# quantum computing energetics, from NISQ to FTQC

**alexia auffèves**
Director of CNRS MajuLab, Singapore,
QEI cofounder
alexia.auffeves@cnrs.fr

**olivier ezratty**
consultant and author,
QEI cofounder
olivier@oezratty.net

**théau péronnin**
CEO and cofounder of Alice&Bob
theau.peronnin@alice-bob.com

**EDF, Palaiseau, January 11th, 2023**

**QEI proposed methodology**

FTQC perspective

NISQ perspective

# QC energetic costs is an open question!

RESEARCH-ARTICLE

## Energy Cost of Quantum Circuit Optimisation: Predicting That Optimising Shor's Algorithm Circuit Uses 1 GWh

**energy hog?**

**Authors:** Alexandru Paler, Robert Basmadjian Authors Info & Claims

ACM Transactions on Quantum Computing, Volume 3, Issue 1 • March 2022 • Article No.: 3, pp

https://dl.acm.org/doi/10.1145/3490172

**or energy saver?**

## Is quantum computing green? An estimate for an energy-efficiency quantum advantage

Daniel Jaschke[1,2,3] and Simone Montangero[1,2,3]

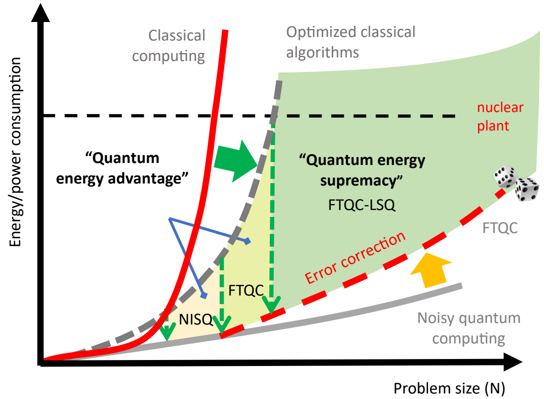
[1]*Institute for Complex Quantum Systems, Ulm University, Albert-Einstein-Allee 11, 89069 Ulm, Germany*
[2]*Dipartimento di Fisica e Astronomia "G. Galilei" & Padua Quantum Technologies Research Center, Università degli Studi di Padova, Italy I-35131, Padova, Italy*
[3]*INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*

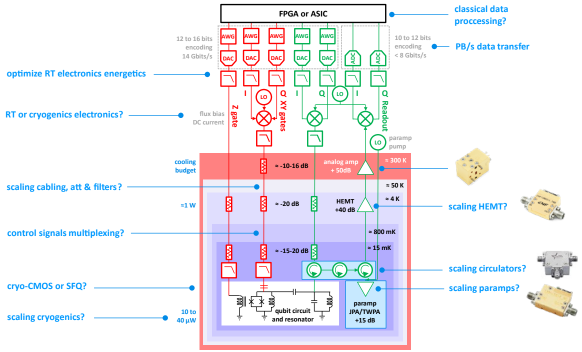
(Dated: May 25, 2022)

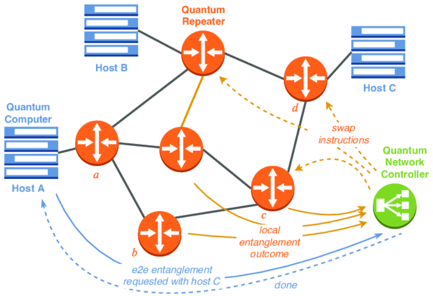
https://arxiv.org/abs/2205.12092

# #QEI key scientific questions

the quantum energy initiative




is there a **quantum energy advantage** vs classical computing as quantum processors scale up?

how different is it from the **quantum computational advantage**?

what is the fundamental **minimal energetic cost** of quantum computing?

how to **avoid energetic dead-ends** on the road to LSQ?

will **other quantum technologies** present energetic challenges?

quantum communications and sensors

# Quantum Energy Initiative vision paper

PRX QUANTUM

*a Physical Review journal*

Highlights Recent Accepted Authors Referees Search About Scope Staff

Perspective Open Access

## Quantum Technologies Need a Quantum Energy Initiative

Alexia Auffèves

PRX Quantum **3**, 020101 – Published 1 June 2022

Article | References | No Citing Articles | PDF | HTML | Export Citation


### ABSTRACT

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

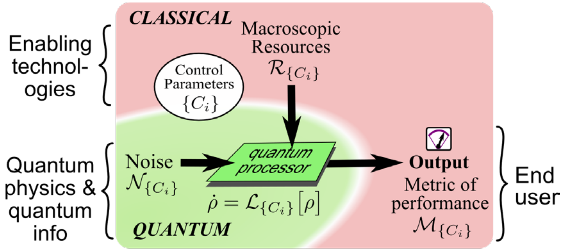

https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.3.020101

# #QEI goals & missions

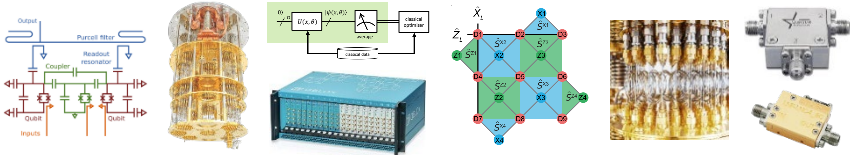
**the quantum energy initiative**

create a **worldwide community** working on quantum technologies energetics associating fundamental research and industry vendors.

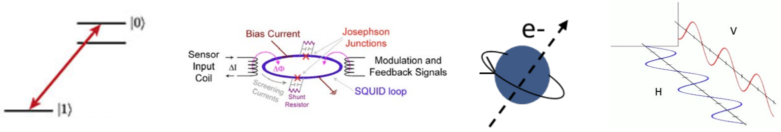
(a) Metric-Noise-Resource (MNR) methodology for the full-stack of a quantum computer




propose **optimization methodologies, frameworks** and **benchmarks** for quantum technologies, enabling technologies and software engineering



create a new **transversal line of research** and **collaborative projects**.

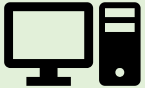



cover **all qubit types**, **programming paradigms**, and other quantum technologies (communications, sensing)

# Generic definition of resource efficiency

## Machine efficiency

$$\boldsymbol{\eta = \frac{M}{R}}$$



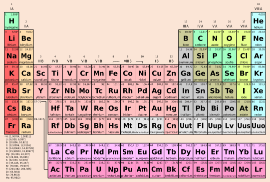
e.g. $\eta = \frac{FLOPs}{W}$ $\quad \eta = \frac{km}{l}$

Target result: operations, distance, etc.

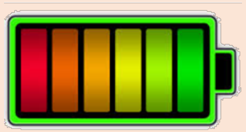
## Performance metric

## Physical resource cost

Materials



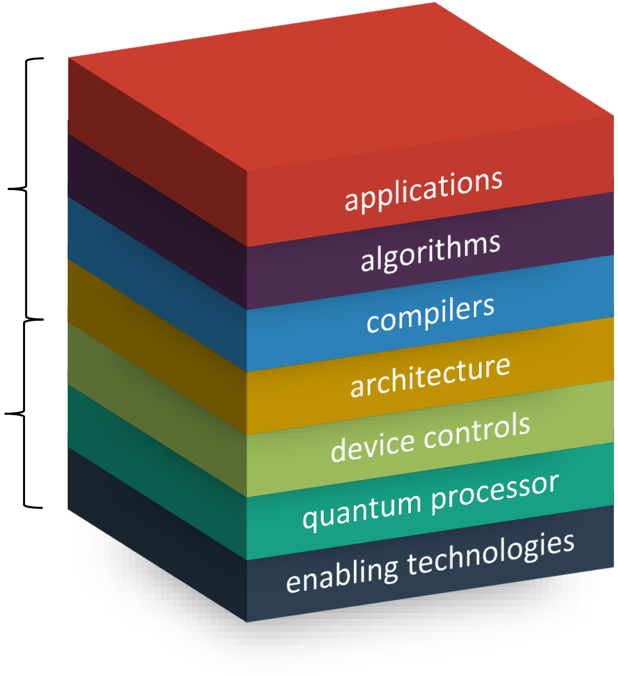
Energy or power

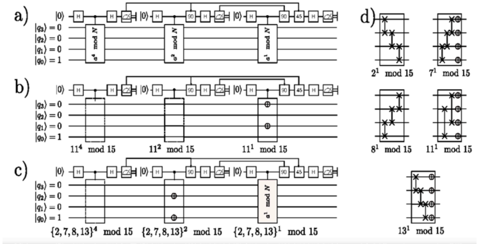


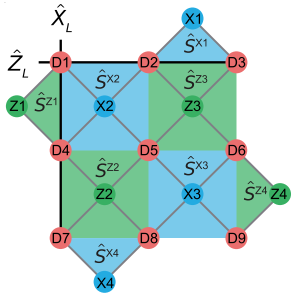
# A full-stack quantum computer

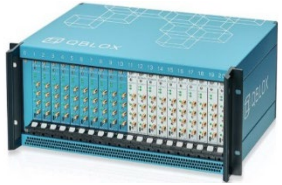
Hardware agnostic

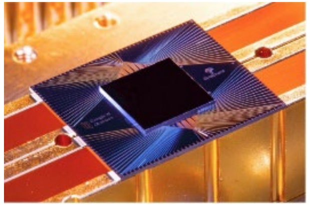
Hardware dependent



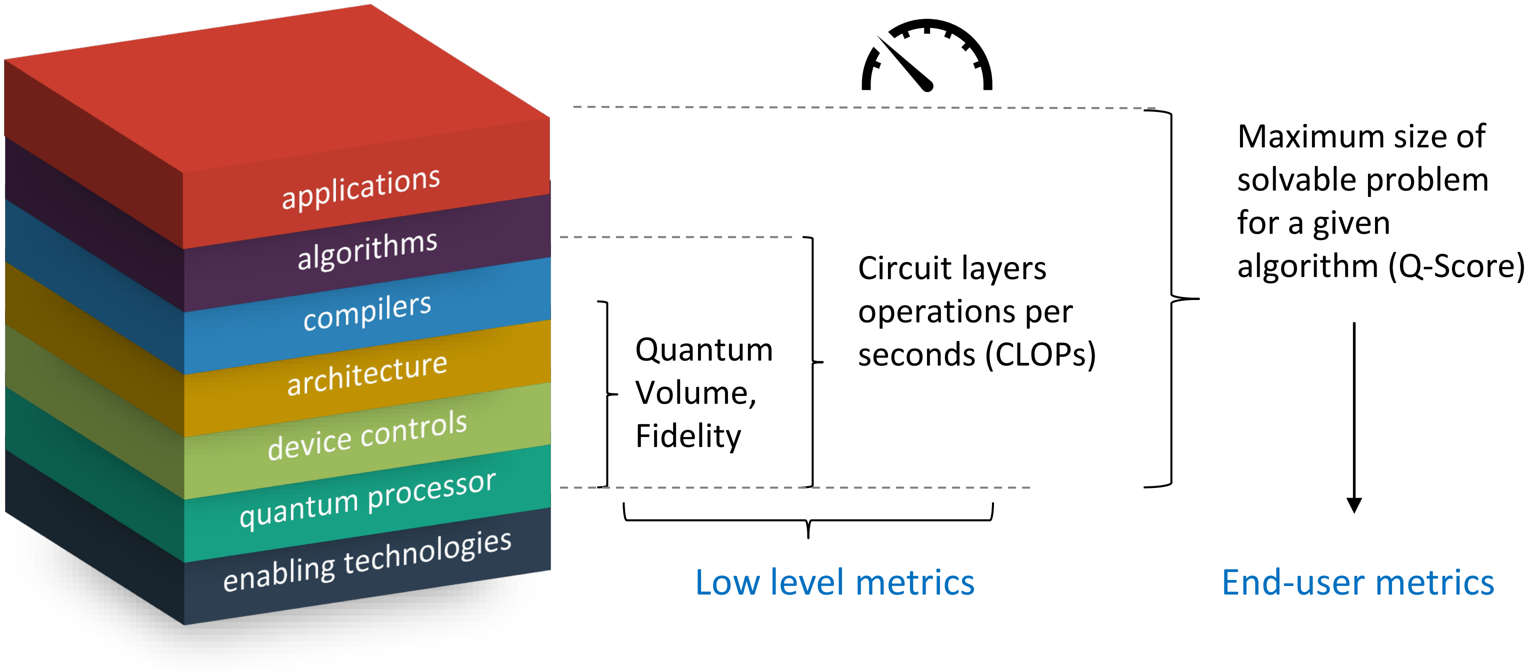



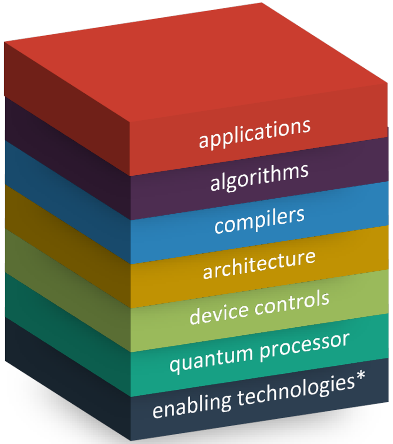
# Metrics of performance

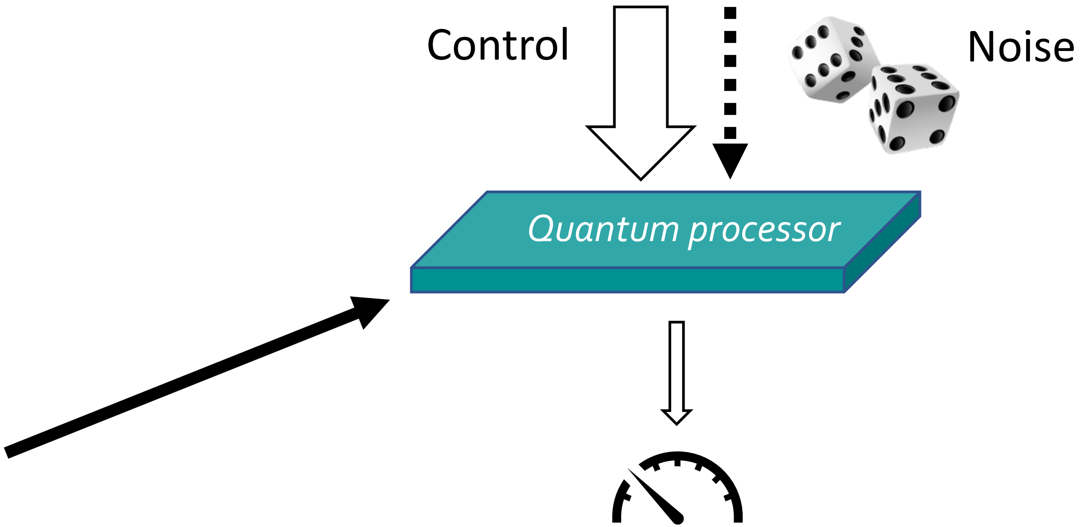
- Intense work nowadays to define metrics of performances & standards
- Performances can be defined at low level or at end-user level (w.r. to applications)



# Metrics of performance

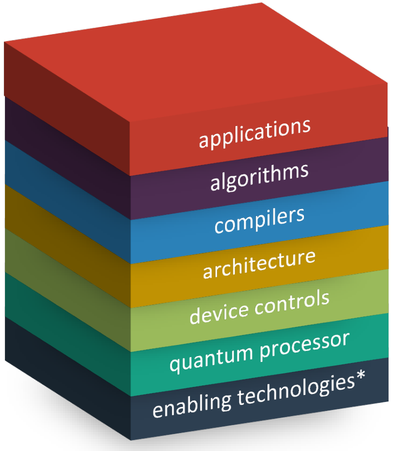
- ➢ All metrics depend on the level of control reached over the noisy processor
- ➢ Fight [control: noise] @**quantum level of the stack**



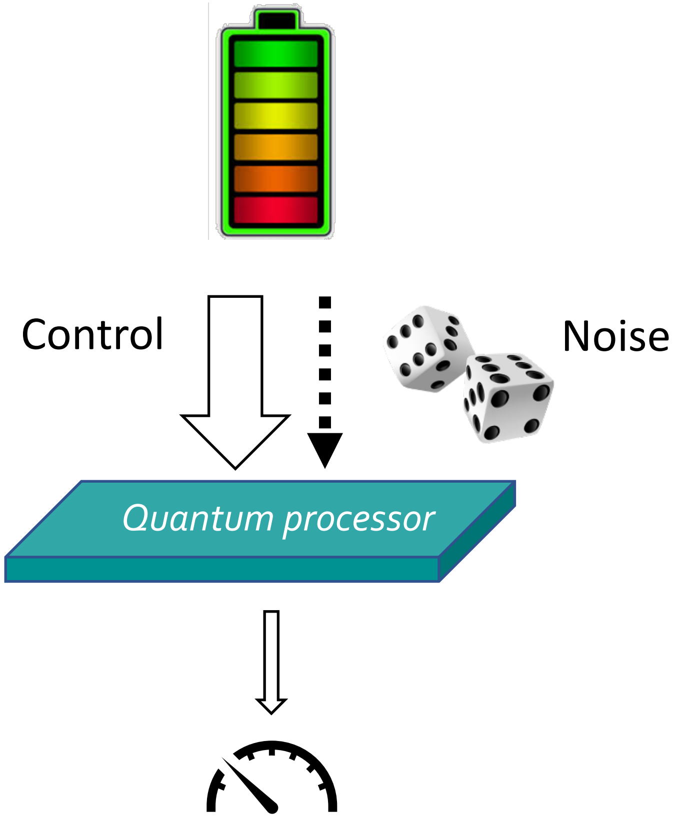
# Resource costs

- ➢ Good performances mandate resources **@ each level of the stack**
- ➢ Hybrid efficiencies $\eta = \frac{M}{R}$




- **@Quantum level:** fundamental bounds
- Involve quantum control, reservoir engineering...

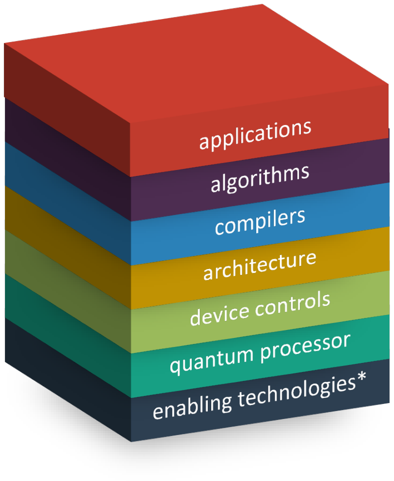
➢ *Must connect to hardware-agnostic levels*

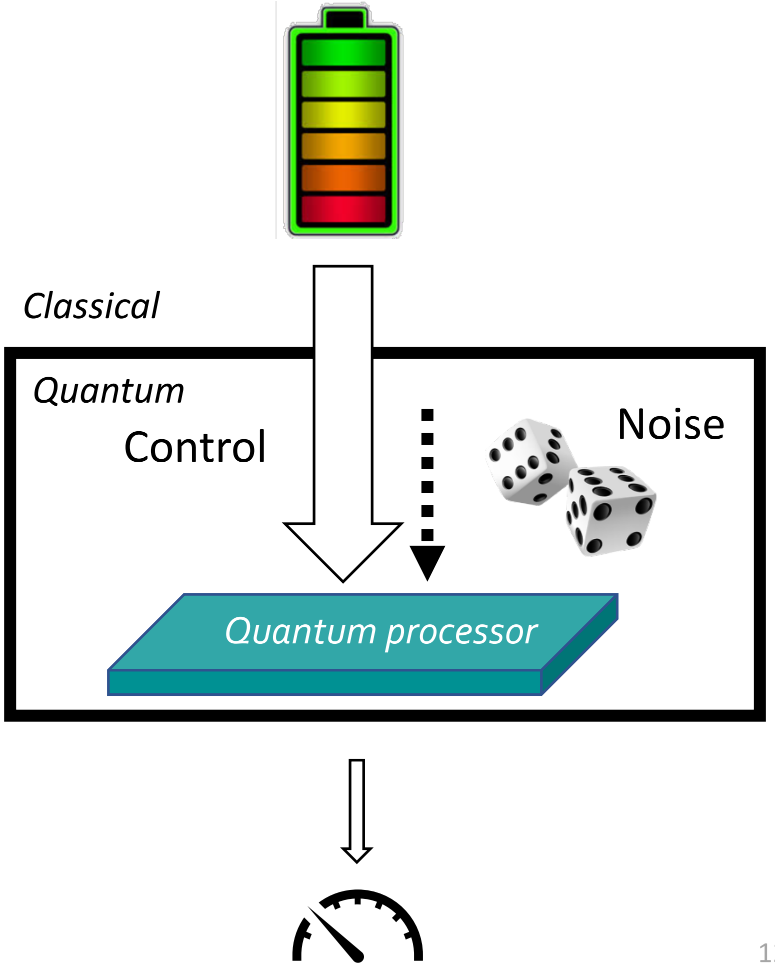


# Resource costs

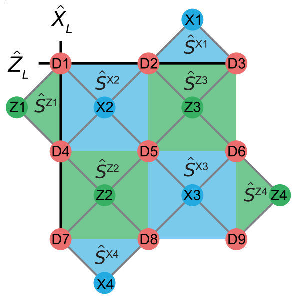
**@All hardware-dependent levels:**

- Cost of trapping and controlling a Schrödinger cat
- Macroscopic resources spent by enabling tech and control chains
- *Must connect quantum and macroscopic levels*



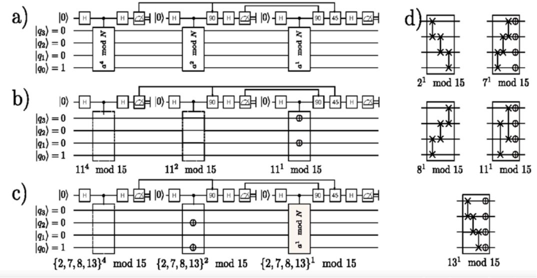



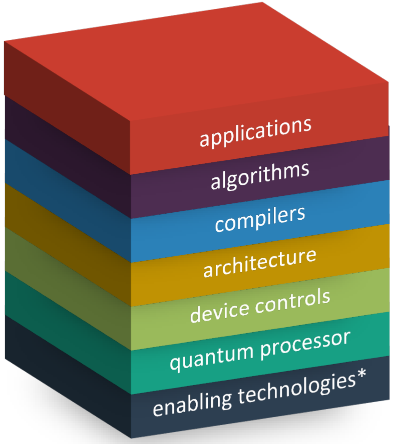
# Resource costs




**@hardware-agnostic levels:**

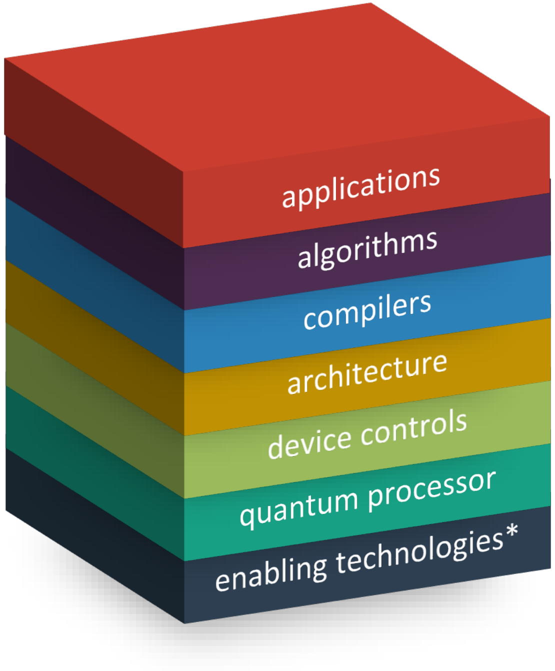
- Number of logical operations and qubits...
- Number of physical qubits per logical qubit, code connectivity, complexity of encoding/decoding operations...



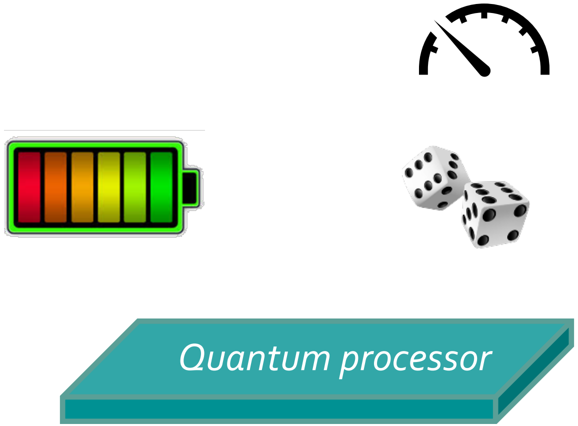




- ➢ Currently: architecture optimizations for fixed hardware noise properties
- ➢ *But the noise depends on the circuit architecture*
- ➢ *Must connect to hardware-dependent levels*

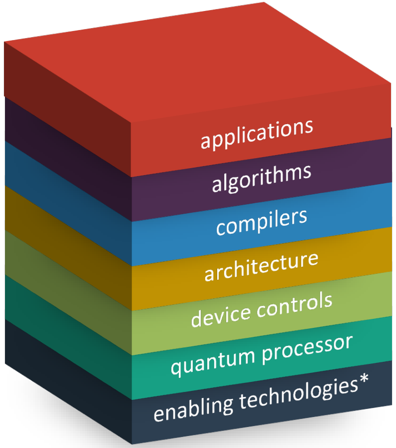
# Need for a holistic approach




- Must connect inputs from all levels of the stack to optimize quantum computing energy efficiencies
- Need for common language and methodology



# Metric-Noise-Resource (MNR) methodology




- Specify the control parameters $\{C_i\}$ and the metric of performance $M$
- Model the processor dynamics $\dot{\rho} = L_{\{C_i\}}[\rho]$ => get the metric $M(\{C_i\})$
- Model the resource cost $R(\{C_i\})$

- Set a target metric $M(\{C_i\}) = M_0$ => Implicit relation on $\{C_i\}$
- Minimize the resource cost $R(\{C_i\})$ under the constraint $M = M_0$
- Maximize the resource efficiency $\eta(M_0) = \frac{M_0}{R_{min}(M_0)}$

# #QEI first partners

the quantum energy initiative

**research**

- PCQT – Paris Centre for Quantum Technologies
- Quantum Information Center – ALLIANCE SORBONNE UNIVERSITÉ
- MajuLab
- CQT – Centre for Quantum Technologies – National University of Singapore
- WACQT – Wallenberg Centre for Quantum Technology

**industry**

- parityqc
- aQuantum® Software Engineering
- Atos
- IQM
- QILIMANJARO QUANTUM TECH
- PASQAL
- siquance
- ALICE & BOB
- C12 Quantum
- QUANDELA
- ATEM CUSTOMIZED CONNECTIVITY
- Radiall™
- Viqthor

**HPC service providers**

- FRANCE HYBRID HPCQUANTUM INITIATIVE
- CSC

**industry associations**

- llq

**#QEI** the quantum energy initiative

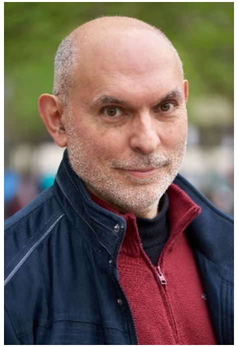
# proposed structure and overview

| | | | |
|---|---|---|---|
| community buildup | **QEI board creation** | **QEI video series** | **QEI workshops** |
| | **more QEI partners** | **QEI research inventory** | **coordinate collaborative projects RFPs responses** |
| creating collaborative research | **Quantum physics**<br>**Quantum thermodynamics** | **Quantum information** (algorithms, compilers, software engineering, error correction) | **Qubit types**<br>**Quantum matter** |
| | **Quantum computing** | **Quantum communications** | **Quantum sensing** |
| | **Enabling technologies** (cryogeny, electronics, cabling, …) | | |
| standardization | **Quantum energetics standardization**<br>CENELEC, IEEE, ISO, national standards bodies | **Benchmarks**<br>QG500 | |

#QEI
the quantum energy initiative

# contacts

contact@quantum-energy-initiative.org



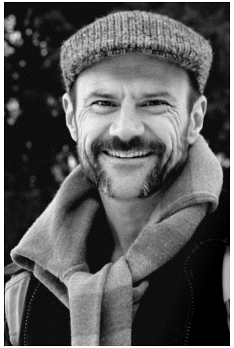

**Olivier Ezratty**
Quantum Technologies
Consultant and Author
olivier@oezratty.net



**Alexia Auffèves**
CNRS Research Director
MajuLab, Singapore
alexia.auffeves@neel.cnrs.fr



**Janine Splettstoesser**
Professor
Chalmers University
janines@chalmers.se


**Robert Whitney**
Researcher
CNRS LPMMC Grenoble
robert.whitney@lpmmc.cnrs.fr

QEI proposed methodology

**FTQC perspective**

NISQ perspective

Optimizing resource efficiencies for scalable full-stack quantum computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3] Yvain Thonnart,[4] Hui Khoon Ng,[5,3,6,†] Robert S. Whitney,[7,‡] and Alexia Auffèves[2,6,§]

[1] *Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*
[2] *Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*
[3] *Centre for Quantum Technologies, National University of Singapore, Singapore*
[4] *Université Grenoble Alpes, CEA-LIST, F-38000 Grenoble, France*
[5] *Yale-NUS College, Singapore*
[6] *MajuLab, International Joint Research Unit UMI 3654, CNRS, Université Côte d'Azur, Sorbonne Université, National University of Singapore, Nanyang Technological University, Singapore*
[7] *Université Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France.*

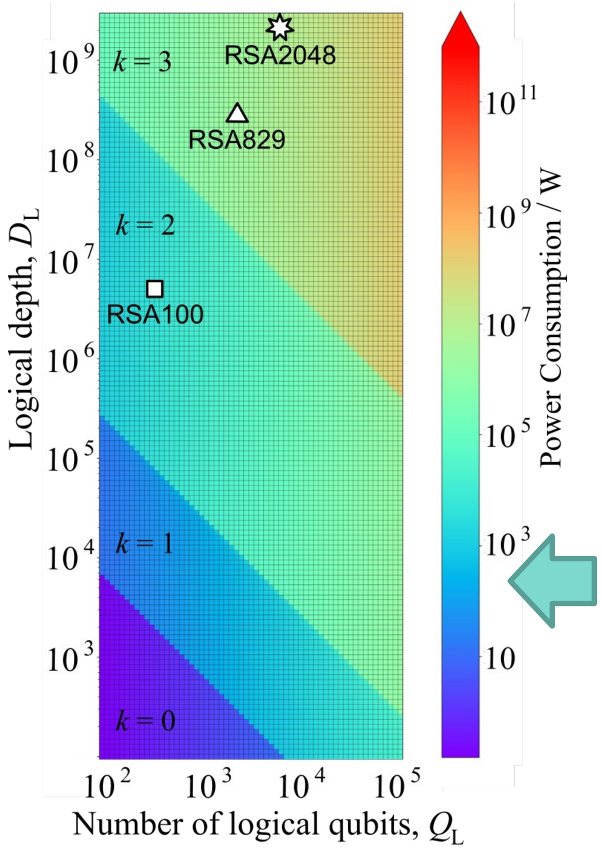
https://arxiv.org/abs/2209.05469

## early findings applying the MNR methodology in a particular example

1. **energy advantage** may show up before **computing advantage**.
2. x10 qubit fidelities => **x100 energy savings**.
3. **quantum error correction codes** impact energetic footprint.
4. in FTQC, **control electronics** consumes more energy than cryogeny.
5. significant progress needed in control electronics (room temperature, cryo-electronics, cabling, multiplexing).

**it's only a beginning, with many outstanding challenges in all quantum technologies**

# Minimizing full stack power consumption




**Methodology**

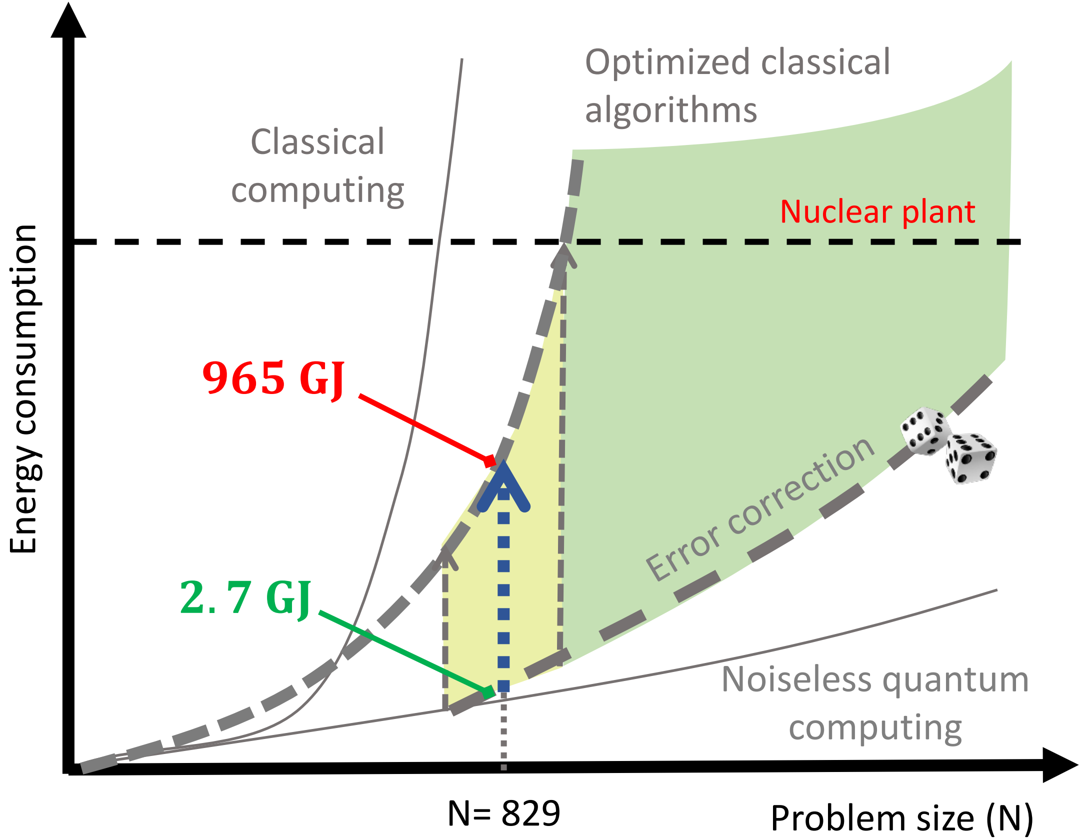
- ✓ Pick a generic circuit $Q_L * D_L$
- ✓ Set $P_{success} = 2/3$
  $\Rightarrow$ Implicit relation between $(A, T_{gen}, T_{qb}, k)$
- ✓ Minimize $P_{FT}$ as a function of $(A, T_{gen}, T_{qb}, k)$

$P_{FT}(Q_L, D_L)$

- ✓ $1/\gamma = 50$ ms (top quality qubits)
- ✓ CMOS electronics

- ➢ Model useful algorithms with our generic circuit
- ➢ RSA-n with $Q_L(n)$ and $D_L(n)$ from Gidney&Ekera, Quantum 5, 433 (2021)

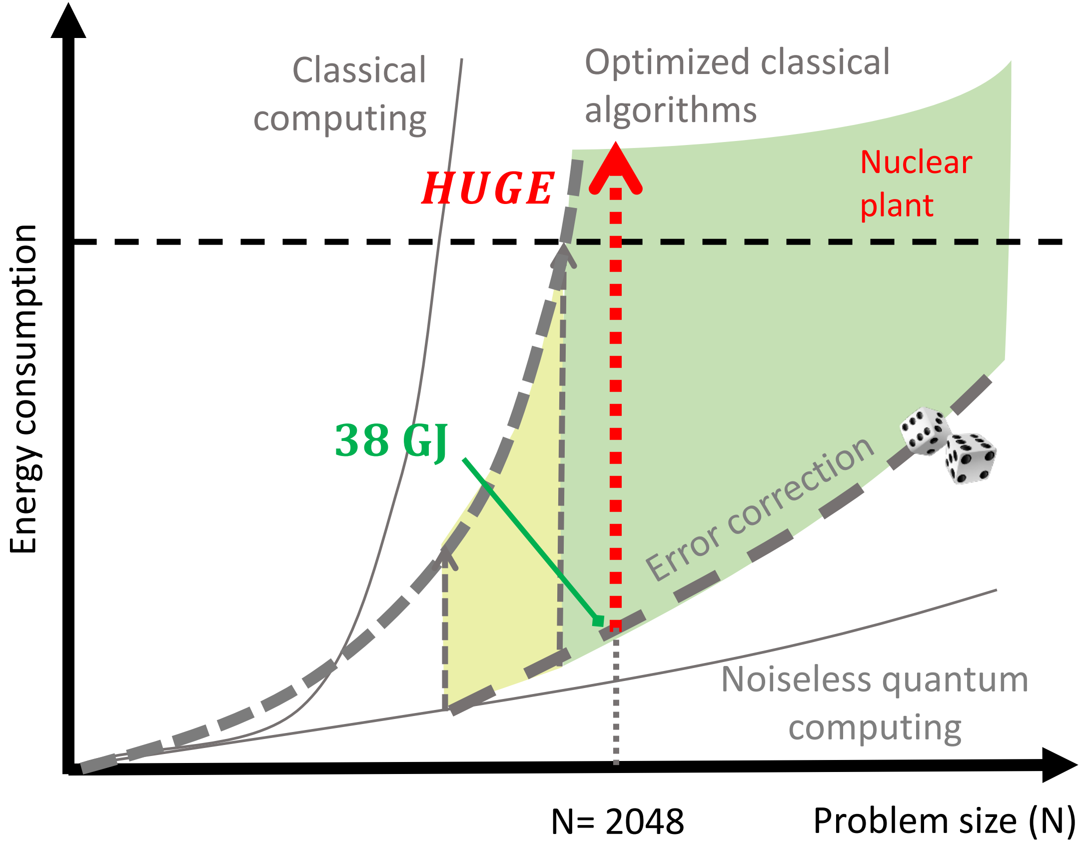
# First estimates on quantum energy advantage




**Breaking RSA-829 key**

- Classical supercomputer (Inria 2021): 965 GJ ≈ 1.3MW in 8.6 days
- Quantum computer with top quality qubits + Steane code
  2.7GJ = 2.9 MW in 16 min

# First estimates on quantum energy advantage



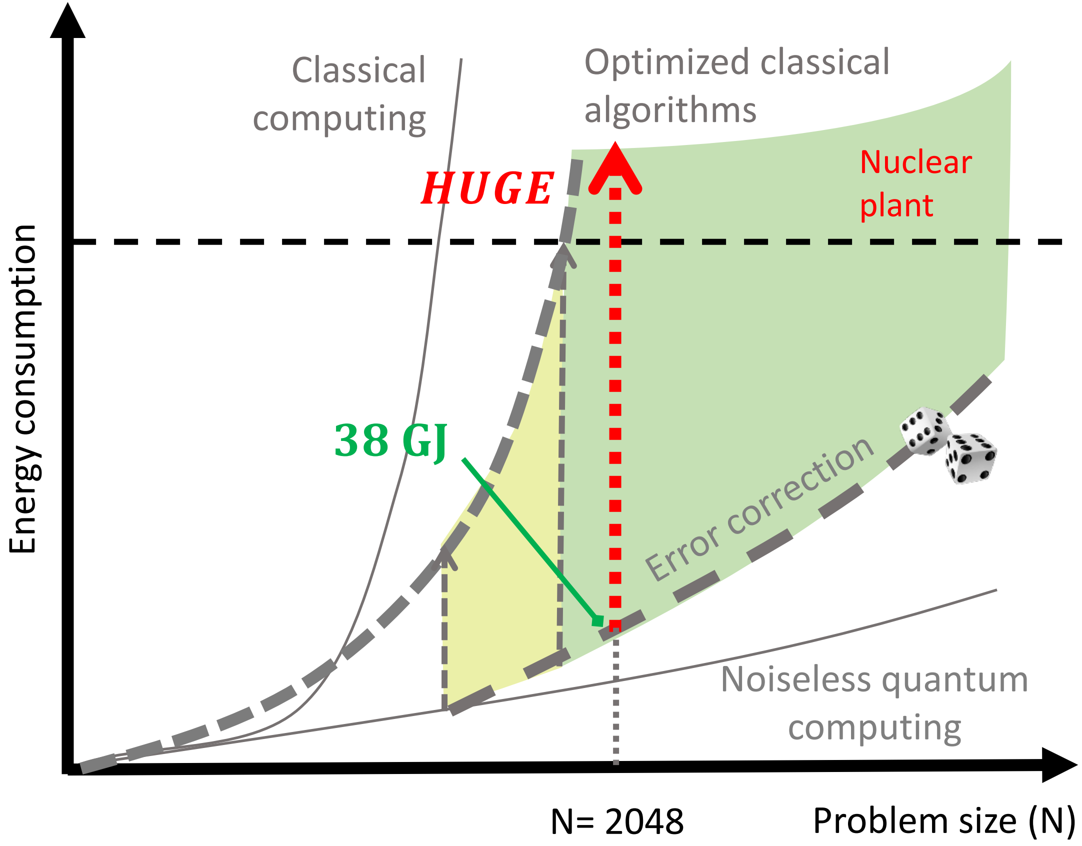

**Breaking RSA 829 key**

- Classical supercomputer
  965 GJ ≈ 1.3MW in 8.6 days
- Quantum computer with top quality qubits (2000 better than Sycamore) + Steane code
  2.7GJ = 2.9 MW in 16 min

**Breaking RSA 2048 key**

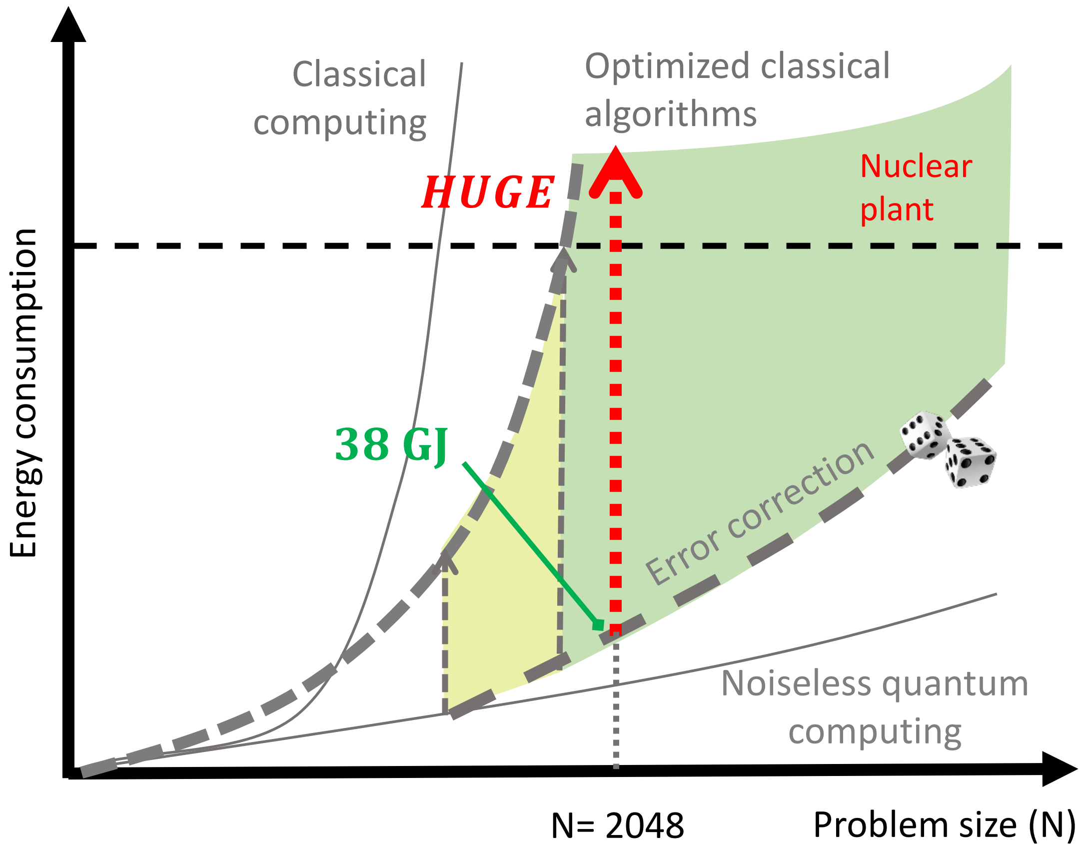
- Classical supercomputer
  TOO MUCH
- Quantum computer (Steane code)
  38 GJ = 7 MW in 1.5 hours

# First estimates on quantum energy advantage




- Potential for a quantum energy advantage, but
  - ✓ to consolidate on more realistic qubits/architectures/ full-stack energy costs
  - ✓ in a coordinated way

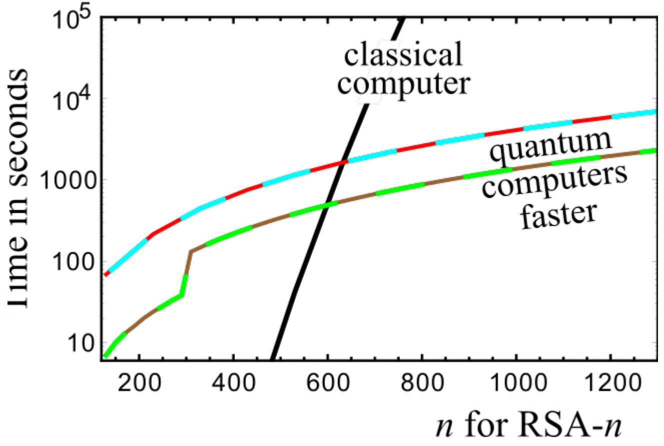
# Energy vs computational advantage




- FAQ: « But isn't that enough to optimize the computational advantage? Lowering the computing time will automatically lower the energy cost! »
- Relation between quantum energy advantage and quantum computational advantage?

# Energy vs computational advantage

Estimated computing time (s)

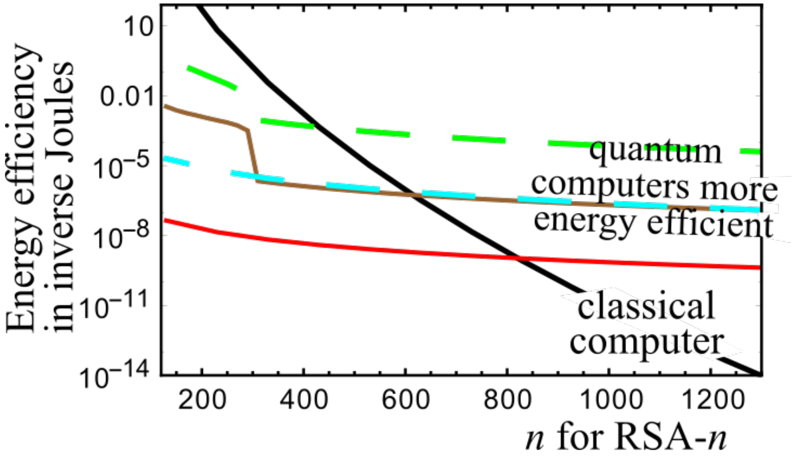



- ✓ red: $1/\gamma = 5$ ms, CMOS control electronics
- ✓ cyan: $1/\gamma = 5$ ms, SFQ control electronics
- ✓ braun: $1/\gamma = 50$ ms, CMOS control electronics
- ✓ green: $1/\gamma = 50$ ms, SFQ control electronics

# Energy vs computational advantage

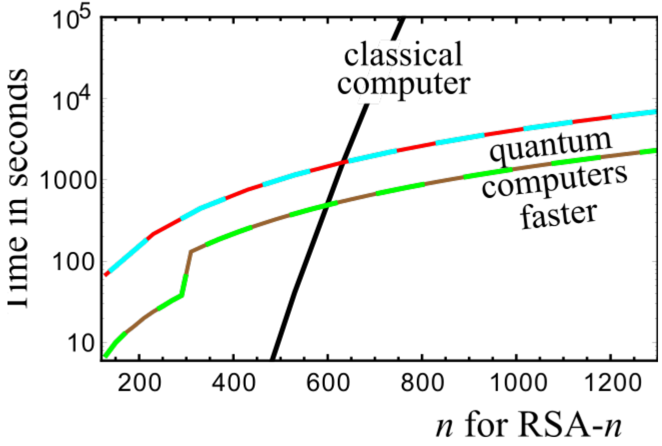
- ✓ red: $1/\gamma = 5$ ms, CMOS control electronics
- ✓ cyan: $1/\gamma = 5$ ms, SFQ control electronics
- ✓ braun: $1/\gamma = 50$ ms, CMOS control electronics
- ✓ green: $1/\gamma = 50$ ms, SFQ control electronics

Efficiency = key size/energy (/J)

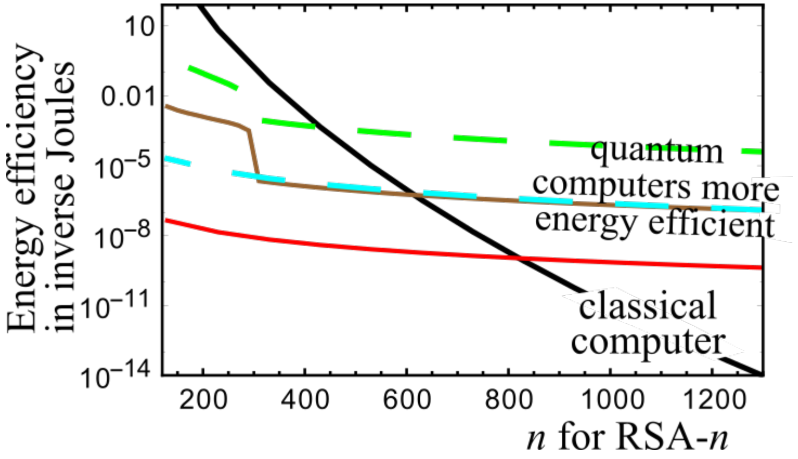


# Energy vs computational advantage

Estimated computing time (s)




Efficiency = key size/energy (/J)




- Energy advantage (power*time) $\neq$ Computational advantage (time) : a practical advantage of different nature!
- One may save energy before saving time...

# Take home messages

- **Quantum energy advantage** = a huge practical interest of quantum computing
  - Different from the quantum computational advantage
  - To explore and optimize now
  - Need to articulate different levels of description in an interdisciplinary research line **#QEI**
- **New benchmark**: Quantum computing energy efficiency $\eta = M/R$
  - New tool for optimizations software/hardware; fundamental/full stack
  - Qubits benchmarking
  - Towards a « Q-Green 500 »

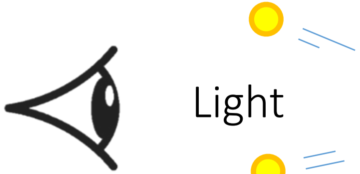
ALICE & BOB

November 2022

Confidential

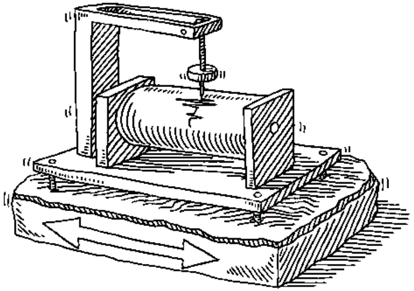
# PROVIDE EXPONENTIAL QUANTUM COMPUTING POWER ACROSS INDUSTRIES

# Why are quantum computers faulty ?



Light

Sound



Vibrations

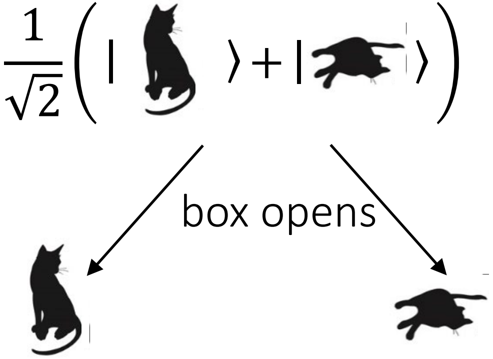
By ADA and Neagoe

Information on the cat

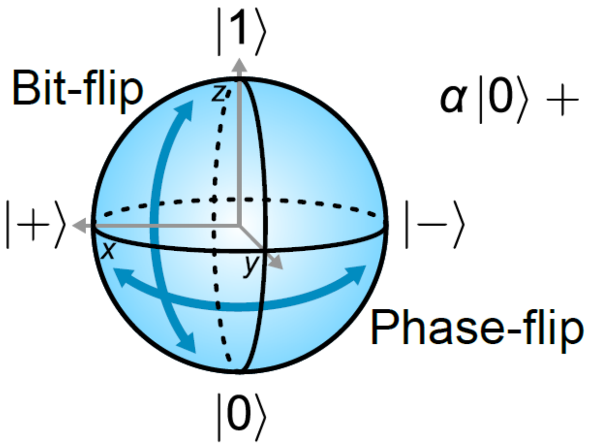
Alive  $0$

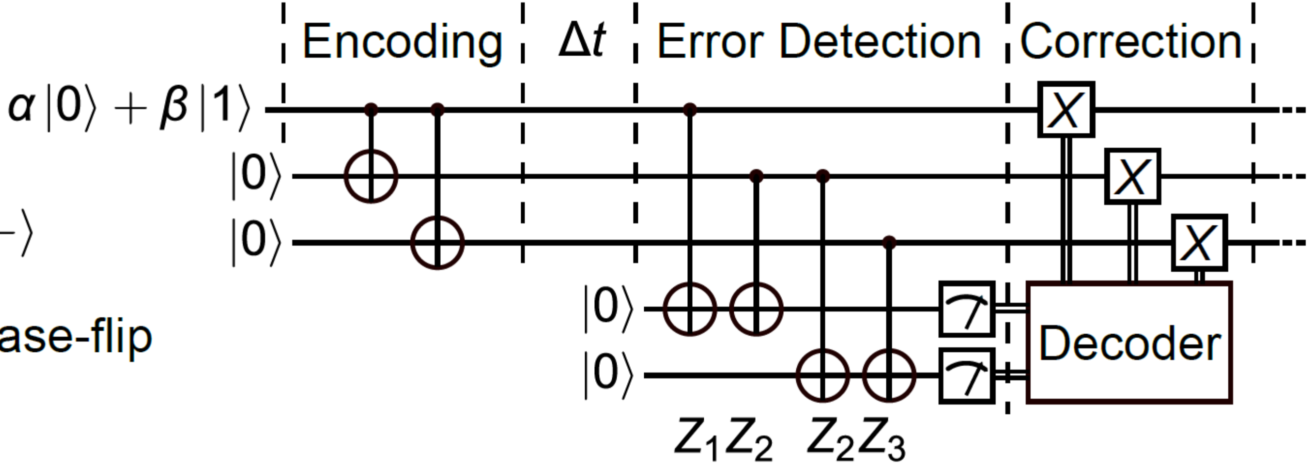
Dead  $1$

Quantum superposition

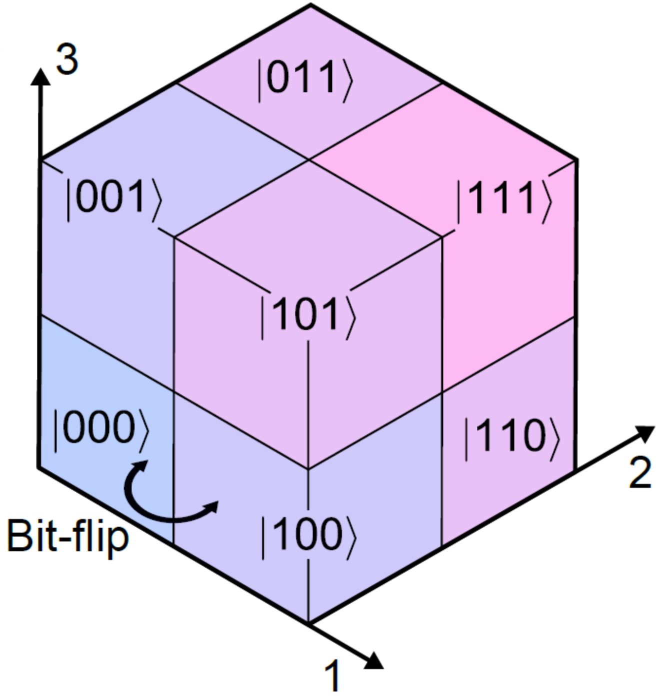


# Bit-flip correction circuit



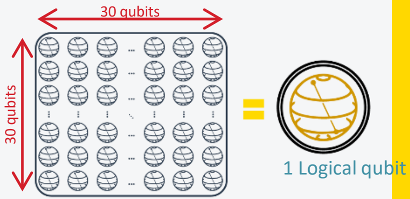
# Bit-flip protection




We need a big Hilbert space to protect against errors

# QUANTITATIVE APPROACH TO REDUCE ERRORS

**30 physical qubits to correct each type of error**




DEFINITION

**Logical qubit**

Qubit able to store quantum information with sufficiently low error probability

**Universal qubit**

Logical qubit able to perform any type of operation

## Universal Quantum Computer would require 1,000,000+ physical qubits

1,000 Physical qubits → 30 x 30 → Bit-flips correction / Phase-flips correction → 1 Logical qubit

100,000 Physical qubits → 100 Logical qubits → 1 Universal qubit

1,000,000+ Physical qubits → 10+ Universal qubits → 1 Universal Quantum Computer

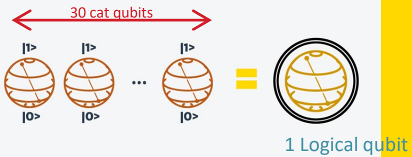
Players following this strategy

Google · IBM · rigetti · IONQ · intel · PsiQuantum

With 128 physical qubits

# A&B'S QUALITATIVE APPROACH

Only 30 cat qubits needed to correct phase-flip errors




## 1,000x fewer physical qubits to build a Universal Quantum Computer

01.

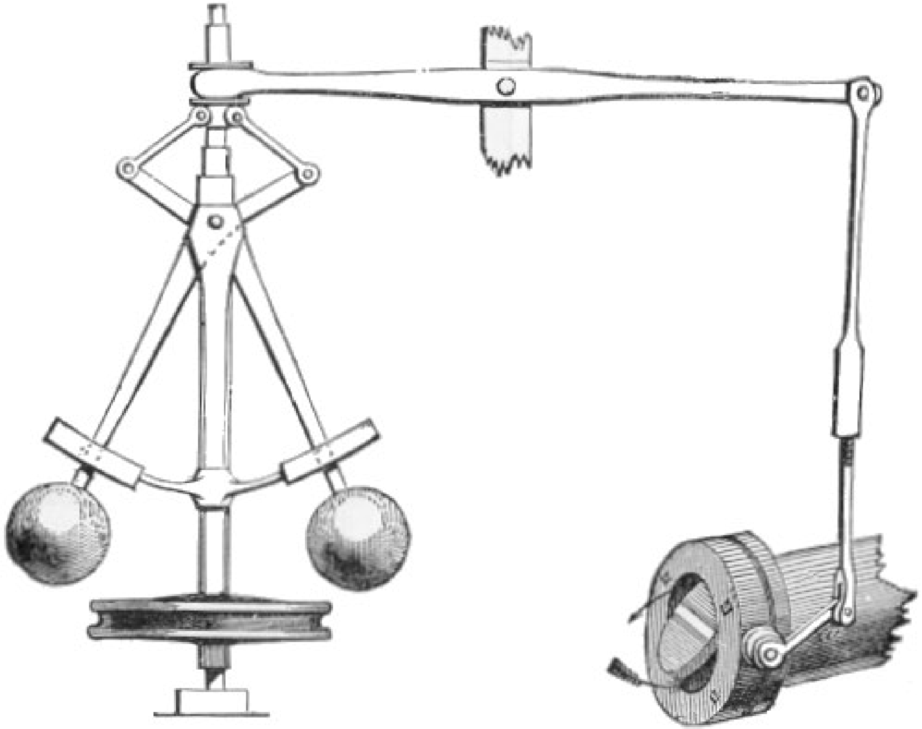
Cat Qubit:
Autonomous error-correction of bit flips by design

02.

Shortcut to universality

| | "QUANTITATIVE" APPROACH: STANDARD QUBITS | | BY DESIGN APPROACH: CAT QUBITS |
|---|---|---|---|
| 1 LOGICAL QUBIT | 1,000 physical qubits | vs / 30 | 30 cat qubits |
| 1 UNIVERSAL QUBIT | 100,000 physical qubits | vs **/ 1,000** | 90 cat qubits |

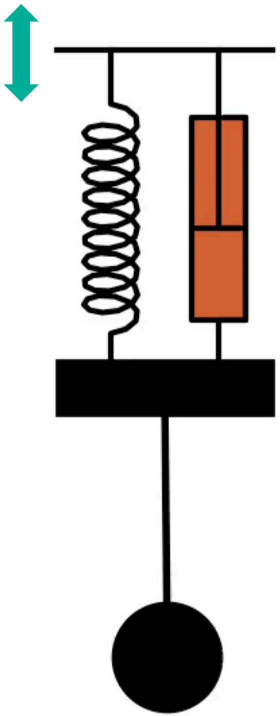
# Autonomous regulation



The Watt regulator autonomously controls the speed of a steam engine

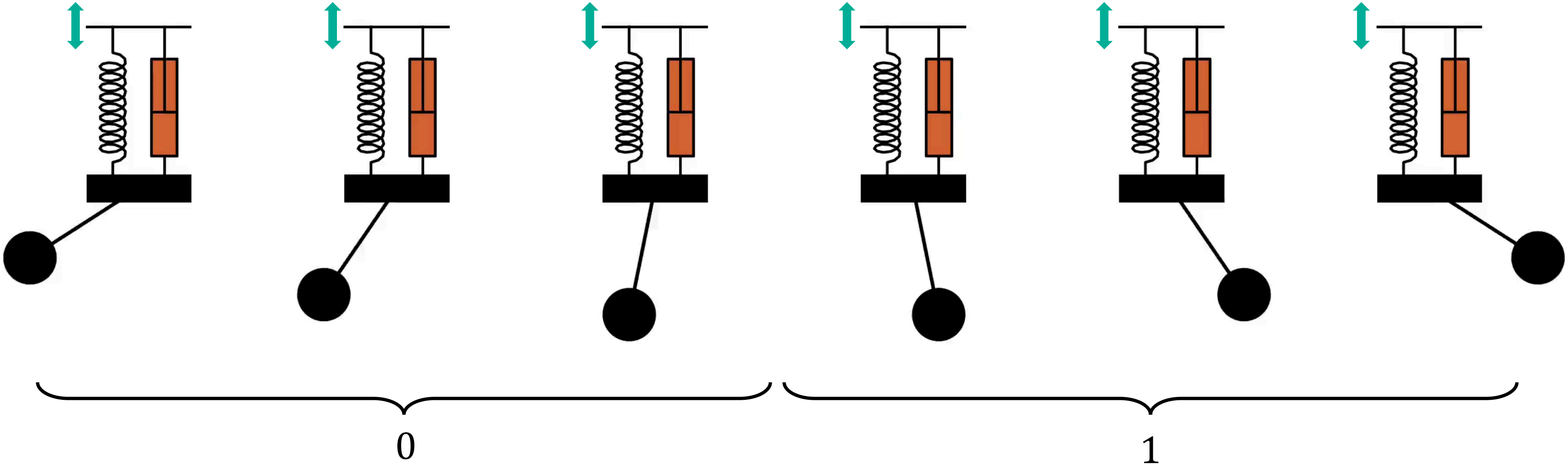
**Can we build a quantum system that self corrects ?**

# Adding dissipation



Dissipation prevents the motion to diverge and **stabilizes** it to a given state.

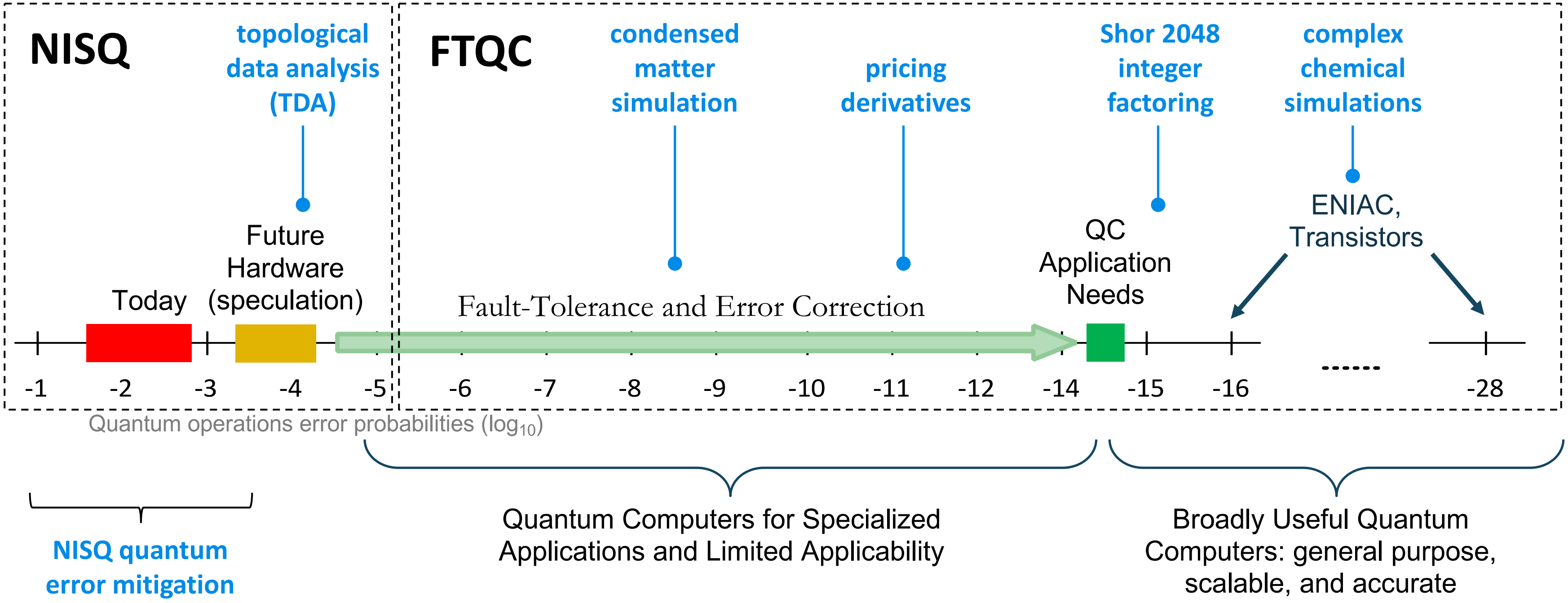
# A bi-stable system




There are **2 steady states** in which we can encode information

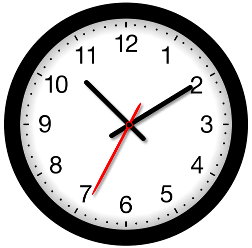
QEI proposed methodology
FTQC perspective
**NISQ perspective**

# from NISQ to FTQC

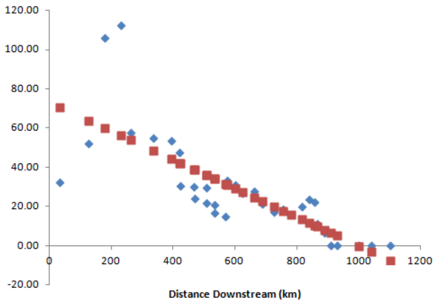



source: How about quantum computing? by Bert de Jong, DoE Berkeley Labs, June 2019 (47 slides) + Olivier Ezratty additions.

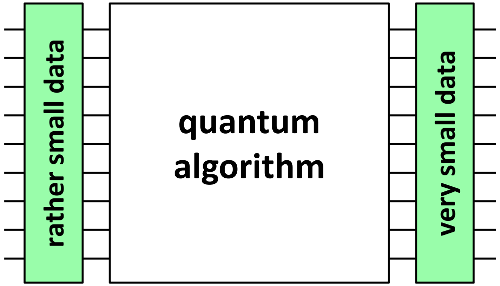
# NISQ figures of merit



what speedup advantage?




what precision advantage?



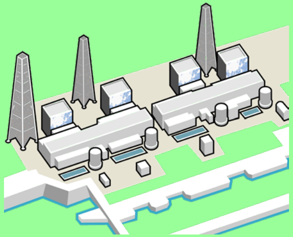

smaller input data?

cost/benefit of quantum error mitigation?

fully-burdened cost with classical+QPU?

analog vs gate-based differences?

which algorithms?



energetic advantage?

total cost?

## Financial Risk Management on a Neutral Atom Quantum Processor

Lucas Leclerc[1,2,*] Luis Ortiz-Gutiérrez[1], Sebastián Grijalva[1], Boris Albrecht[1], Julia R. K. Cline[1], Vincent E. Elfving[1], Adrien Signoles[1], and Loïc Henriet[1†]
[1]*PASQAL, 7 rue Léonard de Vinci, 91300 Massy, France and*
[2]*Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France*

Gianni Del Bimbo[3,*] Usman Ayub Sheikh[3,*] Maitree Shah[4], Luc Andrea[5], Faysal Ishtiaq[3], Andoni Duarte[3], Sam Mugel[4], Irene Cáceres[3], Michel Kurek[5], and Roman Orús[3,6,7]
[3]*Multiverse Computing, Parque Científico y Tecnológico de Gipuzkoa, Paseo de Miramón 170, 20014 San Sebastián, Spain*
[4]*Centre for Social Innovation, 192 Spadina Ave, Suite 509, M5T 2C2 Toronto, Canada*
[5]*WIPSE Paris-Saclay Enterprises 7, rue de la Croix Martre 91120 Palaiseau, France*
[6]*Donostia International Physics Center, Paseo Manuel de Lardizabal 4, E-20018 San Sebastián, Spain and*
[7]*Ikerbasque Foundation for Science, Maria Diaz de Haro 3, E-48013 Bilbao, Spain*

Achraf Seddik[8], Oumaima Hammami[8], Hacene Isselnane[8], and Didier M'tamon[8]
[8]*Crédit Agricole Corporate and Investment Bank, 12 Place des États-Unis, 92545 Montrouge, France*
(Dated: December 7, 2022)

Machine Learning models capable of handling the large datasets collected in the financial world can often become black boxes expensive to run. The quantum computing paradigm suggests new optimization techniques, that combined with classical algorithms, may deliver competitive, faster and more interpretable models. In this work we propose a quantum-enhanced machine learning solution for the prediction of credit rating downgrades, also known as fallen-angels forecasting in the financial risk management field. We implement this solution on a neutral atom Quantum Processing Unit with up to 60 qubits on a real-life dataset. We report competitive performances against the state-of-the-art Random Forest benchmark whilst our model achieves better interpretability and comparable training times. We examine how to improve performance in the near-term validating our ideas with Tensor Networks-based numerical simulations.

https://arxiv.org/abs/2212.03223

CRÉDIT AGRICOLE CORPORATE & INVESTMENT BANK

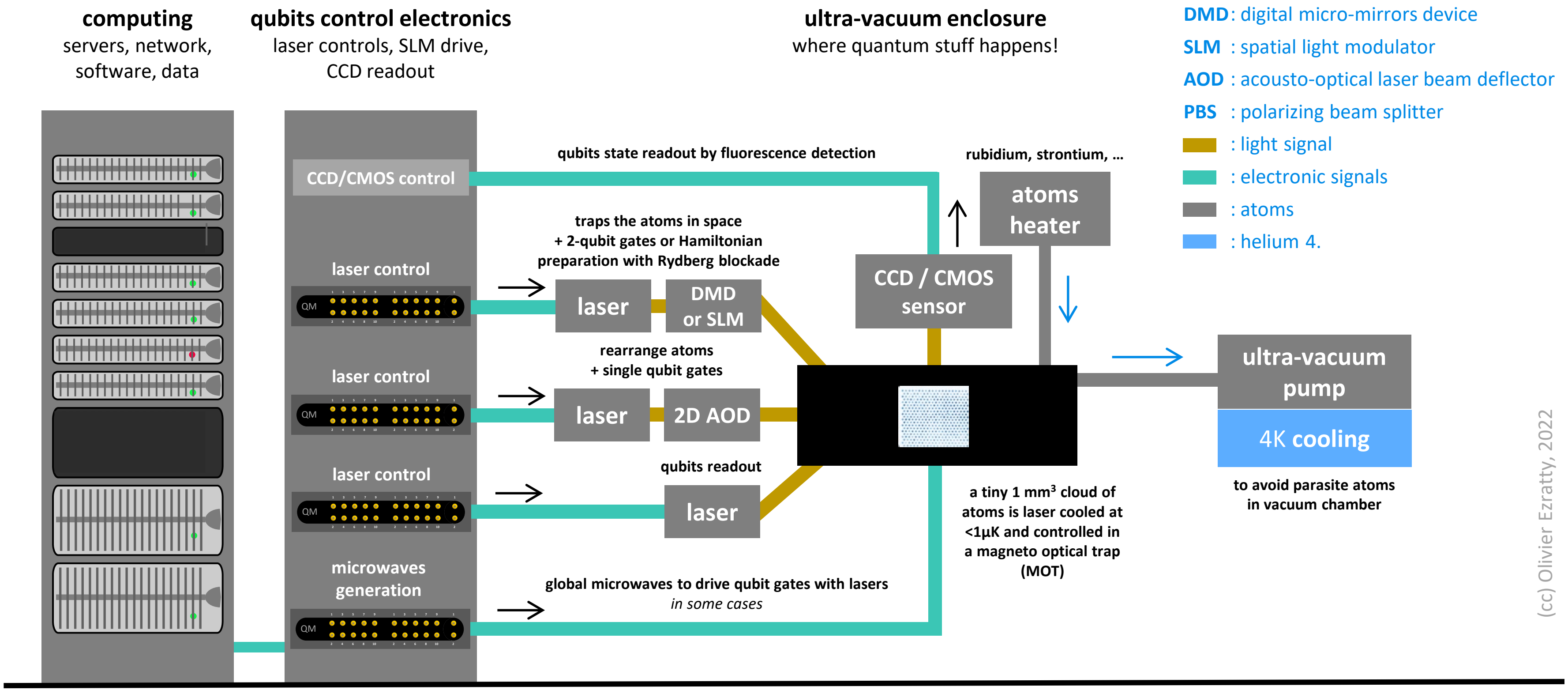
PASQAL MULTIVERSE

**QBoost hybrid algorithm** used to predict « fallen angels », businesses who could fail in loans reimbursements. Quantum algorithm reduced to a QUBO problem.

**data set**: 20 years + 90 000 items with 150 features on 2000 companies in 10 verticals and 100 sub-verticals from 70 countries. 65 000 items in training data and 26 000 items for tests.

**quantum advantage**: could show up with 150 - 342 neutral atoms when compared to a best-in-class classical tensor network, 2800 atoms for the more precise subsampling method.

# inside a neutral atoms QC




**gate-based cold atoms quantum computer simplified view** *

* : AOD and SLM beams can be assembled through a PBS (polarizing beam splitter), atoms cooling lasers not shown.

# computing paradigms and algorithms

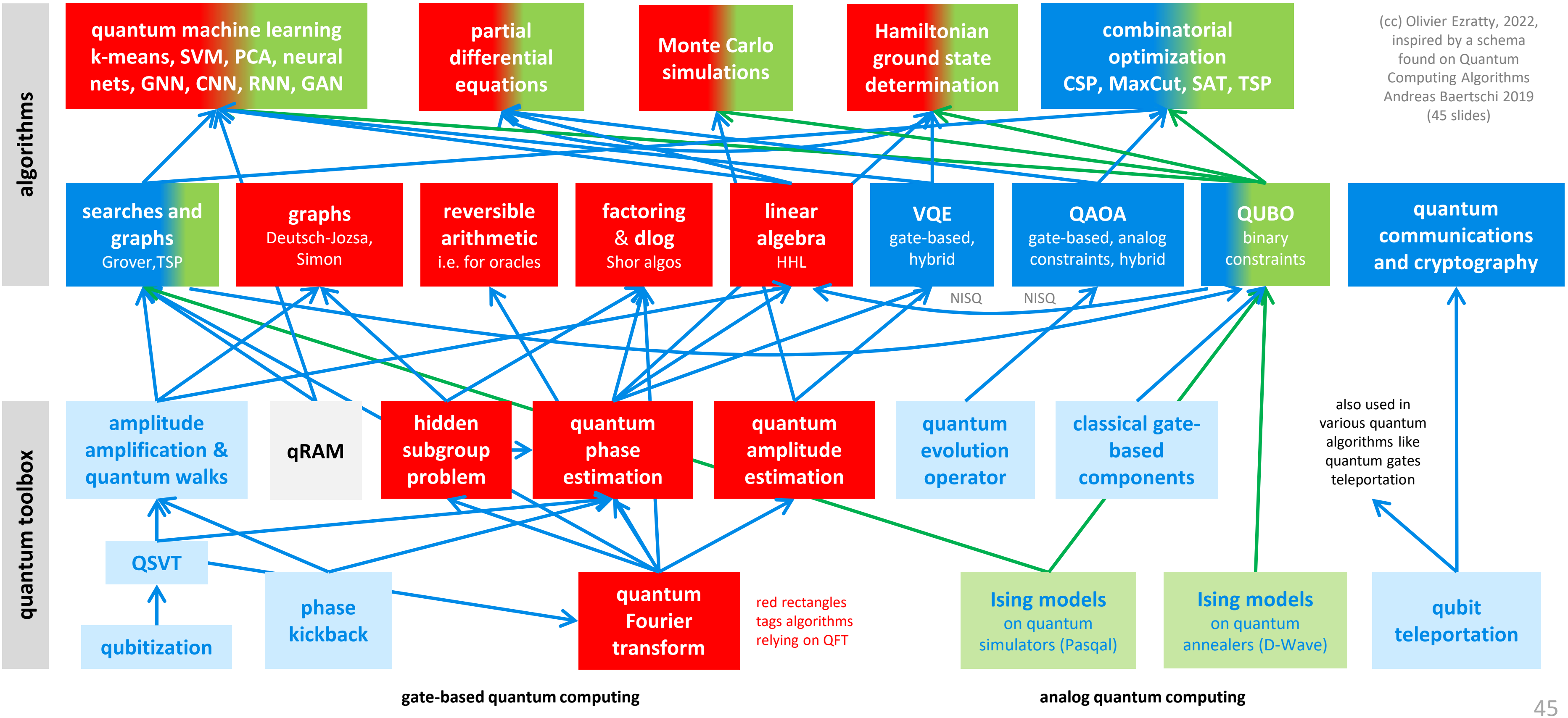
- quantum advantage
- some useful cases
- no useful case so far

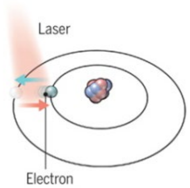
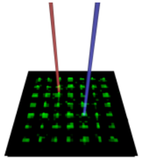
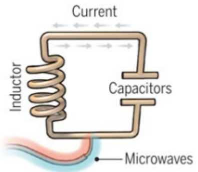
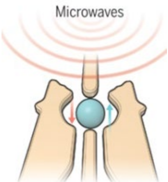
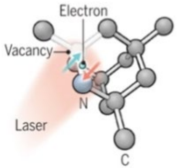
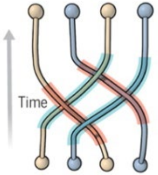
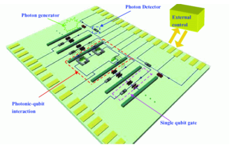
| | classical computers | quantum annealer | quantum simulators | **gate-based** quantum computers: NISQ | **gate-based** quantum computers: FTQC |
|---|---|---|---|---|---|
| **search algorithms** | hybrid algorithms | | | | **polynomial speedup** |
| **optimization algorithms** | hybrid algorithms | | | | **may require qRAM** |
| **quantum machine learning** | hybrid algorithms | | | | **may require qRAM** |
| **physics simulation** | hybrid algorithms | | | | **100 to 10K logical qubits** |
| **organic chemistry simulation** | hybrid algorithms | | | | **100 to 10K logical qubits** |
| **integer factoring** | hybrid algorithms | **6-digit record to date** | | **15-digit record to date** (QAOA, China) | **4K-6K logical qubits** |
| **quantum inspired algorithms** | | | | | |
| | now | now | soon | later | much later |

« quantumness » and arrow of time availability

NISQ: noisy intermediate scale quantum computer, FTQC : lfault tolerant quantum computer

# quantum algorithms map

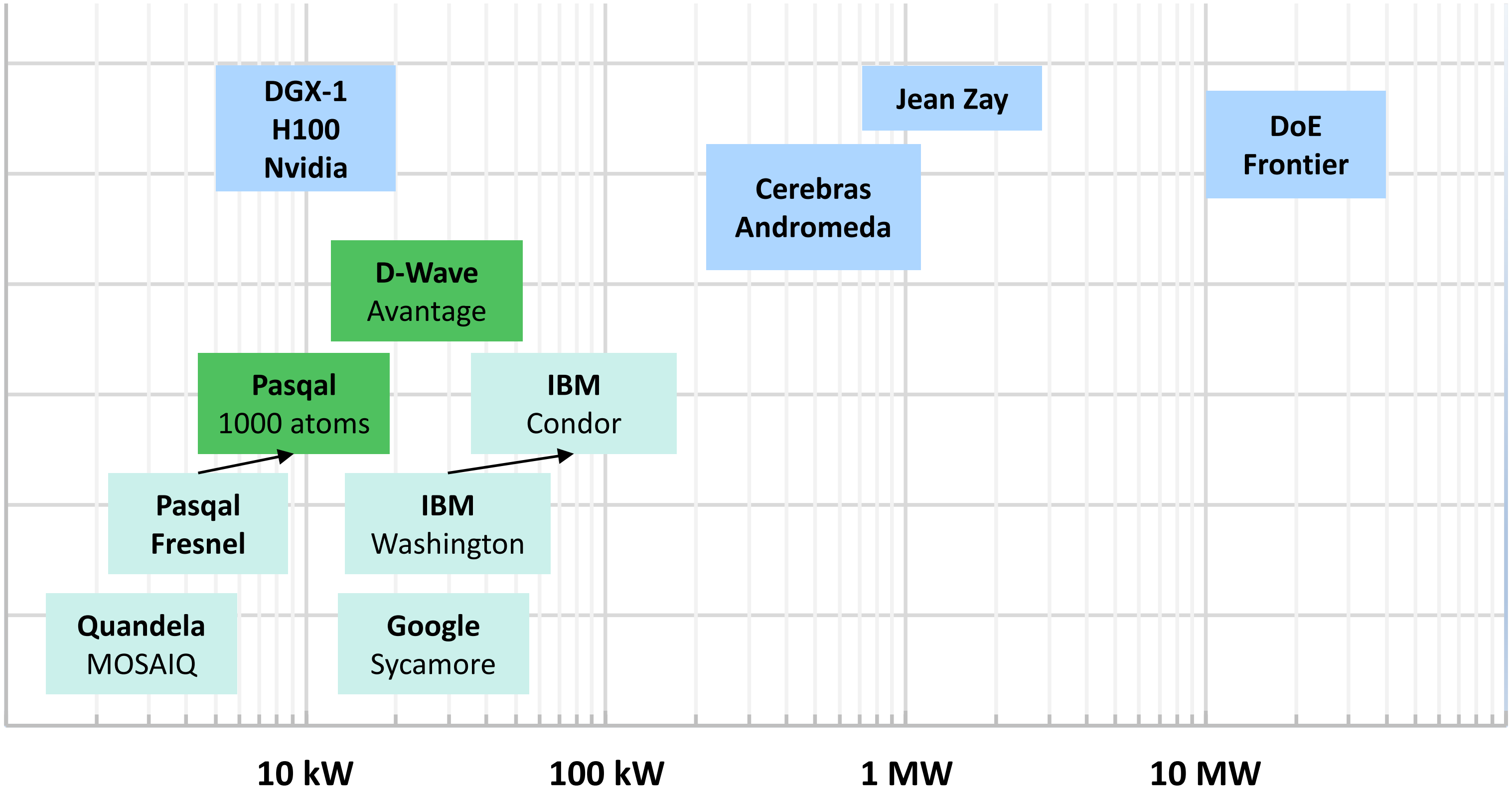


| | atoms | | electron superconducting loops & controlled spin | | | | photons |
|---|---|---|---|---|---|---|---|
| | <br> |  | <br> | <br> | <br> | <br> |  |
| **qubit type** | **trapped ions** | **cold atoms** | **super-conducting** | **silicon** | **NV centers** | **Majorana fermions** | **photons** |
| cryogeny | <300W | N/A | 16 KW | 12 KW | < 1 KW | 16 KW | 3KW |
| vacuum pumps[1] | Vacuum | ultra-vacuum 100W | vacuum | vacuum | vacuum | vacuum | vacuum |
| qubits gate controls | <1.4KW ions heating, lasers, micro-aves generation, CMOS readout electronics | 5,8KW atoms heater, lasers, control (SLM, etc) and readout image sensor + electronics | from 20 mW to 100W / qubit depending on architectures with micro-wave generation outside or inside the cryostat | | N/A | N/A | 300 W for photons sources and detectors, qubit gates controls |
| computing | 300W | 1 KW | 1 KW | 1 KW | <1 KW | 1 KW | 700 W |
| # qubits used | 24 | 100-1000 | 53-433 | 4 | N/A | N/A | 20 |
| **total** | **2 KW** (4) | **7 KW** (1) | **25 KW** (2) | **21 KW** | **N/A** | **N/A** | **4 KW** (3) |

[1] : fixed energetic cost, for preping stage

typical configurations for Pasqal (1), Google Sycamore with 53 qubits (2), Quandela/QuiX (3), AQT (4) rough estimates for others

# QPU + classical energetics scale



# QC energetics benchmarking

QEI WG (C/S2ESC/QEI)

# discussion