Quantum Computing

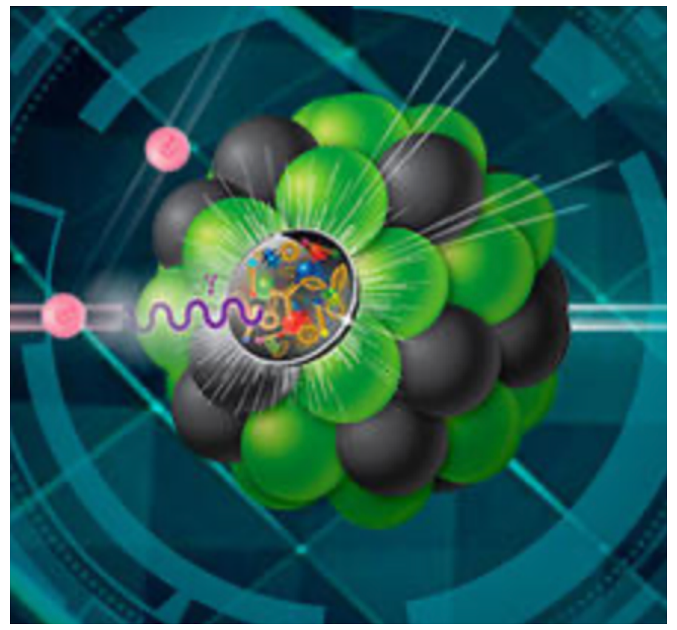
19th July 2022, BNL Physics Summer Lecture

João Barata, Nuclear Theory Group and C2QA

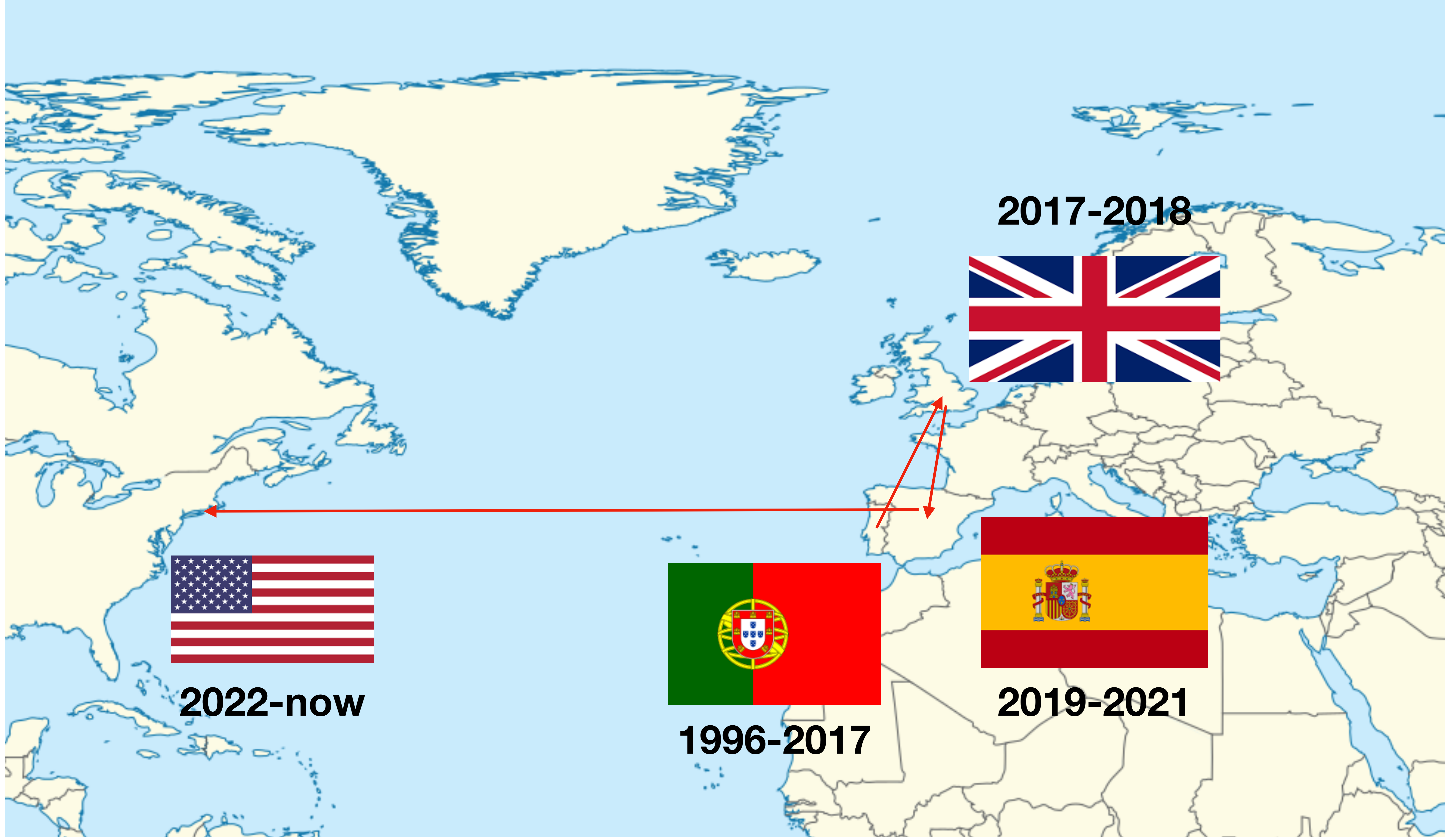
About me

My name: João Barata

Current position: post-doc

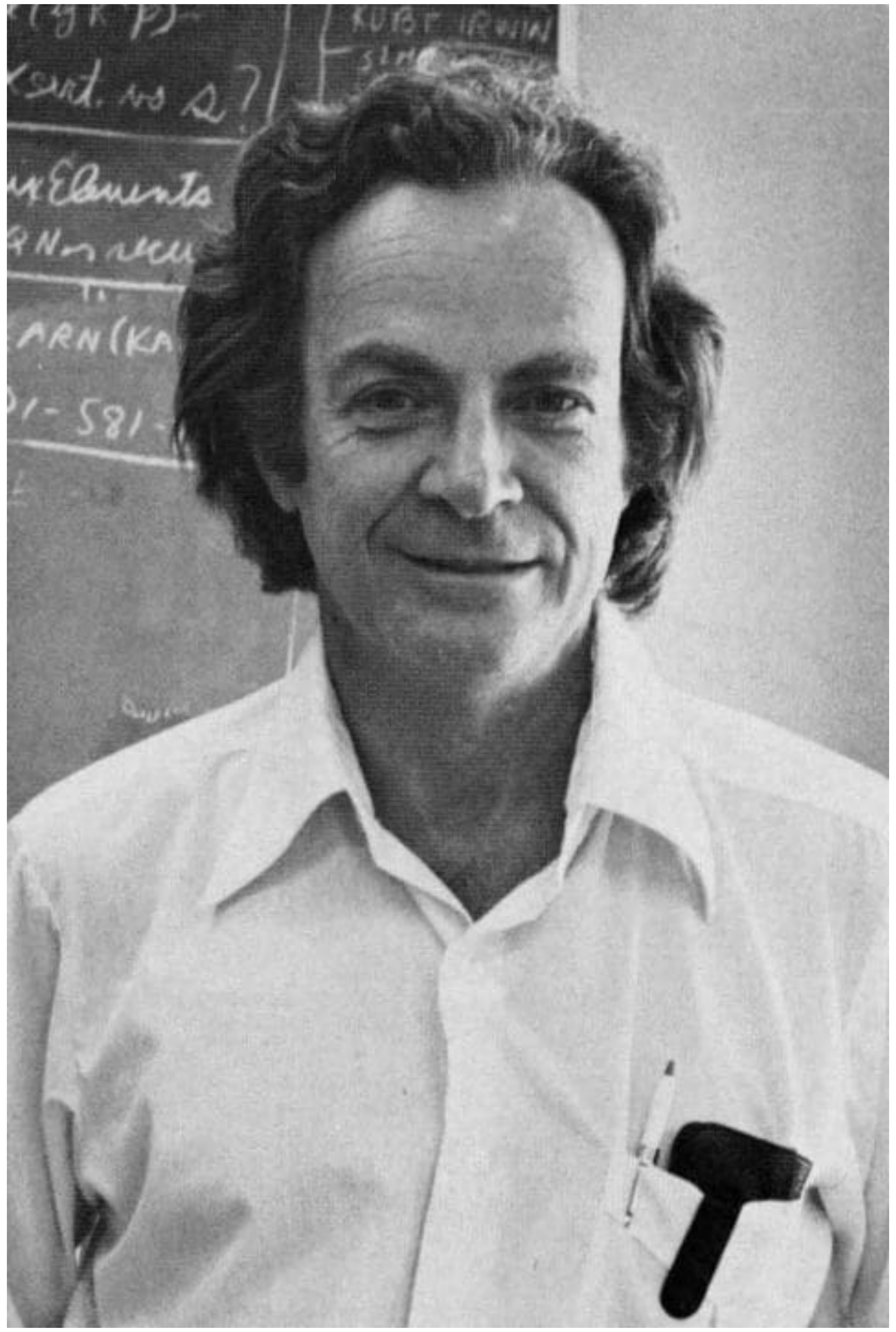


C^2QA



If you have questions or want to chat, you can find me in 2.42

Why Quantum Computing ?



Richard Feynman

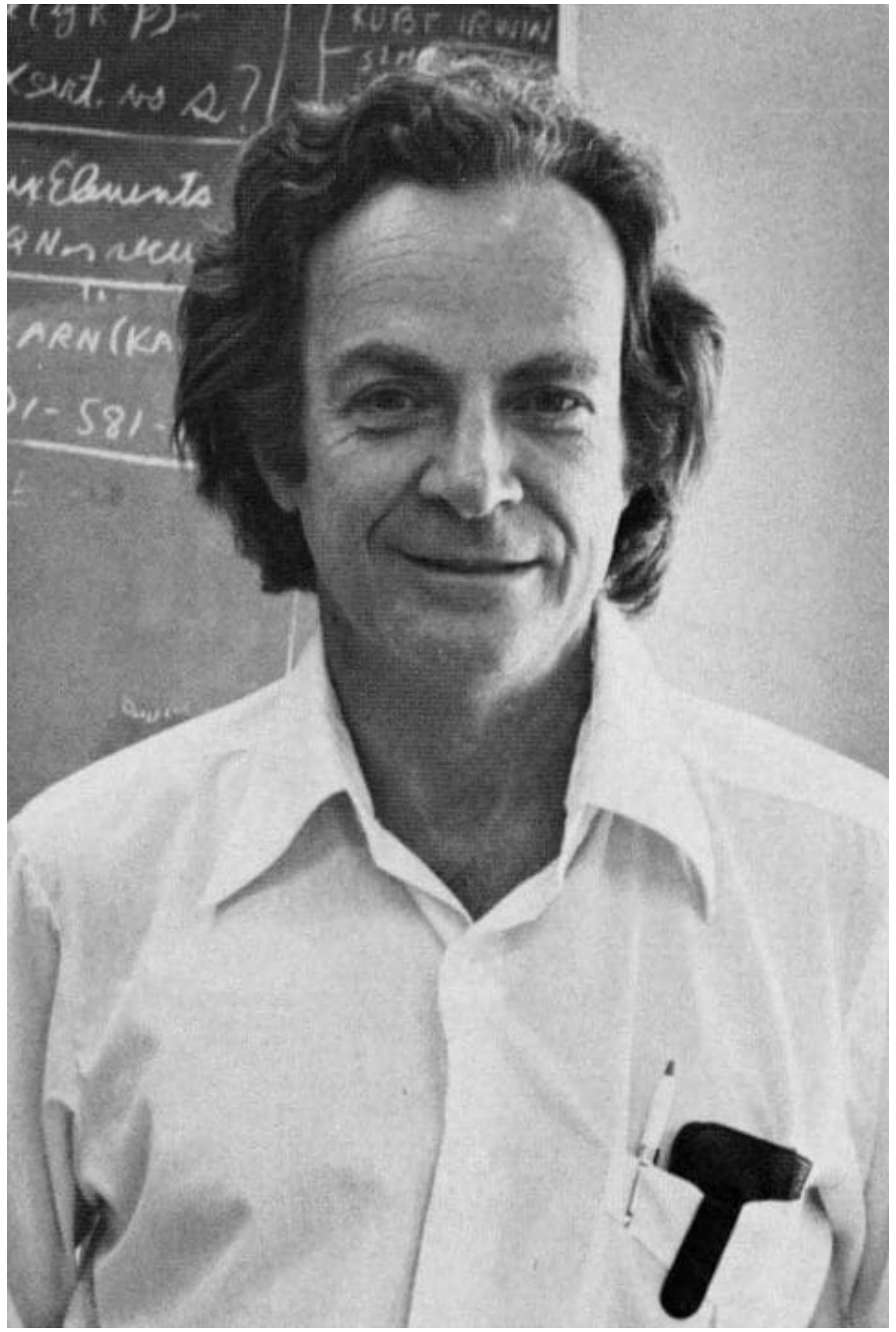
We believe Nature is fundamentally quantum

Simulating Physics with Computers

Richard P. Feynman

"Nature isn't classical
... and if you want to make a simulation of Nature,
you'd better make it quantum mechanical,
and by golly it's a wonderful problem,
because it doesn't look so easy."

Why Quantum Computing ?

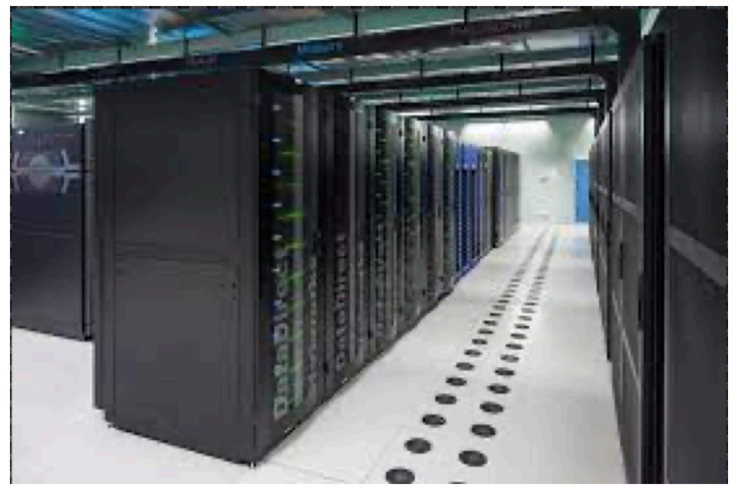


Richard Feynman

We believe Nature is fundamentally quantum

5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY SIMULATED BY A CLASSICAL COMPUTER?

In practice for QCD: $$$$



5. CAN QUANTUM SYSTEMS BE ~~PROBABILISTICALLY~~ SIMULATED BY A ~~CLASSICAL~~ COMPUTER?

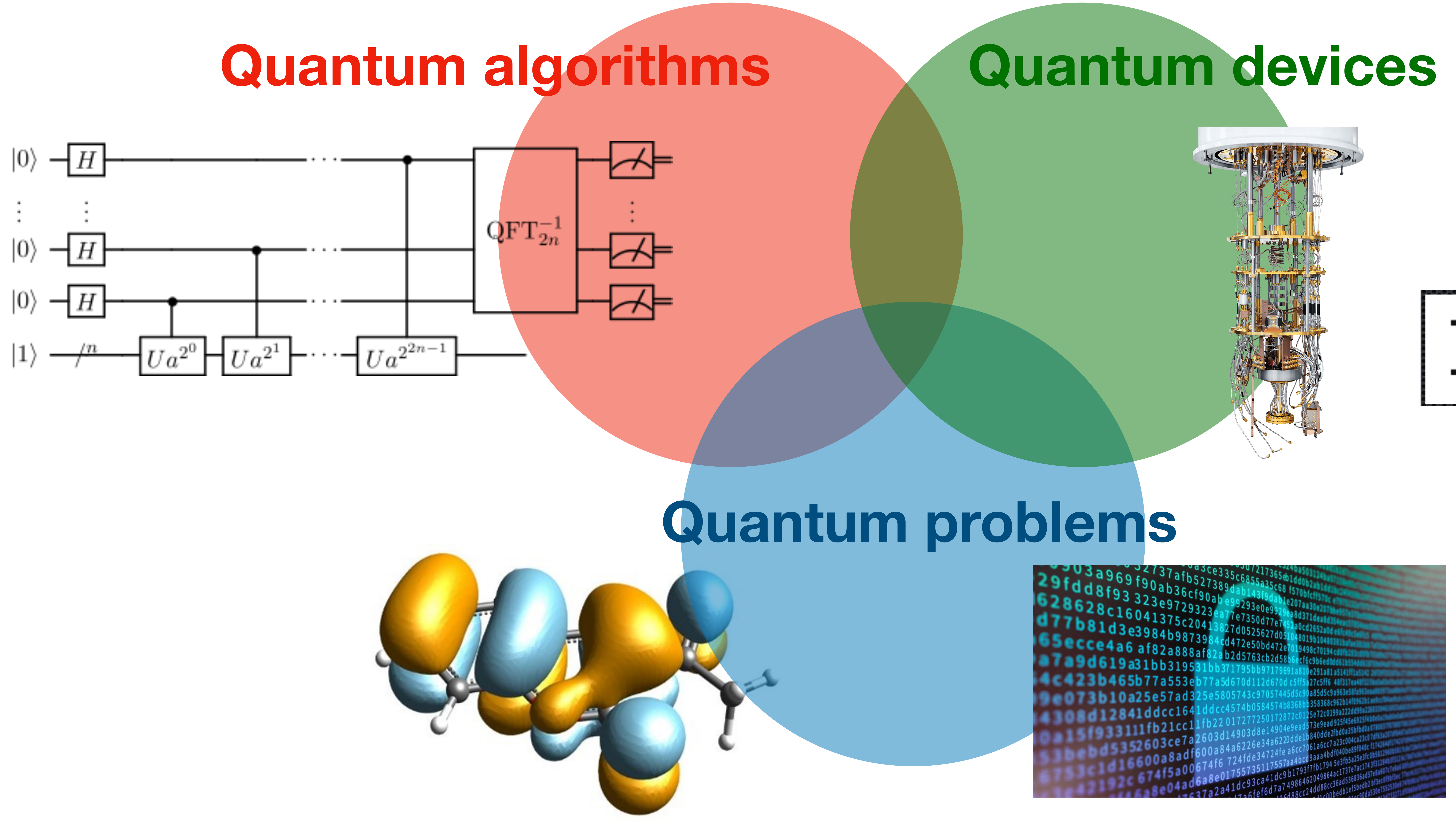
quantum

In principe yes, but

... and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

What is Quantum Computing ?

"Infant" field in the intersection of many sub-fields



D:Wave
The Quantum Computing Company™

Microsoft
Quantum Computer

rigetti

IBM Q

IONQ

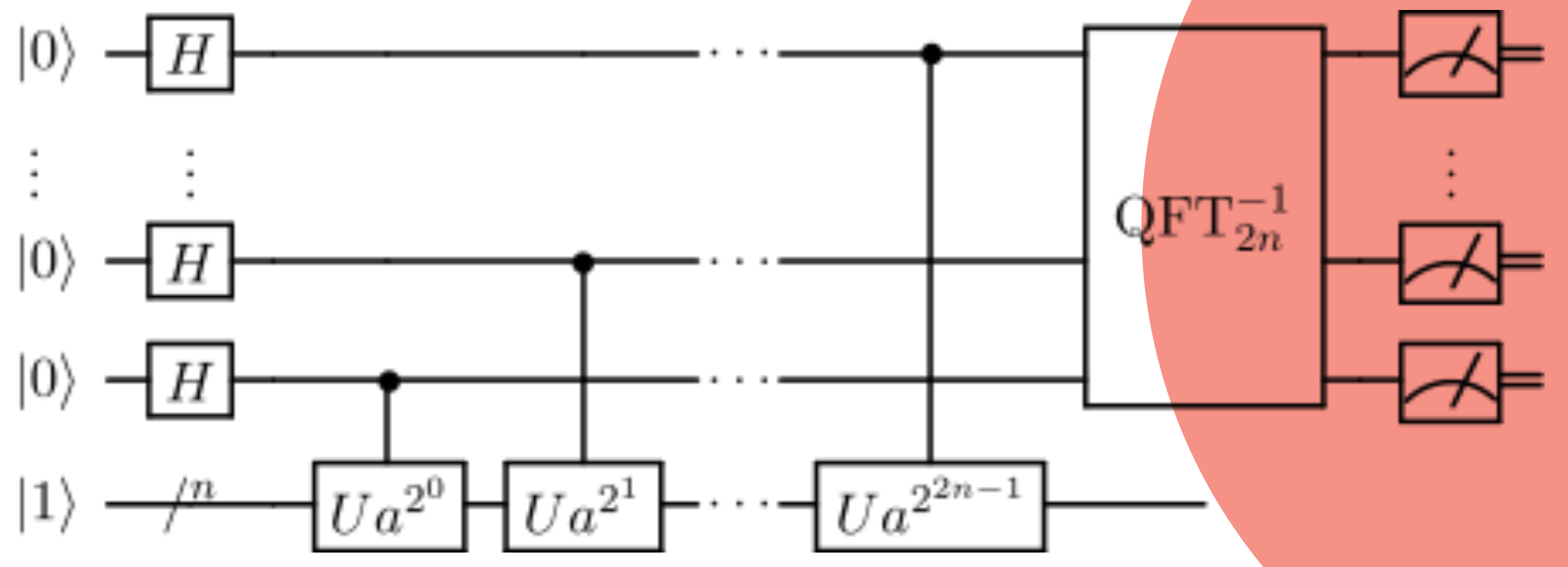
What is Quantum Computing ?

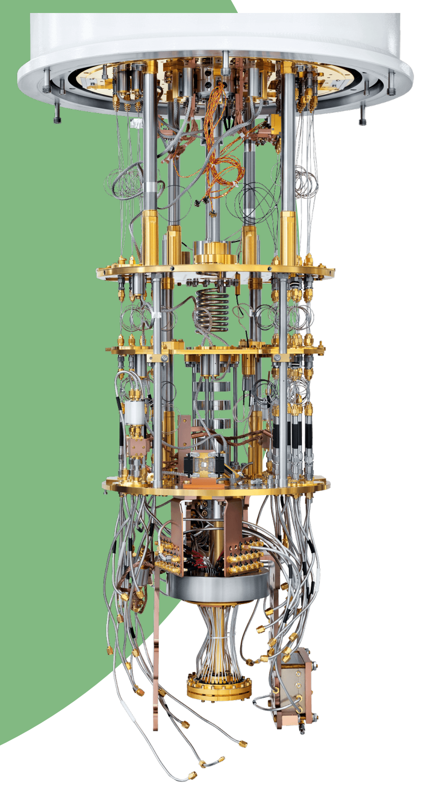
"Infant" field in the intersection of many sub-fields

Quantum algorithms

Today

Quantum devices





D-Wave The Quantum Computing Company™

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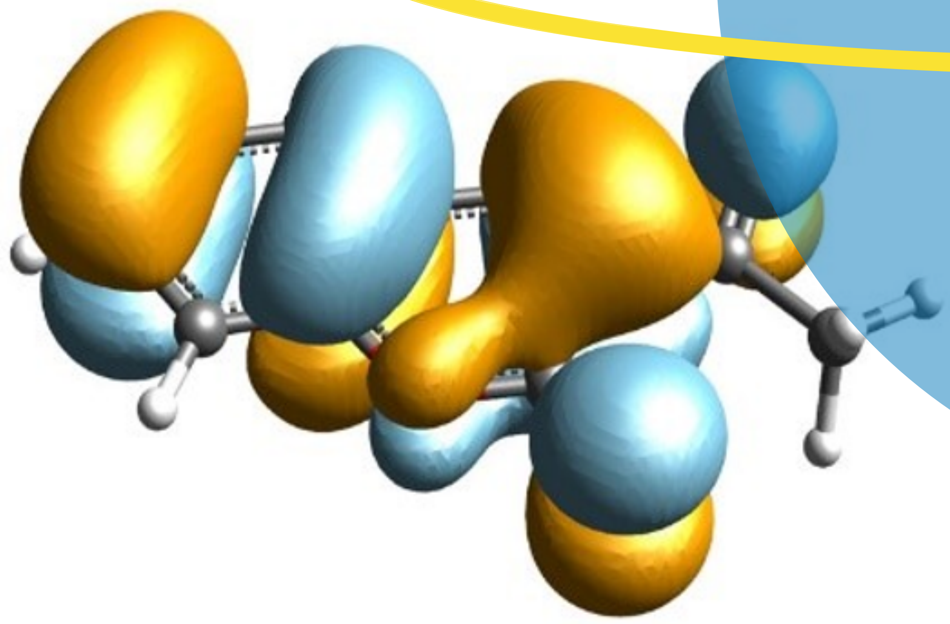
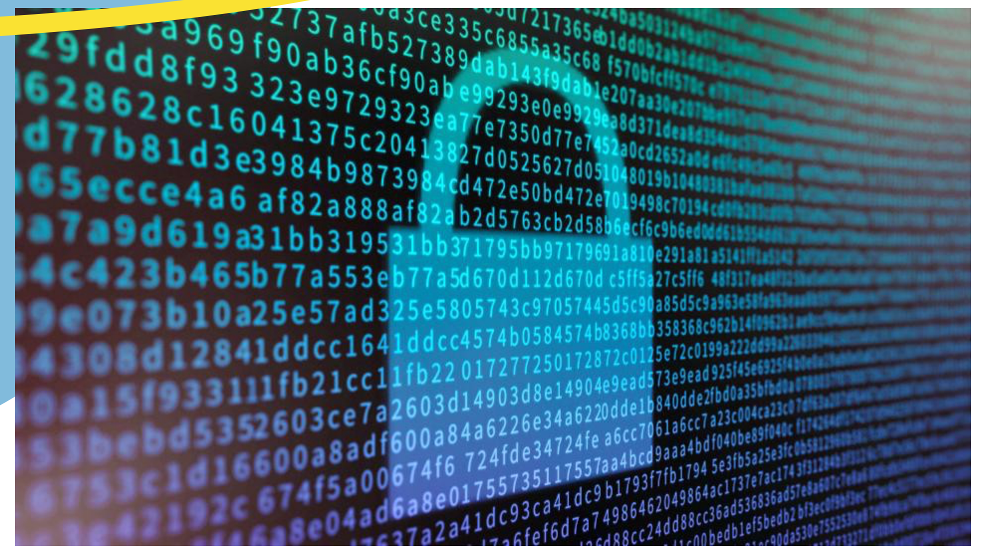
Today

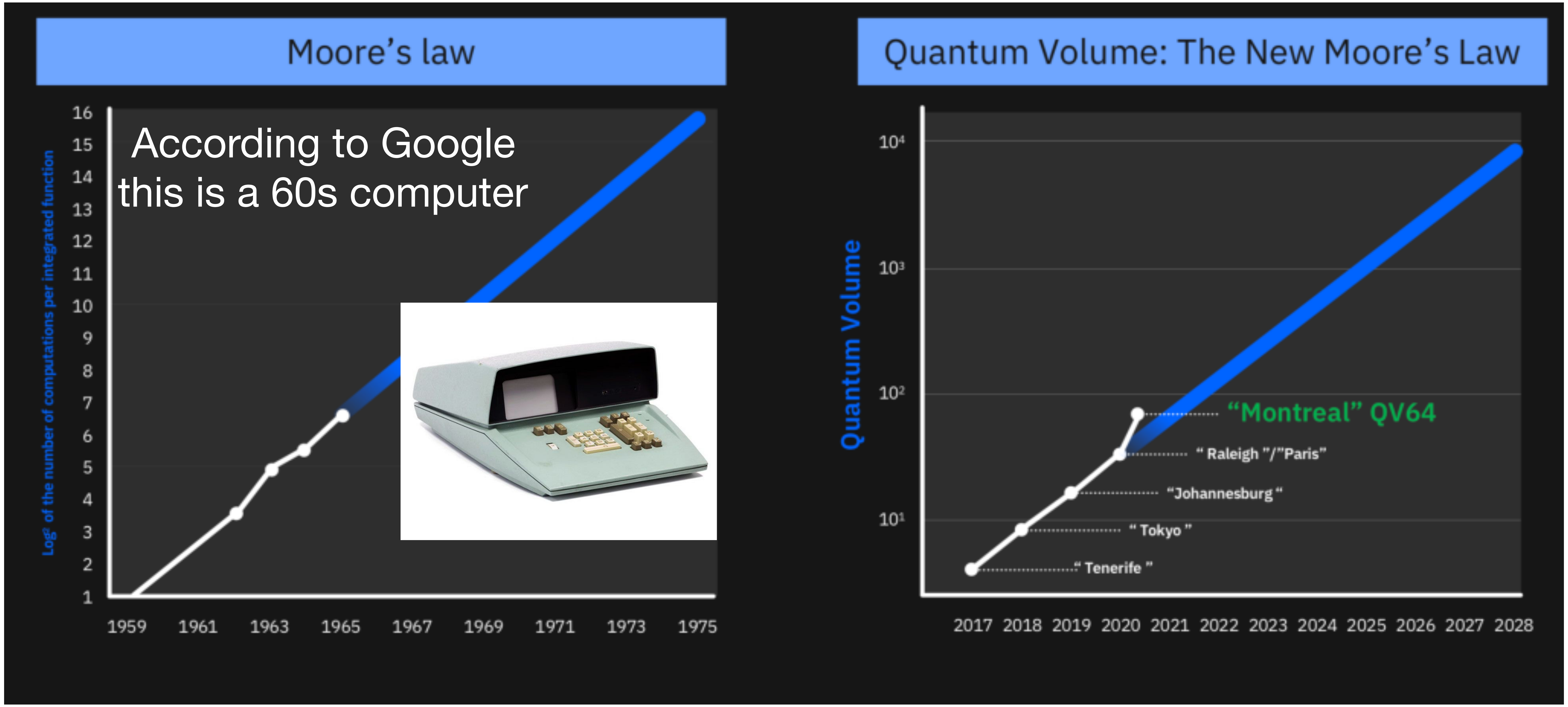
Quantum problems





What is Quantum Computing ?

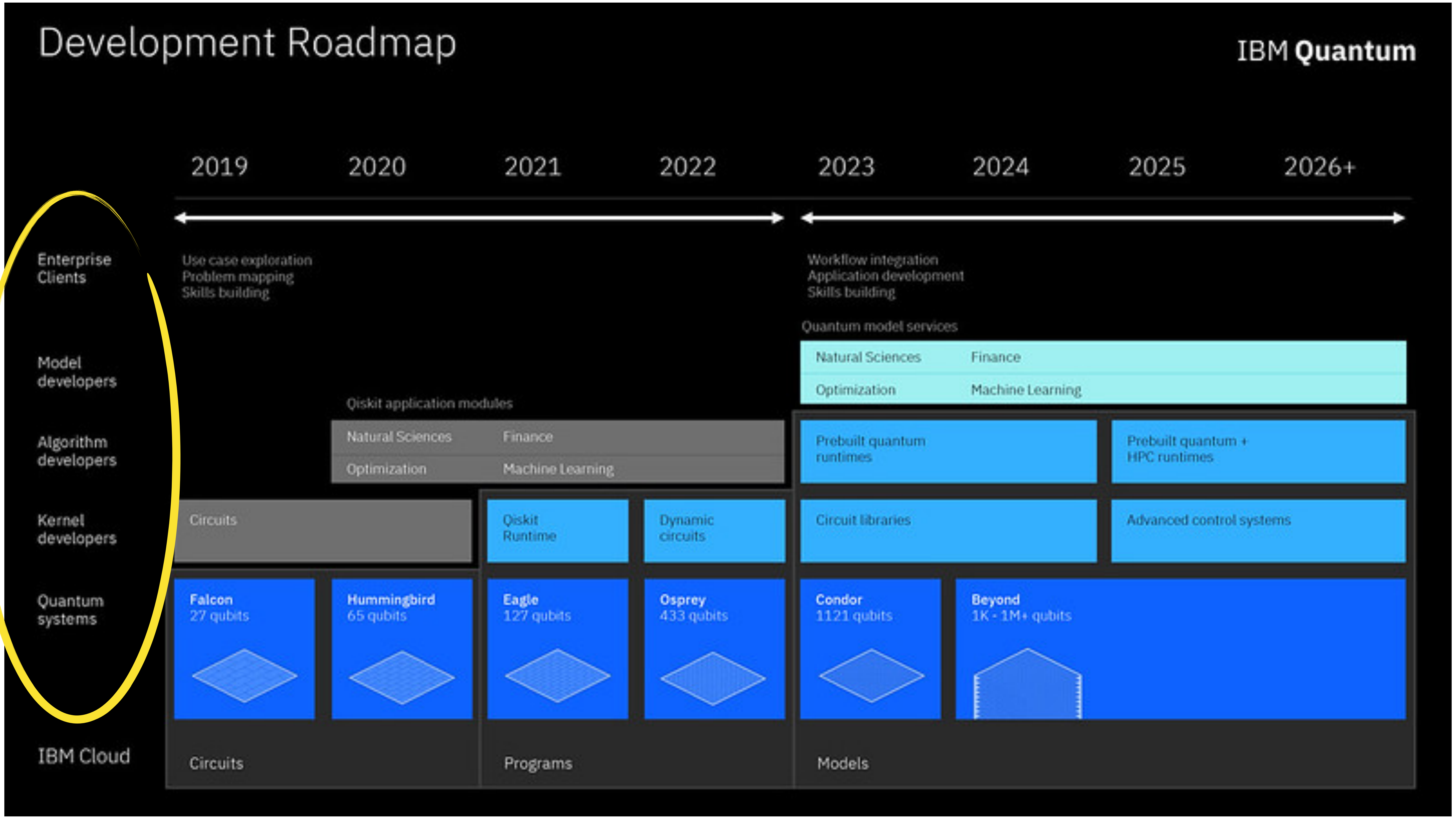
What I mean by infant



Quantum Volume ~ quality of the quantum computer

What is Quantum Computing ?

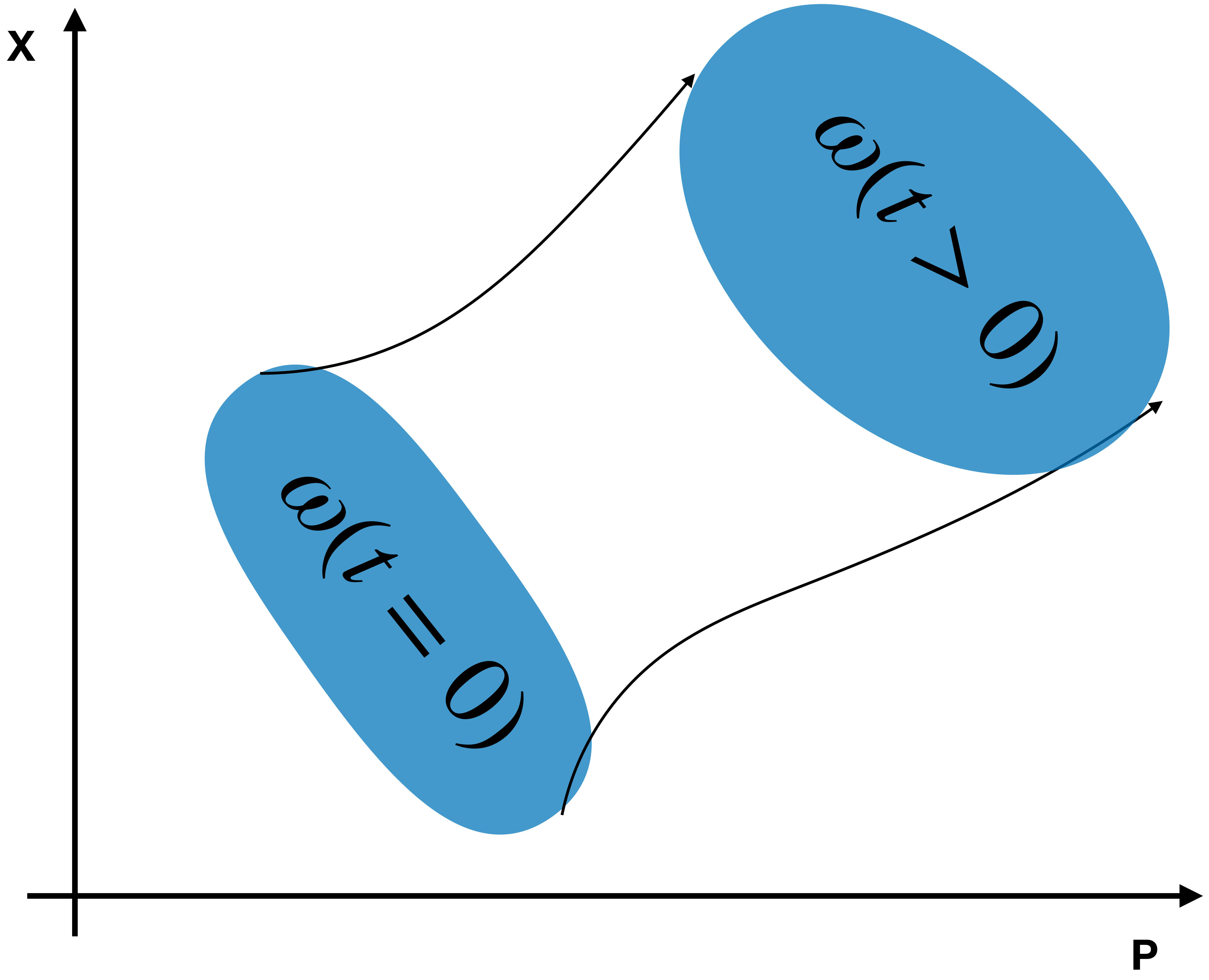
What I mean by infant



Overview

1. From Classical to Quantum Mechanics
2. From Classical to Quantum Computing
3. Application to High Energy Physics (HEP)

Classical mechanics



Consider ω a classical distribution

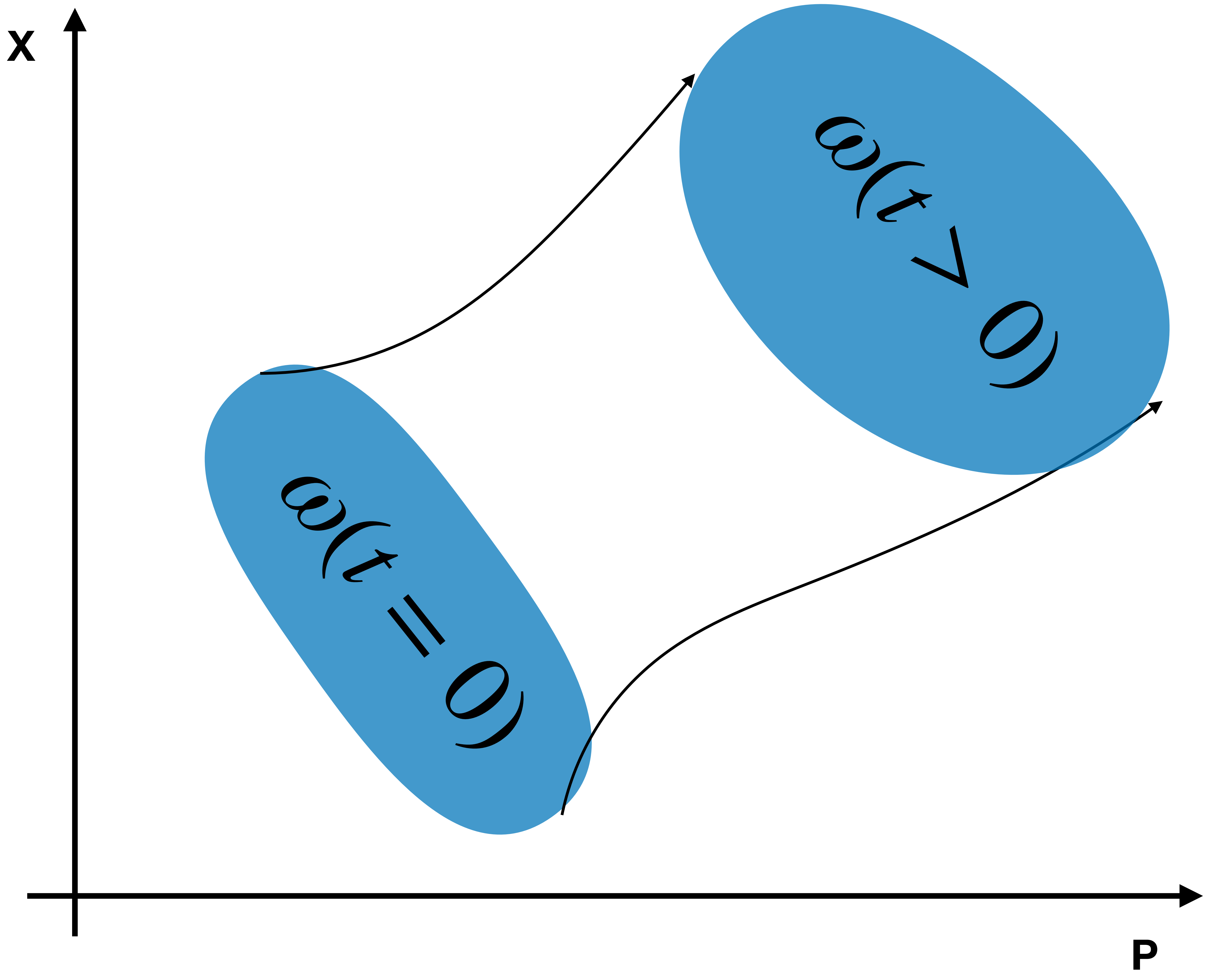
This satisfies a **Liouville equation**

$$\partial_t \omega(x, p) = \mathscr{L}\omega$$

Equivalent to **Newton's laws**

$$\vec{F} = m\,\vec{a}$$

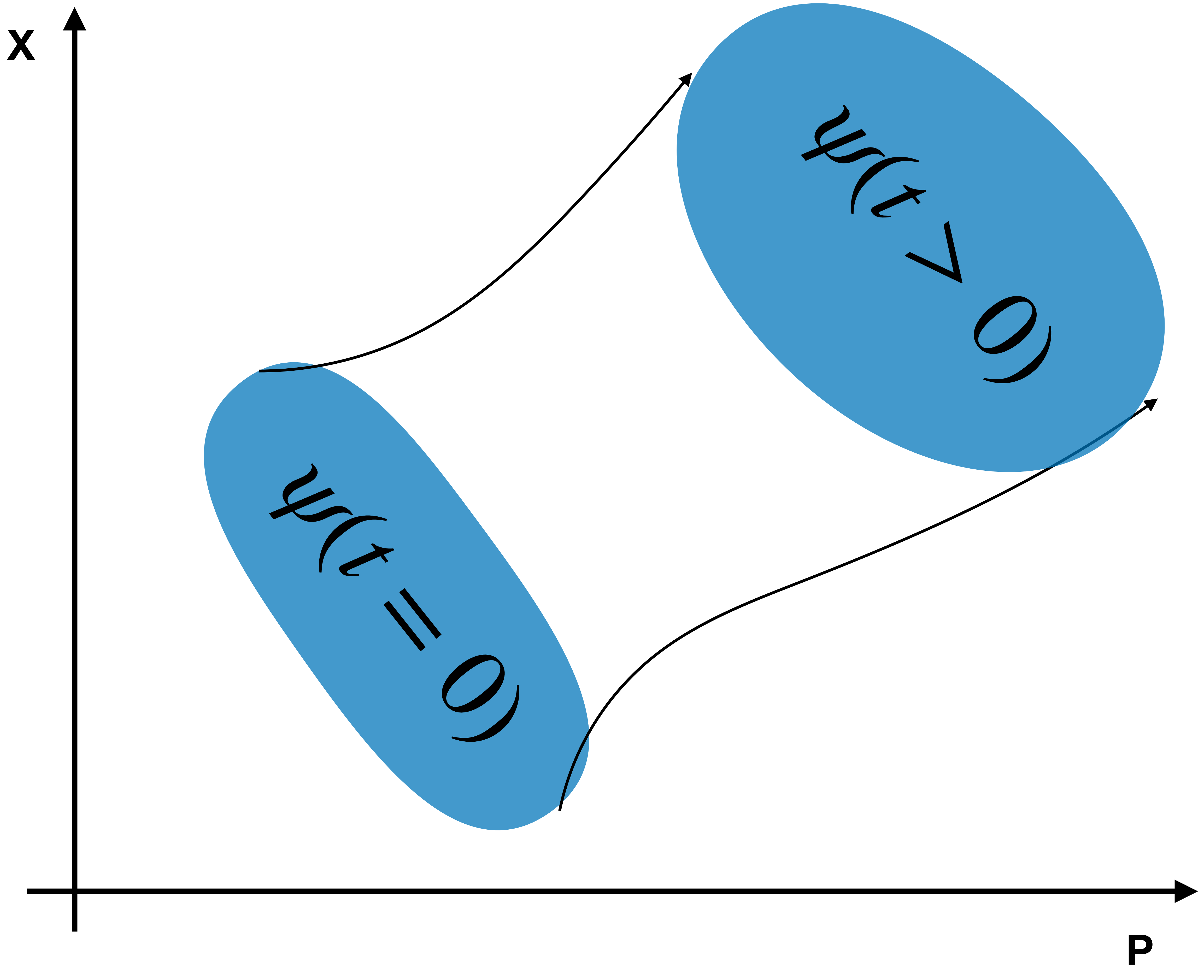
Classical mechanics



Some classical axioms:

- The state of the system can be identified with $\omega \geq 0$
- $$\partial_t \omega(x, p) = \mathscr{L}\omega$$
- Probabilities: $\delta p \, \delta x \, \omega(x, p)$
- The system can be measured trivially

Quantum mechanics



Quantum case: state described by wavefunction ψ

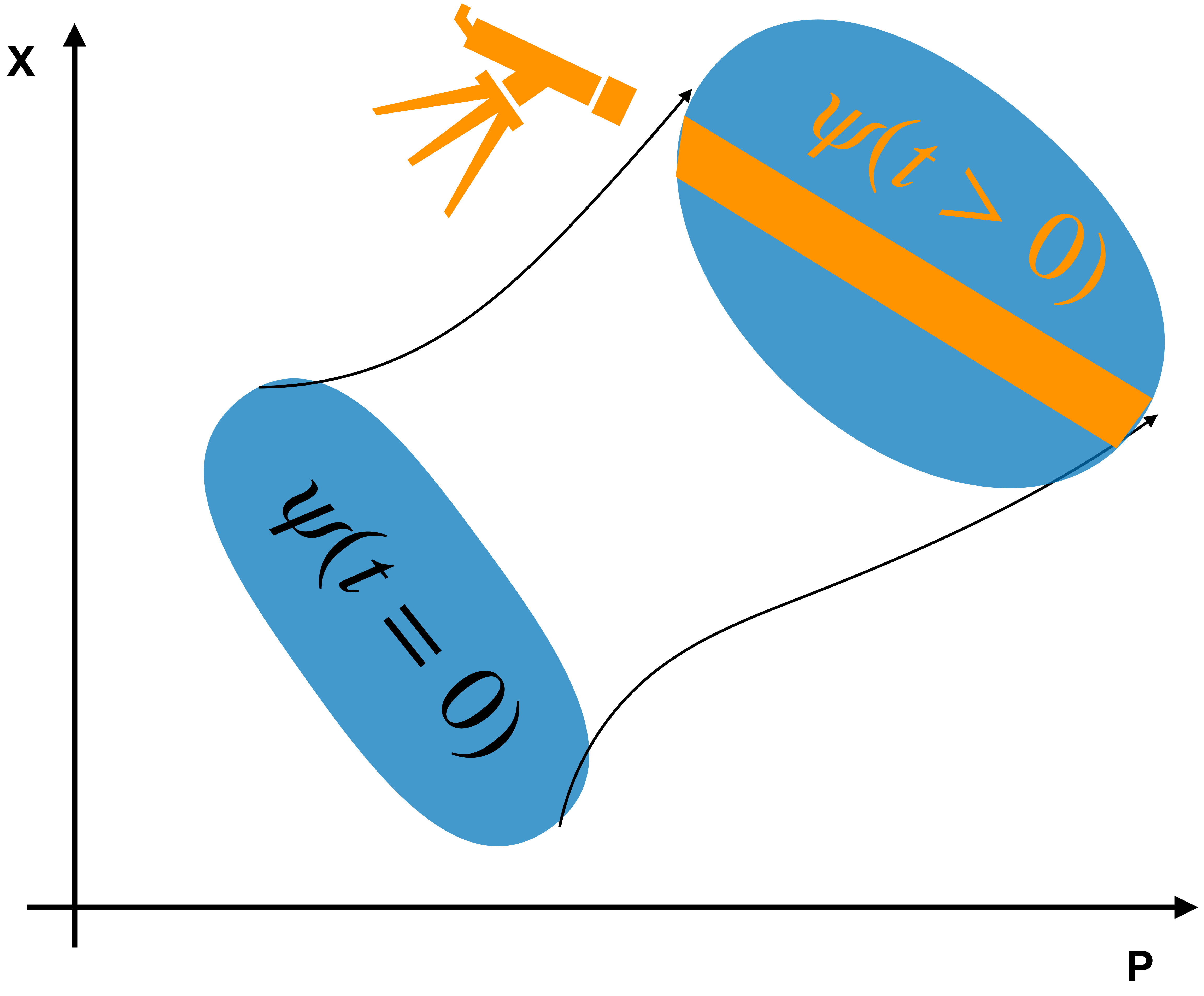
This satisfies a **Schrodinger equation**

$$i\partial_t \psi(x, p) = \mathscr{H}\psi$$

And classical probabilities are related to

$$|\psi(x, p)|^2$$

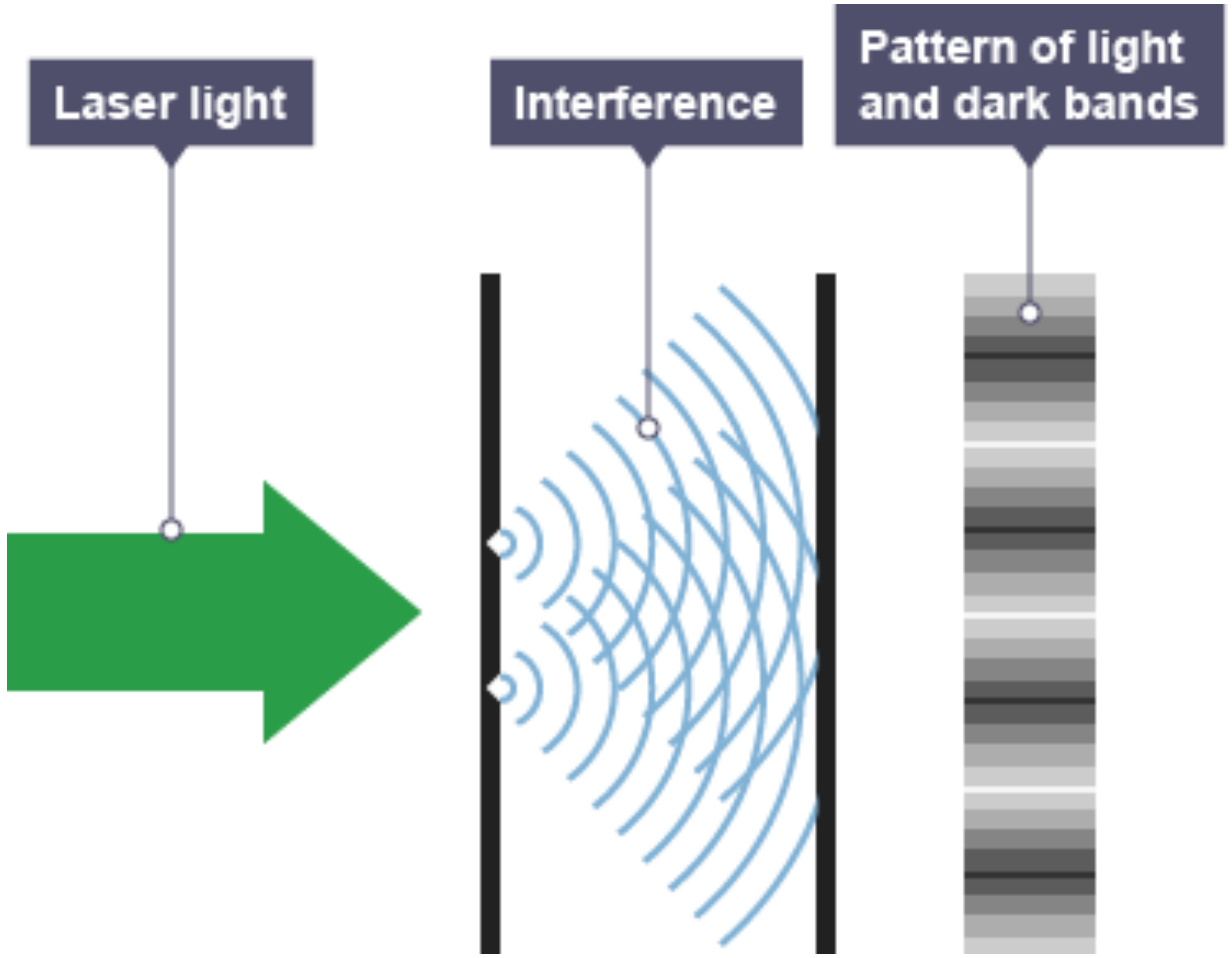
Quantum mechanics



Some quantum axioms:

- The state of the system is described by $\psi \in \mathbf{C}$
- $$i\partial_t\psi(x,p) = \mathscr{H}\psi$$
- Probabilities: $|\psi|^2$
- The system can be measured **but**

Quantum mechanics



Quantum Superposition:

- The state of the system is described by $\psi \in \mathbf{C}$

Any combination of ψ is still a valid state!

but probabilities: $\mathrm{Prob} \sim |\sum \psi|^2$

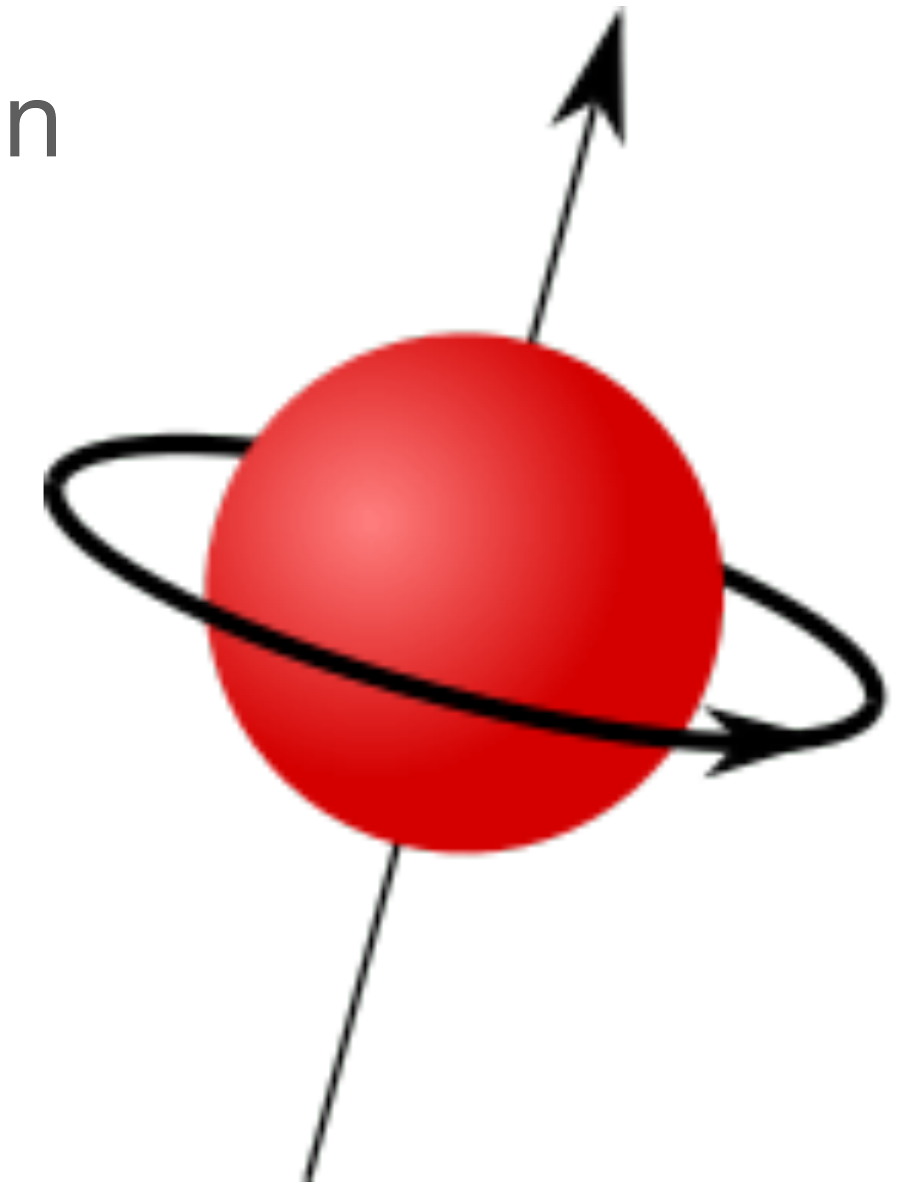
Quantum interference !

Remember: probabilities add to 1

Discrete quantum mechanics

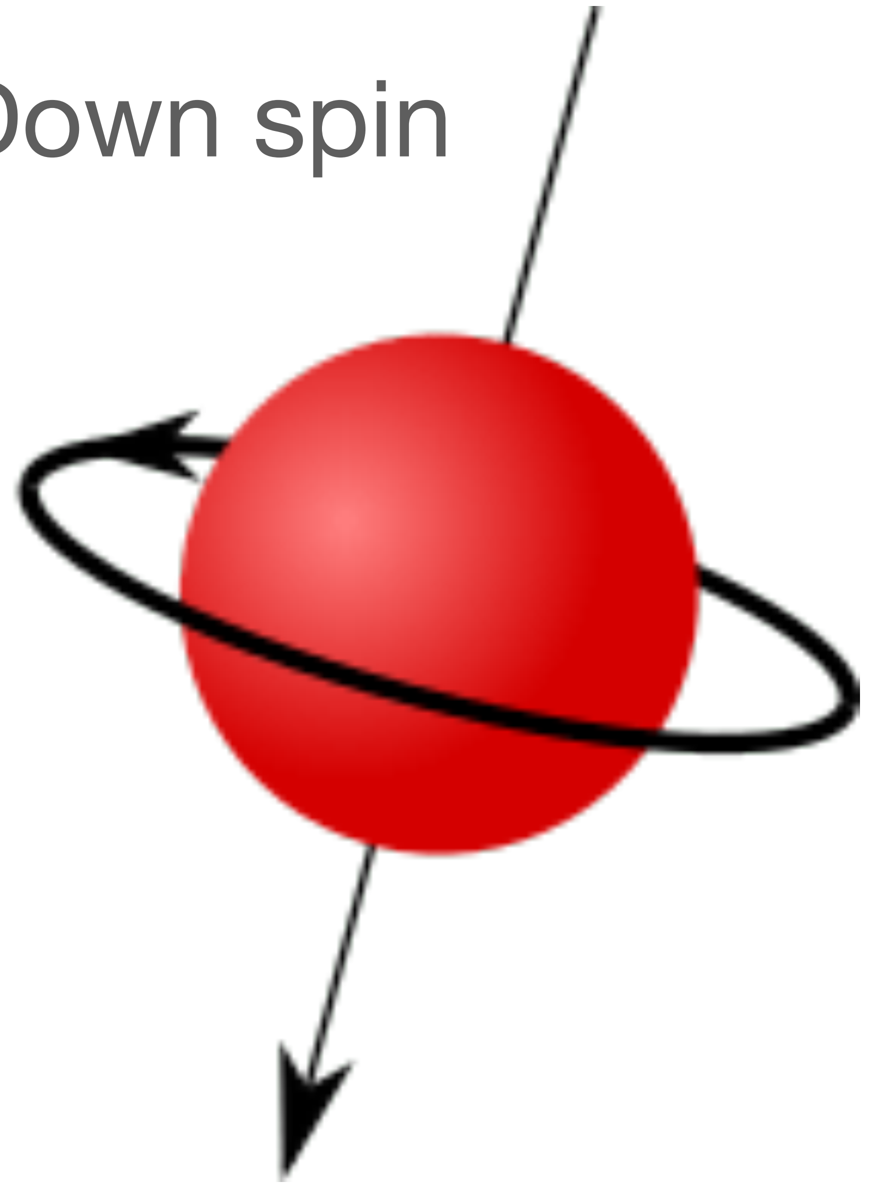
Example: electrons have electric charge -1, mass m_e and spin 1/2

Up spin



$|\uparrow\rangle = |0\rangle$

Down spin

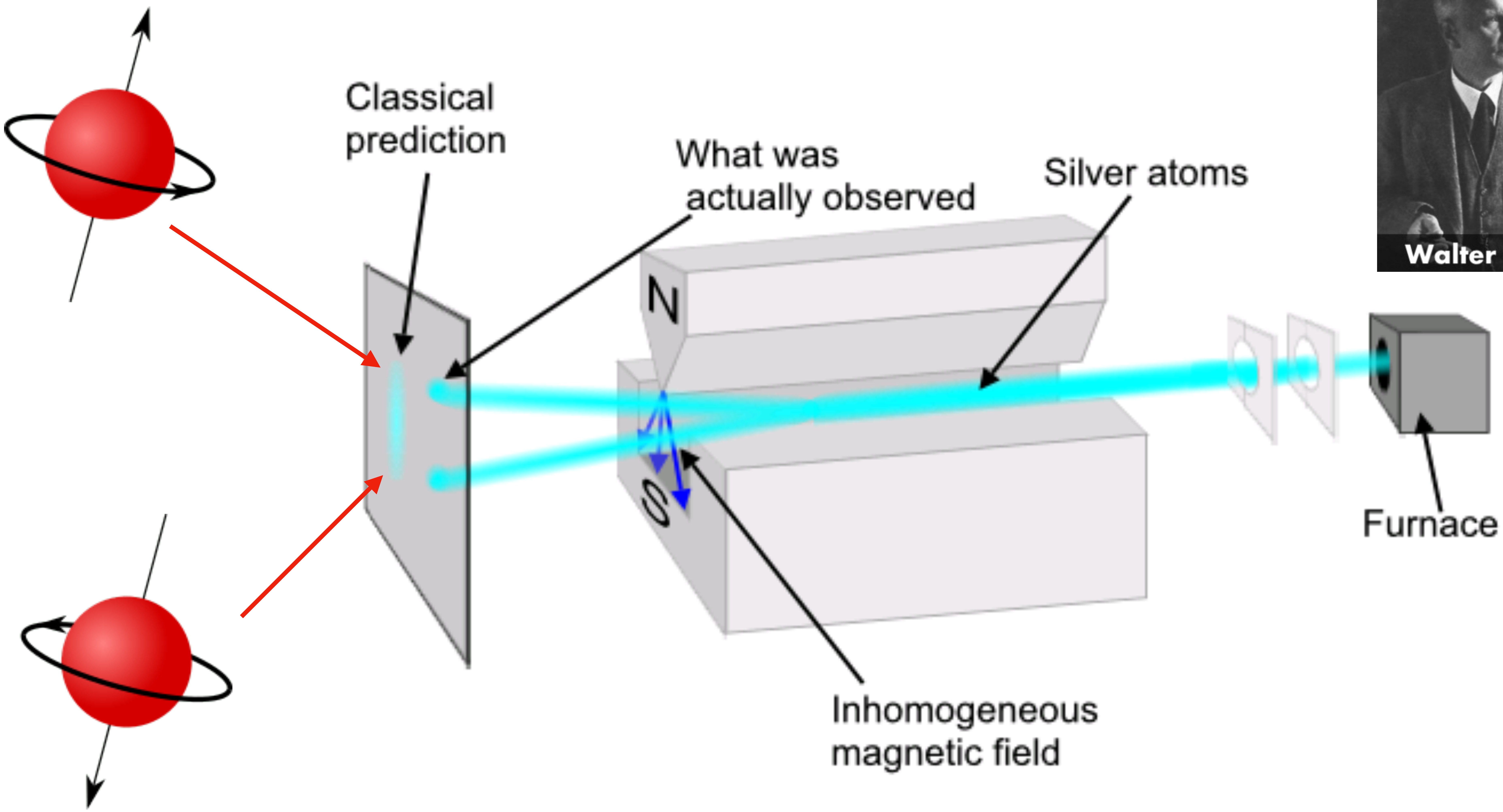


$|\uparrow\rangle = |1\rangle$

If we ignore all other dynamics, then this is a 2 state quantum system

Discrete quantum mechanics

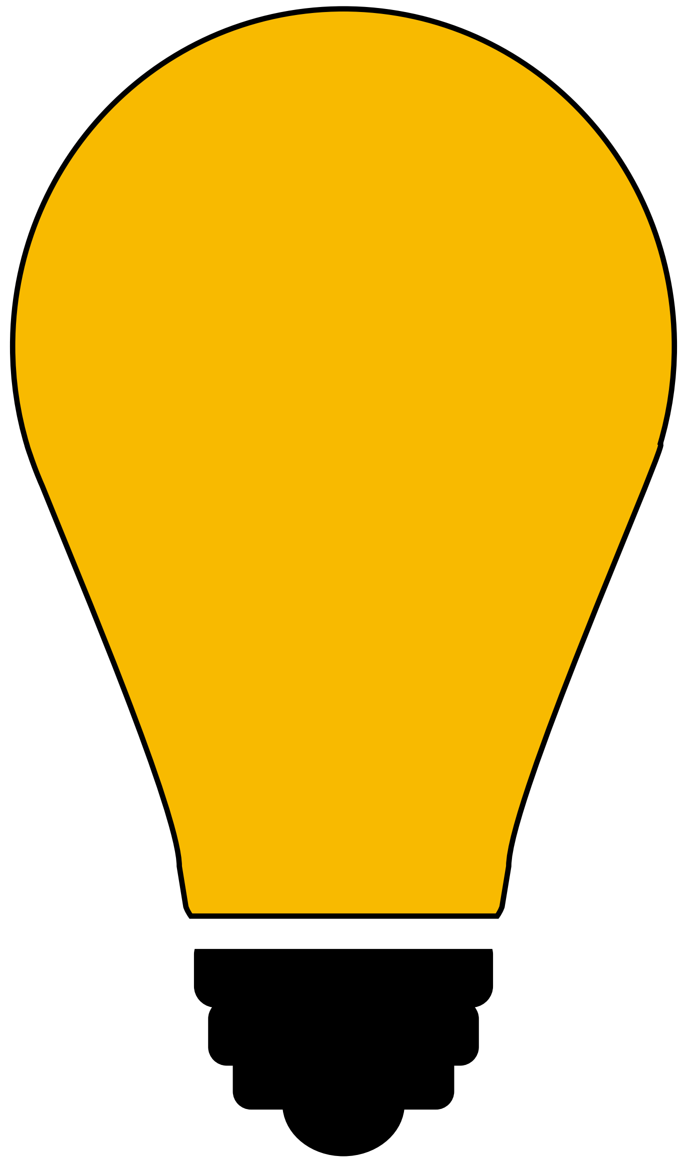
An aside : Stern–Gerlach experiment

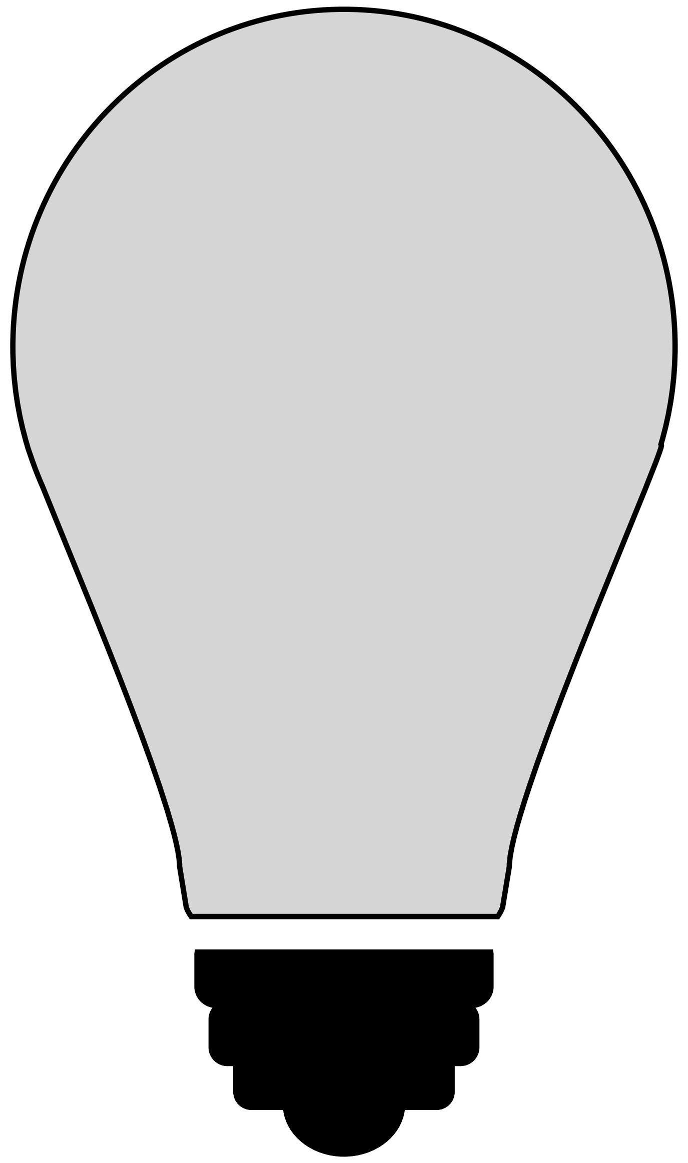


What is the relation to computation?

Classical digital computation

Modern computers are made of basic information units: bits



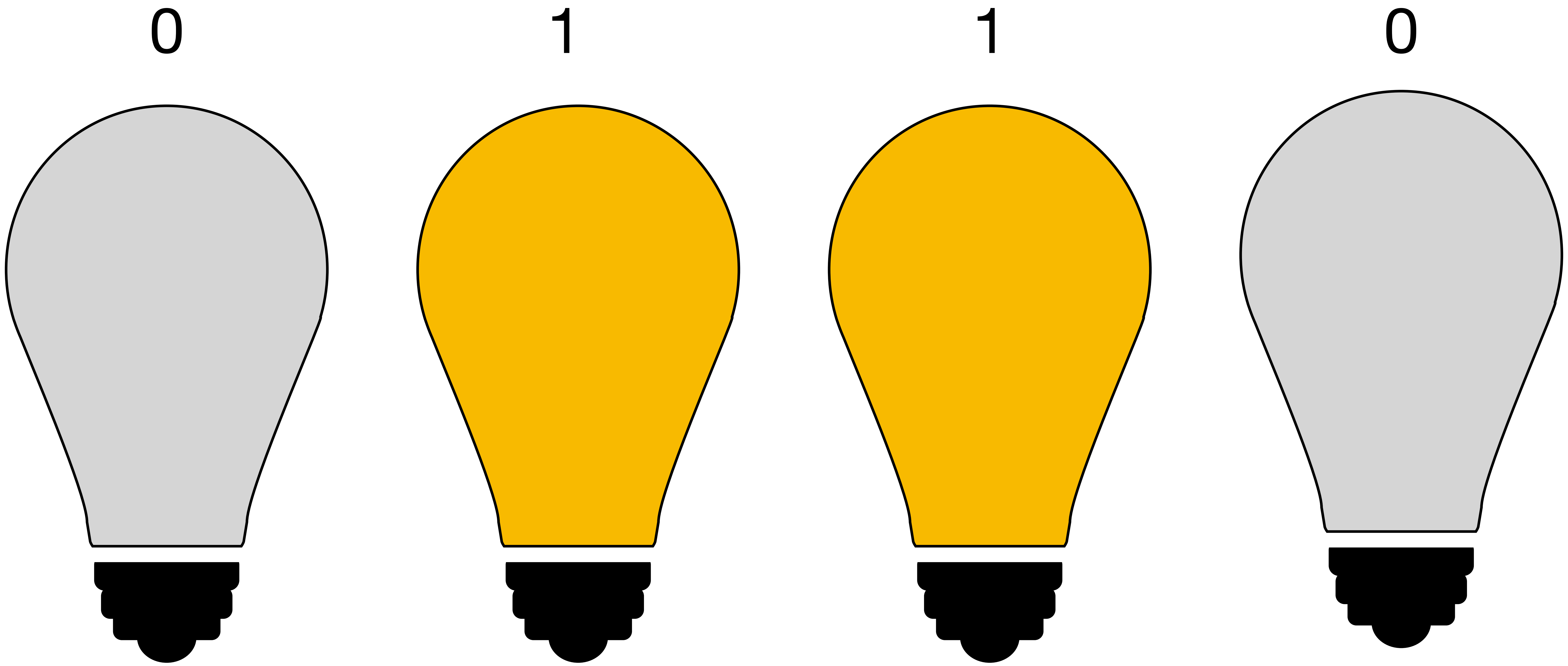


Let's call these: $|1\rangle$ $|0\rangle$

Classical digital computation

Modern computers are made of basic information units: bits

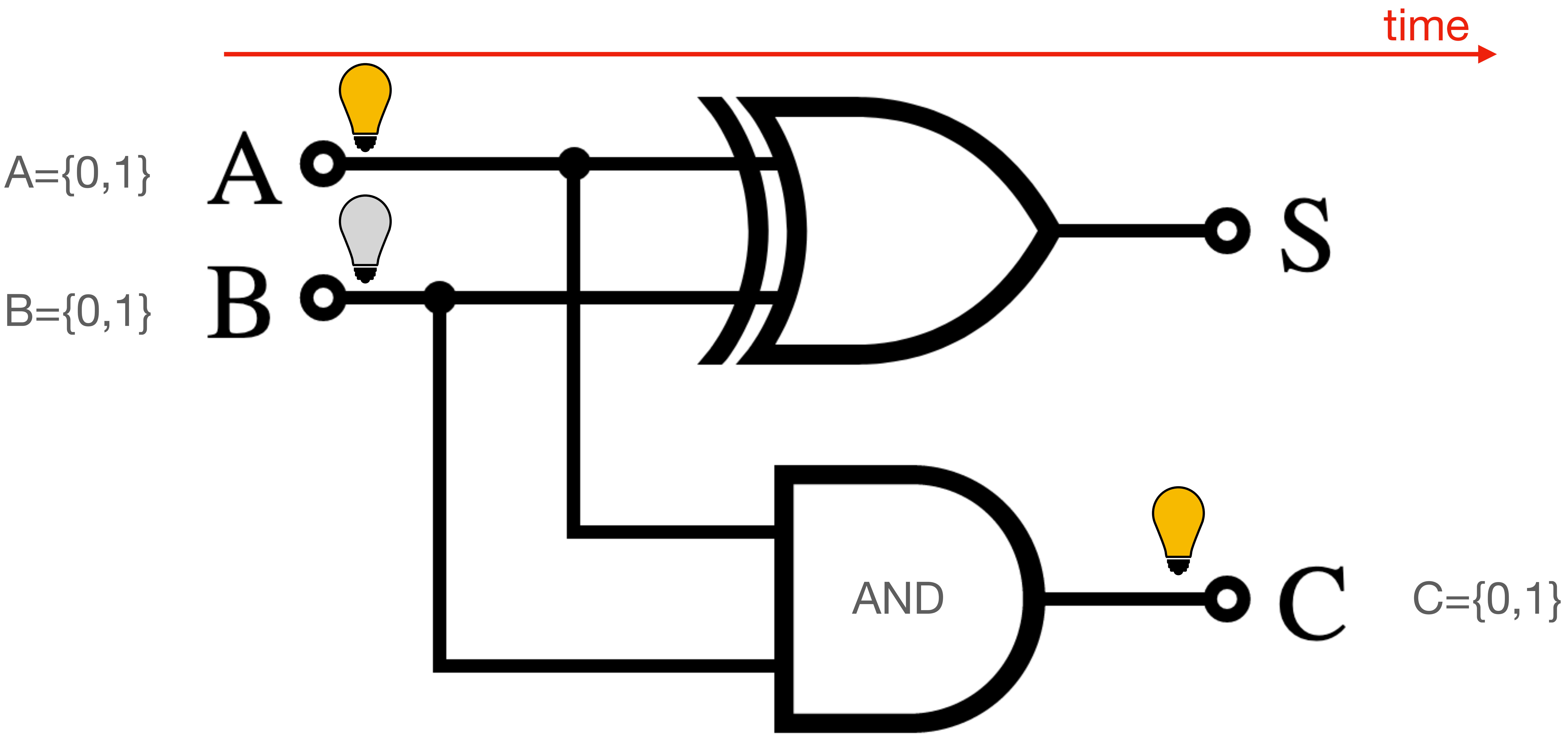
Example:



Classical digital computation

Time evolution of information: just draw some lines

Example:

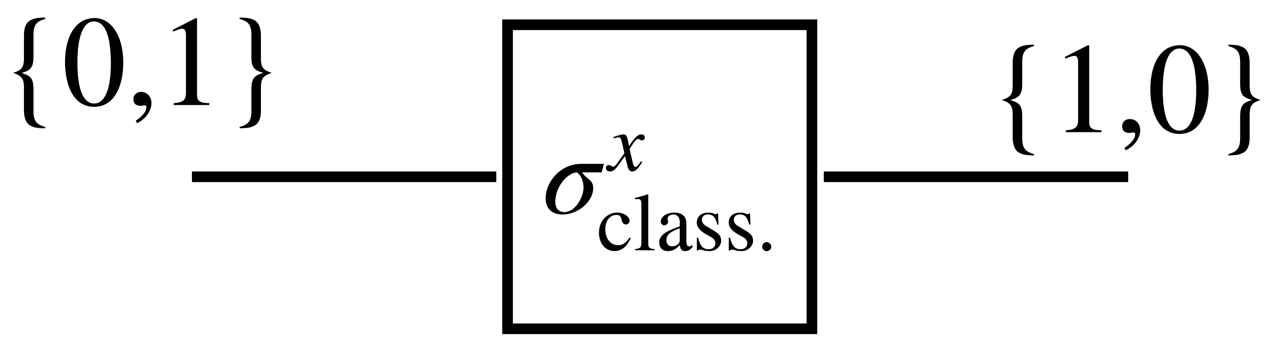


Classical digital computation

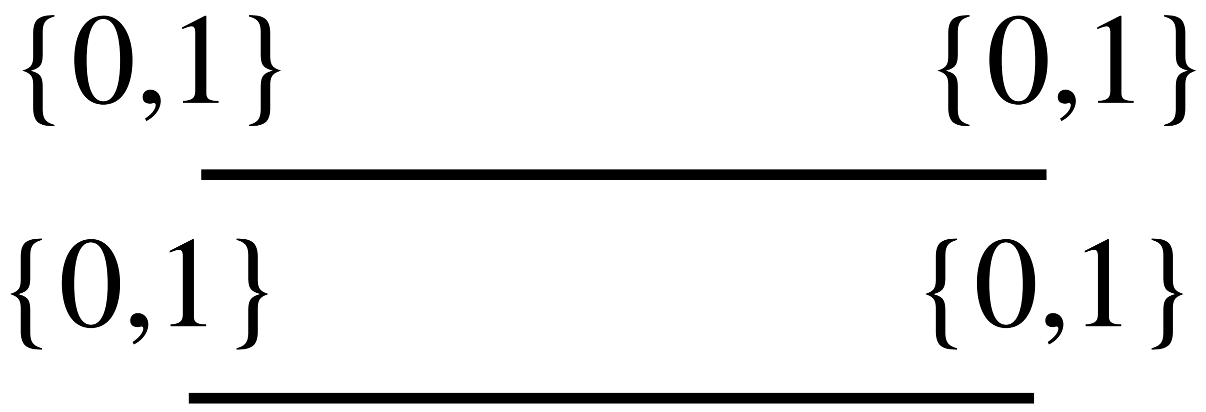
I will rewrite this in a more convenient notation

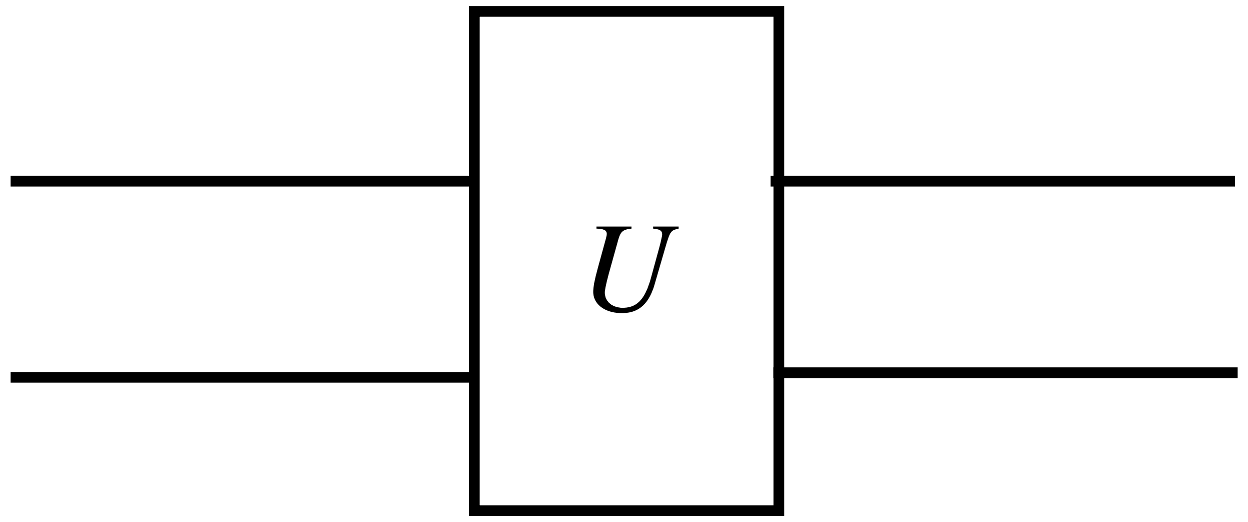
$\psi = \{0,1\}$ (bit). Only **two** possible operations

a.k.a NOT



$\psi = \{0,1,2,3\}$ (in binary)

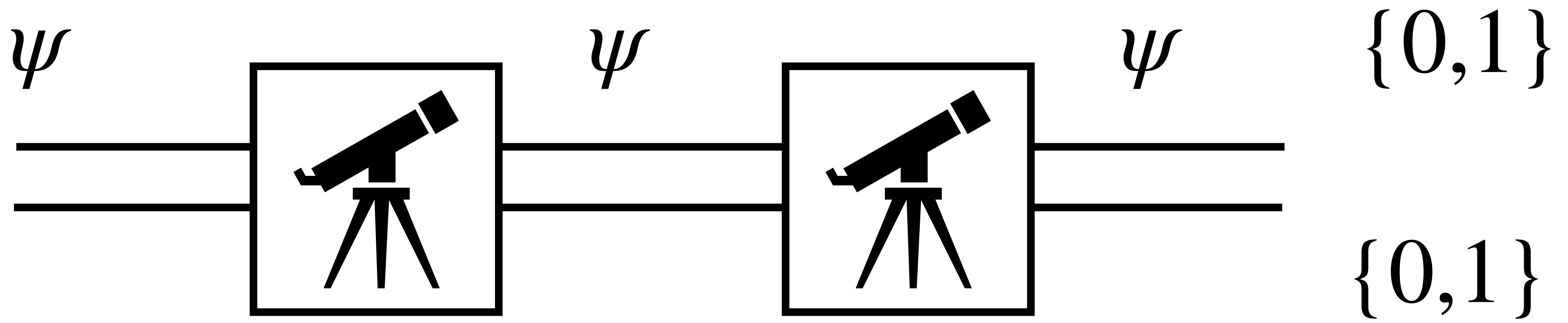




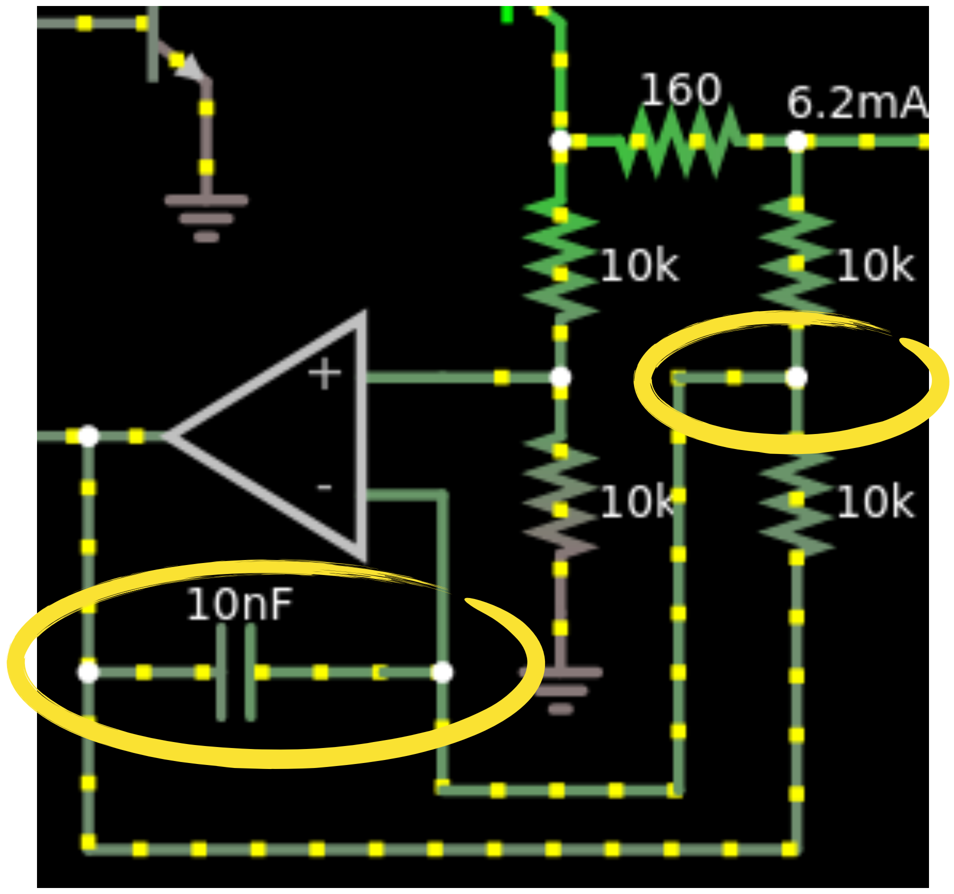
Classical digital computation

I will rewrite this in a more convenient notation

Measurement:



Non-trivial topologies:

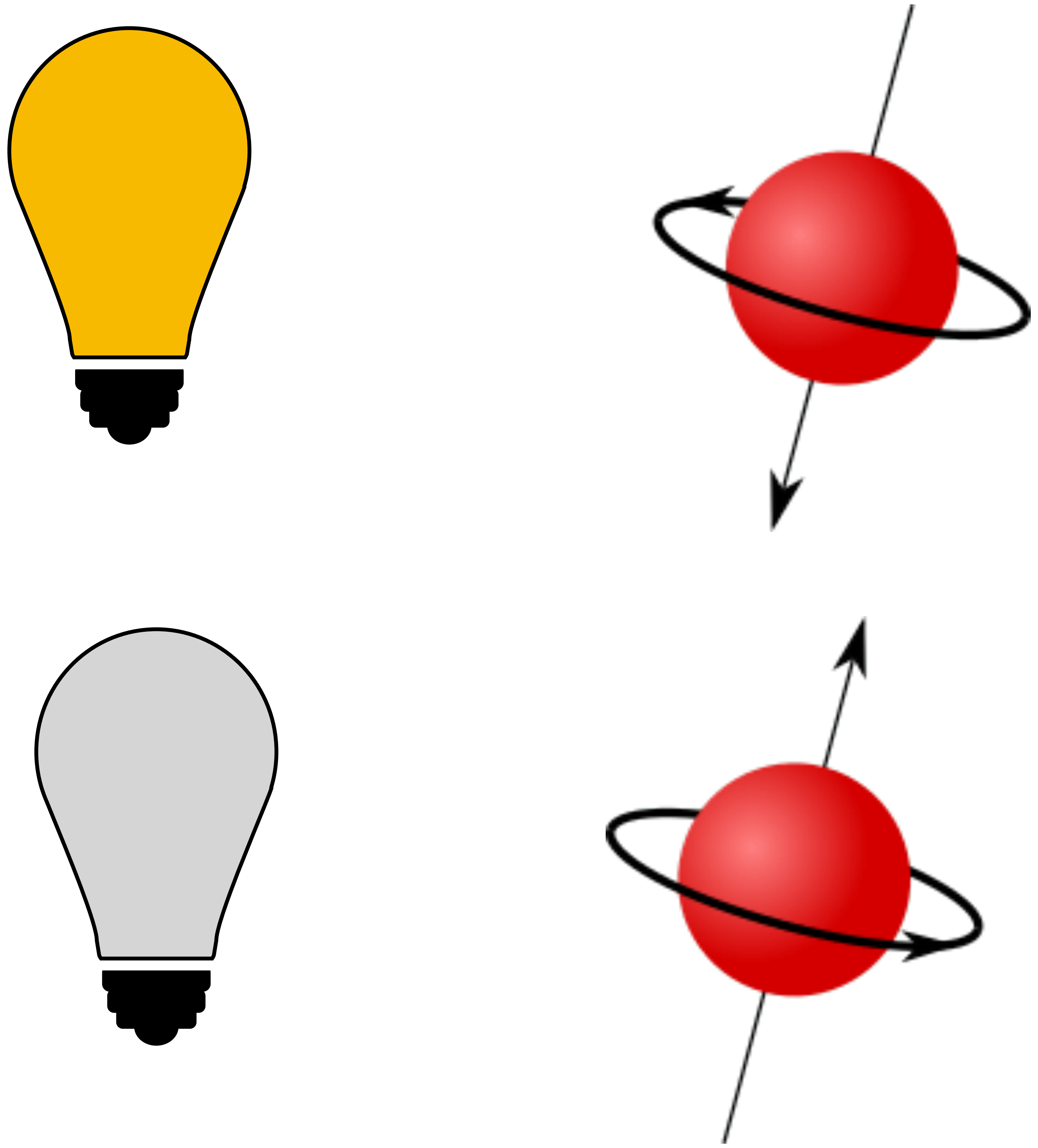


Quantum digital computation

Quantum computers are made of basic information units: qubits

The simplest example: 1 qubit $|\psi\rangle = a\,|0\rangle + b\,|1\rangle \equiv a\,|\uparrow\rangle + b\,|\downarrow\rangle$

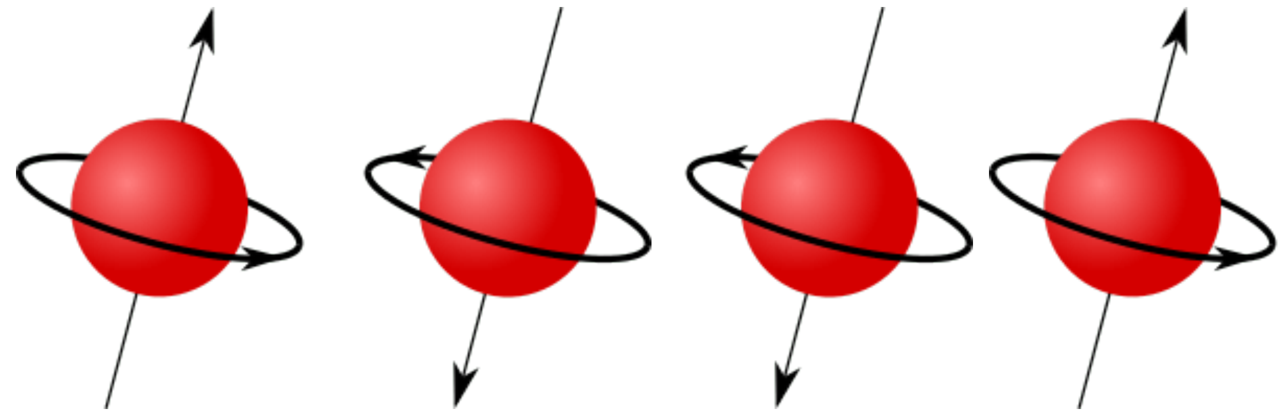
$$|\psi\rangle = \begin{array}{c} a \\ \\ b \end{array}$$



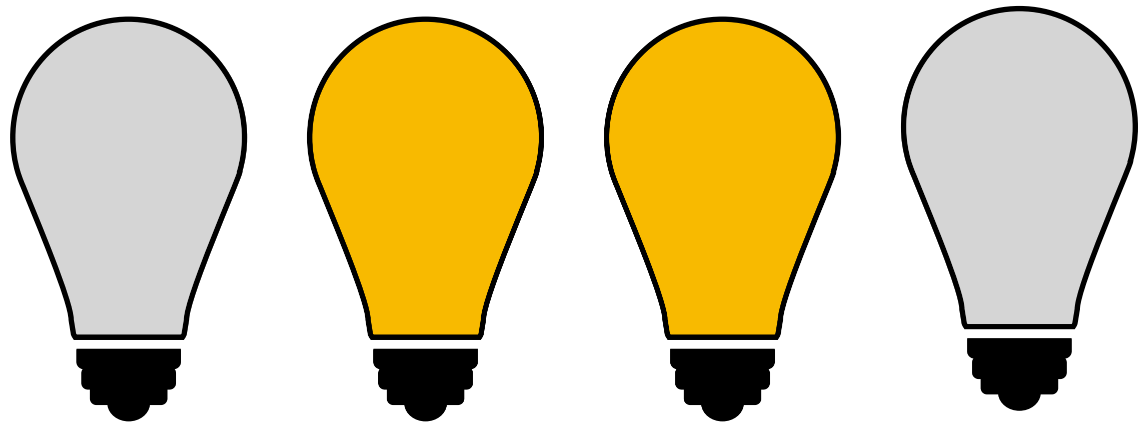
Quantum digital computation

Quantum computers are made of basic information units: qubits

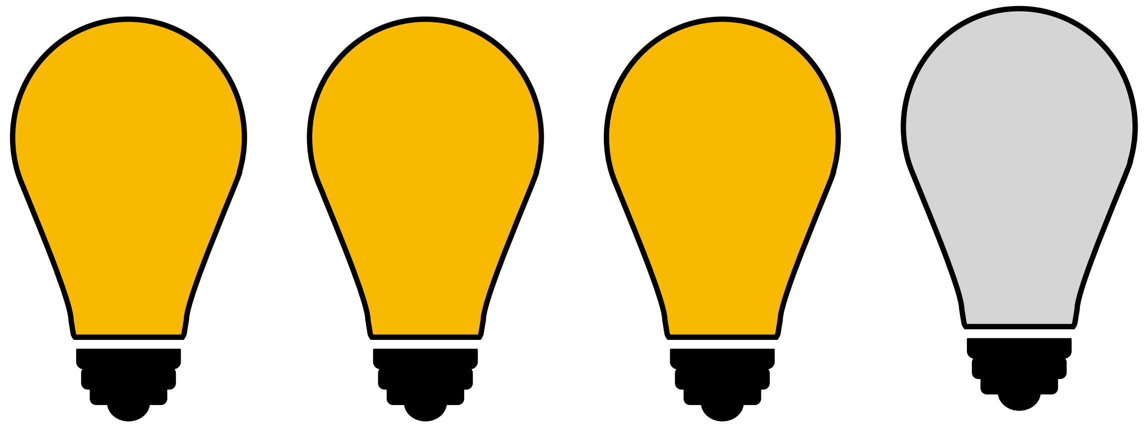
Example: 4 qubits



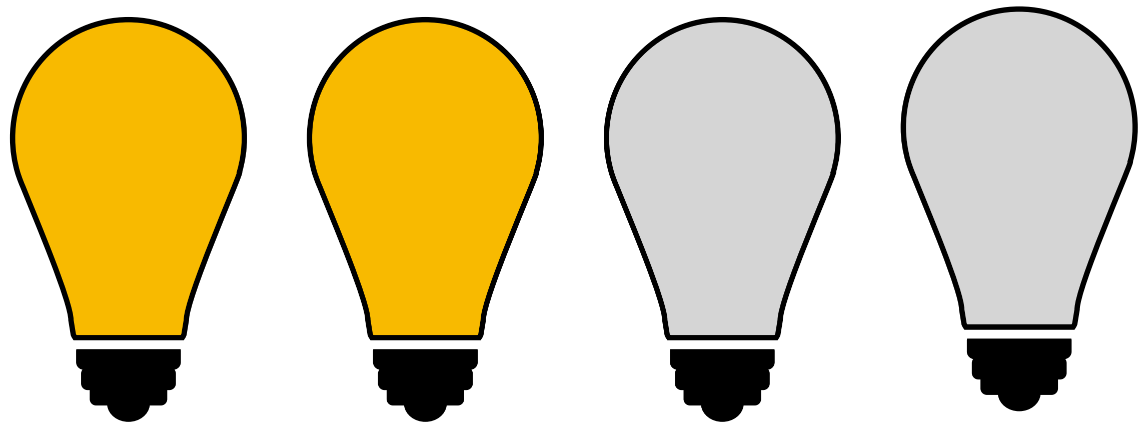
$$|\psi\rangle = a_1$$



$$+a_2$$



$$+a_3$$



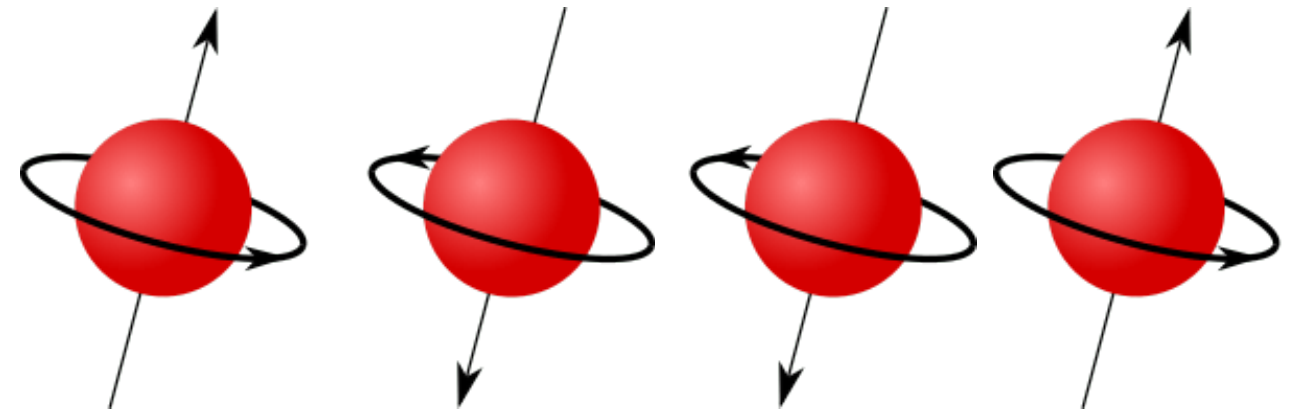
$$+\cdots$$

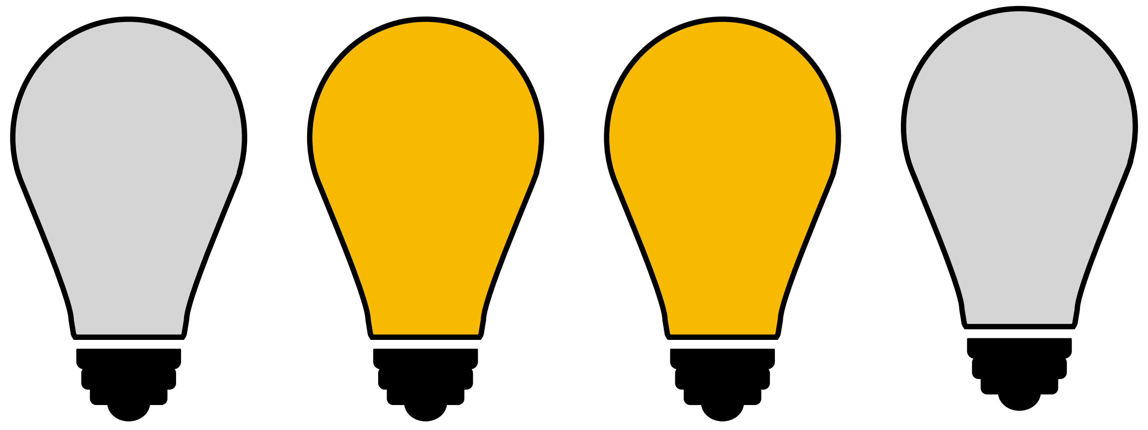
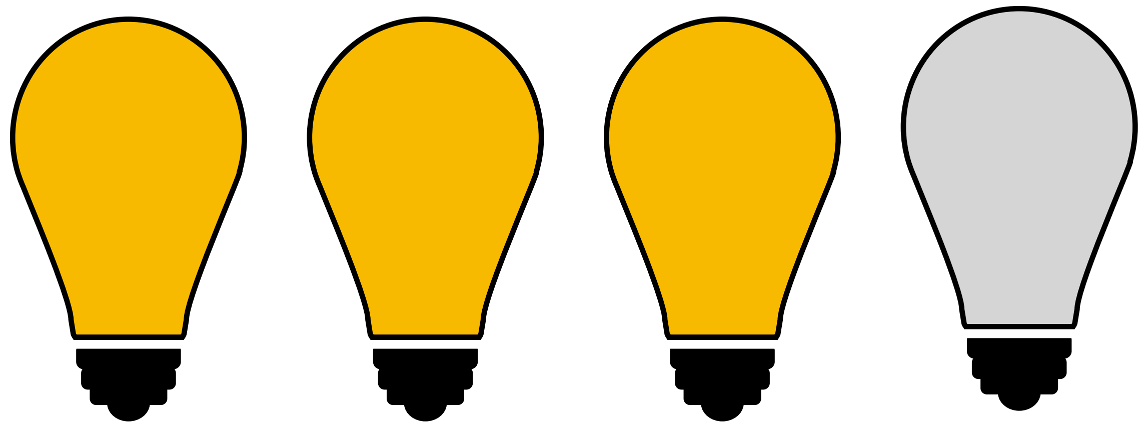
How many bits to get the same computing power?

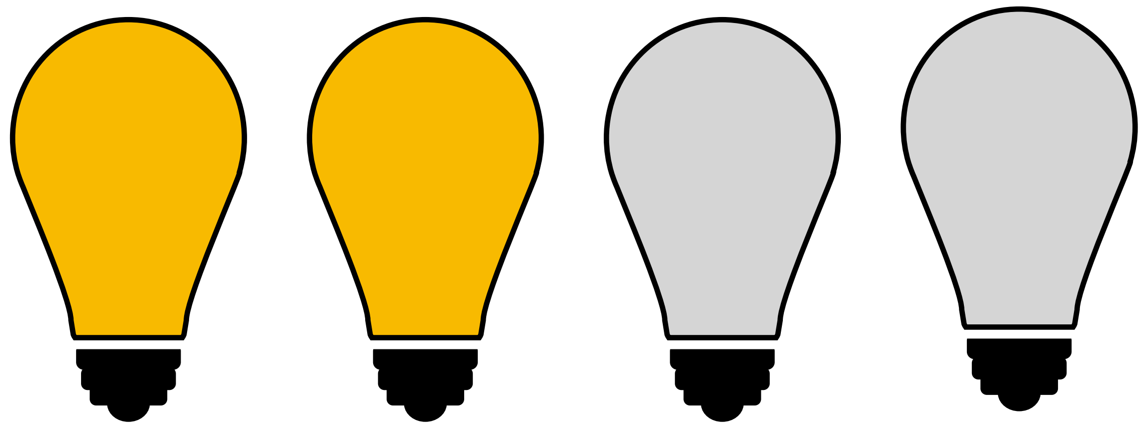
Quantum digital computation

Quantum computers are made of basic information units: qubits

Example: 4 qubits



$$|\psi\rangle = a_1$$  $$+a_2$$ 

$$+a_3$$  $$+\cdots$$

How many bits to get the same computing power? 2^4

Quantum digital computation

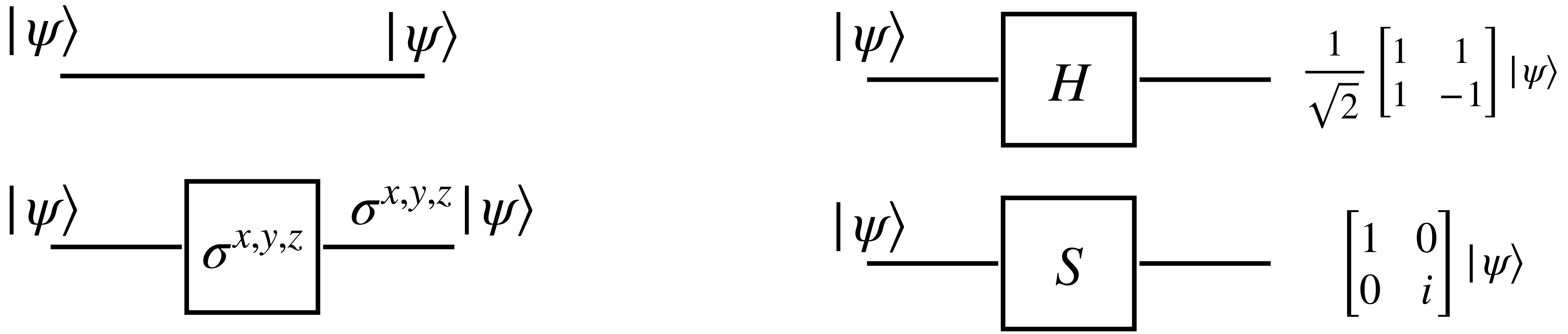
Let's revisit the previous diagrams

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

For 1 qubit

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Infinite set of operations: $|\psi\rangle = a|0\rangle + b|1\rangle \equiv a|\uparrow\rangle + b|\downarrow\rangle$



Remember: probabilities add to 1 $\longrightarrow$ $\boxed{U^\dagger}\,\boxed{U} = 1$

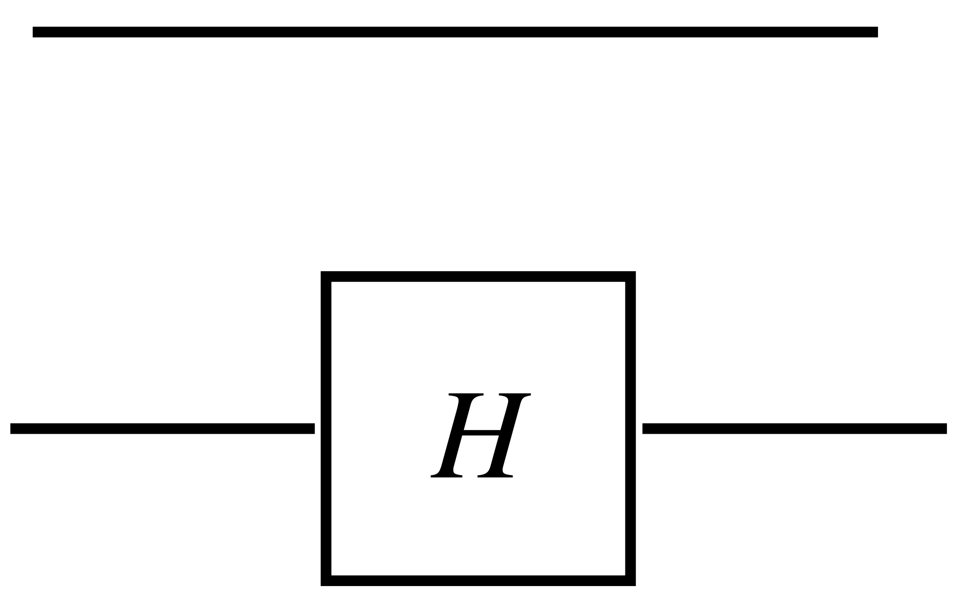
Quantum digital computation

Let's revisit the previous diagrams

For 2 qubits $$|\psi\rangle = \sum_{i,j} c_{ij} |x_i, x_j\rangle$$

Single qubit operations generalize in a simple way, for example

$$1 \otimes H |\psi\rangle \quad =$$



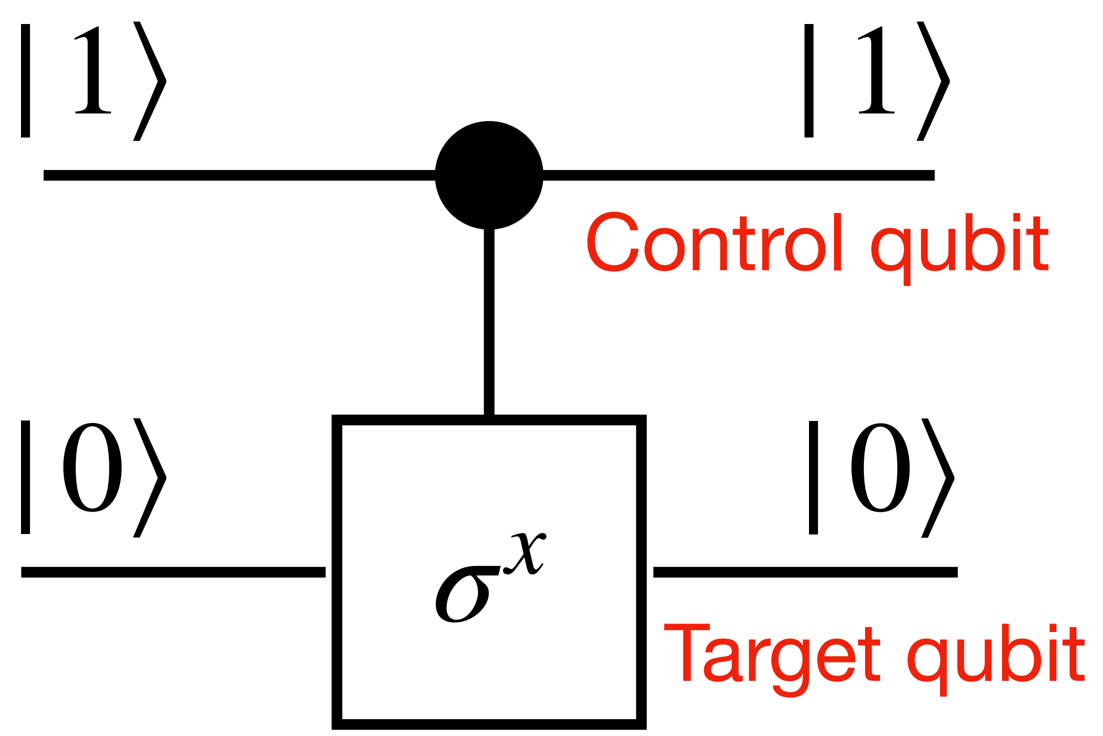
Quantum **digital** computation

Let's revisit the previous diagrams

For 2 qubits $|\psi\rangle = \sum_{i,j} c_{ij} |x_i, x_j\rangle$

But **things can get interesting**

$$\mathrm{CNOT}|\psi\rangle = \mathrm{C}\sigma^x|\psi\rangle =$$



$$= \begin{array}{c} \begin{array}{cccc} |00\rangle & |01\rangle & |10\rangle & |11\rangle \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

Unity Negate

Quantum digital computation

Let's revisit the previous diagrams

Example and first quantum circuit:

$$|\downarrow\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle) \quad \text{Bell state}$$

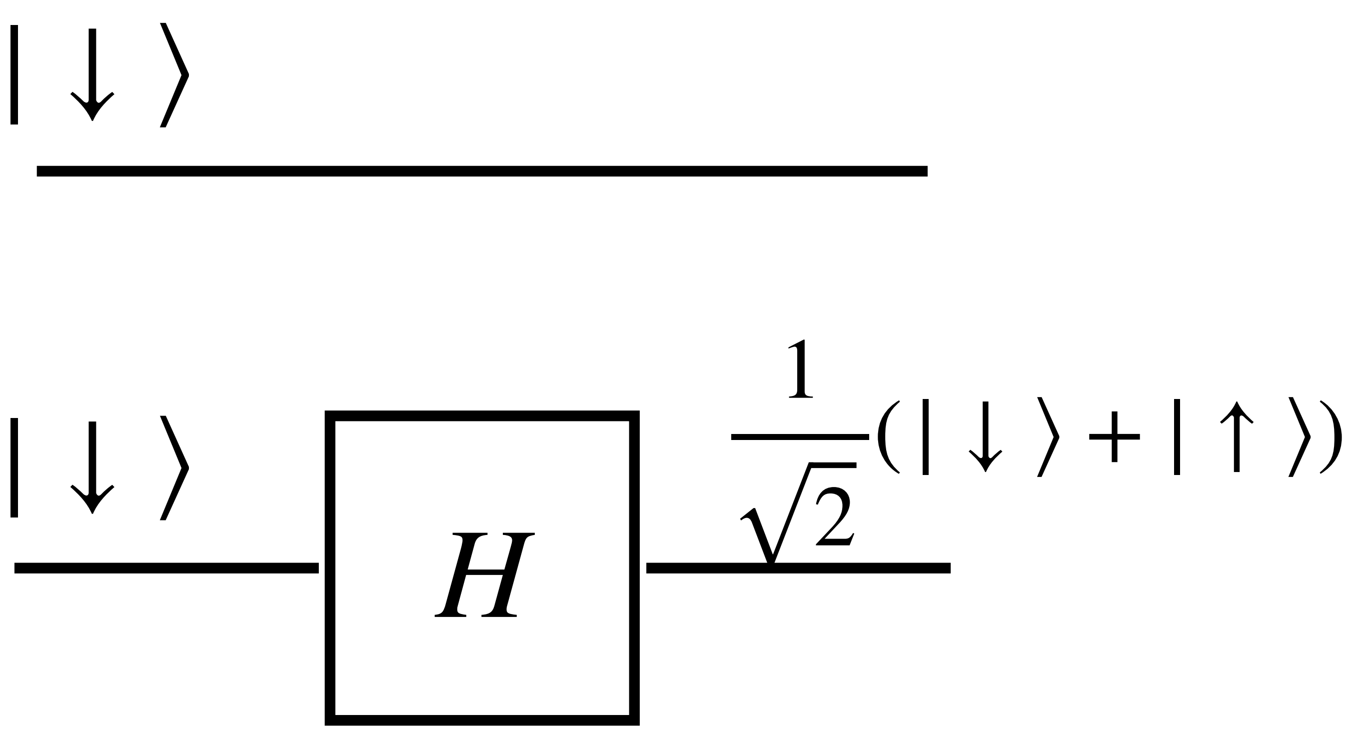
SOLUTION?

Quantum **digital** computation

Let's revisit the previous diagrams

Example and first quantum circuit:

$$|\downarrow\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle) \quad \text{Bell state}$$



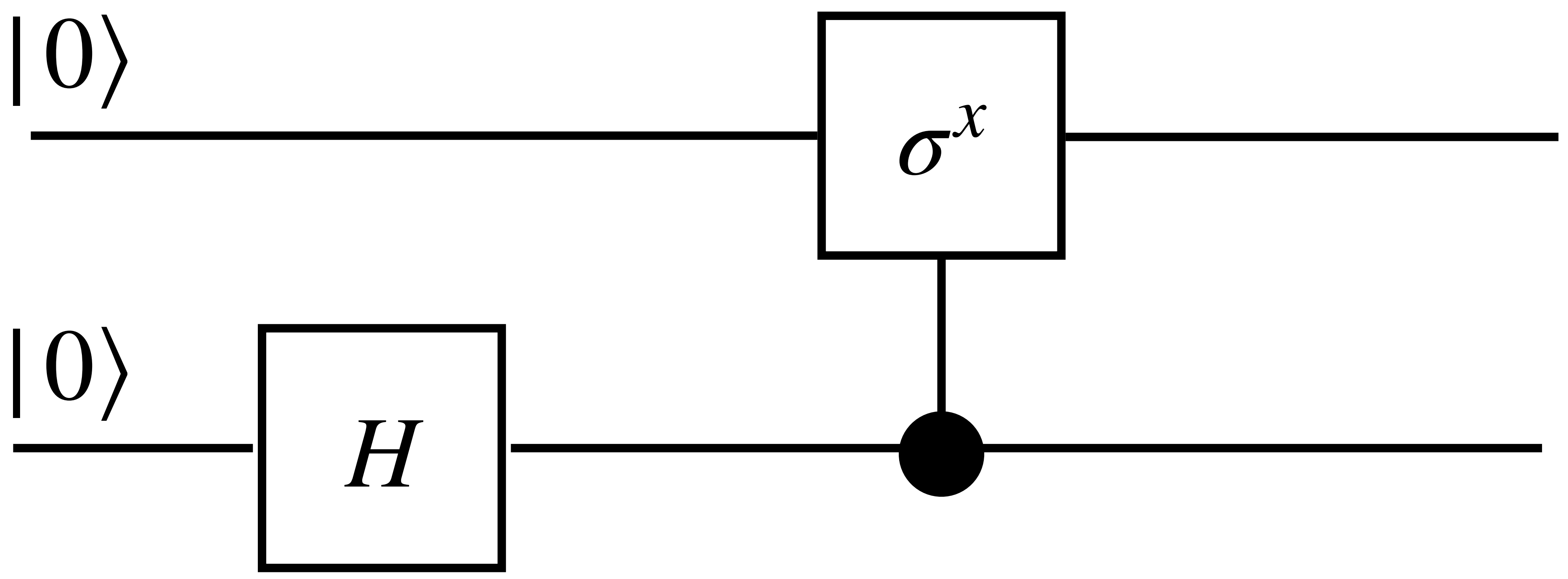
$$|\downarrow\downarrow\rangle \xrightarrow{H\otimes 1} \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\downarrow\rangle)$$

Quantum digital computation

Let's revisit the previous diagrams

Example and first quantum circuit:

$$|\downarrow\downarrow\rangle \to \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle) \quad \text{Bell state}$$

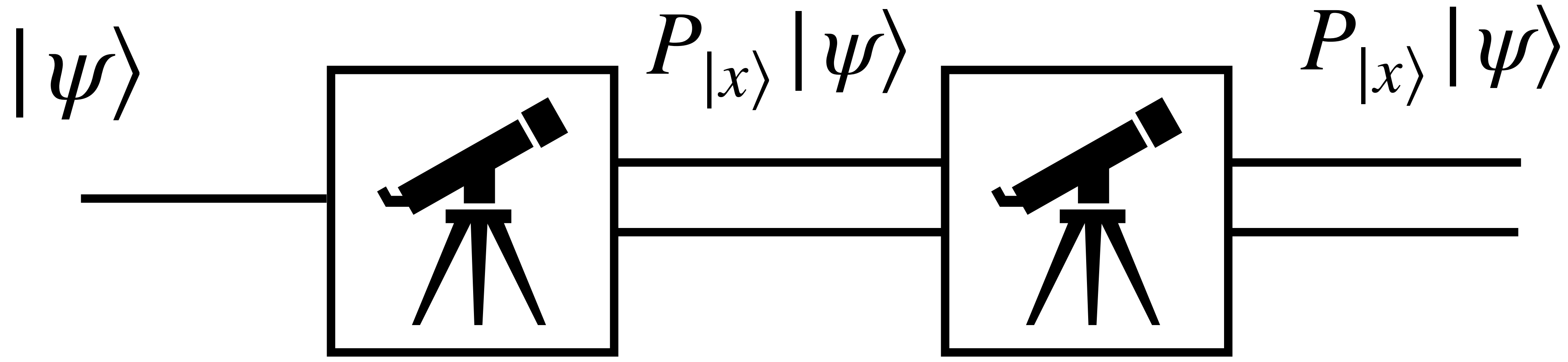


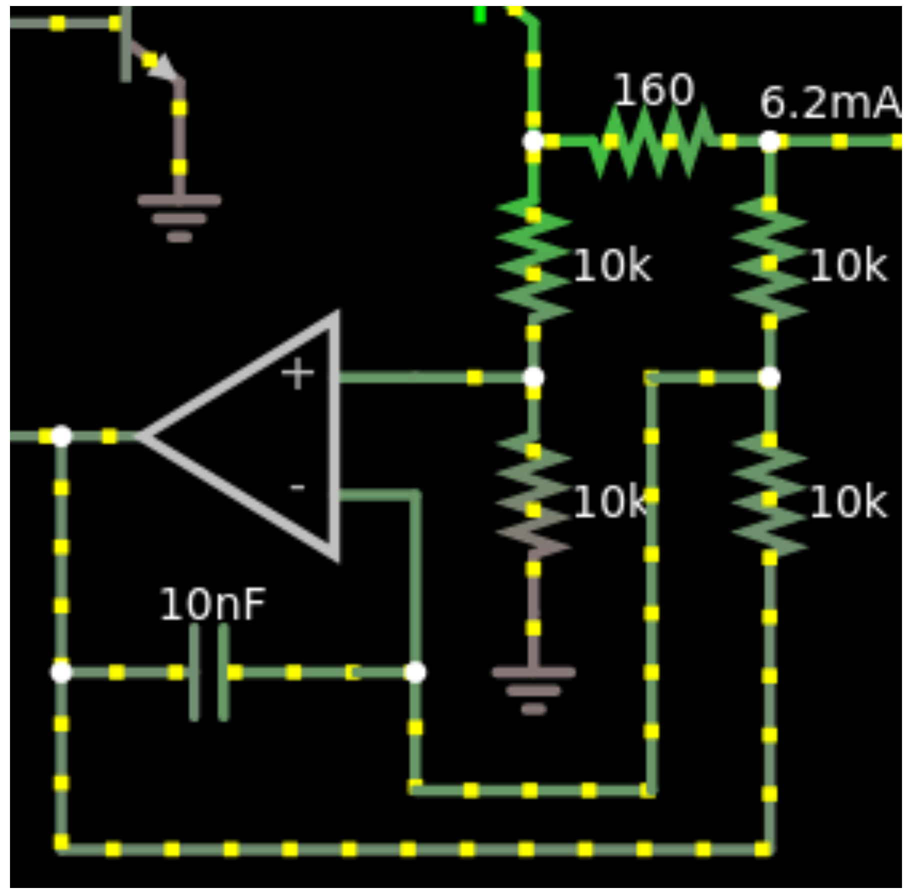
$$|\downarrow\downarrow\rangle \xrightarrow{H\otimes 1} \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\downarrow\rangle) \xrightarrow{\text{CNOT}} \frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle)$$

Quantum digital computation

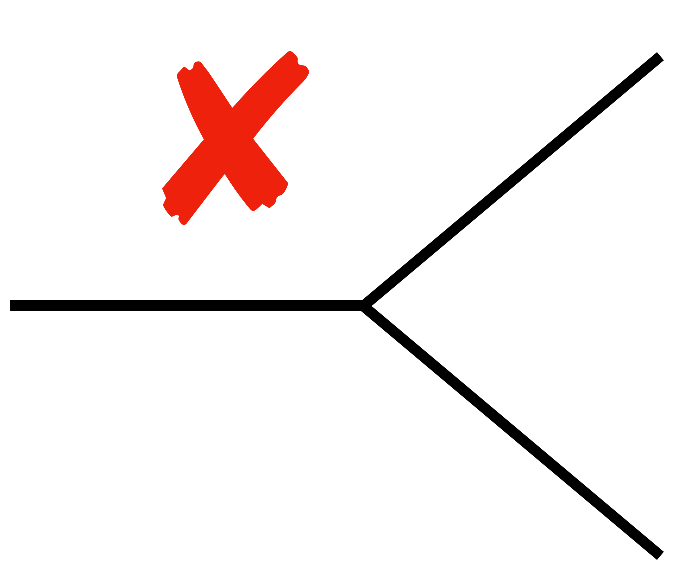
Finally we have

Measurement:





Non-trivial topologies:



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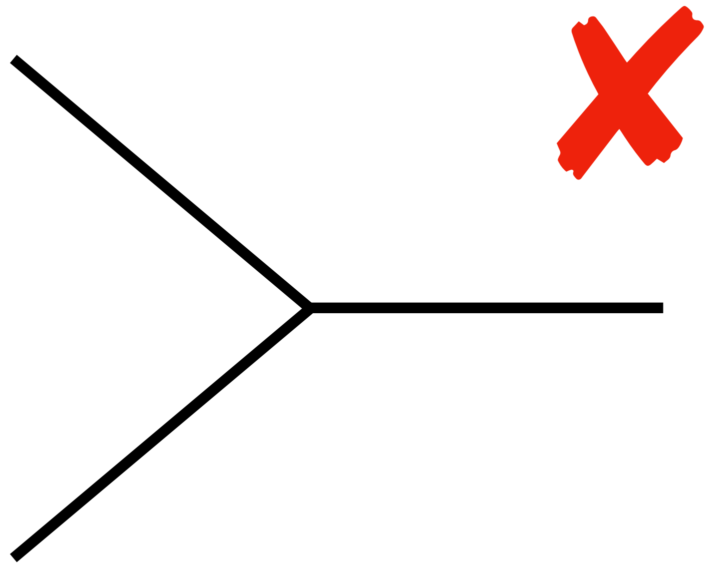

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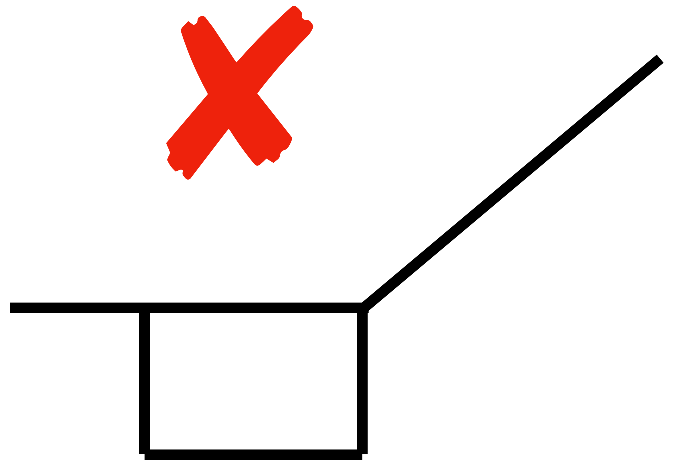
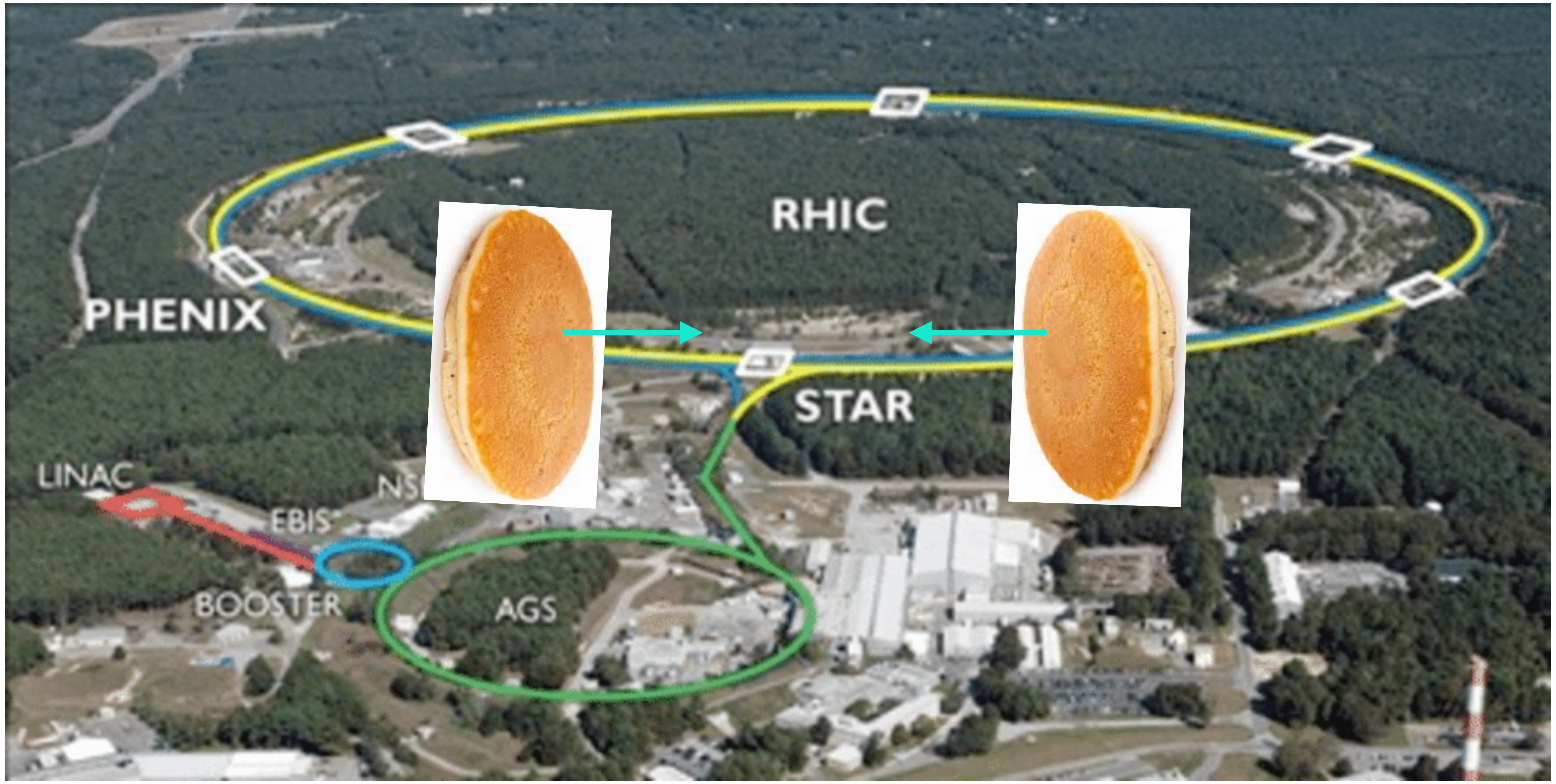


(Linearity)

What is the relation to HEP?

Simulating RHIC in a Qcomputer

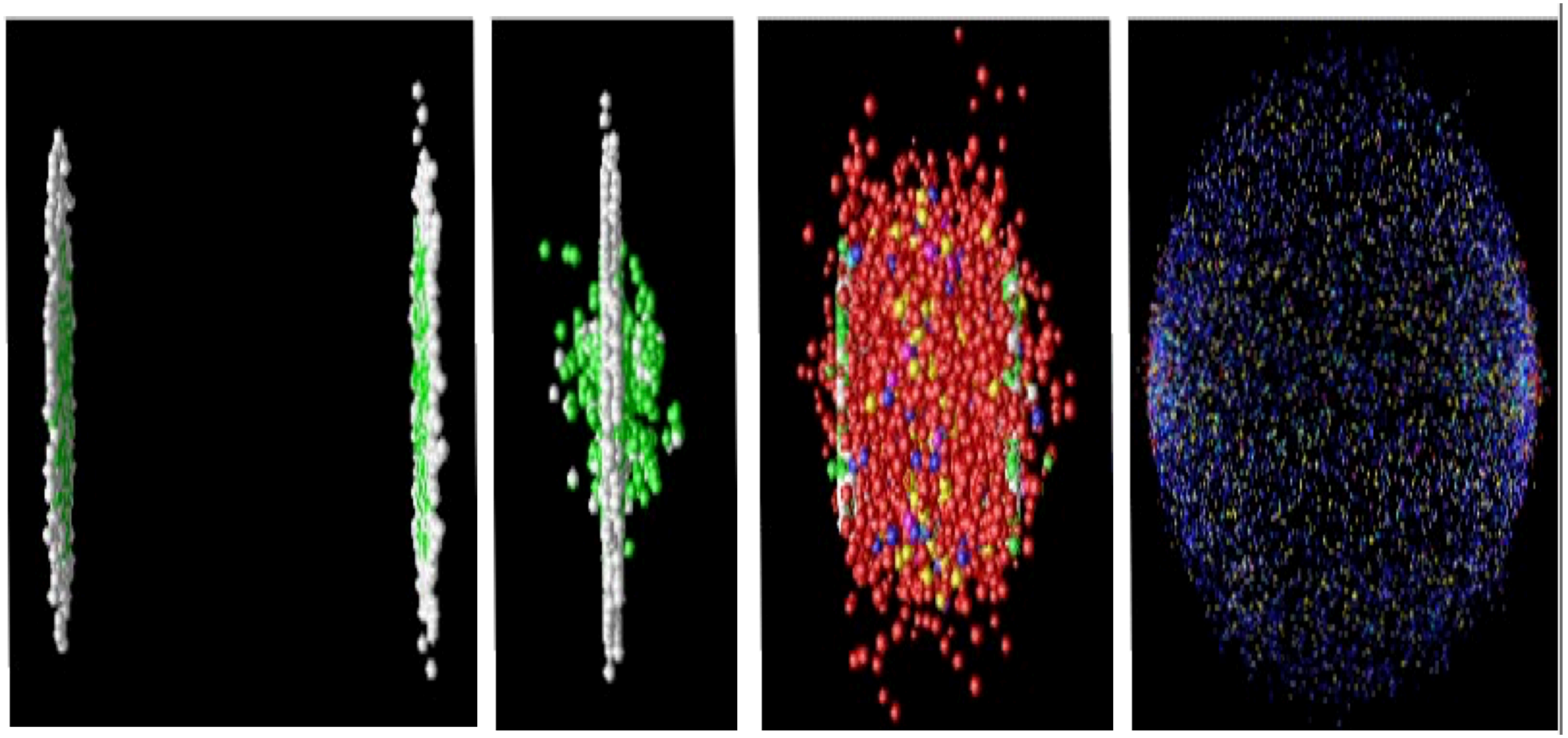
Challenge: Simulate Pancake-Pancake event at RHIC



Relativistic Heavy Ion Collider

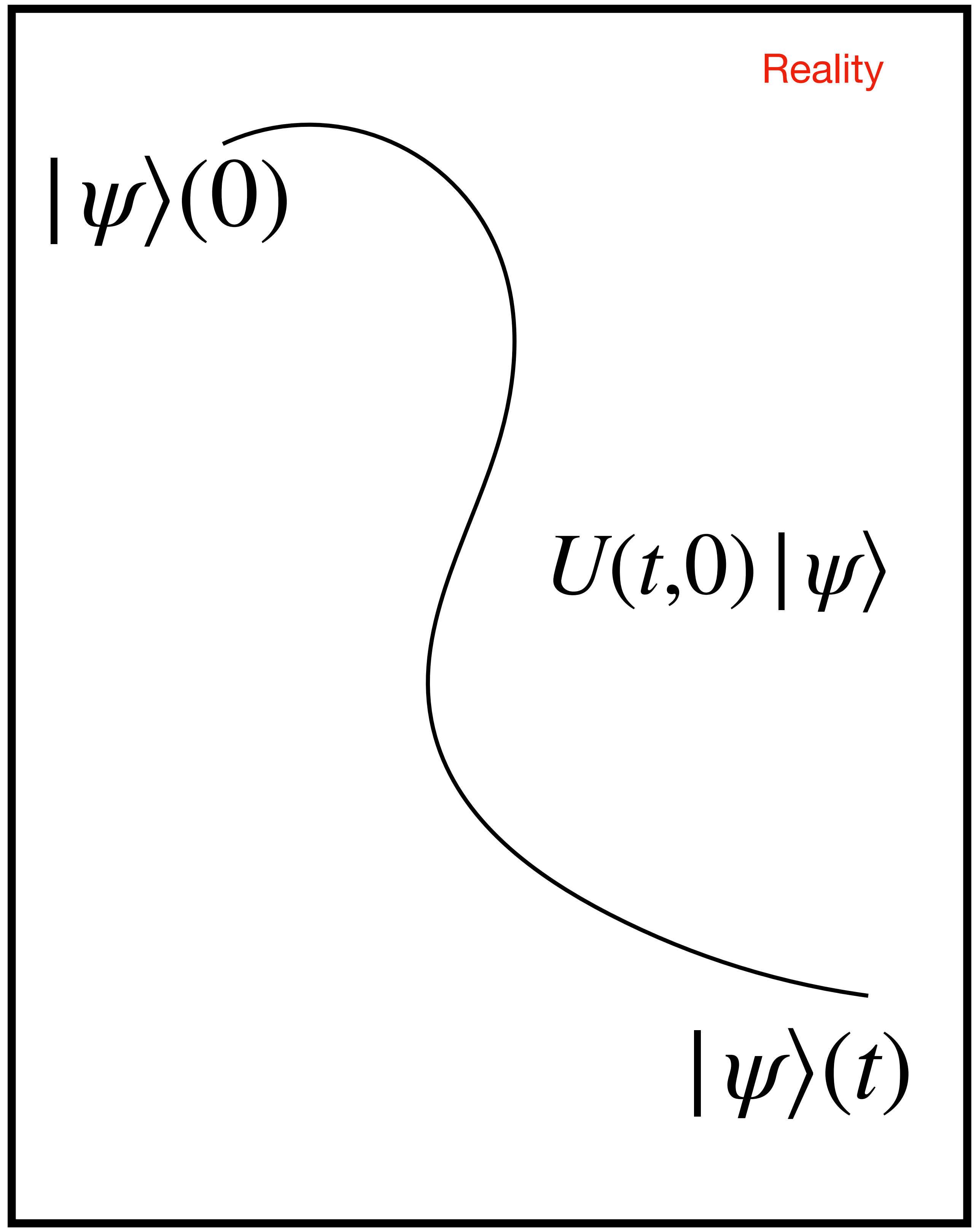
Simulating RHIC in a Qcomputer

Challenge: Simulate Pancake-Pancake event at RHIC

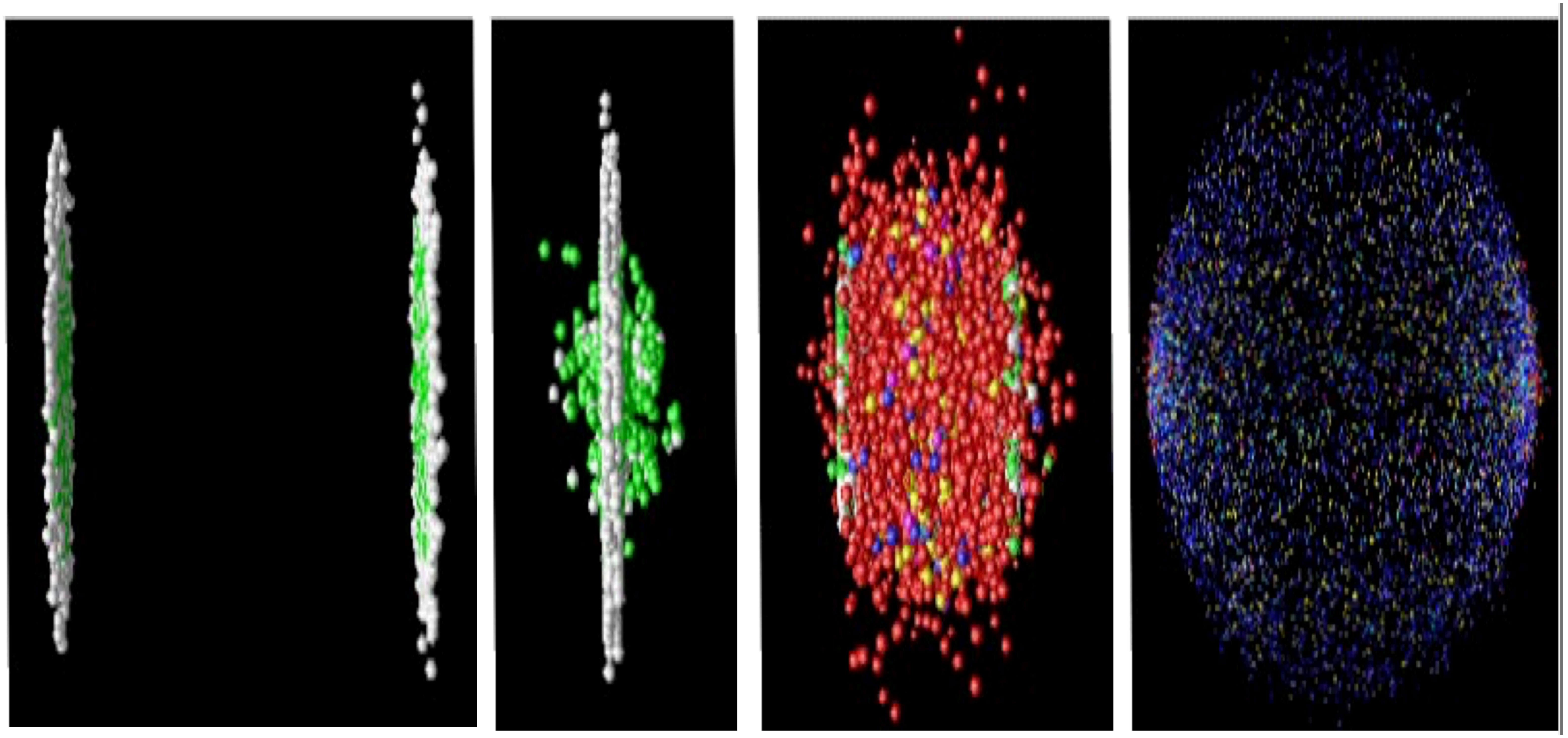


You saw this figure in R. Pisarski lecture a couple of weeks ago

Simulating RHIC in a Qcomputer



Pancake-Pancake event at RHIC

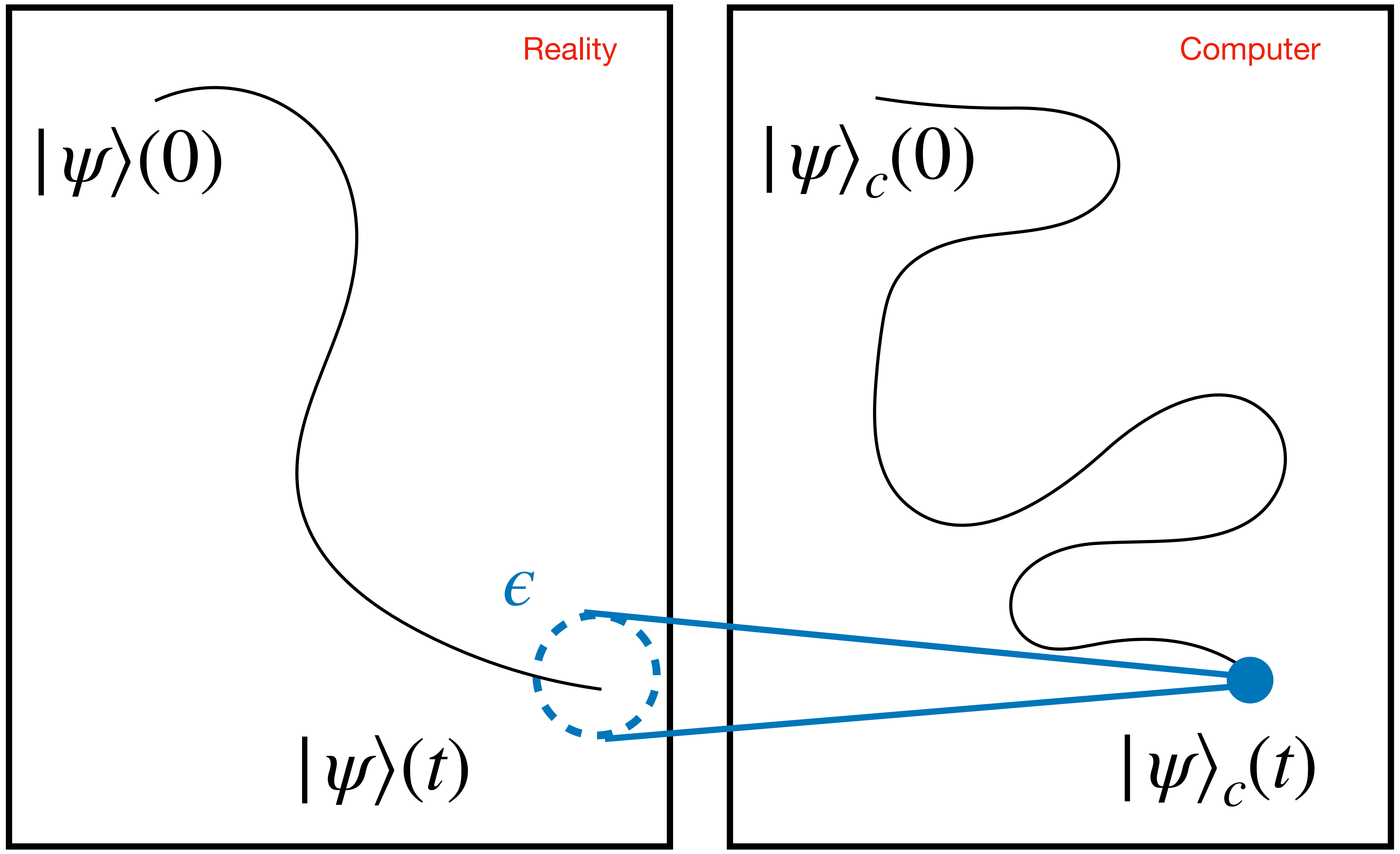


$|\psi\rangle(0)$ $U(t,0)|\psi\rangle$ $|\psi\rangle(t)$

Simulating RHIC in a Qcomputer

Strategy: We know that

$$i\partial_t |\psi\rangle = H |\psi\rangle \quad \text{so} \quad |\psi\rangle(t) = \exp\left(-iHt\right)|\psi\rangle(0)$$



1. Map dofs to qubits
2. Write evolution operator in terms of gates
3. Measure the state

An example

Disclaimer: Going fast here, so don't worry if you don't follow 100%

Suppose: $H = \sigma^x \otimes \sigma^z$ and $\psi(0) = | \downarrow \downarrow \rangle$

$$\sigma^x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad \sigma^z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

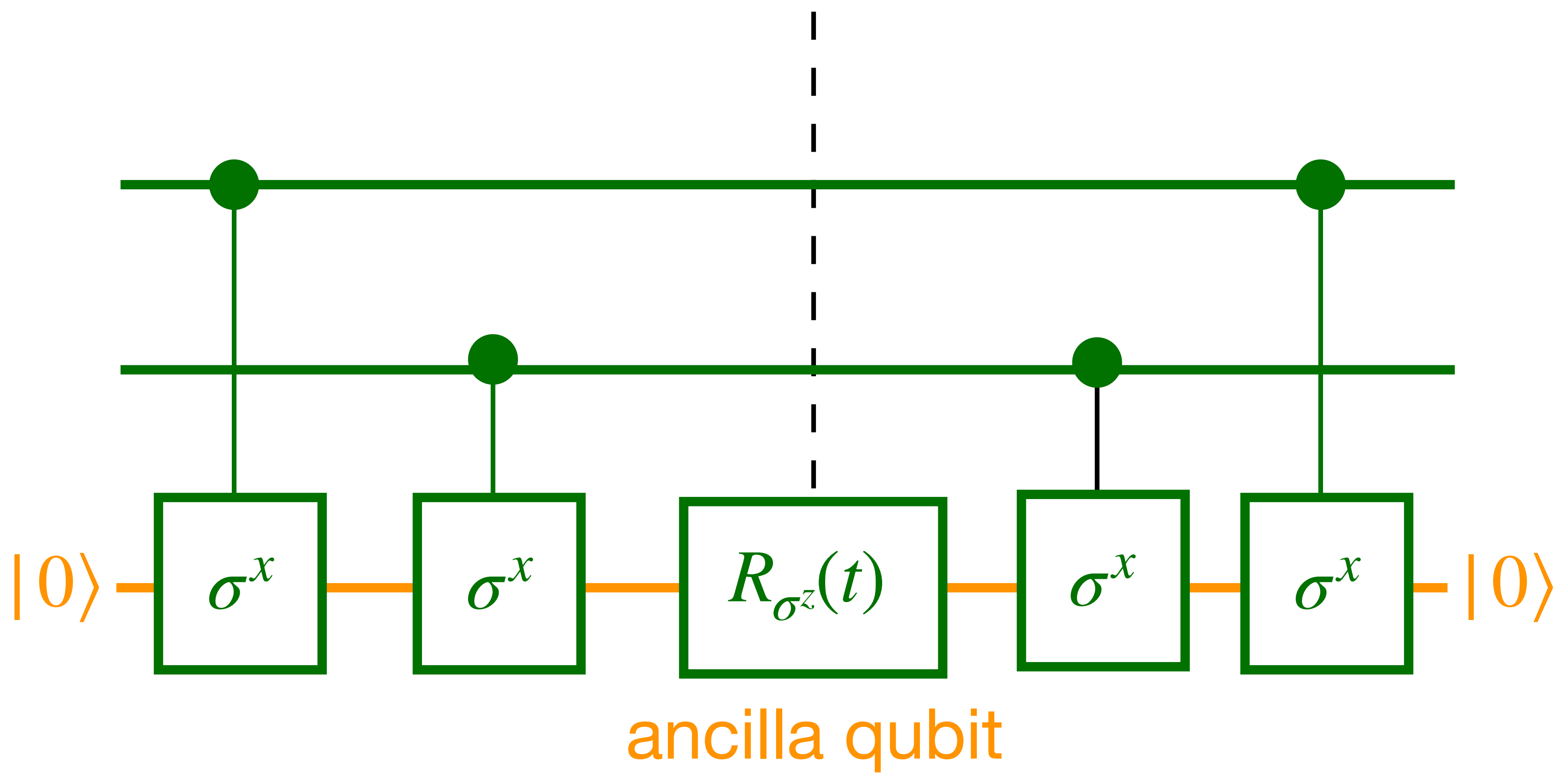
$$H = (Had \otimes 1)(\sigma^z \otimes \sigma^z)\,(Had \otimes 1)^\dagger$$

Exercise: check this

Exercise: check this

$$\sigma^z \otimes \sigma^z \begin{cases} |00\rangle = |00\rangle \\ |01\rangle = -|01\rangle \\ |10\rangle = -|10\rangle \\ |11\rangle = |11\rangle \end{cases}$$

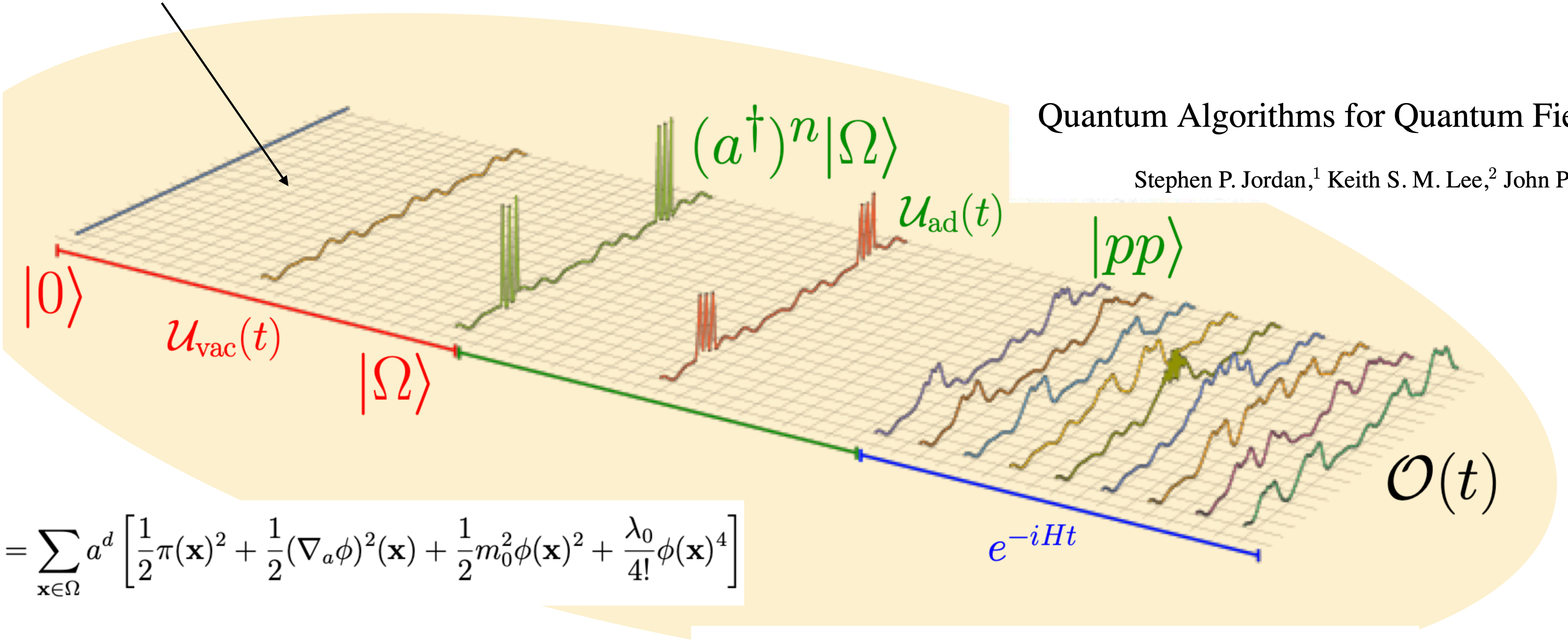
$\exp(-it(\sigma^z \otimes \sigma^z)) =$



In reality: scattering in scalar QFT

Introduce lattice

Two particles scattering to four particles



Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1] Keith S. M. Lee,[2] John Preskill[3]

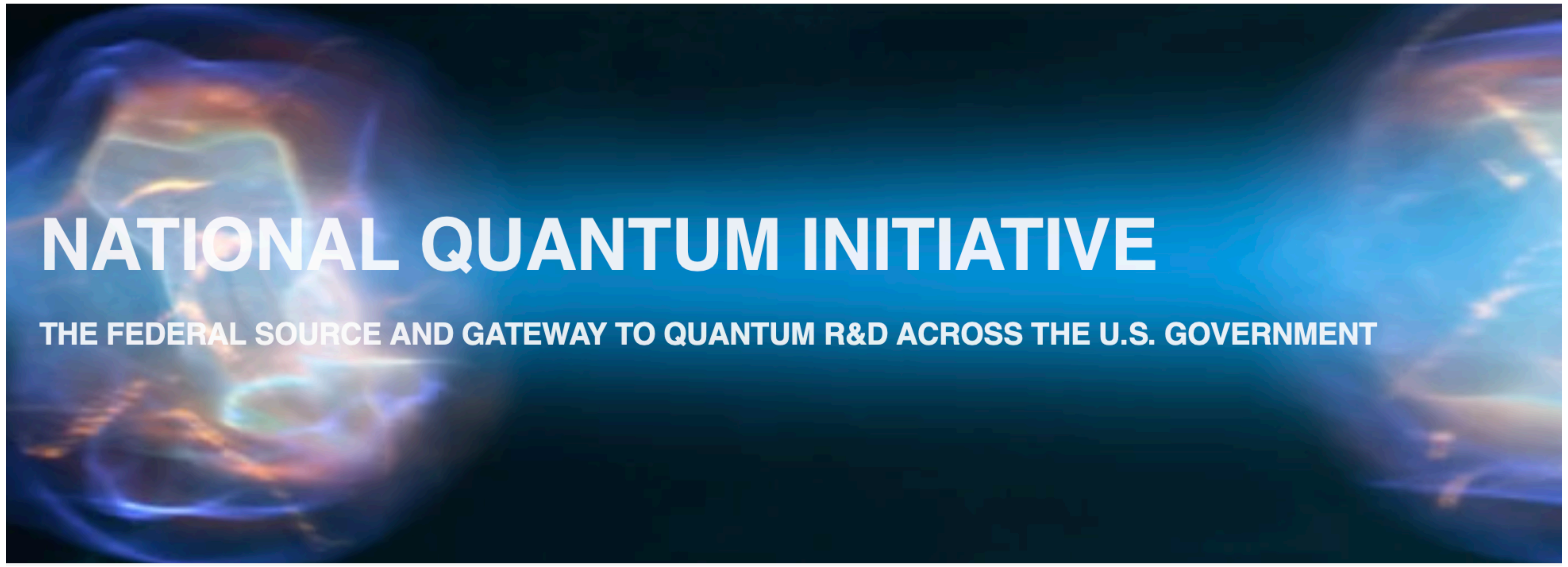
$$H = \sum_{\mathbf{x}\in\Omega} a^d \left[\frac{1}{2}\pi(\mathbf{x})^2 + \frac{1}{2}(\nabla_a\phi)^2(\mathbf{x}) + \frac{1}{2}m_0^2\phi(\mathbf{x})^2 + \frac{\lambda_0}{4!}\phi(\mathbf{x})^4\right]$$

Figure by H. Lamm

Meaningful simulations will require something
in the order of **thousands of high quality qubits** !

Some key ideas

1 **Quantum computing is picking up steam**



D::Wave
The Quantum Computing Company™

Microsoft
Quantum Computer

rigetti

IBM Q

IONQ

Some key ideas

2 **Quantum computing is only starting in HEP/NP**

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Quantum Simulation for High Energy Physics

I. Physics drive: Collider phenomenology

II. Physics drive: Matter in and out of equilibrium

III. Physics drive: Neutrino (astro)physics

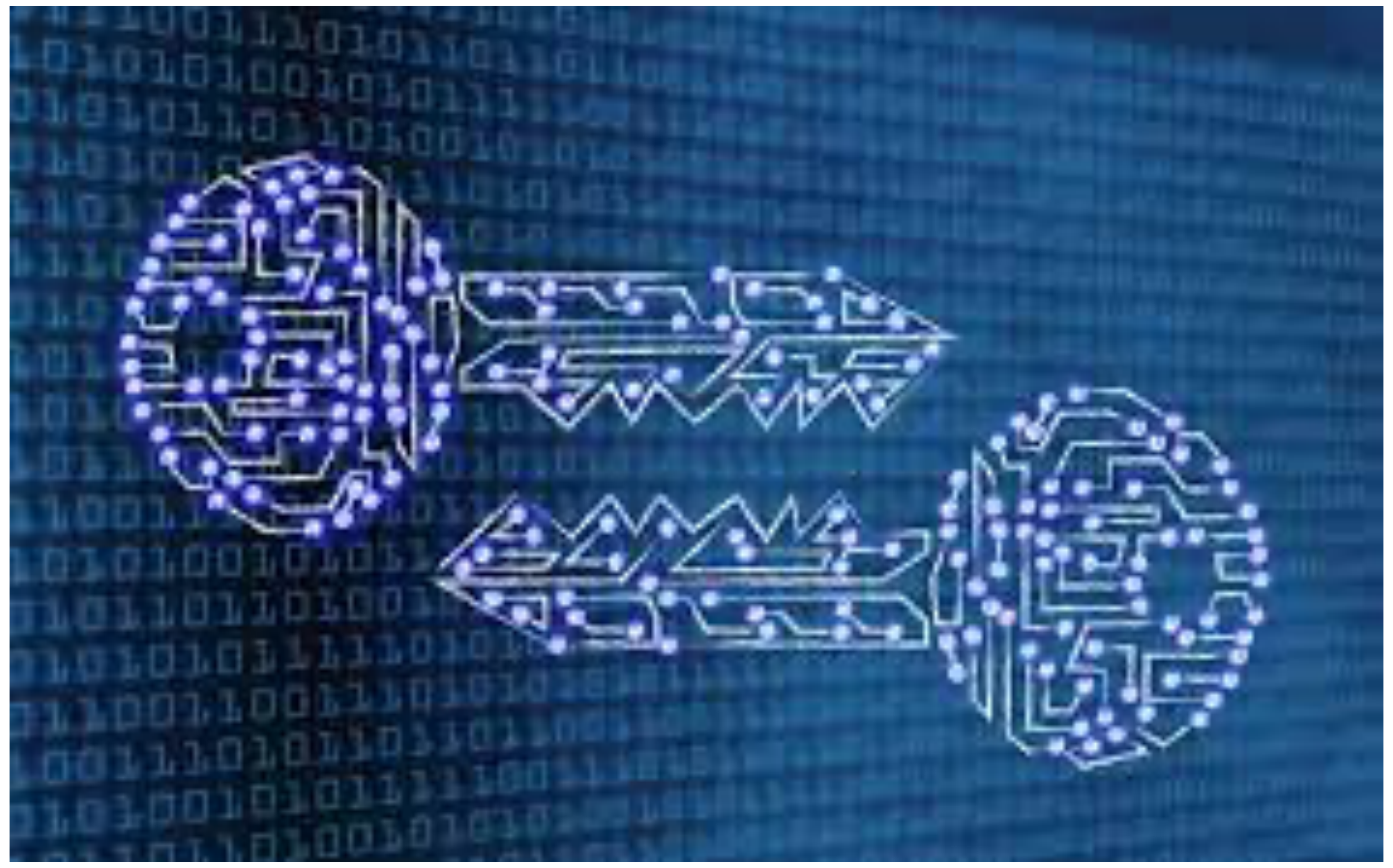
IV. Physics drive: Cosmology and early universe

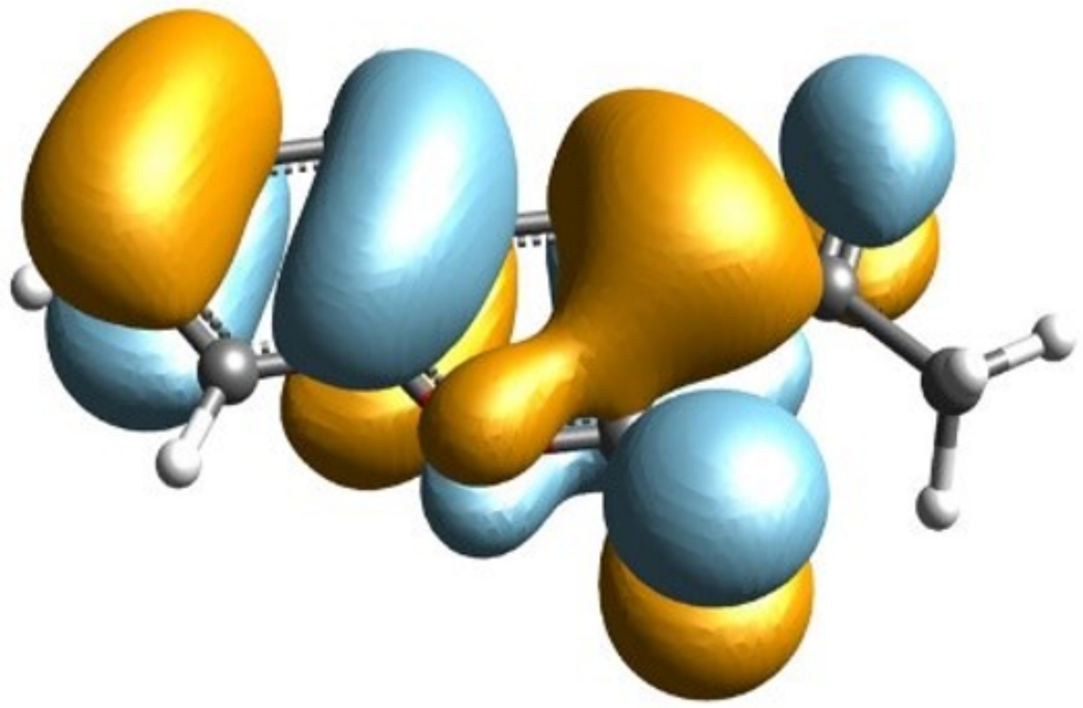
V. Physics drive: Nonperturbative quantum gravity

To find the full document Google: arxiv 2204.03381

Some key ideas

3 **Quantum computing has a wide range of applications**



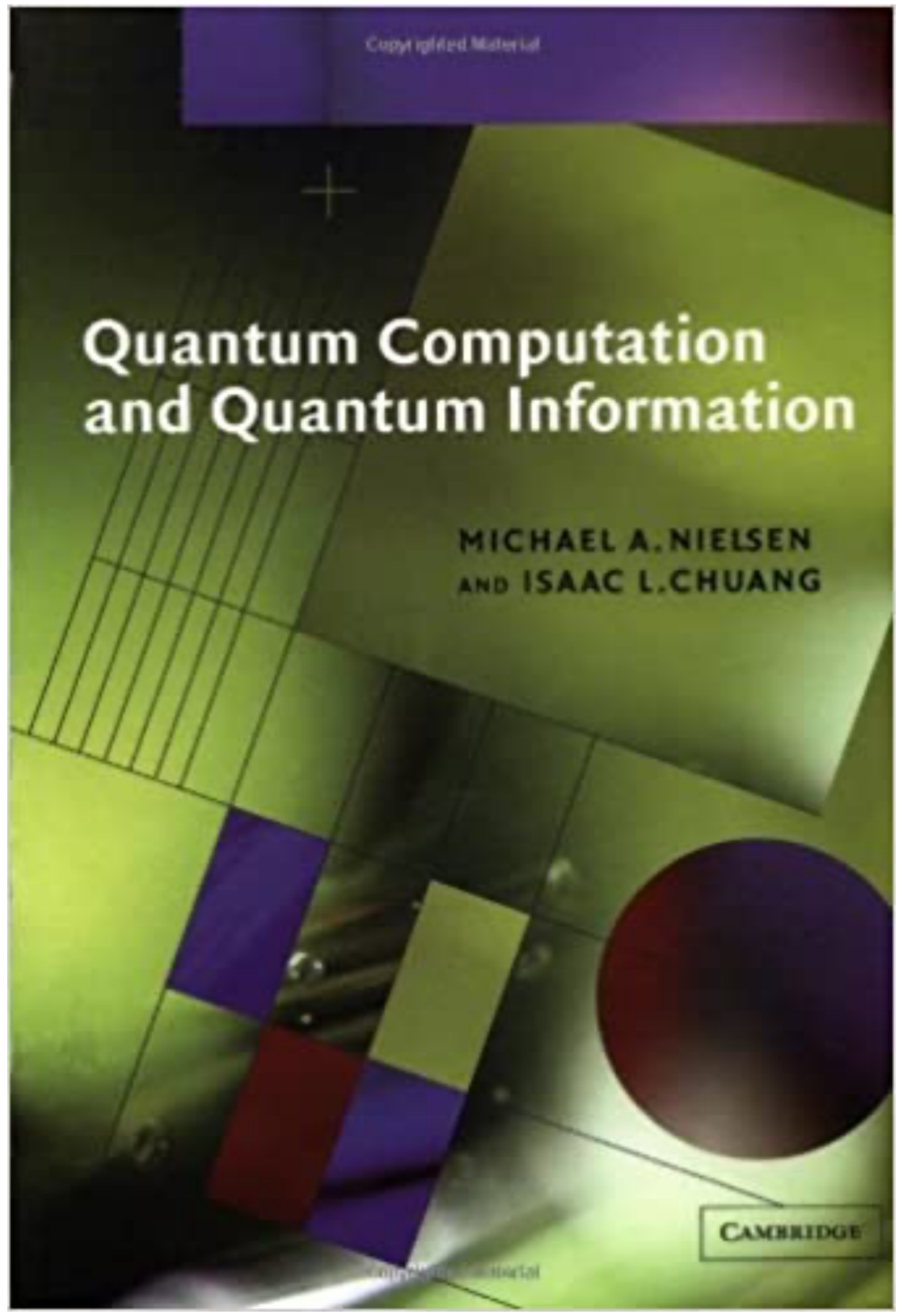


Some places to look for more info

Excellent introduction to QM and QC

+

Software to play around



Global introduction to QC