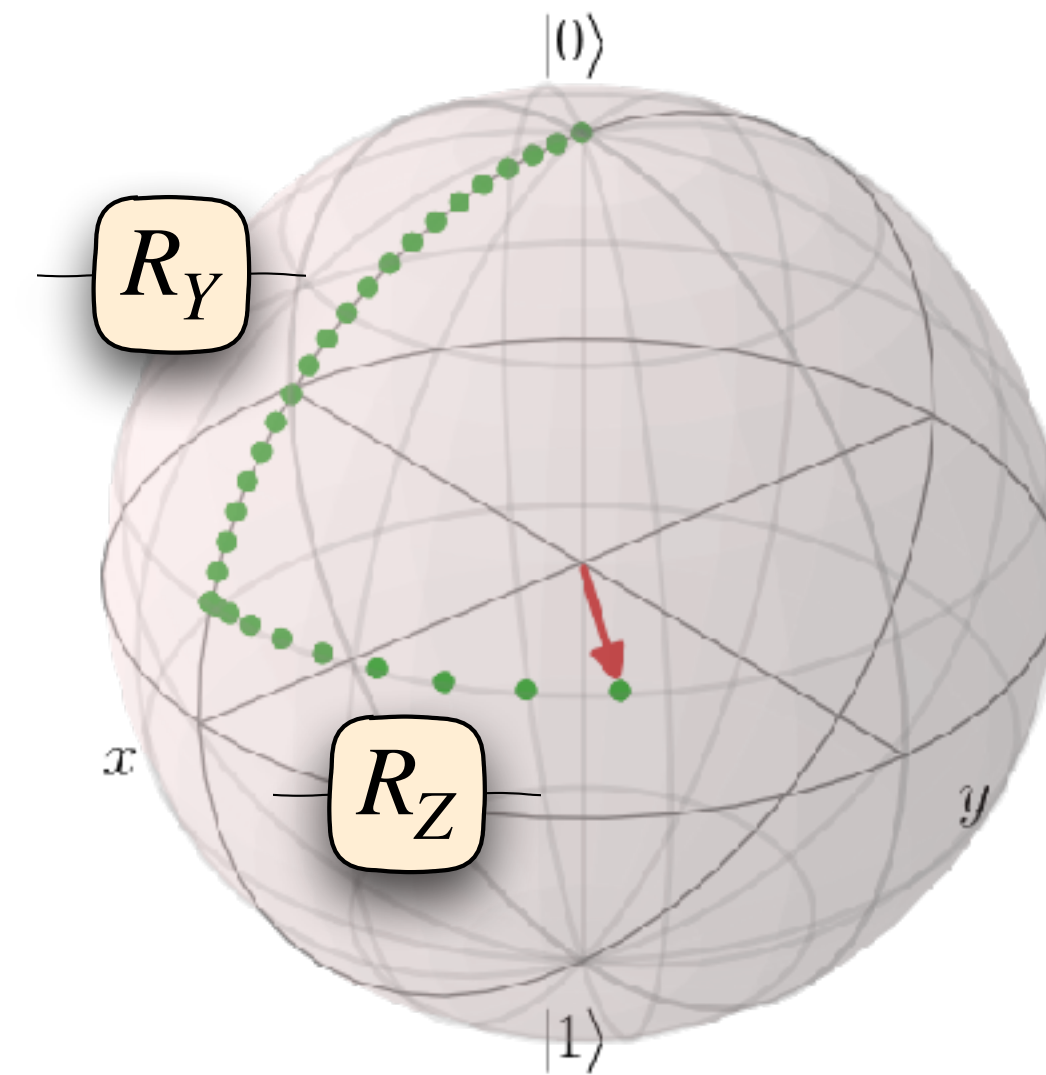
 $\simeq 600 \text{ ns}$ Limit: ~ 166 CNOT gates

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

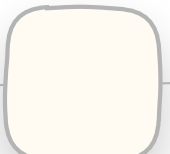
 $\simeq 71 \text{ ns}$ Limit: ~ 1408 single qubit gates

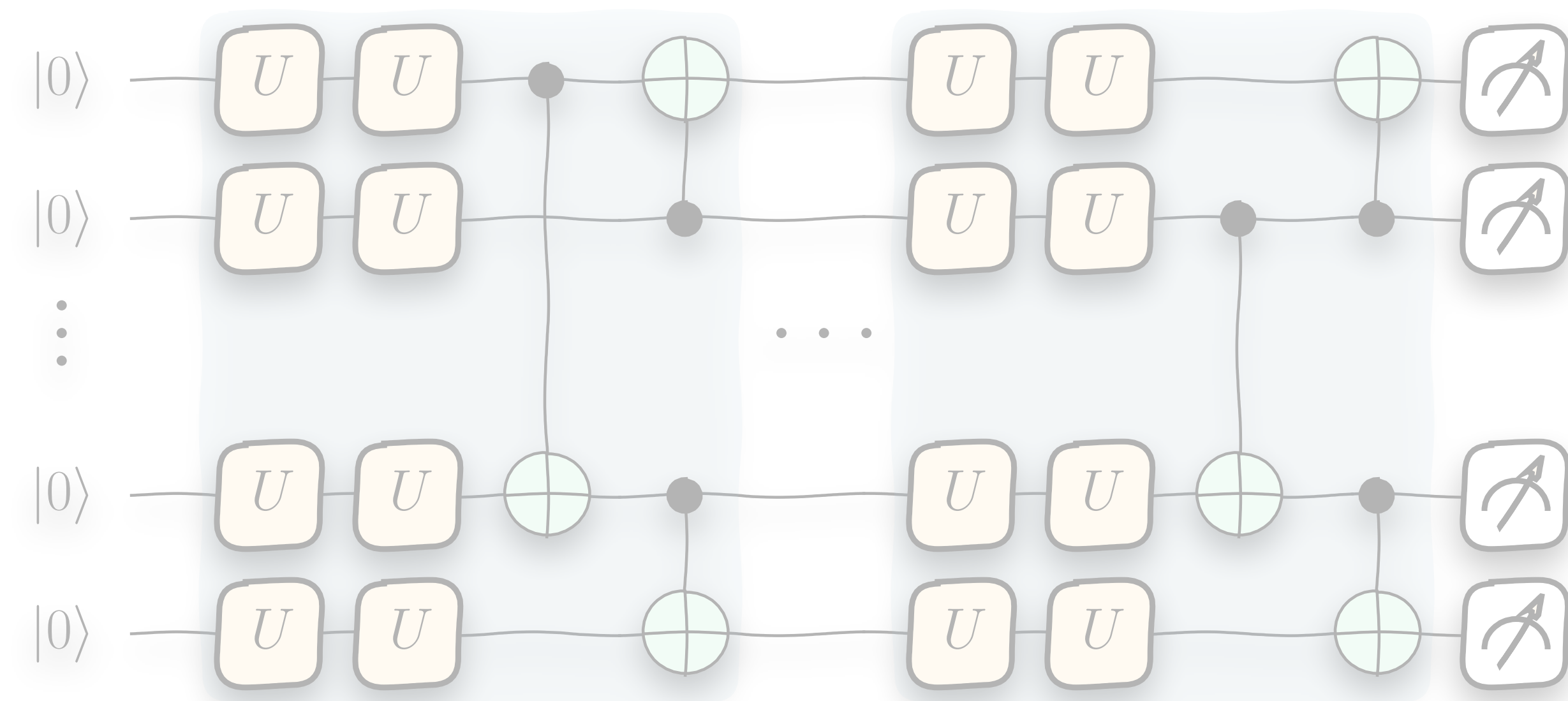


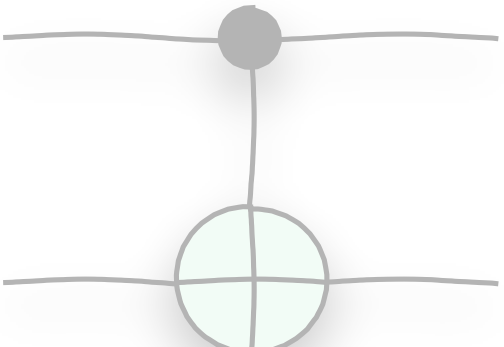
 $\simeq 600 \text{ ns}$ Limit: ~ 166 CNOT gates

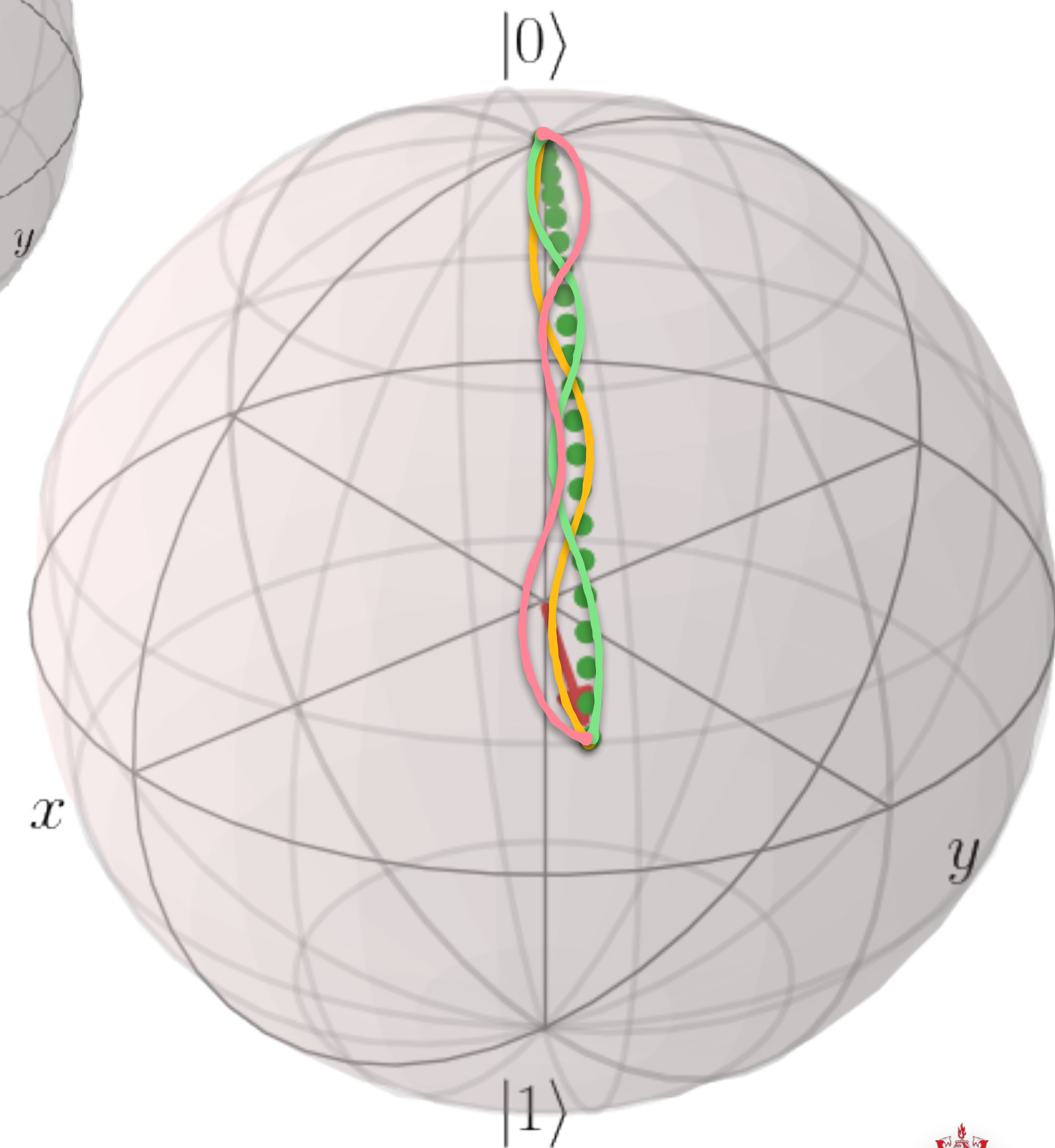
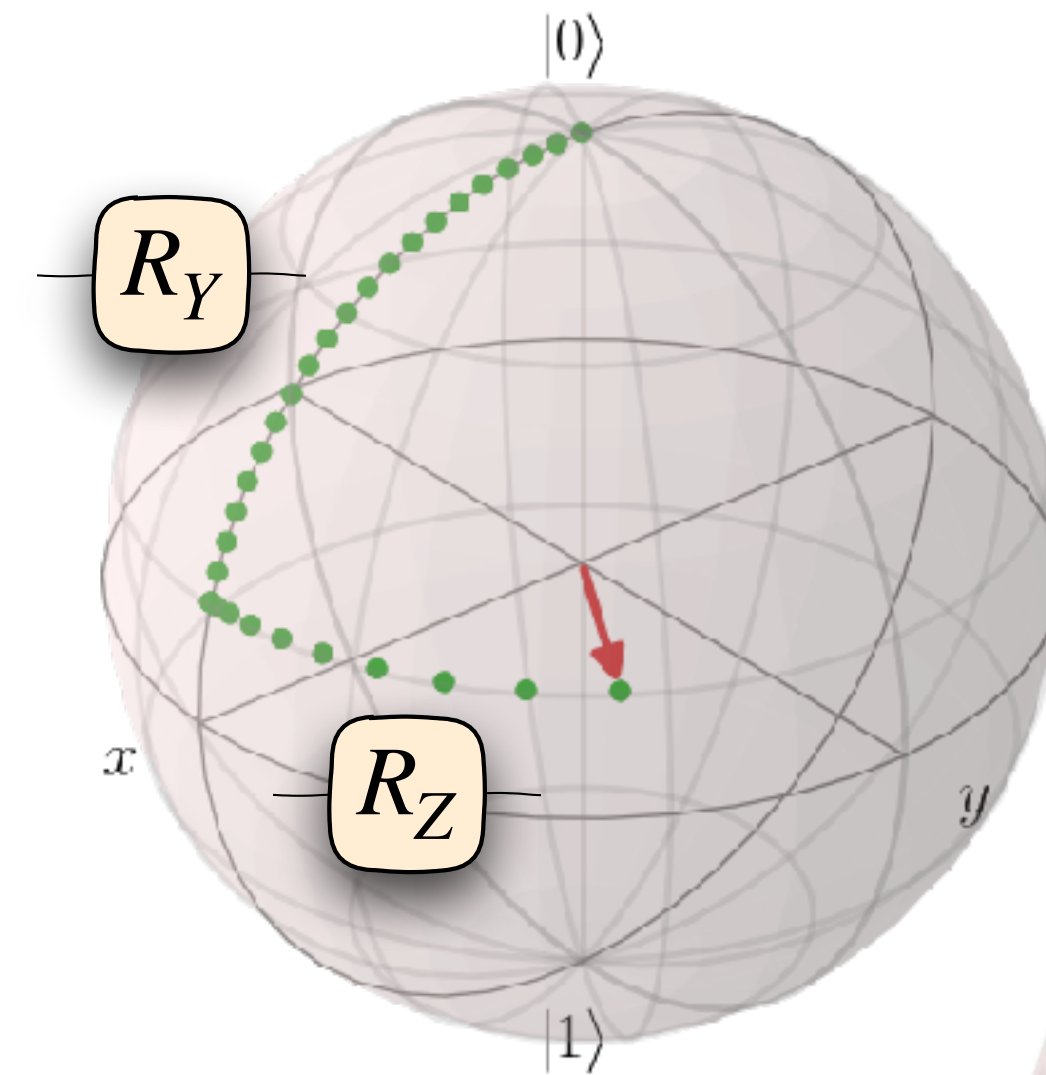


I'll build my own gates, thank you very much!

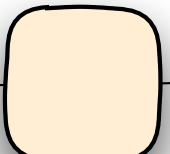
 $\simeq 71 \text{ ns}$ Limit: ~ 1408 single qubit gates



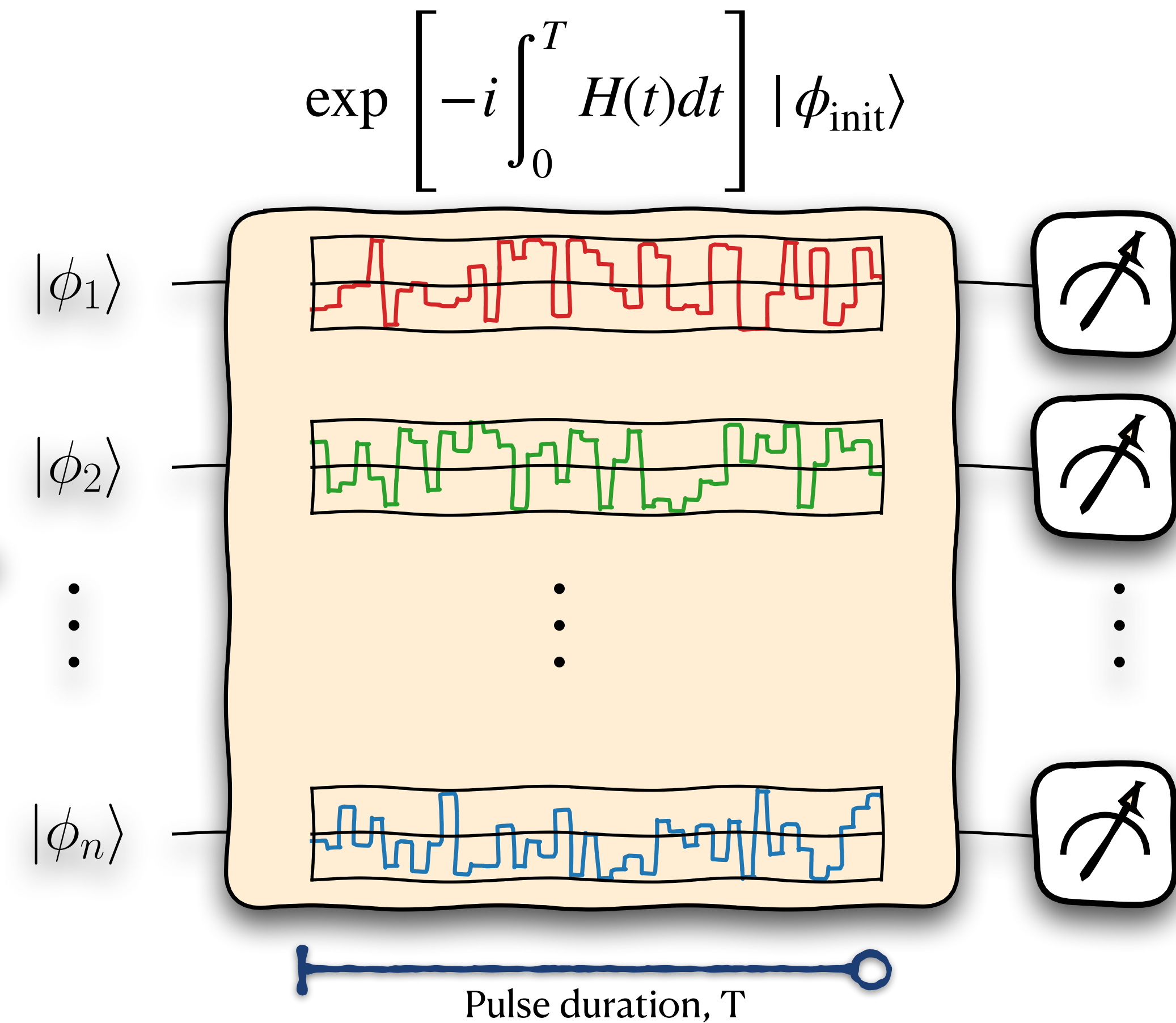
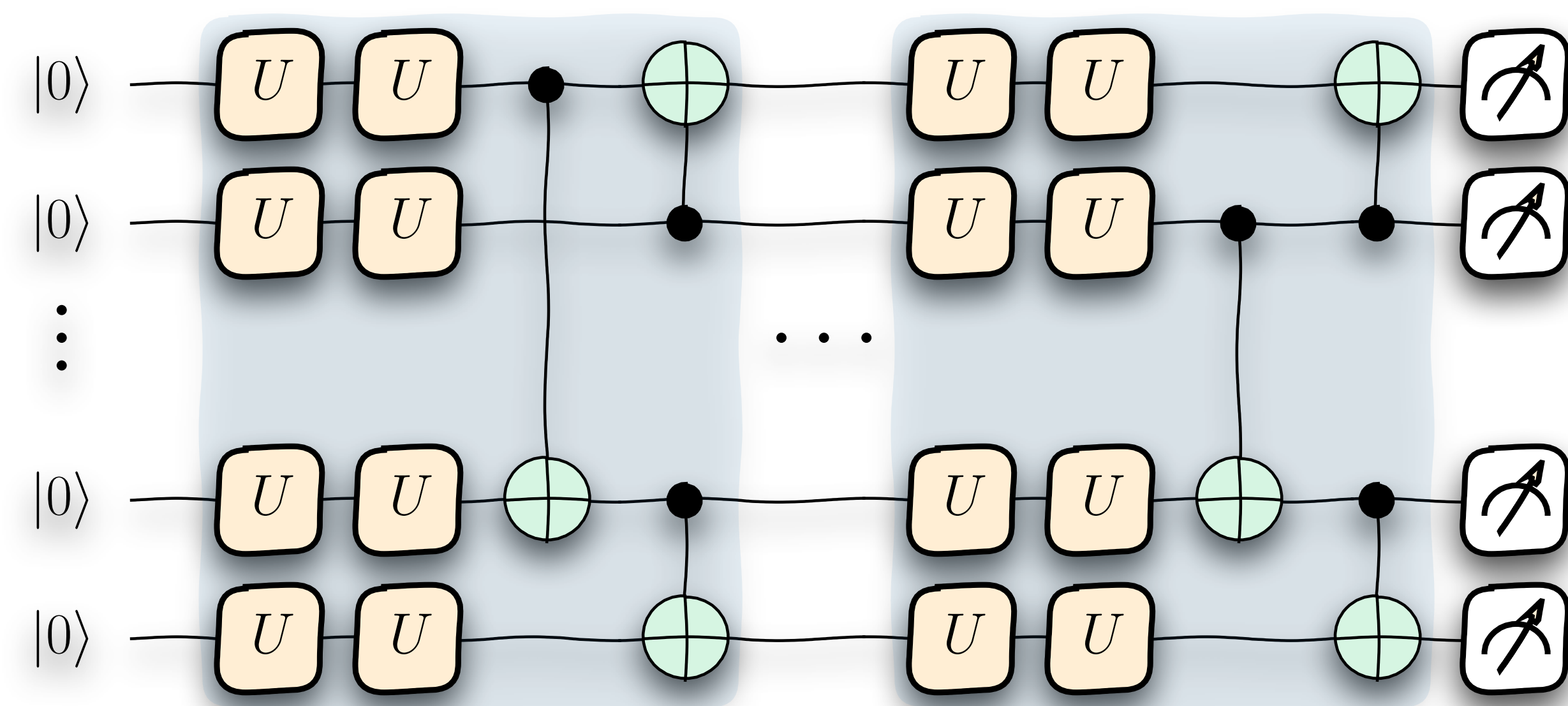
 $\simeq 600 \text{ ns}$ Limit: ~ 166 CNOT gates

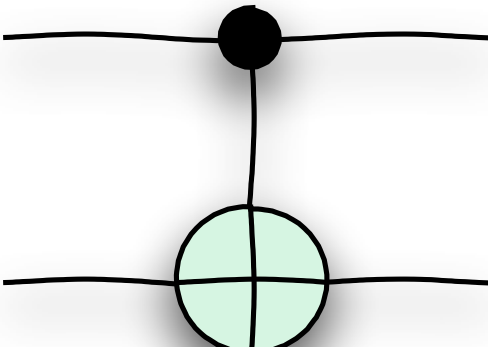


I'll build my own gates, thank you very much!

 $\simeq 71 \text{ ns}$

 Limit: ~ 1408 single qubit gates



 $\simeq 600 \text{ ns}$

 Limit: ~ 166 CNOT gates

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

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

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

v : Phase, $|v_i - \omega_i| \leq 1$ GHz

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

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

Our new ansatz

Asthana et. al.

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.

Meitei et. al. arXiv:2008.04302

Schwinger Model

Schwinger Model with topological term

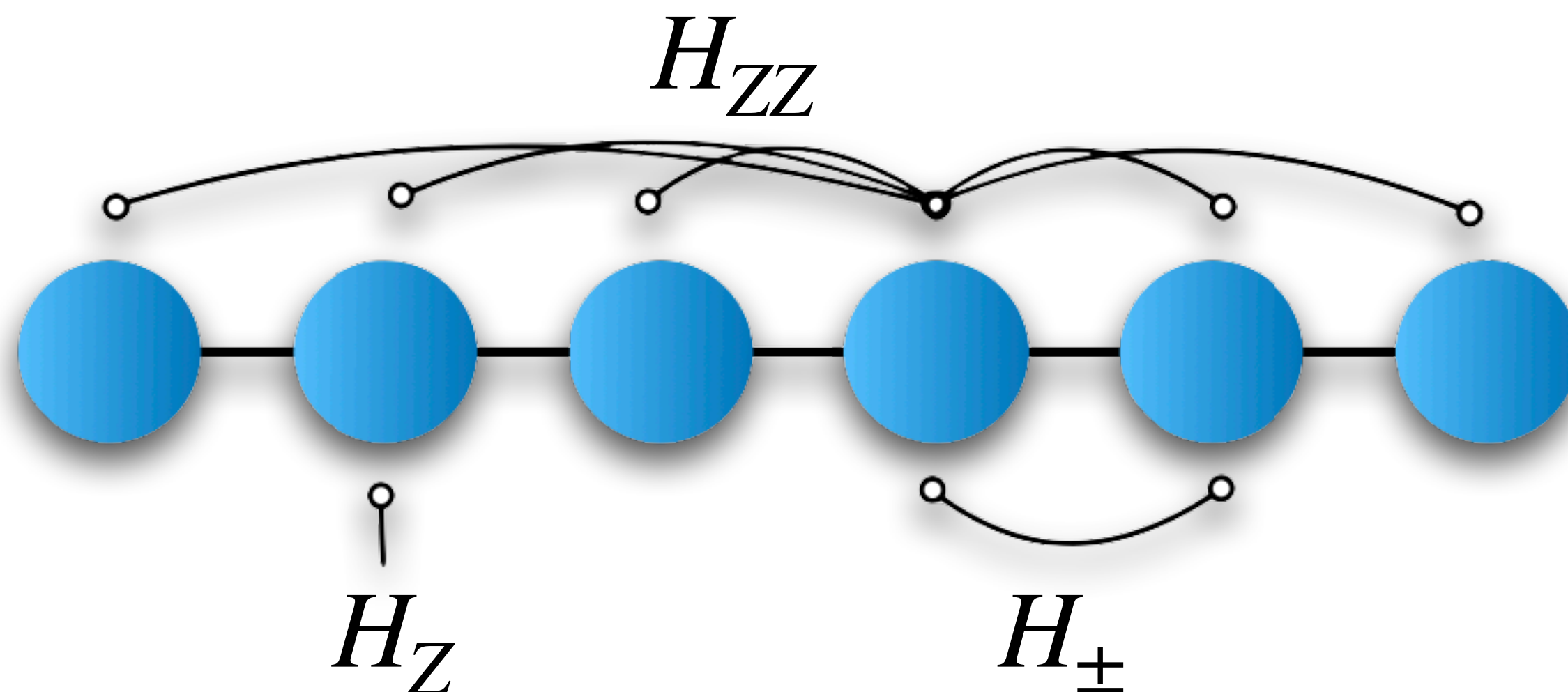
Simple QED

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

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

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

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



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

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

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

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

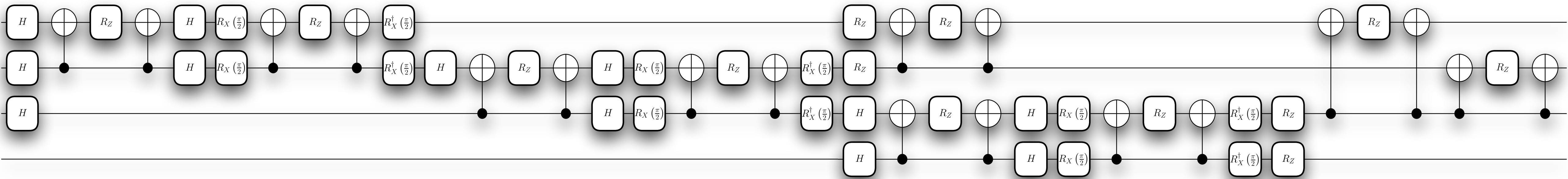
Without θ :

Chakraborty et al. arXiv: 2001.00485

Farrell et al. arXiv: 2308.04481

Jack Y. Araz

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



$\sim 11 \mu s$

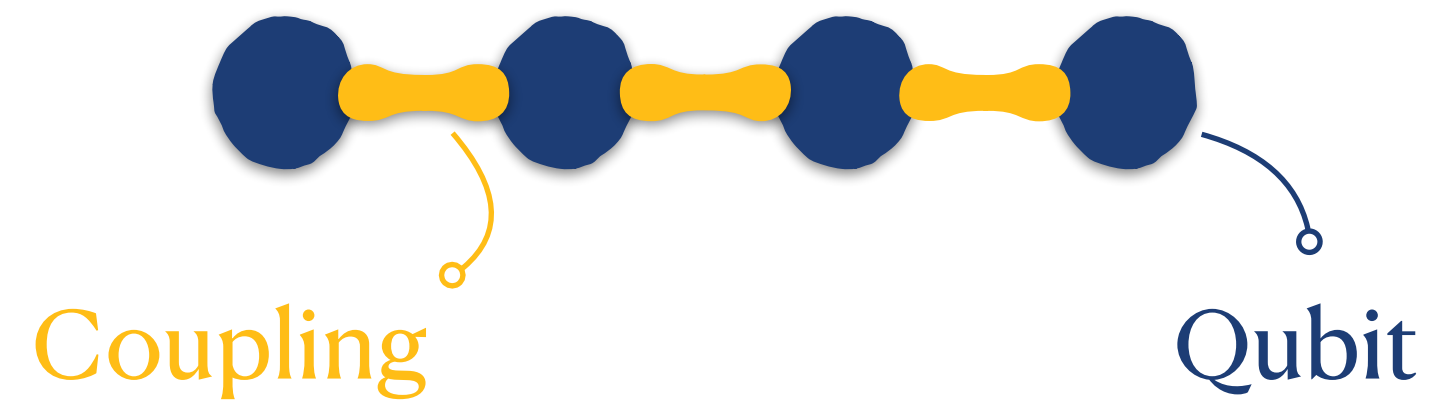
Limit: ~9 trotter steps

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

The Schwinger Gate!

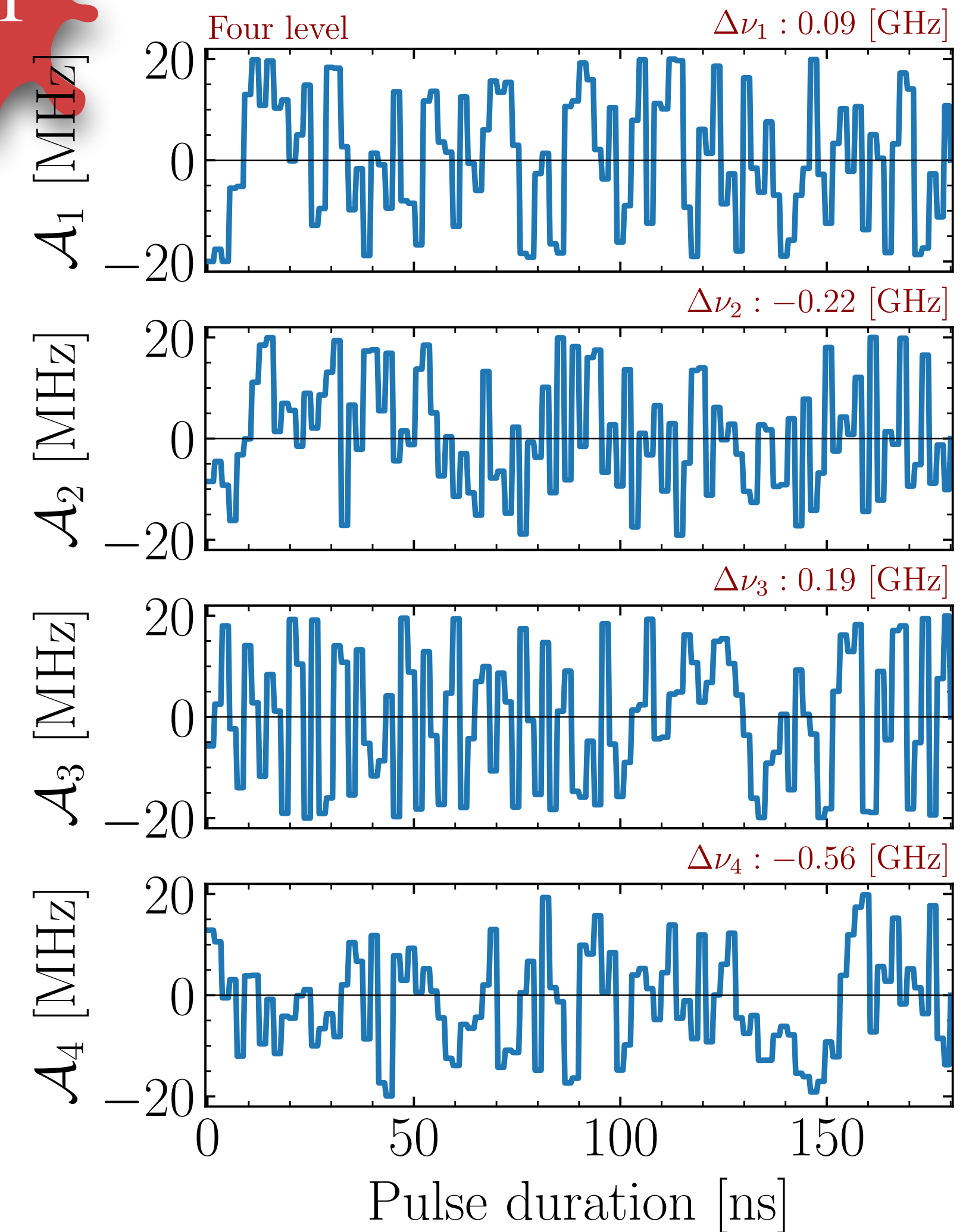
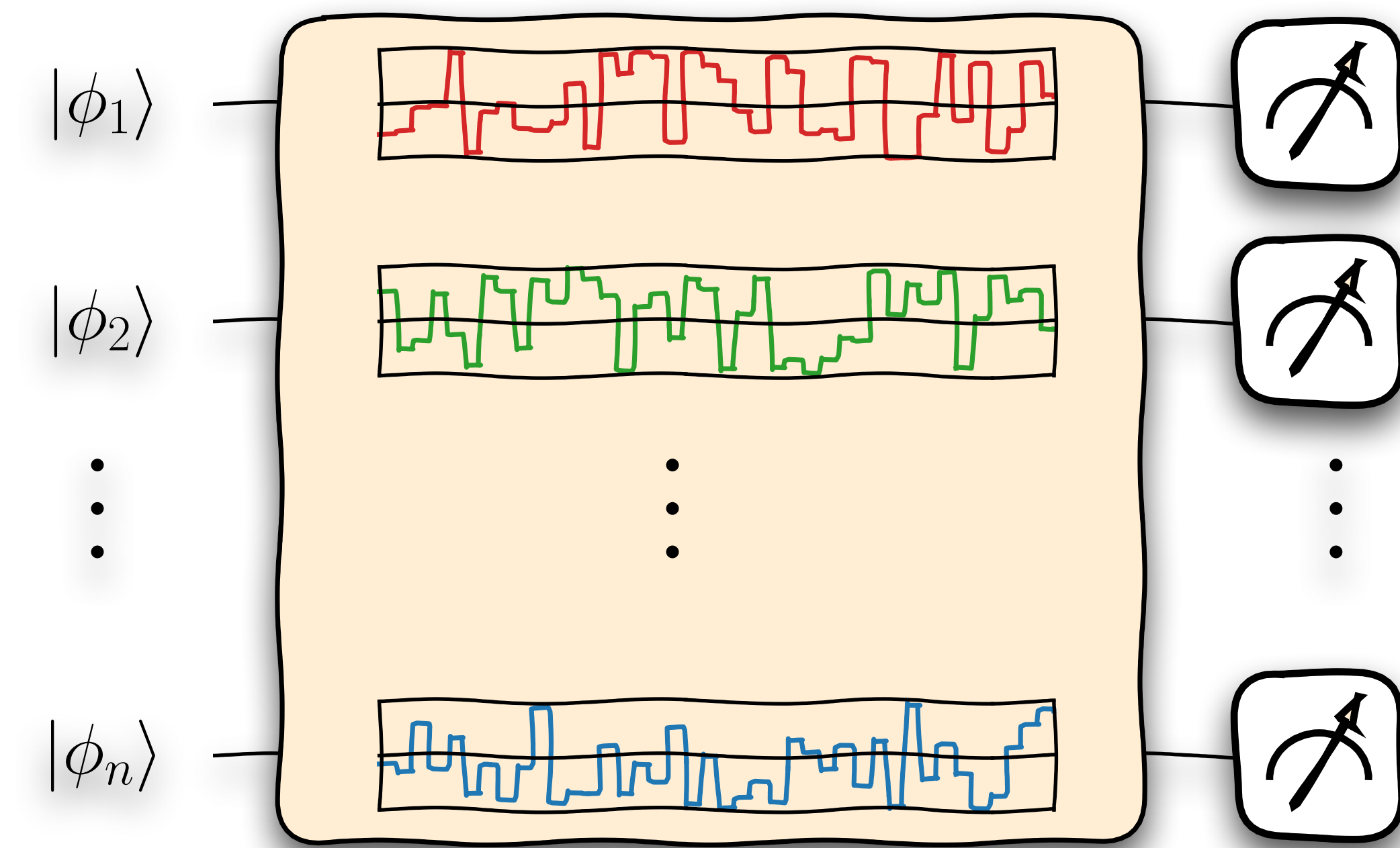
[JYA, Bhowmick, Grau, McEntire, Ringer; PRD '25]

Quantum Computer:



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

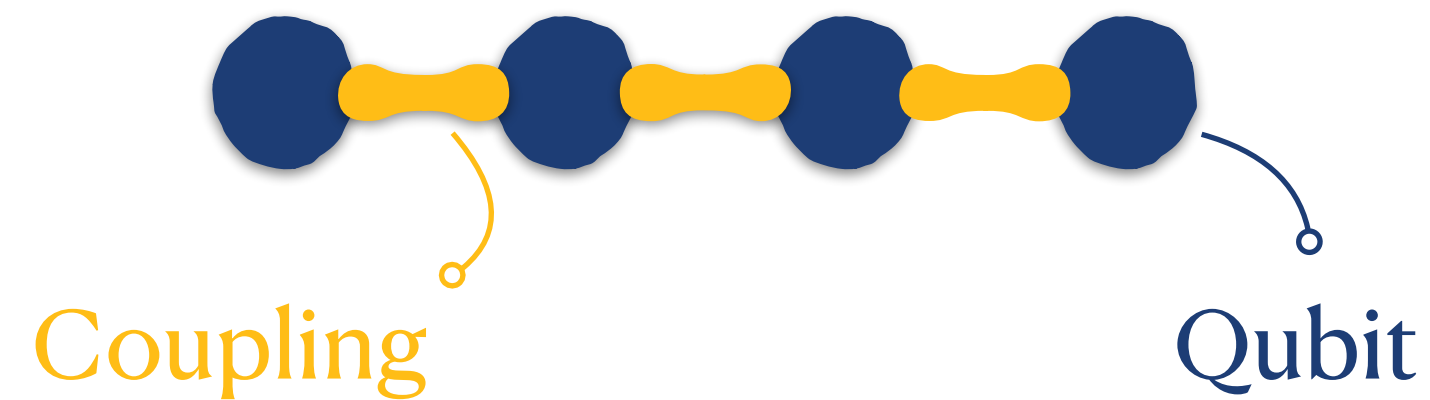
× 61



The Schwinger Gate!

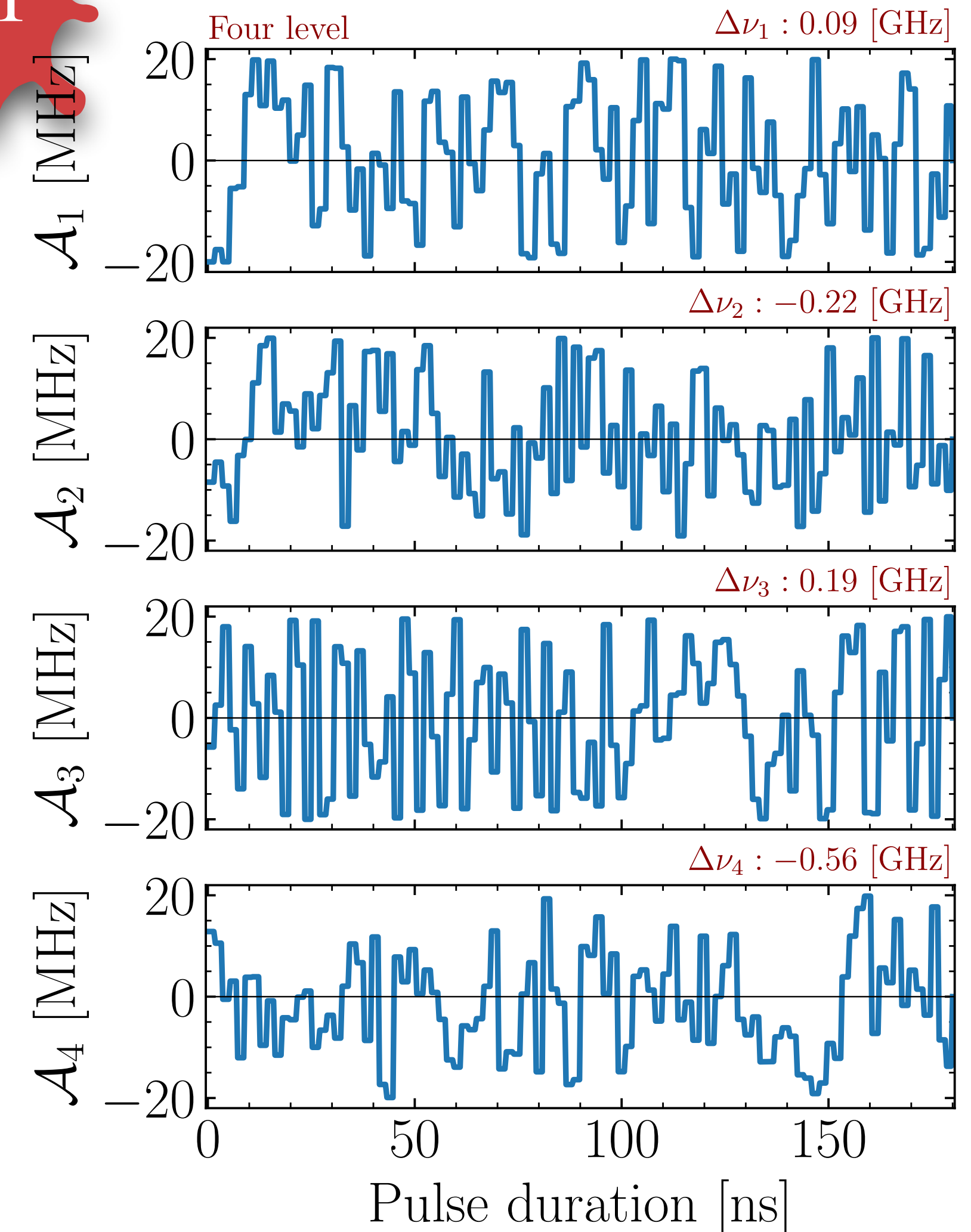
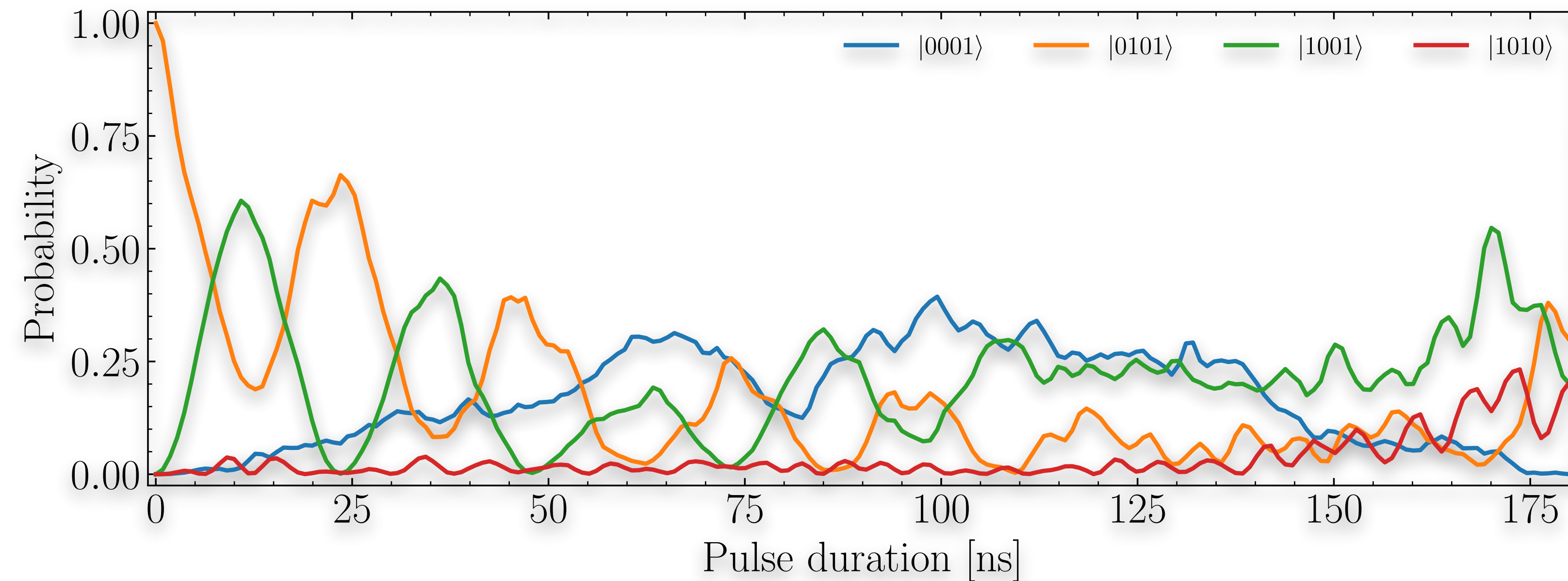
[JYA, Bhowmick, Grau,
McEntire, Ringer; PRD '25]

Quantum Computer:



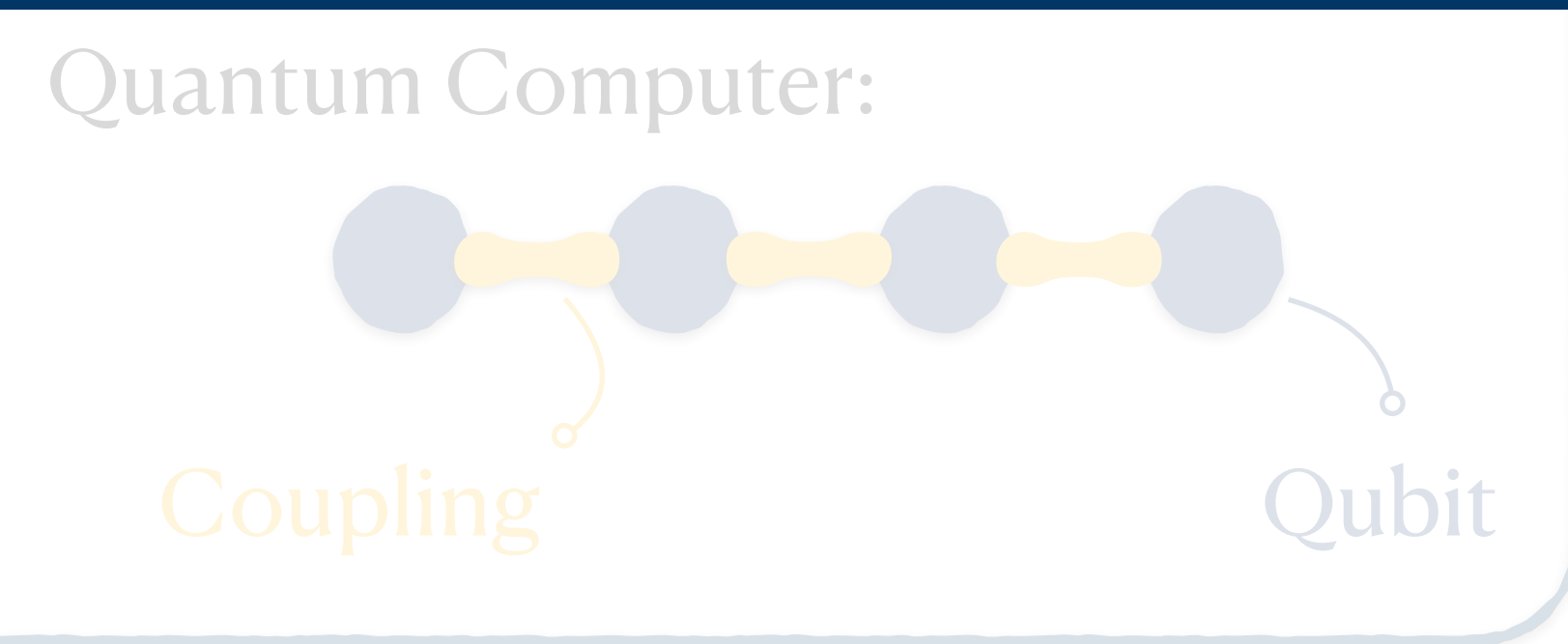
180 ns
 $\Delta E \sim 5 \times 10^{-3}$

× 61

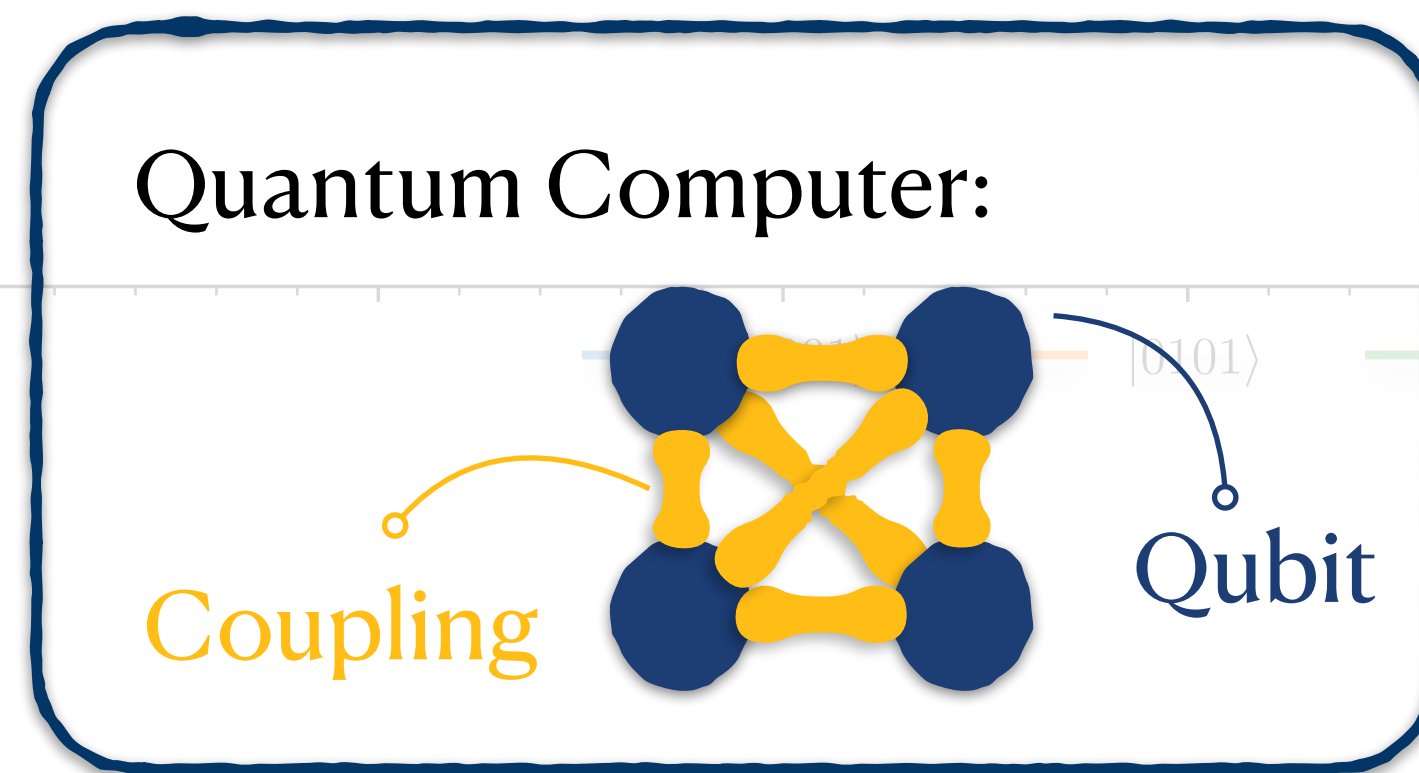


The Schwinger Gate!

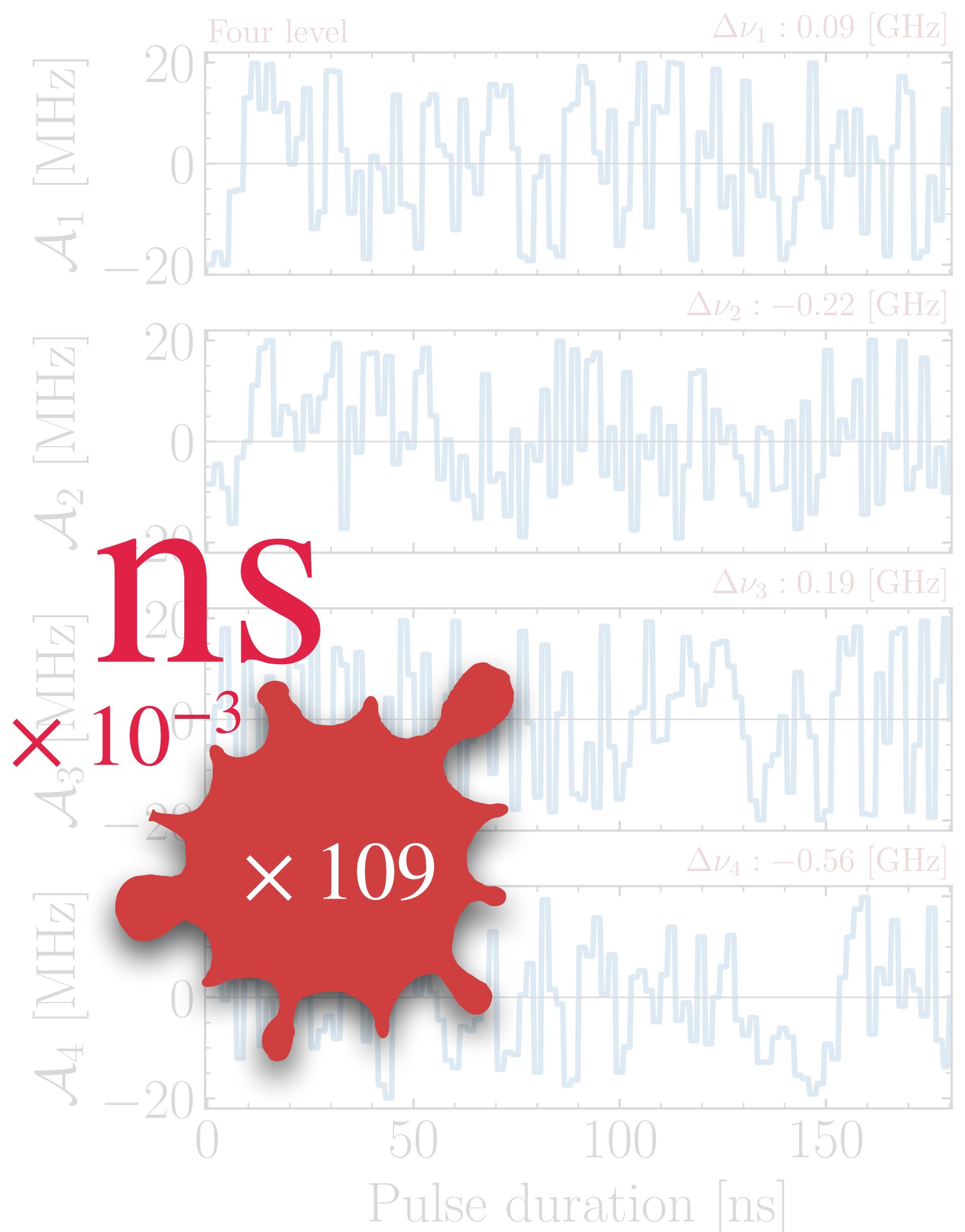
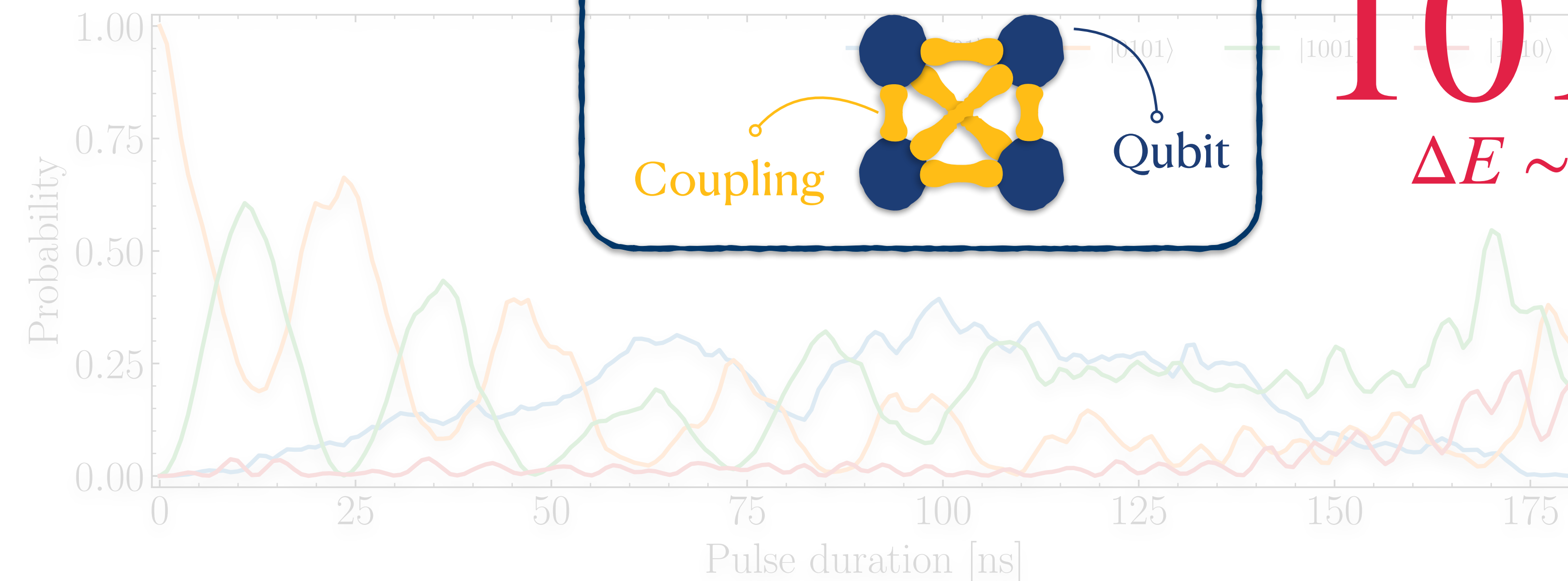
[JYA, Bhowmick, Grau,
McEntire, Ringer; PRD '25]



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



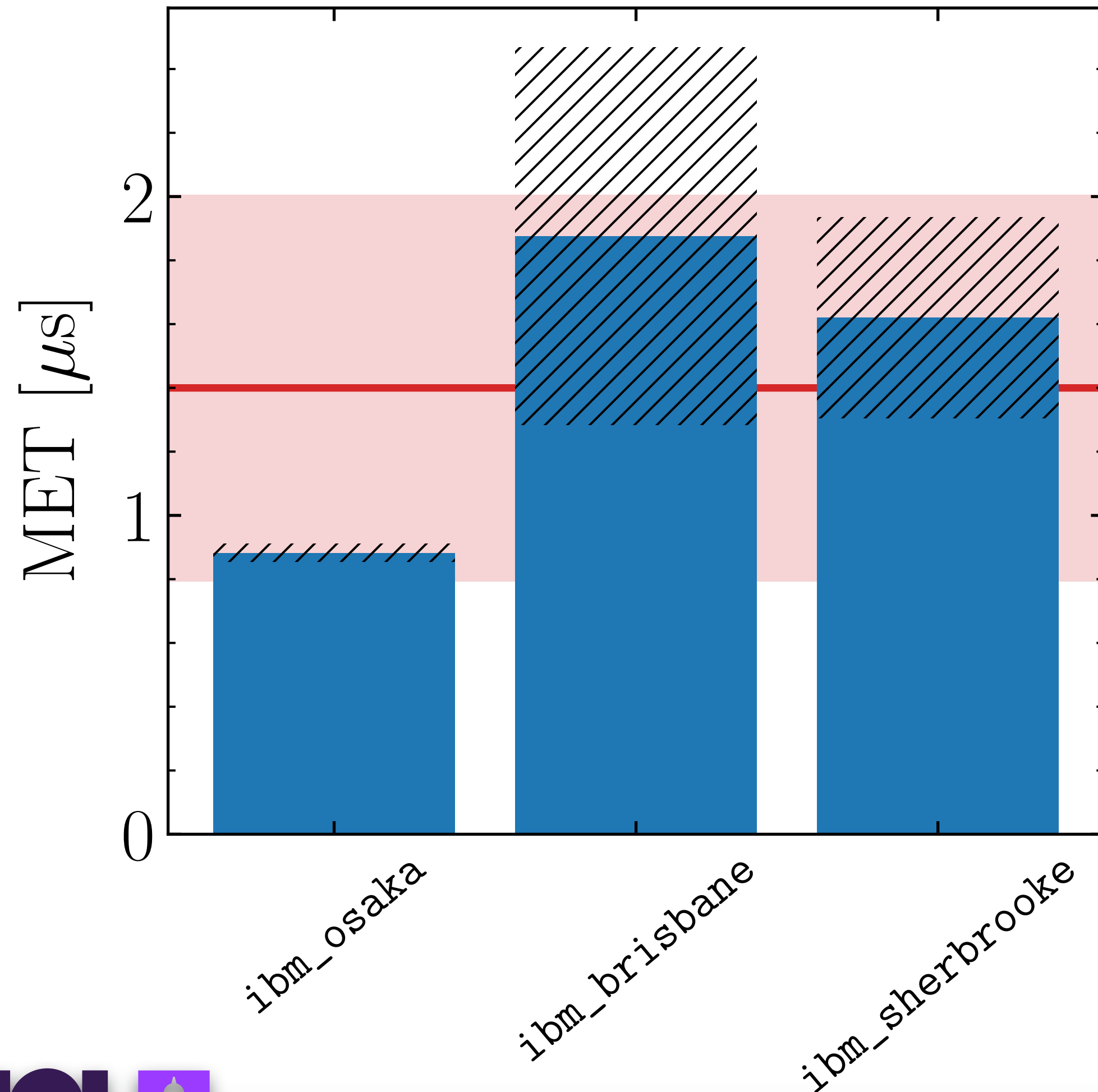
101 ns
 $\Delta E \sim 5 \times 10^{-3}$



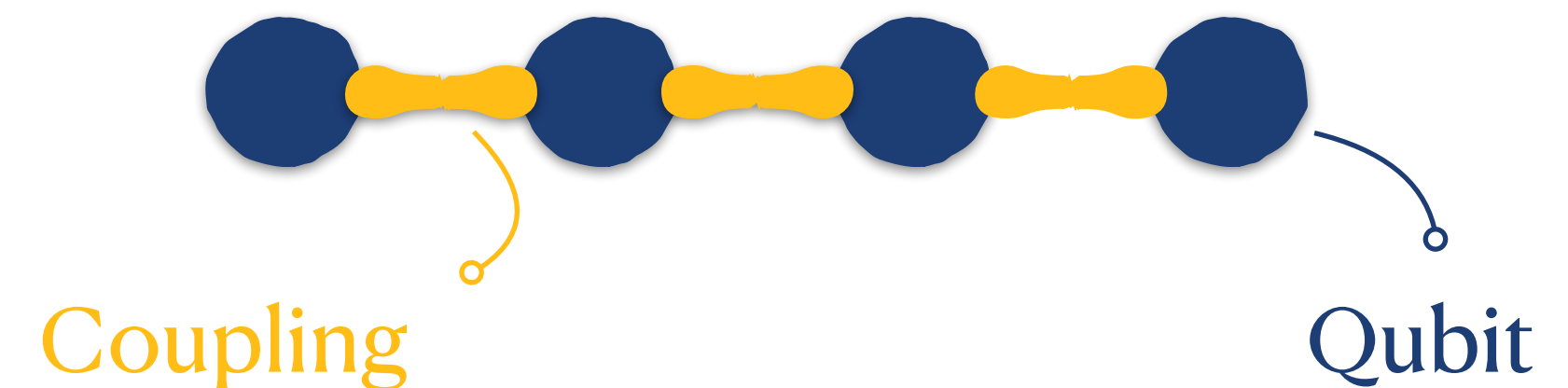
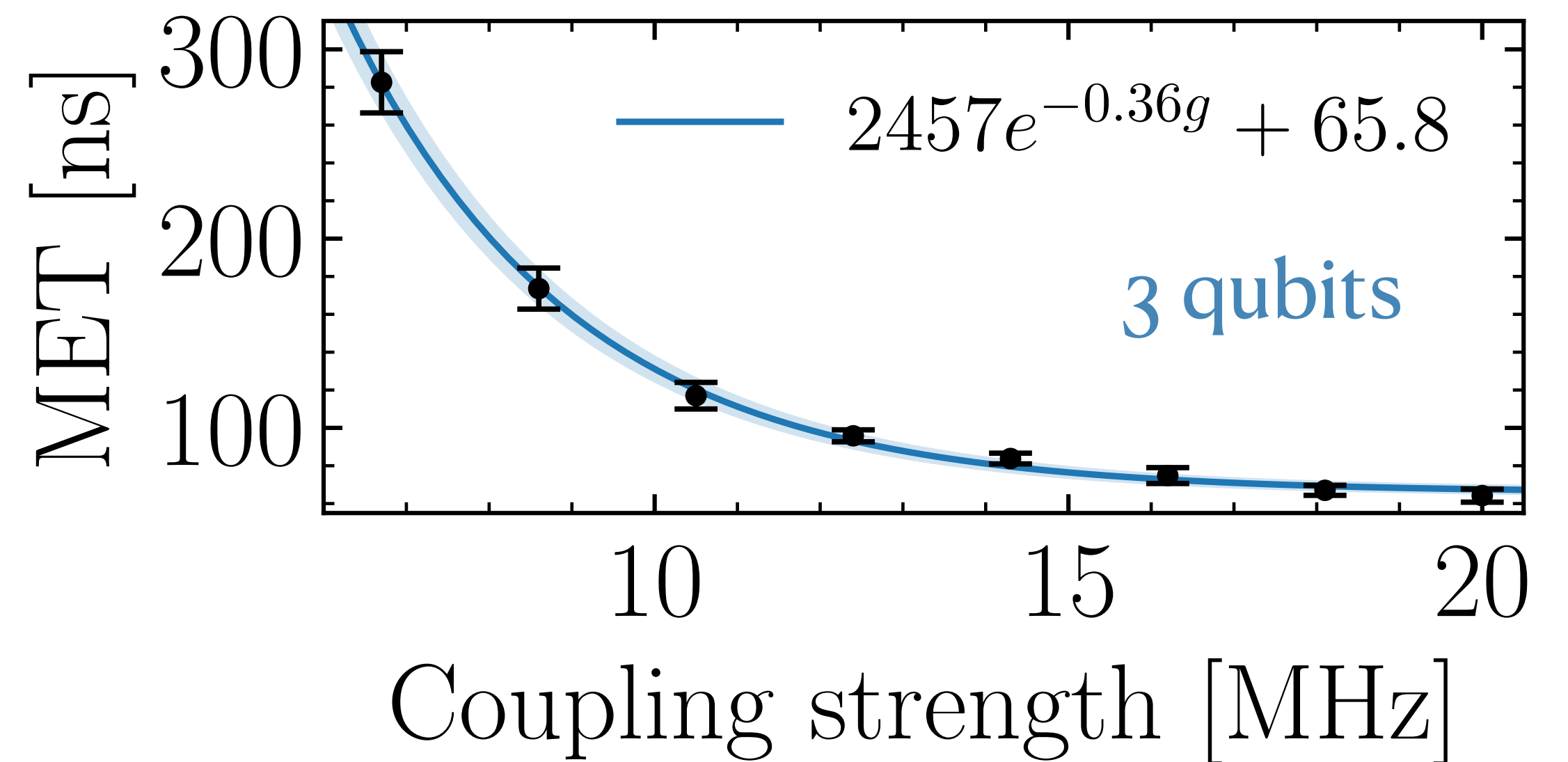
Can we improve the quantum device?

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

Coupling strength: 2 MHz

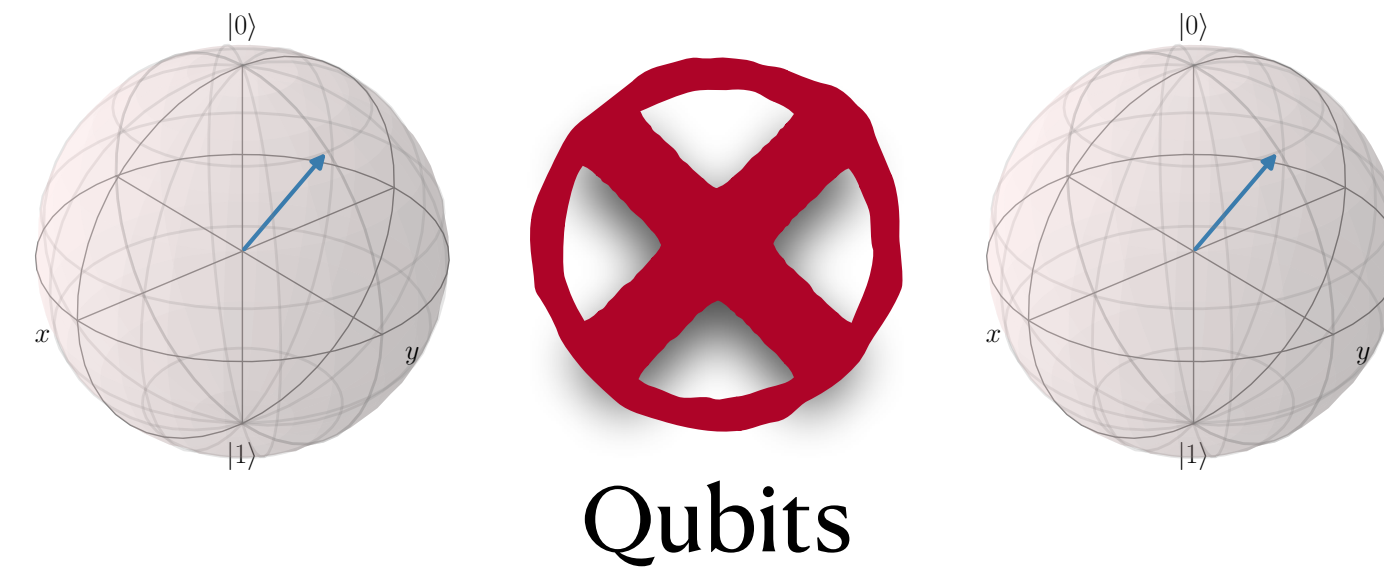


❖ What if we can improve the Josephson junction to have a better-entangled state?



Towards simulating the Standard Model

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



Short Coherence
Time



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

Barren Plateaus



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

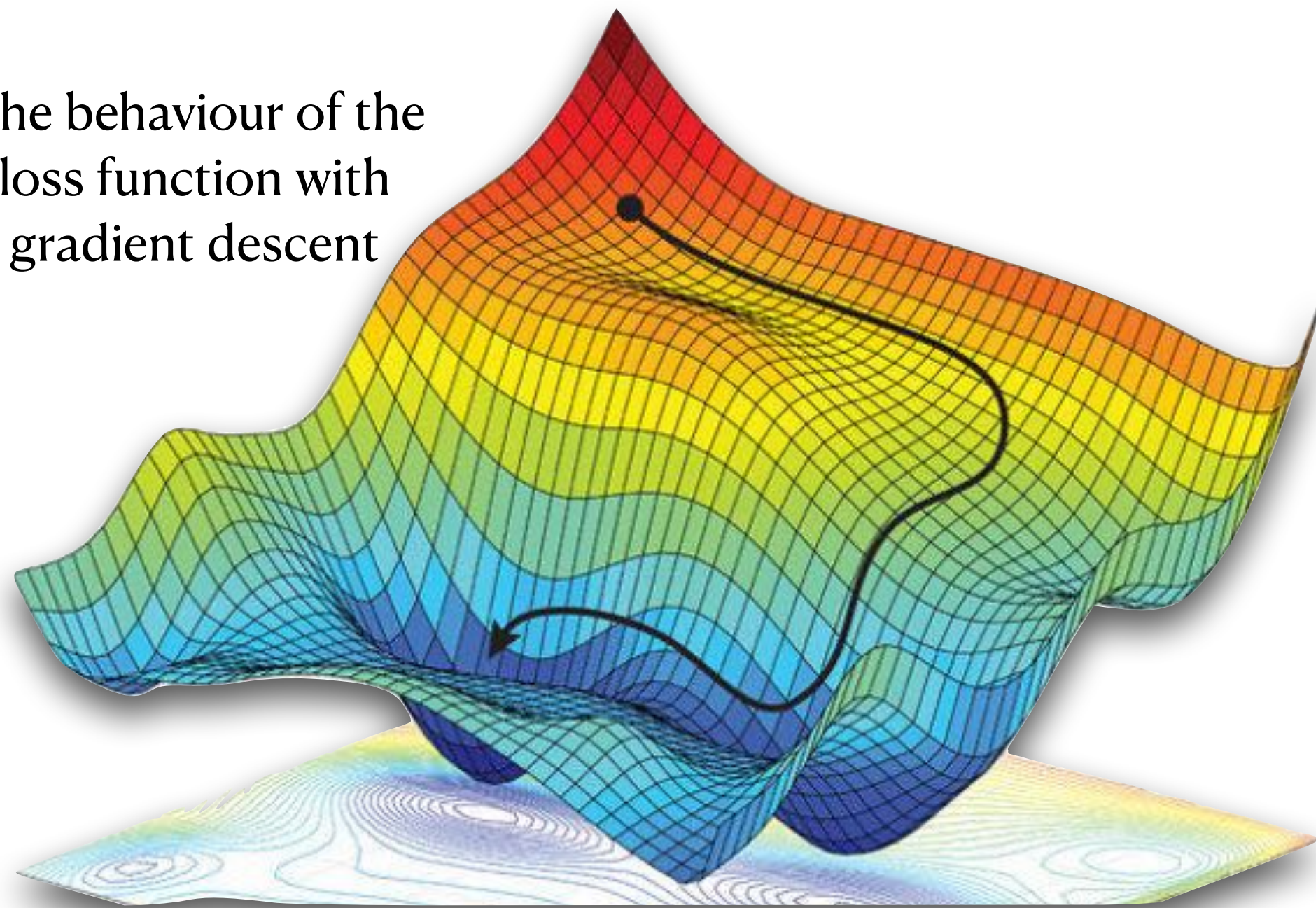
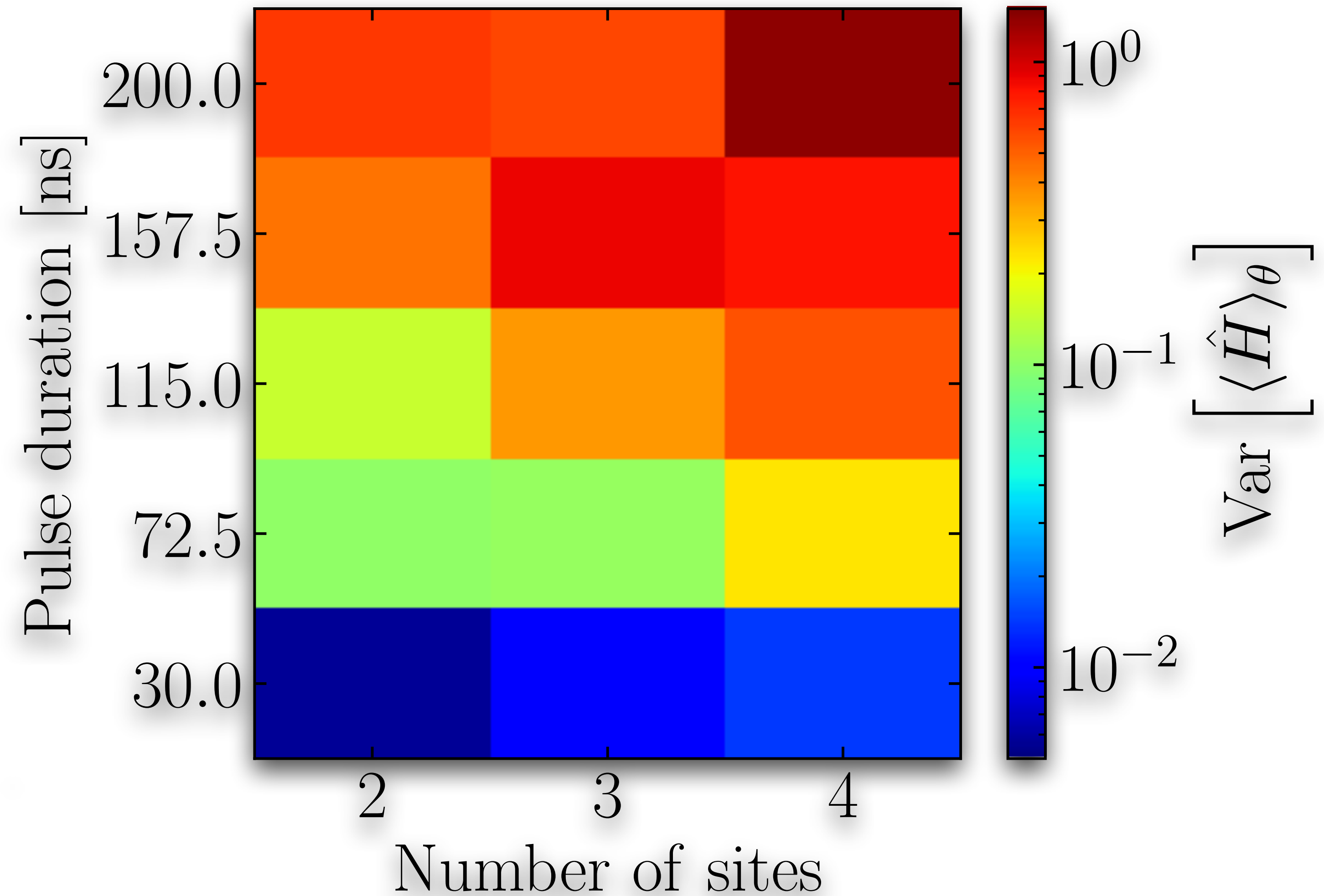


Image credit: Francisco Lima



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



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?

Sponsors

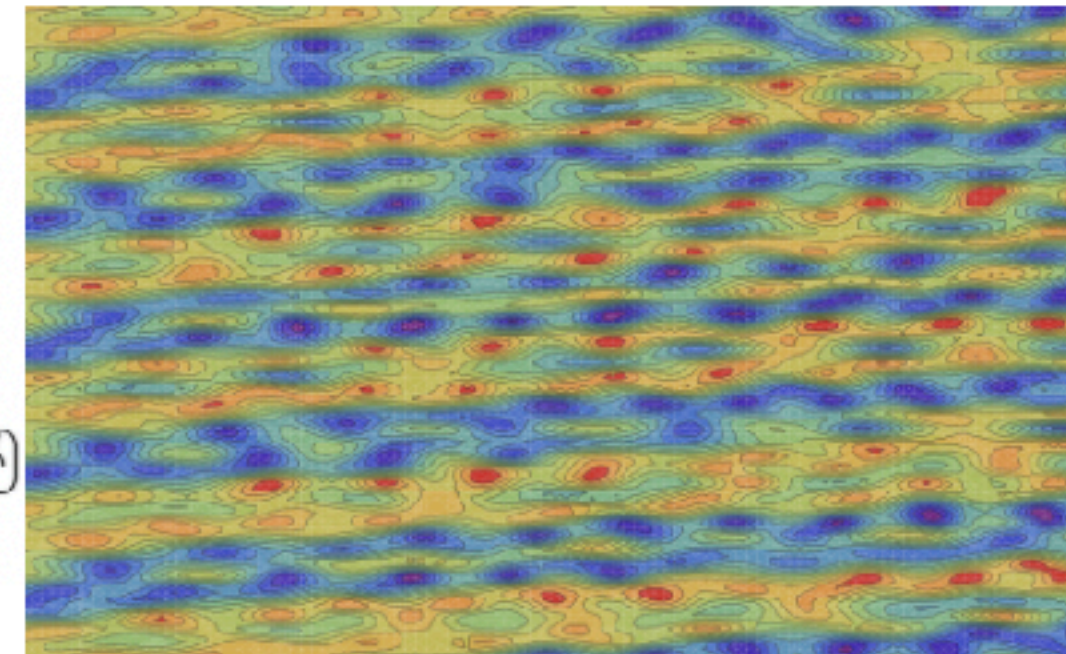
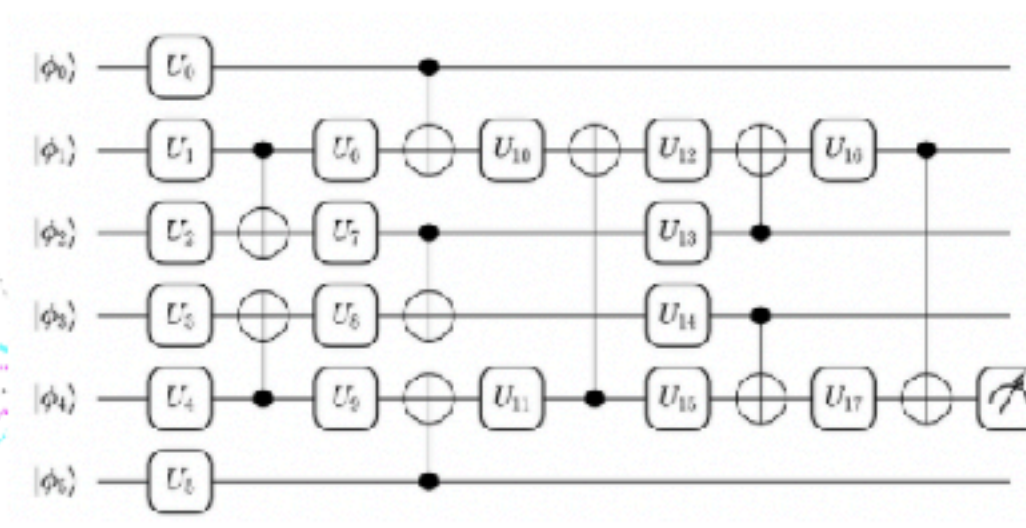
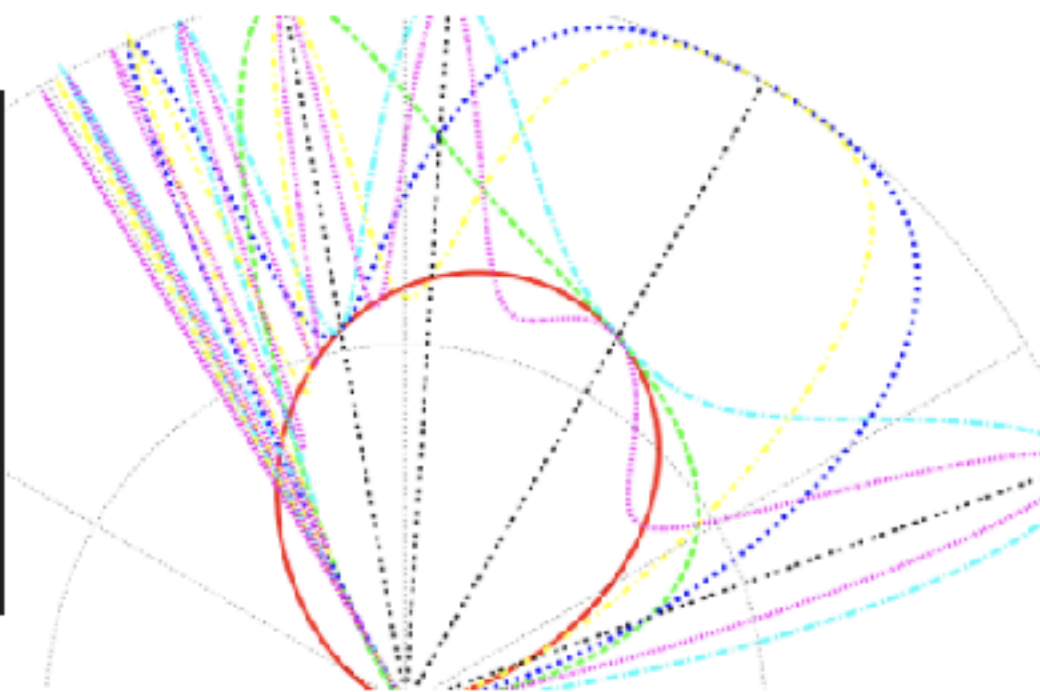


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Quantum Science & Technology Research Group

Home Group Members Group Meetings Group Seminars Group Publications



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Founded in 2026, the **Quantum Science and Technology Research Group** brings together colleagues from several Schools and Departments at City St George's, University of London, whose research falls fully or partially within the area of **quantum science**. This