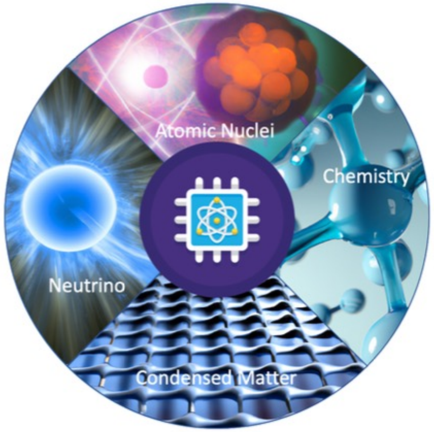
FRANCE HYBRID HPCQUANTUM INITIATIVE

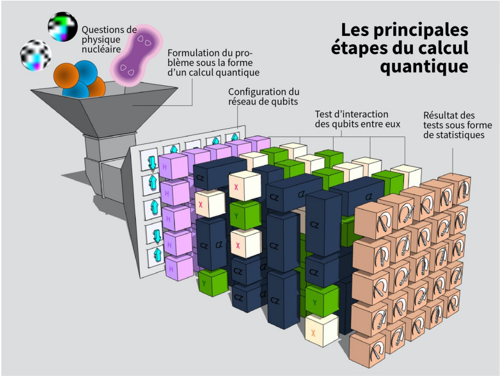
Quantum computing

Denis Lacroix (IJCLab, Paris-Saclay University)

Brief Discussion on Quantum computing today

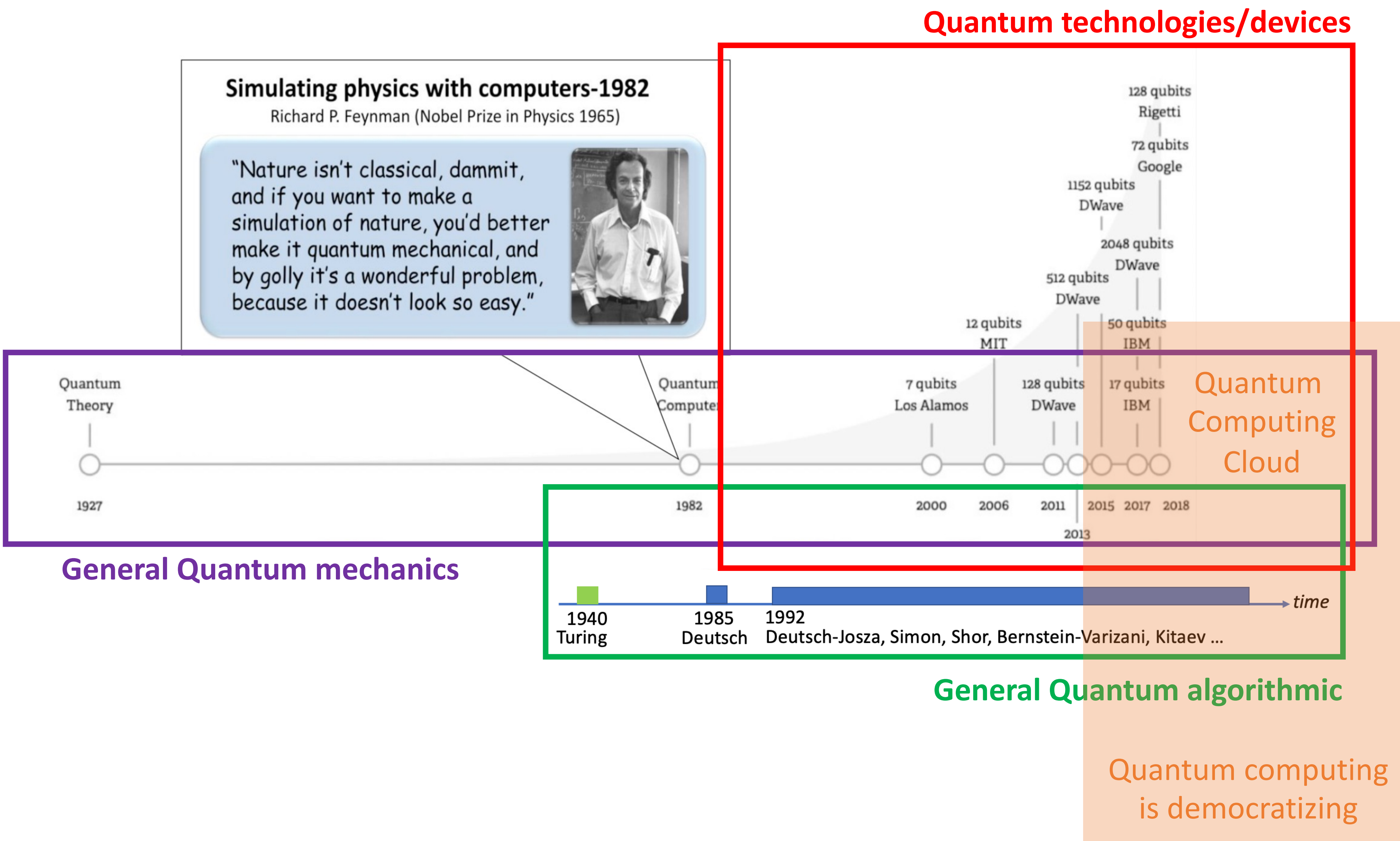
Current Challenges and applications





General aspects of quantum computers and quantum advantage

Why quantum computing is becoming mature now ?

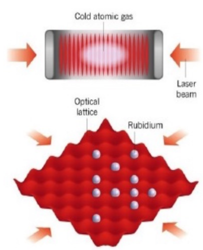


What means quantum devices today

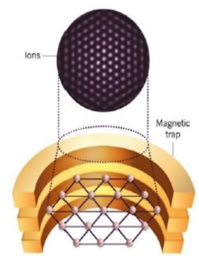
There are many types of quantum computers: ***analog versus digital quantum computers***

There are now many quantum objects one can manipulate

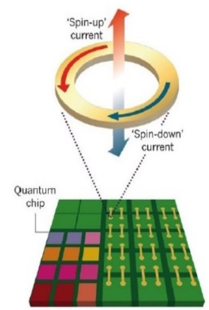
Cold atoms



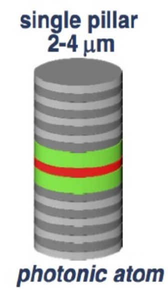
Trapped ions

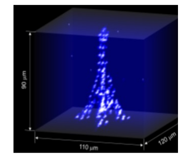


Superc. loops



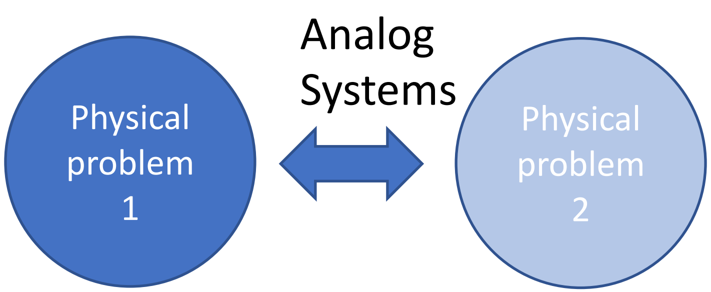
Polaritons





Atomes de Rydberg dans des pinces optiques

Analog quantum simulator

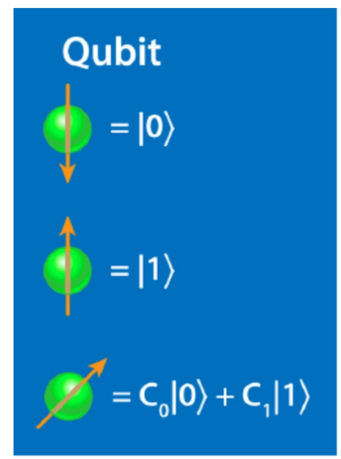


Complex problem that cannot or hardly be simulated on classical computers

Analog problem to 1 that could be tested in laboratory

➡ Non-universal

Digital quantum simulator



➡ Universal Quantum simulation

Quantum analogue simulation

There are many types of quantum computers: ***analog versus digital quantum computers***

A few examples

Analog quantum simulator

Analog Systems

Physical problem 1 ⟷ Physical problem 2

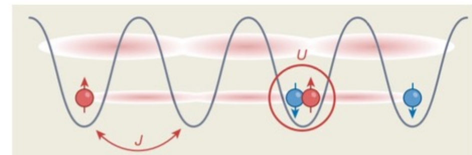
Complex problem that cannot or hardly be simulated on classical computers

Analog problem to 1 that could be tested in laboratory

➡ The mapping from one physical problem to another physical problem is a delicate issue

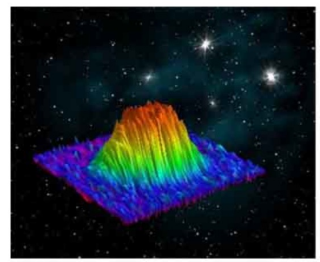
➡ It strongly depends on the problem itself (non-universality)

Analog systems on lattice (fFermi-Hubbard, Schwinger model, …)



Analog simulation of astrophysics/cosmology

Ultracold Fermi gas

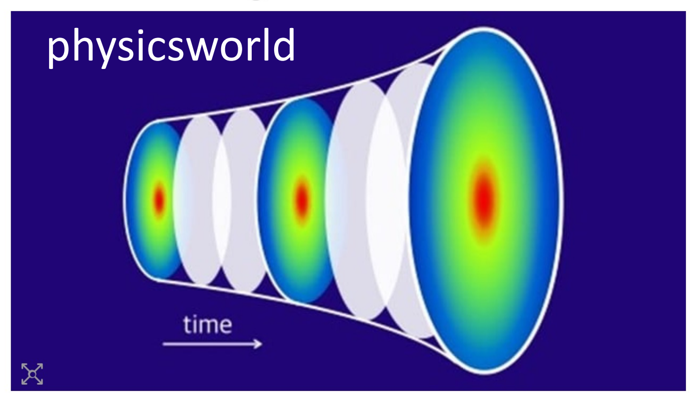


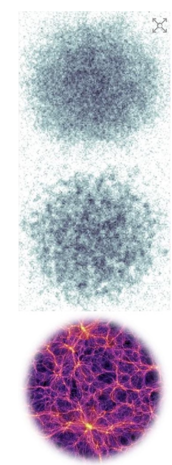
Neutron stars

Viermann et al. Nature

An expanding universe is simulated in a quantum droplet

22 Mar 2023 Campbell McLauchlan



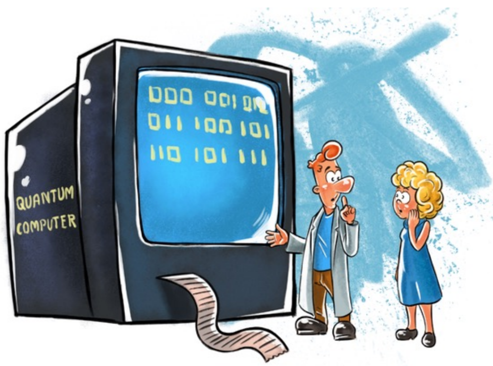


Ultracold atoms

Dark matter

Digital quantum devices are supposed to be universal

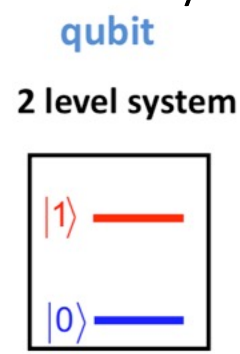
Classical computers
Works with bits

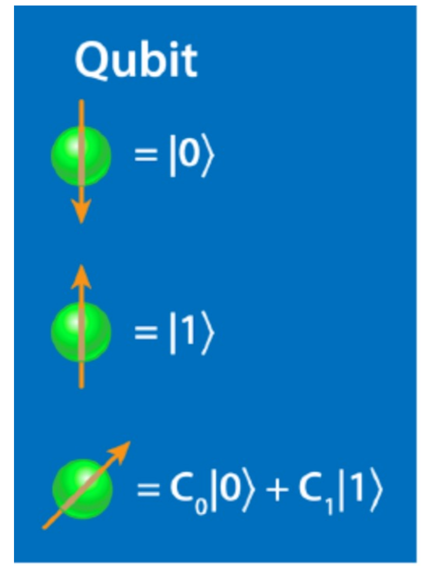


Bits are only 0 or 1

Quantum computers with
Quantum bits

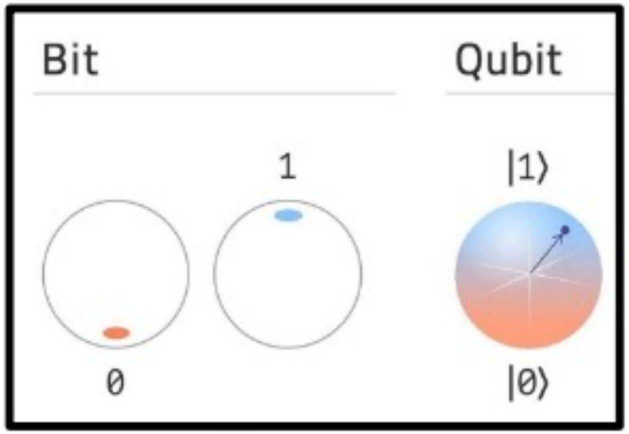
Qubits can be seen
As two-level systems

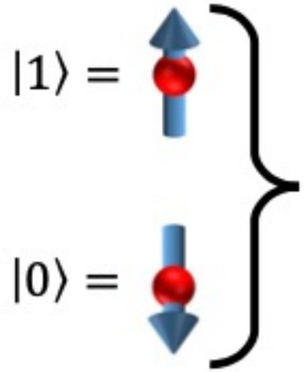




Where do we expect quantum advantage?

A few examples

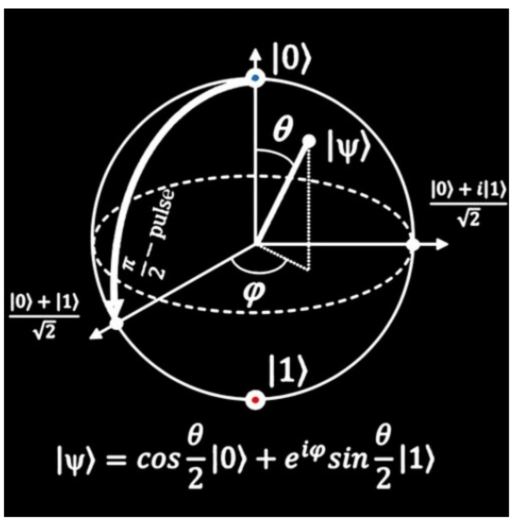




Quantum RAM advantage

Storing with
-1 bit: 2 integers 0,1
-2 bits: 4 integers 0,1,2,3
...

Bloch sphere picture



Storing with one qubit

$$|\Phi\rangle = f_1(\theta)|0\rangle + f_2(\theta,\varphi)|1\rangle$$

Two-qubits

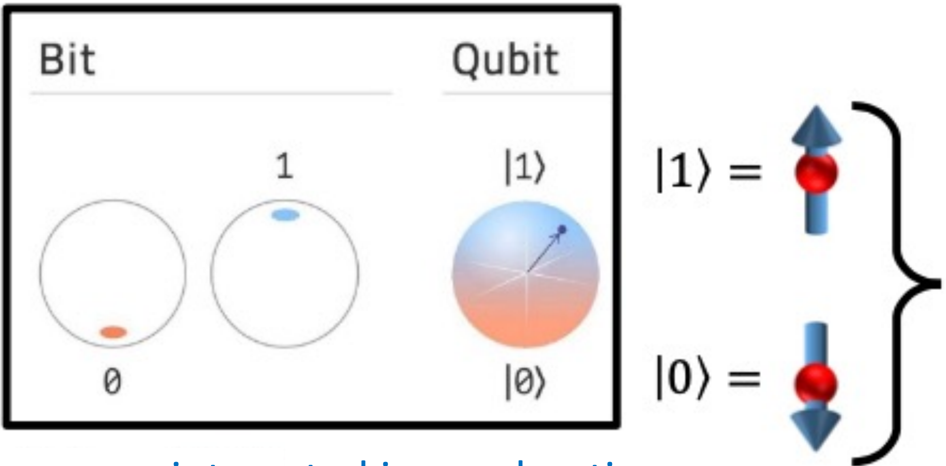
$$|\Phi\rangle = f_1(\theta_1,\theta_2)|00\rangle + \cdots$$

...

Direct multi-parameter function encoding
Continuous function programming

Where do we expect quantum advantage?

A few examples



we are interested in accelerating to perform a calculation

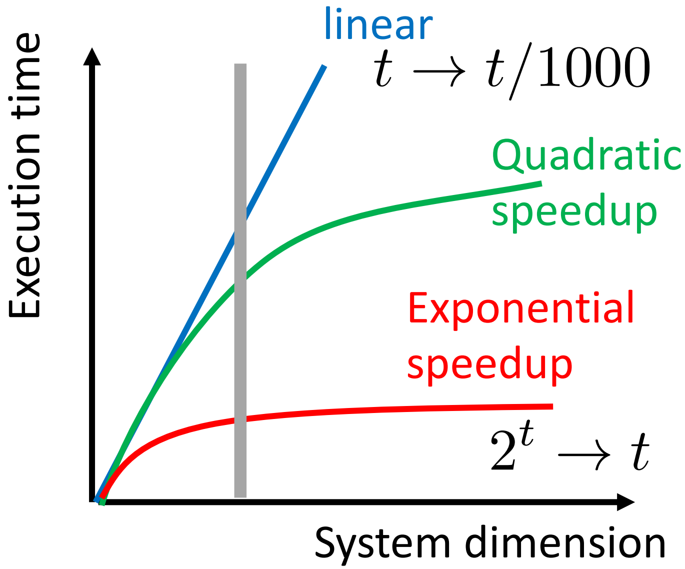
Quantum Algorithm advantage

A fundamental question is how much “computational time” it takes to solve a problem – this is linked to the complexity of the problem

(Church-Turing thesis, Problem complexity classification, …)

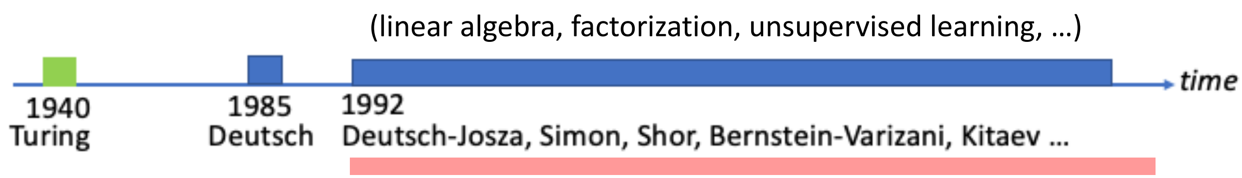
Church-Turing thesis says that the speedup could not be exponential!

Speedup can be:



A calculation that takes 1 year in a “linear” takes 24 seconds with exp. speedups!

Quantum computers contradict this thesis- some algorithms Promises exponential speedup for specific calculations

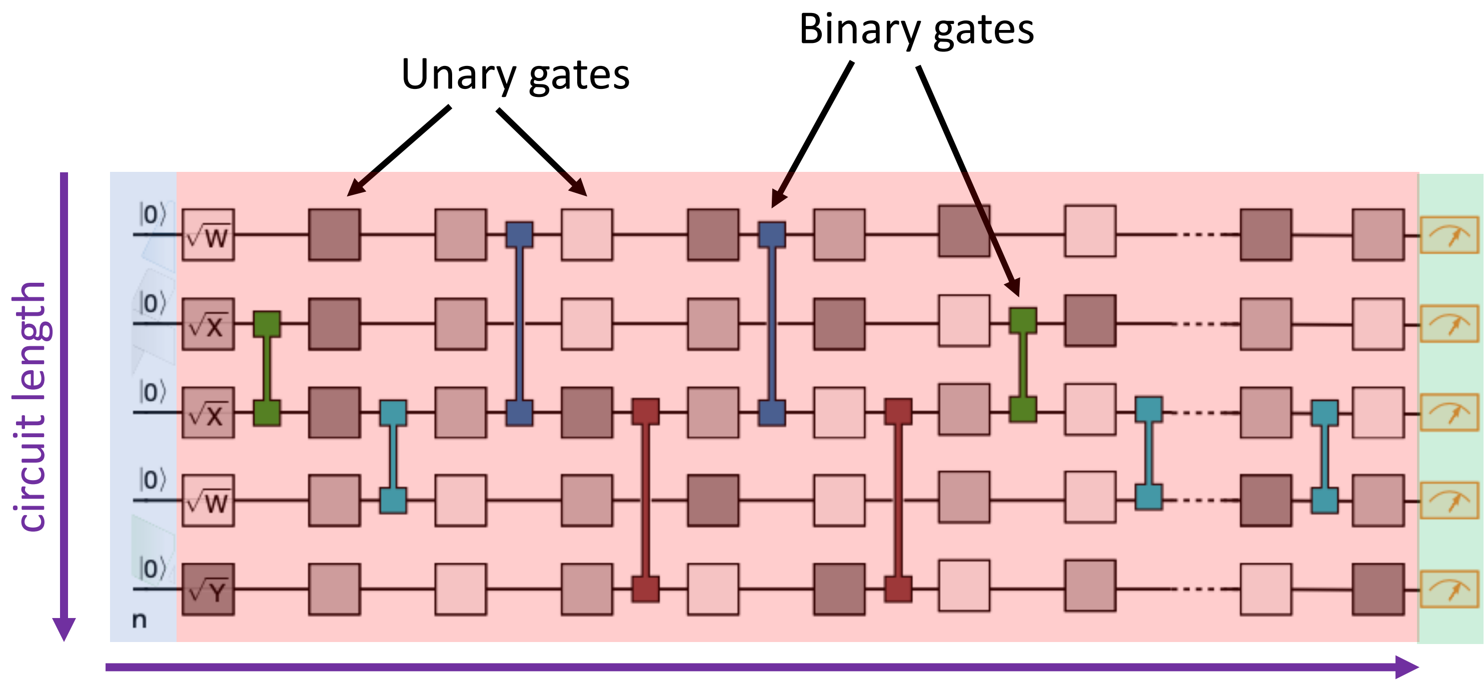


Either polynomial or exponential acceleration

Trick: use quantum entanglement and measurement rules. Measuring one qubit can give information on the whole system.

Some terminology – general aspects

Quantum circuits with more than one qubit



Quantum register:
Define the qubit computational basis: $|0, 0, \cdots, 0, 0\rangle$

$|0, 0, \cdots, 1, 1\rangle$

$|0, 0, \cdots, 0, 1\rangle$

$\cdots$

Hilbert space size 2^n

Quantum circuits:

Constraint: the circuit makes Unitary transformation, i.e. no loss of information

Quantum measurement of qubits – leads to a set of events In the form of bitstring

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

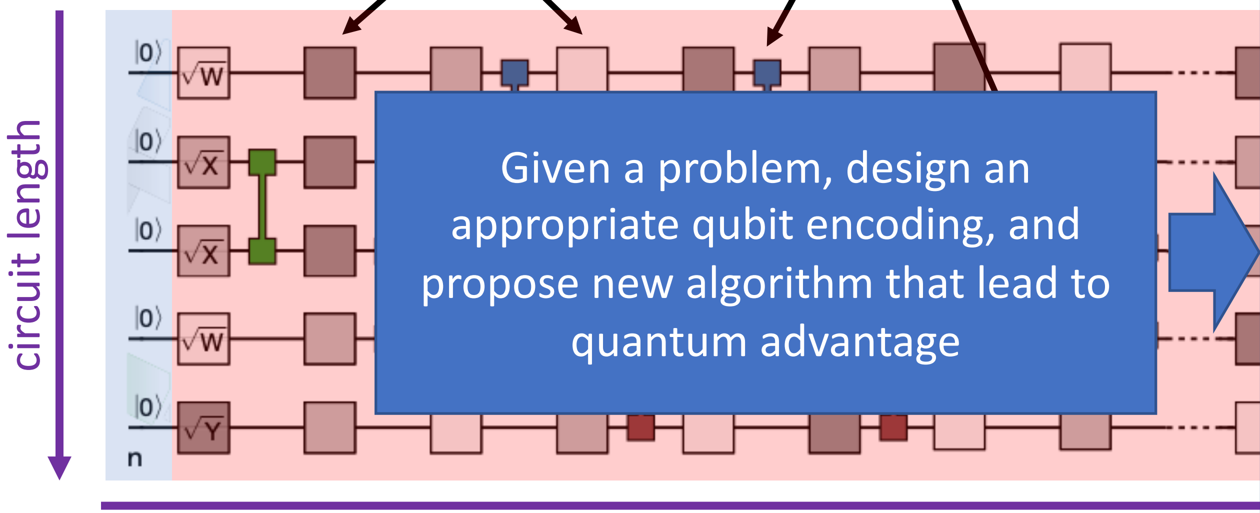
Gives the |a|^2

Some terminology – general aspects

Quantum circuits with more than one qubit

Binary gates

Unary gates



Given a problem, design an appropriate qubit encoding, and propose new algorithm that lead to quantum advantage

As the length increases
Find ways to deal with
The classical information flow.
Hybrid Quantum-Classical problem

Quantum register:
De
ba

Today's status:
Quantum Computers are imperfect
(Noisy, limited in depth and length)

Hilbert space size 2^n

Quantum circuits:

Constraint: the circuit makes Unitary transformation, i.e. no loss of information

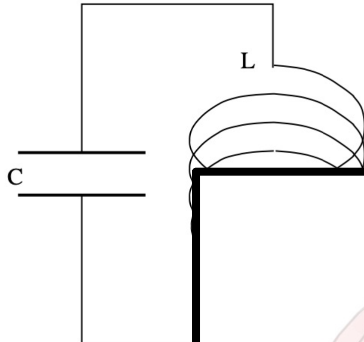
to a set of events
In the form of
bitstring

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

Gives the $|a|^2$

One example : Superconducting qubits

Simple oscillator by LC circuit



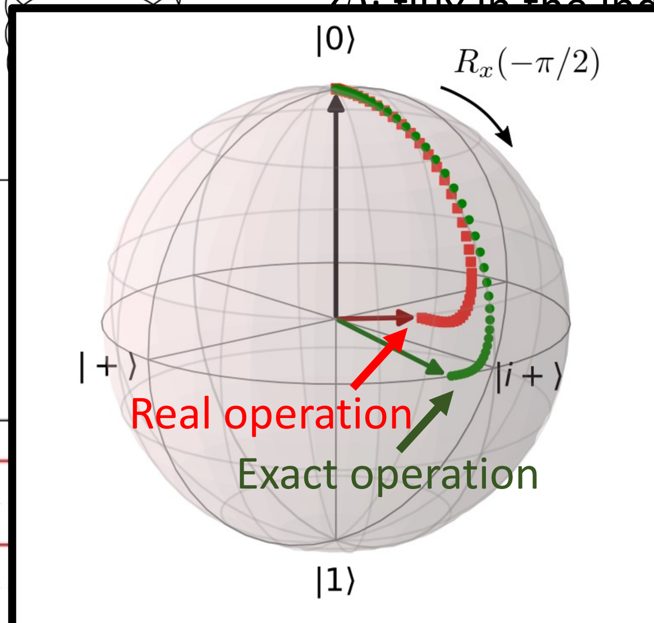
$$H = \frac{1}{2L}\phi^2 + \frac{1}{2C}n^2$$

ϕ: flux in the inductor

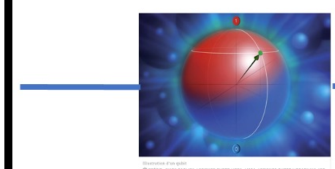
capacitor

ested in isolating $|0\rangle$ and $|1\rangle$

repare the system in any combination

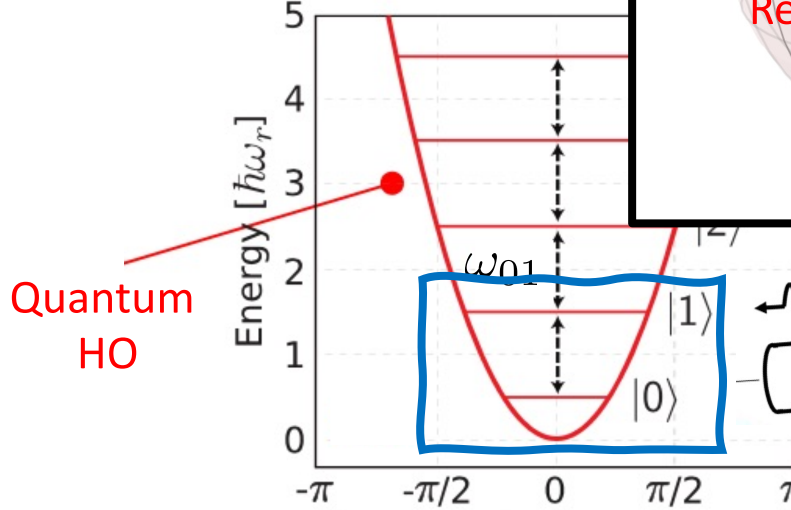


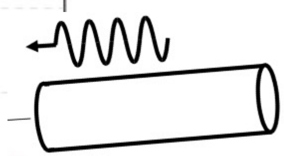
Qubit identification and manipulation



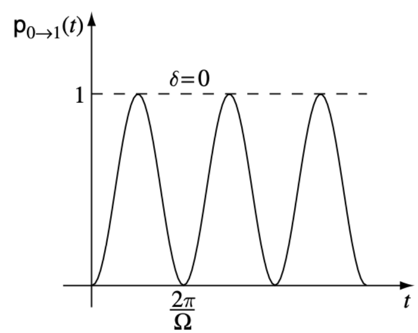
$c_0|0\rangle + c_1|1\rangle$

ce Rabi-like oscillation





External perturbation



Difficulties

Each operation takes some Times/ has a certain error

System is not fully isolated

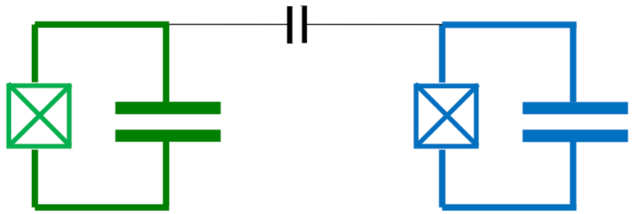
→ Decoherence

Constraint $T_{\rm run} \leq T_{\rm dec}$

Example: Superconducting qubits

Next step: putting several qubits together

2 qubits can be coupled through electrostatic interactions



With this one can manipulate/entangle qubits

IBM Google rigetti IQM

Some specific Operations

When

Fidelity

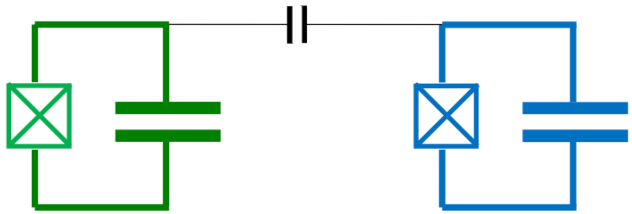
Acronym[b]	Layout[c]	First demonstration [Year]	Highest fidelity [Year]	Gate time
CZ (ad.)	T–T	DiCarlo et al. (72) [2009]	99.4%[e] Barends et al. (3) [2014]	40 ns
			99.7%[e] Kjaergaard et al. (73) [2020]	60 ns
√iSWAP	T–T	Neeley et al. (81)[d] [2010]	90%[g] Dewes et al. (74) [2014]	31 ns
CR	F–F	Chow et al. (75)[h] [2011]	99.1%[e] Sheldon et al. (5) [2016]	160 ns
√bSWAP	F–F	Poletto et al. (76) [2012]	86%[g] Poletto et al. (76) [2012]	800 ns
MAP	F–F	Chow et al. (77) [2013]	87.2%[g] Chow et al. (75) [2011]	510 ns
CZ (ad.)	T–(T)–T	Chen et al. (55) [2014]	99.0%[e] Chen et al. (55) [2014]	30 ns
RIP	3D F	Paik et al. (78) [2016]	98.5%[e] Paik et al. (78) [2016]	413 ns
√iSWAP	F–(T)–F	McKay et al. (79) [2016]	98.2%[e] McKay et al. (79) [2016]	183 ns
CZ (ad.)	T–F	Caldwell et al. (80) [2018]	99.2%[e] Hong et al. (6) [2019]	176 ns
$CNOT_L$	BEQ-BEQ	Rosenblum et al. (13) [2018]	~99%[f] Rosenblum et al. (13) [2018]	190 ns
$CNOT_{T\text{-}L}$	BEQ-BEQ	Chou et al. (82) [2018]	79%[g] Chou et al. (82) [2018]	4.6 µs

M. Kjaergaard, Annual Review of Cond. Matt (2020)

Example: Superconducting qubits

Next step: putting several qubits together

2 qubits can be coupled through electrostatic interactions



With this one can manipulate/entangle qubits

IBM Google rigetti IQM

Some specific Operations (see next lecture)

When

Fidelity

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CZ (ad.)	T–(T)–T	Chen et al. (55) [2014]	99.0%[e] Chen et al. (55) [2014]
RIP	3D F	Paik et al. (78) [2016]	98.5%[e] Paik et al. (78) [2016]
$\sqrt{\text{iSWAP}}$	F–(T)–F	McKay et al. (79) [2016]	98.2%[e] McKay et al. (79) [2016]
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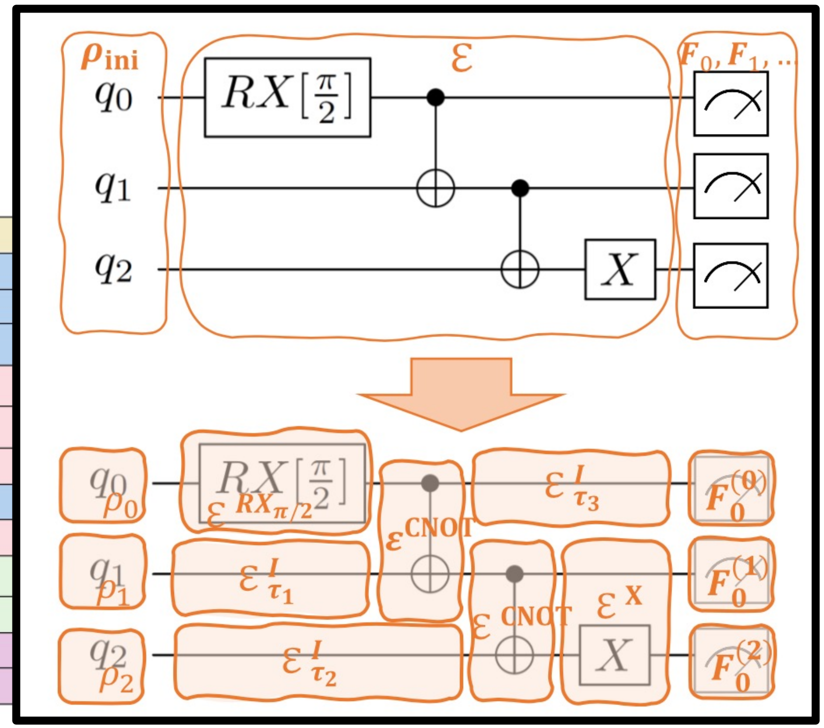
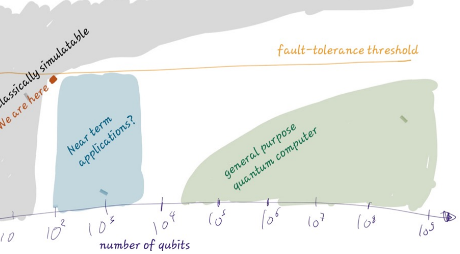
CNOT_{L}	BEQ-BEQ	Rosenblum et al. (13) [2018]	~99%[f] Rosenblum et al. (13) [2018]
$\text{CNOT}_{\text{T-L}}$	BEQ-BEQ	Chou et al. (82) [2018]	79%[g] Chou et al. (82) [2018]

As a result



M. Kjaergaard, Annual Review of Cond. Matt (2020)



Some proofs of principle

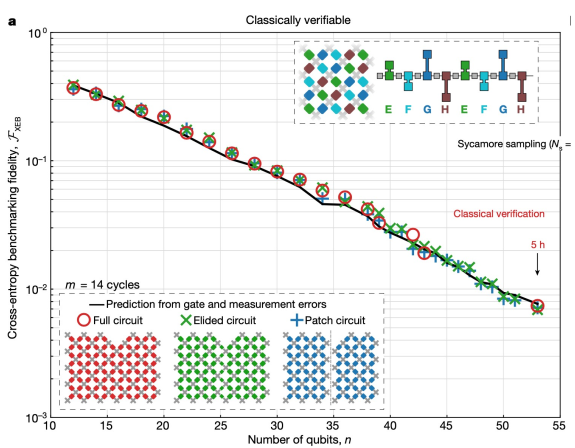
Quantum advantage

Article

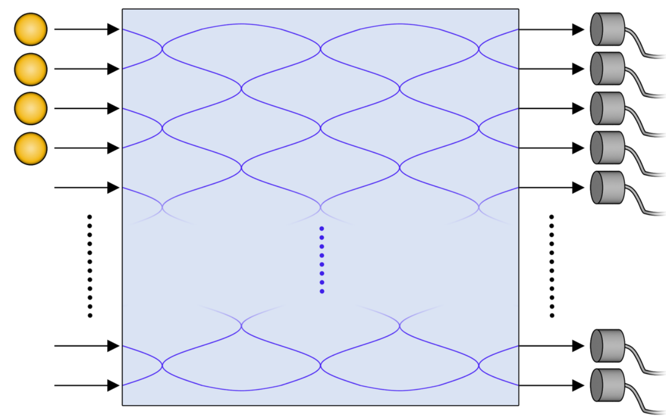
Quantum supremacy using a programmable superconducting processor

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

Proofs of fidelity



Photonic Devices



QUANTUM COMPUTING

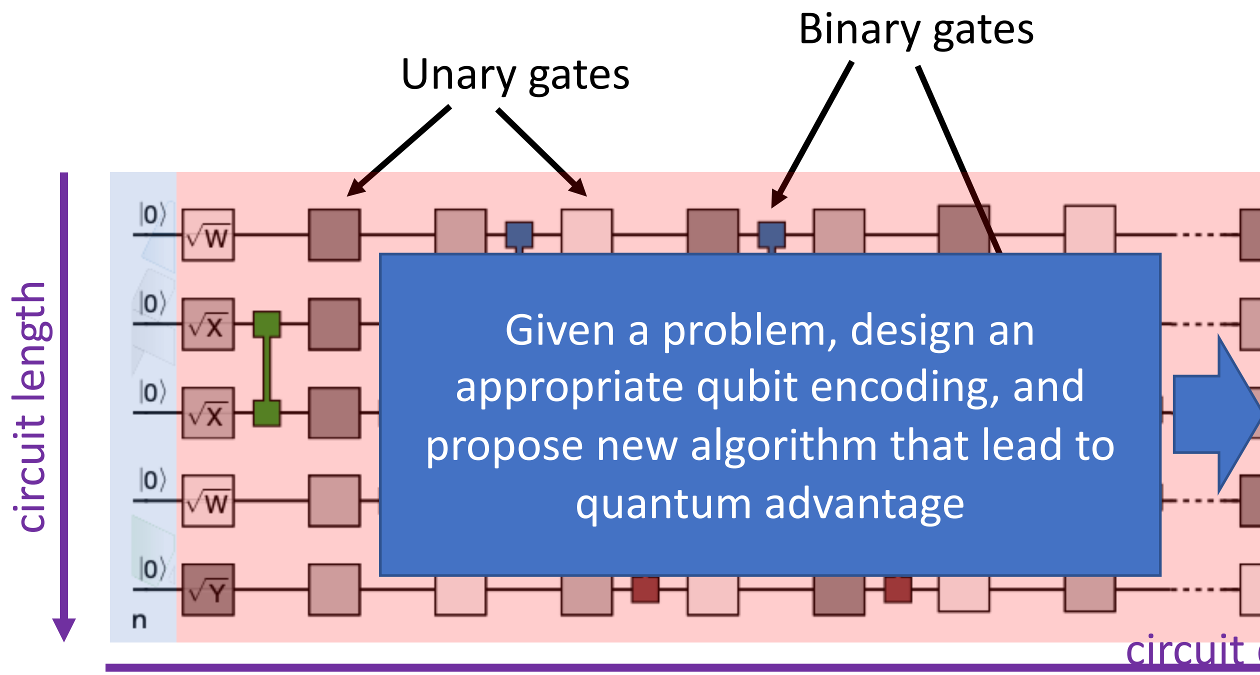
Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

Quantum computers promise to perform certain tasks that are believed to be intractable to classical computers. Boson sampling is such a task and is considered a strong candidate to demonstrate the quantum computational advantage. We performed Gaussian boson sampling by sending 50 indistinguishable single-mode squeezed states into a 100-mode ultralow-loss interferometer with full connectivity and random matrix—the whole optical setup is phase-locked—and sampling the output using 100 high-efficiency single-photon detectors. The obtained samples were validated against plausible hypotheses exploiting thermal states, distinguishable photons, and uniform distribution. The photonic quantum computer, *Jiuzhang*, generates up to 76 output photon clicks, which yields an output state-space dimension of 10^{30} and a sampling rate that is faster than using the state-of-the-art simulation strategy and supercomputers by a factor of ~10^{14}.

Science, 2020

Quantum circuits with more than one qubit



Given a problem, design an appropriate qubit encoding, and propose new algorithm that lead to quantum advantage

As the length increases
Find ways to deal with
The classical information flow.
Hybrid Quantum-Classical problem

In the form of

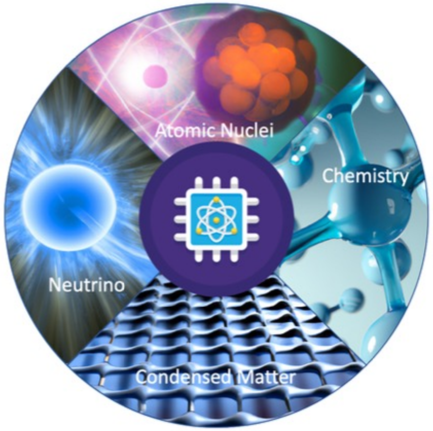
Today's status:
Quantum Computers are imperfect
(Noisy, limited in depth and length)

Develop methods to correct for these imperfections

One major activity/challenge today
Find in our fields pilot applications

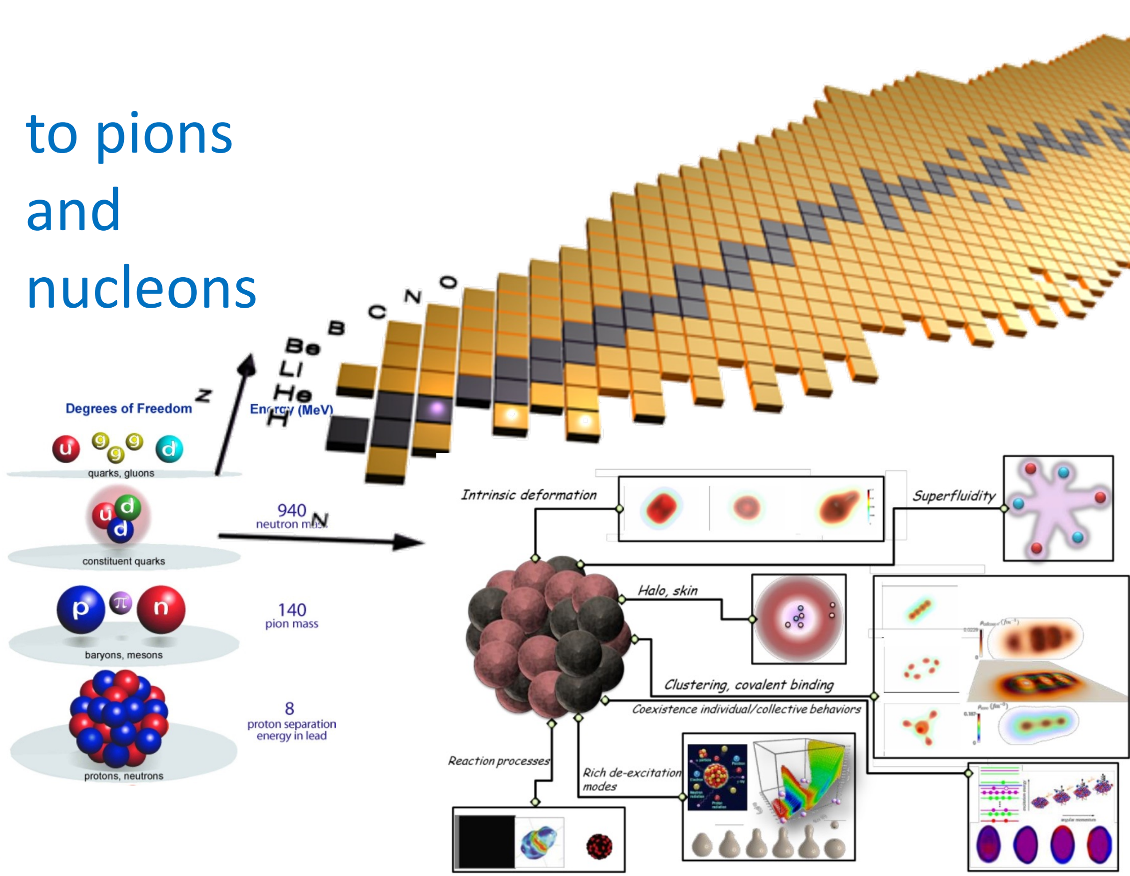
Quantum computers are often themselves many-body interacting systems

Quantum computing for the infinities

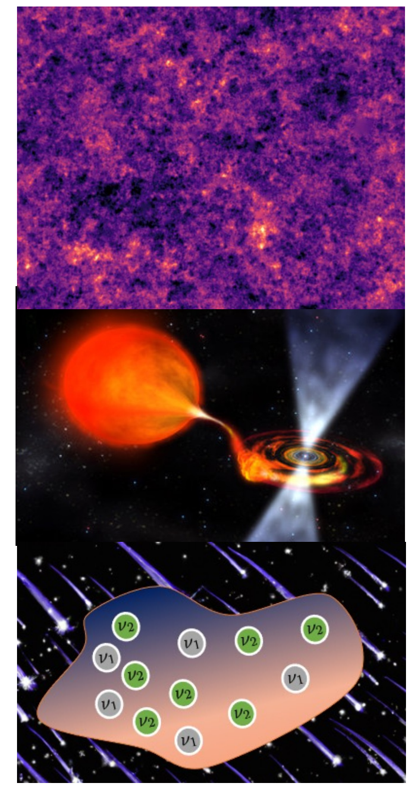


to atomic nuclei

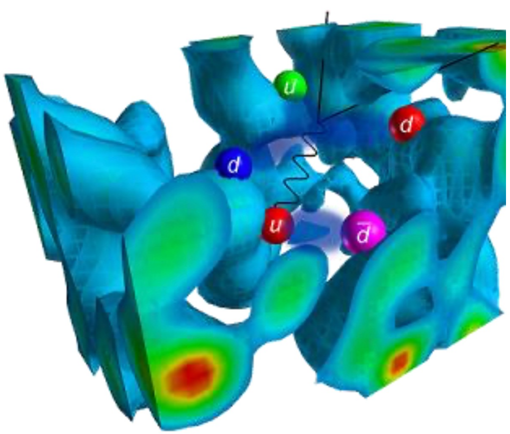
to pions and nucleons



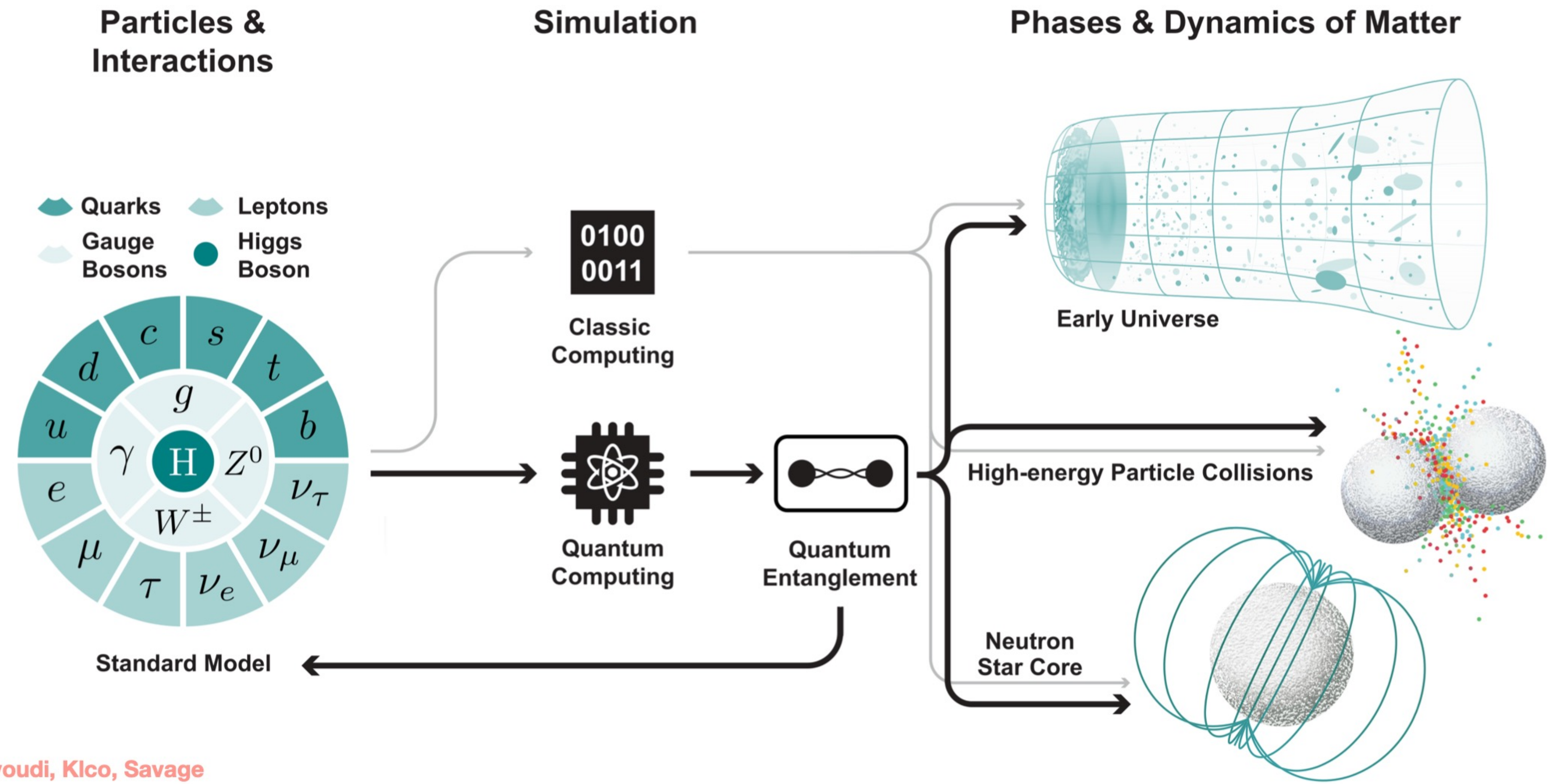
to stellar processes



from quark



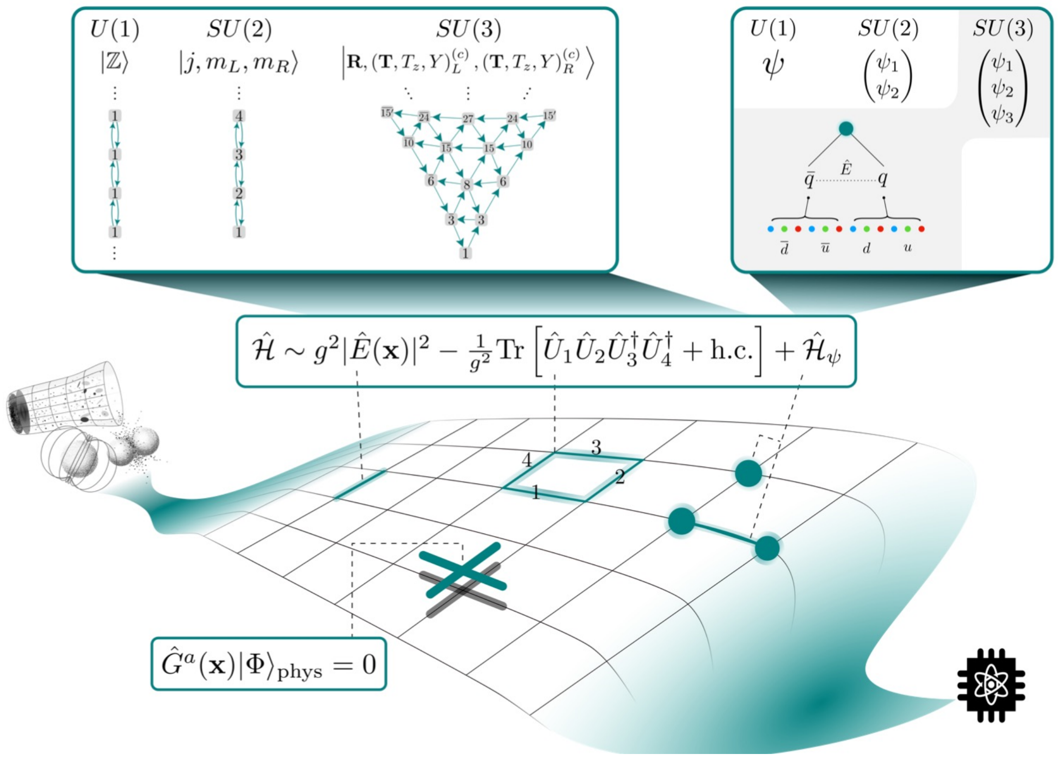
Courtesy J.P. Ebran

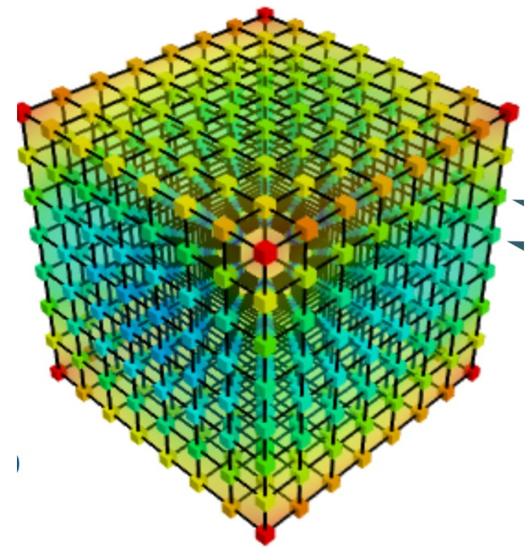


Bauer, Davoudi, Klco, Savage

Courtesy M. Savage

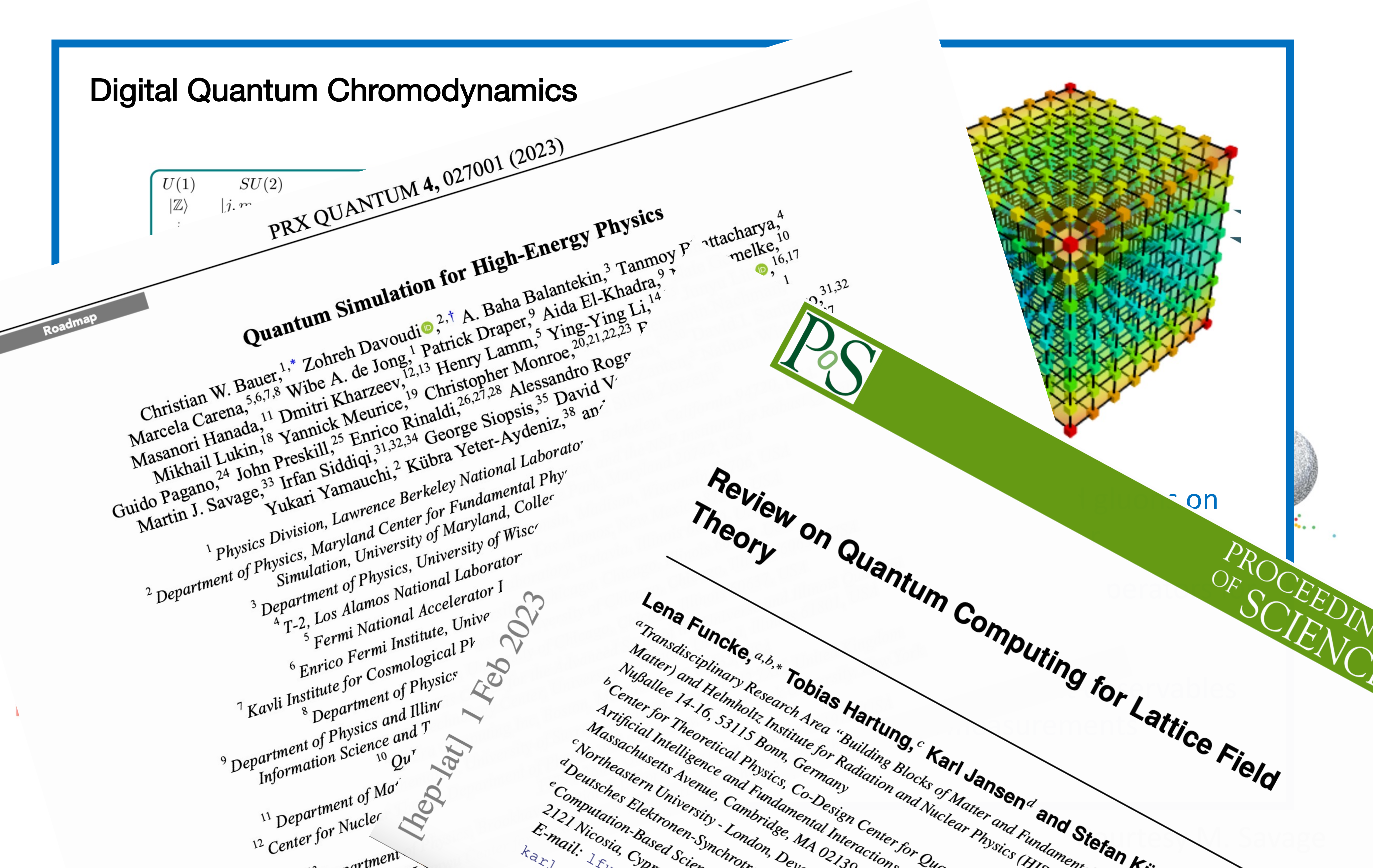
Digital Quantum Chromodynamics





- Map quarks and gluons on quantum register
- Develop unitary operators for their evolution
- Obtain relevant observables from measurements

Courtesy M. Savage



Digital Quantum Chromodynamics

$U(1)$ $SU(2)$

PRX QUANTUM 4, 027001 (2023)

Roadmap

Quantum Simulation for High-Energy Physics

Christian W. Bauer,[1,*] Zohreh Davoudi,[2,†] A. Baha Balantekin,[3] Tanmoy B...ttacharya,[4]
Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] ...melke,[10]
Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[14] ...[16,17]
Mikhail Lukin,[18] Yannick Meurice,[19] Christopher Monroe,[20,21,22,23] ...
Guido Pagano,[24] John Preskill,[25] Enrico Rinaldi,[26,27,28] Alessandro Rogg...
Martin J. Savage,[33] Irfan Siddiqi,[31,32,34] George Siopsis,[35] David V...
Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[38] an...

[1] Physics Division, Lawrence Berkeley National Laborato...
[2] Department of Physics, Maryland Center for Fundamental Phy...
Simulation, University of Maryland, Colle...
[3] Department of Physics, University of Wisc...
[4] T-2, Los Alamos National Laborator...
[5] Fermi National Accelerator I...
[6] Enrico Fermi Institute, Unive...
[7] Kavli Institute for Cosmological Ph...
[8] Department of Physics...
[9] Department of Physics and Illin...
Information Science and T...
[10] Qu...
[11] Department of Ma...
[12] Center for Nucle...

[hep-lat] 1 Feb 2023

PoS

PROCEEDIN... OF SCIENC...

Review on Quantum Computing for Lattice Field Theory

Lena Funcke,[a,b,*] Tobias Hartung,[c] Karl Jansen[d] and Stefan K...

[a] Transdisciplinary Research Area "Building Blocks of Matter and Fundamental... Matter) and Helmholtz Institute for Radiation and Nuclear Physics (HIS...
Nußallee 14-16, 53115 Bonn, Germany
[b] Center for Theoretical Physics, Co-Design Center for Qu... Artificial Intelligence and Fundamental Interactions... Massachusetts Avenue, Cambridge, MA 02139...
[c] Northeastern University - London, Dev...
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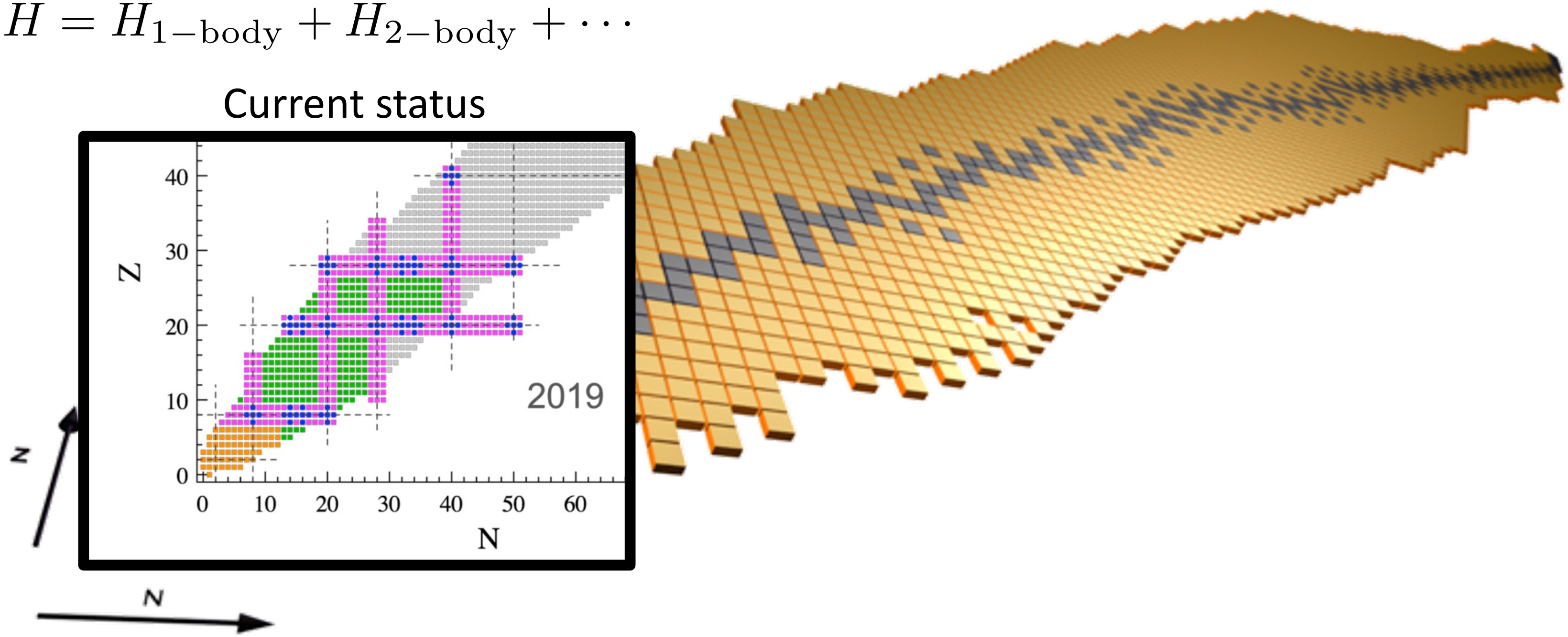
[e] Computation-Based Scien... 2121 Nicosia, Cypr...
E-mail: lfu...

Actual tendency : Towards Full configuration-Interaction description ?

$$H = H_{1-\text{body}} + H_{2-\text{body}} + \cdots$$



Actual tendency : Towards full configuration-Interaction description ?

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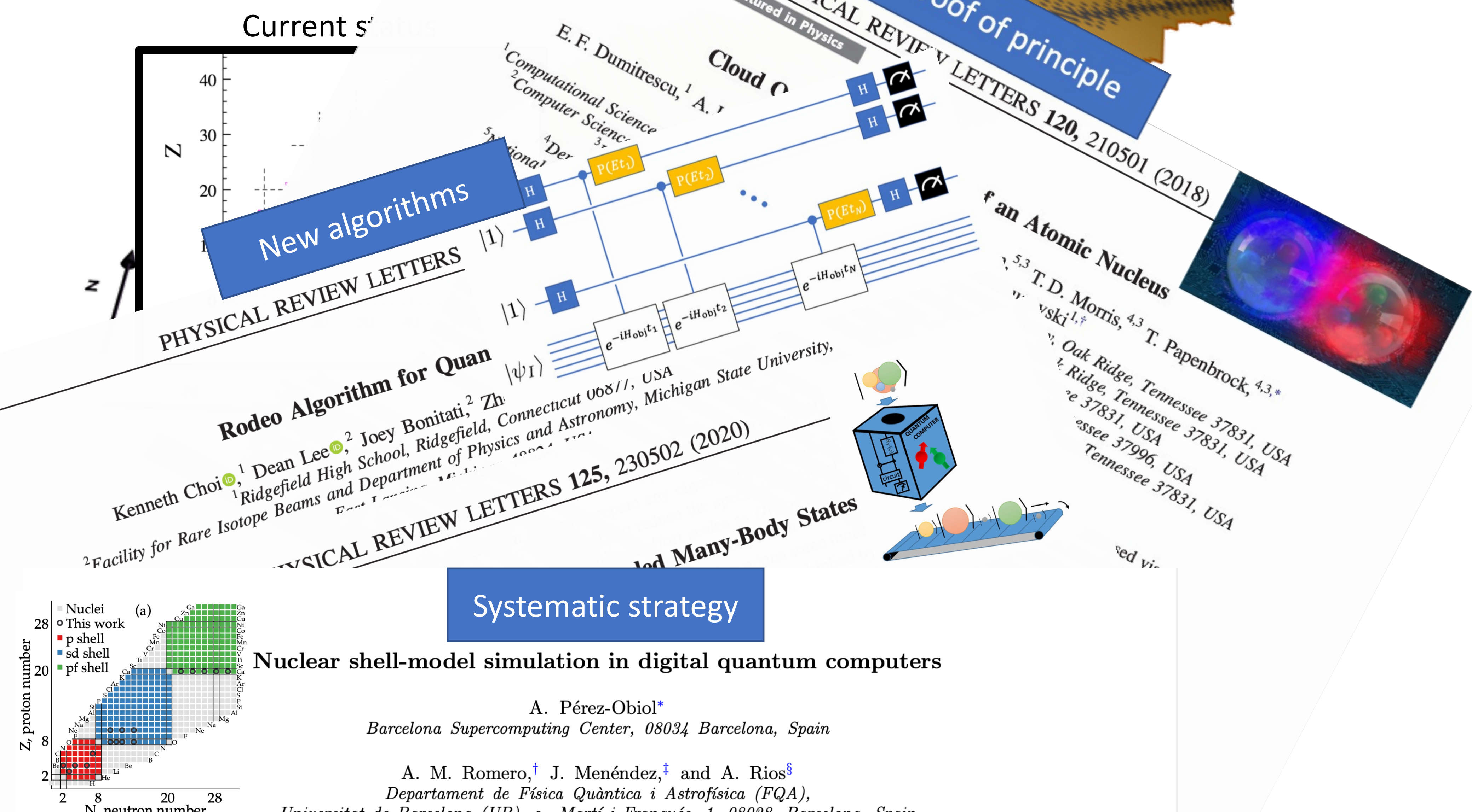
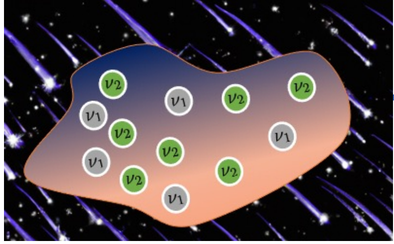
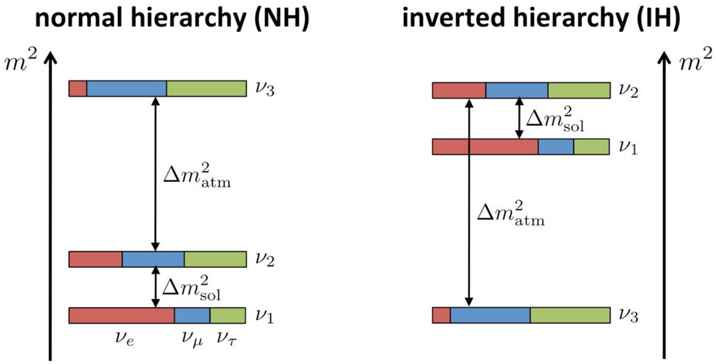
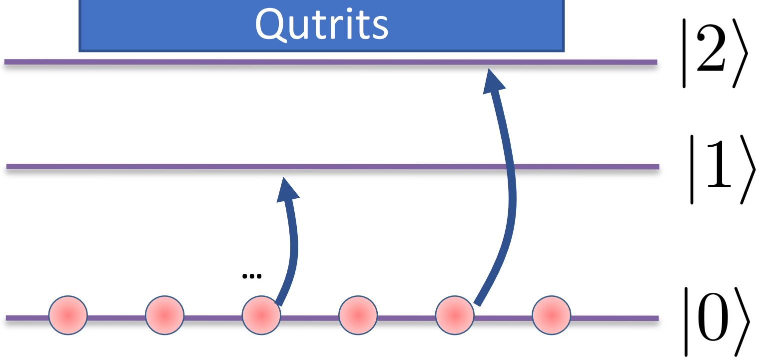




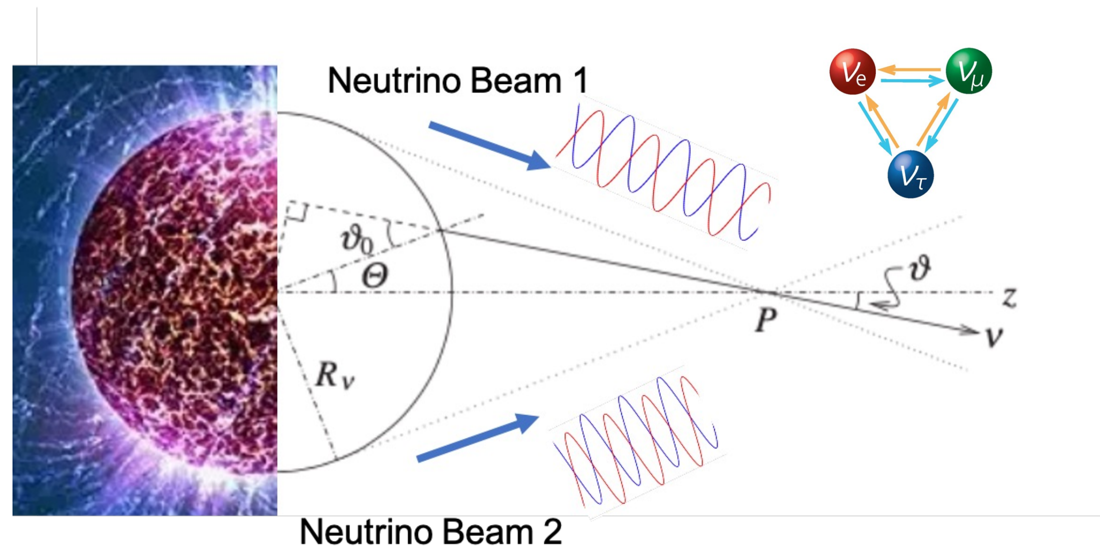


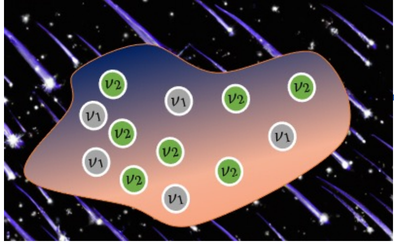
2-flavor approx. directly treated as Qubit

Natural treatment as Qutrits



Neutrino oscillations in beams



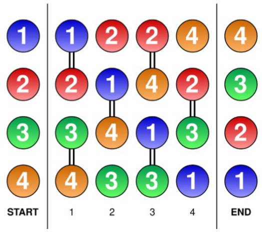


Nowadays: Increasing number of applications

2-flavor approx. directly treated as

- $|1\rangle$
- $|0\rangle$

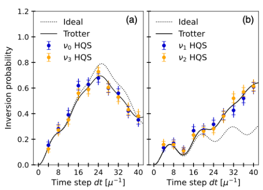
Quantum Information And entanglement



PHYSICAL REVIEW D **104,** 063009 (2021)

Simulation of collective neutrino oscillations on a quantum computer

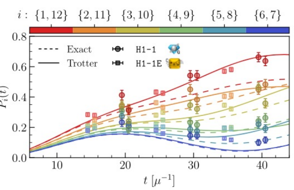
Benjamin Hall,[1] Alessandro Roggero,[2,3] Alessandro Baroni,[4] and Joseph Carlson[4]



PHYSICAL REVIEW D **107,** 023007 (2023)

Trapped-ion quantum simulation of collective neutrino oscillat

Valentina Amitrano,[1,2,*] Alessandro Roggero,[1,2] Piero Luchi,[1,2] Frances
Luca Vespucci,[1,2,3] and Francesco Pederiva[1,2]



PHYSICAL REVIEW LETTERS **130,** 221003

Multi-Neutrino Entanglement and Corr

Marc Illa* and Martin
InQubator for Quantum Simulation (IQuS), Department of Physics, U

(Received 7 December 2022; revised 27 April 2023; acce

The time evolution of multi-neutrino entanglement and corre
neutrino oscillations, relevant for dense neutrino environments, bu
simulations performed of systems with up to 12 neutrinos using Q
quantum computer are used to compute n-tangles, and two- and th
mean-field descriptions. n-tangle rescalings are found to converge
presence of genuine multi-neutrino entanglement.

DOI: 10.1103/PhysRevLett.130.221003

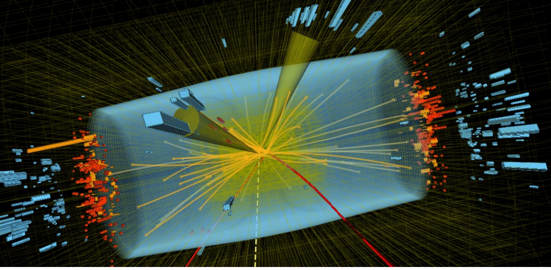
Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

Quantum information and quantum simulation of neutrino physics

A. B. Balantekin[a,1], Michael J. Cervia[b,2,3], Amol V. Patwardhan[c,4], Ermal Rrapaj[d,5,6,7],
Pooja Siwach[e,1]

[1] University of Wisconsin, 1150 University Ave, Madison, WI 53706
[2] George Washington University, 725 21st St NW, Washington, DC 20052
[3] University of Maryland, College Park, MD, USA 20742
[4] SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025
[5] ERSC, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
iTHEMS, Wako, Saitama 351-0198, Japan
California, Berkeley, CA 94720-7300

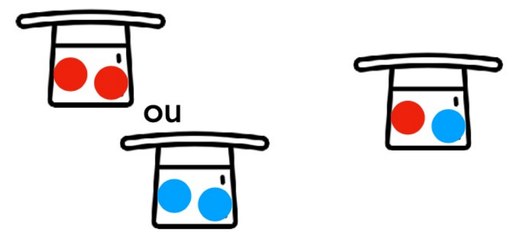
1 Neutrinos in extreme astrophysical environ



Quantum Machine Learning and event classification

Some quantum historical algorithms are very fast for pattern recognition.

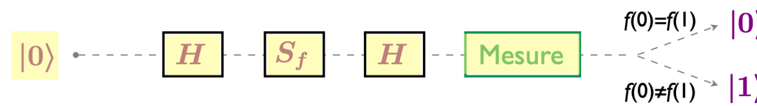
Deutsch (1985), Simon (1994), …

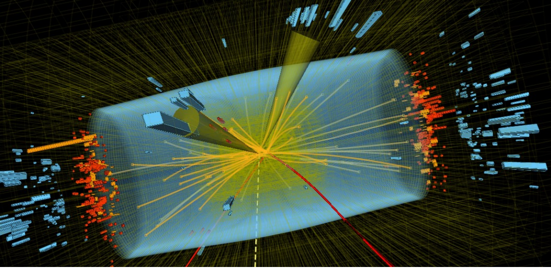


The "simple" Deutsch problem: $f : \{0,1\} \rightarrow \{0,1\}$ (Oracle)

Q: determine if $f(0)=f(1)$

- Classically requires to have 2 answers $f(0)$? $f(1)$?
- Quantum: one can directly ask $f(0)=f(1)$





Some quantum historical algorithms are very fast for pattern recognition.

994), …

1 } (Oracle)

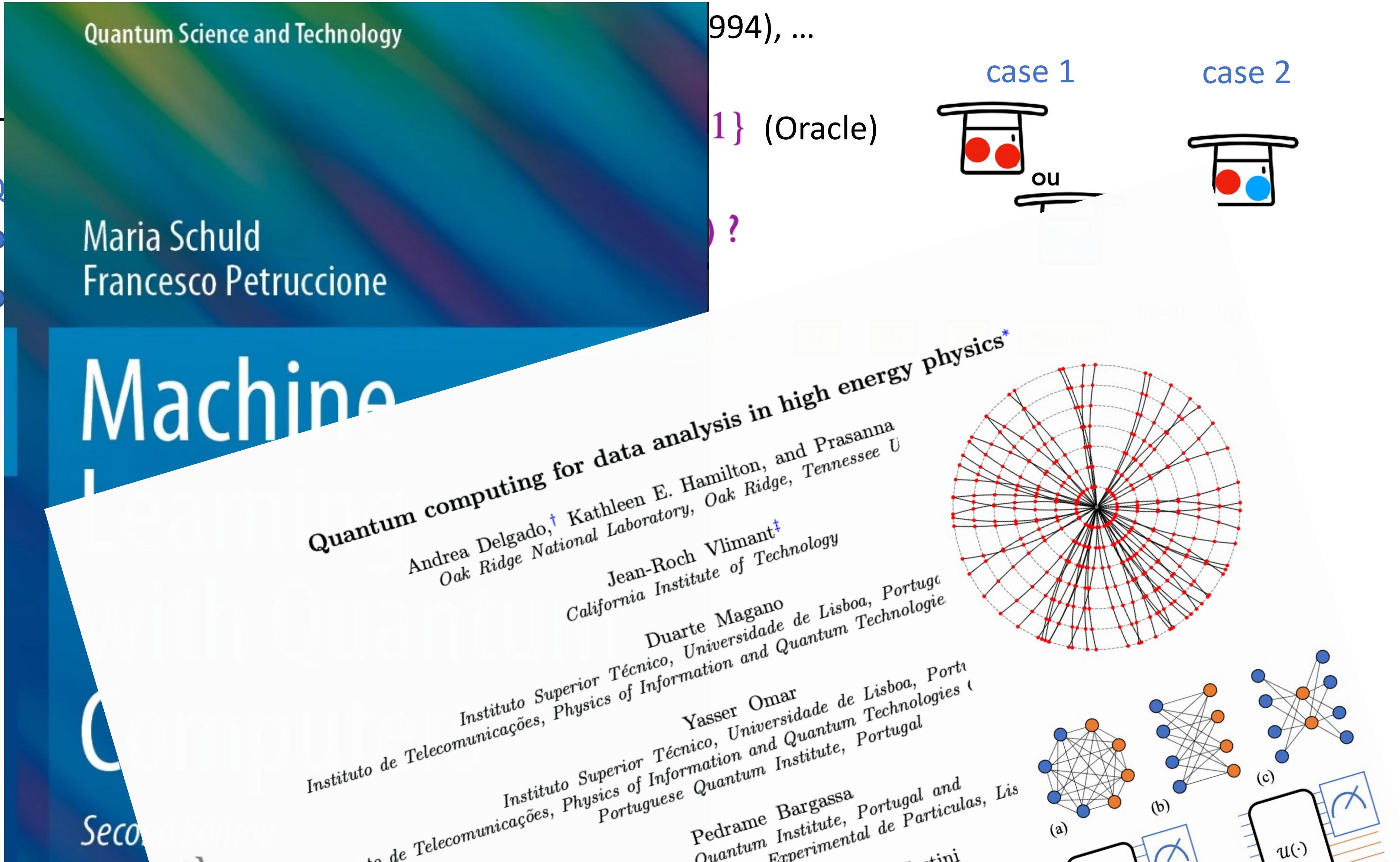
) ?

Q

case 1

case 2

ou



Quantum computing for data analysis in high energy physics*

Andrea Delgado,† Kathleen E. Hamilton, and Prasanna
Oak Ridge National Laboratory, Oak Ridge, Tennessee U

Jean-Roch Vlimant‡
California Institute of Technology

Duarte Magano
Instituto Superior Técnico, Universidade de Lisboa, Portug
Instituto de Telecomunicações, Physics of Information and Quantum Technologie

Yasser Omar
Instituto Superior Técnico, Universidade de Lisboa, Port
Instituto de Telecomunicações, Physics of Information and Quantum Technologies
Portuguese Quantum Institute, Portugal

Pedrame Bargassa
Quantum Institute, Portugal and
Experimental de Partículas, Lis

Some current initiatives

Some recent examples of initiatives in Europe for promoting quantum computing

Increasing the number of workshops/Lectures in Schools/Event

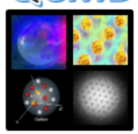
International Conference on Quantum Technologies for High-Energy Physics (QT4HEP22)

CERN | QUANTUM TECHNOLOGY INITIATIVE

1–4 nov. 2022
CERN
Fuseau horaire Europe/Zurich
There is a live webcast for this event.

Entrer le texte à rechercher

QCMB



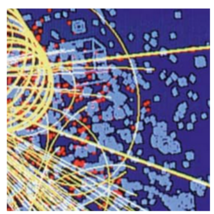
Quantum Computing for Many-Body problems (QCMB): atomic nuclei, neutrinos, and other strongly correlated Fermi systems

22–24 nov. 2022 Fuseau horaire Europe/Paris

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS



05 June 2023 — 09 June 2023

NUCLEAR AND PARTICLE PHYSICS ON A QUANTUM COMPUTER: WHERE DO WE STAND NOW?

It is now a great time for the community to share the recent progress in this emerging field and establish a coherent vision of the outstanding questions to be addressed in the near future in order to fully capitalize on the rapid growth in quantum computing platforms.

QSG

02 May 2023 — 05 May 2023

QUANTUM SCIENCE GENERATION | QSG

Quantum science and technology are playing an ever growing role in contemporary scientific developments in a wide range of areas, from physics (where they originated) to computer science and engineering. One of their specificity is the interdisciplinarity nature, which calls for researchers with a wide expertise. This requires a specific training and, in particular, the ability of crossing traditional boundaries between disciplines.

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

Topical issue on:
"Quantum computing in low-energy nuclear theory"

Guests Editors:
Thomas Ayral, Thomas Duguet, Denis Lacroix, Vittorio Somà

Tentative Date - November 2022

Table of contents (tentative)

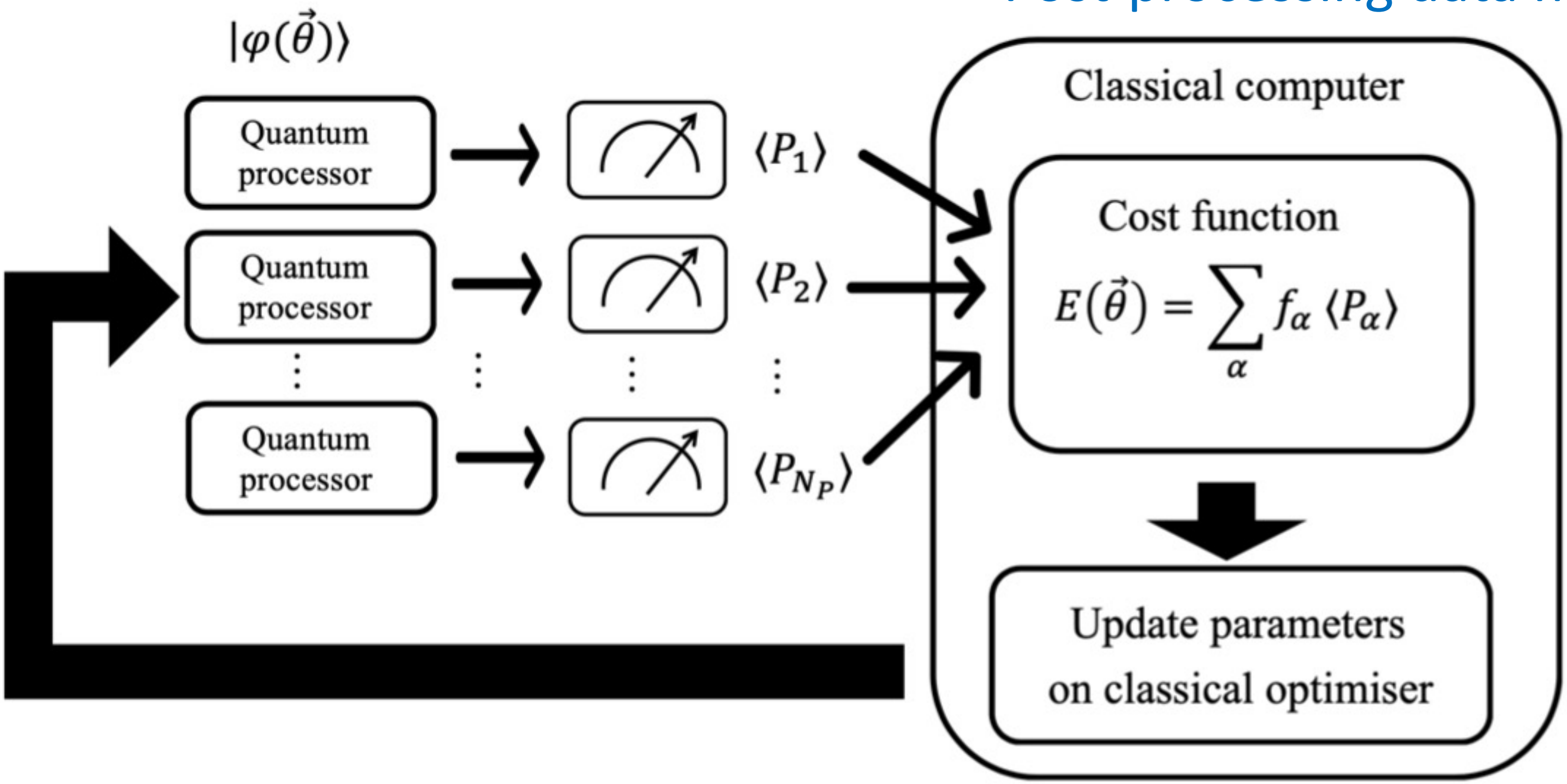
The community working on quantum computers is growing up and starts to organize around this emerging activity.

Hybrid Quantum-Classical High-Performance Computing

HPC on classical devices

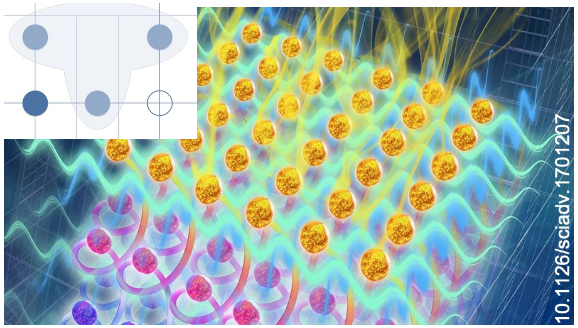
Parallel Quantum Computing →

- Large data flow
- Error correction
- Post-processing data mining



Summary

Lattice gauge theories



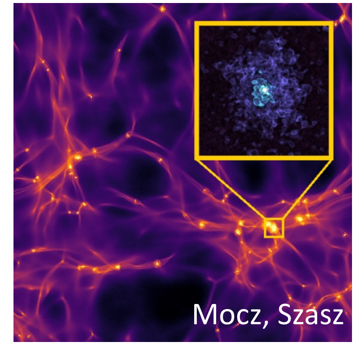
Zohar, Kolck, Savage, …

N-body problem

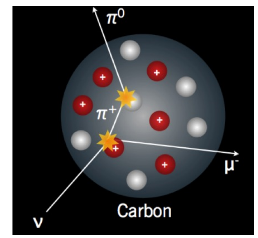
N-body nuclear systems

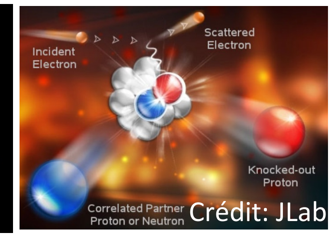
Dumitrescu, Hagen, Carlson, Papenbrock…

Dark matter



Dynamics: e, ν scattering





Roggero, Carlson, …

E. Zohar, J. I. Cirac, B. Reznik, Phys. Rev. Lett. **110**, 125304 (2013)
E. Zohar, J. I. Cirac, B. Reznik, Phys. Rev. A **88** 023617 (2013)
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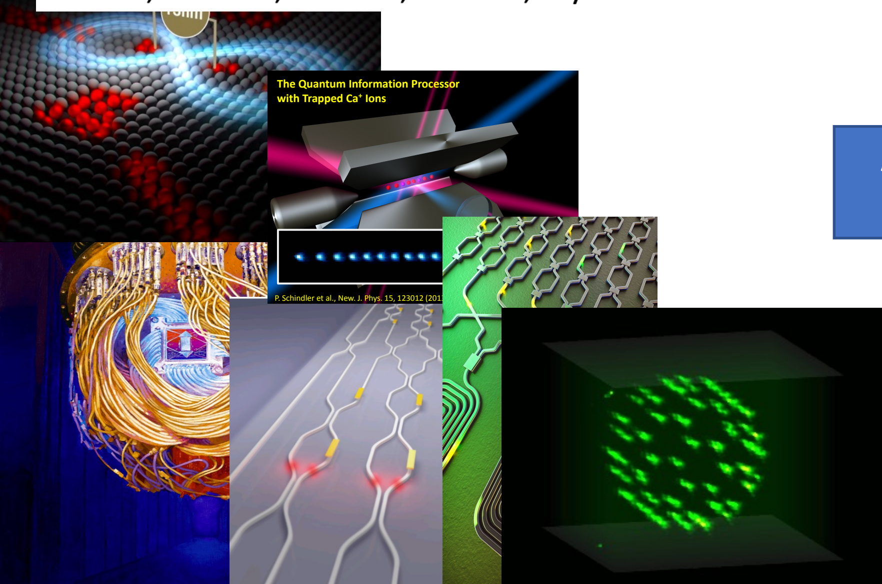
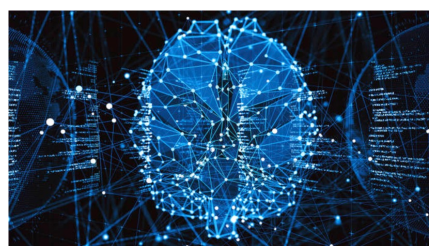
D. González Cuadra, **E. Zohar**, J. I. Cirac, New J. Phys. **19** 063038 (2017)

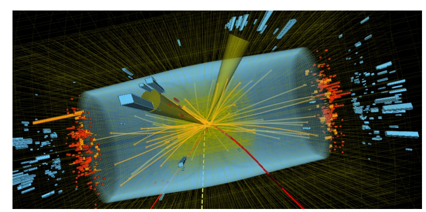
E. Zohar, A. Farace, B. Reznik, J. I. Cirac, Phys. Rev. Lett. 118 070501 (2017)



Applications to data mining (event classification)



CMS-detector



Thank you!