LLR Seminar, March 8th 2021

Using Quantum Computers (QC) for complex quantum systems simulation

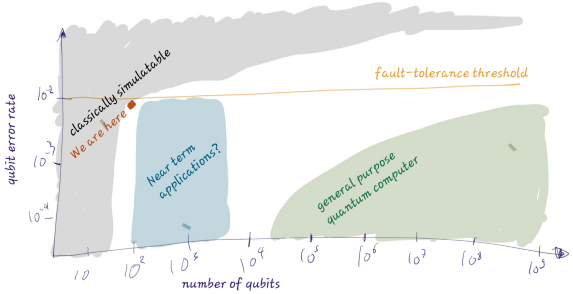
Denis Lacroix (IJCLab)

QC2I project

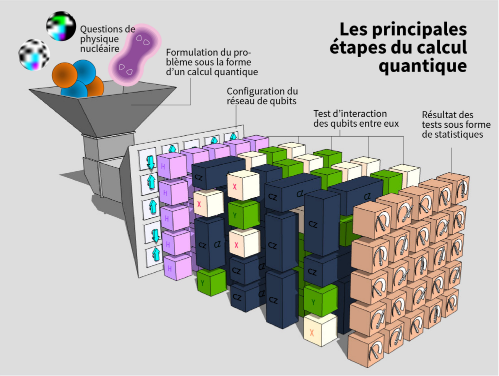
Depuis 80 ans, nos connaissances bâtissent de nouveaux mondes

Brief introduction to QC

Current status and opportunities



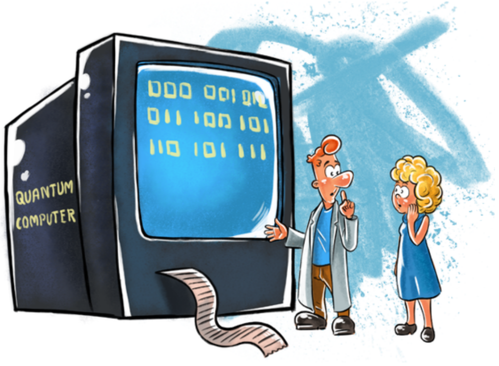
Discussion on ongoing projects in complex many-body systems



Short introduction to bit versus Qubits

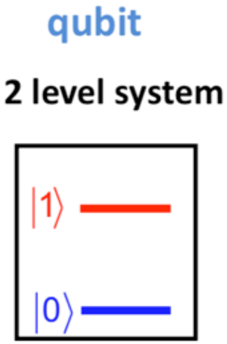
Classical computers Works with bits

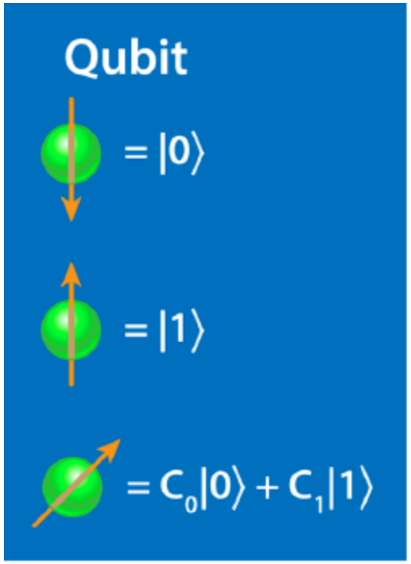
Quantum computers with Quantum bits



Bits are only 0 or 1

Qubits can be seen
As two-level systems





A single Qubit can be any superposition of 0 and 1

Obvious advantage

Imagine you want to simulate where 0 appears with a probability p_0 and 1 appears with a probability p_1. On a classical computer, you do many events and average over events. On a quantum computer 1 single simulation is necessary.

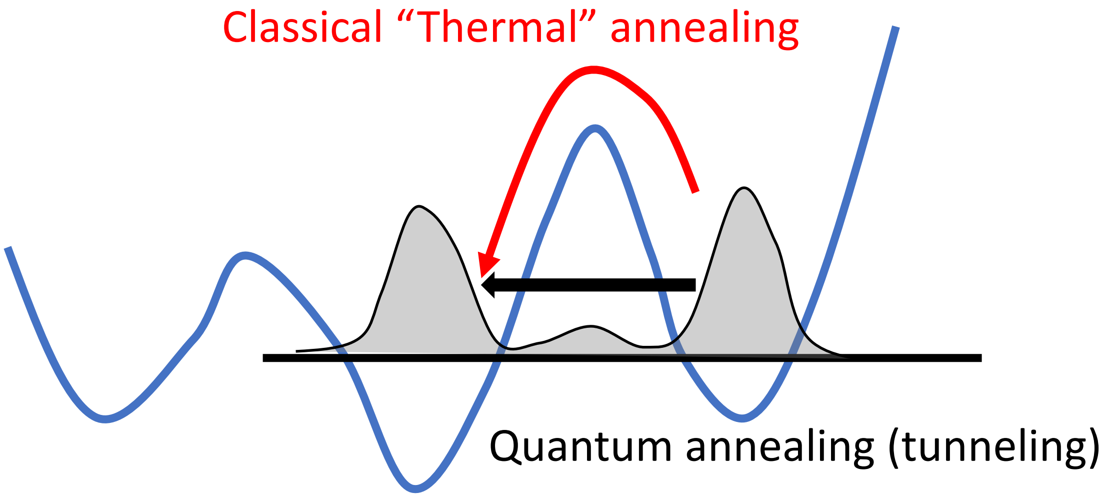
And with many Qubits

New aspects can be used like quantum interference and entanglement

Short introduction to bit versus Qubits

Illustration of quantum advantages

Quantum Tunneling and quantum annealing


Classical "Thermal" annealing

Quantum annealing (tunneling)

Quantum entanglement

Assume two persons (Alice and Bob)

The humor of A&B are encoded in the wave-function

$$|\Phi\rangle = \alpha|\overset{\overset{A}{\Downarrow}}{😀}\overset{\overset{B}{\Downarrow}}{😀}\rangle + \beta|\overset{\overset{A}{\Downarrow}}{😫}\overset{\overset{B}{\Downarrow}}{😫}\rangle$$

Suppose I measure Bob 😀 ➡ 😀

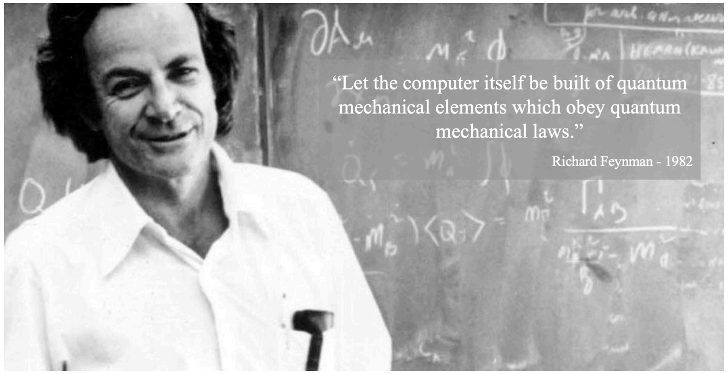
😫 ➡ 😫

I can measure partial info and get the full info

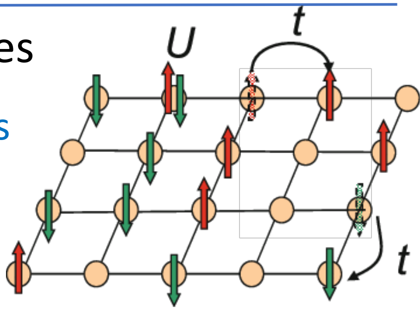
The info is destroyed after measurement

What are the anticipated applications ?

Simulation of Quantum complex systems



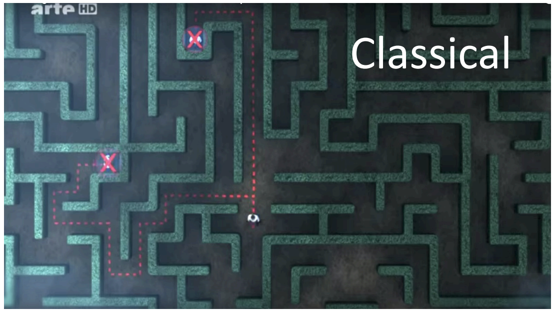
Ex: systems on lattices



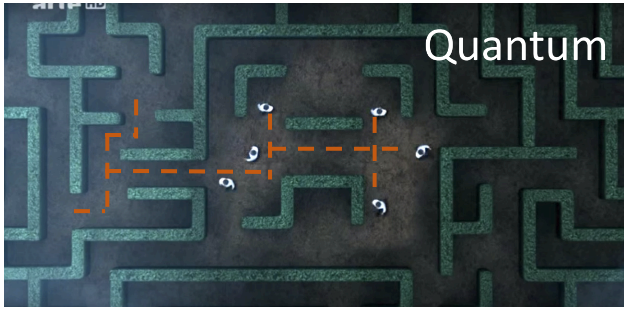
On classical computers
Can be solved exactly
For max 20 particles.

On quantum computers:
N sites means only N qubits

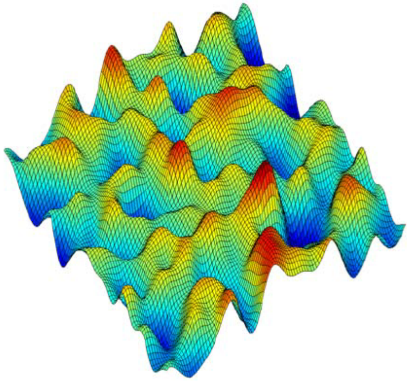
Quantum versus classical search



vs

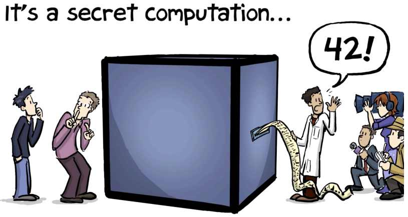


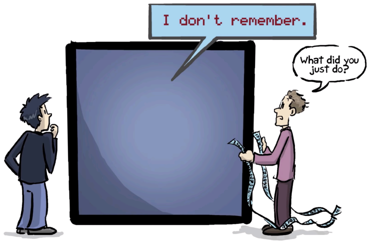
Credit: The Fabric of The Cosmos: Quantum Leap

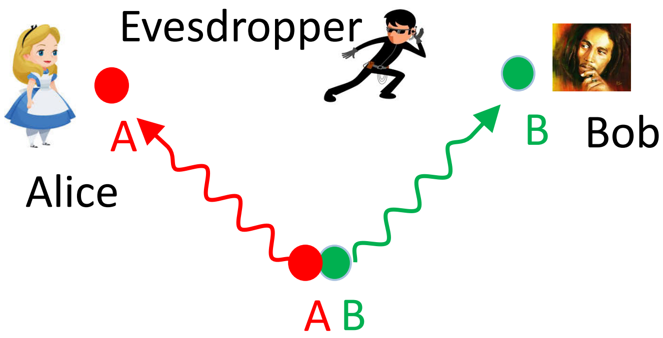


Exploring complex landscape:
molecules,
customers preferences (amazon), …

Quantum secrets (cryptography, quantum key, …)



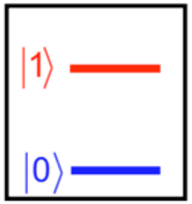




Minimal - Practical aspects of quantum computers

qubit

2 level system



Manipulate the Qubits (Make rotations)

$|0\rangle$ Initial state

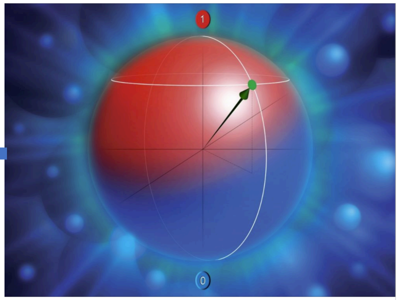


Illustration d'un qubit

CRÉDIT : MARK GARLICK / SCIENCE PHOTO LIBRA / MGA / SCIENCE PHOTO LIBRARY VIA AFP

Final state $c_0|0\rangle + c_1|1\rangle$

Measure the state

$|c_0|^2, \; |c_1|^2$

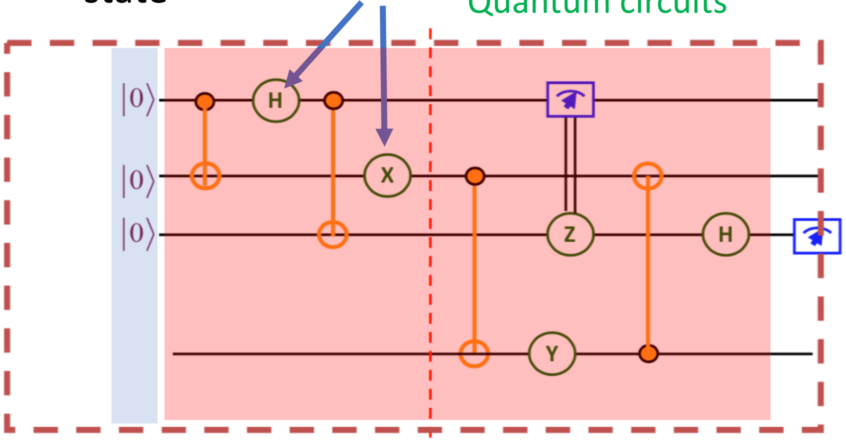
("destroy" the state)

With many Qubits

Initial state

Elementary operations

Quantum circuits



N = 2^n computational basis states

$$\overbrace{|010001\dots1\rangle}^{n} = |p\rangle$$

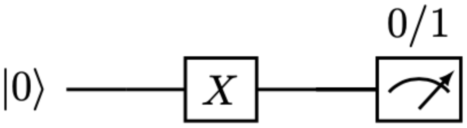
$$\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_4 \dots i_{2^N}} |i_1, i_2, i_3 \dots i_{2^N}\rangle$$

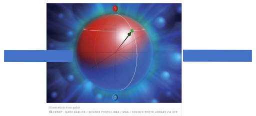
Gives the $|a|^2$

Minimal - Practical aspects of quantum computers

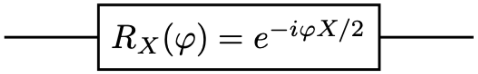
The quantum computing toolkit

Unary operations



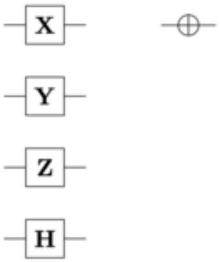


Rotations



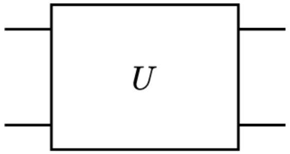
$$R_X(\varphi) = e^{-i\varphi X/2}$$

Standard examples

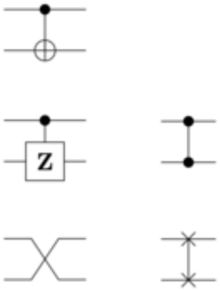


Pauli-X (X)	$\begin{array}{ccc} \vert 0\rangle & \vert 1\rangle & \\ 0 & 1 & \vert 0\rangle \\ 1 & 0 & \vert 1\rangle \end{array}$
Pauli-Y (Y)	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

Binary operations



Standard examples



Controlled Not (CNOT, CX)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$|11\rangle \leftrightarrow |10\rangle$

Controlled Z (CZ)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

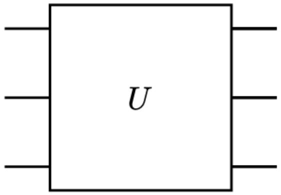
$|11\rangle \leftrightarrow -|11\rangle$

SWAP

$$\begin{array}{ccccc} 1 & 0 & 0 & 0 & |00\rangle \\ 0 & 0 & 1 & 0 & |01\rangle \\ 0 & 1 & 0 & 0 & |10\rangle \\ 0 & 0 & 0 & 1 & |11\rangle \end{array}$$

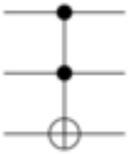
$|01\rangle \leftrightarrow |10\rangle$

Ternary operations



Standard example

Toffoli (CCNOT, CCX, TOFF)



$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$|110\rangle \leftrightarrow |111\rangle$

Quantum computing today is firstly an experimental challenge

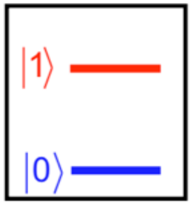
REALITY

Everything around want to destroy the ideal picture and the quantum coherence.

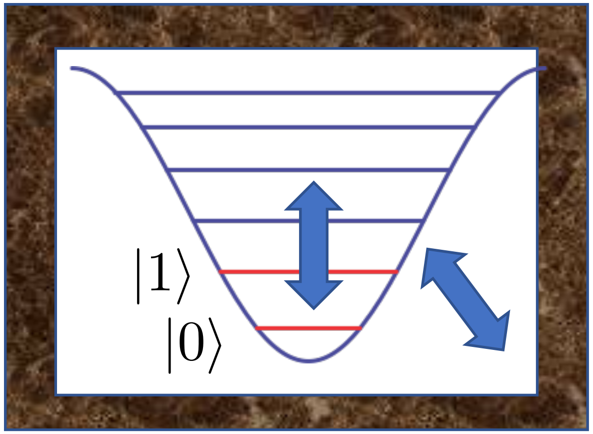
Leads to loss of information
And decoherence

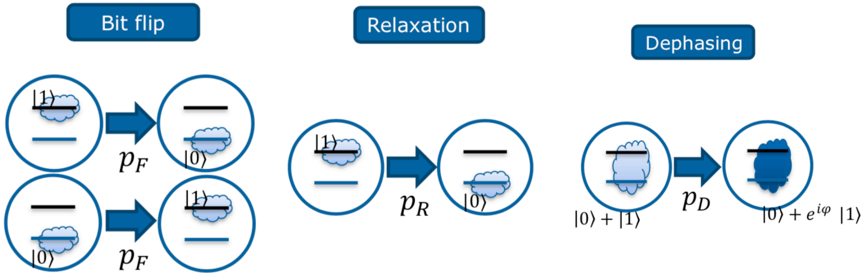
Ideal Qubits

2 level system



External Exp. Setup

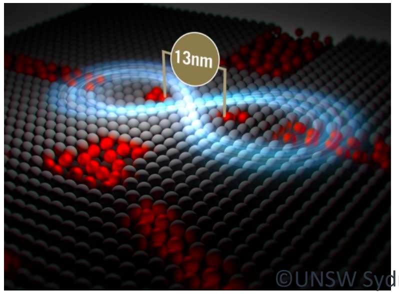




For multi-Qubits, also cross-talk
(making operations on one qubit
Impacts other qubits)

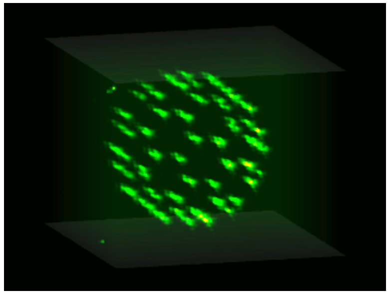
Working with quantum computers now means working in a noise environment short programs
(before decoherence occurs)

Building quantum computers: companies



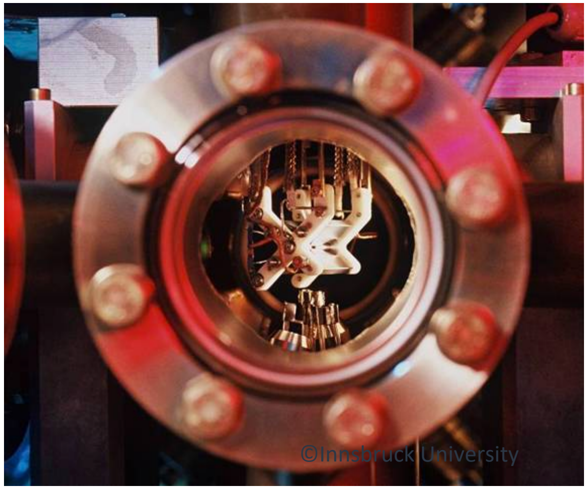
©UNSW Sydney

Silicon qubits



Neutral atoms

NMR



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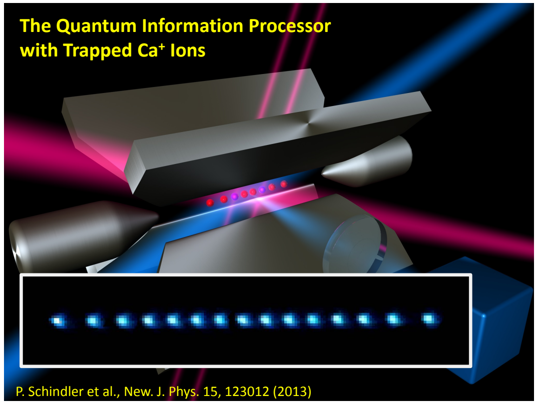
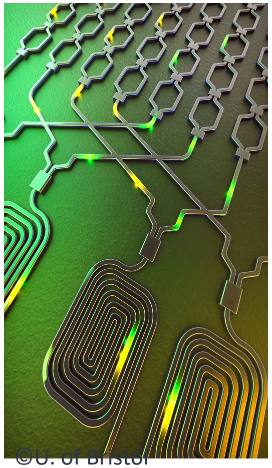
Trapped ions



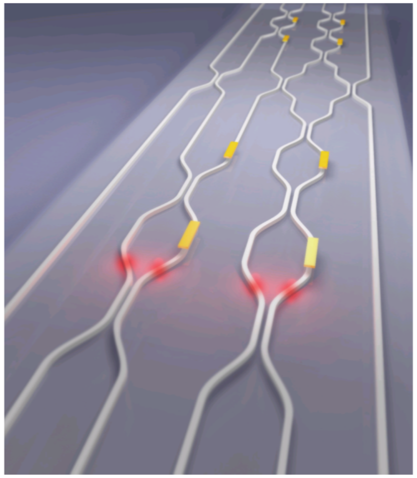
The Quantum Information Processor with Trapped Ca^+ Ions

P. Schindler et al., New. J. Phys. 15, 123012 (2013)



©U. of Bristol

Photons



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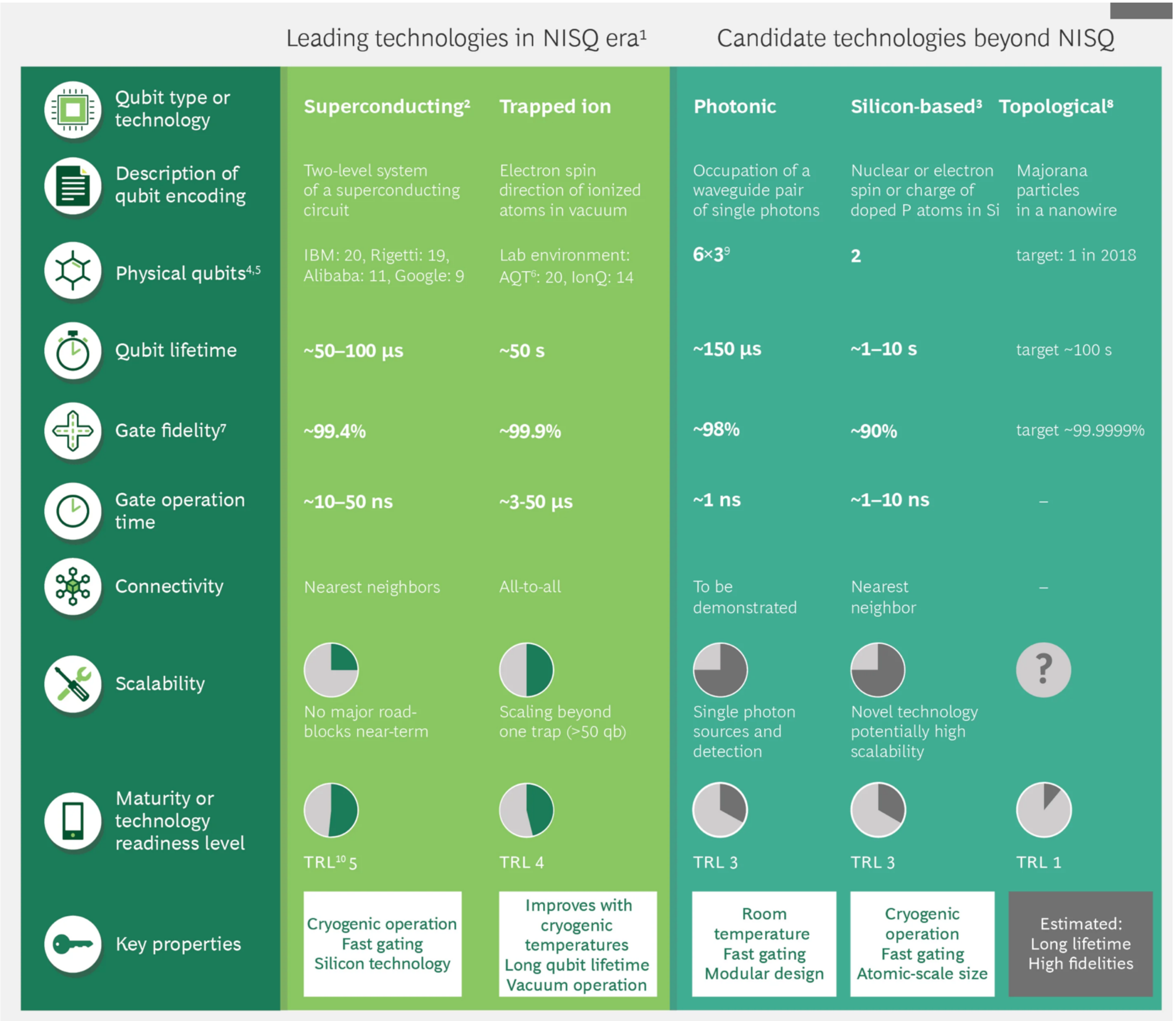
Superconducting qubits

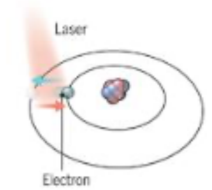
Platforms comparison

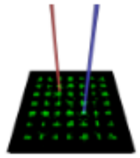


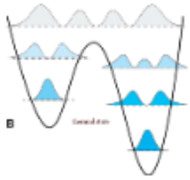
	Leading technologies in NISQ era[1]		Candidate technologies beyond NISQ		
Qubit type or technology	**Superconducting[2]**	**Trapped ion**	**Photonic**	**Silicon-based[3]**	**Topological[8]**
Description of qubit encoding	Two-level system of a superconducting circuit	Electron spin direction of ionized atoms in vacuum	Occupation of a waveguide pair of single photons	Nuclear or electron spin or charge of doped P atoms in Si	Majorana particles in a nanowire
Physical qubits[4,5]	IBM: 20, Rigetti: 19, Alibaba: 11, Google: 9	Lab environment: AQT[6]: 20, IonQ: 14	**6×3[9]**	**2**	target: 1 in 2018
Qubit lifetime	**~50–100 µs**	**~50 s**	**~150 µs**	**~1–10 s**	target ~100 s
Gate fidelity[7]	**~99.4%**	**~99.9%**	**~98%**	**~90%**	target ~99.9999%
Gate operation time	**~10–50 ns**	**~3-50 µs**	**~1 ns**	**~1–10 ns**	–
Connectivity	Nearest neighbors	All-to-all	To be demonstrated	Nearest neighbor	–
Scalability	◔ No major road-blocks near-term	◑ Scaling beyond one trap (>50 qb)	◕ Single photon sources and detection	◕ Novel technology potentially high scalability	?
Maturity or technology readiness level	◑ TRL[10] 5	◑ TRL 4	◔ TRL 3	◔ TRL 3	◔ TRL 1
Key properties	Cryogenic operation Fast gating Silicon technology	Improves with cryogenic temperatures Long qubit lifetime Vacuum operation	Room temperature Fast gating Modular design	Cryogenic operation Fast gating Atomic-scale size	Estimated: Long lifetime High fidelities

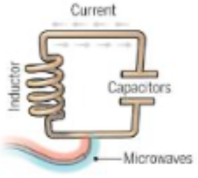
Boston Consulting Group – Nov 2018

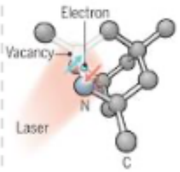
Building quantum computers: companies

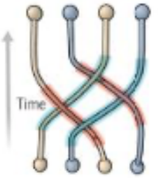


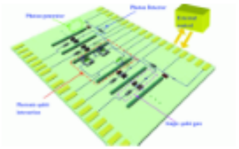










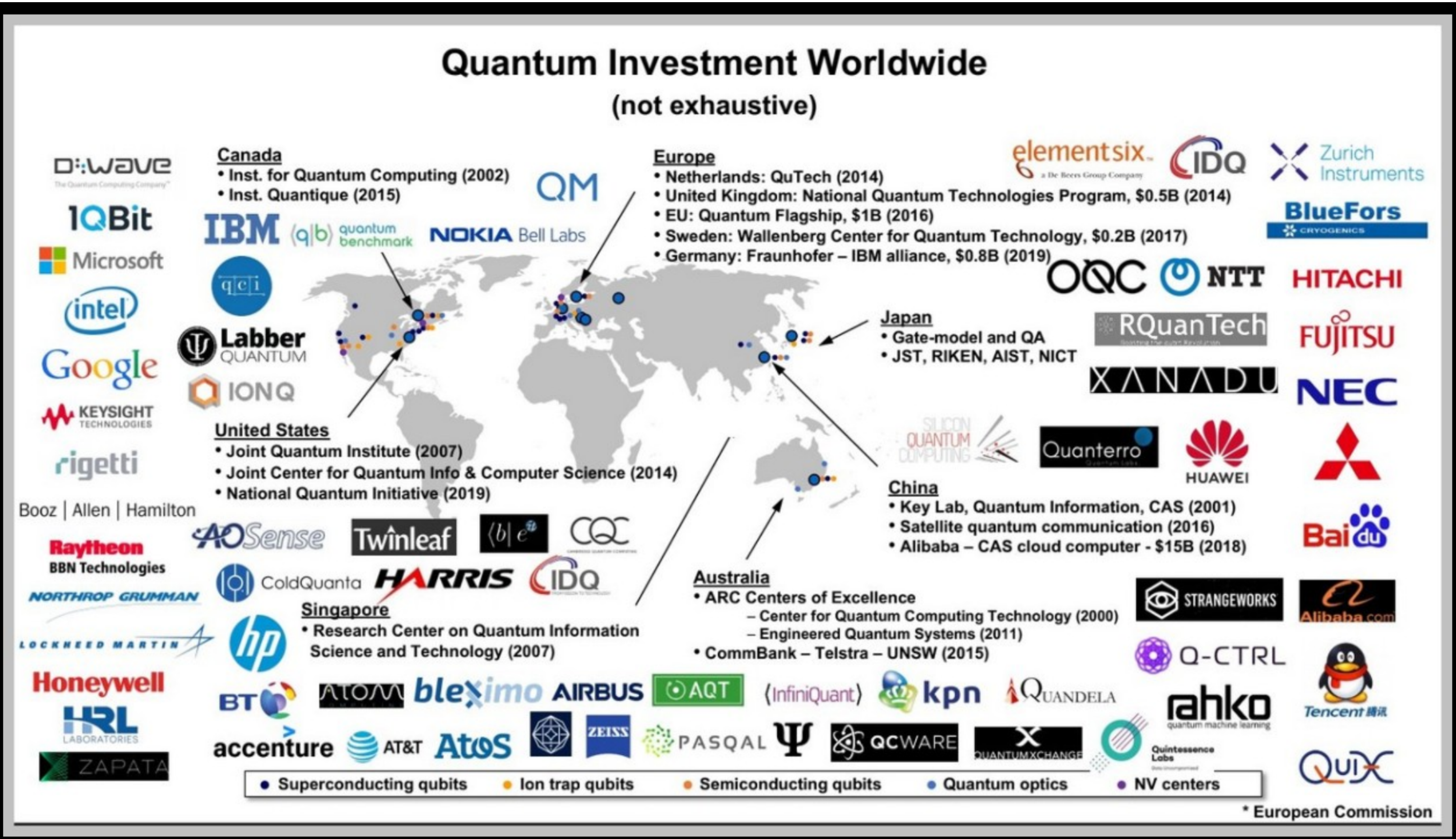


	atomes		**électrons**					**photons**
	ions piégés	**atomes froids**	**recuit quantique**	**supra-conducteurs**	**silicium**	**centres NV (diamant)**	**qubits topologiques**	**photons**
entreprises et startups	Quantum Factory IONQ Honeywell AQT Oxford Ionics NextGenQ	PASQAL Atom Computing QuEra	D-Wave The Quantum Computing Company	Google intel IBM OQC rigetti bleximo qci Raytheon EeroQ Oxford Quantum Alice & Bob MDR	intel Quantum Motion NTT Silicon Quantum Computing equal1.labs	QDTI TURING	Microsoft NOKIA	XANADU ORCA Computing PSIQUANTUM TUNDRASYSTEMS GLOBAL LTD LightOn Quandela QuiX BardeenQ Labs
laboratoires (*)	MIT University of Maryland IQST JGU Johannes Gutenberg Universität Mainz IQOQI universität innsbruck Sandia National Laboratories KIT NIST Harvard University University of Sussex	cnrs Harvard University Jülich Forschungszentrum EPFL PennState The Ohio State University	NEDO KIT MIT ETH zürich (*) inventaire non exhaustif, il manque notamment les Chinois qui sont partout	cea cnrs Inria UCSB QuTech Berkeley University of California Universität des Saarlandes UMassAmherst ETH zürich MIT 東京大学 The University of Tokyo Yale	cea cnrs University of Bristol University of Oxford UNSW Sydney Yale HRL Laboratories Princeton University University of Wisconsin Madison RIKEN	cea cnrs MIT University of Maryland TU Delft Harvard University Universität Stuttgart The University of Chicago	cea cnrs TU Delft UCSB University of Maryland QuTech Niels Bohr Institutet The University of Sydney	cnrs University of Bristol University of Oxford Sapienza Università di Roma universität wien 東京大学 The University of Tokyo

(cc) Olivier Ezratty, septembre 2020

From article O. Ezratty

Building quantum computers: companies



Quantum Investment Worldwide

(not exhaustive)

Canada
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

Europe
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program, \$0.5B (2014)
- EU: Quantum Flagship, \$1B (2016)
- Sweden: Wallenberg Center for Quantum Technology, \$0.2B (2017)
- Germany: Fraunhofer – IBM alliance, \$0.8B (2019)

Japan
- Gate-model and QA
- JST, RIKEN, AIST, NICT

United States
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
- National Quantum Initiative (2019)

China
- Key Lab, Quantum Information, CAS (2001)
- Satellite quantum communication (2016)
- Alibaba – CAS cloud computer - \$15B (2018)

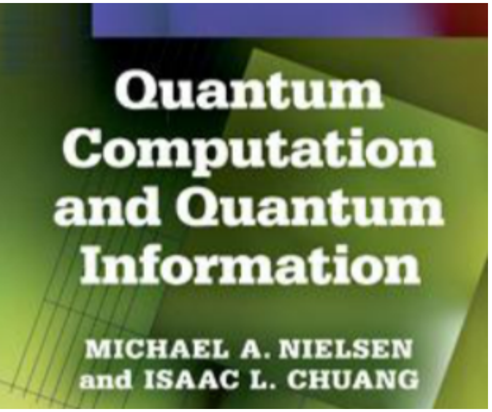
Singapore
- Research Center on Quantum Information Science and Technology (2007)

Australia
- ARC Centers of Excellence
  - – Center for Quantum Computing Technology (2000)
  - – Engineered Quantum Systems (2011)
- CommBank – Telstra – UNSW (2015)

● Superconducting qubits ● Ion trap qubits ● Semiconducting qubits ● Quantum optics ● NV centers

* European Commission

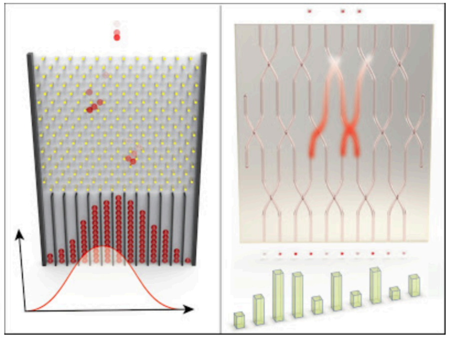
William Oliver, MIT -



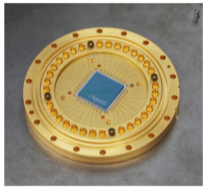
Quantum Computation and Quantum Information

MICHAEL A. NIELSEN and ISAAC L. CHUANG

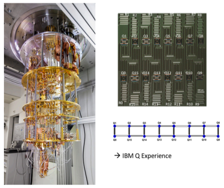
Quantum computational advantage using photons, Science 370 (2020)



RIGETTI superconducting 19 Qubit



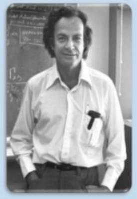
IBM QX5 (16 qubits)

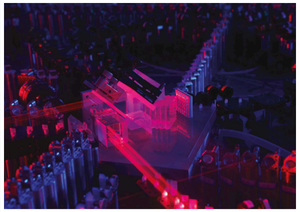


Simulating physics with computers-1982

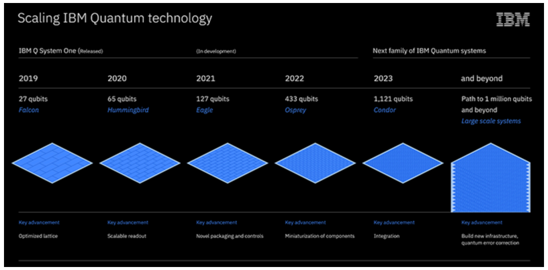
Richard P. Feynman (Nobel Prize in Physics 1965)

> "Nature isn't classical, dammit, 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."





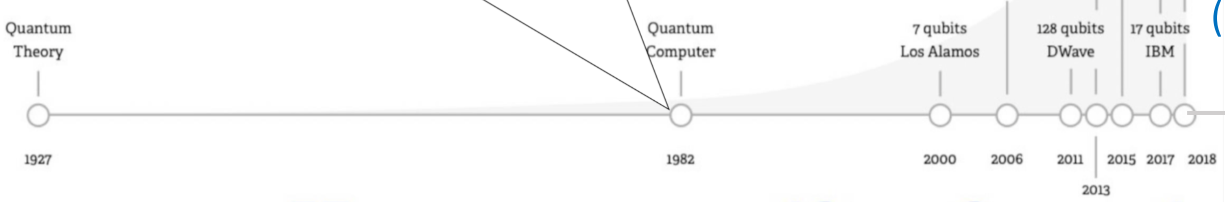
This photonic computer did a task that would take a classical computer 2.5 billion years.



Scaling IBM Quantum technology

IBM

IBM Q System One (Released)		(In development)		Next family of IBM Quantum systems	
2019	2020	2021	2022	2023	and beyond
27 qubits *Falcon*	65 qubits *Hummingbird*	127 qubits *Eagle*	433 qubits *Osprey*	1,121 qubits *Condor*	Path to 1 million qubits and beyond *Large scale systems*
Key advancement Optimized lattice	Key advancement Scalable readout	Key advancement Novel packaging and controls	Key advancement Miniaturization of components	Key advancement Integration	Key advancement Build new infrastructure, quantum error correction



(2020)

(2021)

?

IonQ Gemini desk computer

55 YEARS

18 YEARS

6 YEARS

1 YEAR

IBM Cloud

Quantum supremacy using a programmable superconducting processor

Nature | Vol 574 | 24 OCTOBER 2019 | **505**

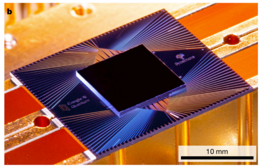
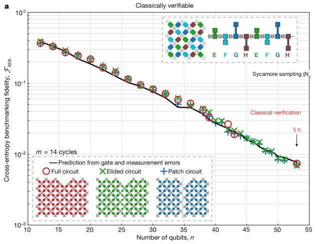
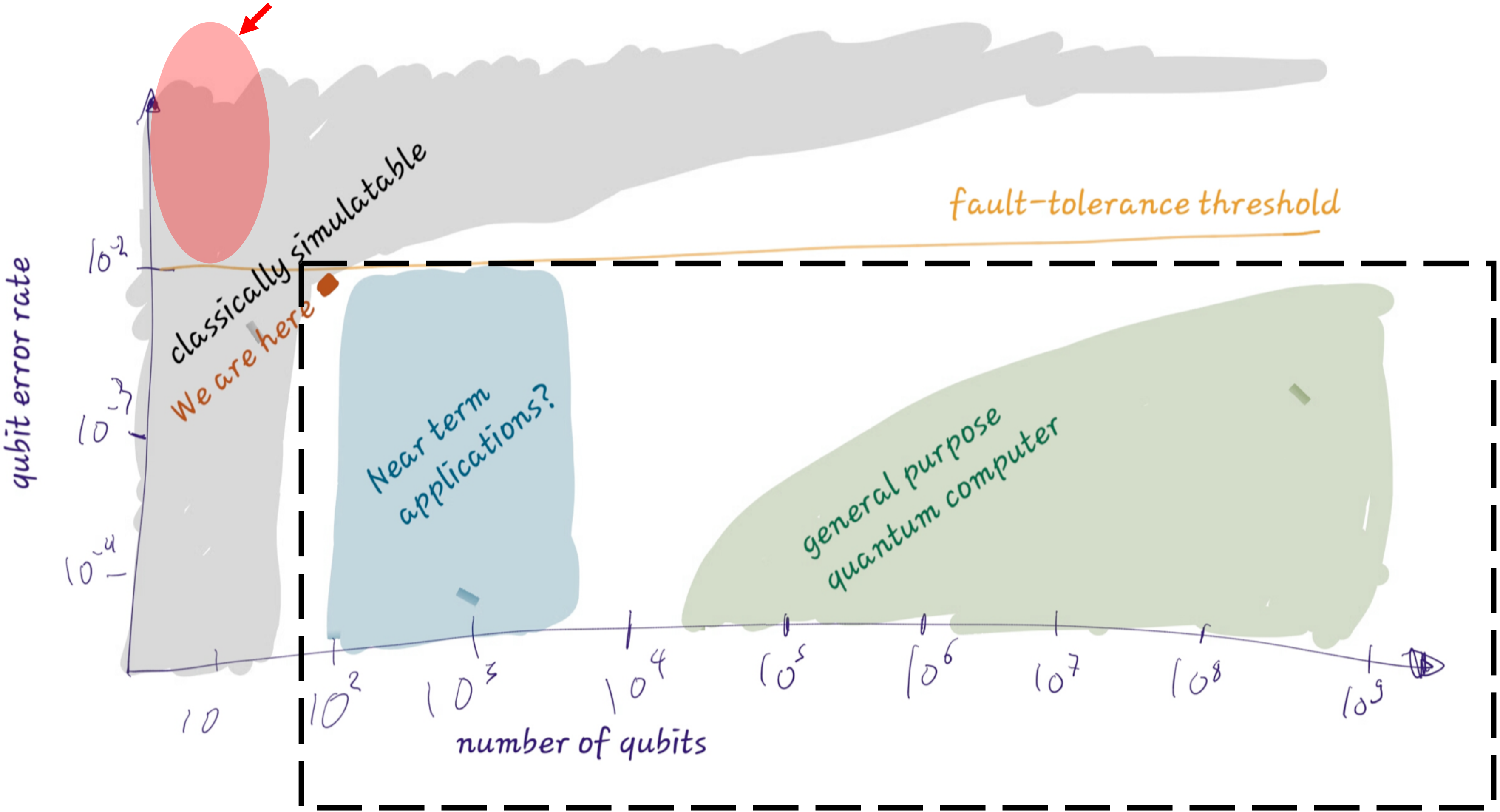


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.



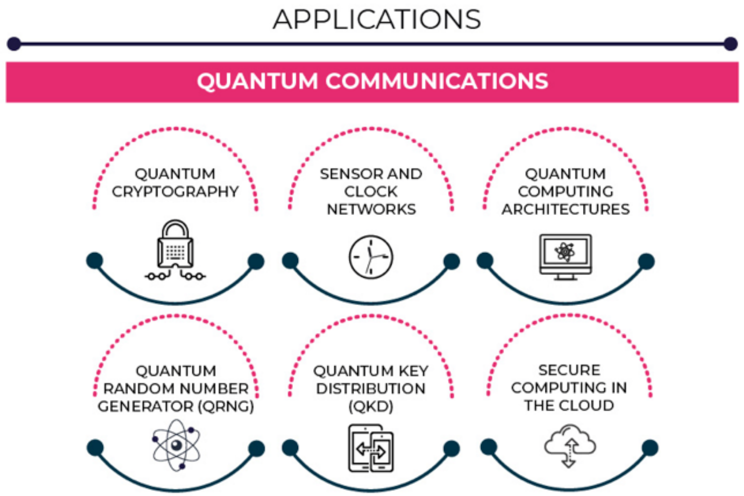
The Google illustration

Applications I will show are still tested here



Quantum supremacy

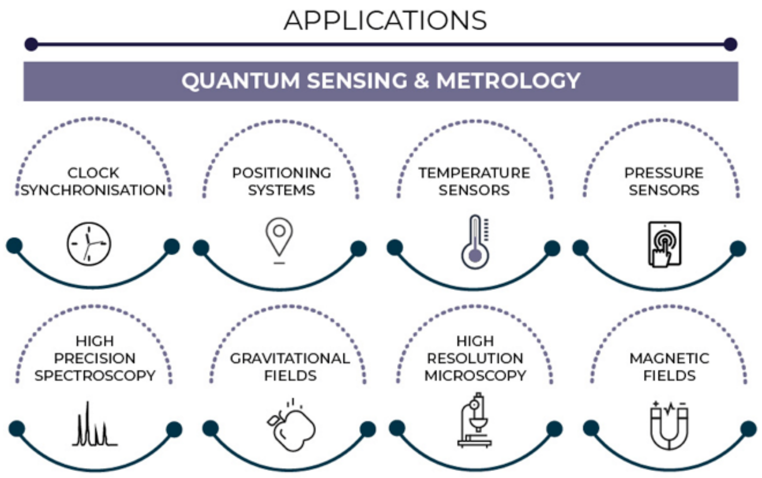
What are the anticipated applications ?



APPLICATIONS

QUANTUM COMMUNICATIONS

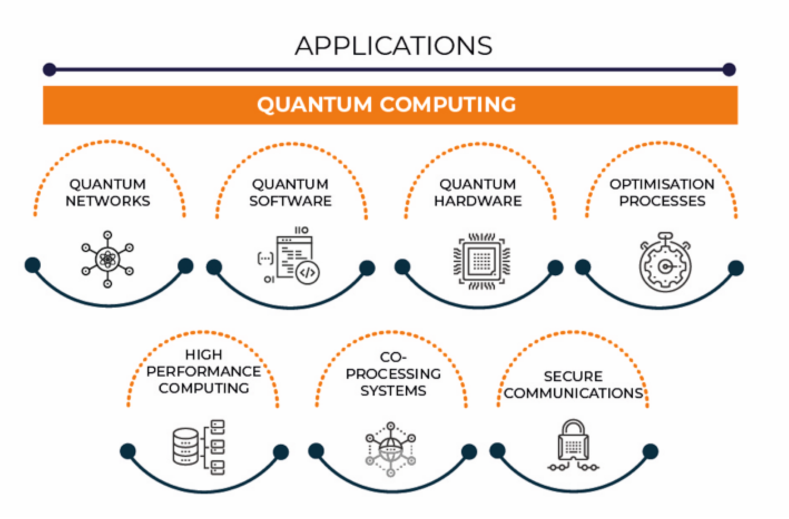
- QUANTUM CRYPTOGRAPHY
- SENSOR AND CLOCK NETWORKS
- QUANTUM COMPUTING ARCHITECTURES
- QUANTUM RANDOM NUMBER GENERATOR (QRNG)
- QUANTUM KEY DISTRIBUTION (QKD)
- SECURE COMPUTING IN THE CLOUD



APPLICATIONS

QUANTUM SENSING & METROLOGY

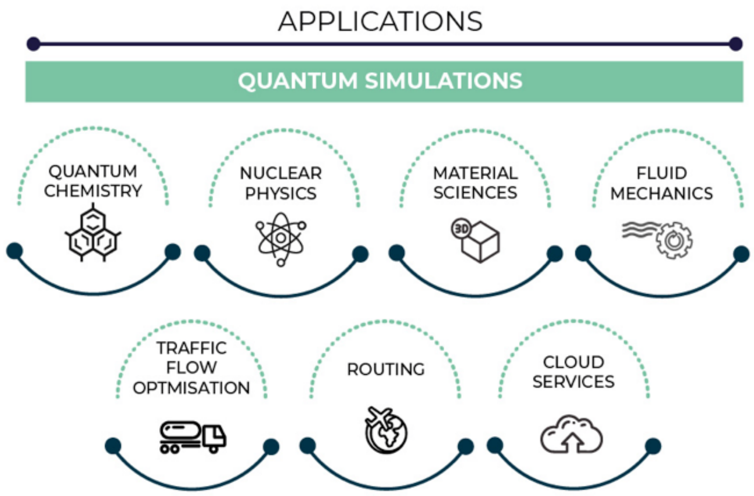
- CLOCK SYNCHRONISATION
- POSITIONING SYSTEMS
- TEMPERATURE SENSORS
- PRESSURE SENSORS
- HIGH PRECISION SPECTROSCOPY
- GRAVITATIONAL FIELDS
- HIGH RESOLUTION MICROSCOPY
- MAGNETIC FIELDS



APPLICATIONS

QUANTUM COMPUTING

- QUANTUM NETWORKS
- QUANTUM SOFTWARE
- QUANTUM HARDWARE
- OPTIMISATION PROCESSES
- HIGH PERFORMANCE COMPUTING
- CO-PROCESSING SYSTEMS
- SECURE COMMUNICATIONS



APPLICATIONS

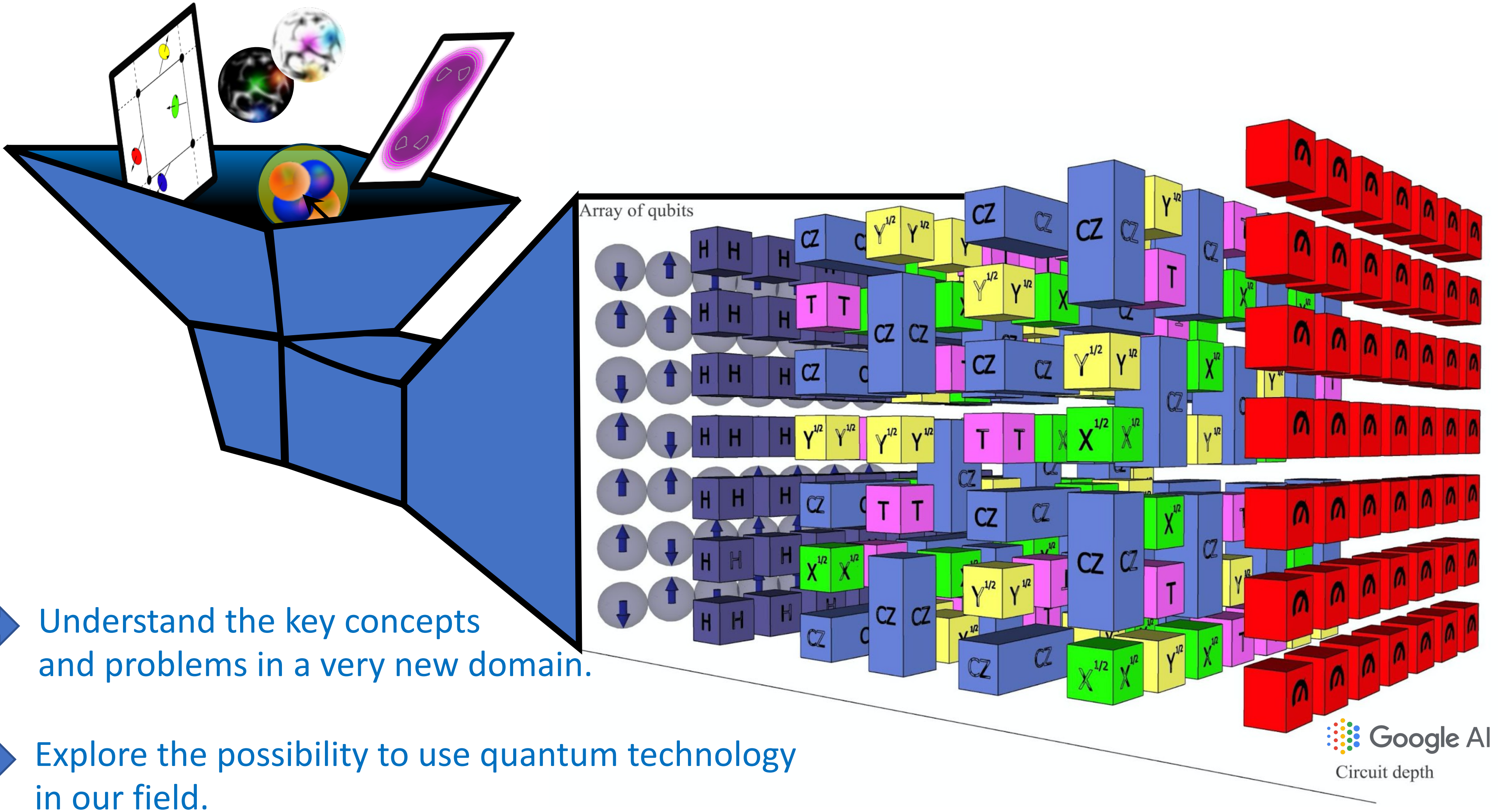
QUANTUM SIMULATIONS

- QUANTUM CHEMISTRY
- NUCLEAR PHYSICS
- MATERIAL SCIENCES
- FLUID MECHANICS
- TRAFFIC FLOW OPTMISATION
- ROUTING
- CLOUD SERVICES

Quantum European Flagship

Coming back to the IN2P3 physics case

Personal motivations



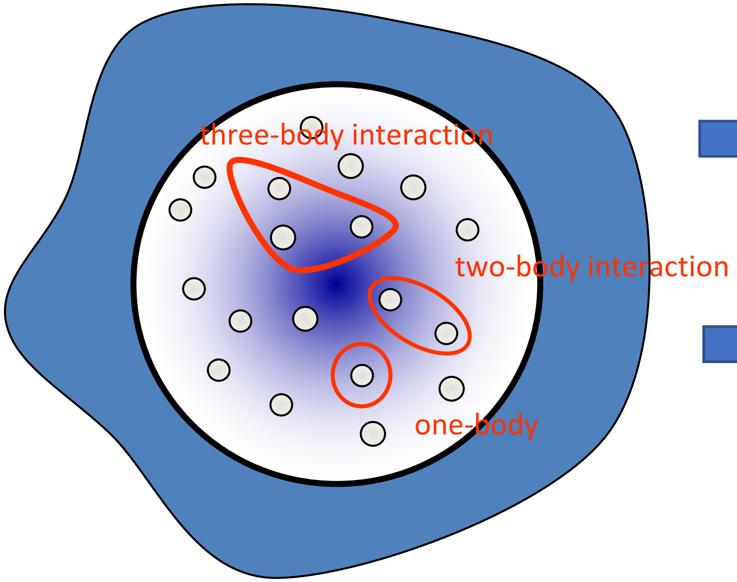
- Understand the key concepts and problems in a very new domain.
- Explore the possibility to use quantum technology in our field.
- Prepare the arrival of a new disruptive technology that might give a significant boost in our domain.
- Try to contribute to this enthusiastic adventure.

Depuis 80 ans, nos connaissances bâtissent de nouveaux mondes

QC2I

One example:

Simulation of complex quantum (interacting) systems



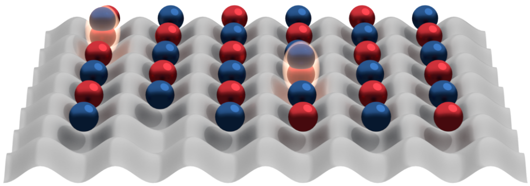
If you have N one-body degrees of freedoms
The Hilbert space has an exponential
Scaling (~N!)

Even today, only a limited area (small systems- few %)
of the nuclear Chart can be calculated with most
powerful Supercomputers.

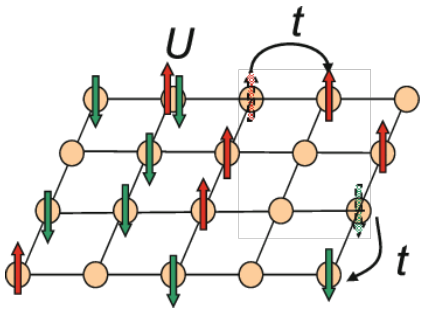
Solution of simple many-body problem with QC: a brief history

Jordan-Wigner (1928)

Fermions on [1D] lattice



Spin systems



Quantum chemistry
Condensed matter

1997- Abrams and Loyds

A quantum algorithm
For eigenvalue problems

2001- Bravyi-Kitaev
Mapping fermions-Qubits

-2011-2012-Whitfield et al
-Seeley et al
The H_2 Hamiltonian

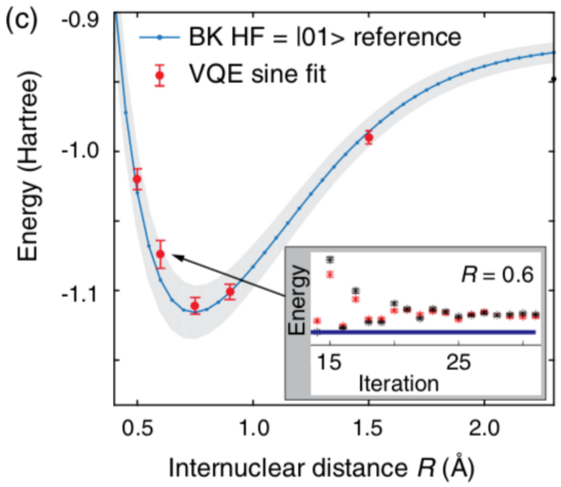
-2014 – Peruzzo et al,
The VQE algorithm
For classical-quantum calc.

-2016 - O'Malley et al
First "real" calculations H_2

-2017 - Kandala et al
Calculations for H_2, LiH, HBeH

-2018 - Hempel et al
…

Nuclear Physics



Creation of a US coll. To Prepare QC

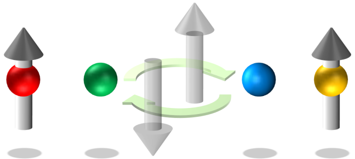
-2018 - Dimitrescu et al

First "real" calculations
For deuteron

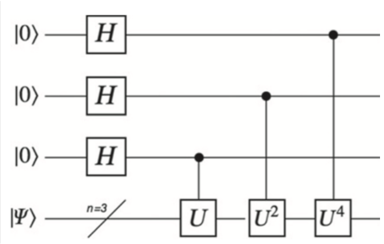
-2019 - Lu et al
^{3}H, ^{3}He, α

General strategy

Take a simple version of
your favorite many-body problem



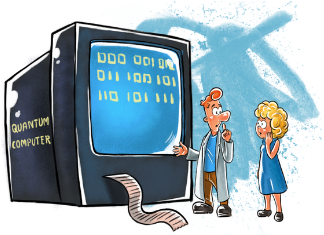
Map/formulate it as a problem
with Qubit



Use standard QC algorithms
or
Propose new QC algorithms

Test on a real
Quantum
platforms

It works sometimes !

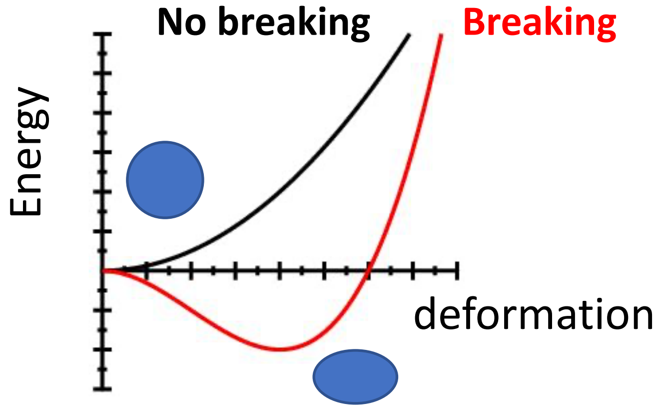


Test on a
QC emulator

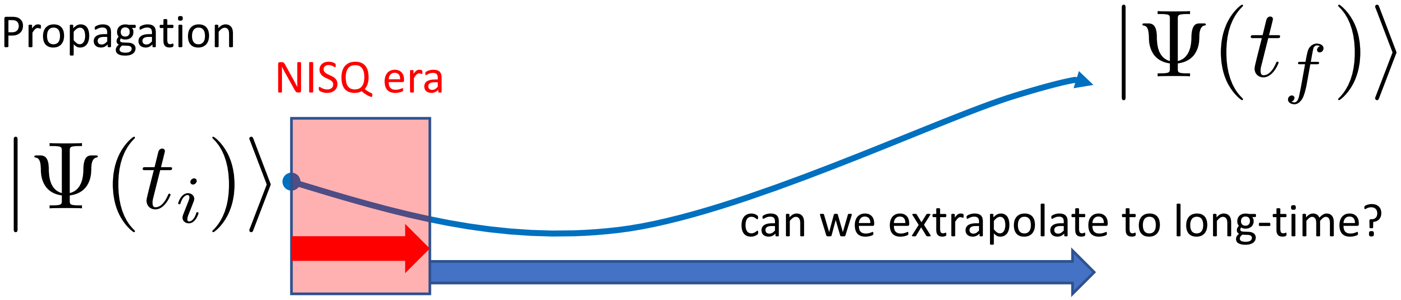
It works !

The recent applications we made (in many-body systems)

- Breaking symmetries and restoration of symmetries in many-body systems on quantum computers
  - Application to the counting of particle number (for superfluid systems)



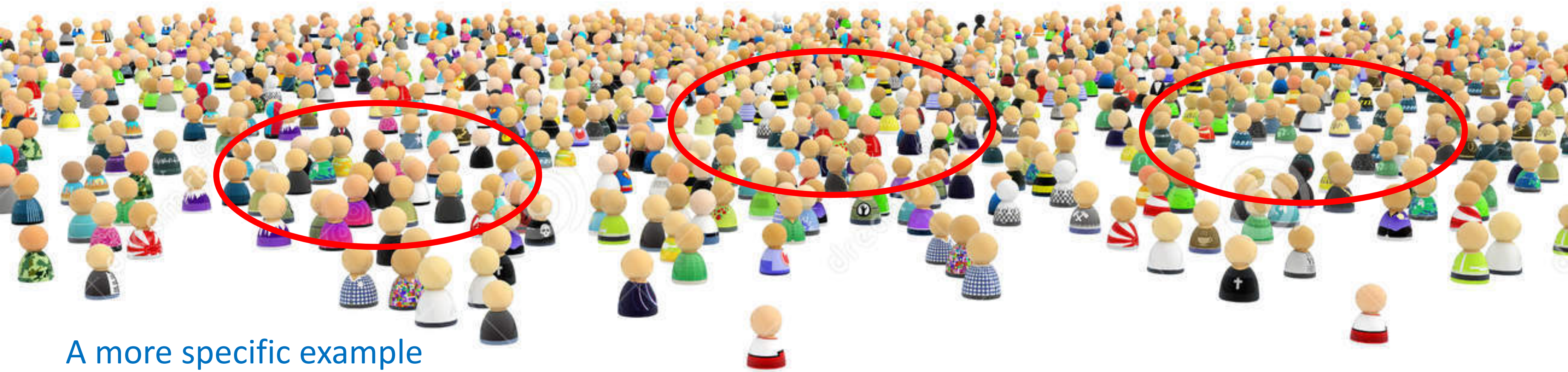
- Replacing bosons by pairs of fermions to probe quantum supremacy
  - Prediction of long time evolution from short-time Propagation



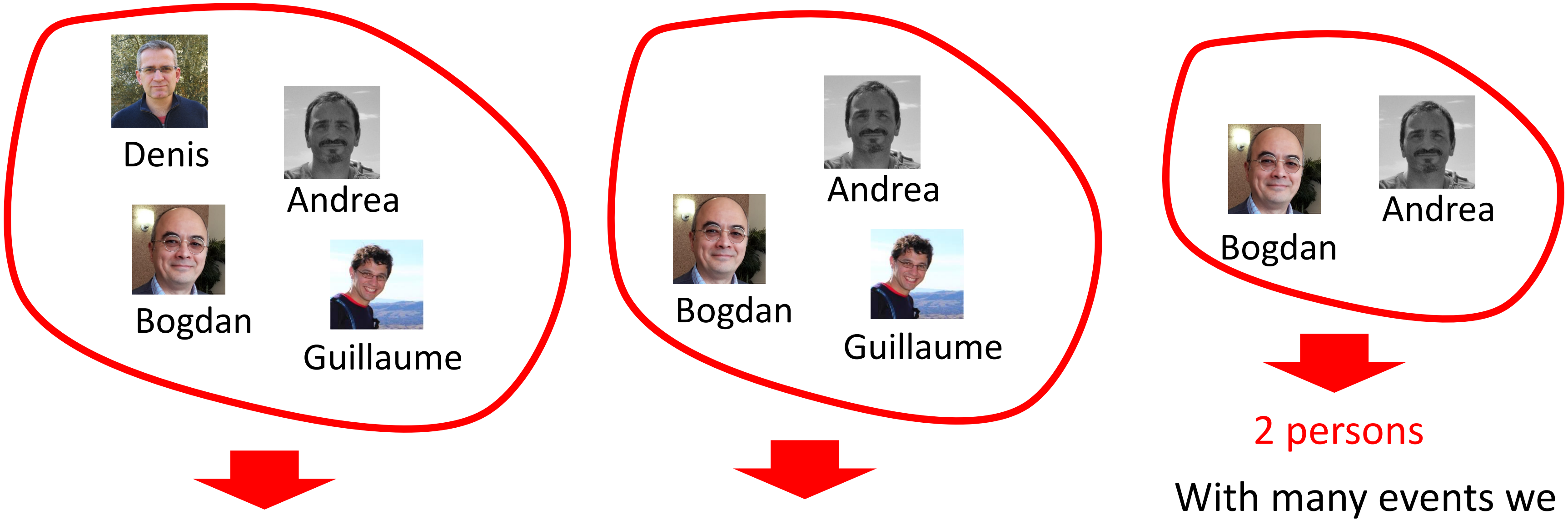
Broken symmetry/restoration

The counting statistic problem

I want to count people



A more specific example



4 persons

3 persons

2 persons

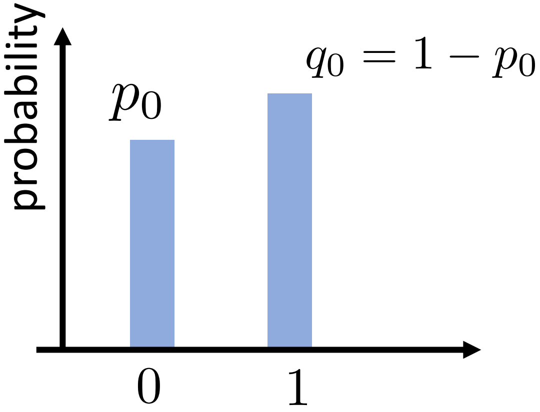
With many events we can do
Probabilities, statistical analysis

The counting statistic problem
In quantum systems

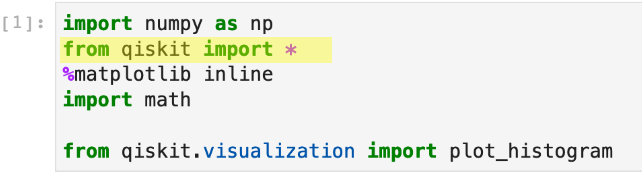
I assign a qubit to each person

$$\left|\quad\right\rangle = \sqrt{p_0}|0\rangle + \sqrt{1-p_0}|1\rangle$$

Measuring the qubit gives the probability

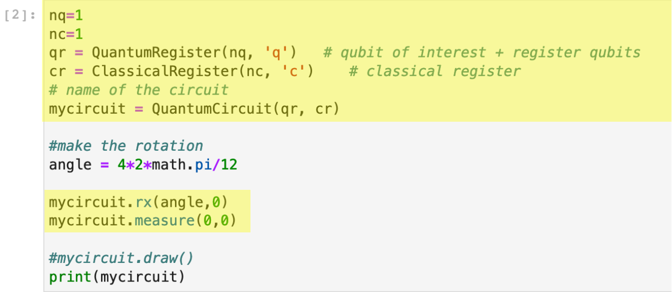


Demystifying QC Illustration with qiskit

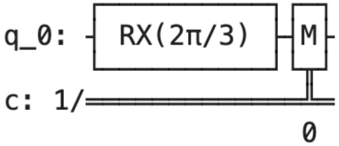


```
[1]: import numpy as np
     from qiskit import *
     %matplotlib inline
     import math

     from qiskit.visualization import plot_histogram
```

Creation of the circuit

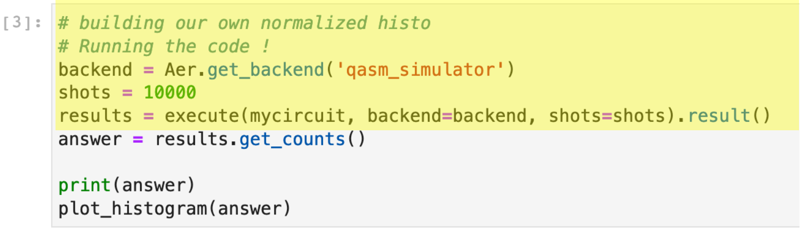


```
[2]: nq=1
     nc=1
     qr = QuantumRegister(nq, 'q')   # qubit of interest + register qubits
     cr = ClassicalRegister(nc, 'c')    # classical register
     # name of the circuit
     mycircuit = QuantumCircuit(qr, cr)

     #make the rotation
     angle = 4*2*math.pi/12

     mycircuit.rx(angle,0)
     mycircuit.measure(0,0)

     #mycircuit.draw()
     print(mycircuit)
```



```
      ┌──────────┐┌─┐
q_0: ─┤ RX(2π/3) ├┤M├
      └──────────┘└╥┘
c: 1/══════════════╩═
                   0
```

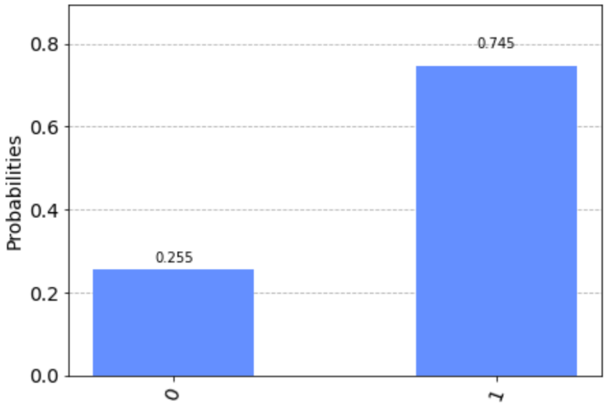
Running the circuit



```
[3]: # building our own normalized histo
     # Running the code !
     backend = Aer.get_backend('qasm_simulator')
     shots = 10000
     results = execute(mycircuit, backend=backend, shots=shots).result()
     answer = results.get_counts()

     print(answer)
     plot_histogram(answer)
```

```
{'0': 2546, '1': 7454}
```

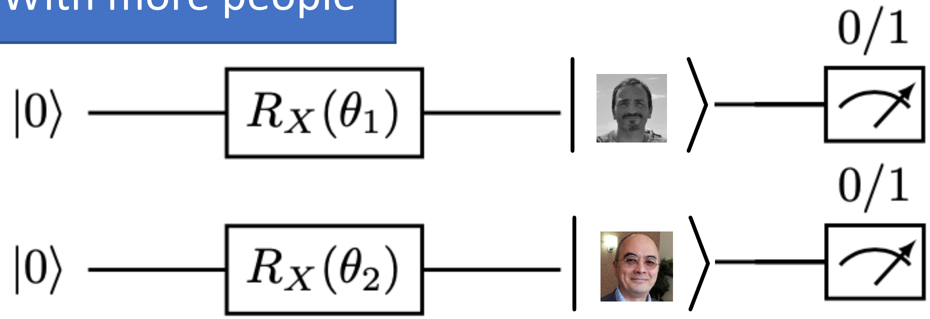
[3]:

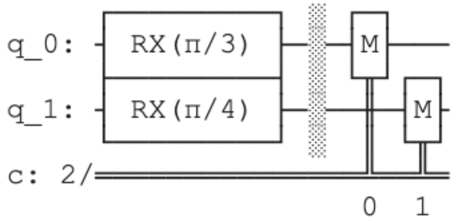


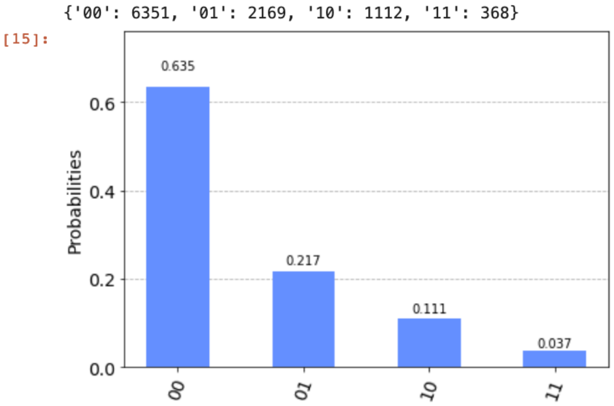
The counting statistic problem

In quantum systems

With more people

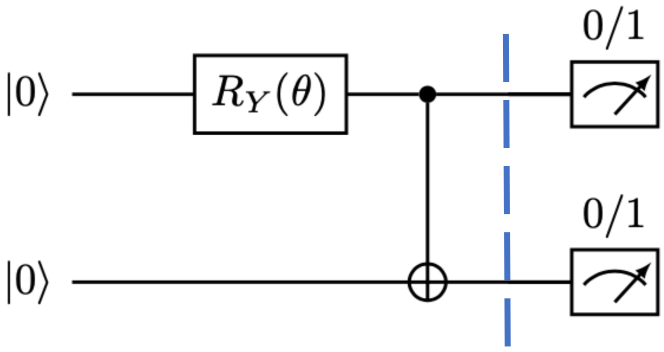




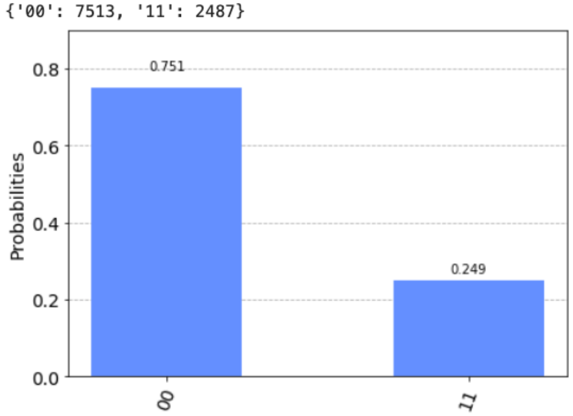


```
{'00': 6351, '01': 2169, '10': 1112, '11': 368}
[15]:
```

People can be entangled



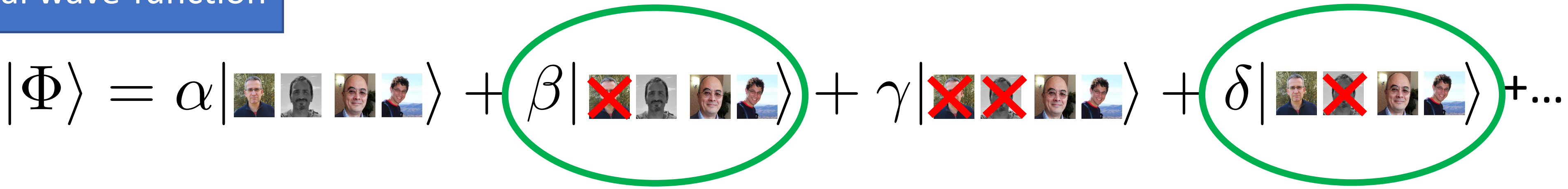
Here I created a Bell state



```
{'00': 7513, '11': 2487}
```

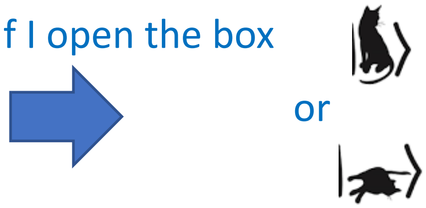
The counting statistic problem without destroying the wave-function

Initial wave-function



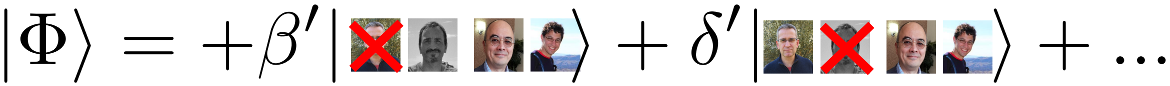
After the measurement the wave-function collapse to one of the state

If I open the box

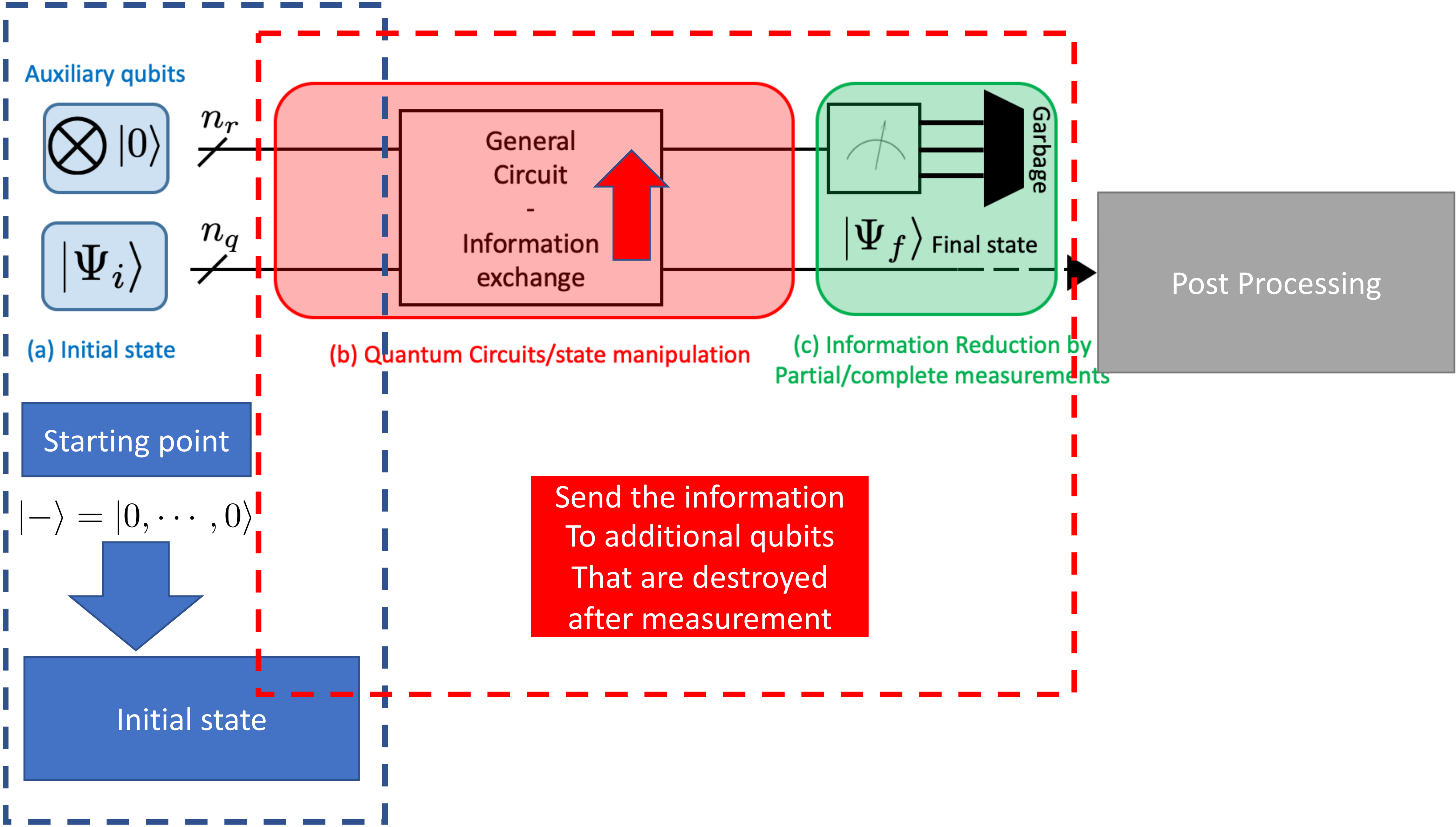


A more difficult problem

I want to select the component with 3 persons without completely destroying it



Non-destructive counting on a quantum computer



(a) Initial state

(b) Quantum Circuits/state manipulation

(c) Information Reduction by Partial/complete measurements

Post Processing

Starting point

$|-\rangle = |0, \cdots, 0\rangle$

Initial state

Send the information
To additional qubits
That are destroyed
after measurement

The quantum-Phase estimate (QPE) algorithm

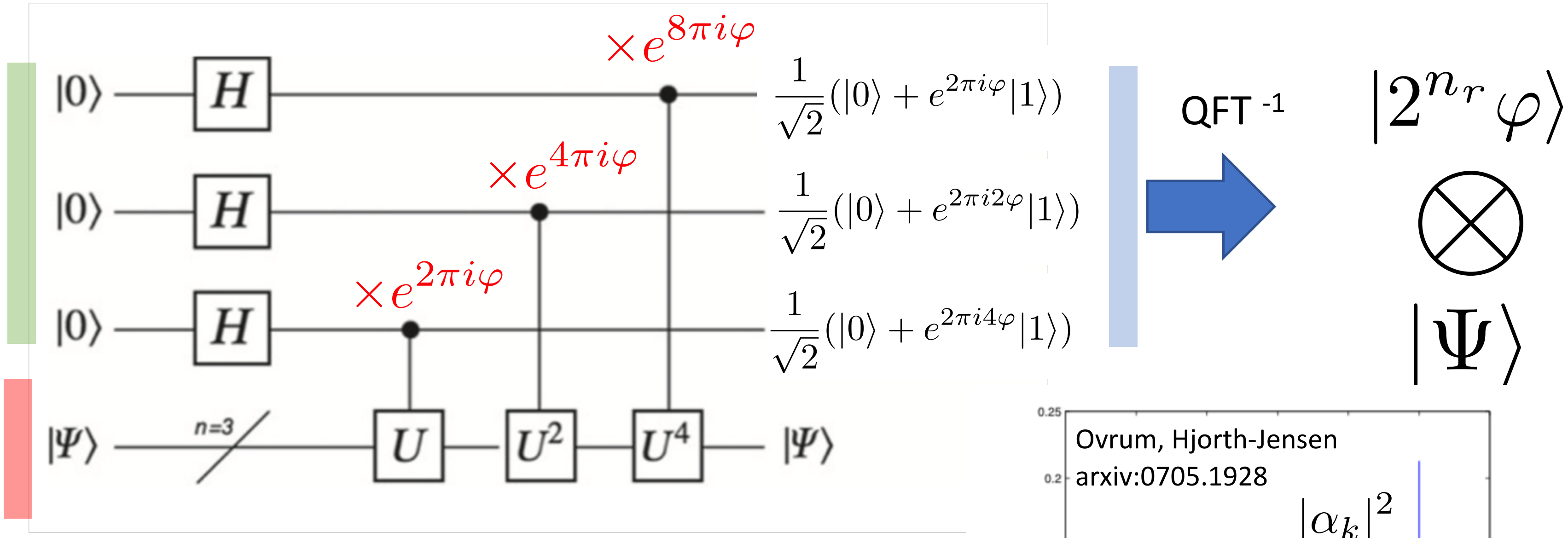
For eigenvalue problems

Assume a unitary operator U

Assume an eigenstate $|\Psi\rangle$ Such that $U|\Psi\rangle = e^{2\pi i\varphi}|\Psi\rangle$

nr Register qubits

Working qubits



General Case

Example

$$|\Psi\rangle = \sum_k \alpha_k|\phi_k\rangle \xrightarrow{\text{QPE}} \sum_k \alpha_k \underbrace{|\theta_k 2^{n_r}\rangle}_{\text{register}} \otimes \underbrace{|\phi_k\rangle}_{\text{eigenstate}}$$

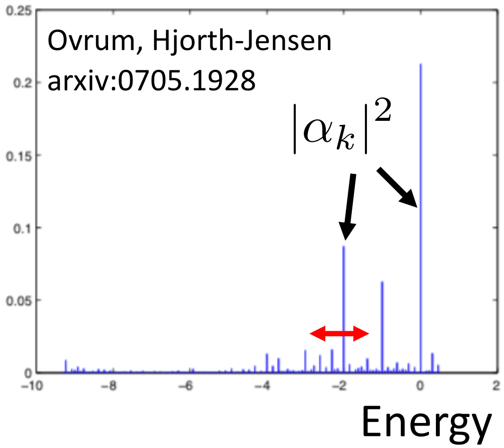


FIG. 7: Pairing model simulated with 24 qubits, where 14 were simulation qubits, i.e. there are 14 available quantum levels, and 10 were work qubits. The correct eigenvalues are 0, −1, −2, −3, −4, −5, −6, −8, −9. In this run we did not divide up the time interval to reduce the error in the Trotter approximation, i.e., $I = 1$.

Simple Idea: take the phase proportional to the number of persons!

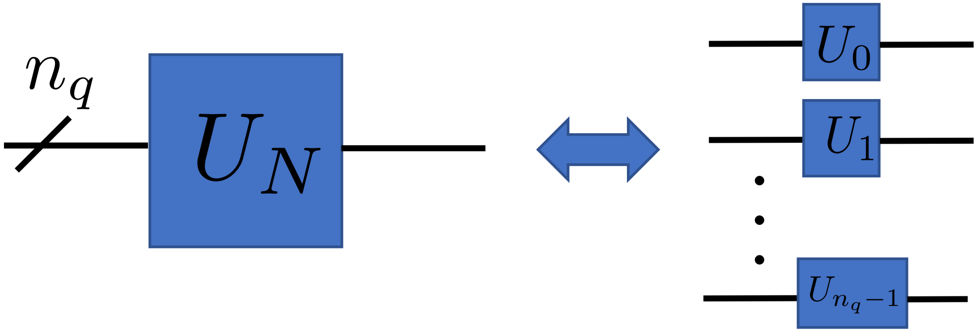
QPE applied to the number of persons

Practical details

$$U_N = \prod_j U_j$$

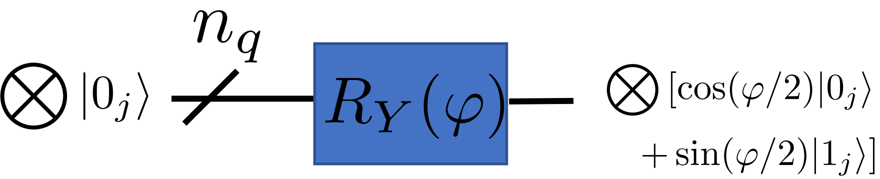
$$U_i = |0_i\rangle\langle 0_i| + \exp(i\pi/2^{n_0-1})|1_i\rangle\langle 1_i|$$

$$U_i = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/2^{n_0-1}} \end{bmatrix}$$



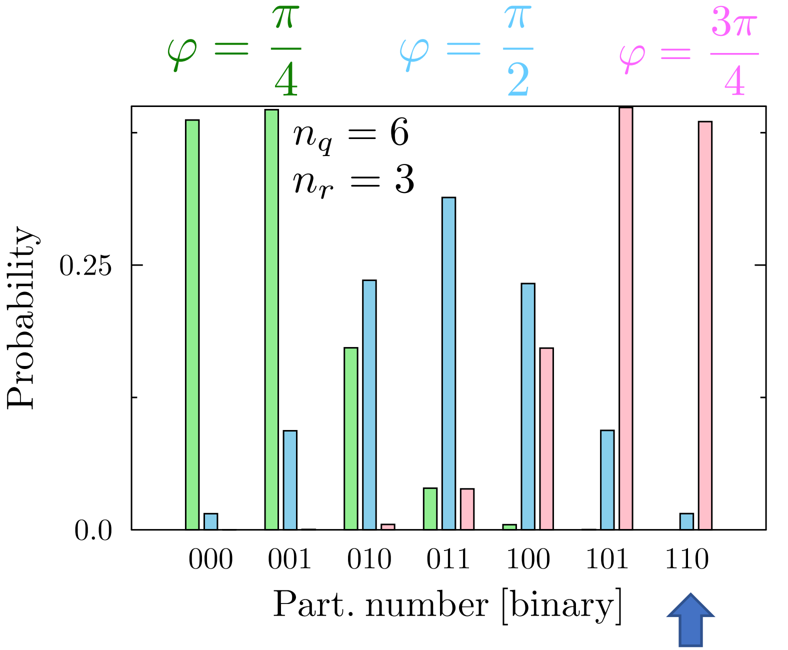
Example: Qubit counting statistics

Initial state



$$\Rightarrow P(A) = C^A_{n_q} p^A (1-p)^{n_q - A}$$

$$p = \sin^2(\varphi/2)$$



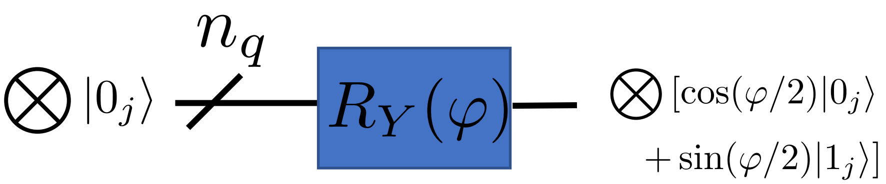
$$6/2^4 = 1/2 + 1/4 + 0/8 \equiv [110]$$

Calculation made with the IBM Qiskit python package

Working with real quantum devices ?

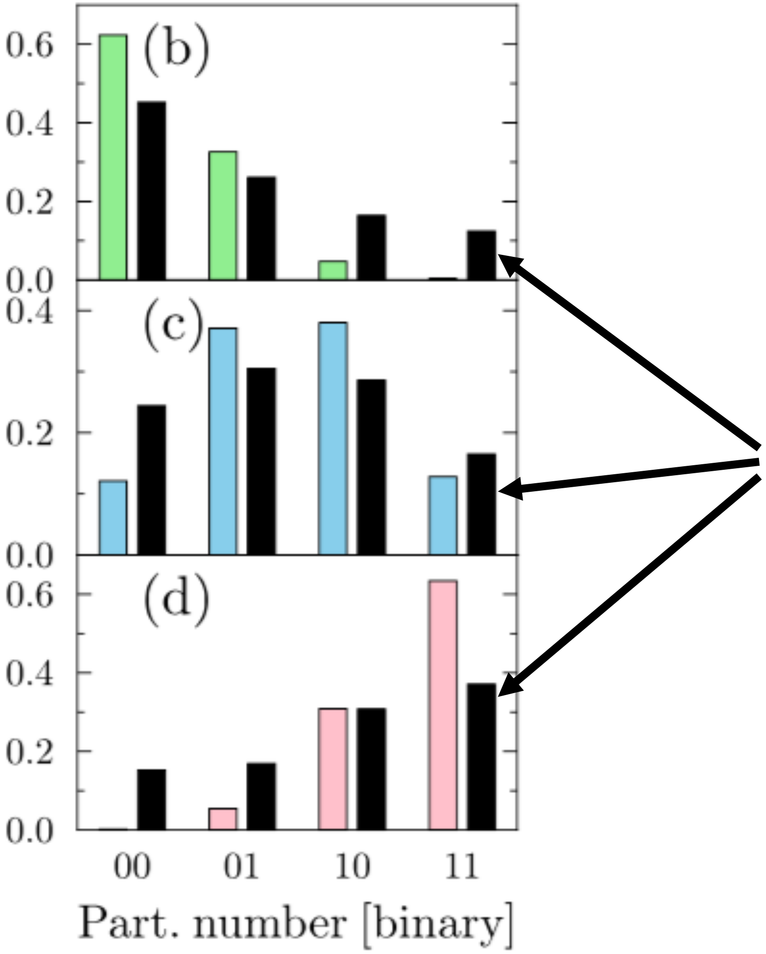
Example: Qubit counting statistics

Initial state



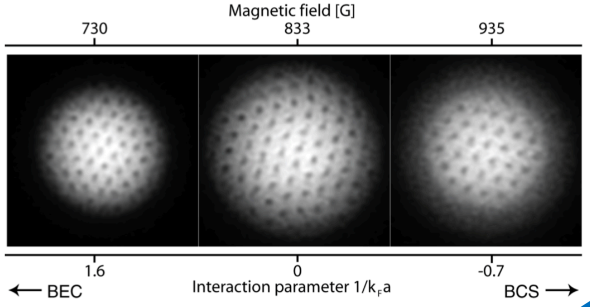
$$P(A) = C^A_{n_q} p^A (1-p)^{n_q - A}$$
$$p = \sin^2(\varphi/2)$$

3 qubits and 2 register qubits

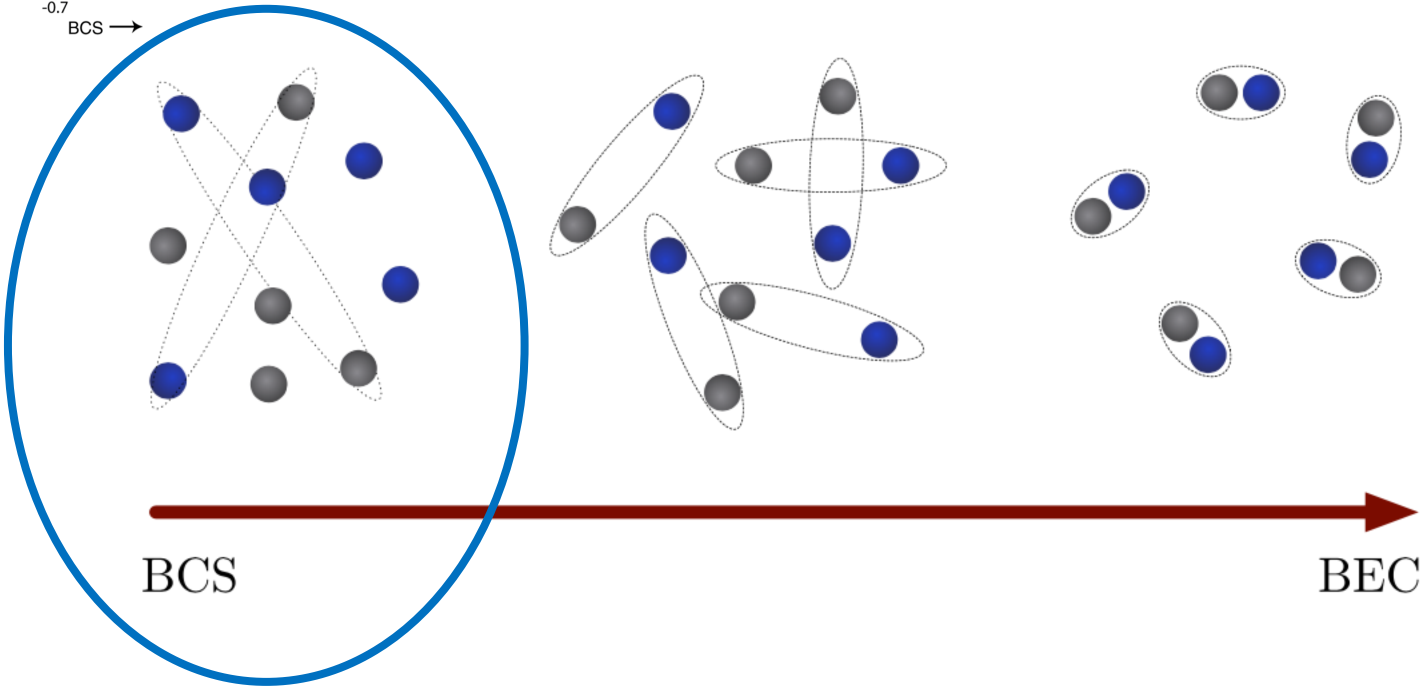


Result on IBMq_vigo 5 qubits device

But what is the connection with interacting systems ???



Cooper pairs and superfluidity are rather universal phenomena: (condensed matter, Atomic physics, Nuclear physics, …)



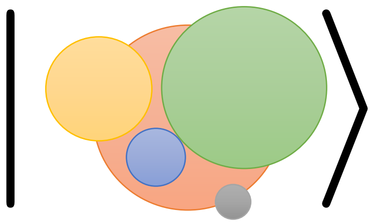
This problem is an archetype of spontaneous symmetry breaking.
A “easy” way to describe it is to break the particle number symmetry, i.e. consider wave-function that mixes different particle number

Example

$$|\Phi_0\rangle = \Pi_i (u_i + v_i a_i^\dagger a_{\bar{i}}^\dagger)|-\rangle$$

⇒ Mixes states with 0, 2, 4, … particles

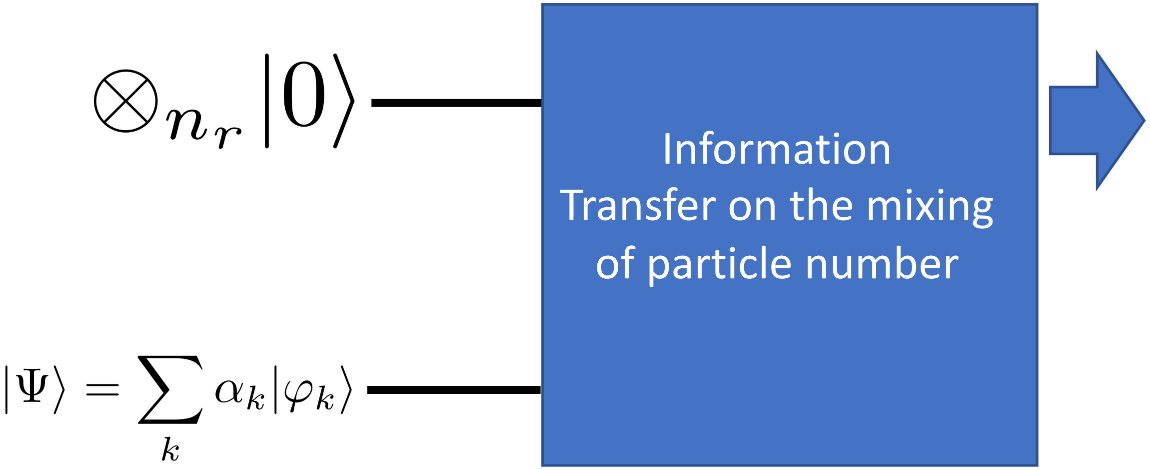
We say that a symmetry (particle number) is broken



But ultimately number of Particle should be restored !

Making projection on particle number

A schematic view



$$\otimes_{n_r}|0\rangle$$

$$|\Psi\rangle = \sum_k \alpha_k |\varphi_k\rangle$$

Information Transfer on the mixing of particle number

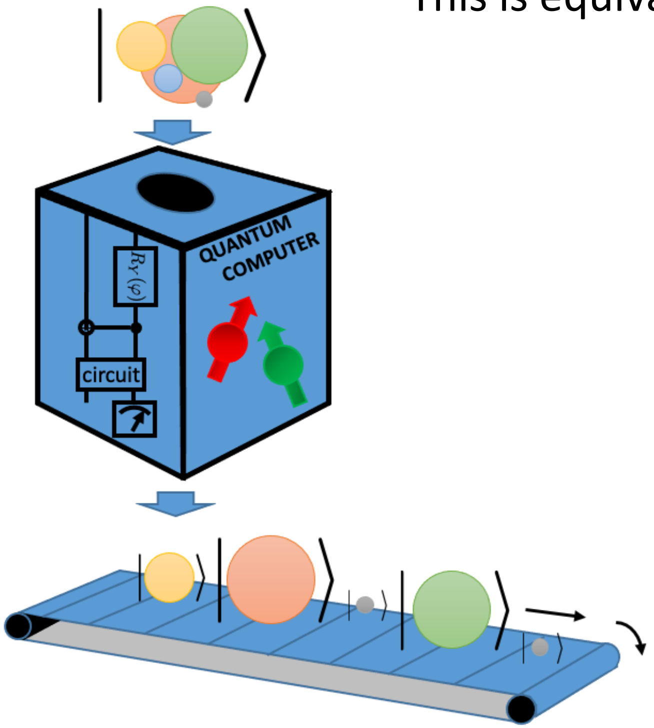
$$\sum_k \alpha_k|\underline{01001\cdots1}\rangle \otimes |\varphi_k\rangle$$

= Particle number written as a binary number

We can measure the register qubit

This is equivalent to project on $|\varphi_k\rangle$

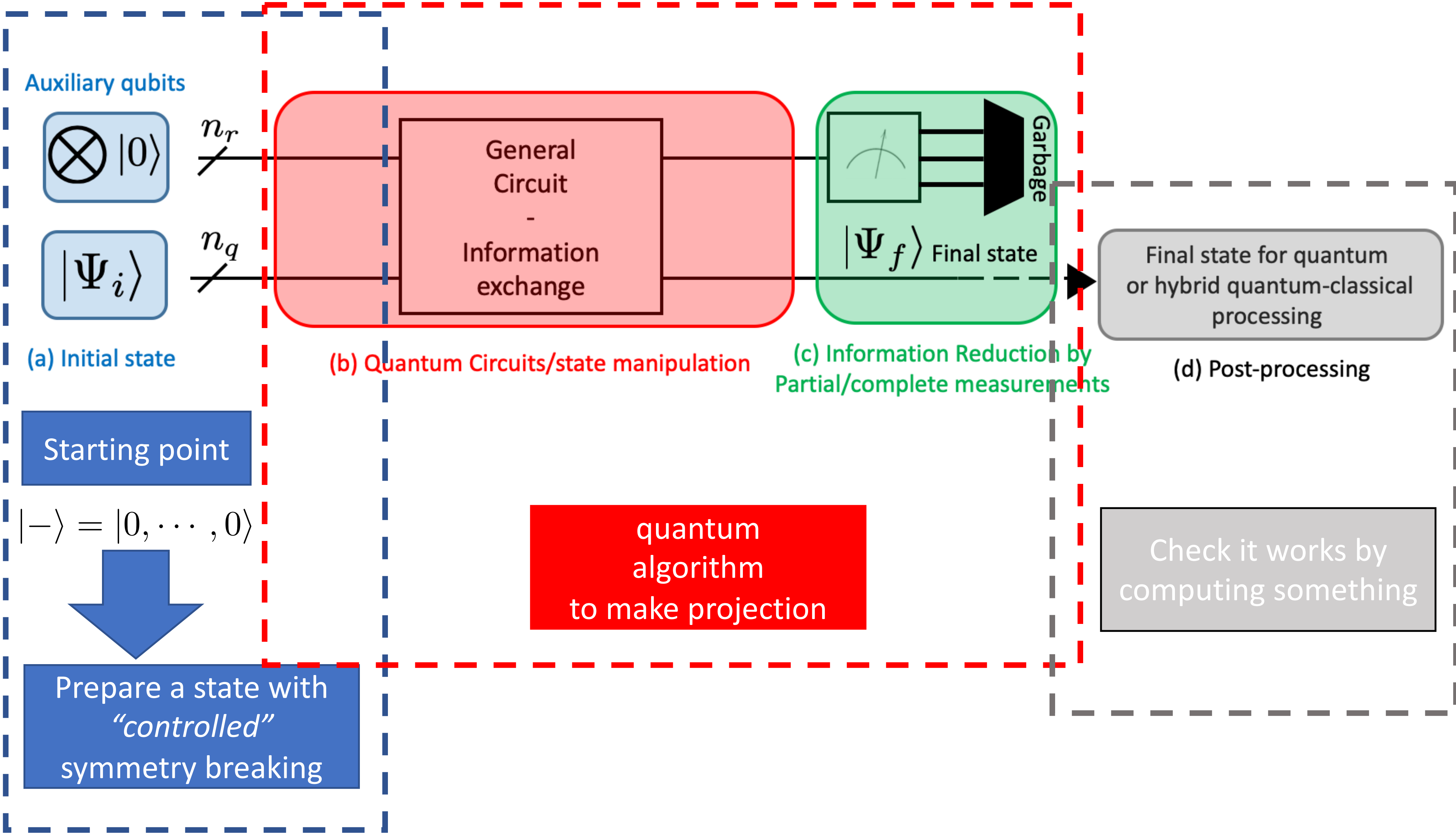
An even more schematic view



Then I can use this Wave-function for post-processing

D. Lacroix, “*Symmetry-Assisted Preparation of Entangled Many-Body States on a Quantum Computer*”, PRL 125, 230502 (2020).

Project goal: make symmetry breaking/restoration on Quantum Computers



(a) Initial state

(b) Quantum Circuits/state manipulation

(c) Information Reduction by Partial/complete measurements

(d) Post-processing

Starting point

$$|-\rangle = |0, \cdots, 0\rangle$$

Prepare a state with *"controlled"* symmetry breaking

quantum algorithm to make projection

Check it works by computing something

Mapping the Many-Body problem on quantum computers

The Jordan-Wigner transformation

Mapping the Fock space into Qubits

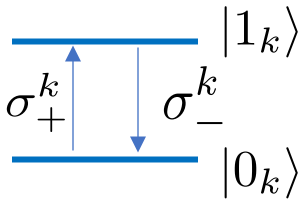
$$|-\rangle = |0\cdots0\rangle$$

For fermions

$$a_k^\dagger|-\rangle = |0\cdots0\ 1_k\ 0\cdots0\rangle$$

$$\{a_k^\dagger, a_k\} = 1$$

For qubits

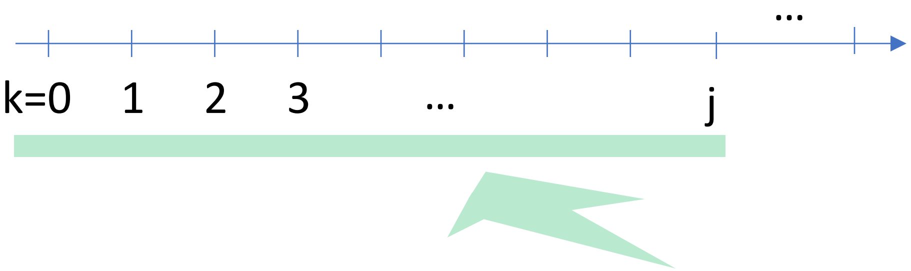


$$\{\sigma_+^k, \sigma_-^k\} = 1$$

Problem $\{a_k^\dagger, a_l\} = 1$ **while** $[\sigma_+^k, \sigma_-^l] = 0$

One possible solution (Jordan-Wigner transformation -1928)

1. Order the index like in a lattice
2. Define new mapping



$$a_k^\dagger \to \prod_{k<j}(-\sigma_z^j)\sigma_j^+$$

Application to the N-body pairing problem

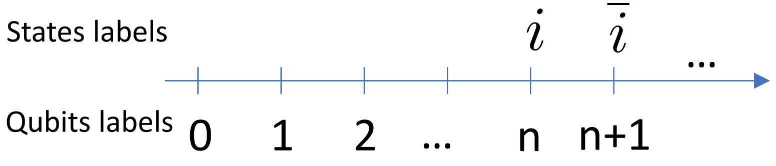
Hamiltonian and initial state

Pairing Hamiltonian

$$H_{\mathrm{P}} = \sum_{i>0} \varepsilon_i (a_i^\dagger a_i + a_{\bar{i}}^\dagger a_{\bar{i}}) - g \sum_{i,j>0} a_i^\dagger a_{\bar{i}}^\dagger a_{\bar{j}} a_j$$

Jordan-Wigner trans: $\frac{1}{2}(I_i - Z_i)$

State ordering is important !



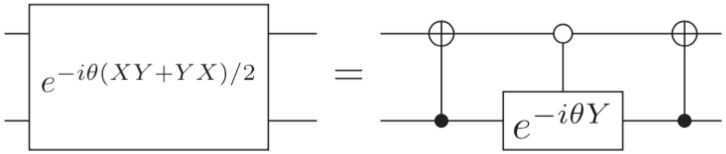
$$a_i^\dagger a_{\bar{i}}^\dagger \Longrightarrow Q_n^+ Q_{n+1}^+$$

I considered the degenerate case $\varepsilon_i = \varepsilon = 0$

Initial (symmetry breaking) state preparation

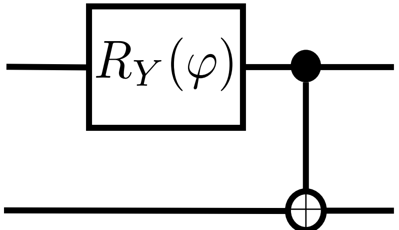
$$|\Psi\rangle = \exp\left\{-\sum_{i>0} \varphi_i \left(a_i^\dagger a_{\bar{i}}^\dagger - a_{\bar{i}} a_i\right)\right\} |0\rangle \xRightarrow{\varphi_i = \varphi} |\Psi\rangle = \prod_{n>0} e^{i\varphi(X_n Y_{n+1} + Y_n X_{n+1})/2} |-\rangle$$

Equivalent universal gate on pairs



Simplified circuit (generalized Bell state)

$$|\Psi\rangle = \prod_n \left[\cos\left(\frac{\varphi}{2}\right) I_n \otimes I_{n+1} + \sin\left(\frac{\varphi}{2}\right) Q_n^+ Q_{n+1}^+\right] |-\rangle$$



Zhang Jiang et al, Phys. Rev. Applied 9, 044036 (2018).

Applying the strategy to the pairing problem

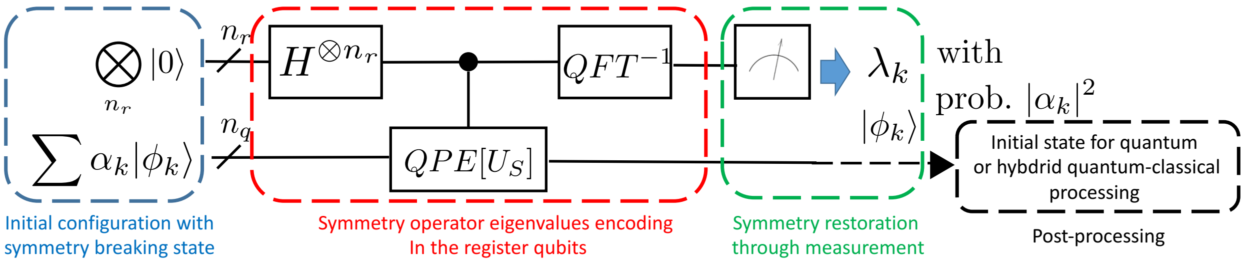
$$\bigotimes |0_j\rangle$$

Symmetry-breaking state

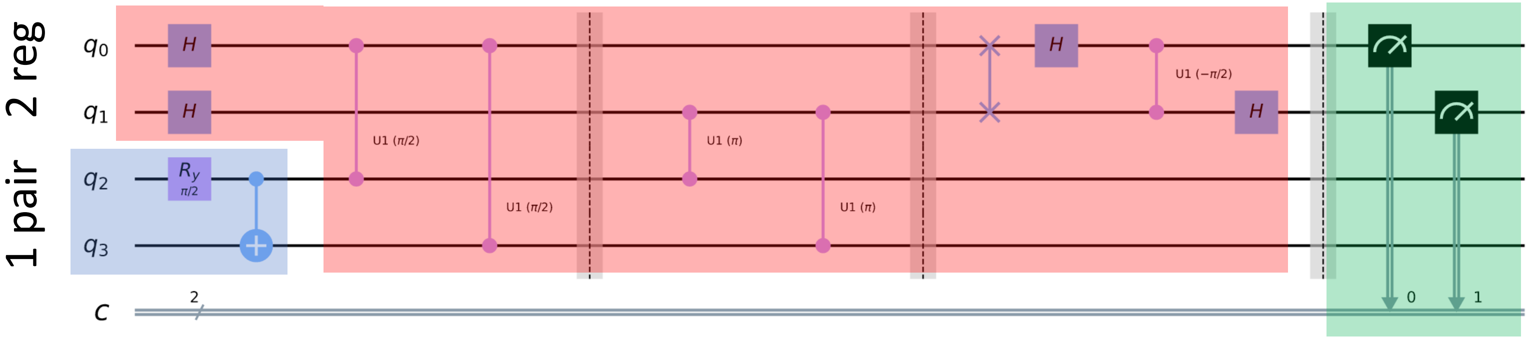
QPE+QFT^{-1}

Register Qubit Measurement

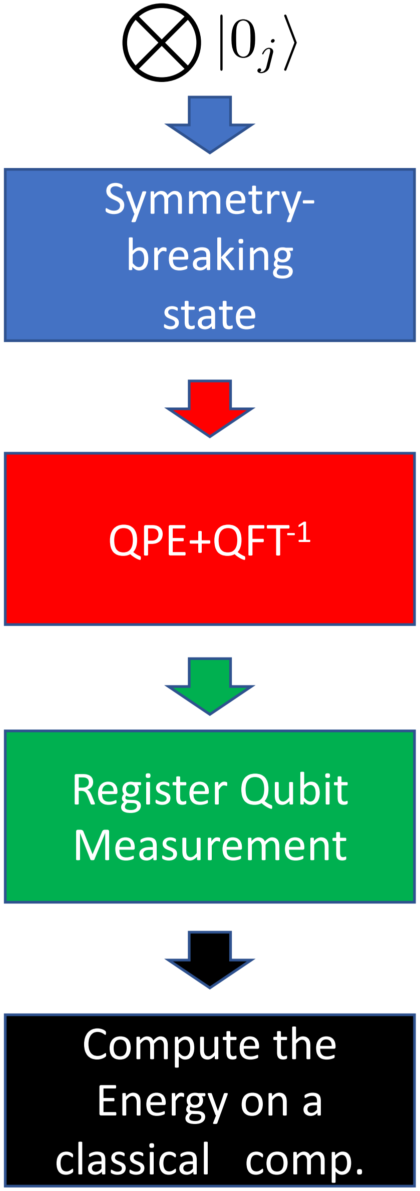
Compute the Energy on a classical comp.



Qiskit circuit for a single pair



Applying the strategy to the pairing problem



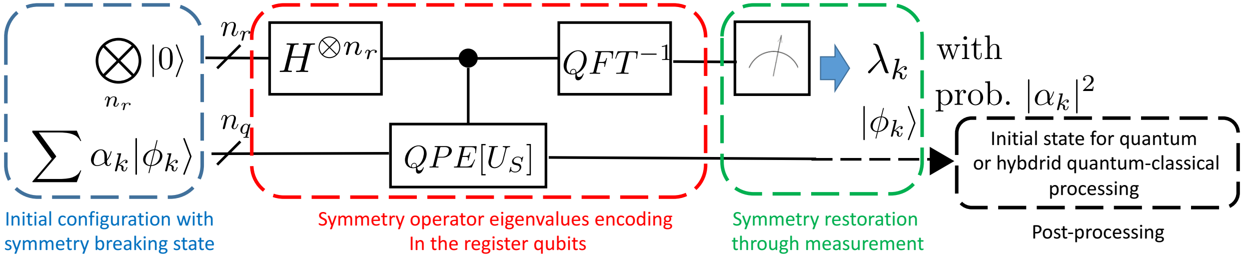
$\bigotimes |0_j\rangle$

Symmetry-breaking state

QPE+QFT^{-1}

Register Qubit Measurement

Compute the Energy on a classical comp.



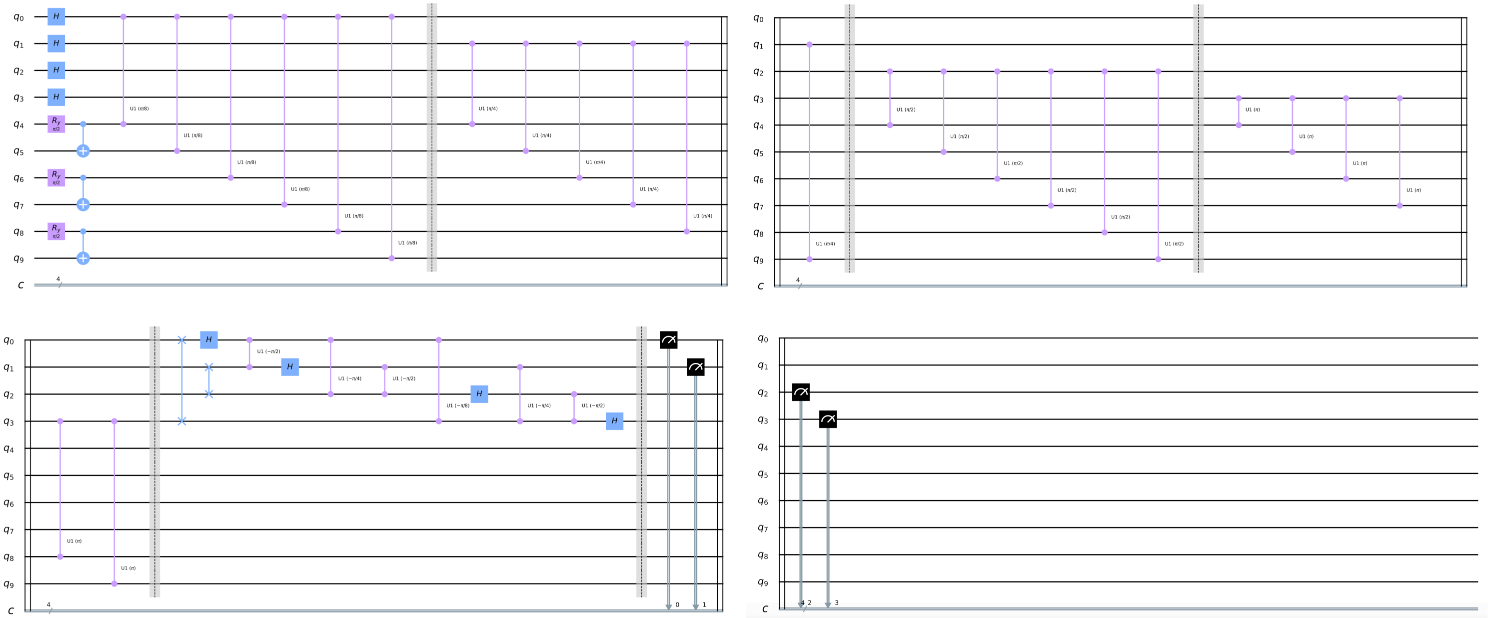
Initial configuration with symmetry breaking state

Symmetry operator eigenvalues encoding In the register qubits

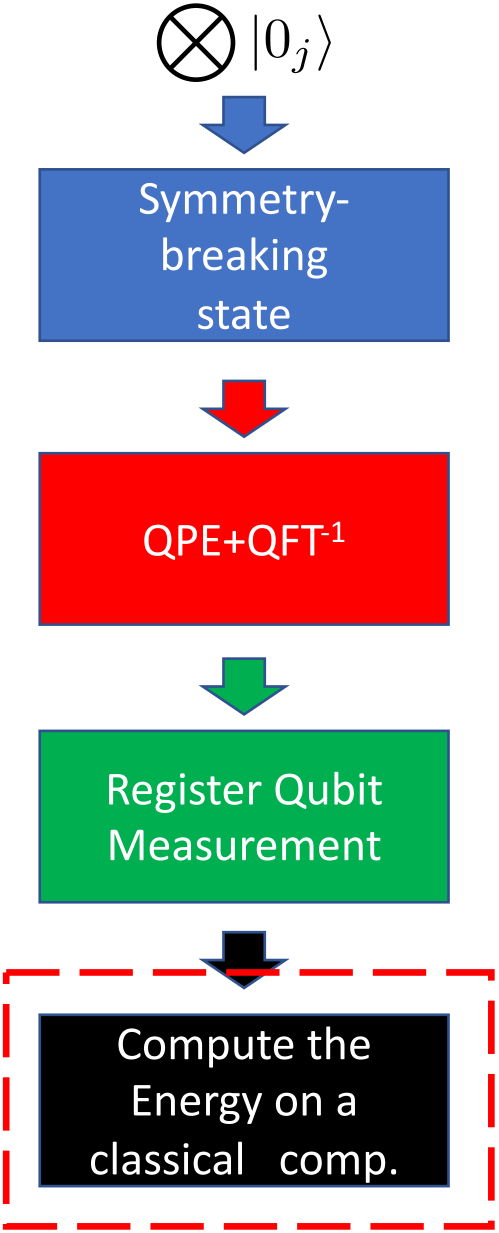
Symmetry restoration through measurement

Post-processing

3 pairs, 4 register



Applying the strategy to the pairing problem



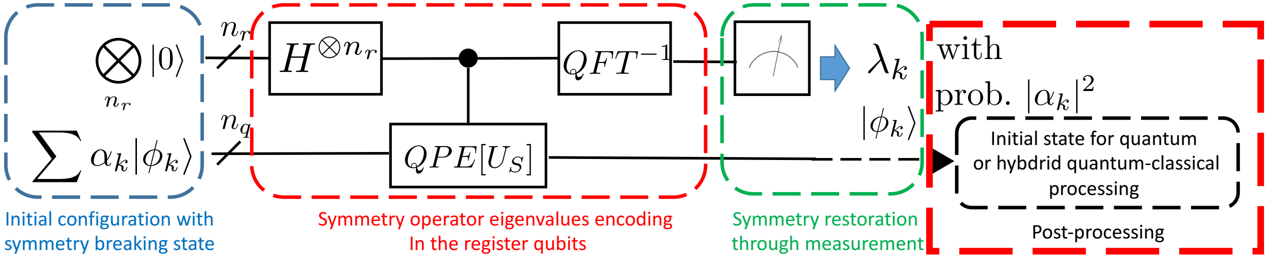
$\bigotimes |0_j\rangle$

Symmetry-breaking state

QPE+QFT^{-1}

Register Qubit Measurement

Compute the Energy on a classical comp.



Initial state for quantum or hybdrid quantum-classical processing

Post-processing

Initial configuration with symmetry breaking state

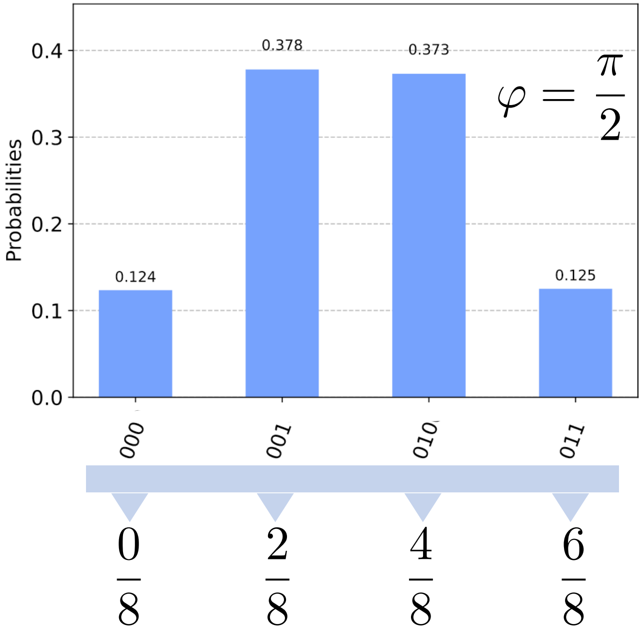
Symmetry operator eigenvalues encoding In the register qubits

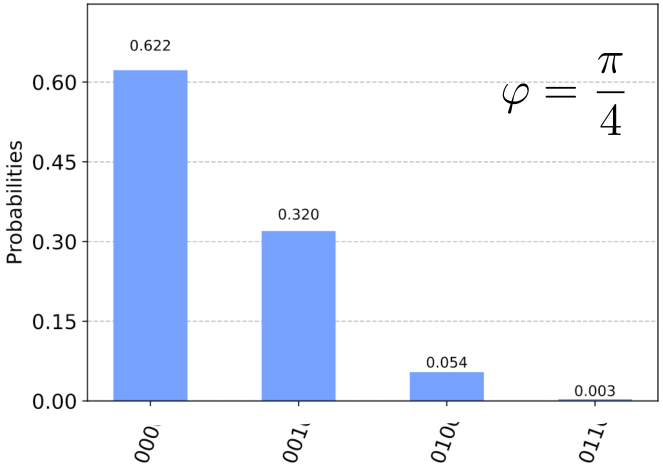
Symmetry restoration through measurement

Qubit counting statistics

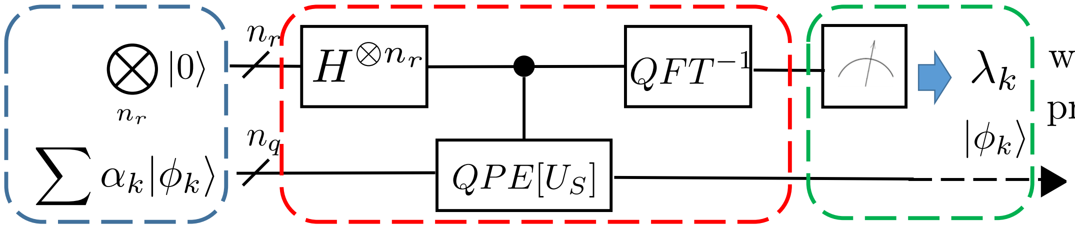
Initial state $$|\Psi\rangle = \prod_n \left[\cos\left(\frac{\varphi}{2}\right) I_n \otimes I_{n+1} + \sin\left(\frac{\varphi}{2}\right) Q_n^+ Q_{n+1}^+\right] |-\rangle$$

Example: 3 pairs, 3 registers





Eigenvalues-Ground state and excited states



Initial configuration with symmetry breaking state

Symmetry operator eigenvalues encoding In the register qubits

Symmetry restoration through measurement

with prob. $|\alpha_k|^2$

Measurement

Example of an event:

$$\underbrace{|011\cdots010\rangle^{(\lambda)}}_{=A^{(\lambda)}}\otimes|\phi_{A^{(\lambda)}}\rangle$$

BCS/HFB state

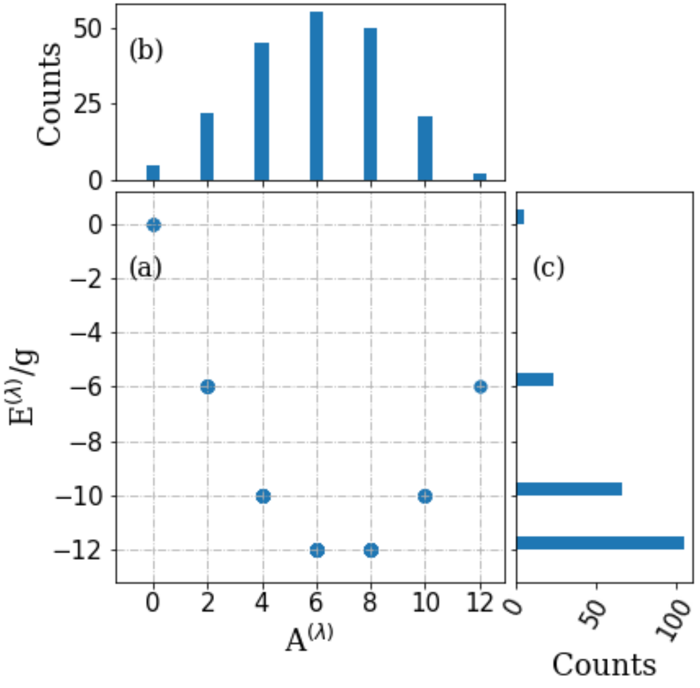
$$|\Psi\rangle=\prod_n\left[\cos\left(\frac{\varphi}{2}\right)I_n\otimes I_{n+1}+\sin\left(\frac{\varphi}{2}\right)Q_n^+Q_{n+1}^+\right]|-\rangle$$

Measurement

Projected BCS or HFB state with varying number Of particles

$$\langle\phi_{A^{(\lambda)}}|H|\phi_{A^{(\lambda)}}\rangle$$

6 pairs



Exact solution

$$E/g=-\frac{1}{4}(A-\nu)(2n_q-A-\nu-2).$$

H was encoded on the full Fock space with $A < n_q$

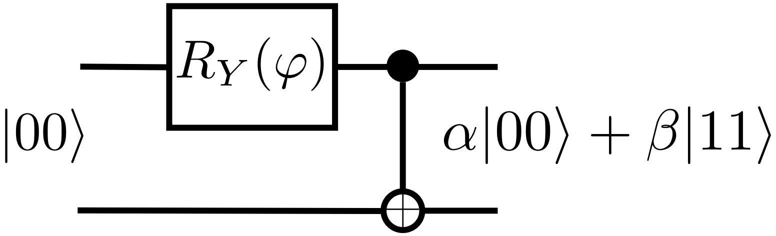
For the degenerate case, this should give the exact solution

Exploring the possibilities of QC

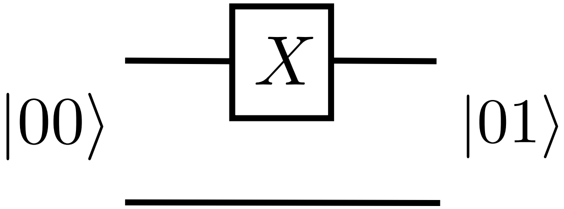
Using the Broken pair approximation

BCS/HFB state

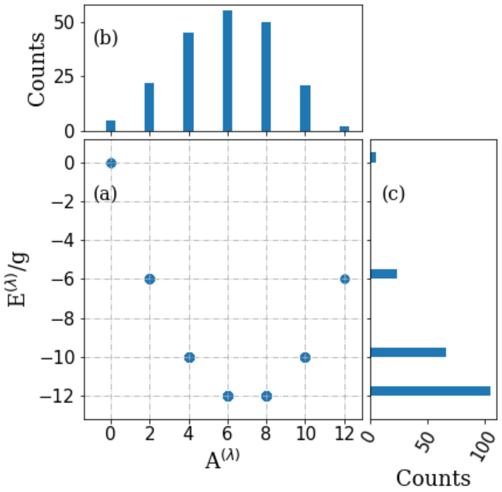
All pairs= generalized Bell state



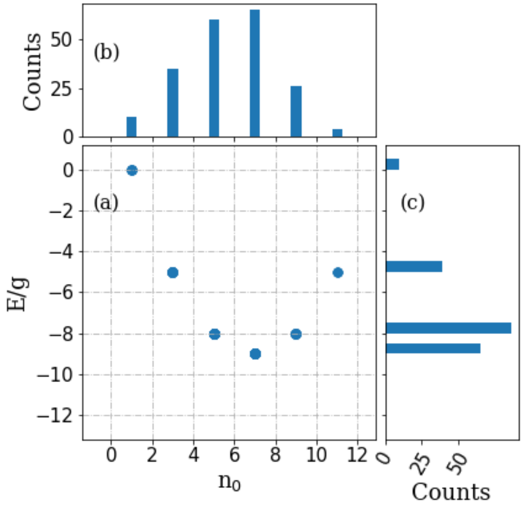
BCS/HFB state + some broken pairs



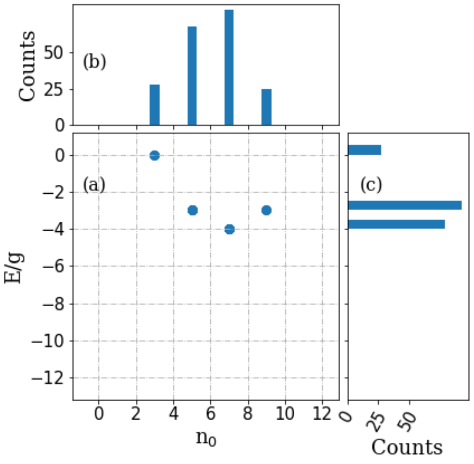
No broken pairs



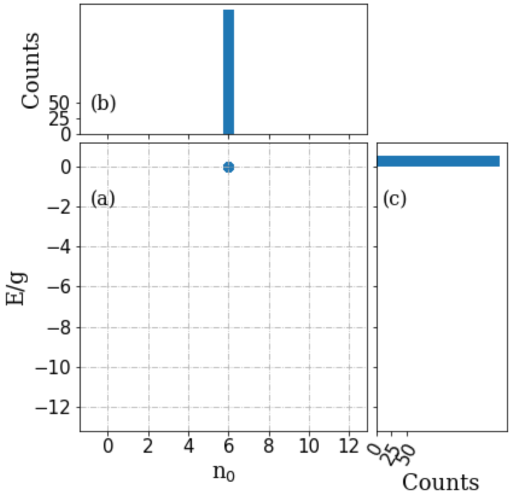
1 broken pairs



3 broken pairs



6 broken pairs

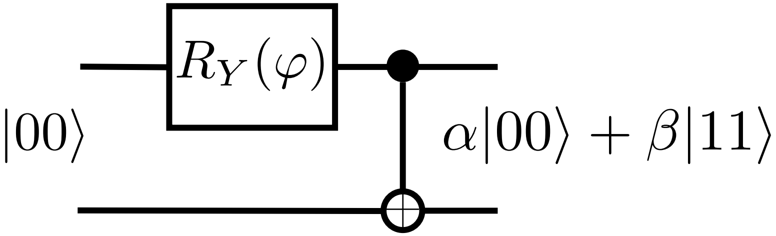


Exploring the possibilities of QC

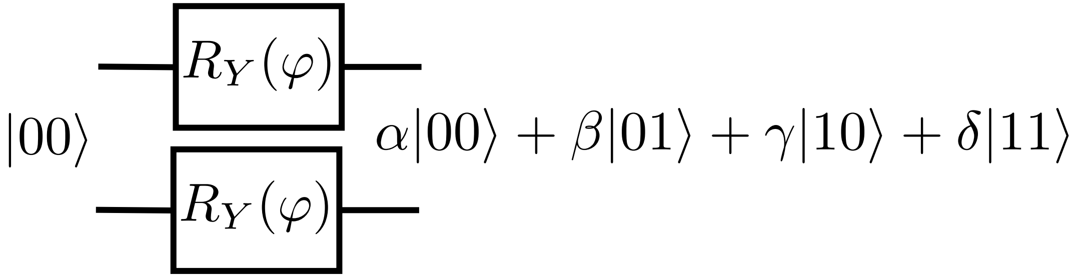
Some additional remarks

BCS/HFB state

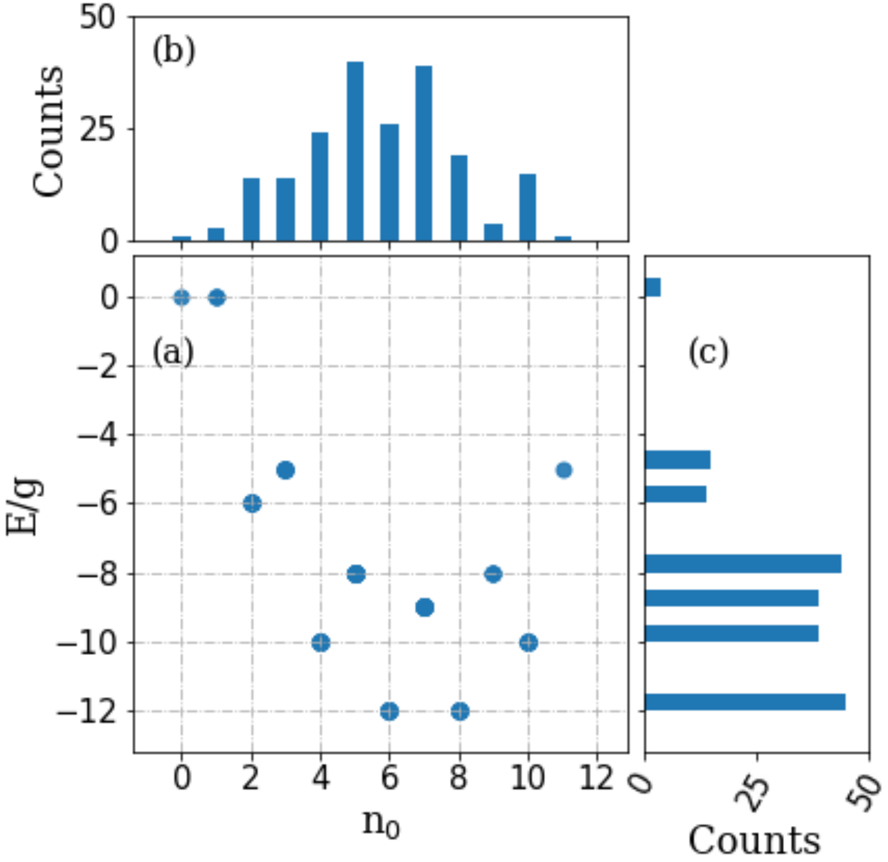
All pairs= generalized Bell state



Alternative circuits



Can give both odd and even simultaneously

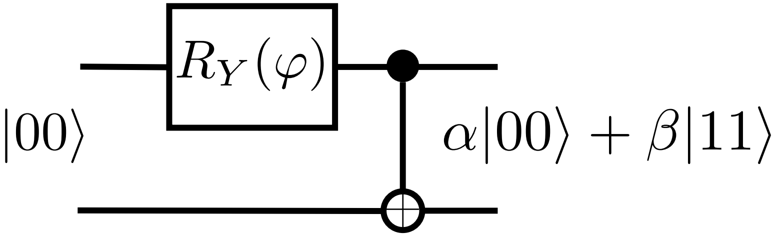


Exploring the possibilities of QC

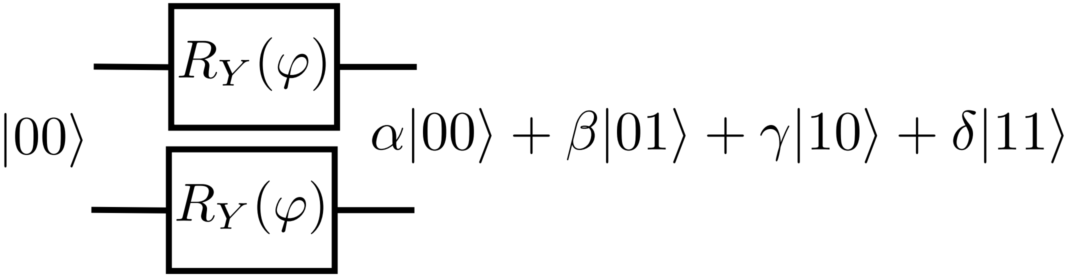
Some additional remarks

BCS/HFB state

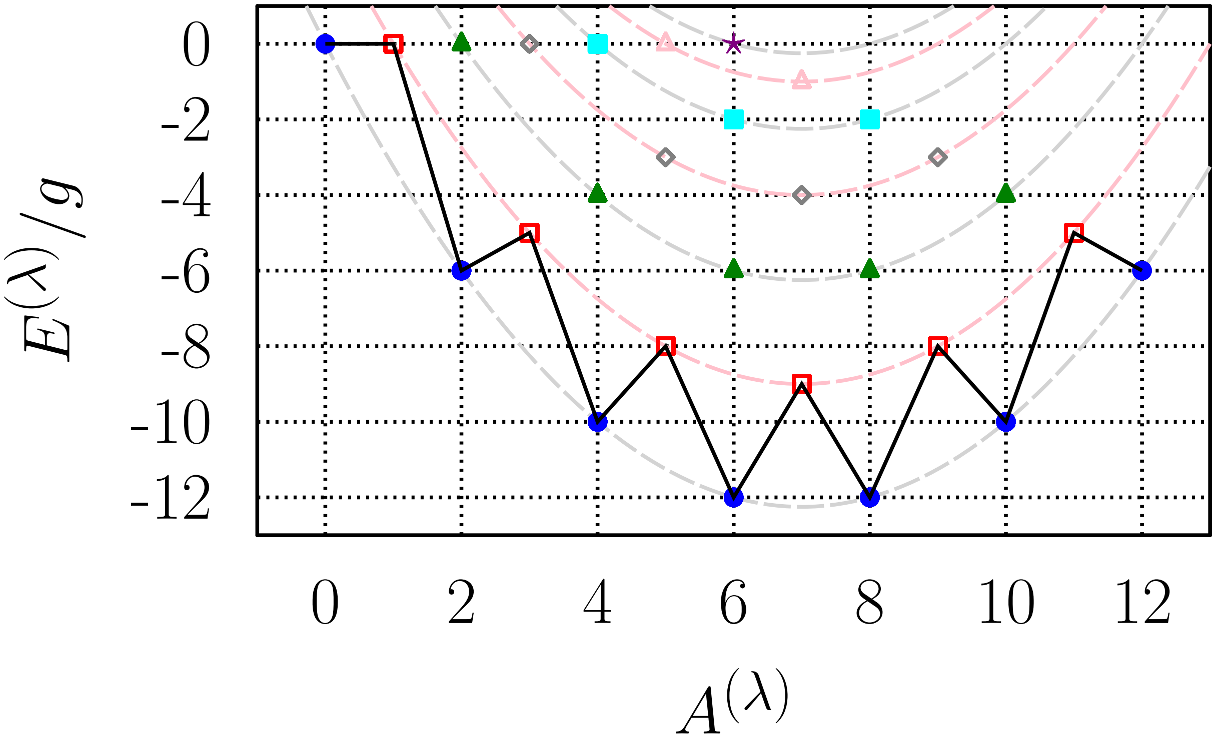
All pairs= generalized Bell state



Alternative circuits



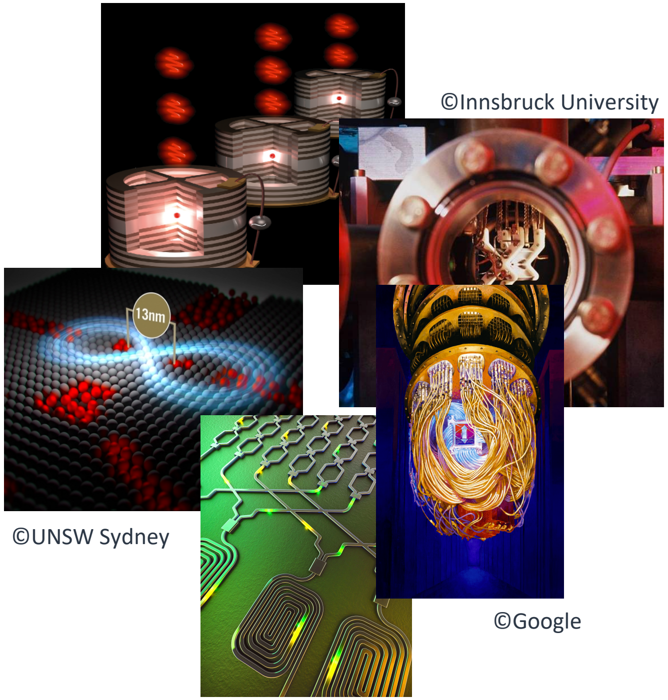
Altogether



Exact solution (lines)

$$E/g = -\frac{1}{4}(A-\nu)(2n_q - A - \nu - 2).$$

Summary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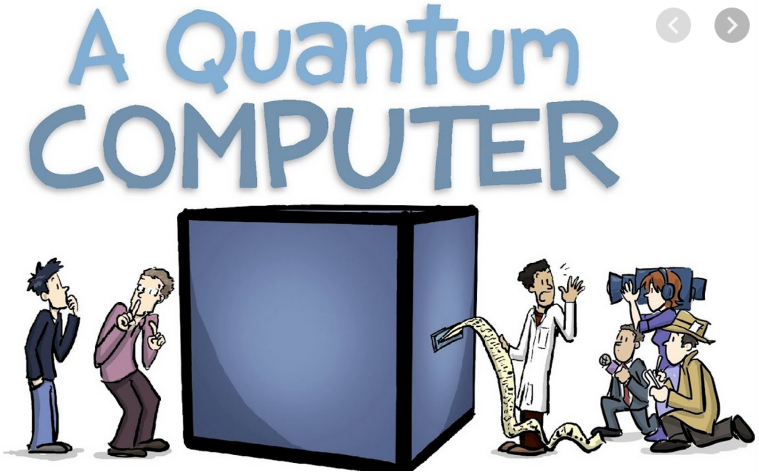
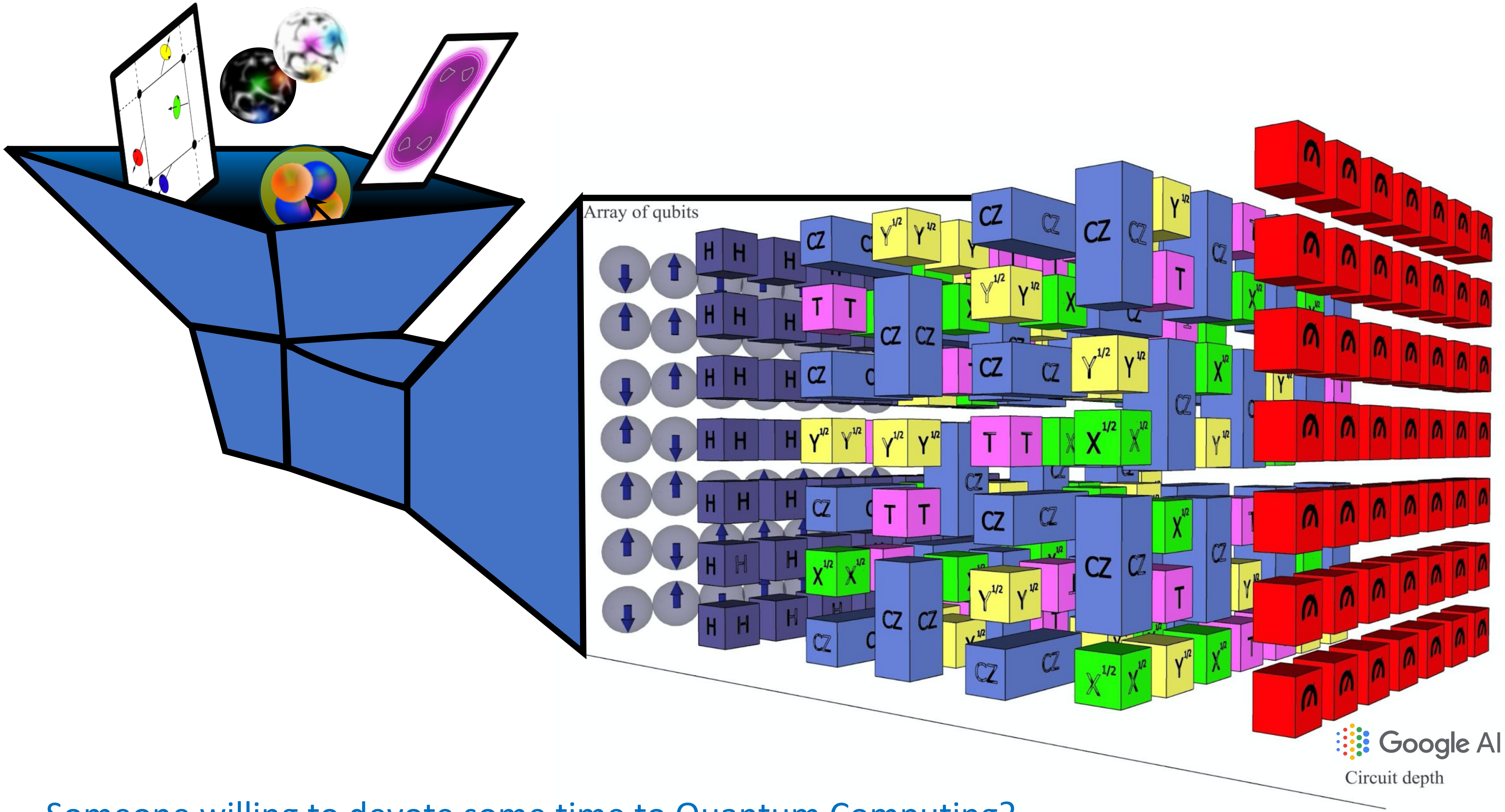
- Quantum computing is a high risk/high benefit interdisciplinary field
- It might lead to unprecedented boost in theory (or more generally in complex problems)
- It leads to natural link between public research and private companies (IBM, Google, …)
- Emerging QC programs in France



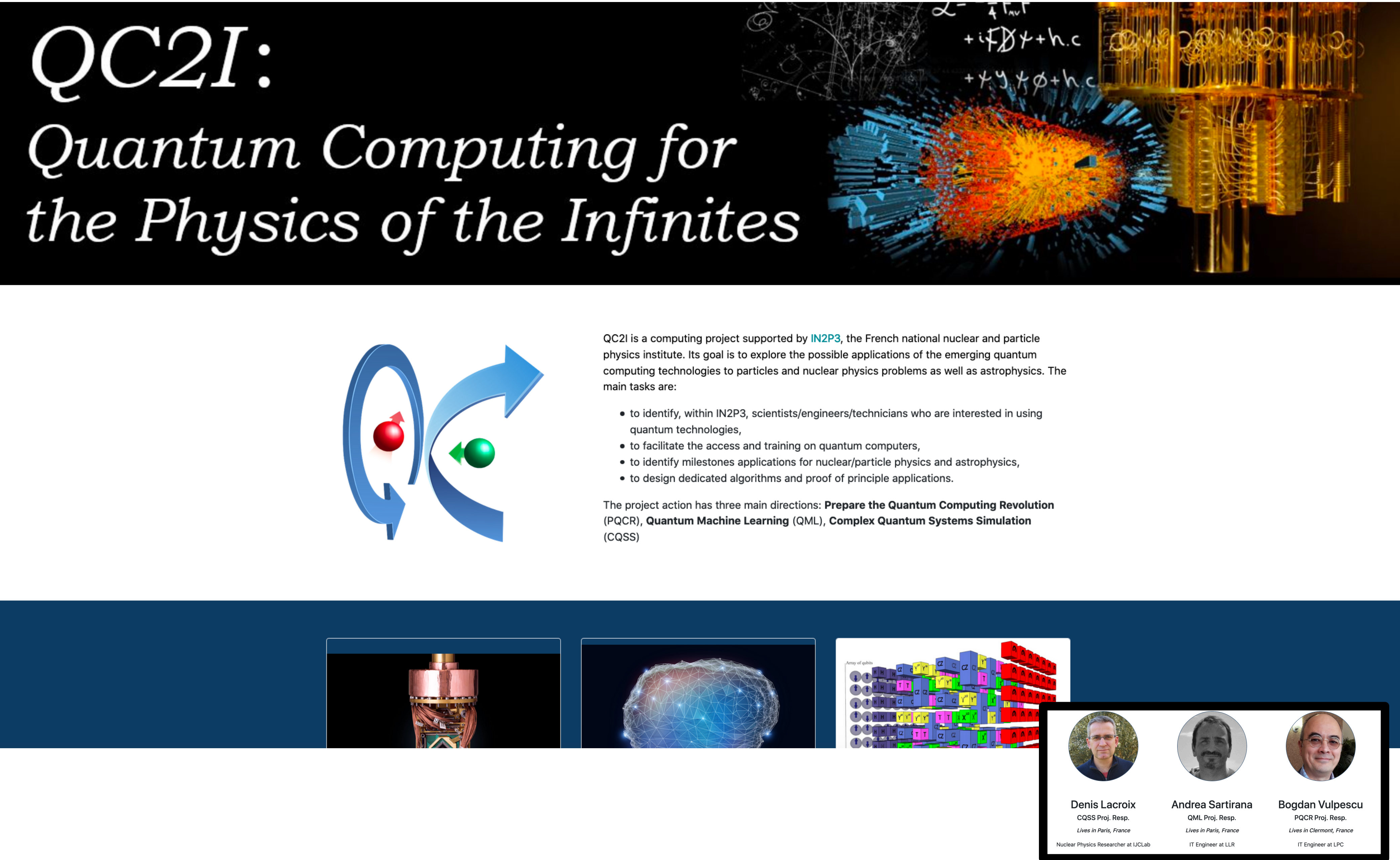
Summary



Someone willing to devote some time to Quantum Computing?

Thank you…

Some advertising



QC2I:

Quantum Computing for the Physics of the Infinites

QC2I is a computing project supported by IN2P3, the French national nuclear and particle physics institute. Its goal is to explore the possible applications of the emerging quantum computing technologies to particles and nuclear physics problems as well as astrophysics. The main tasks are:

- to identify, within IN2P3, scientists/engineers/technicians who are interested in using quantum technologies,
- to facilitate the access and training on quantum computers,
- to identify milestones applications for nuclear/particle physics and astrophysics,
- to design dedicated algorithms and proof of principle applications.

The project action has three main directions: **Prepare the Quantum Computing Revolution** (PQCR), **Quantum Machine Learning** (QML), **Complex Quantum Systems Simulation** (CQSS)

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