Le défi interdisciplinaire de l’optimisation de la consommation énergétique des calculateurs quantiques

Alexia Auffèves (CNRS)

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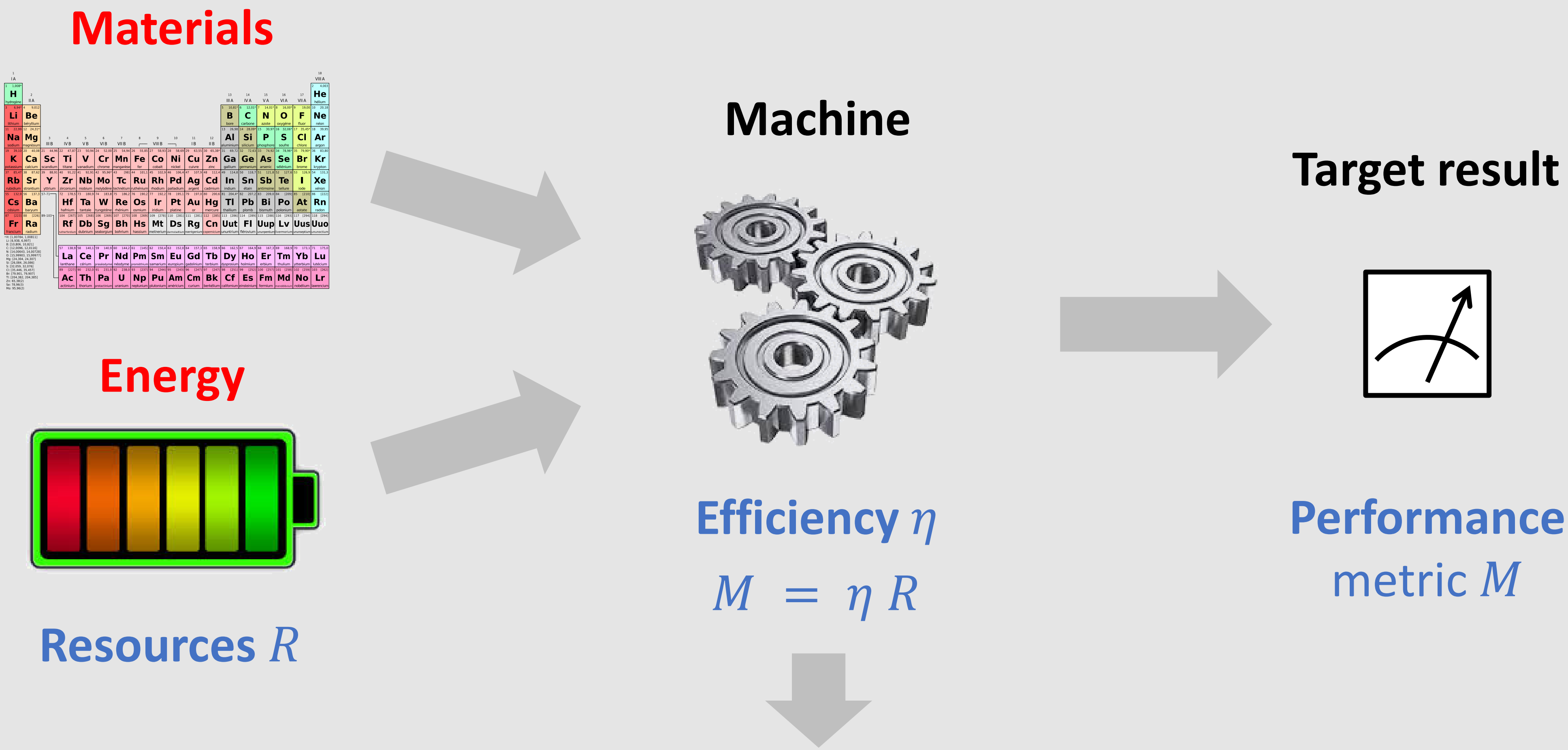
A very schematic view on human activities



Materials

Energy

Resources R

Machine

Efficiency η

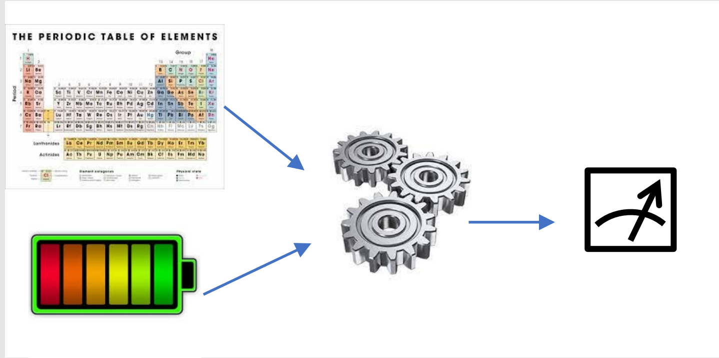
$$M = \eta R$$

Target result

Performance
metric M

Purpose of science and technology: increase efficiencies

Jevons' paradox

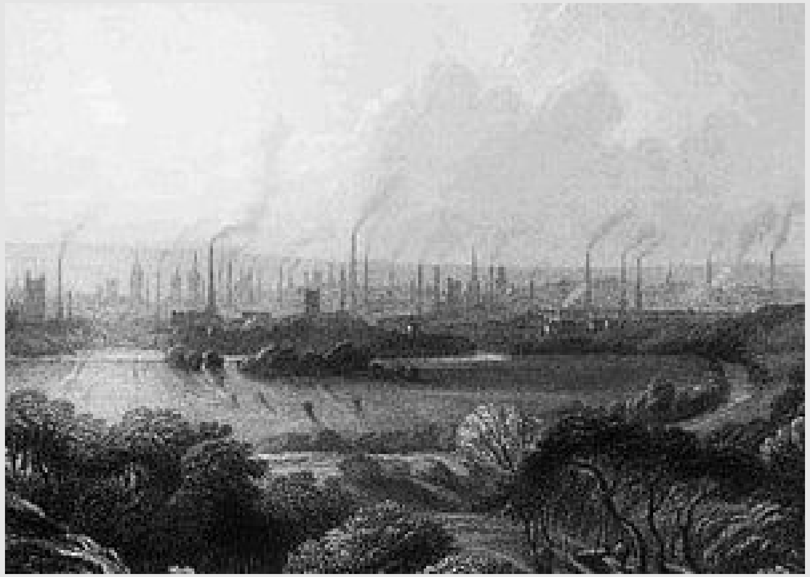


Increase of efficiency

Global resource consumption growth
aka **rebound effect**

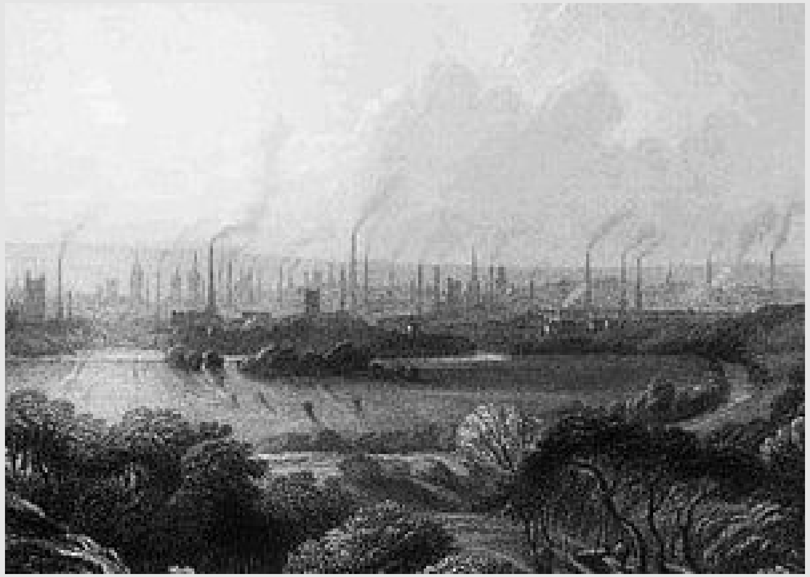
Negative environmental consequences

William Stanley Jevons
1865



Coal burning factories in Manchester,
Engraving by E. Goodall (1795-1870)

Jevons' paradox



Coal burning factories in Manchester,
Engraving by E. Goodall (1795-1870)

Increase of efficiency

Decrease of resource cost

Decrease of product price

Increase of demand

Economy

Global resource
consumption growth
aka **rebound effect**

Negative
environmental
consequences,
but not a fatality!

William Stanley Jevons
1865

Increasing efficiency is good!

Resource R

Efficiency η

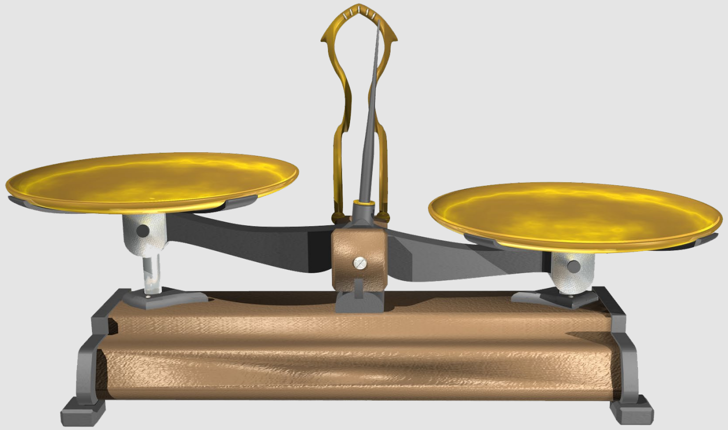
$$M = \eta R$$

Performance M

Decrease of resource cost

Jevons' paradox
Rebound effect
☹

Negative environmental consequences resulting from societal choices



Same performance with less resource
☺

Reasonable paradigm shift in a finite physical world

Classical computing energy efficiency

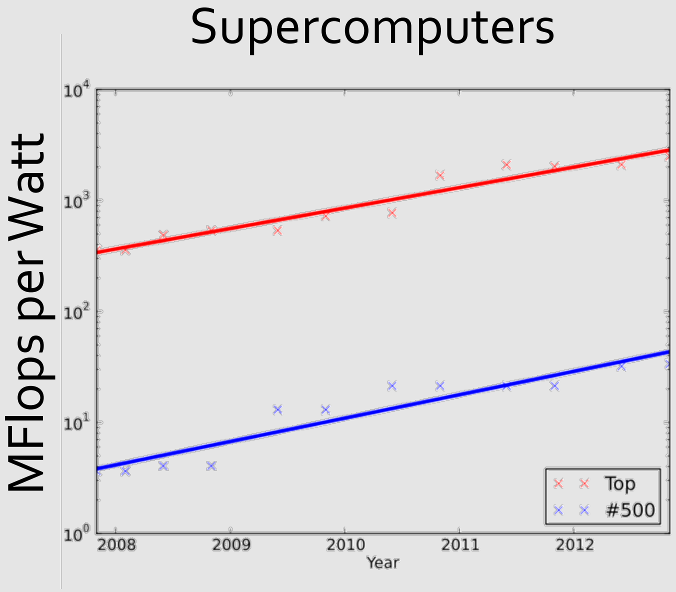
R = Power consumption

M = Number of FLoating-point Operations Per second (FLOPs)

η = Performance per Watt (FLOPs/W)

Koomey's law

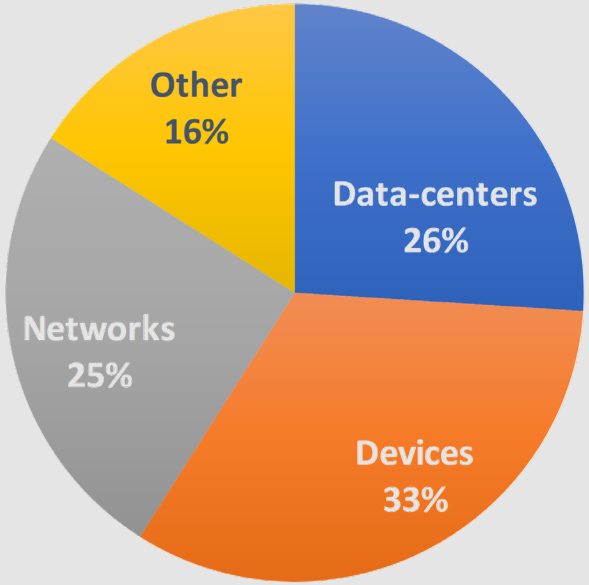
- ➢ η doubles every 18 months
- ➢ Saturation since 2010



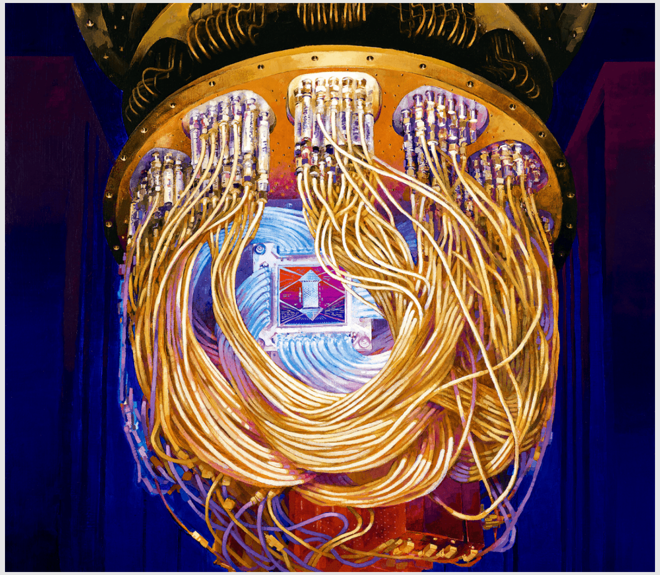
- ✓ Improvement of component energy efficiency
- ✓ Improvement of architectures (GPU)
- ➢ State of the art: **40 GFlops/W** (2021)

Information and Communication Technologies (ICT)

- Jevons' paradox (again): ICT global electricity consumption in 2020: **11%** (Puebla et al, 2020).

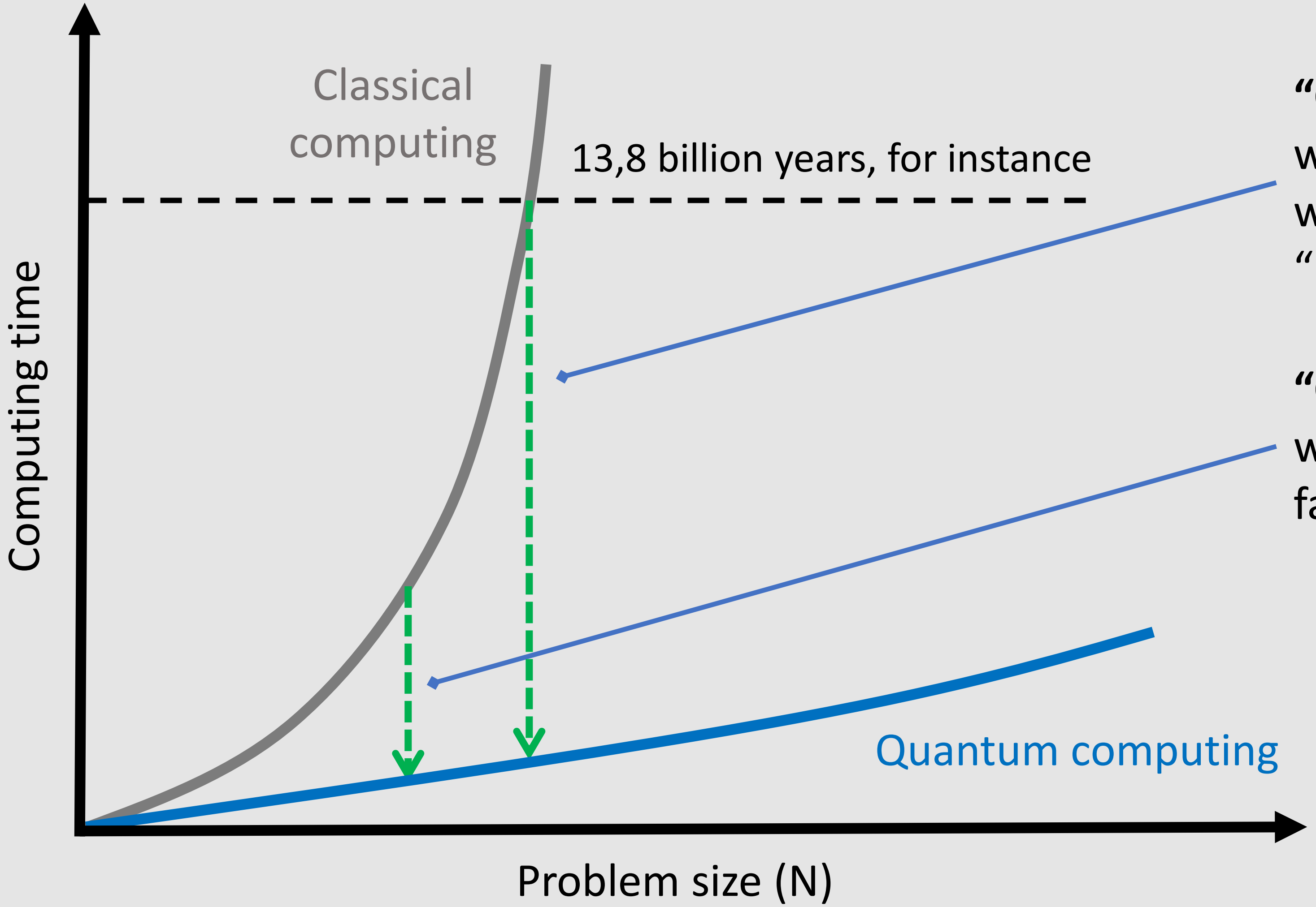


- No expected gain in efficiency due to end of Koomey's law.
- Raw materials consumption and products lifecycle environmental costs.



➢ **Need for paradigm shift and alternative technologies to store-process-transfer information**
=> Quantum technologies?

Boosting computing power with quantum?

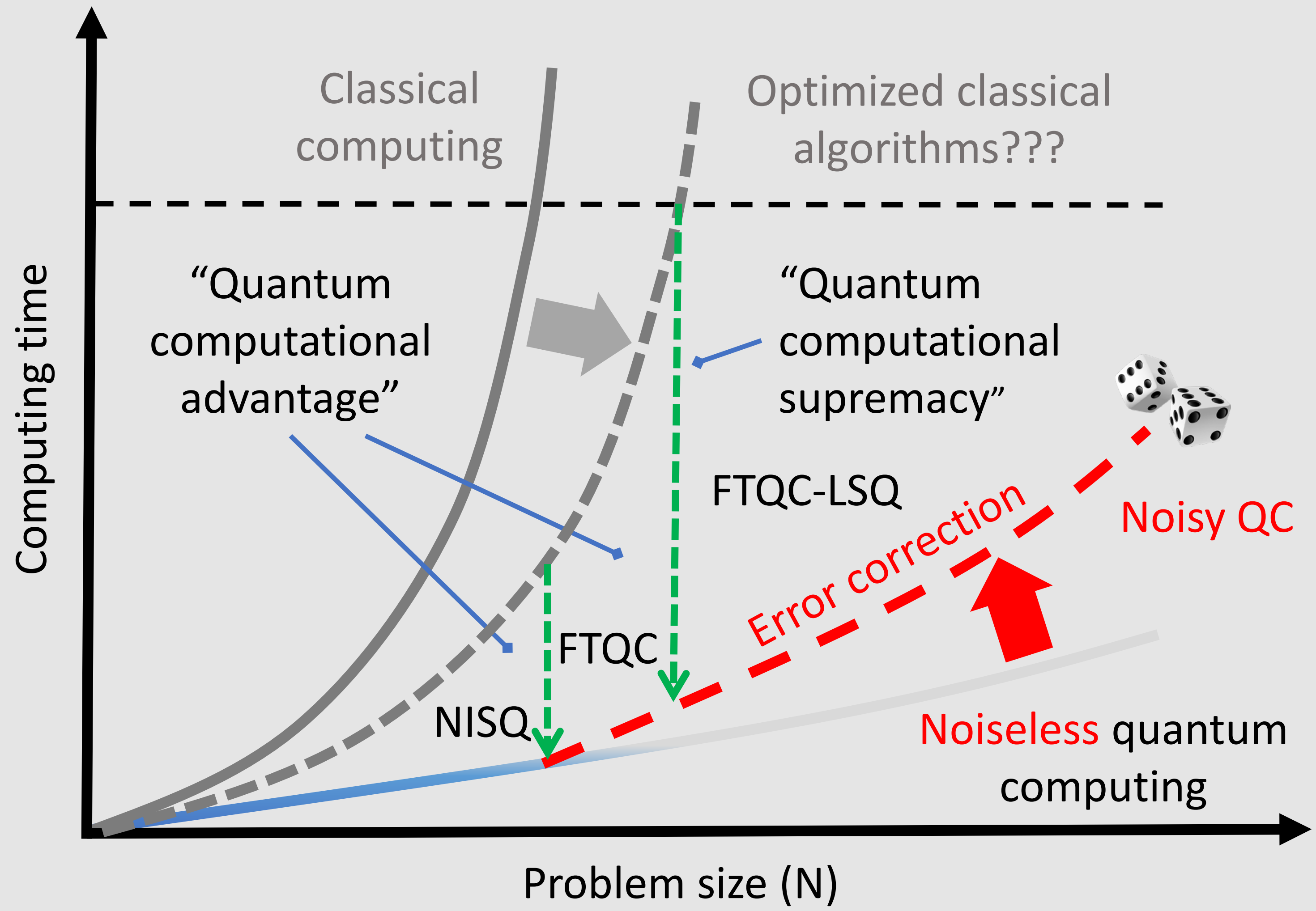


“Quantum computational supremacy” when a quantum computer can do what no classical computer could in a “reasonable” time

“Quantum computational advantage” when a quantum computer computes faster than a classical computer

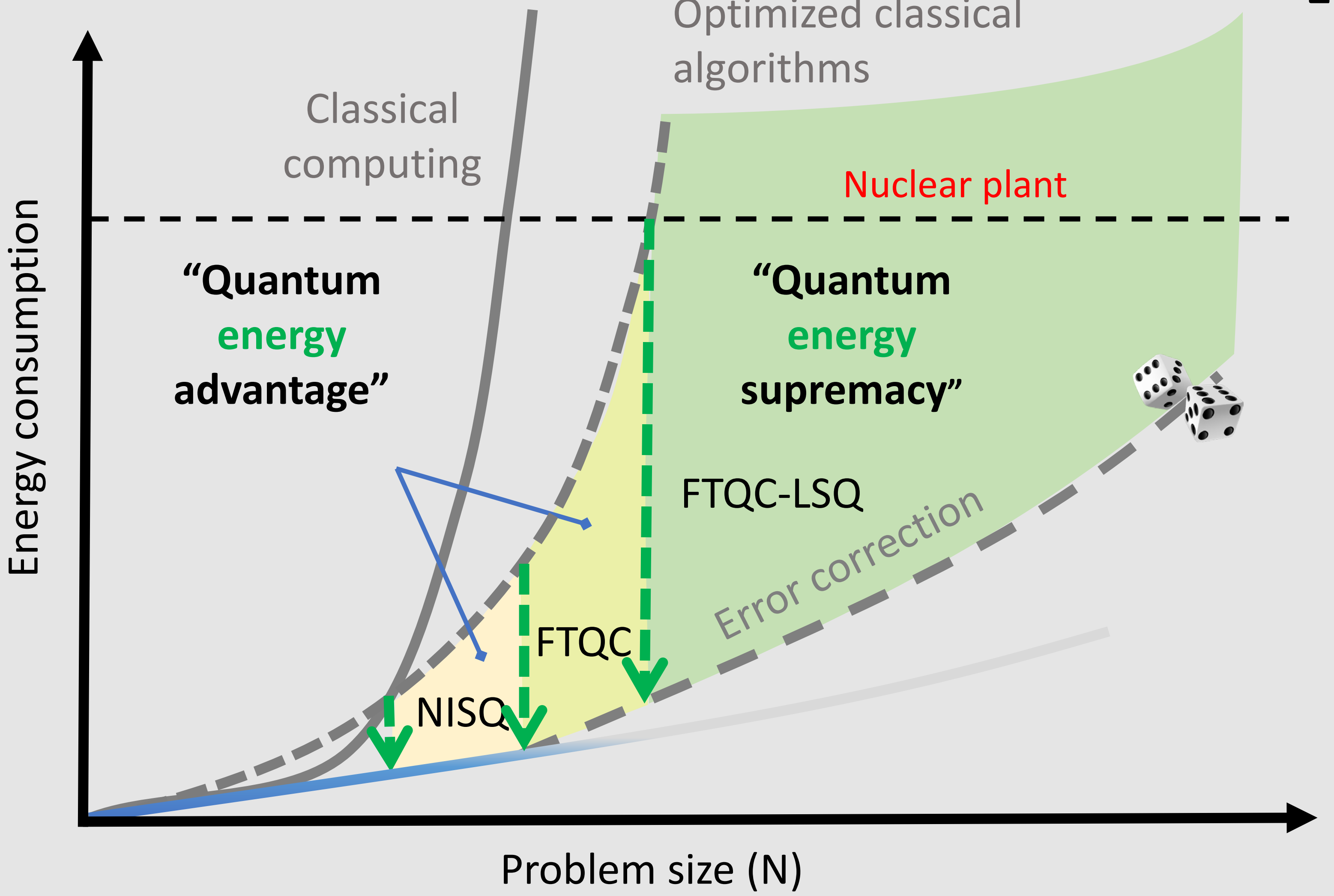
Performance = Computing power = Problem size/Time

Boosting computing power with quantum?



=> Noise resilience of these concepts?

Boosting energy efficiency with quantum?

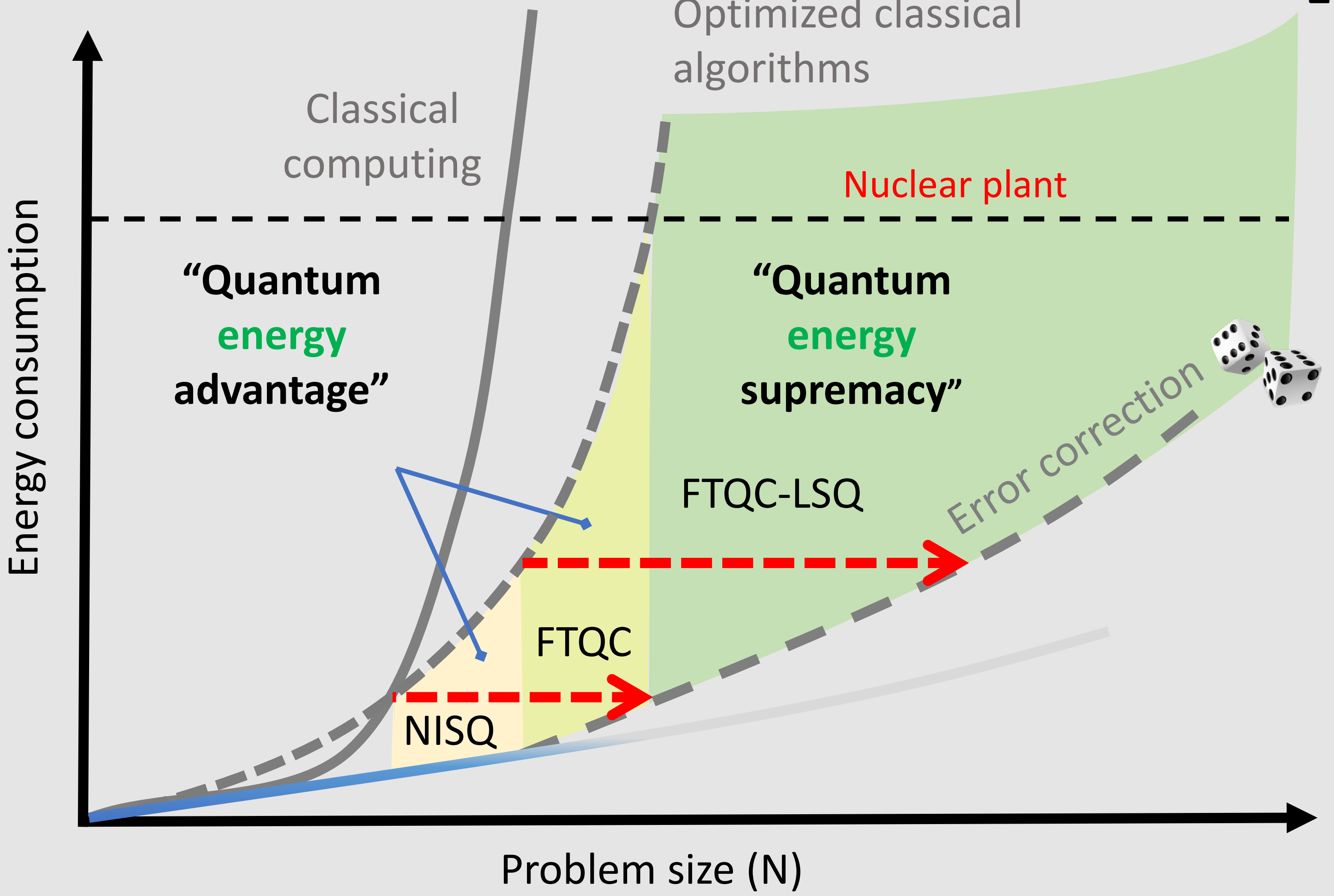


Efficiency = Problem size/Energy

"Quantum energy advantage": when a quantum computer solves a problem with less energy than best in-class classical computers and algorithms.

"Quantum energy supremacy": when a quantum computer solves a problem no classical computer could do with **"reasonable"** energy.

Computing under energetic constraint

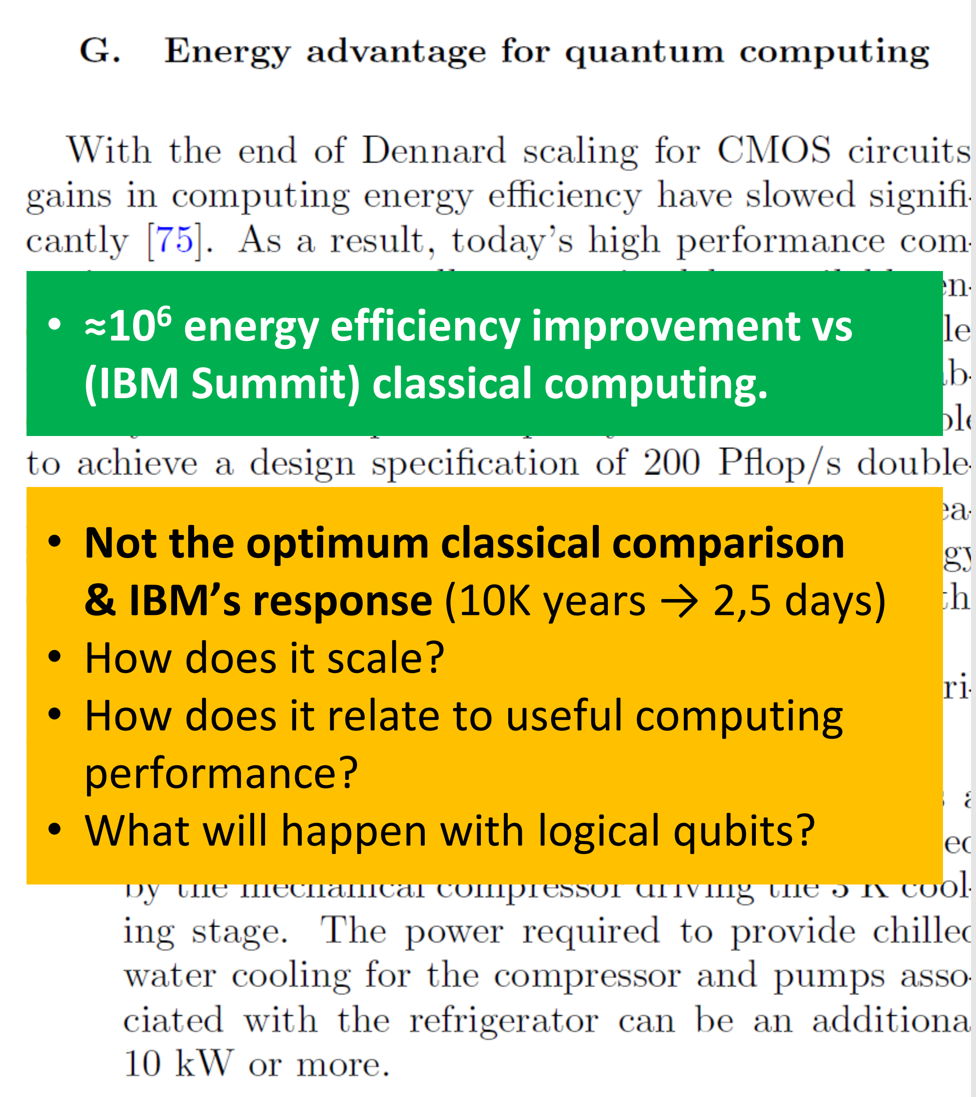


Efficiency = Problem size/Energy

"Quantum energy supremacy": when a quantum computer solves a problem no classical computer could do with **"reasonable"** energy.

"Quantum energy advantage": when a quantum computer solves a problem with less energy than best in-class classical computers and algorithms.

First clue of quantum energy advantage



G. Energy advantage for quantum computing

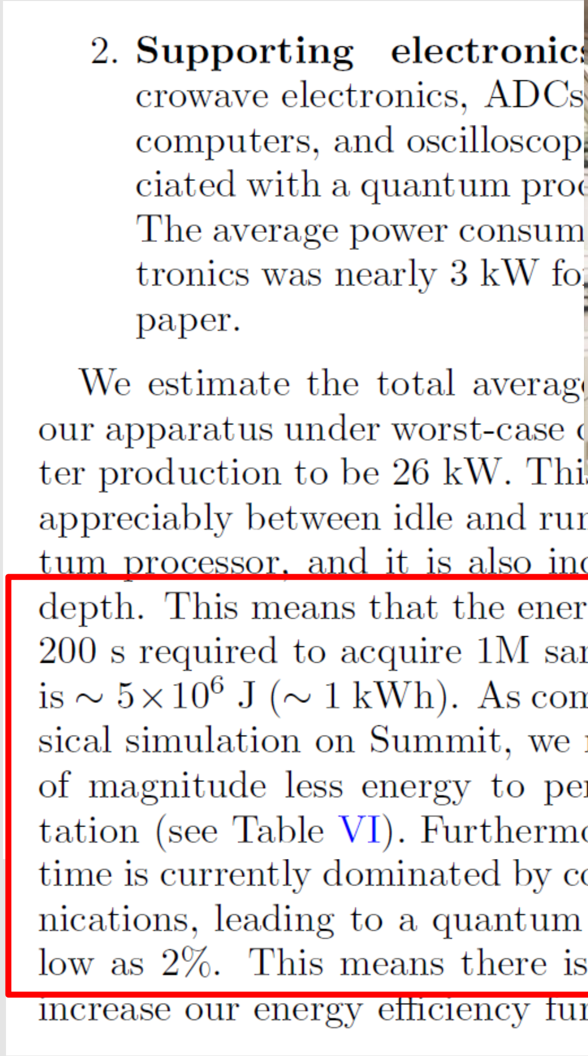
With the end of Dennard scaling for CMOS circuits gains in computing energy efficiency have slowed significantly [75]. As a result, today's high performance com-

to achieve a design specification of 200 Pflop/s double-

by the mechanical compressor driving the 3 K cool-
ing stage. The power required to provide chille
water cooling for the compressor and pumps asso-
ciated with the refrigerator can be an additiona
10 kW or more.

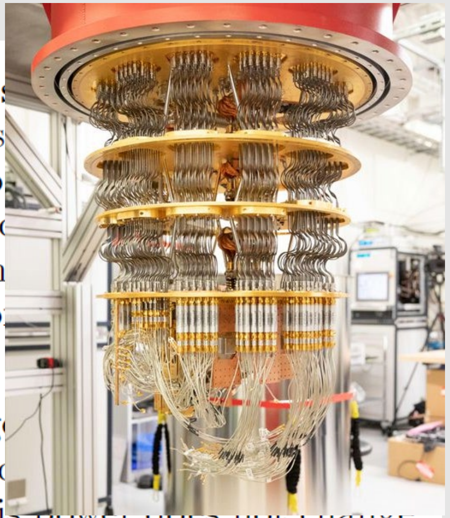
- ≈10^6 energy efficiency improvement vs (IBM Summit) classical computing.

- **Not the optimum classical comparison & IBM's response** (10K years → 2,5 days)
- How does it scale?
- How does it relate to useful computing performance?
- What will happen with logical qubits?



2. **Supporting electronic**
crowave electronics, ADCs
computers, and oscilloscop
ciated with a quantum proc
The average power consum
tronics was nearly 3 kW fo
paper.

We estimate the total averag
our apparatus under worst-case c
ter production to be 26 kW. This power does not change appreciably between idle and running states of the quantum processor, and it is also independent of the circuit depth. This means that the energy consumed during the 200 s required to acquire 1M samples in our experiment is ∼ 5×10^6 J (∼ 1 kWh). As compared to the qFlex classical simulation on Summit, we require roughly 7 orders of magnitude less energy to perform the same computation (see Table VI). Furthermore, the data acquisition time is currently dominated by control hardware communications, leading to a quantum processor duty cycle as low as 2%. This means there is significant potential to increase our energy efficiency further.



Supplementary information for "Quantum supremacy using a programmable superconducting processor", Google AI Quantum and collaborators, July 22, 2019 - https://arxiv.org/abs/1910.11333

Optimizing energy efficiency: an interdisciplinary challenge

Macroscopic resources R

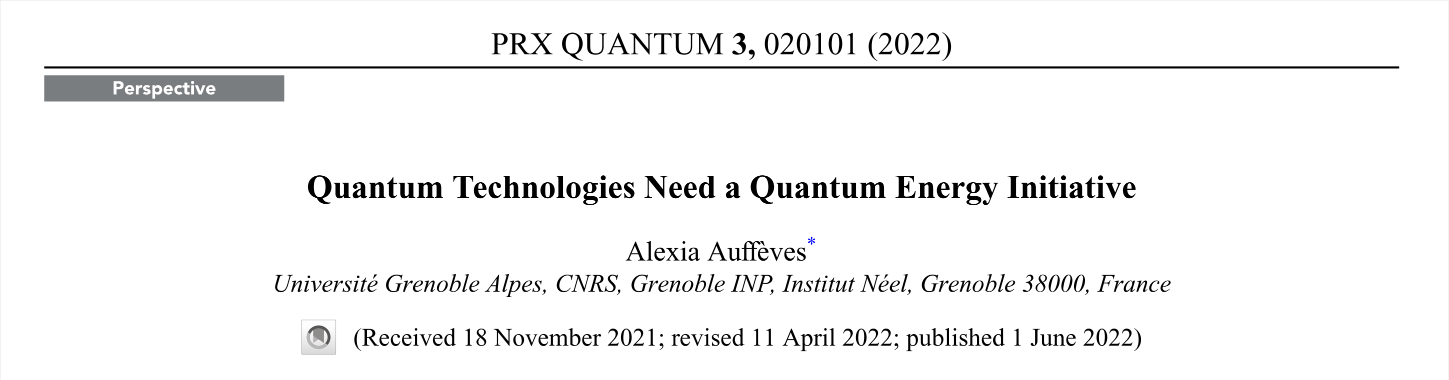
Full stack level
Enabling technologies

Quantum processor efficiency

Metric of performance M

Quantum level - Fundamental research

$\eta = M/R$ requires full stack and fundamental inputs!



PRX QUANTUM **3,** 020101 (2022)

Perspective

Quantum Technologies Need a Quantum Energy Initiative

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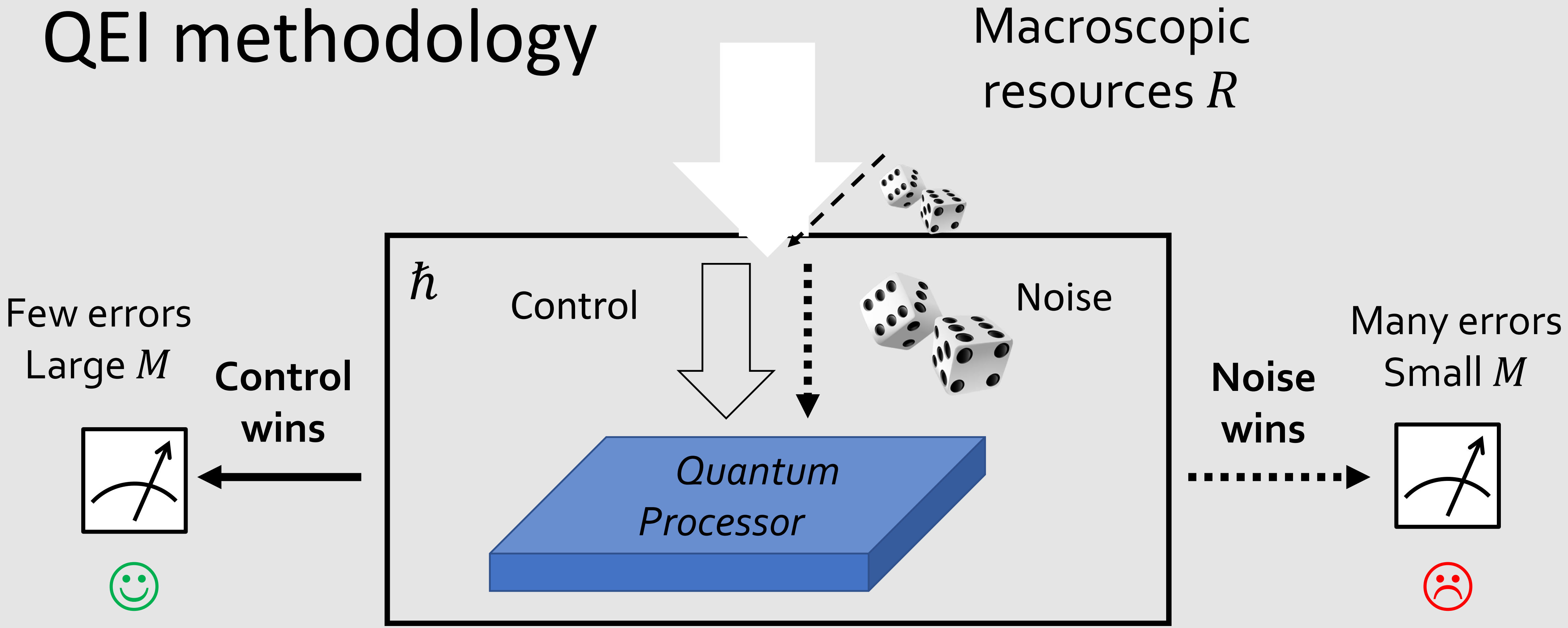
#QEI

QEI methodology



Macroscopic resources R

$\hbar$

Control

Noise

Quantum Processor

Few errors
Large M

Control wins

☺

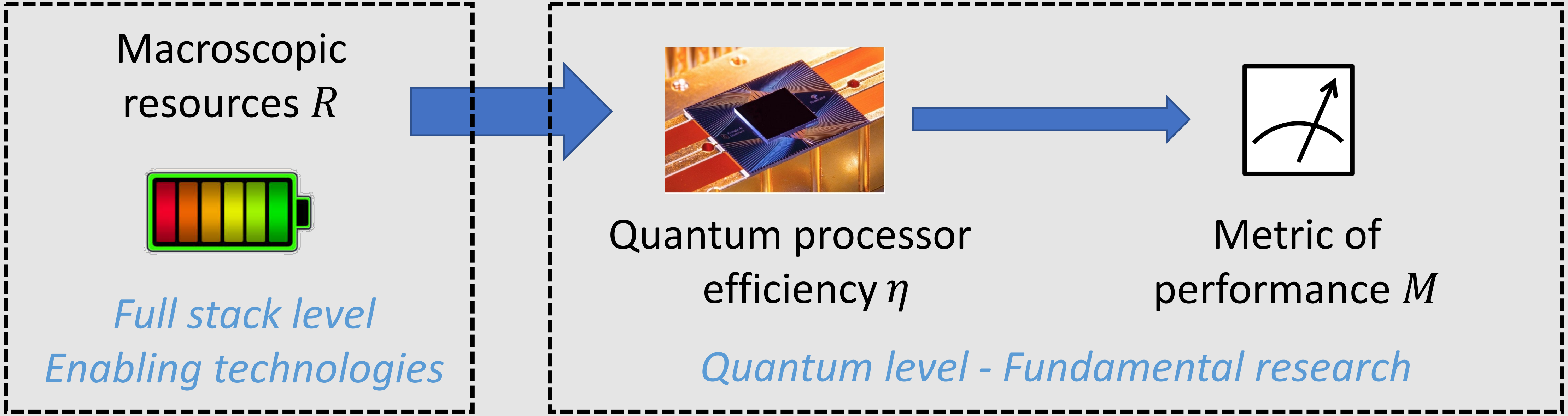
Noise wins

Many errors
Small M

☹

- Set a **target performance metric** $M = M_0$
- **Minimize resource cost** R under the constraint $M = M_0$
- Non trivial sweet spots: inputs from the **macroscopic** and the **quantum** realms

QEI big questions and goals



Macroscopic resources R

Full stack level
Enabling technologies

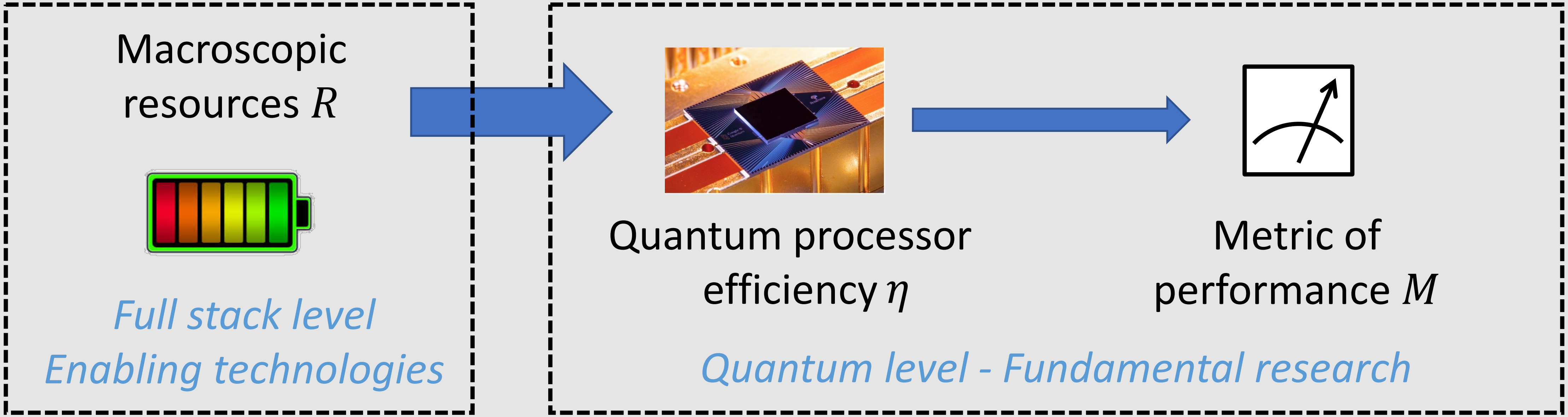
Quantum processor efficiency η

Metric of performance M

Quantum level - Fundamental research

- Is there a **quantum energy advantage** as the processors scale up ?
- How different is it from the quantum computational advantage?
- What is the fundamental **minimal energetic cost** of quantum computing?
- What is **quantum energy efficiency** and what are its scaling laws?

QEI big questions and goals



Macroscopic resources R

Full stack level
Enabling technologies

Quantum processor efficiency η

Metric of performance M

Quantum level - Fundamental research

- How to **avoid energetic dead-ends** on the road to LSQ?
- Create **optimization tools** for qubit technology, enabling technologies and software engineering.
- Propose **energy-based benchmarks**.
- Foster a **cross-disciplinary** research-industry collaboration.

QEI seed: Optimizing energy efficiency for full-stack quantum computers

Marco Fellous-Asiani[1],
Jing Hao Chai[1, 2],
Yvain Thonnart[3],
Hui Khoon Ng[4,2,5],
Robert S. Whitney[6],
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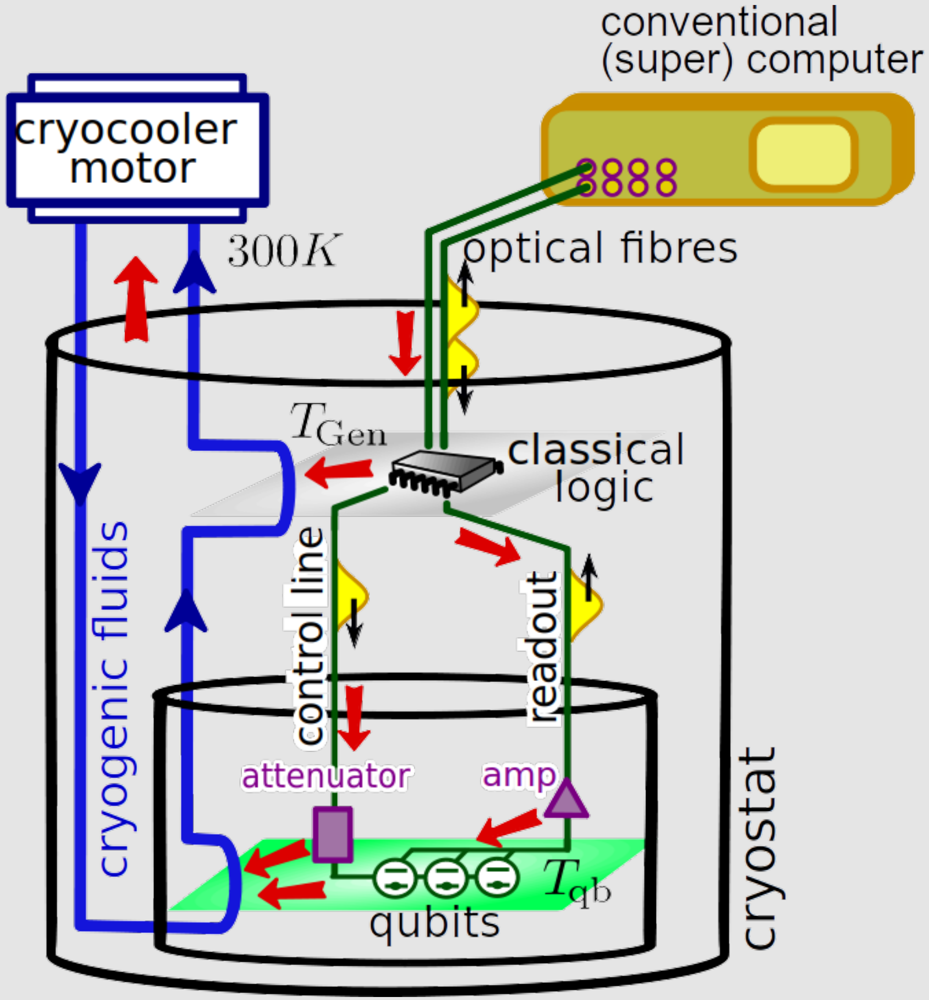
2 - Centre for Quantum Technologies, National University of Singapore
3 - Université Grenoble Alpes, CEA-LIST, Grenoble
4 - Yale-NUS College, Singapore
5 - MajuLab, International Joint Research Unit, CNRS France-Singapore
6 - Université Grenoble Alpes, CNRS, LPMMC, Grenoble

Full-stack superconducting quantum computer



Superconducting qubits model

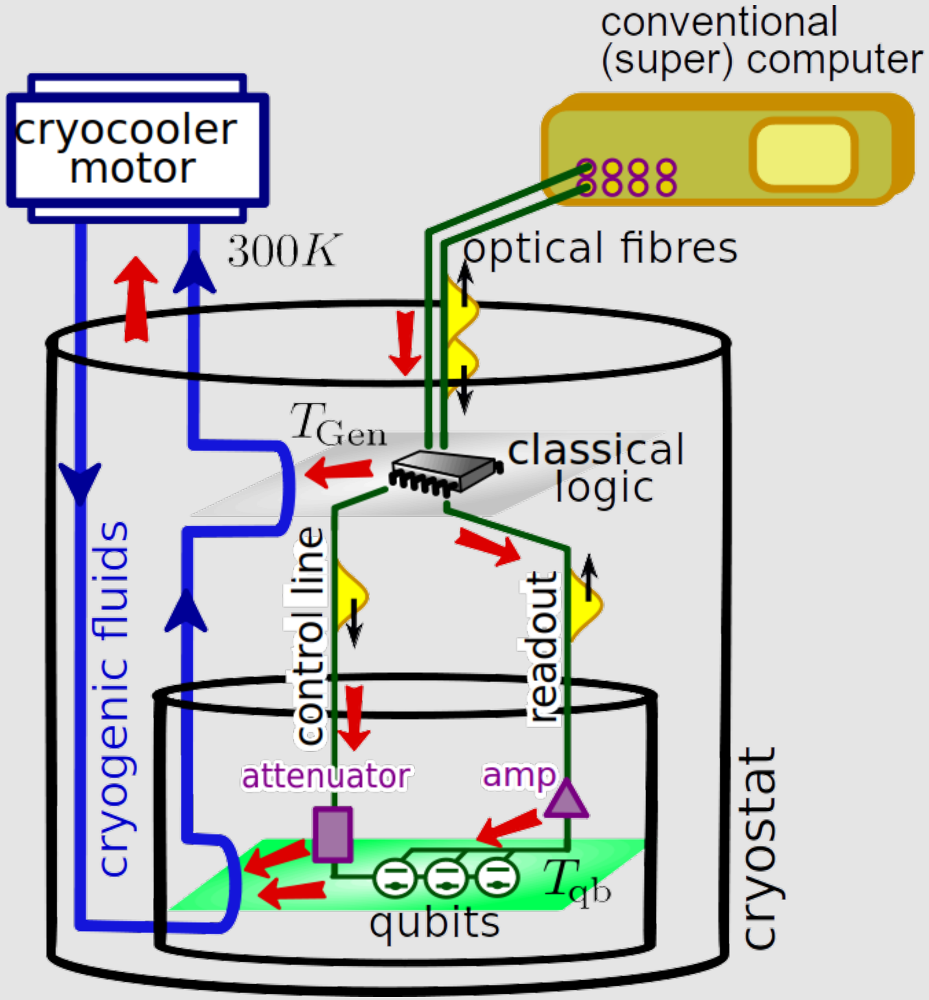
Macroscopic level

- **Resource = Power consumption:** cryo-power + control electronics
- **Model parameters:** wiring & multiplexing, attenuators, amplifiers, control electronics, cryogenic stages ..

Fundamental level

- Microscopic model of fault tolerant quantum processor (Steane code)
- **Performance**: Successful computation

Full-stack superconducting quantum computer

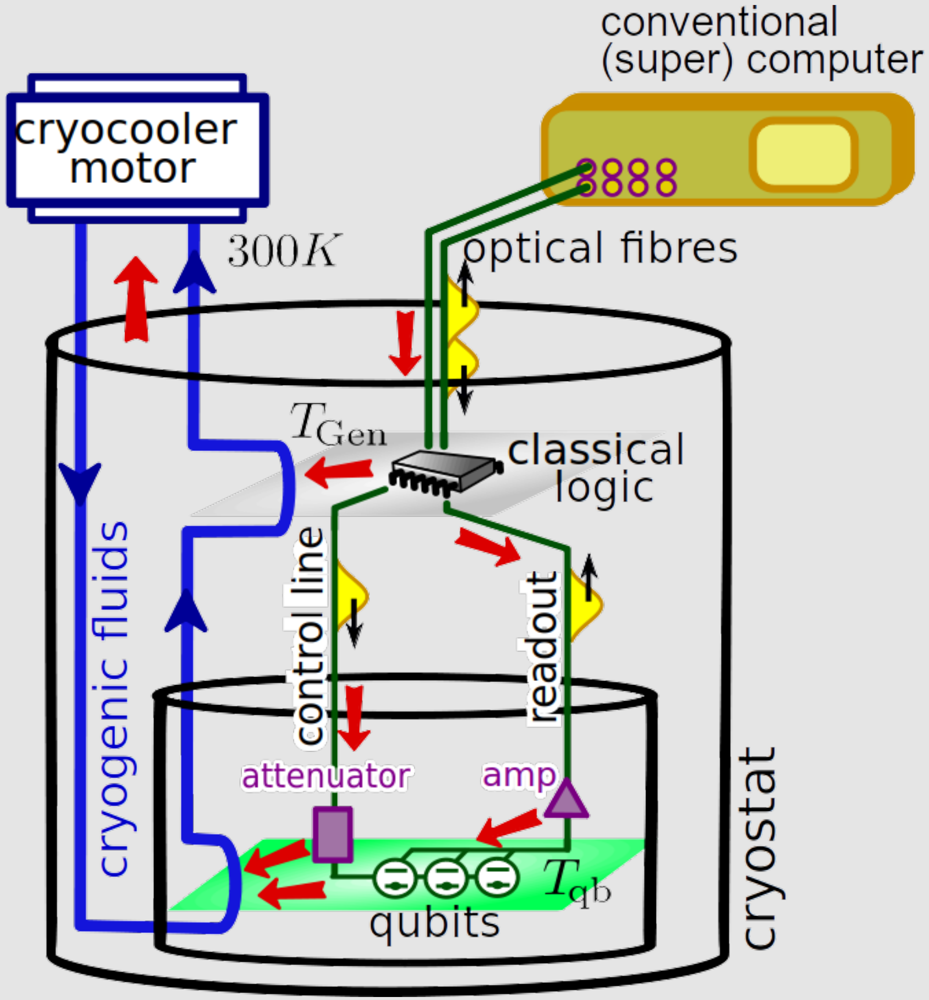


Superconducting qubits model

Methodology

- ✓ Pick a « N-size » algorithm
- ✓ Impose error probability = 1/3
  - ⇒ Sets implicit relation between micro/macro parameters
- ✓ Minimize power consumption as a function of micro and macro parameters

Full-stack superconducting quantum computer

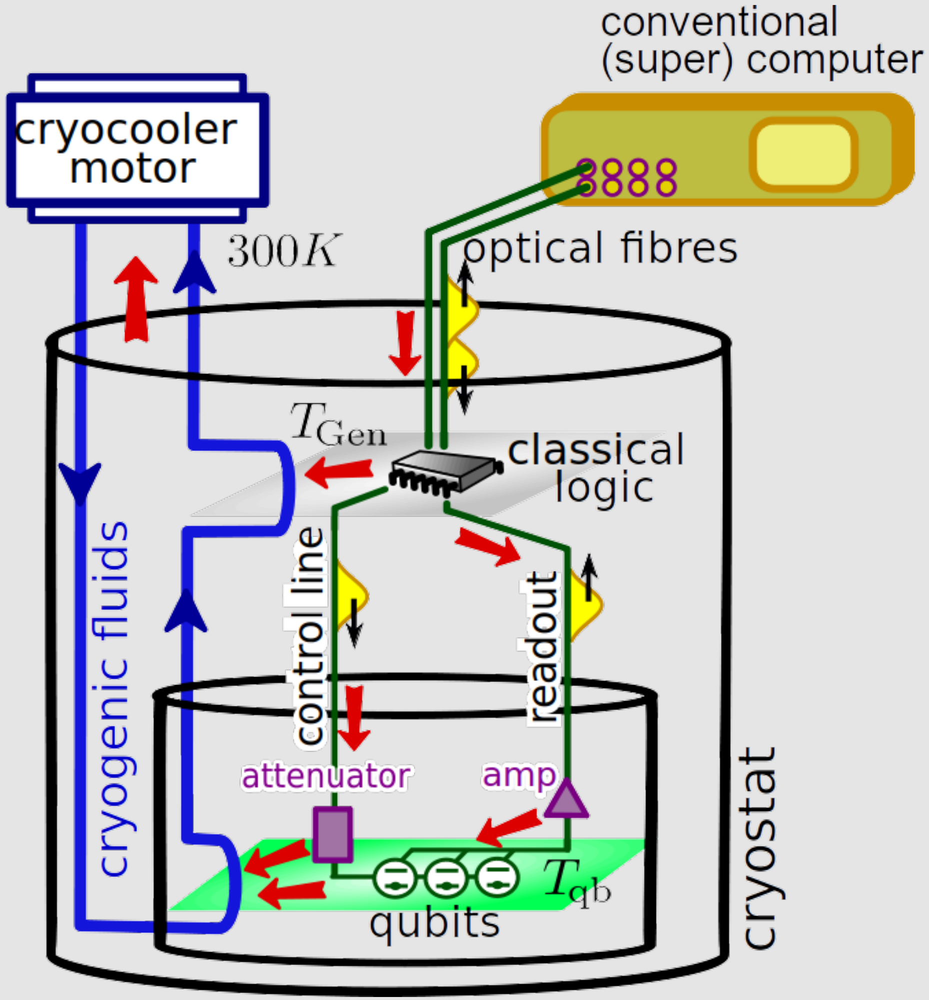


Superconducting qubits model

Questions

- ✓ Control electronics: in or out?....
- ✓ Which qubit temperature? ...
- ✓ How much error correction? ...
- ✓ Impact of computing architecture?
- ✓ Impact of qubits quality?
- ✓ ...

Full-stack superconducting quantum computer



Superconducting qubits model

Outcome

Qubit and signal generation temperature & attenuations & error correction level minimizing power consumption (algorithm-dependent!)

First answers

✓ Control electronics: in or out?....

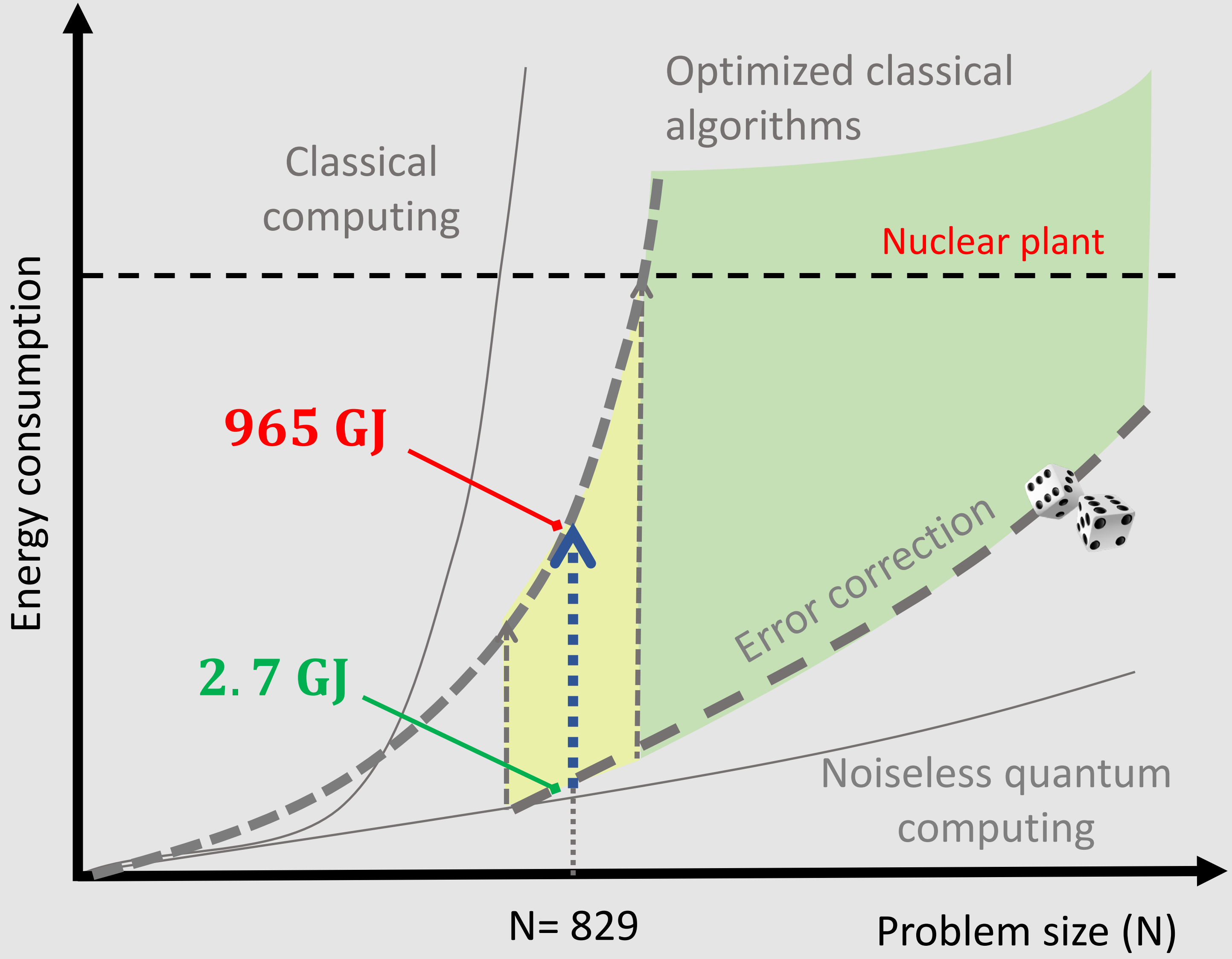
=> for 1mW/qubit: OUT!

=> constraint on wiring

✓ Impact of qubits quality?

$\Rightarrow$ **enormous! => quality *10 → power /100**

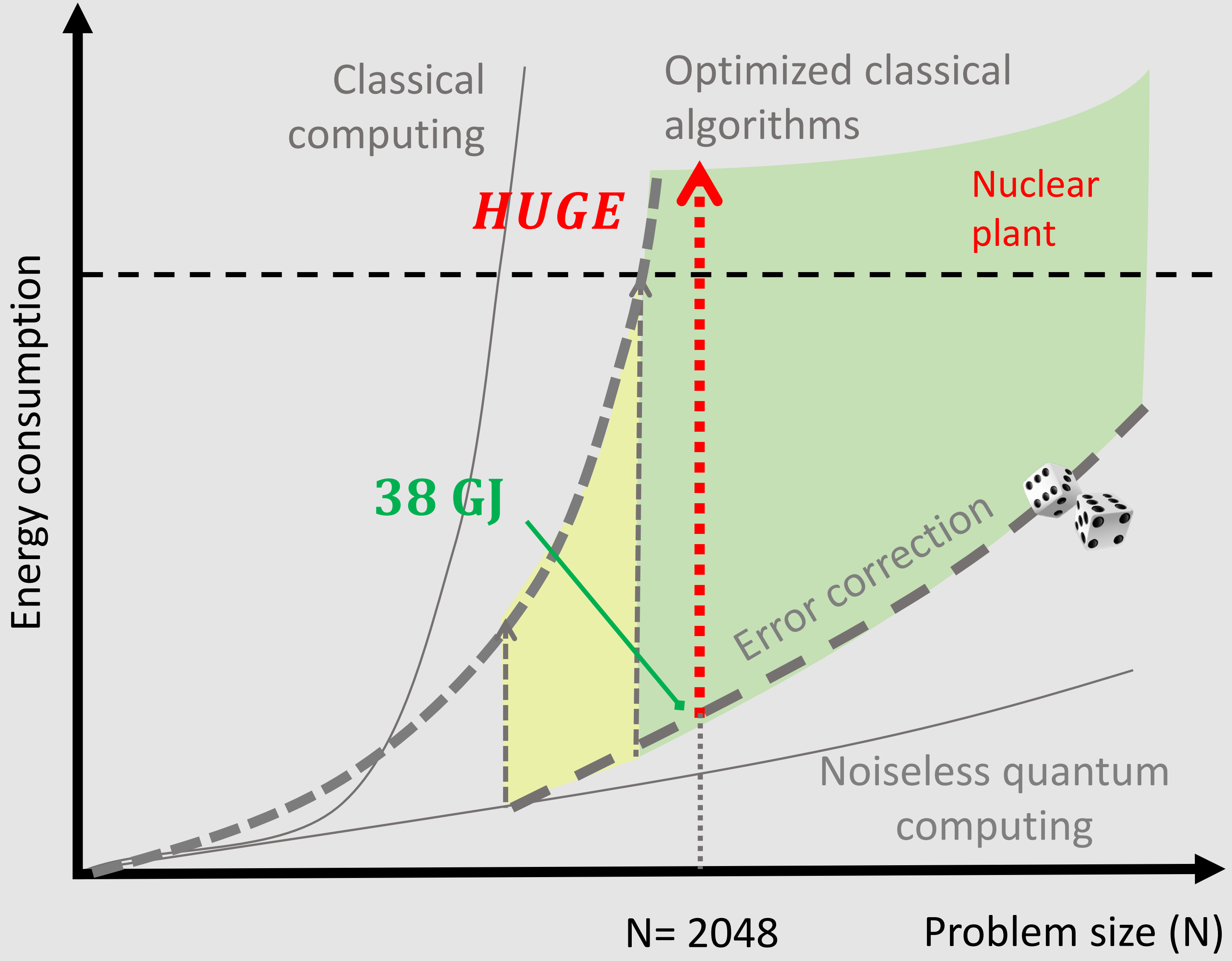
First results on quantum advantages



Breaking RSA 829 key

- Classical supercomputer (Inria 2021): 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

First results on quantum advantages



Breaking RSA 829 key

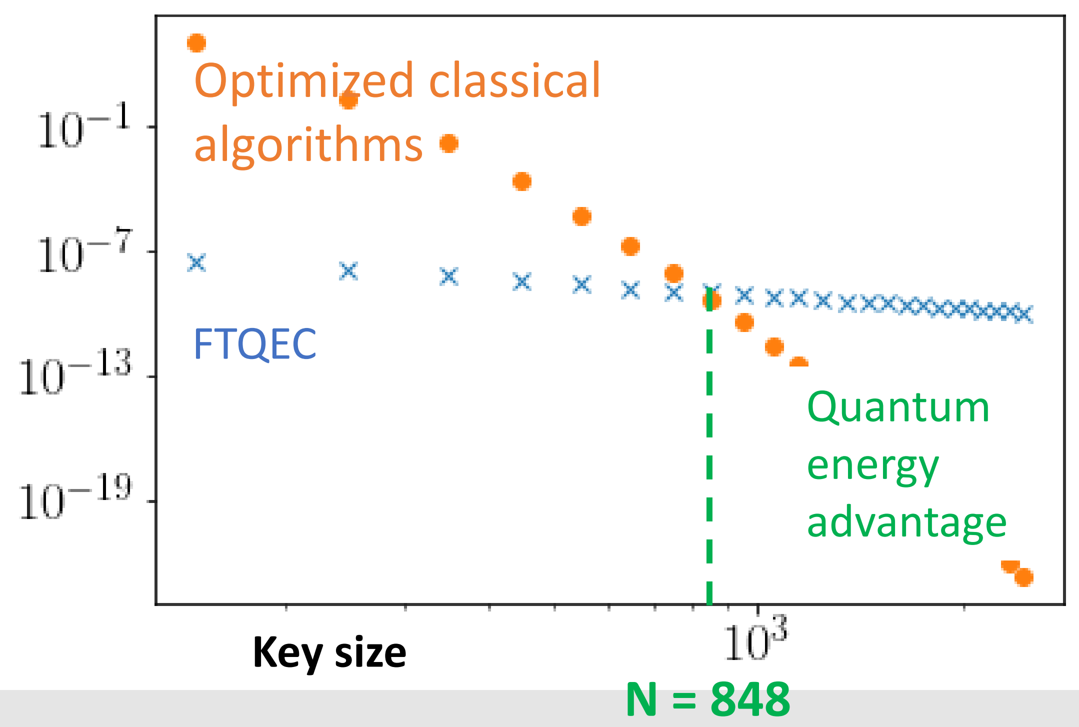
- Classical supercomputer
  965 GJ $\approx$ 1.3MW in 8.6 days
- Quantum computer with top quality qubits (2000 better than Sycamore) + Steane code
  2.7GJ $=$ 2.9 MW in 16 min

Breaking RSA 2048 key

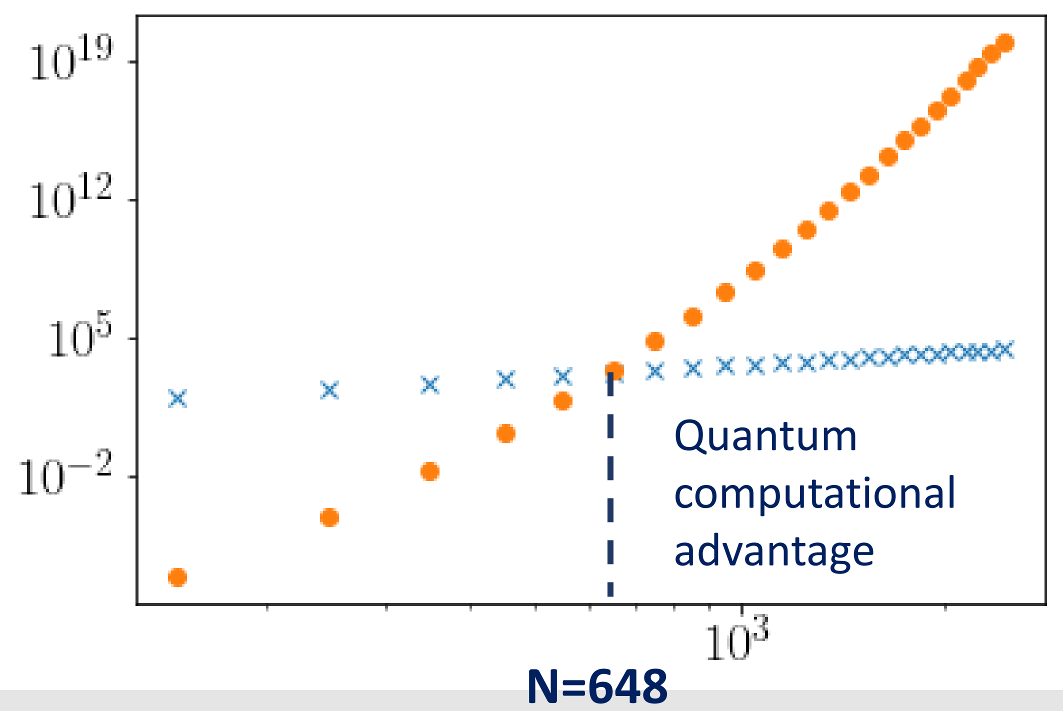
- Classical supercomputer
  TOO MUCH
- Quantum computer (Steane code)
  38 GJ $=$ 7 MW in 1.5 hours
- *Quantum computer (Surface code)*
  $0.57\ GJ = 20\ kW\ in\ 8\ hours$

First results on quantum energy efficiency

Efficiency = key size/energy (/J)



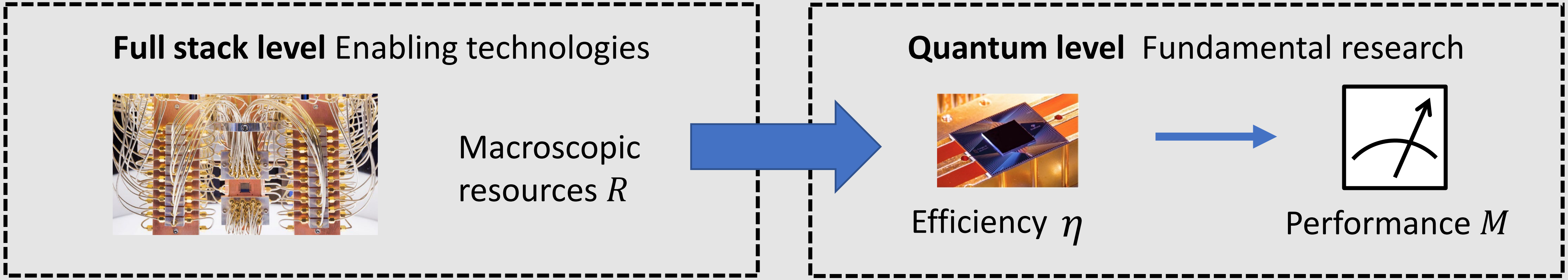
Estimated computing time (s)



- Energy advantage (power*time) ≠ Computational advantage (time) : a practical advantage of different nature!
- Surface code may allow saving 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 for specific optimizations within an interdisciplinary research line = QEI
- **New benchmark**: Quantum energy efficiency $\eta = M/R$
  - New tool for optimizations software/hardware; fundamental stage/full stack
  - Towards a « Q-Green 500 »



Full stack level Enabling technologies

Macroscopic resources R

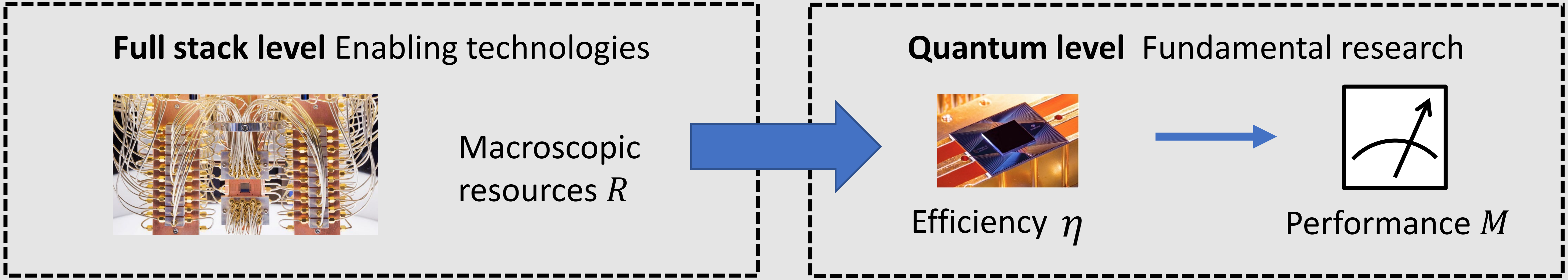
Quantum level Fundamental research

Efficiency η

Performance M

Perspectives: Energetic optimizations & benchmarks

- Various qbit technologies: superconducting qubits, photons, ions, silicon spins qubits, Rydberg atoms...
- Various computing paradigms: analog vs gate-based/FT vs NISQ...
- Various quantum technologies: computing, communication & sensing
- Engineering, methodologic and fundamental challenges



Full stack level Enabling technologies

Macroscopic resources R

Quantum level Fundamental research

Efficiency η

Performance M

The Grenoble-Singapore « quantum channel » seed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Singapore


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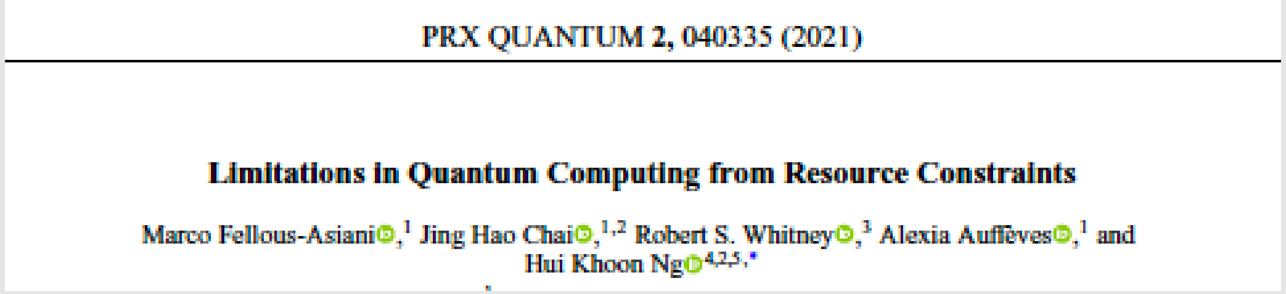
CEA-List Grenoble

anr
NATIONAL RESEARCH FOUNDATION
INVESTISSEMENTS D'AVENIR
financed by
IDEX Université Grenoble Alpes
PHC MERLION
FRANCE - SINGAPORE


Marco Fellous-Asiani, PhD
2018-2021


Jing Hao Chai, CQT PhD
(2017-2020), Néel &
CQT post-doc

- ➢ General methodology
- ➢ Theory and modeling


PRX QUANTUM 2, 040335 (2021)

Limitations in Quantum Computing from Resource Constraints

Marco Fellous-Asiani,[1] Jing Hao Chai,[1,2] Robert S. Whitney,[3] Alexia Auffèves,[1] and Hui Khoon Ng[4,2,5,*]

Ongoing work with qubits creation teams

Silicon spin

Tristan Meunier
Institut Néel, CNRS

Photons

Pascale Senellart
C2N, CNRS

Loic Lanco
C2N, CNRS

Carbon nanotubes

Natalia Ares
Oxford University

anr
Marie Skłodowska-Curie Actions
QUANTUM FLAGSHIP
FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

Superconducting

Benjamin Huard
ENS Lyon

Kater Murch
Saint Louis, USA

Rydberg atoms

Igor Dotsenko
LKB-Collège de France

- ✓ *Energetic cost of measurements using quantum, coherent and thermal light*, Linpeng et al, PRL 128, 220506 (2022).
- ✓ *Energetics of a single qubit gate*, arXiv: 2109.09648.
- ✓ *Coherence-powered energy exchanges between a qubit and light fields*, arXiv:2202.01109.
- ✓ *Energy efficient entanglement generation and readout in a spin photon interface*, arXiv: 2205.09623.
- ✓ …

First Industry participants

bpifrance

FRANCE 2030

QRYOlink project

ALICE & BOB

C12

QUANDELA

QCOSMOS

AtoS

Air Liquide

Radiall™

ATEM
CUSTOMIZED CONNECTIVITY

SILENT WAVES

You are welcome to join!