Investigating the use of Quantum Computers for Final State Radiation

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Based in part on 1904.03196 in collaboration with D. Provasoli, C. Bauer, and W. de Jong

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Overview

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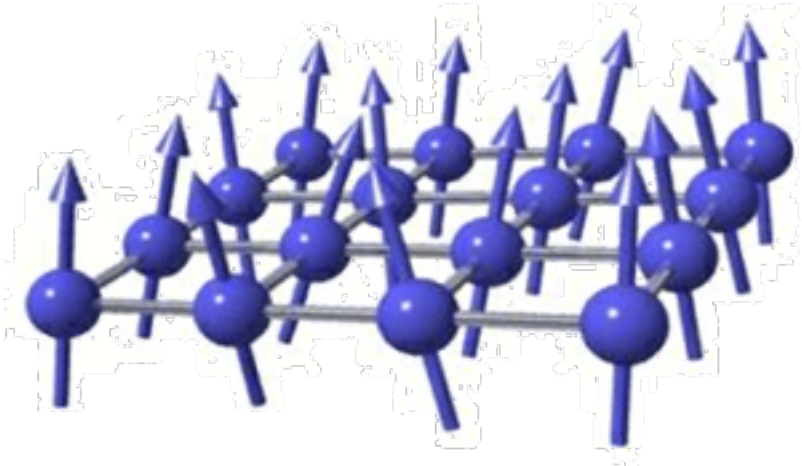
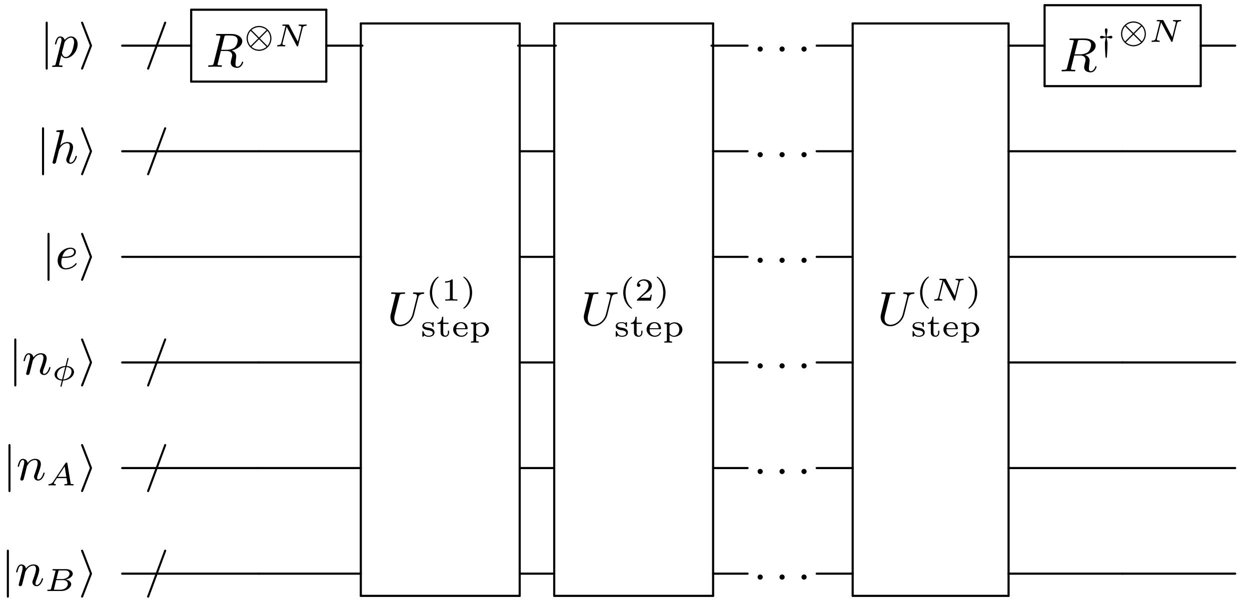
~ Outline ~

Quantum machines
("quantum computers")





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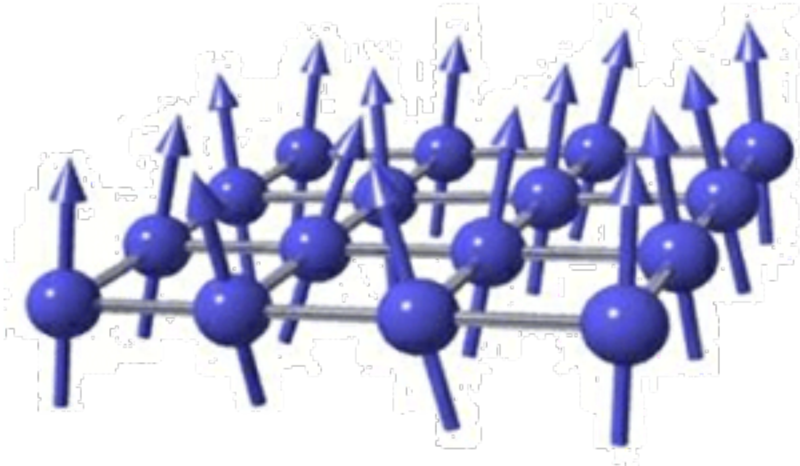
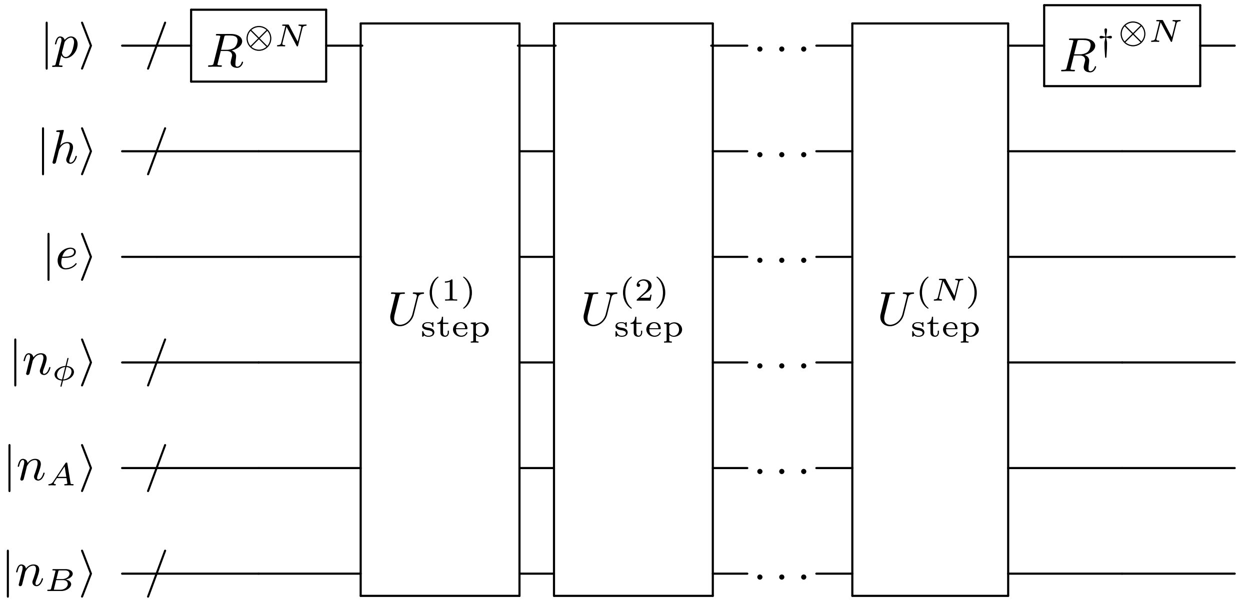
Quantum machines (“quantum computers”)

A simple, but real model





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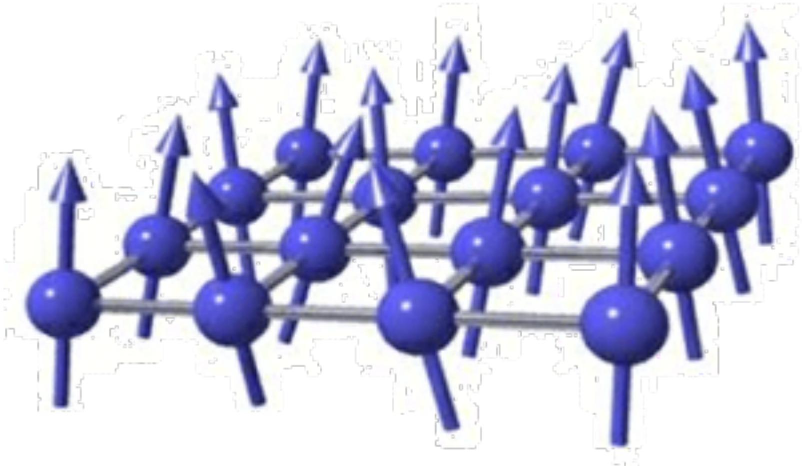
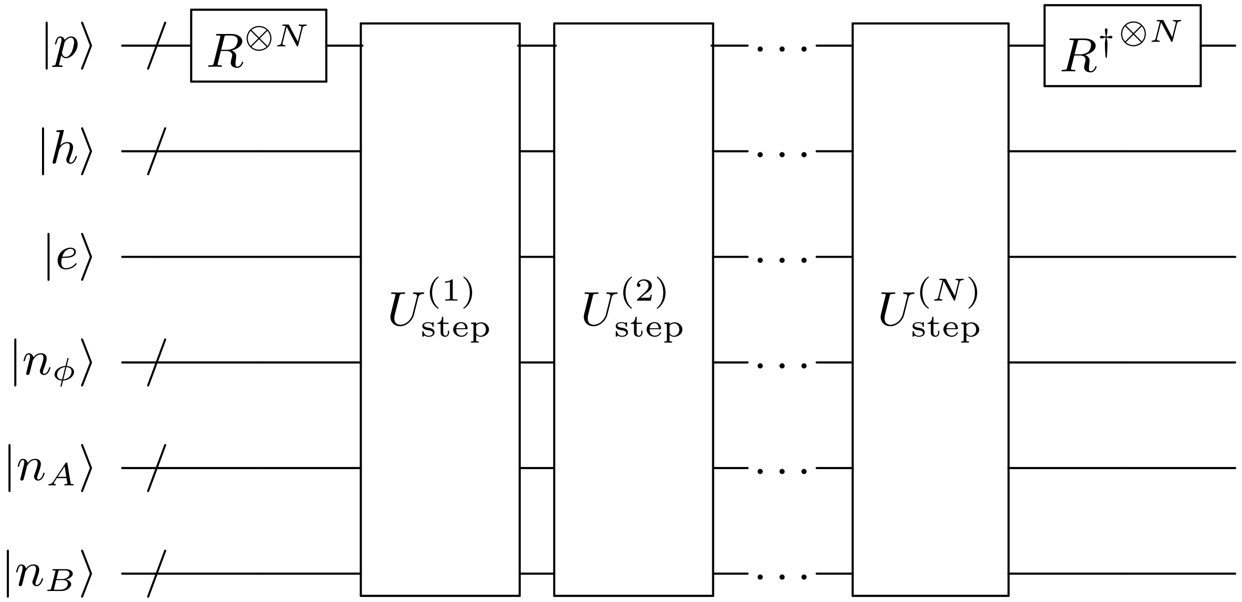


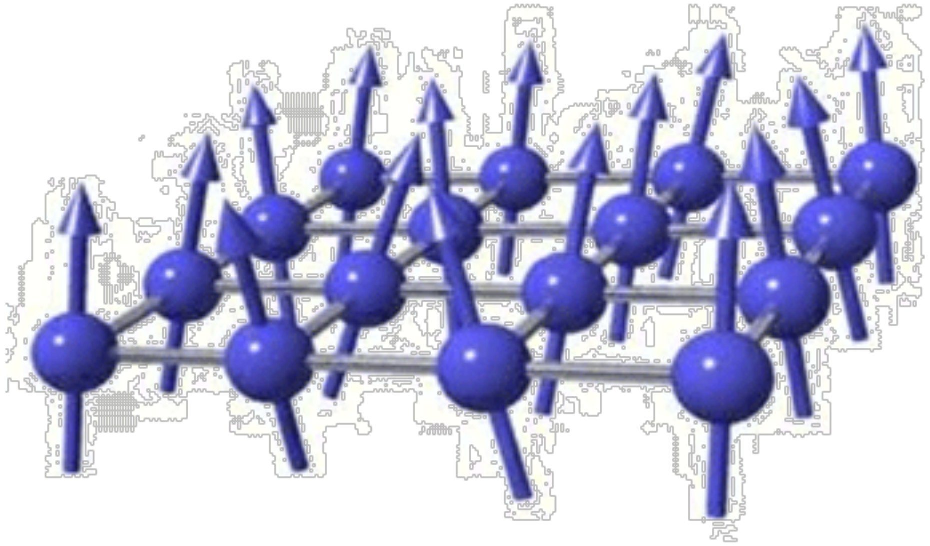


Quantum computers

Goal: implement our system’s Hamiltonian (e.g. the SM) in a proxy system (“quantum computer”) and let it evolve.

What can be a proxy system?

…any quantum system, like a collection of spins.



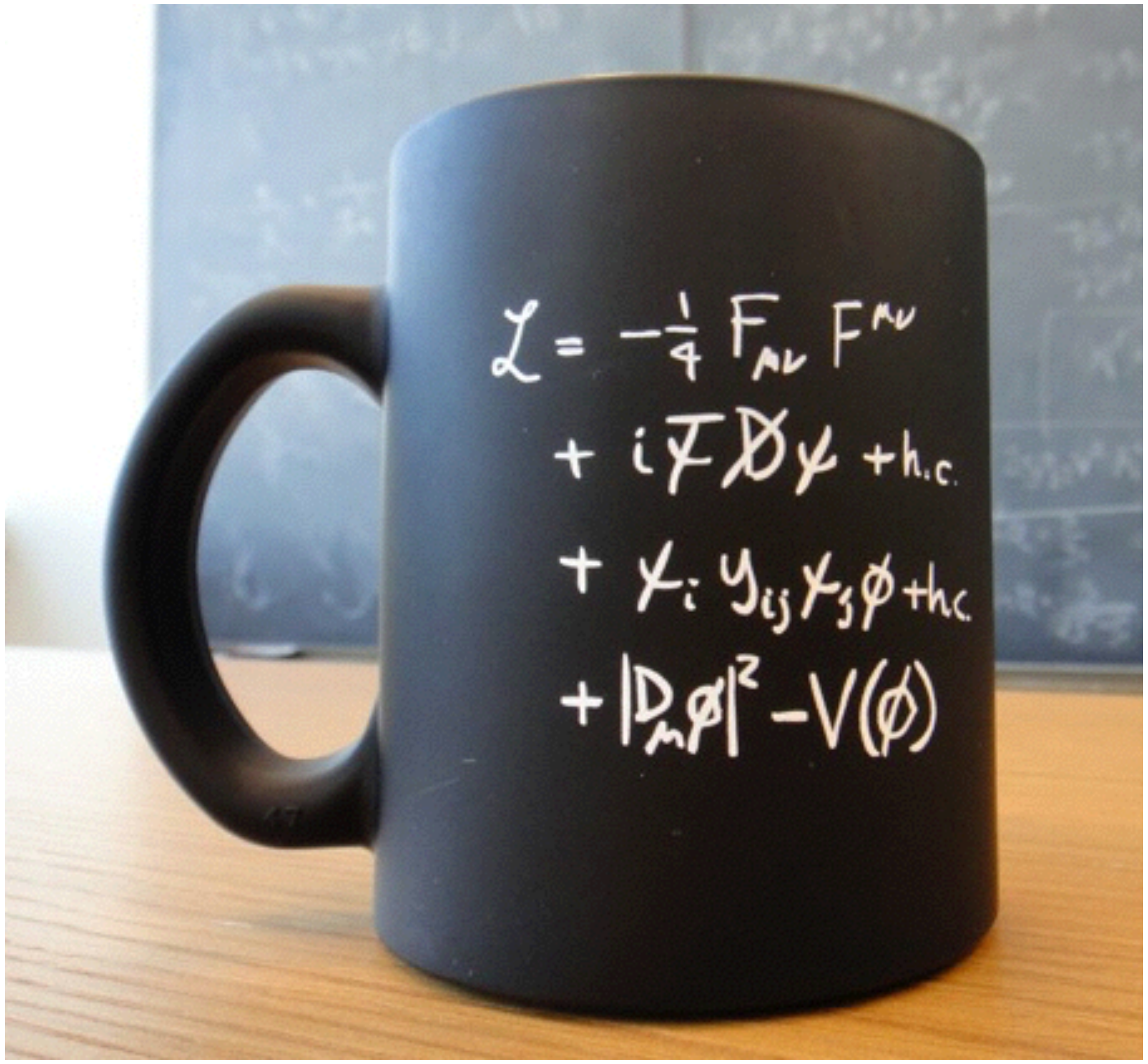


Image credit: Flip Tanedo

Analog versus Digital Quantum Circuits

Goal: implement our system’s Hamiltonian (e.g. the SM) in a proxy system (“quantum computer”) and let it evolve.

The best quantum computer is the one that looks just like the system you are trying to model!

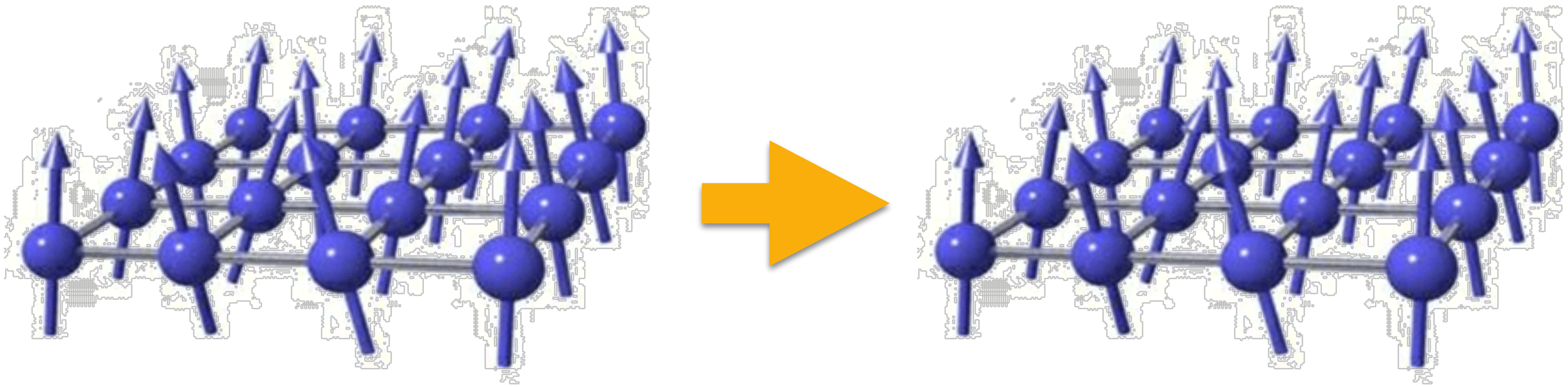


Image credit: https://www3.physik.uni-stuttgart.de/TR21/en/about/research.php

Analog versus Digital Quantum Circuits

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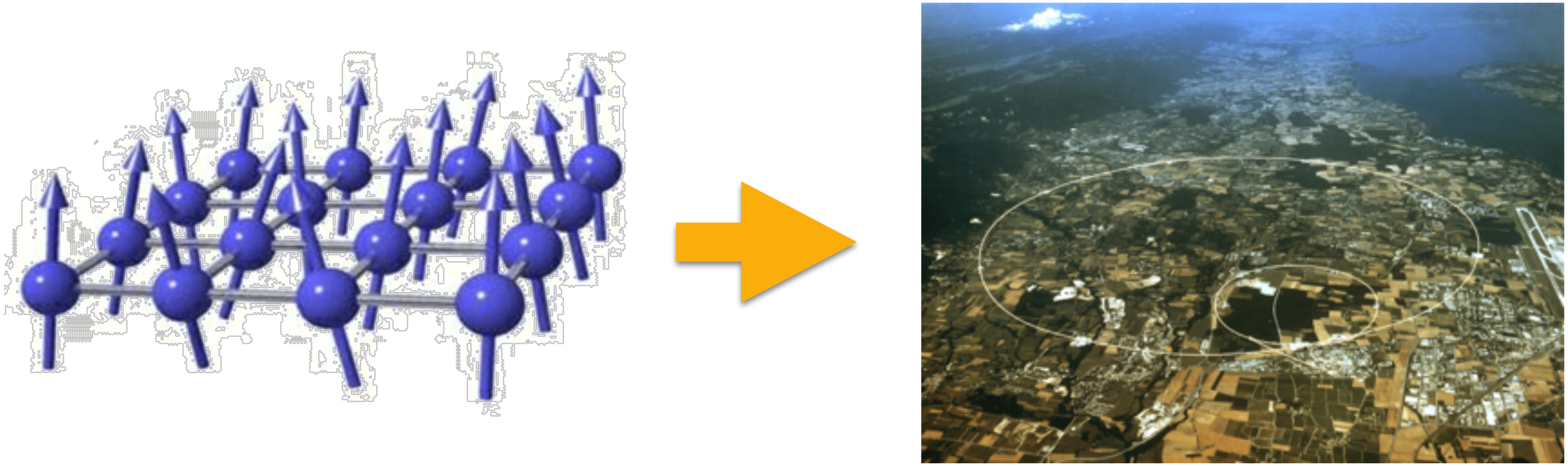
Not always possible!

Image credit: CERN

Analog versus **Digital** Quantum Circuits

Goal: implement our system's Hamiltonian (e.g. the SM) in a proxy system ("quantum computer") and let it evolve.

In this setup, the possibilities are endless; the key is efficiency.



Modern Universal Quantum Computers

There is no consensus on architecture, but most efforts for universal quantum computing use superconductors.

I’m not going to talk about hardware,
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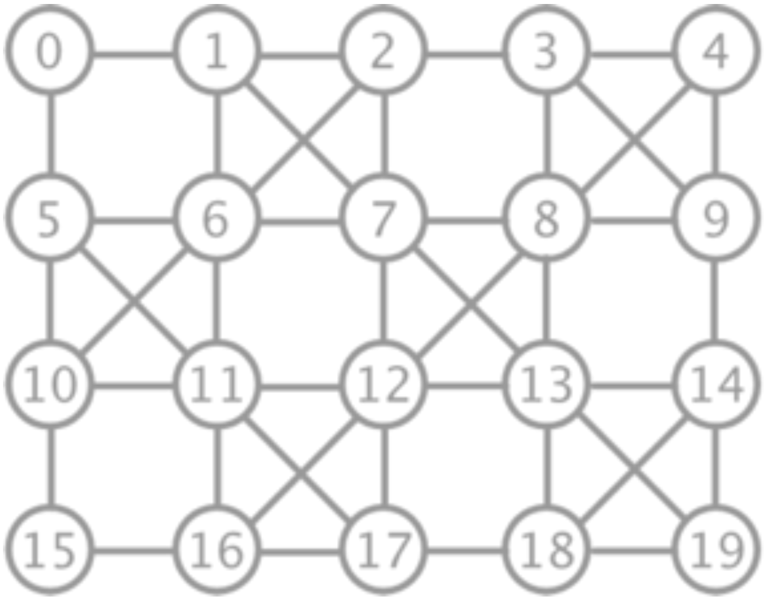
classical computing in the 1970's

quantum computing now

State-of-the-art quantum computers

The best quantum computers have O(10) **qubits** with O(1) connections per qubit and can stay coherent for O(100) of operations.

*A **qubit** is an abstract representation of a quantum system that can be in a superposition of two states (often thought of as a spin)*



This is one of IBM’s 20-qubit quantum computers. Lines represent connections.

Programming

Just like a classical computer, one can write programs for a universal quantum computer.

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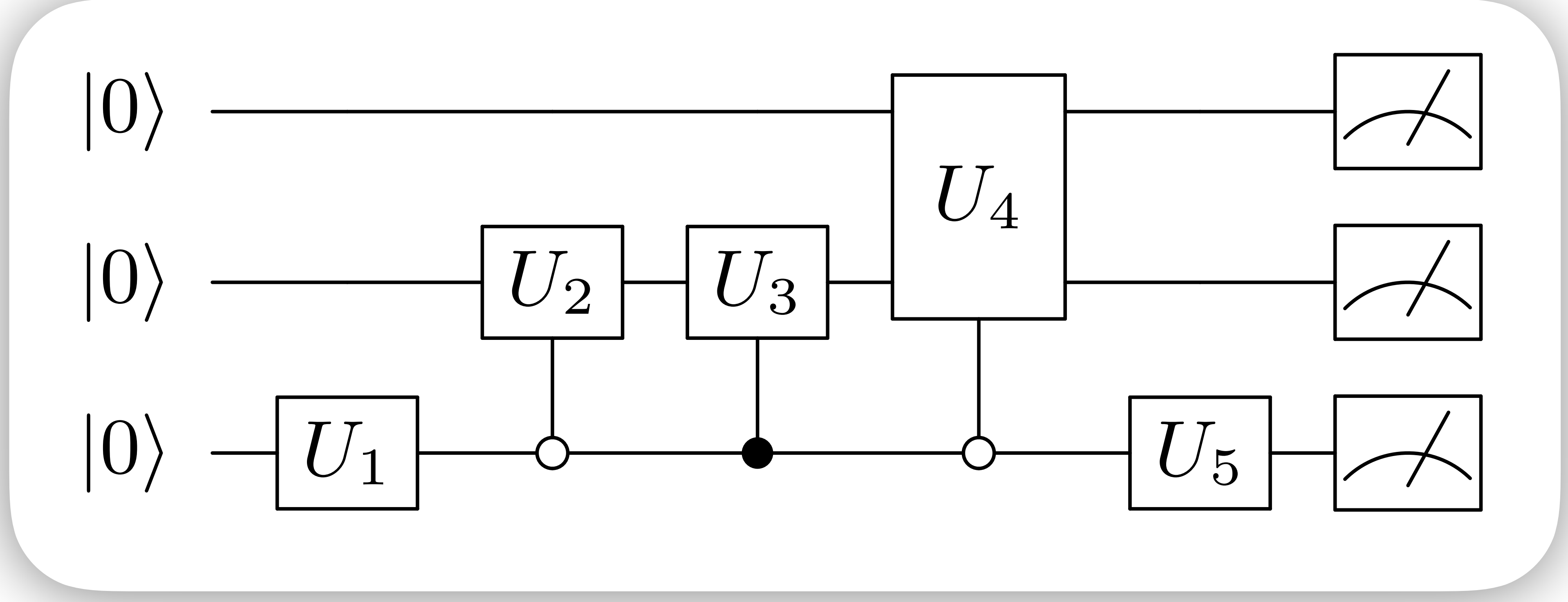

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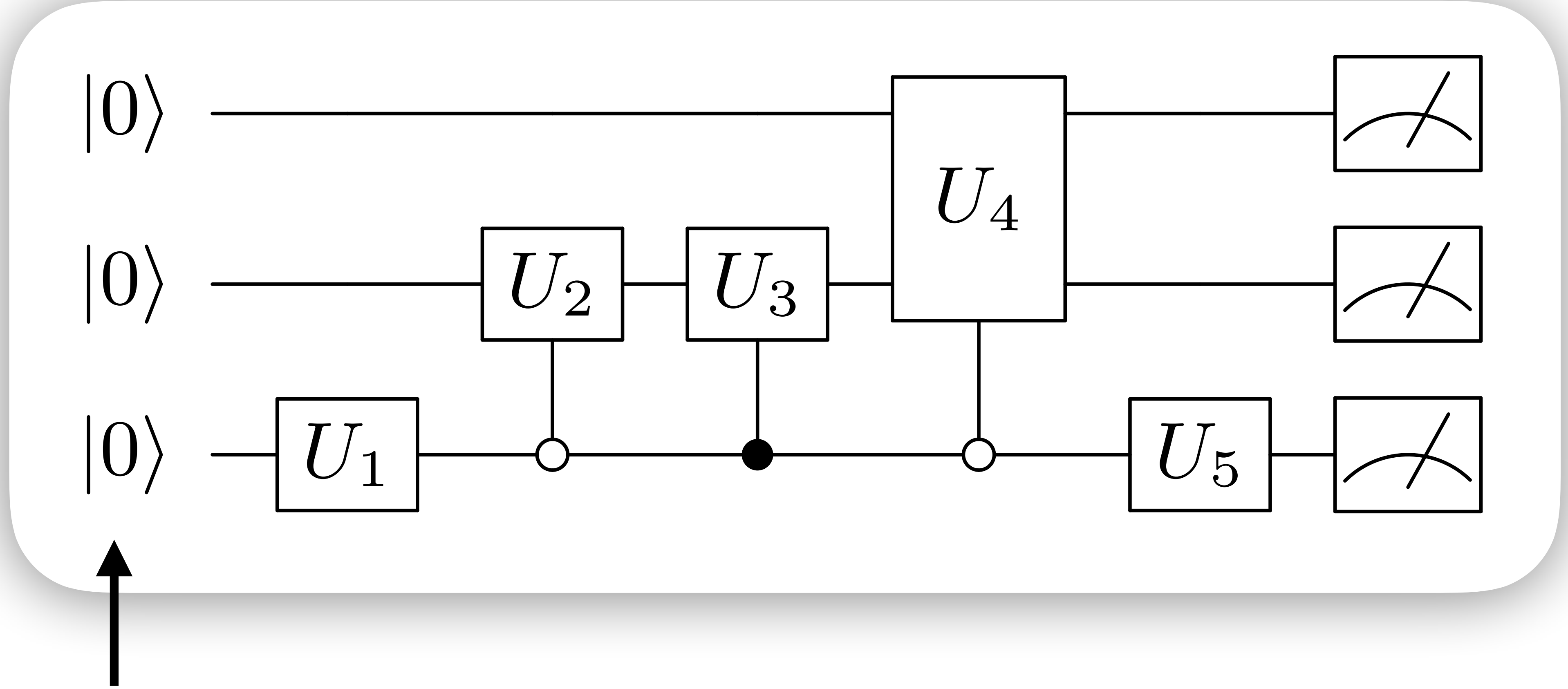

Initialize in the ground state.

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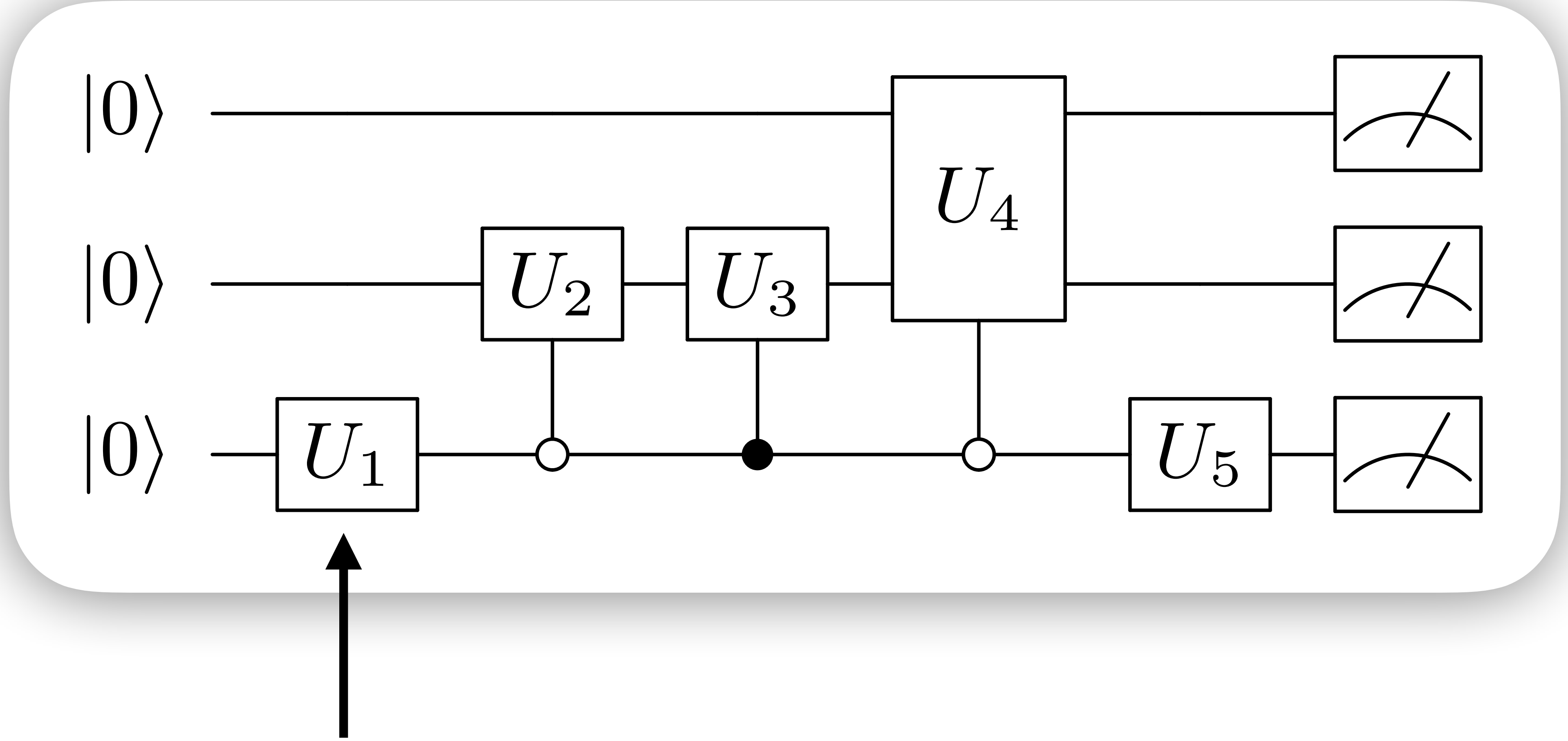
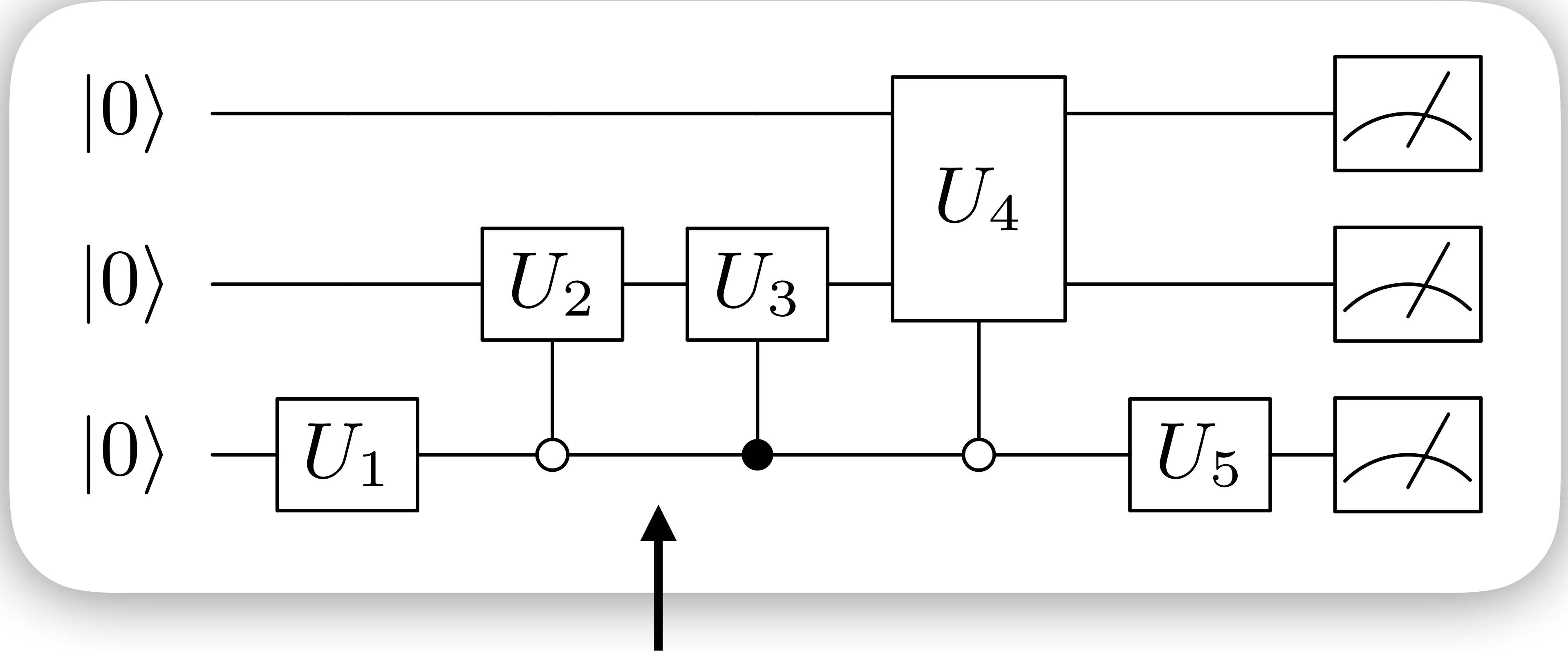


Apply unitary matrix U_1 to the third qubit

Programming

Just like a classical computer, one can write programs for a universal quantum computer.



Apply unitary matrix U_2 to the second qubit when the third is 0, else apply U_3.

Programming

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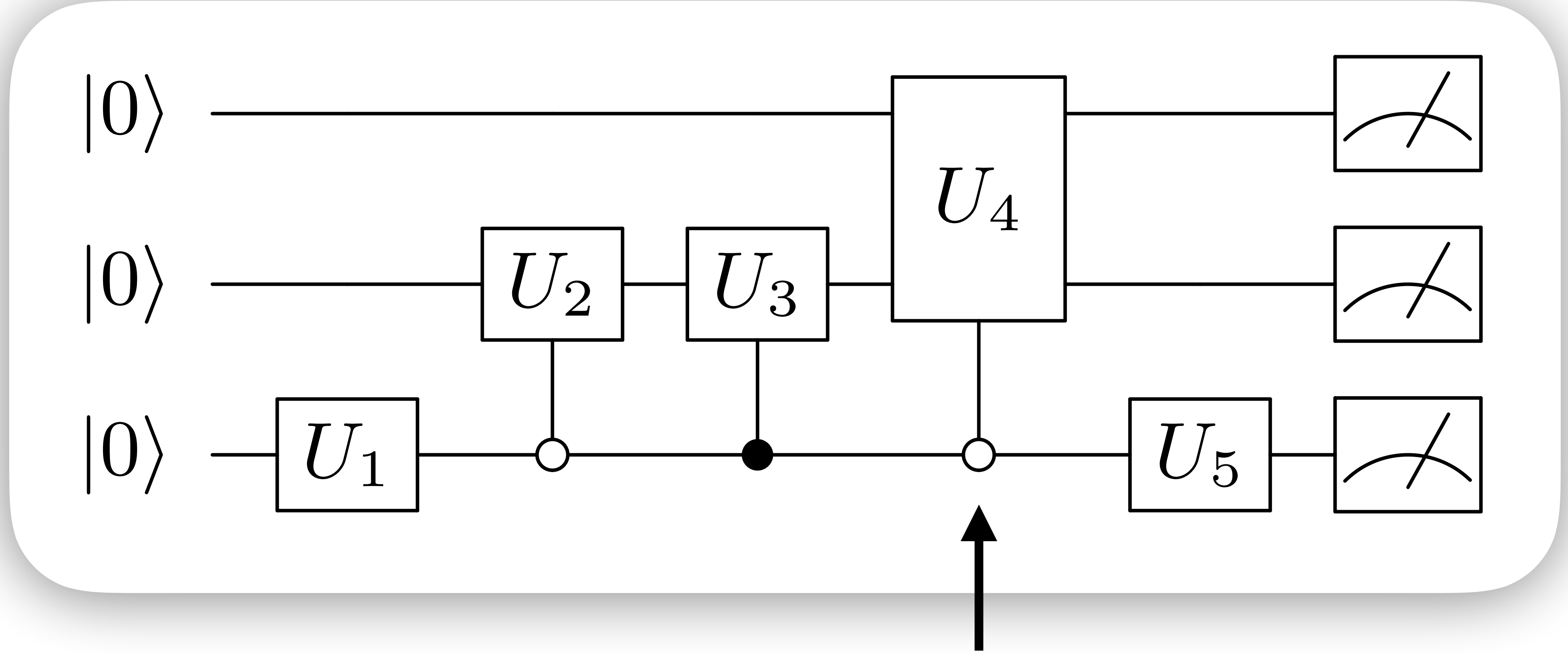

Apply unitary matrix U_4 to both the first and second quits when the third is 0.

Programming

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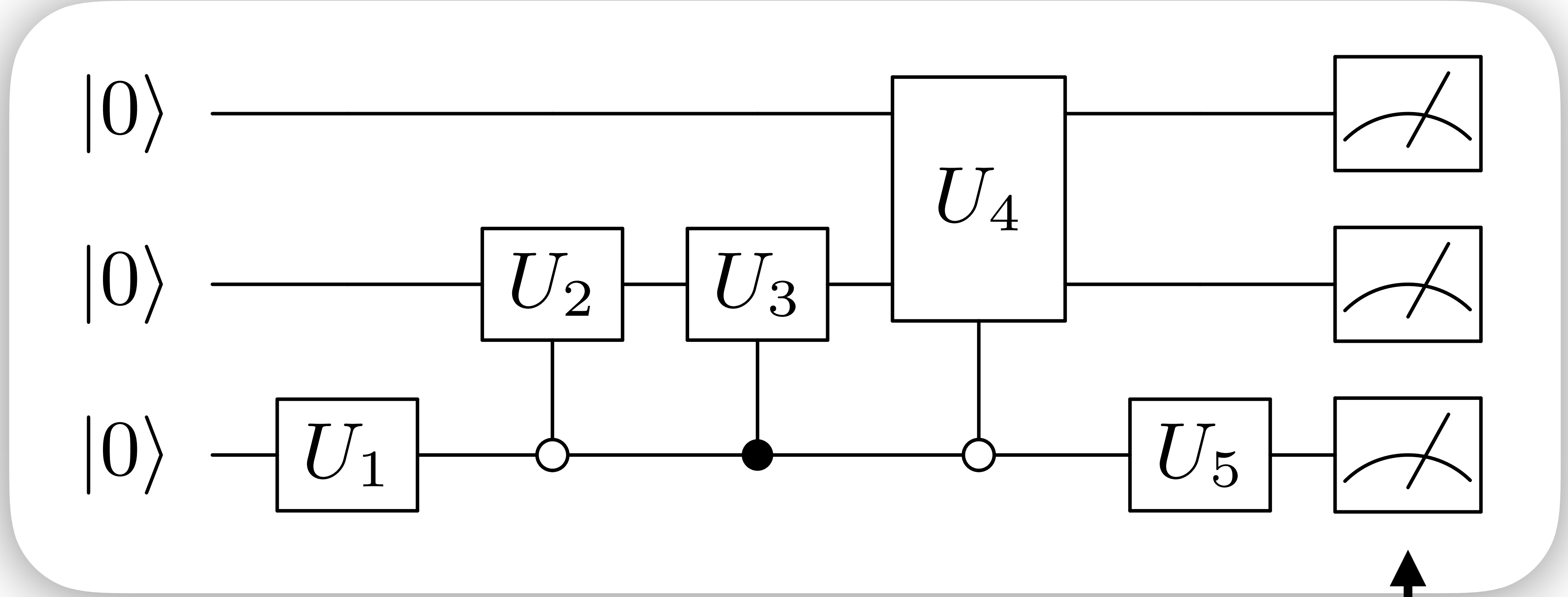
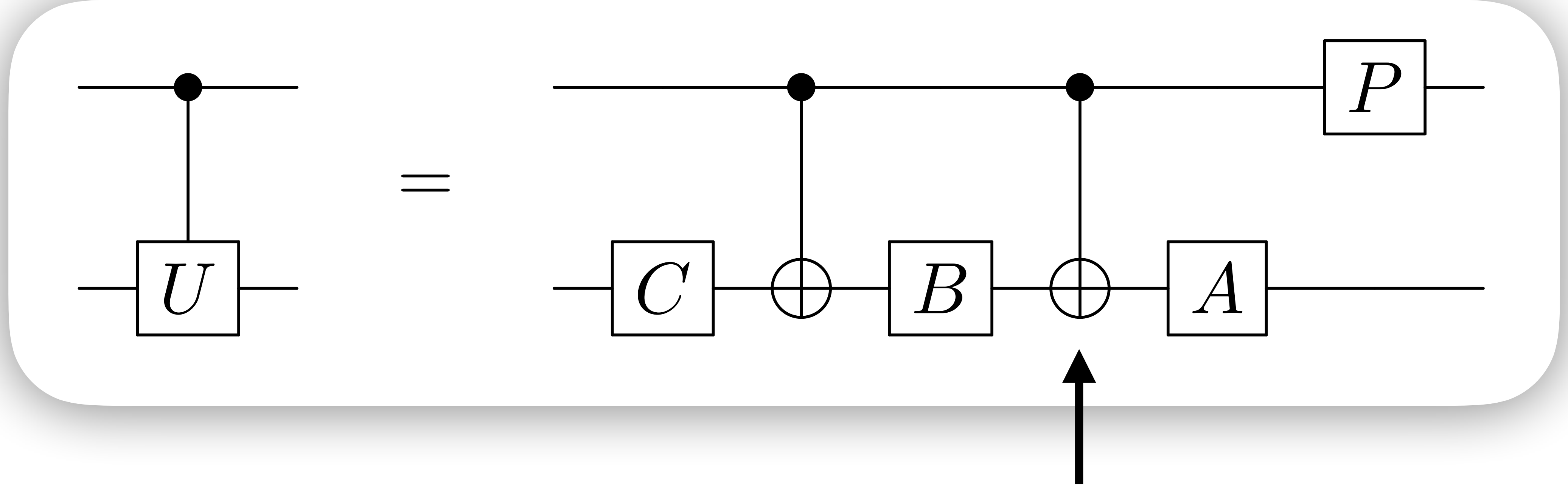


Measure all the qubits

Challenges with current computers

In practice: only controlled operation that is allowed is CNOT (swap if 1 otherwise do nothing) … need to decompose.



CNOT

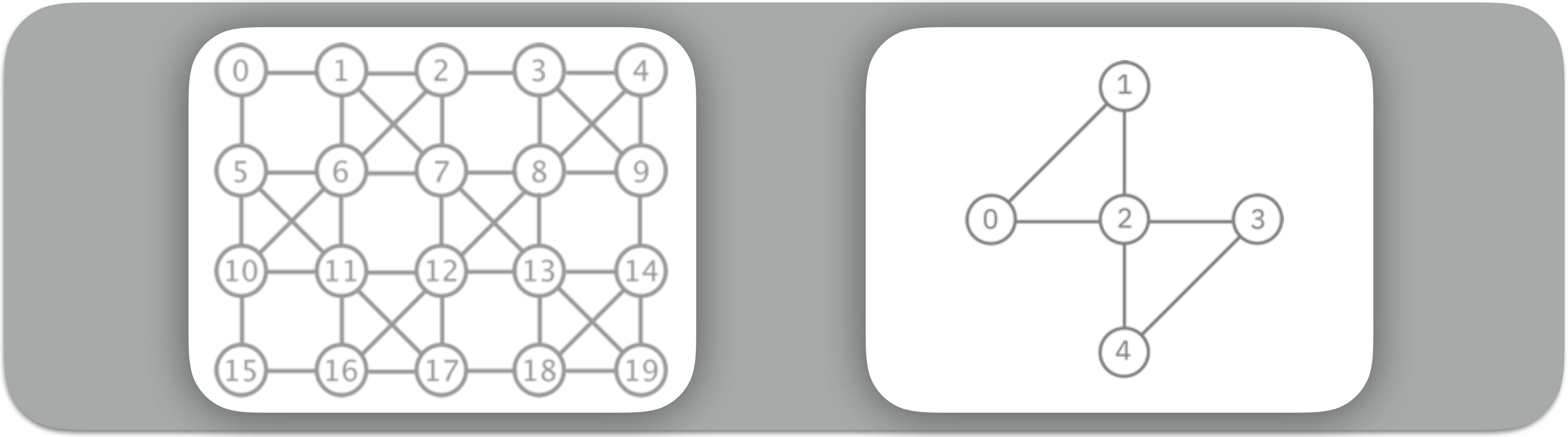
There is no compiler … need to do circuit decomposition by hand (!)

Challenges with current computers

In practice: only controlled operation that is allowed is CNOT (swap if 1 otherwise do nothing) … need to decompose.

Circuit implementation is architecture-dependent
need to know what connections are available

(can swap, but CANNOT clone qubits!)



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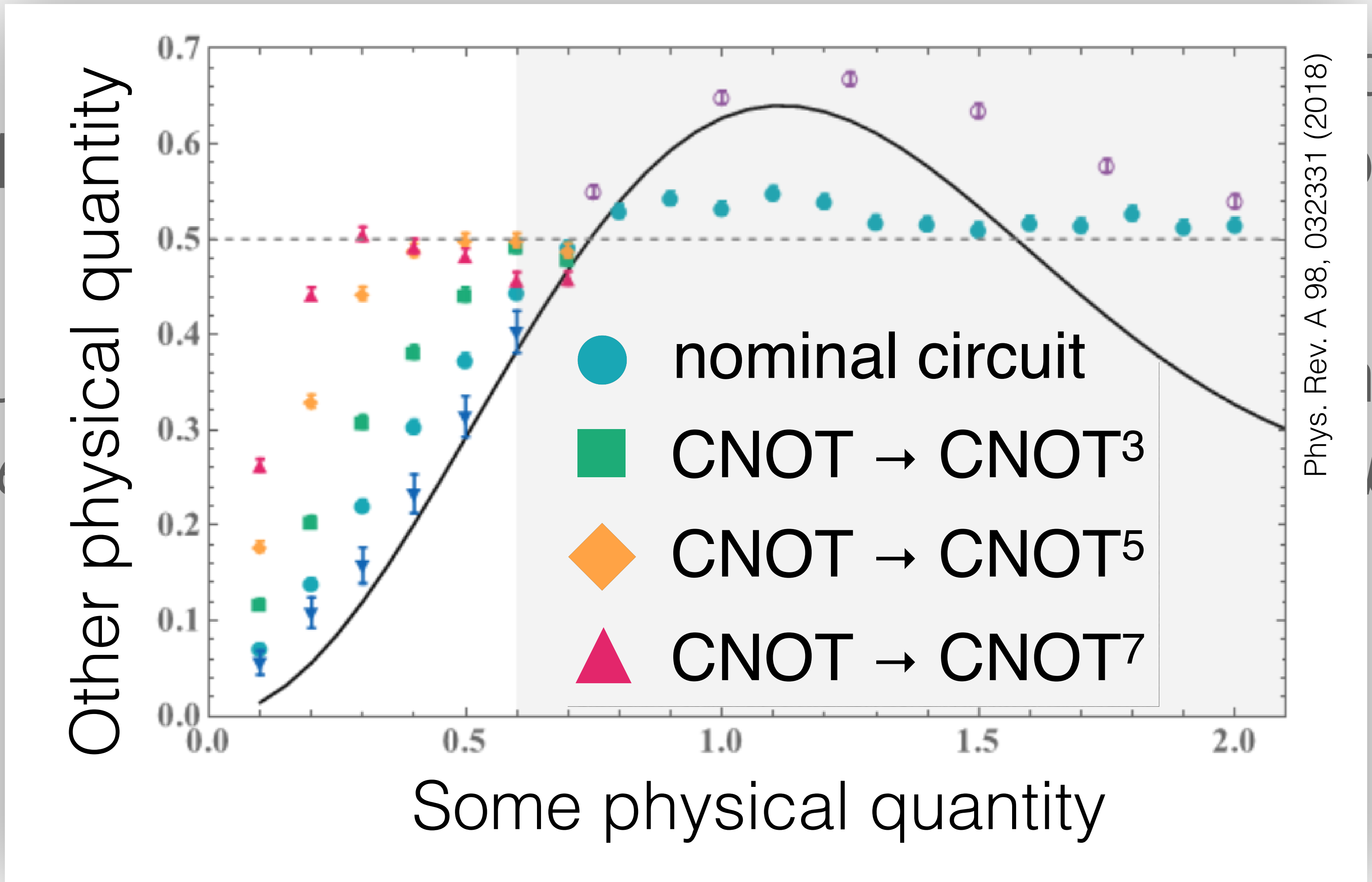


Phys. Rev. A 98, 032331 (2018)

N.B. CNOT^2
= identity

Most importantly: current quantum computers are super noisy. Need to minimize number of operations.

Potential of quantum computers

Caveats aside, there is a good reason to be excited.

There have been impressive leaps in hardware, “firmware”, & algorithms in the last years and interest has exploded.

perhaps some misguided …

Will you have a QPU in your laptop 5 years from now?

No. But you may be able to run on a QPU in 5 years that allows you to make a calculation that was not possible before (!)

Our goal

There are many ongoing efforts to do full QFT calculations with a QPU lattice*.

Our goal is more focused: many aspects of QFT calculations can be performed well on classical computers

(e.g. automated NLO with MadGraph … N.B. high energy part hardest for lattice)

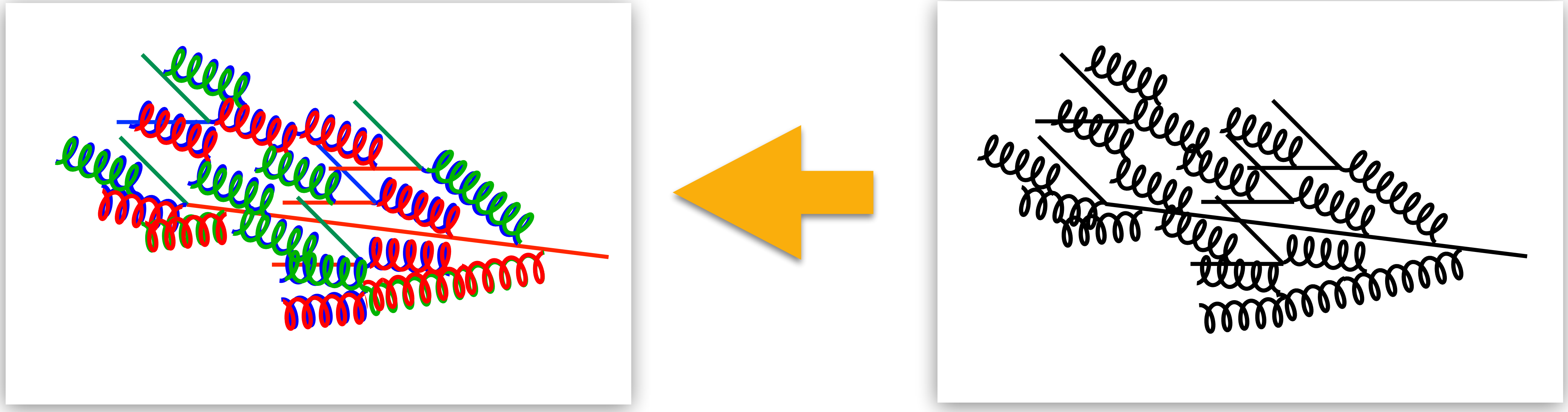
Can a piece of the calculation that is hard/impossible with classical computers & accelerate it on a QPU?

**for a great perspective piece, see Preskill's recent Lattice2018 talk:1811.10085*

One challenge: Final state radiation

FSR is a complex many-body quantum system.

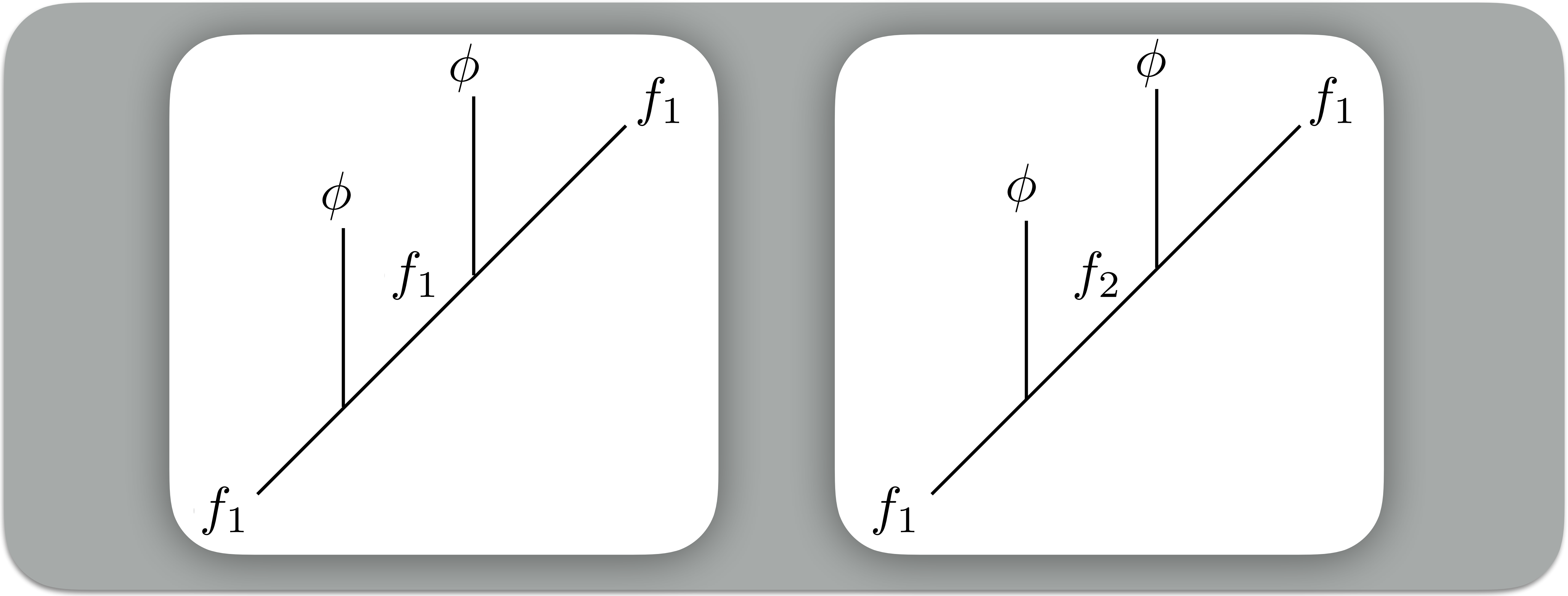
Perhaps quantum tools can be used to incorporate quantum degrees of freedom!



A simple model with complex pheno

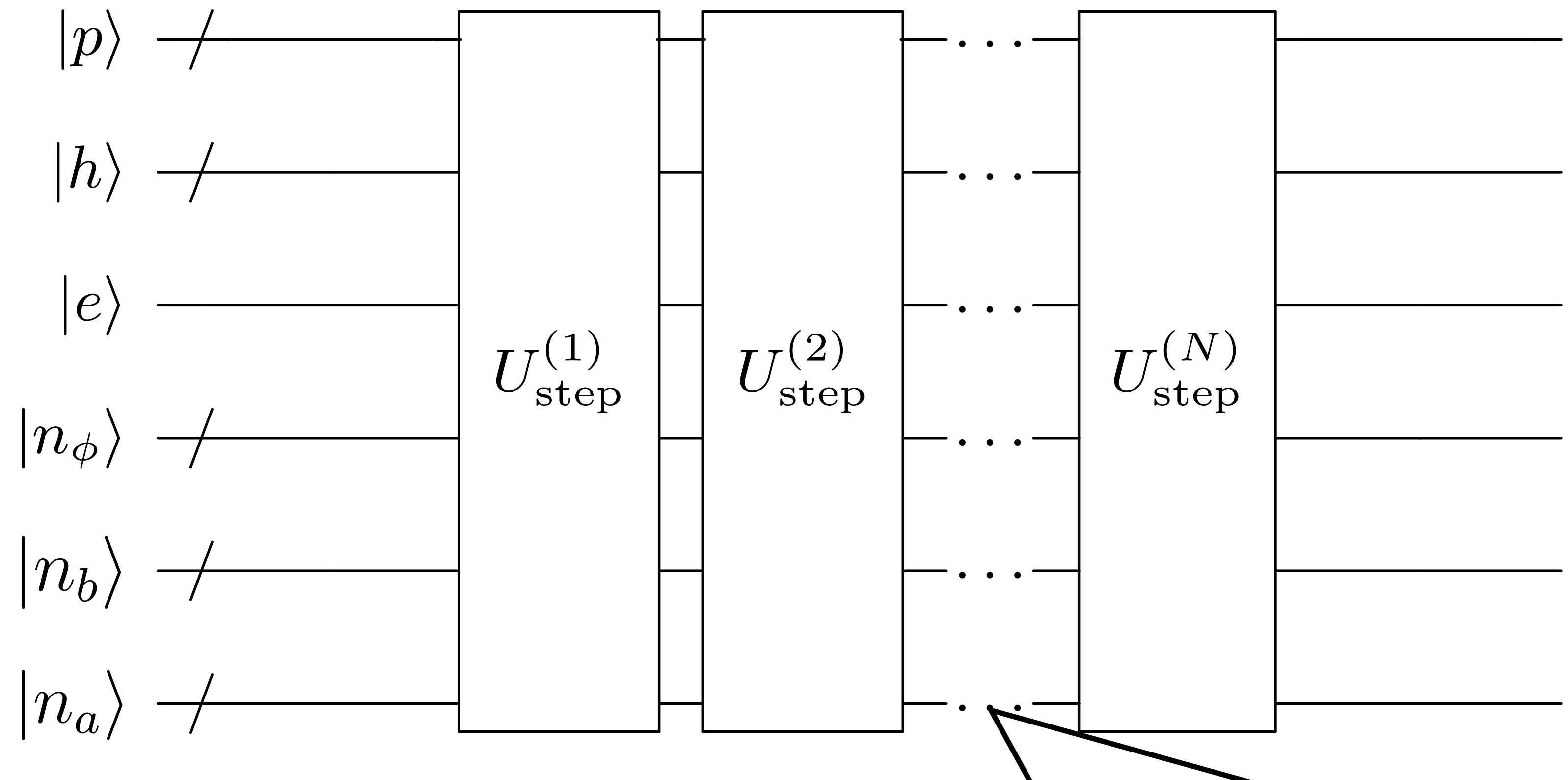
$$\begin{aligned}\mathcal{L} =& \bar{f}_1 i(\not{\partial} + m_1) f_1 + \bar{f}_2 (i\not{\partial} + m_2) f_2 + (\partial_\mu \phi)^2 \\ &+ g_1 \bar{f}_1 f_1 \phi + g_2 \bar{f}_2 f_2 \phi + g_{12} \left[\bar{f}_1 f_2 + \bar{f}_2 f_1 \right] \phi\end{aligned}$$

(like the SM Higgs when $g_{12} \sim m/v$ and $g_1 = g_2 = 0$)

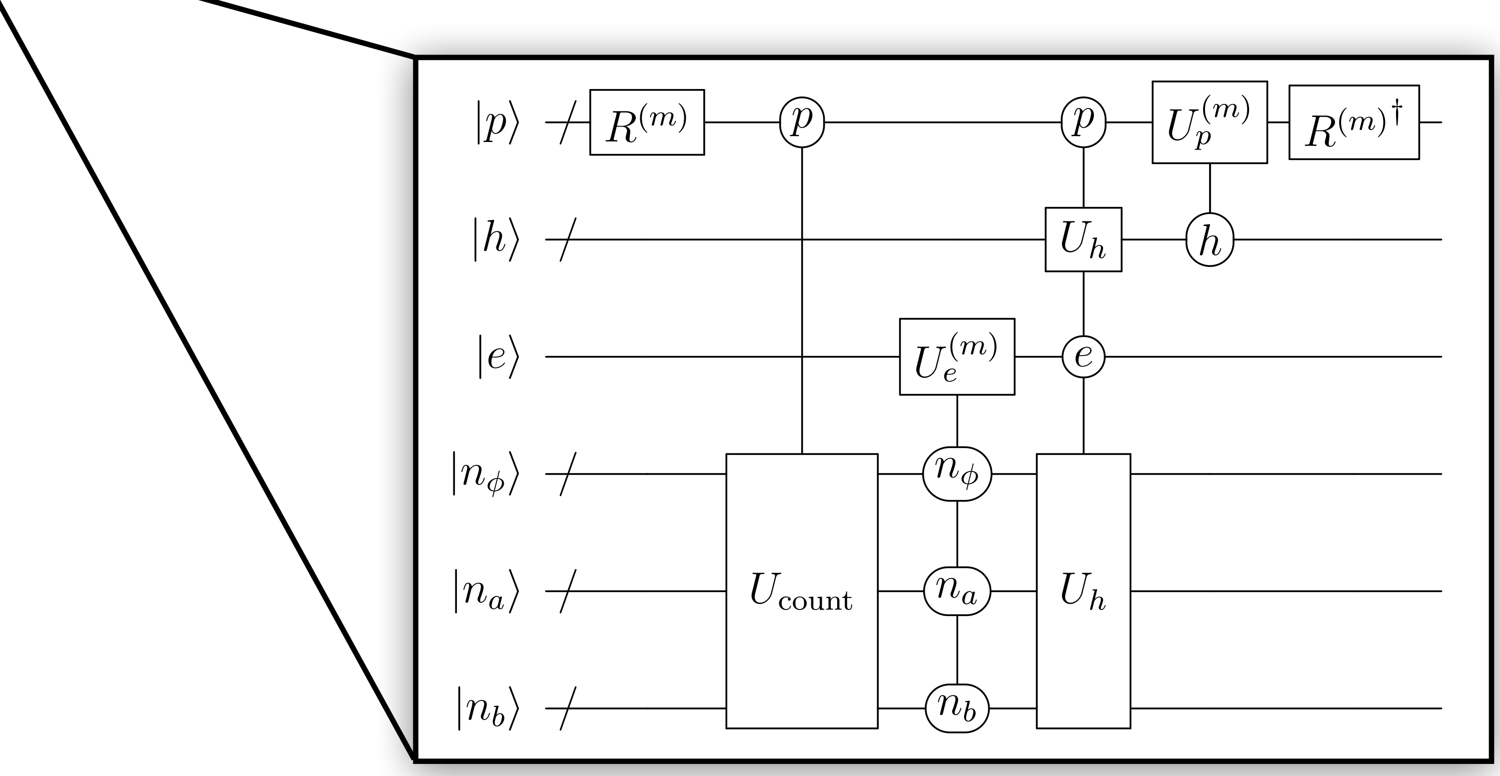


aka baby electroweak shower … not QCD because Sudakov independent of spin

The quantum algorithm



Register	Purpose	# of qubits
$\lvert p\rangle$	Particle state	$3(N+n_I)$
$\lvert h\rangle$	Emission history	$N\lceil\log_2(N+n_I)\rceil$
$\lvert e\rangle$	Did emission happen?	1
$\lvert n_\phi\rangle$	Number of bosons	$\lceil\log_2(N+n_I)\rceil$
$\lvert n_a\rangle$	Number of f_a	$\lceil\log_2(N+n_I)\rceil$
$\lvert n_b\rangle$	Number of f_b	$\lceil\log_2(N+n_I)\rceil$



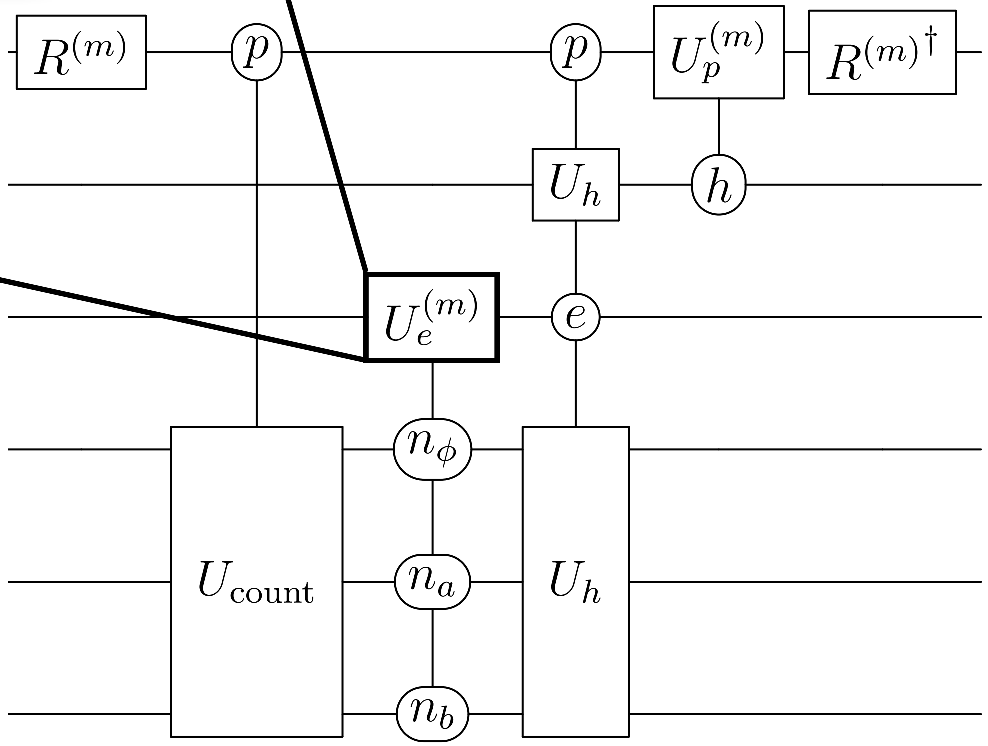
The quantum circuit - U_e (e = emit)

$$U_e^{(m)} = \begin{pmatrix} \Delta^{(m)}(\theta_m) & -\sqrt{1-\Delta^{(m)}(\theta_m)} \\ \sqrt{1-\Delta^{(m)}(\theta_m)} & \Delta^{(m)}(\theta_m) \end{pmatrix}$$

$$\Delta_i(\theta_m, \theta_{m+1}) = e^{-\Delta\theta P_i(\theta_m)}$$

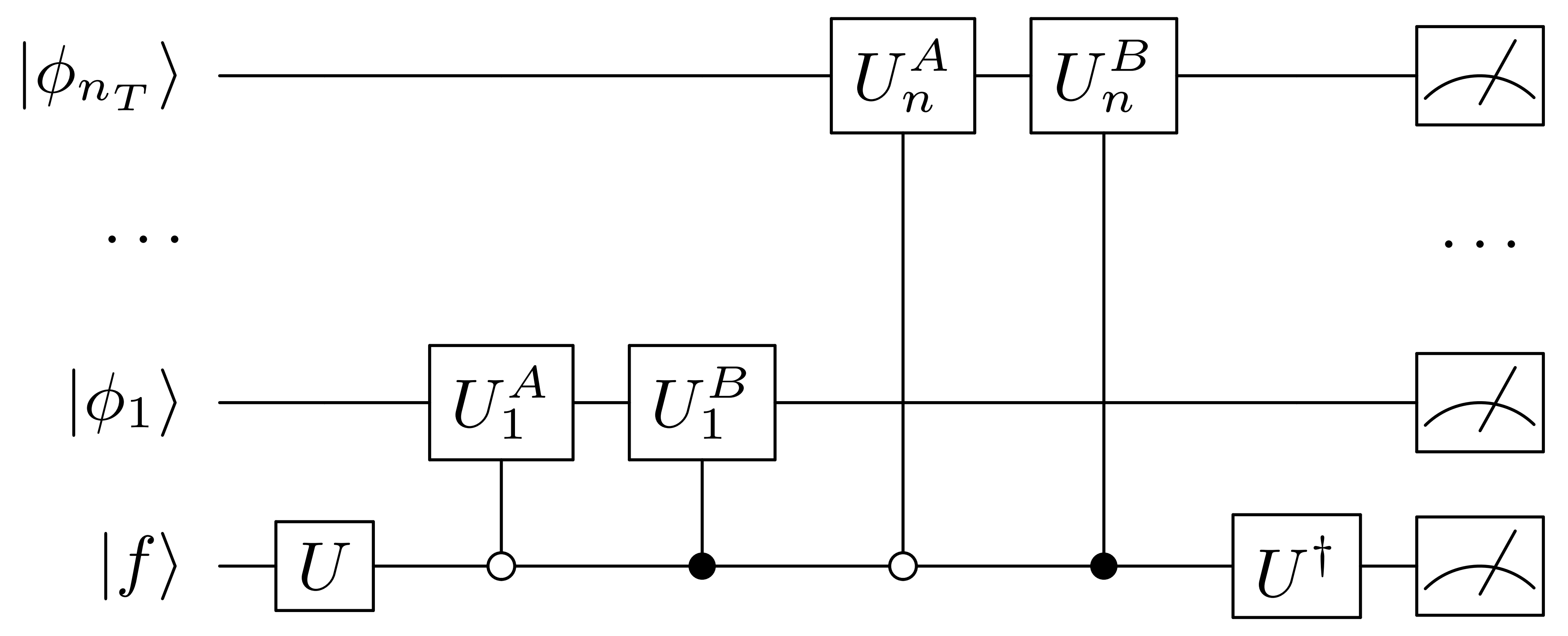
(Sudakov factor)

$$\Delta^{(m)}(\theta_m) = \Delta_\phi^{n_\phi}(\theta_m)\Delta_{f_1}^{n_{f_1}}(\theta_m)\Delta_{f_2}^{n_{f_2}}(\theta_m)$$



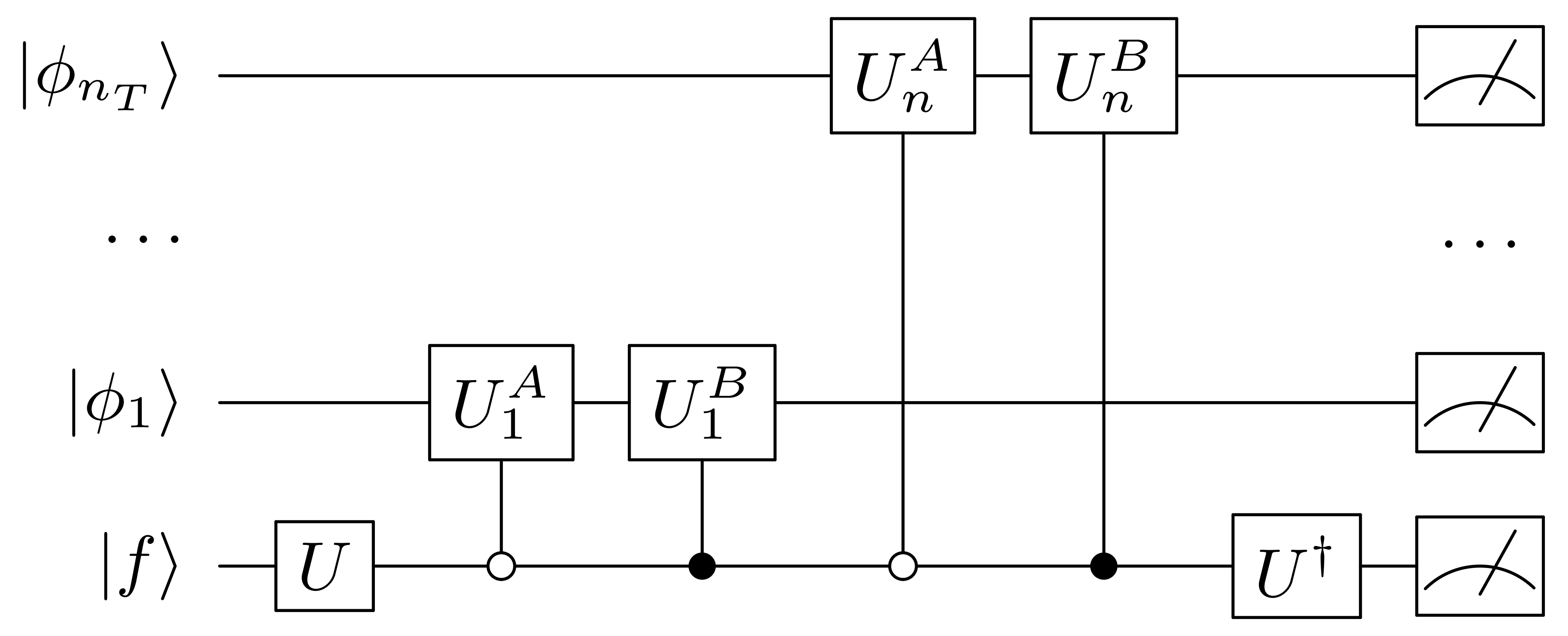
I'll show you the circuit when the splitting is turned off in a moment, but for fun, let's talk about one element.

The circuit without scalar splitting



In words: rotate to the basis where there is no interference, "emit" scalars (at the **amplitude** level), and then rotate back to the physical basis at the end.

The circuit without scalar splitting



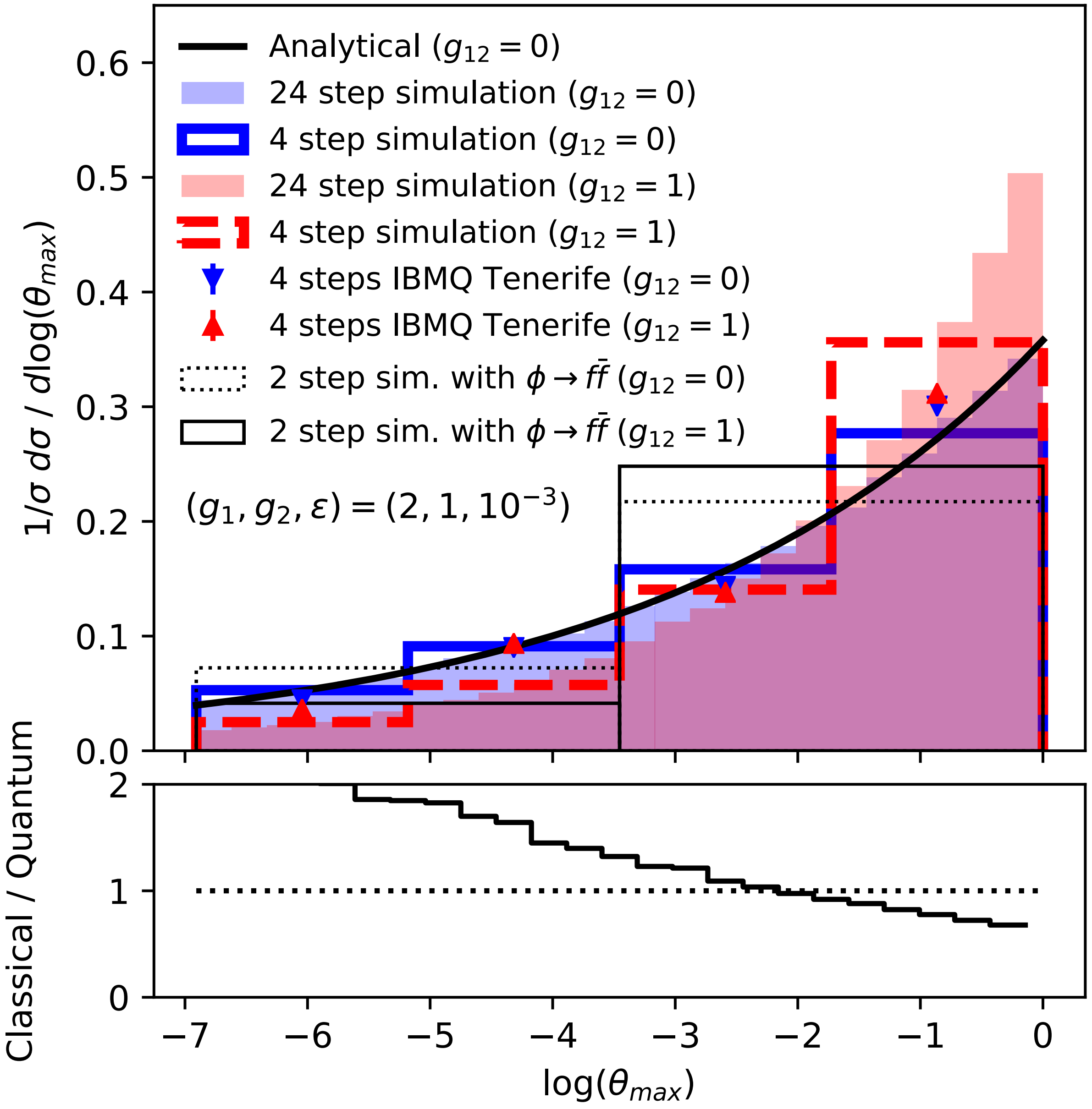
Note: $|\phi_i\rangle$ is not touched after tilmestep i and so one can reuse qubits … only need 2 total qubits (!)

Fine print: (1) re-measurement is not a feature of most current quantum computers and (2) this led us to a classical algorithm that can capture the full interference effects (but is not the naive MCMC).

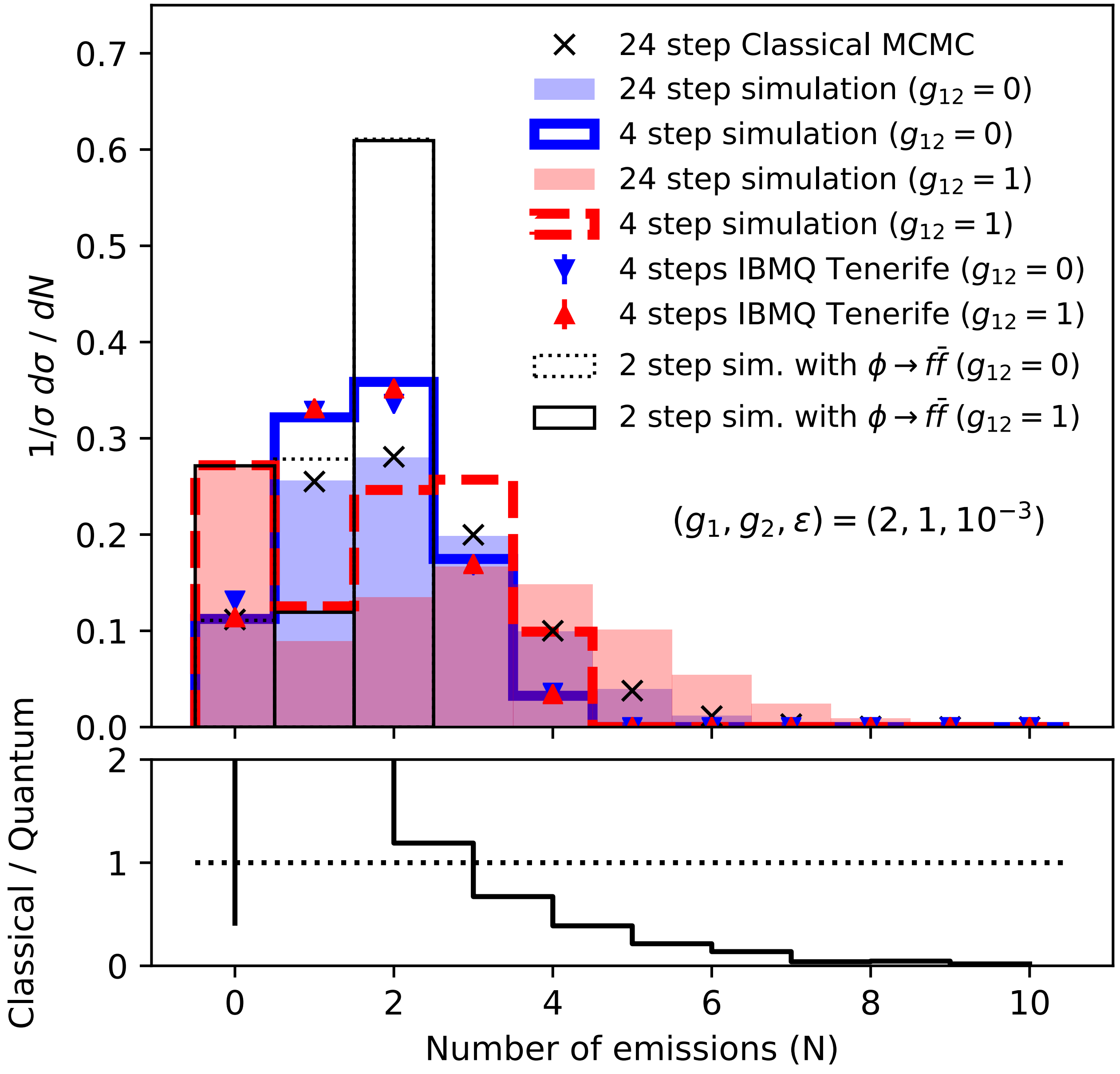
Some numerical results

no interference

with interference



angle of maximum emission



number of emissions

The future

There is a long road ahead, but quantum algorithms are very promising for modeling high energy scattering processes.

Today I gave you a small taste of what is possible - stay tuned for more!

Still serious challenges: scalability, noise, etc.

…in the mean time, note that there is an impressive effort to add in quantum effects to parton showers as corrections.

see e.g. this pioneering work: Nagy and Soper, JHEP 09 (2007) 114

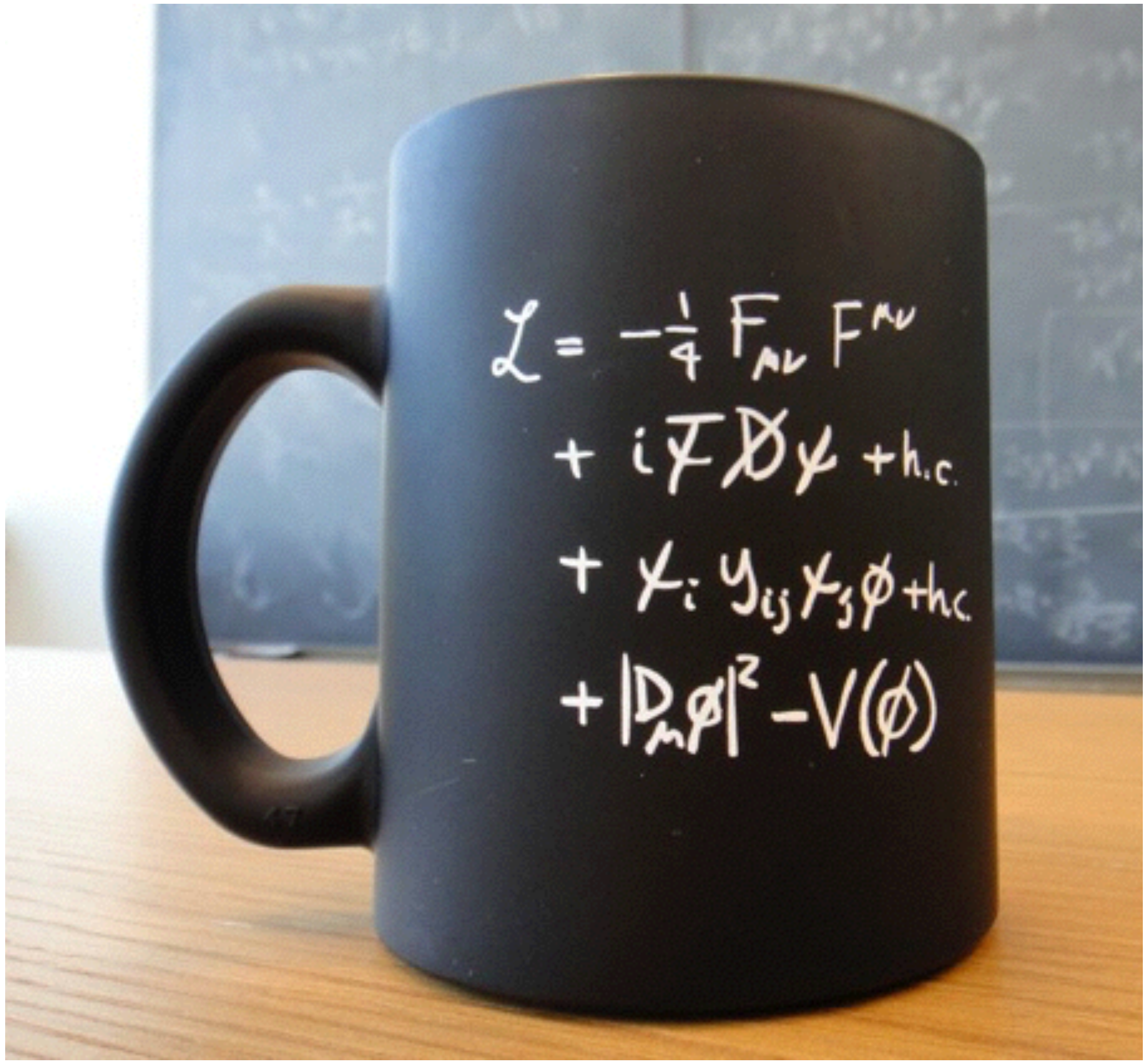
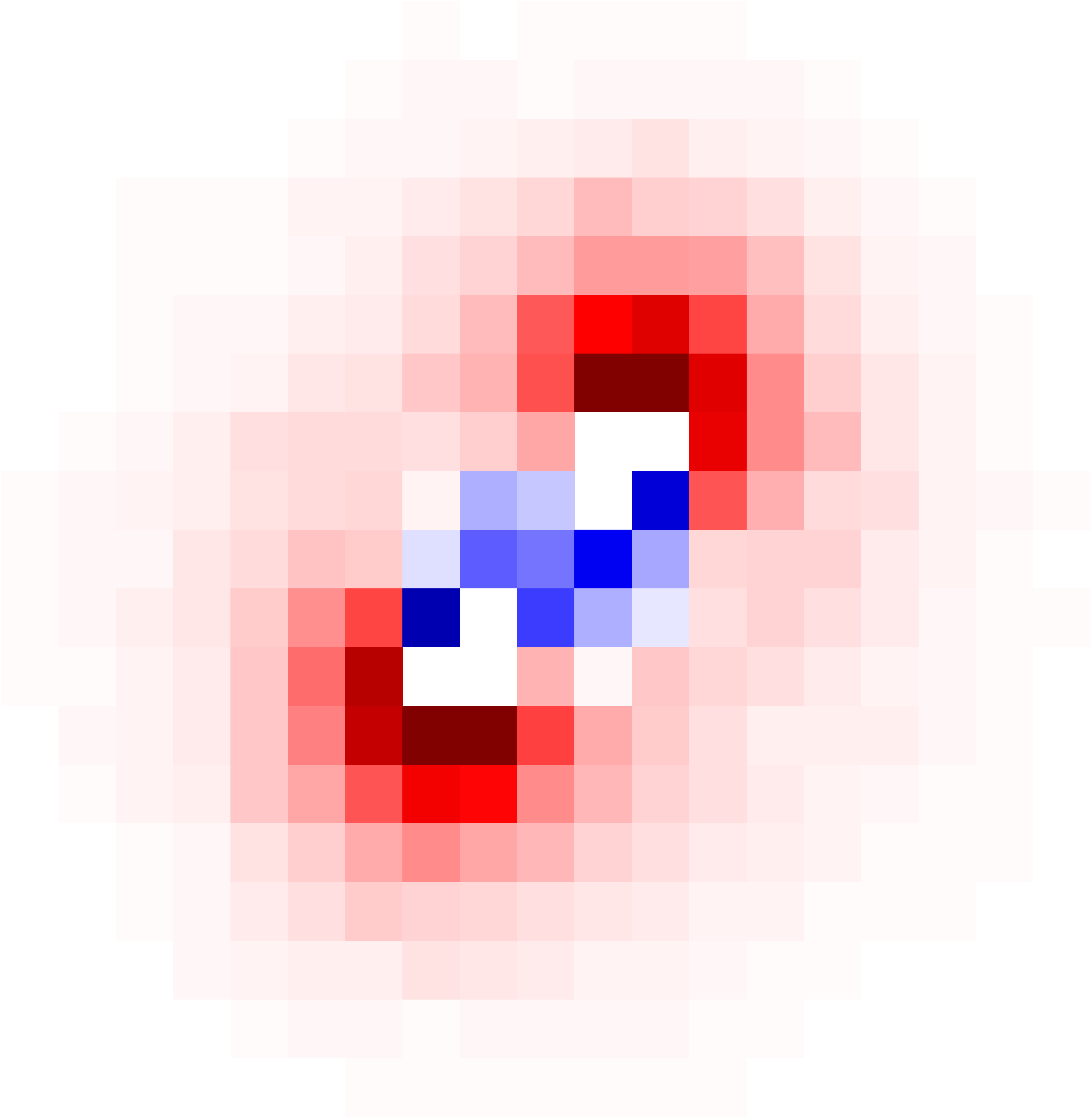
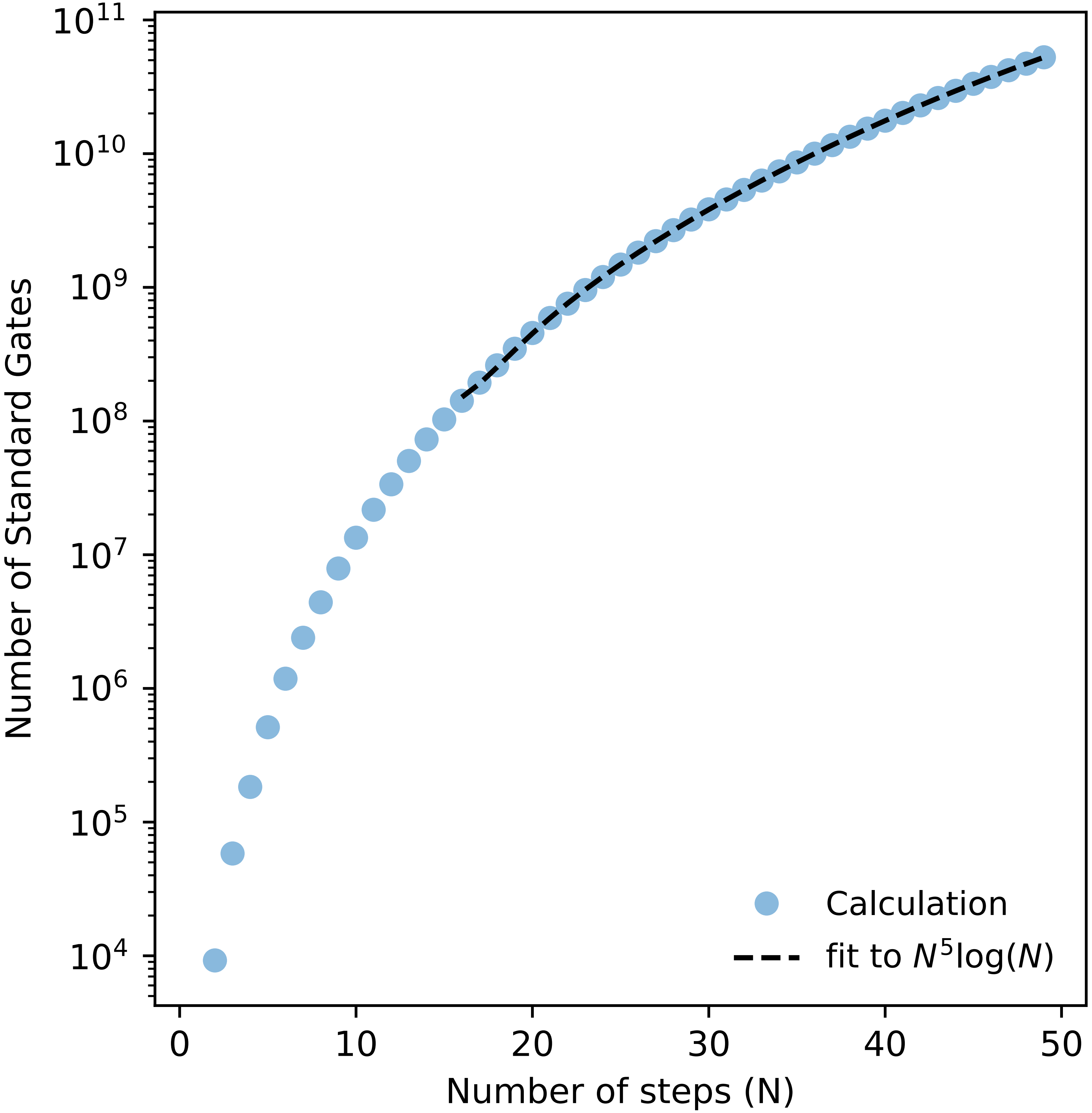


Image credit: Flip Tanedo



Fin.


10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
Number of Standard Gates
0
10
20
30
40
50
Number of steps (N)
Calculation
fit to $N^5\log(N)$

Operation	Complexity		
	Scaling	$(N = 4)$	$(N = 24)$
count particles $[U_{\text{count}}]$	$N \ln N$	4.93×10^2	5.45×10^4
decide emission $[U_e]$	$N^4 \ln N$	9.29×10^3	8.75×10^6
create history $[U_h]$	$N^5 \ln N$	1.69×10^5	1.19×10^9
adjust particles $[U_p]$	$N^2 \ln N$	5.01×10^3	3.37×10^5

$$|p\rangle_i = \begin{pmatrix} 000 \\ 001 \\ 010 \\ 011 \\ 100 \\ 101 \\ 110 \\ 111 \end{pmatrix} = \begin{pmatrix} 0 \\ \phi \\ - \\ - \\ f_1/f_a \\ f_2/f_b \\ \bar{f}_1/\bar{f}_a \\ \bar{f}_2/\bar{f}_b \end{pmatrix}$$