THE AVAQUS PROJECT: ANNEALING-BASED VARIATIONAL QUANTUM PROCESSORS

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CGC online international conference, Apr. 7th

HQS QUANTUM SIMULATIONS
CSIC Consejo Superior de Investigaciones Científicas
IFAE Institut de Física d'Altes Energies
Excelencia Severo Ochoa
BIST Barcelona Institute of Science and Technology
KIT
Qilimanjaro Quantum-Tech
University of Glasgow
Néel institut
cnrs
Delft Circuits Hardware for quantum engineers

AVaQus

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European Commission | Horizon 2020 European Union funding for Research & Innovation

Outline

- Introducing the Barcelona QC community
- The AVaQus project
  - Coherent quantum annealing
  - Superconducting flux qubits
  - Applications
- Conclusions

The Barcelona QC community

Barcelona is becoming a booming ecosystem for QC from all axes:

Academia

- ICFO
- IFAE – Institut de Física d'Altes Energies
- BSC – Barcelona Supercomputing Center – Centro Nacional de Supercomputación
- Universitat de Barcelona
- UAB – Universitat Autònoma de Barcelona
- UPC

Tech giants

- Keysight Technologies

Quantum-related Startups

- Entanglement Partners_ >
- QUSIDE
- Signadyne
- Metempsy
- QILIMANJARO QUANTUM · TECH

The Barcelona QC community

The Quantum Computing Technology group


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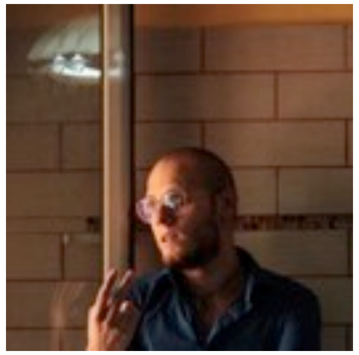
Luca Cozzolino, PhD


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https://qct.ifae.es

The Barcelona QC community

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Víctor Canivell (CBO)


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Jordi Blasco (CFO)


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https://qilimanjaro.tech


Jordi Riu


David Eslava


Yifei Chen


Matthias Werner

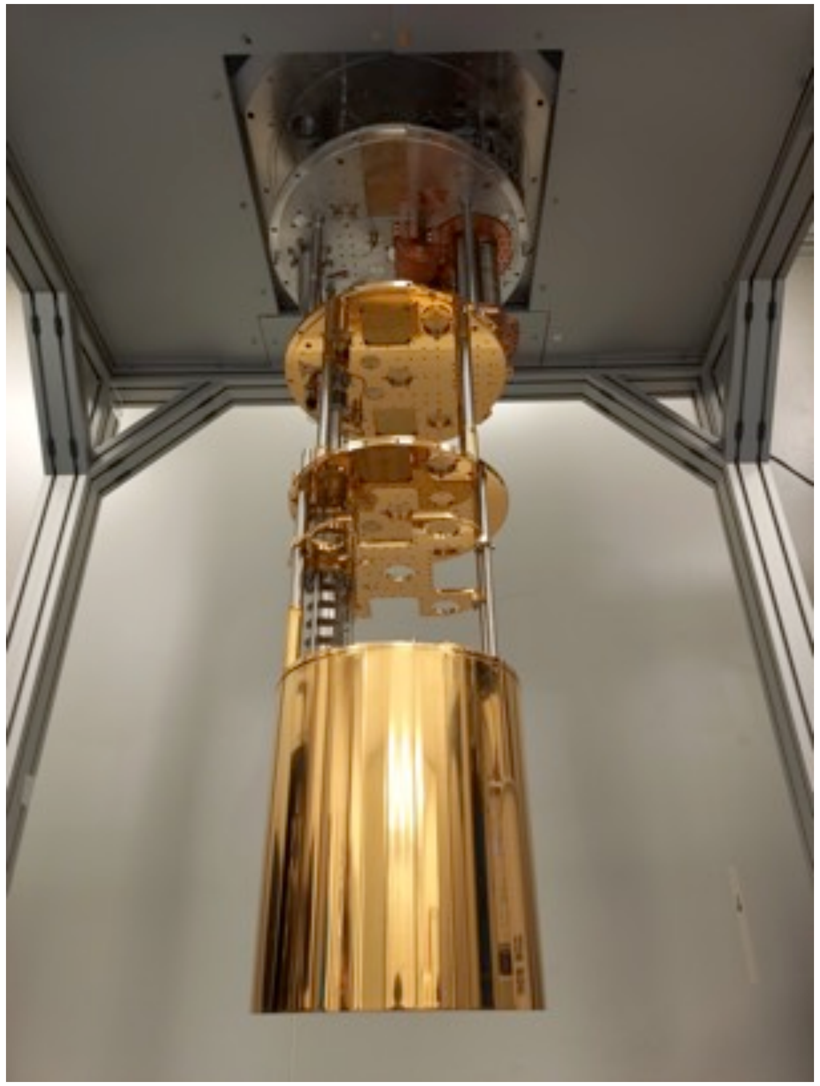

Joel Pérez


Albert Solana

The Barcelona QC community

The newly established QC lab at IFAE

Two dilution refrigerators for millikelvin qubit experiments



Ebeam deposition system for qubit production

QILIMANJARO QUANTUM · TECH

https://qct.ifae.es

IFAE Institute for High Energy Physics

EXCELENCIA SEVERO OCHOA

BIST

The AVaQus project: Annealing-based Variational Quantum processorS

European Commission

Horizon 2020
European Union funding
for Research & Innovation

The AVaQus project: What?

AVaQus is an European consortium formed by 8 partners and funded by the European Commission in the **FET Open** call from September 2019.

	Academia	Startups
Experiment	IFAE Institut de Física d'Altes Energies; KIT; University of Glasgow; Néel institut (CNRS)	Delft Circuits – Hardware for quantum engineers.
Theory	CSIC – Consejo Superior de Investigaciones Científicas	Qilimanjaro Quantum-Tech; HQS Quantum Simulations

Advisors: William Oliver (QEO), Daniel Lidar (QEO), Frank Wilhelm (QEO, OSQ), Florian Neukart (VW), Tsuyoshi Yamamoto (NEC), Barbara Terhal (Delft), Stefan Filipp (WMI)

The AVaQus project: Why?

- ➡ Europe is at a competitive **disadvantage** with respect to USA and China in quantum computation. Quantum annealing could provide **opportunities.**
- ➡ Quantum annealing is **not widely being pursued** as alternative to gate-based quantum computation. **Lack/Need** of experimental efforts [1].
- ➡ Quantum annealing has potential for short-term quantum advantage, even in the **long-term as a universal AQC** [2].
- ➡ **No quantum advantage** detected yet in a D-Wave machine.
- ➡ **No** European funded project on **quantum annealing.**

[1] Preskill, Quantum Computing in the NISQ era and beyond. Quantum 2, 79 (2018)
[2] Adiabatic Quantum Computation is Equivalent to Standard Quantum Computation. Aharonov et al., SIAM Journal of Computing, Vol. 37, Issue 1, p. 166-194 (2007).

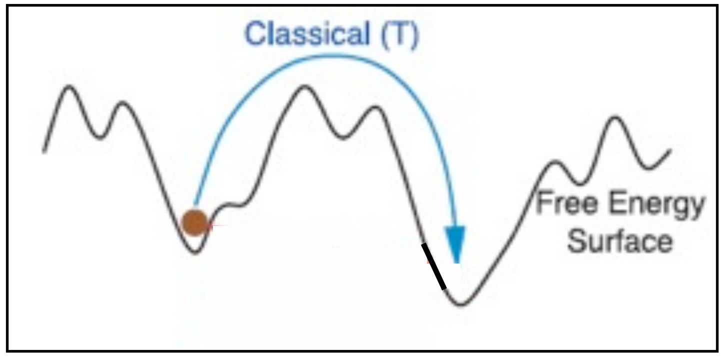
The AVaQus project: Coherent Quantum Annealing

Solving optimization problems with annealers

Example: 2-SAT

$$f(x_{i_C}, x_{j_C}) \begin{cases} = 0 & \text{, if } (x_{i_C}, x_{j_C}) \text{ satisfies clause C} \\ = 1 & \text{, if } (x_{i_C}, x_{j_C}) \text{ violates clause C} \end{cases}$$

Finding minimum of potential energy = Solving optimization problem



Quadratic cost functions can be cast in the form of classical Ising model (QUBO):

$$\mathcal{H}_{\mathrm{IC}} = -\sum_{i,j}^{N} J_{ij}\sigma_i^z\sigma_j^z - h\sum_{i}^{N}\sigma_i^z \qquad \{x_i\} \Longleftrightarrow \{\sigma_i^z\}$$

Quantum Annealing: Ising model in a transverse magnet [1]

$$\mathcal{H}_{IT} = -\sum_{i,j}^{N} J_{ij}\sigma_i^z\sigma_j^z - h\sum_{i}\sigma_i^z - \Gamma(t)\sum_{i}^{N}\sigma_i^x$$

$\Gamma \neq 0 \Rightarrow [\mathcal{H}_{IT}, \sigma_i^z] \neq 0$

σ_i^z is not a conserved quantity, it fluctuates ("tunnels")

Γ controls effective precession rate of spins! System can tunnel through potential energy to reach ground state

Example of 2-SAT problem:

$$\mathcal{H}_{IT}(|x_1\rangle|x_2\rangle\ldots|x_N\rangle) = f(x_{i_C}, x_{j_C})(|x_1\rangle|x_2\rangle\ldots|x_N\rangle)$$

Minimum energy of system coincides with optimal configuration of cost function.

Many classical optimization problems can be cast into the classical Ising model.

➡ HOW TO PREPARE THIS GROUND STATE?

[1] Kadowaki, Nishimori, Phys. Rev. E **58**, 5355 (1998)

The AVaQus project: Coherent Quantum Annealing

Adiabatic evolution [1]: Adiabatic theorem of Quantum Mechanics [2]

$$H_{D_i} = \frac{1}{2}(1 - \sigma_i^x) \qquad H_D = \sum_i H_{D_i}$$

Initial state: uncoupled qubits

$$H_P|\psi\rangle = 0 \qquad H_P = \sum_C H_{P,C}$$

Final state: ground state of problem Hamiltonian

$$H_C(t/T) = (1 - t/T)H_{D,C} + (t/T)H_{P,C}$$

Trivial   Problem

$$H(t/T) = \sum_C H_C(t/T)$$

Sum of total number of clauses

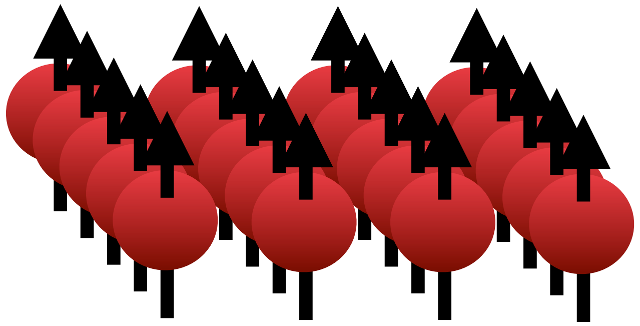
[1] E. Farhi et al., arxiv:quant-ph/0001106

[2] Messiah, Albert (1999). "XVII". Quantum Mechanics.

The AVaQus project: Coherent Quantum Annealing

Adiabatic Quantum Processor

$|\Psi_{\mathrm{GS}}(0)\rangle$

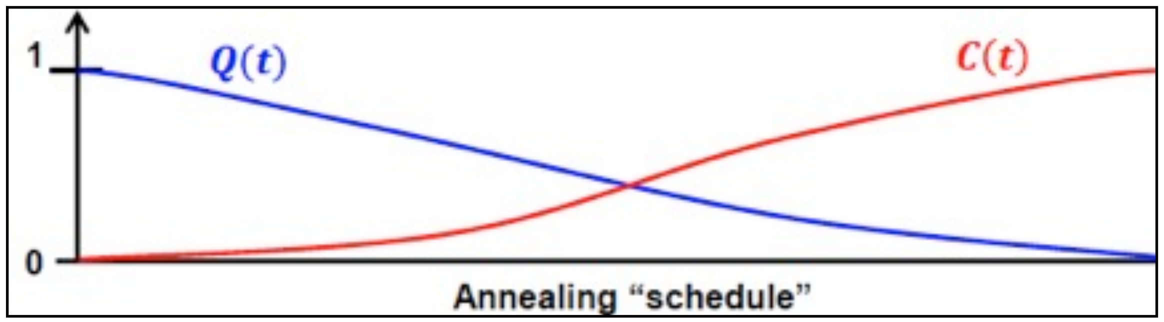


$\mathcal{H}(t)$

$|\Psi_{\mathrm{GS}}(t)\rangle$

Final complex ground state maps into solution of optimization problem

PROS:
Does not require quantum error correction.
Near-term applications: Optimization problems



$$\mathcal{H}(t) = Q(t)\mathcal{H}_D + C(t)\mathcal{H}_P$$

Trivial Problem

CONS:
Non-universal processor

E. Farhi et al., arxiv:quant-ph/0001106

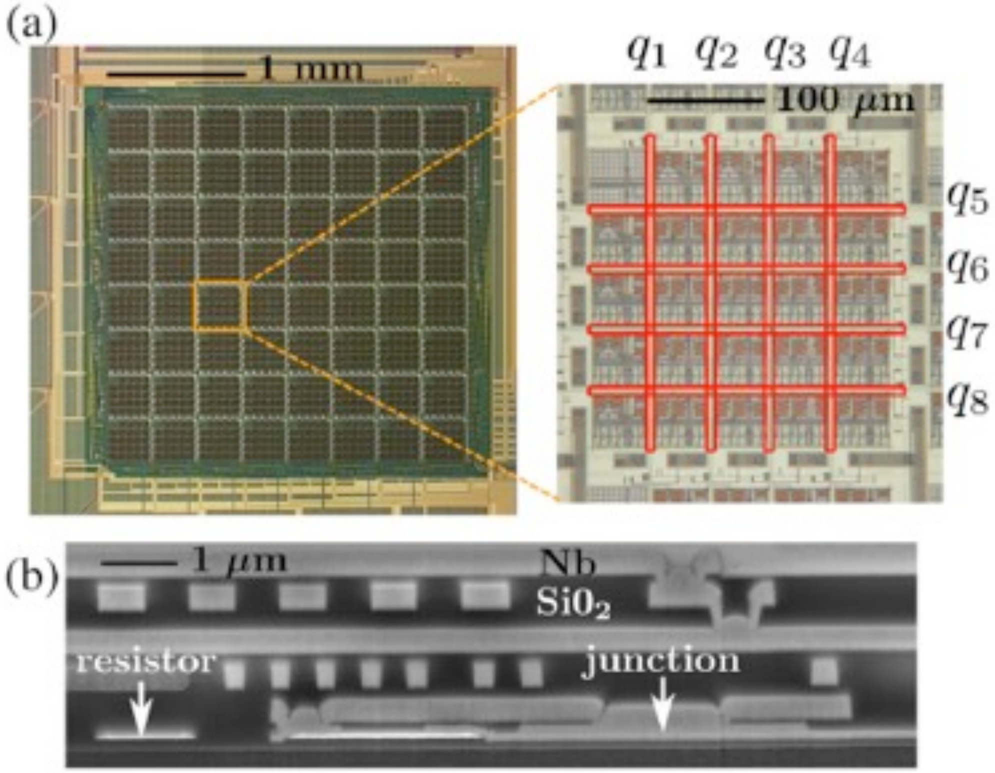
E. Farhi et al., Science 292, 472 (2001)

T. Albash and D. Lidar, Rev. Mod. Phys. 90, 015002 (2018)

The AVaQus project: Coherent Quantum Annealing

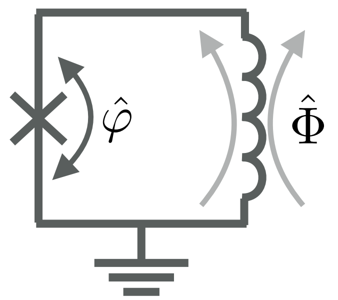
Current quantum annealers: D-Wave

Complex tri-layer chip architecture

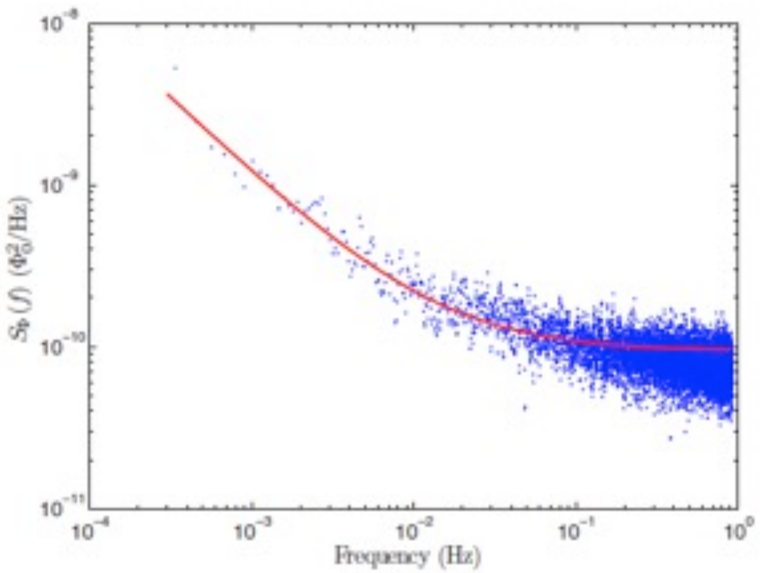


Harris *et al.*, Phys. Rev. B **81**, 134510 (2010)

Qubit: rf-SQUID



Displaying flux noise



Many achievements…

Harris *et al.*, Science **361**, 162 (2018)

King *et al.*, Nature **560**, 458 (2018)

… but no quantum advantage yet

Ronow *et al.*, Science **345**, 420 (2014)

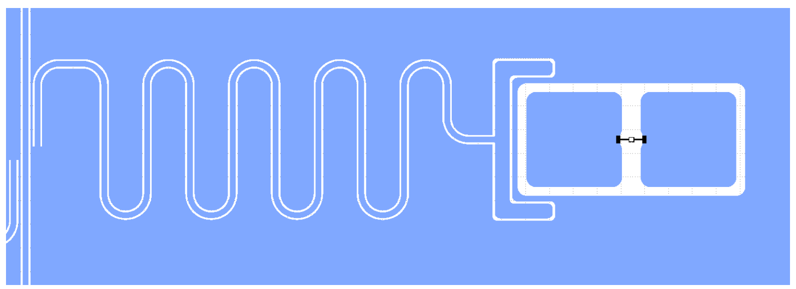
	Coherent Quantum Annealer	D-Wave
Qubit quality	**Highly** coherent	Low quantum coherence
Qubit-qubit interactions	Quantum model **hard** to simulate classically	Quantum model easy to simulate classically
Qubit connectivity	**High,** using long-range interactions	Low
Quantum Algorithms	Annealing, simulation, **Variational**	Annealing, simulation

The AVaQus project: Coherent Quantum Annealing

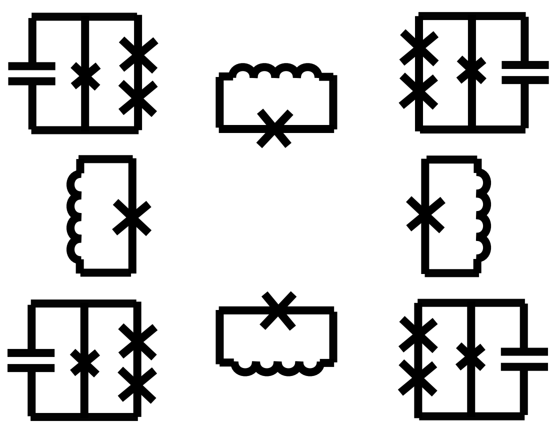
AVaQus main goals:

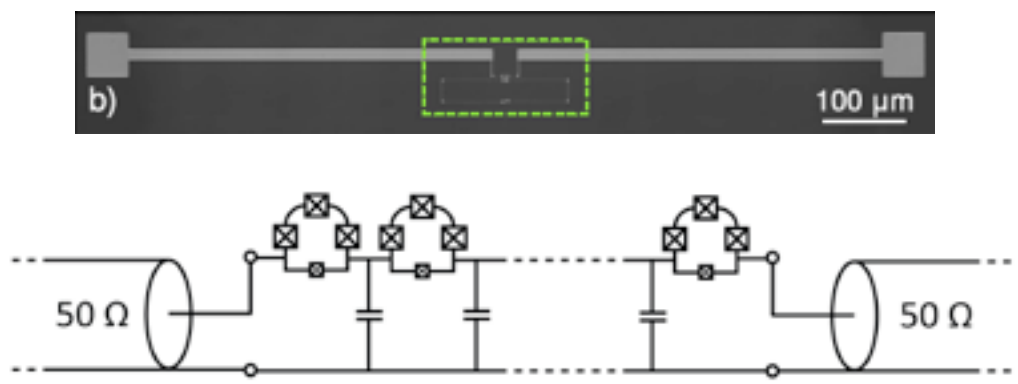
•Build 5-qubit **prototype,** superconducting coherent quantum annealer with flux qubits, defined as:

1. Qubits exhibit **coherence times exceeding annealing times,** with **fast** multiqubit control and measurement, and **low noise**.
2. Study **diabatic quantum annealing.**
3. Qubit-qubit interactions not easy to simulate classically: **beyond Ising**.
4. Complex (**non-planar**) connectivity qubit network.
5. Operate annealer as quantum simulator and as a non-universal, **variational quantum computer**.



Test c-shunt flux qubit

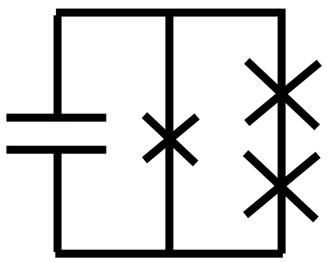




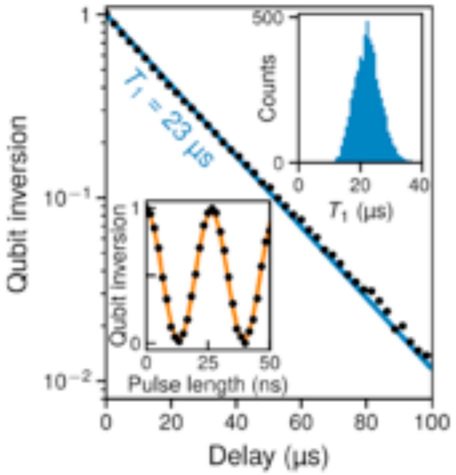
The AVaQus project: Superconducting flux qubits

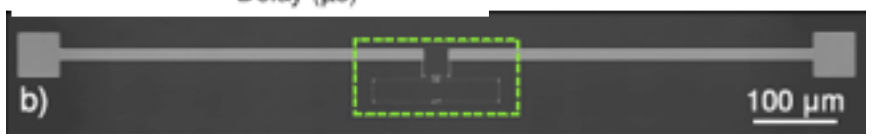
Employ flux qubits which retain coherence longer than relevant timescales

C-shunt persistent current qubits [2]

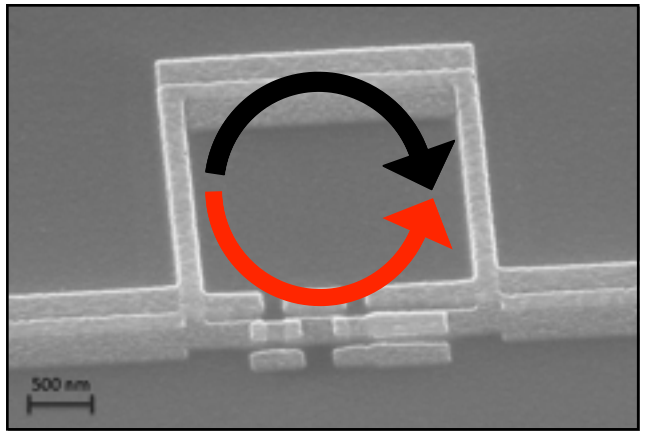


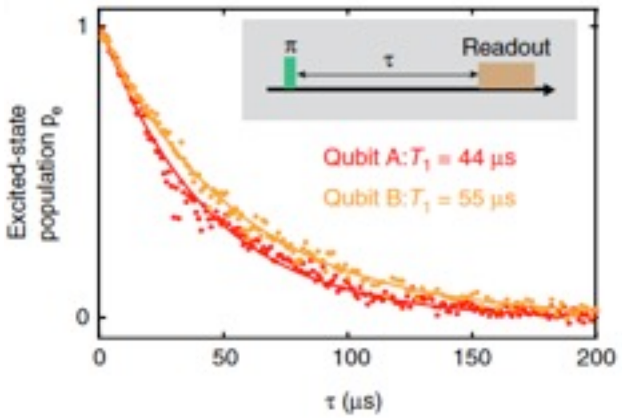
High impedance [3]



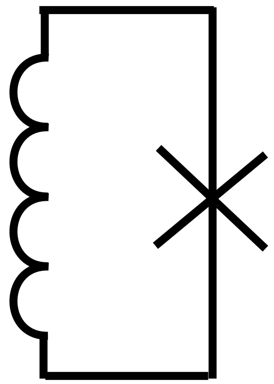


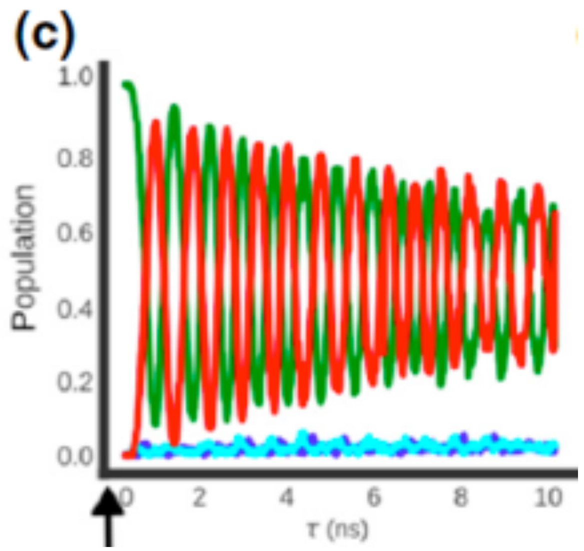
Low impedance [1]

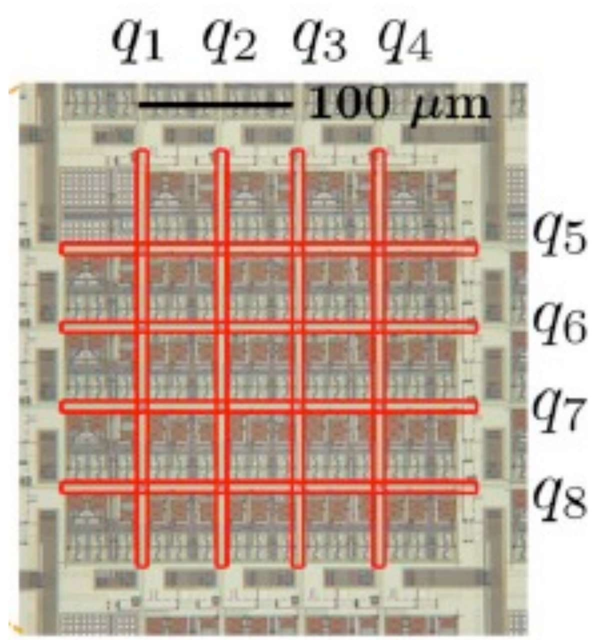




D-Wave rf SQUIDs [4]



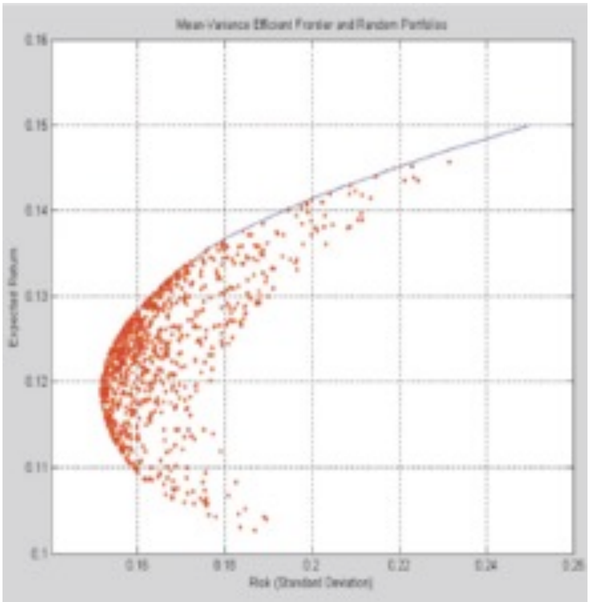




[1] T. P. Orlando et al., PRB 60, 15398 (1999)
[2] F. Yan et al., Nature Communications 7, 12964 (2016)
[3] Grünhaupt et al., Nature Materials 18, 816 (2019)
[4] Ozfidan et al., PHYSICAL REVIEW APPLIED 13, 034037 (2020)

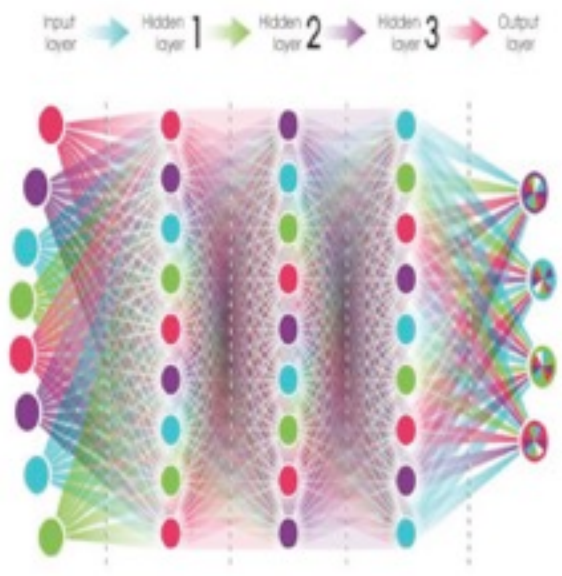
The AVaQus project: applications

Quantum annealing solves classical optimization problems and quantum simulations. AVaQus coherent quantum annealer can be programmed for variational/simulation algorithms



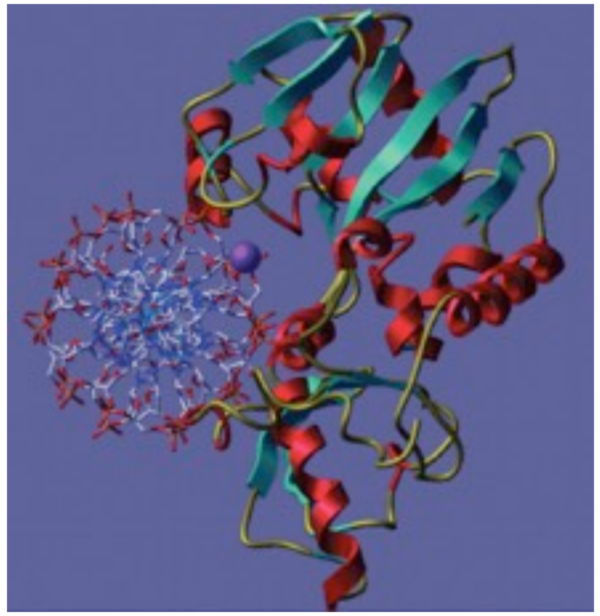
Optimization

Navigation, scheduling, portfolio management in finance, etc.



AI/ML

Neural networks trained more efficiently by quantum annealers



(Bio-)chemistry

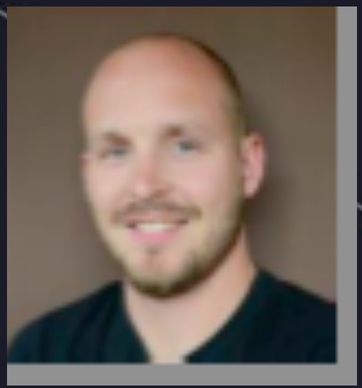
Study complex molecules to yield new drugs, fertilizers, CO2 capture, etc.

QIBO

- https://github.com/Quantum-TII/qibo
- arxiv.org/abs/2009.01845

Conclusions

- Barcelona Quantum Computing hub is emerging
- Coherent Quantum annealers show potential for quantum advantage
- AVaQus is the first big European funded project on quantum annealing
- CQA build out of coherent superconducting flux qubits
- AVaQus to produce a 5-qubit prototype CQA
- The QC effort in Barcelona will keep focusing on near-term applications for near-term devices



Nicolas Roch
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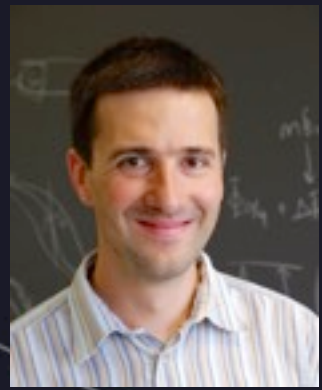

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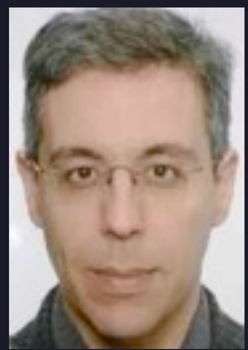

Dr. J. J. García-Ripoll
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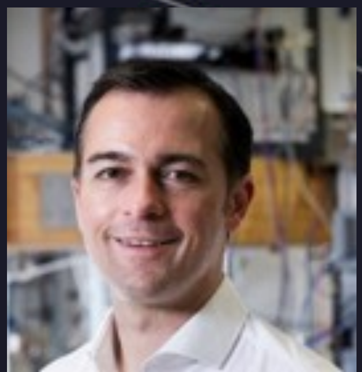
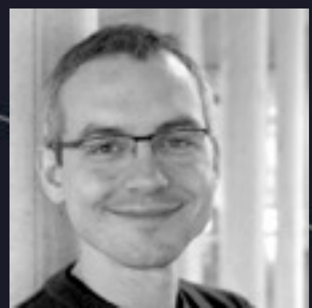


Prof. Martin Weides
(University of Glasgow)



Dr. Michael Marthaler
(HQS)

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AVaQus
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QUANTERA

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

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Delft Circuits
Hardware for quantum engineers.

THANK YOU!