eman ta zabal zazu

Universidad del País Vasco Euskal Herriko Unibertsitatea

QUTIS
QUANTUM TECHNOLOGIES FOR INFORMATION SCIENCE

ikerbasque
Basque Foundation for Science

Digital quantum computers
versus
Analog Quantum Simulators

Enrique Solano

University of the Basque Country, Bilbao, Spain

Solvay Workshop on Quantum Simulations, Brussels, February 2016

eman ta zabal zazu

Universidad del País Vasco / Euskal Herriko Unibertsitatea

QUTIS
Quantum Technologies for Information Science

ikerbasque
Basque Foundation for Science

Honouring Peter Zoller by showing some of the works in quantum simulation … I did without him

Enrique Solano

University of the Basque Country, Bilbao, Spain

Solvay Workshop on Quantum Simulations, Brussels, February 2016

Iker Millán	**QUTIS Group**	M. Sc. Laura García-Álvarez
Amaia Irastorza	**Prof. Enrique Solano**	M. Sc. Unai Alvarez-Rodriguez
Cristián Romero-García		M. Sc. Julen S. Pedernales
B. Sc. Adrián Parra	**Quantum optics**	Dr. Mikel Sanz
B. Sc. Hodei Eneriz	**Quantum information**	Dr. Daniel Rossatto
M. Sc. Íñigo Arrazola	**Superconducting circuits**	Dr. Enrique Rico
M. Sc. Xiao-Hang Cheng	**Condensed matter**	Dr. Lucas Lamata
M. Sc. Urtzi Las Heras	**Quantum biomimetics**	Prof. Íñigo Egusquiza

In this talk, I will share my views on how to positively answer to the key question:

Is it possible to outperform classical computers in the next 10 years?

Evidently, any such proposal can only involve:

i) few tens of qubits, cavities, motional modes, open transmission lines
ii) novel paradigms for quantum computing and quantum simulation

Most of my examples will be in circuit QED (cQED) and superconducting circuits (SC)

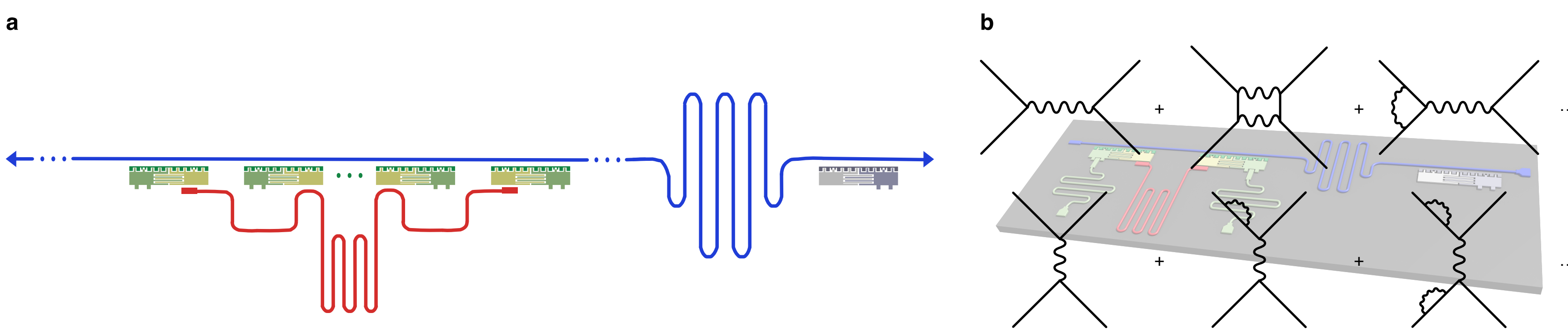
QUTIS
QUANTUM TECHNOLOGIES FOR INFORMATION SCIENCE

Bilbao Quantum Machine

BQM

Quantum field theory models

L. García-Álvarez et al., PRL 2015



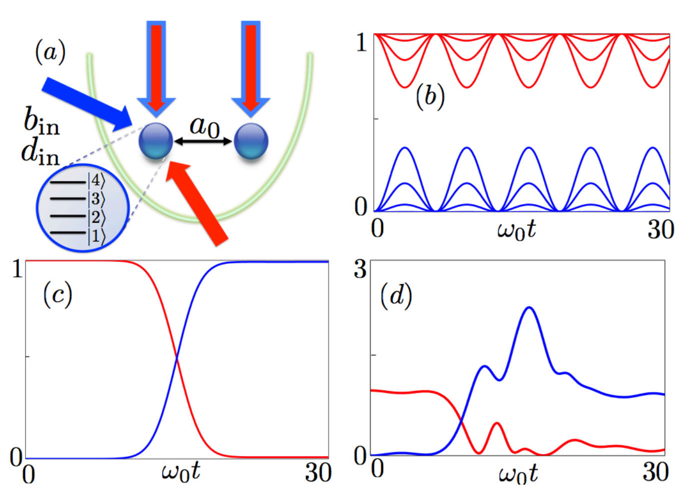
Superconducting circuits

Complexity simulating complexity

Digital-analog quantum simulation

Quantum Field Theory models

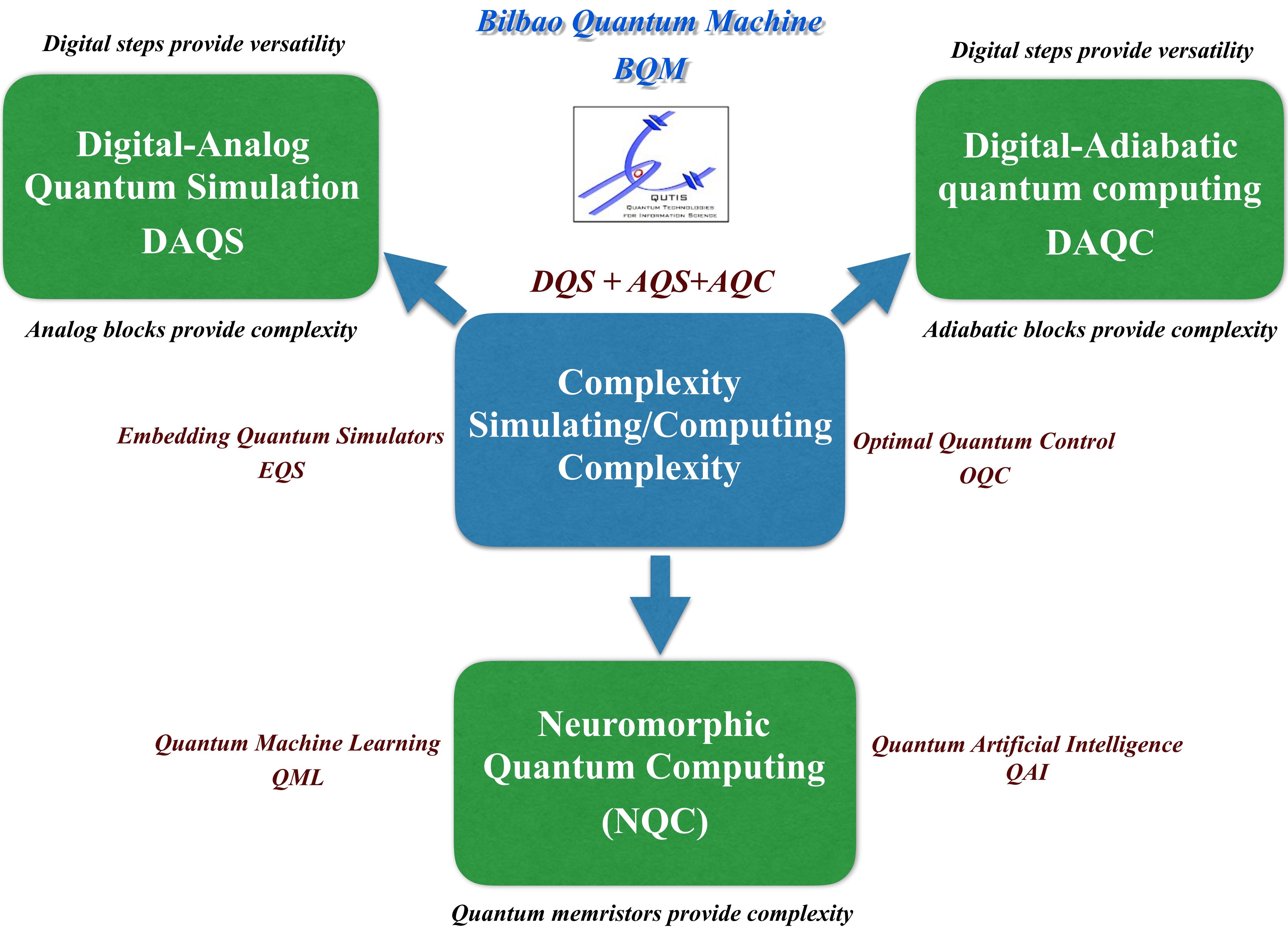
Casanova et al., PRL 2011



Trapped ions

Trapped ions require discretized field modes

cQED naturally enjoys a continuum of bosonic modes

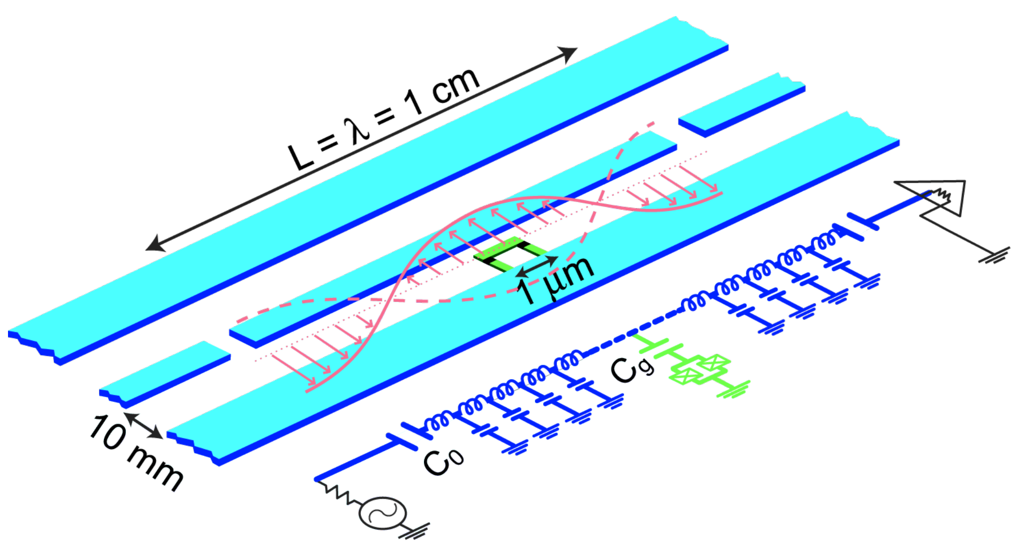


Bilbao Quantum Machine
BQM
QUTIS
Quantum Technologies for Information Science
Digital steps provide versatility
Digital-Analog Quantum Simulation
DAQS
Analog blocks provide complexity
Digital steps provide versatility
Digital-Adiabatic quantum computing
DAQC
Adiabatic blocks provide complexity
DQS + AQS+AQC
Complexity Simulating/Computing Complexity
Embedding Quantum Simulators
EQS
Optimal Quantum Control
OQC
Quantum Machine Learning
QML
Neuromorphic Quantum Computing
(NQC)
Quantum Artificial Intelligence
QAI
Quantum memristors provide complexity

Circuit QED (cQED) and Superconducting Circuits (SC)

Jaynes-Cummings (JC) model in circuit QED: a field mode represents the field mode, the two-level atom is replaced by a superconducting qubit, also called artificial atom.

$$H^T = \omega_r a^\dagger a + \sum_{i=1}^{N} [4E_{C,i}(n_i - n_{g,i})^2 - E_{J,i}\cos\phi_i + 2\beta_i e V_{\mathrm{rms}} n_i (a + a^\dagger)].$$



Yale group

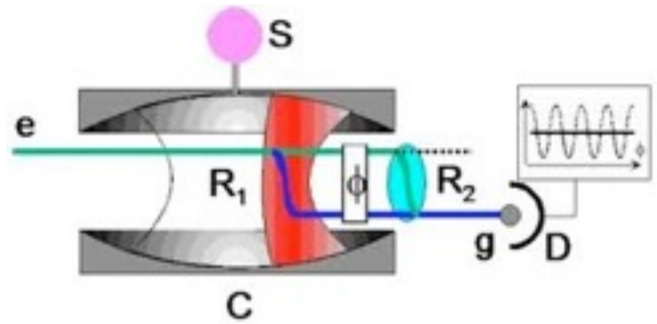
A. Wallraff et al., Nature 2004

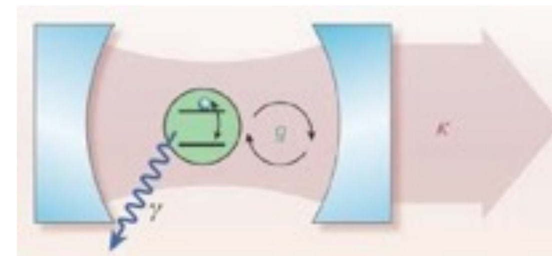
$$H_{JC} = \frac{\hbar\omega_0}{2}\sigma_z + \hbar\omega\, a^\dagger a + \hbar g\left(\sigma^+ a + \sigma^- a^\dagger\right)$$

It is an unacknowledged quantum simulation of the JC model in circuit QED.

Two motivations for quantum simulations

I) Quantum simulation establishes analogies between unconnected fields,
it is a communication vessel producing a flood of knowledge in both directions.



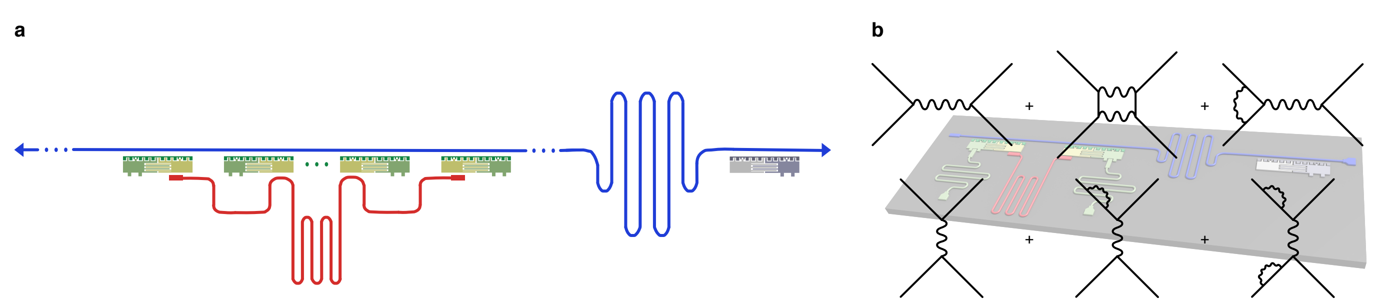


cQED has advantages in atomic control that overcomes those of microwave CQED,
and, at the same time, it enjoys longitudinal and transversal driving as in optical CQED.

MANTRA: the same model in another quantum platform always brings novel physics: strongly dispersive regime, USC & DSC of light-matter in cavities and open TLs, etc.

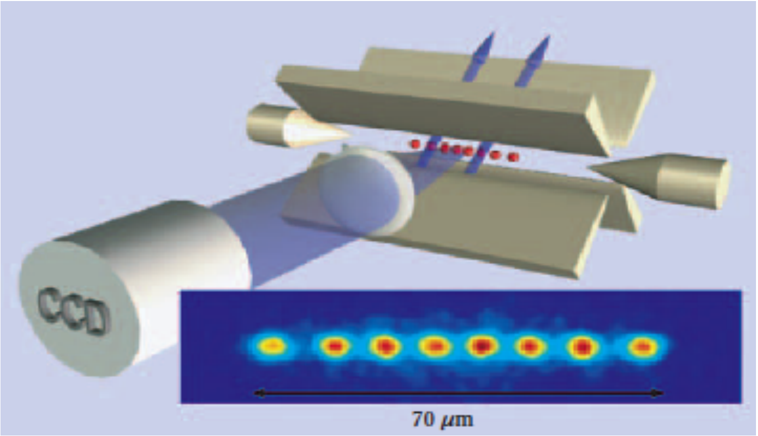
II) Quantum simulations will allow us to predict and explain novel physics
when we will be able to implement scalable quantum simulators.

For instance, solving complex problems in condensed matter, quantum chemistry,
quantum field theory, machine learning, and artificial intelligence.



Which was the first quantum simulation experiment?

We could consider the implementation of the JC model in trapped ions
as (one of) the first nontrivial quantum simulations.



$$H_0 = \hbar\nu(a^\dagger a + \frac{1}{2})$$

$$H_r = \hbar\eta\tilde{\Omega}_r\left(\sigma^+ a e^{i\phi_r} + \sigma^- a^\dagger e^{-i\phi_r}\right)$$

Red sideband excitation of the ion = JC interaction

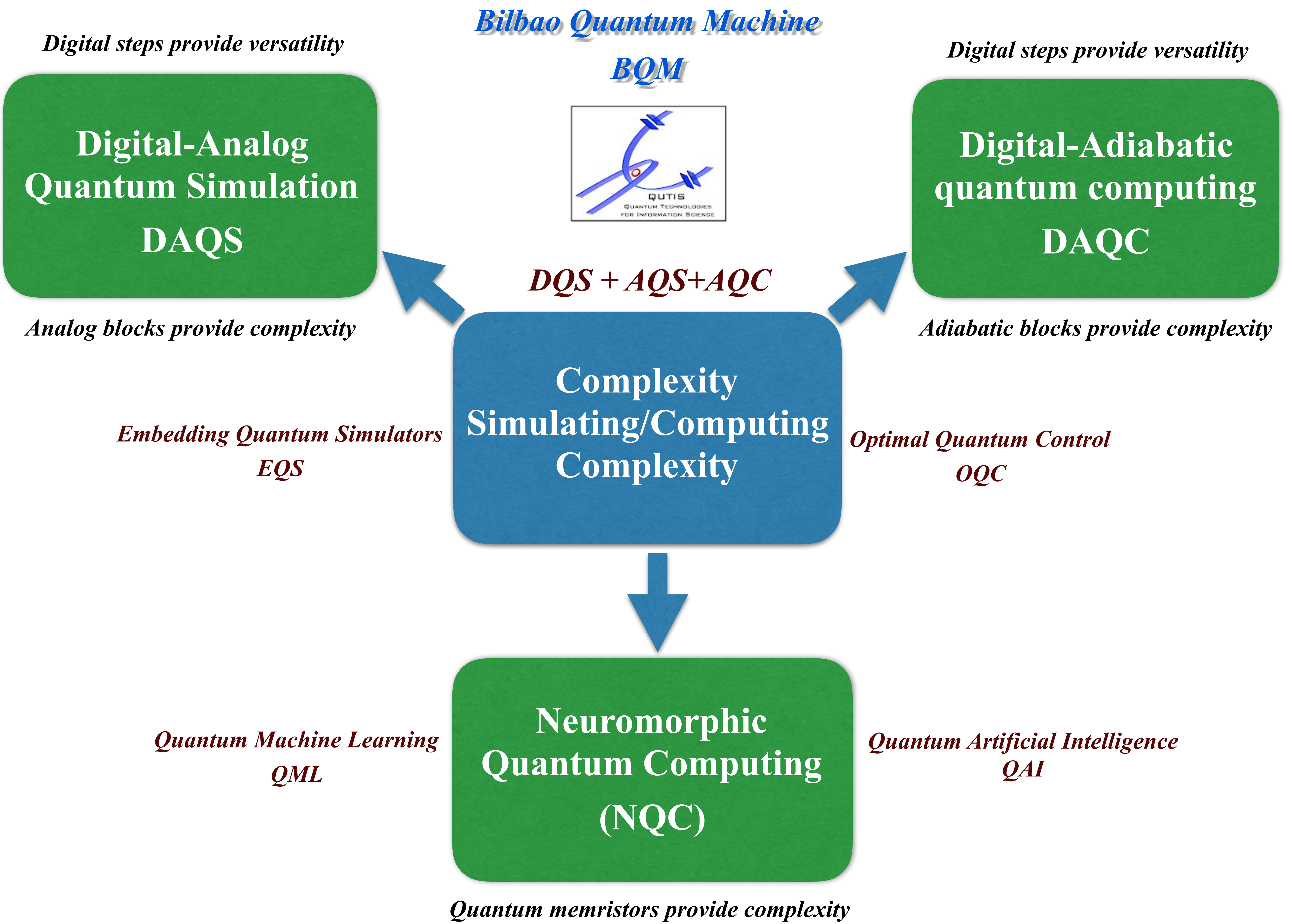
$$H_b = \hbar\eta\tilde{\Omega}_b\left(\sigma^+ a^\dagger e^{i\phi_b} + \sigma^- a e^{-i\phi_b}\right)$$

Blue sideband excitation of the ion = anti-JC interaction

The quantized electromagnetic field is replaced by quantized ion motion

This allowed Cirac & Zoller to propose in 1995 the first implementable two-qubit gate for universal QC in trapped ions!

MANTRA: the same model in another quantum platform always brings novel physics, … if you are creative enough.



Bilbao Quantum Machine
BQM
QUTIS
QUANTUM TECHNOLOGIES FOR INFORMATION SCIENCE
Digital steps provide versatility
Digital-Analog Quantum Simulation
DAQS
Analog blocks provide complexity
Digital steps provide versatility
Digital-Adiabatic quantum computing
DAQC
Adiabatic blocks provide complexity
DQS + AQS+AQC
Complexity Simulating/Computing Complexity
Embedding Quantum Simulators
EQS
Optimal Quantum Control
OQC
Quantum Machine Learning
QML
Neuromorphic Quantum Computing
(NQC)
Quantum Artificial Intelligence
QAI
Quantum memristors provide complexity

Digital quantum machines

There are two classes of digital quantum machines:

1) Digital (gate-based) quantum computer (DQC)

2) Digital quantum simulator (DQS)

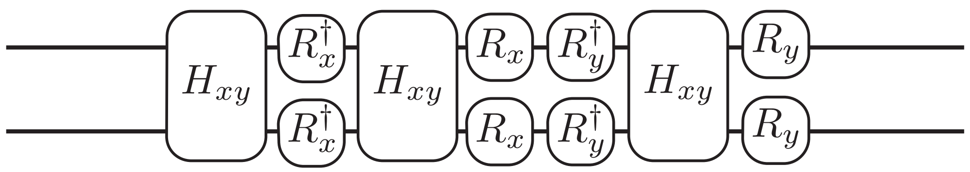
A DQC can become universal, fault tolerant, and scalable.
It is meant to perform general-purpose quantum algorithms (e.g., Grover & Shor).

A DQS is not meant to be universal, but it could turn fault tolerant and scalable.
It is essentially a purpose-oriented DQC that mimics models (spins, bosons, fermions).

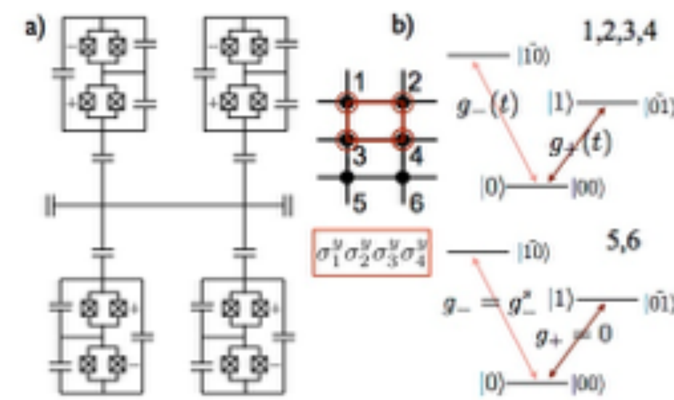
DQC/DQS may not be able to outperform classical computers with prethreshold quantum platforms, and fault-tolerant approaches demand millions of gates/qubits.

DQS with superconducting circuits: Bilbao theory

DQS of spin Models with SC
Las Heras et al., PRL 2014

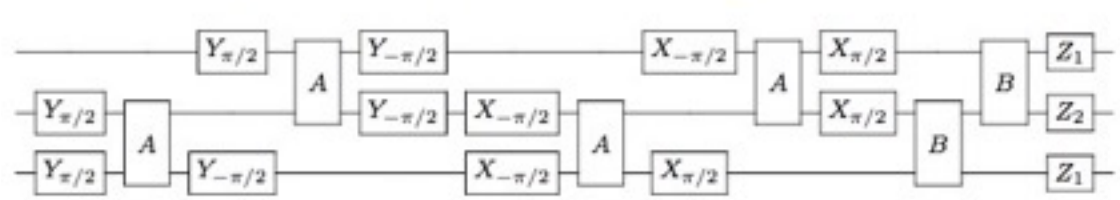


Multiqubit gates & MS gates with SC
Mezzacapo et al. PRL 2014



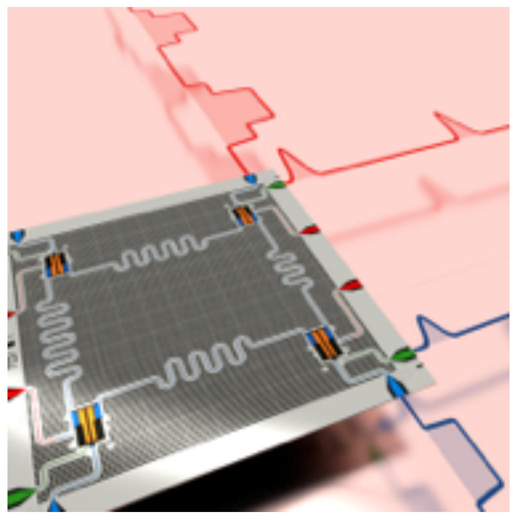
DQS of fermionic models with SC
Las Heras et al., EPJ QT 2015

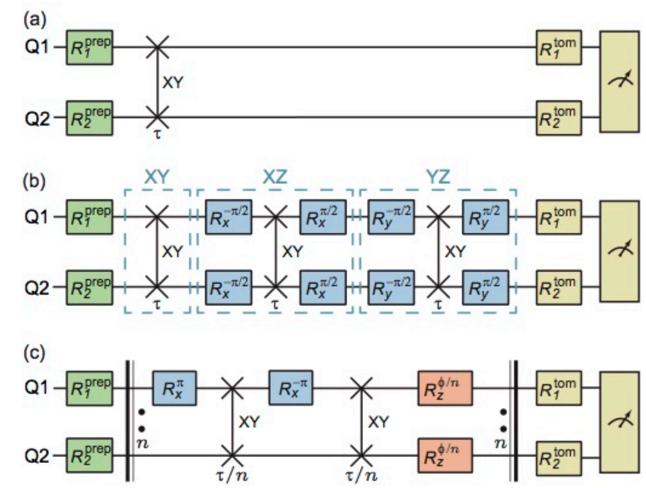
Table 1 Sequence of gates for one Trotter step of Hamiltonian 2.



First DQS of spin models with superconducting circuits

Collaboration Bilbao-Zürich





PHYSICAL REVIEW X **5,** 021027 (2015)

Digital Quantum Simulation of Spin Models with Circuit Quantum Electrodynamics

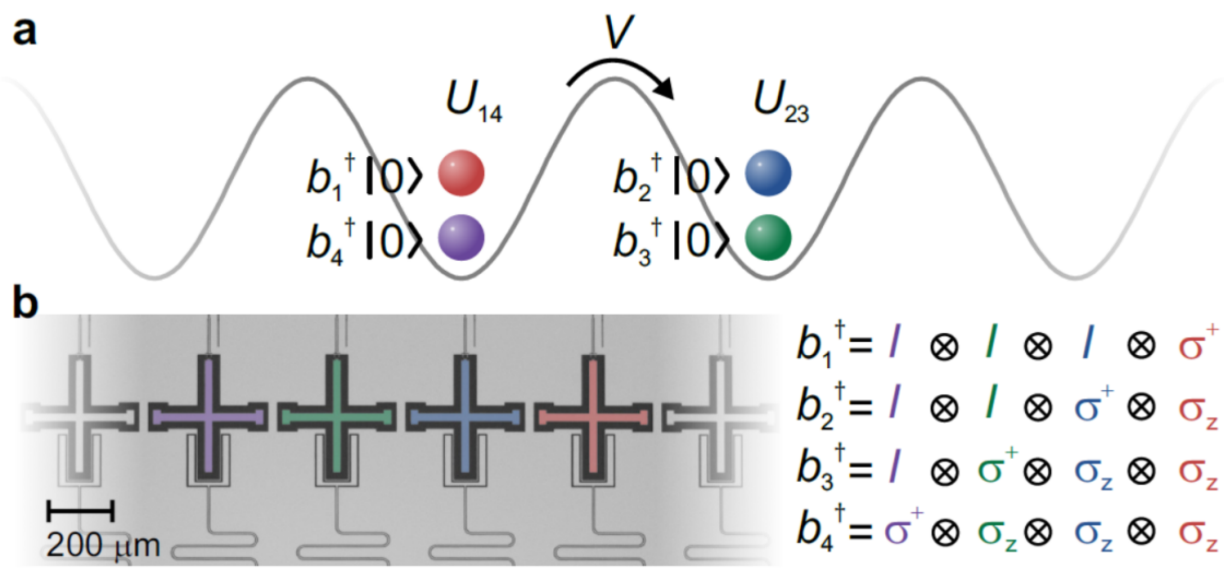
Y. Salathé,[1,*] M. Mondal,[1] M. Oppliger,[1] J. Heinsoo,[1] P. Kurpiers,[1] A. Potočnik,[1] A. Mezzacapo,[2] U. Las Heras,[2] L. Lamata,[2] E. Solano,[2,3] S. Filipp,[1,†] and A. Wallraff[1]

[1]*Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland*
[2]*Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*
[3]*IKERBASQUE, Basque Foundation for Science, Maria Diaz de Haro 3, 48013 Bilbao, Spain*
(Received 6 March 2015; published 17 June 2015)

DQS with superconducting circuits: experiments

First DQS of fermionic models with superconducting circuits

Collaboration Bilbao-Google (UCSB)



nature COMMUNICATIONS

ARTICLE

Received 16 Mar 2015 | Accepted 24 May 2015 | Published 8 Jul 2015 DOI: 10.1038/ncomms8654 OPEN

Digital quantum simulation of fermionic models with a superconducting circuit

R. Barends[1], L. Lamata[2], J. Kelly[3,†], L. García-Álvarez[2], A.G. Fowler[1], A. Megrant[3,4], E. Jeffrey[1], T.C. White[3], D. Sank[1], J.Y. Mutus[1], B. Campbell[3], Yu Chen[1], Z. Chen[3], B. Chiaro[3], A. Dunsworth[3], I.-C. Hoi[3], C. Neill[3], P.J.J. O'Malley[3], C. Quintana[3], P. Roushan[1], A. Vainsencher[3], J. Wenner[3], E. Solano[2,5] & John M. Martinis[1,3]

First digitization of adiabatic quantum computing with superconducting circuits

Collaboration Bilbao-Google (UCSB & LA)

Digitized adiabatic quantum computing with a superconducting circuit

R. Barends,[1] A. Shabani,[2] L. Lamata,[3] J. Kelly,[1] A. Mezzacapo,[3,*] U. Las Heras,[3] R. Babbush,[2] A. G. Fowler,[1] B. Campbell,[4] Yu Chen,[1] Z. Chen,[4] B. Chiaro,[4] A. Dunsworth,[4] E. Jeffrey,[1] E. Lucero,[1] A. Megrant,[4] J. Y. Mutus,[1] M. Neeley,[1] C. Neill,[4] P. J. J. O'Malley,[4] C. Quintana,[4] P. Roushan,[1] D. Sank,[1] A. Vainsencher,[4] J. Wenner,[4] T. C. White,[4] E. Solano,[3,5] H. Neven,[2] and John M. Martinis[1,4]

[1]*Google Inc., Santa Barbara, CA 93117, USA*
[2]*Google Inc., Venice, CA 90291, USA*
[3]*Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*
[4]*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[5]*IKERBASQUE, Basque Foundation for Science, Maria Diaz de Haro 3, 48013 Bilbao, Spain.*

A major challenge in quantum computing is to solve general problems with limited physical hardware. Here, we implement digitized adiabatic quantum computing, combining the generality of the adiabatic algorithm with the universality of the digital approach, using a superconducting circuit with nine qubits. We probe the adiabatic evolutions, and quantify the success of the algorithm for random spin problems. We find that the system can approximate the solutions to both frustrated Ising problems and problems with more complex interactions, with a performance that is comparable. The presented approach is compatible with small-scale systems as well as future error-corrected quantum computers.

R. Barends et al., arXiv:1511.03316

Analog quantum machines

There are two classes of analog quantum machines:

1) Analog quantum simulator (AQS)

2) Analog quantum computer (AQC)

An AQS is not meant to be universal but it could, in principle, outperform classical computers.
Optical lattices and quantum photonics are trying hard. Trapped ions and SC should also bet.

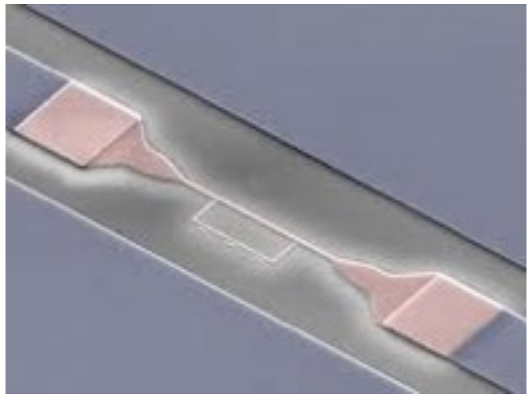
An AQC can be represented by adiabatic quantum computing or quantum annealing.
It performs quantum computations by encoding classes of optimization problems.

AQS/AQC may not outperform classical devices with prethreshold quantum platforms.
It is usually accepted without demonstration that AQS/AQC cannot become fault tolerant.

Ultrastrong coupling (USC) regime of the quantum Rabi model

We have recently seen the advent of the ultrastrong coupling (USC) regime of light-matter interactions in cQED, where 0.1< g/w < 1, and RWA cannot be applied.

$$H_{QRM} = \frac{\hbar\omega_0}{2}\sigma_z + \hbar\omega a^\dagger a + \hbar g(\sigma^+ + \sigma^-)(a^\dagger + a)$$



T. Niemczyk et al., Nature Phys. **6**, 772 (2010)

P. Forn-Díaz et al., PRL **105**, 237001 (2010)

Recently, the analytical solutions of the QRM were presented: D. Braak, PRL **107**, 100401 (2011).

Current experimental efforts are trying to approach nonperturbative USC regimes, where g/w ~ 0.5-1.0

Very recent works, see arXiv and APS March Meeting abstracts, announce even the experimental arrival of the deep strong coupling (DSC) regime of light-matter interactions.

The DSC regime was proposed and studied in Casanova et al., PRL 2010

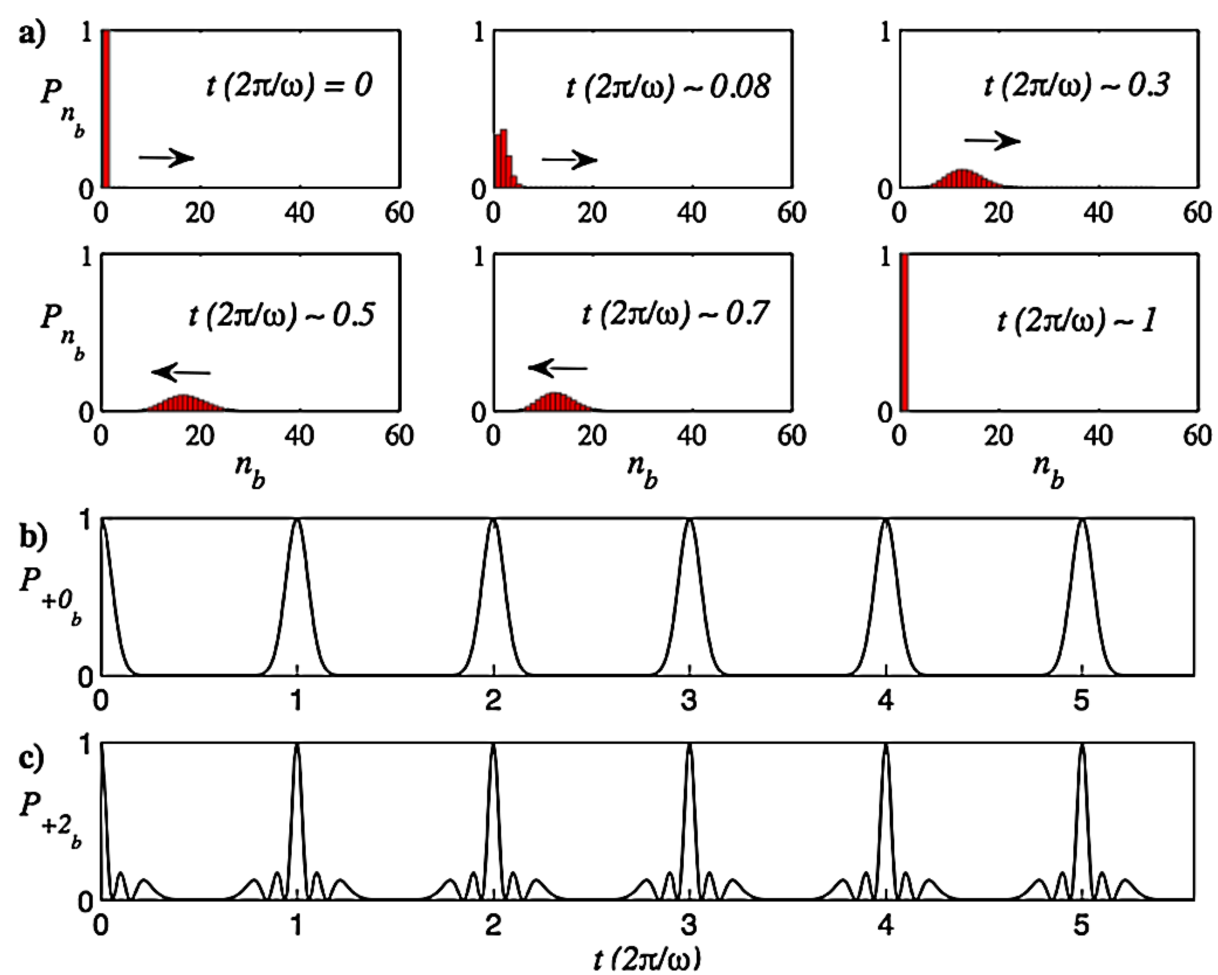
Deep strong coupling (DSC) regime of the QRM

The DSC regime of the JC model happens when g/w > 1.0, and it has been questioned whether such a regime could be experimentally reached or ever exist in nature.

$$\Pi = -\sigma_z(-1)^{n_a} = -(|e\rangle\langle e| - |g\rangle\langle g|)(-1)^{a^\dagger a}$$

$$|g0_a\rangle \leftrightarrow |e1_a\rangle \leftrightarrow |g2_a\rangle \leftrightarrow |e3_a\rangle \leftrightarrow \ldots (p = +1)$$
$$|e0_a\rangle \leftrightarrow |g1_a\rangle \leftrightarrow |e2_a\rangle \leftrightarrow |g3_a\rangle \leftrightarrow \ldots (p = -1)$$

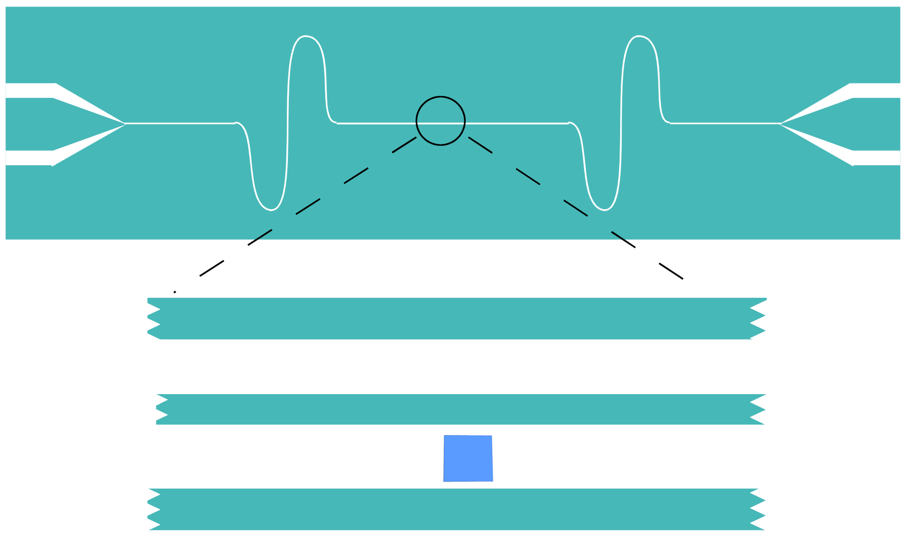
Forget about Rabi oscillations or perturbation theory:
parity chains and photon number wavepackets
define the physics of the DSC regime.



J. Casanova, t al., PRL **105**, 263603 (2010)

AQS with superconducting circuits: Bilbao theory

AQS of USC & DSC regimes of the quantum Rabi model



$$\mathcal{H}_{\rm JC} = \frac{\hbar\omega_q}{2}\sigma_z + \hbar\omega a^\dagger a + \hbar g(\sigma^\dagger a + \sigma a^\dagger)$$

Two-tone microwave driving

$$\mathcal{H}_D = \hbar\Omega_1(e^{i\omega_1 t}\sigma + \text{H.c.}) + \hbar\Omega_2(e^{i\omega_2 t}\sigma + \text{H.c.})$$

Leads to the effective Hamiltonian: QRM in all regimes

$$\mathcal{H} = \hbar(\omega - \omega_1)a^\dagger a + \frac{\hbar\Omega_2}{2}\sigma_z + \frac{\hbar g}{2}\sigma_x(a + a^\dagger)$$

A two-tone driving in cavity QED or circuit QED can turn any JC model into a USC or DSC regime of the QRM model.

D. Ballester et al., PRX 2012

Digital quantum machines or analog quantum machines?

Digital quantum machines and analog quantum machines have polarized
SS and AMO communities. Where is your place in this debate?

This debate is flawed or may not exist at all.

We propose

digital-analog quantum simulation (DAQS)

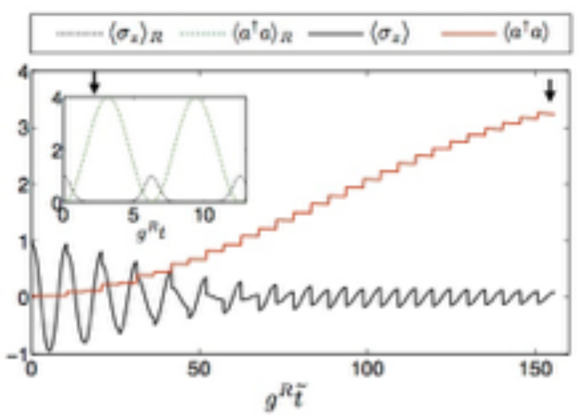
with prethreshold quantum devices to outperform classical computers in the next 10 years.

Complexity Simulating Complexity

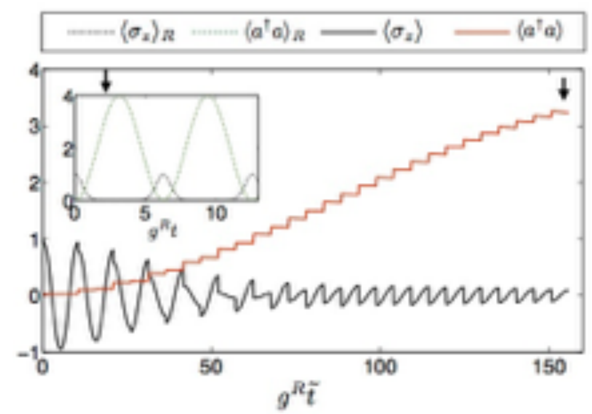
A fist experiment in DAQS for superconducting circuits

Bilbao theory + Delft experiment?

Digital quantum Rabi and Dicke models
Mezzacapo et al., Sci. Rep. 2014



Experiment at TU Delft?



In DAQS, **analog blocks** are combined sequentially with **digital steps**.

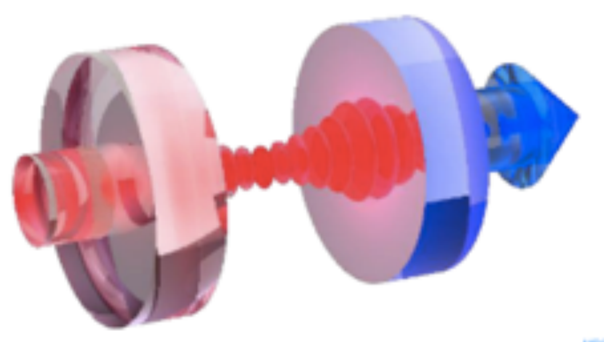
Analog blocks are made of collective quantum gates, that is, in-built complex operations.
Digital steps are local quantum operations that may act also in a global manner.

Analog blocks provide the complexity of the simulated model, **digital steps provide flexibility**.
Similar spirit can be followed by introducing digital-adiabatic quantum computers (DAQC).

How DAQS works on superconducting circuits?

Digital quantum Rabi and Dicke models
Mezzacapo et al., Sci. Rep. 2014

Quantum Rabi model: most fundamental light-matter interaction



$$H_R = \omega_r^R a^\dagger a + \frac{\omega_q^R}{2}\sigma^z + g^R \sigma^x (a^\dagger + a)$$

Small coupling as compared to mode & qubit frequencies: Jaynes-Cummings model

$$H = \omega_r a^\dagger a + \frac{\omega_q}{2}\sigma^z + g(a^\dagger \sigma^- + a\sigma^+)$$

Digital quantum Rabi and Dicke models

Mezzacapo et al., Sci. Rep. 2014

Interaction available in cQED: Jaynes-Cummings model

$$H = \omega_r a^\dagger a + \frac{\omega_q}{2}\sigma^z + g(a^\dagger \sigma^- + a\sigma^+)$$

↓

Digital decomposition: JC + local rotations

$$H_R = H_1 + H_2,$$

$$H_1 = \frac{\omega_r^R}{2} a^\dagger a + \frac{\omega_q^1}{2}\sigma^z + g(a^\dagger \sigma^- + a\sigma^+),$$

$$H_2 = \frac{\omega_r^R}{2} a^\dagger a - \frac{\omega_q^2}{2}\sigma^z + g(a^\dagger \sigma^+ + a\sigma^-),$$

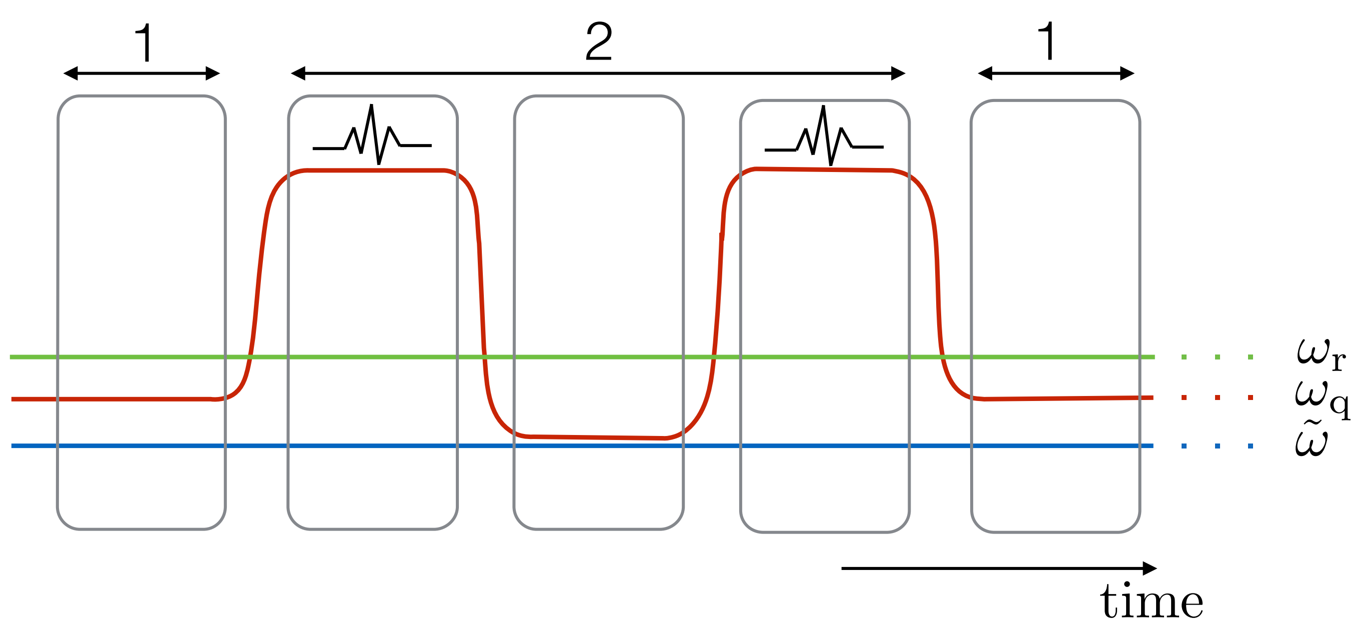
Digital quantum Rabi and Dicke models

Mezzacapo et al., Sci. Rep. 2014

JC in interaction picture $\tilde{H} = \tilde{\Delta}_r a^\dagger a + \tilde{\Delta}_q \sigma^z + g(a^\dagger \sigma^- + a\sigma^+),$

and we get AJC $e^{-i\pi\sigma^x/2}\tilde{H}e^{i\pi\sigma^x/2} = \tilde{\Delta}_r a^\dagger a - \tilde{\Delta}_q \sigma^z + g(a^\dagger \sigma^+ + a\sigma^-).$

→ Trotterization

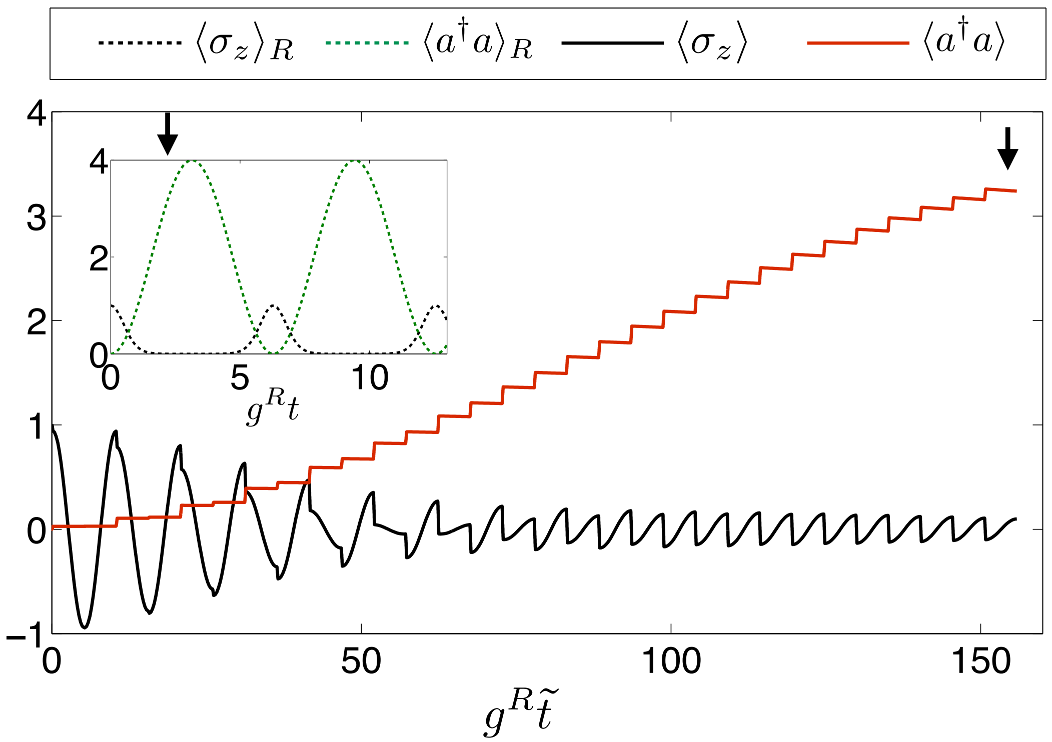


Digital quantum Rabi and Dicke models

Mezzacapo et al., Sci. Rep. 2014

$g^R = \omega_q^R/2 = \omega_r^R/2$	$\tilde{\omega} = 7.4$ GHz, $\omega_q^1 - \omega_q^2 = 200$ MHz
$g^R = \omega_q^R = \omega_r^R$	$\tilde{\omega} = 7.45$ GHz, $\omega_q^1 - \omega_q^2 = 100$ MHz
$g^R = 2\omega_q^R = \omega_r^R$	$\tilde{\omega} = 7.475$ GHz, $\omega_q^1 - \omega_q^2 = 100$ MHz

Some parameters…

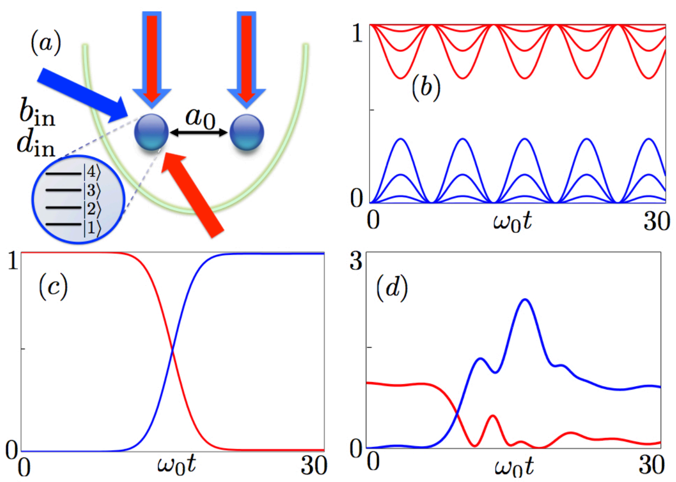


$$\omega_q^R = 0, \text{ and } g^R = \omega_r^R.$$

USC & DSC regimes are simulated. Move now towards to the Dicke model!

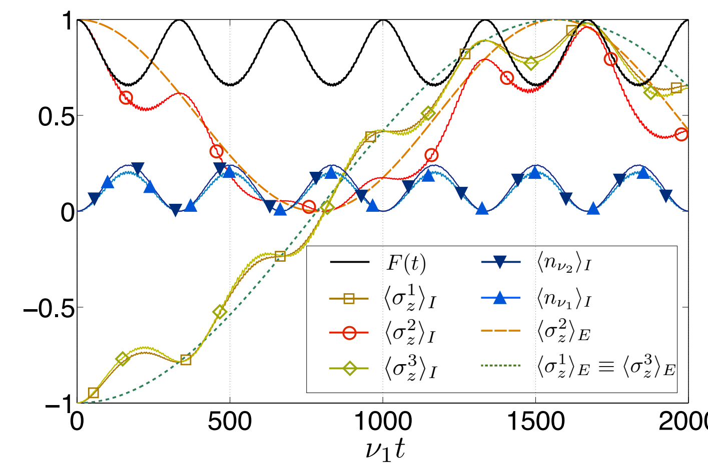
Further works involving DAQS concepts

Quantum Field Theory models
Casanova et al., PRL 2011



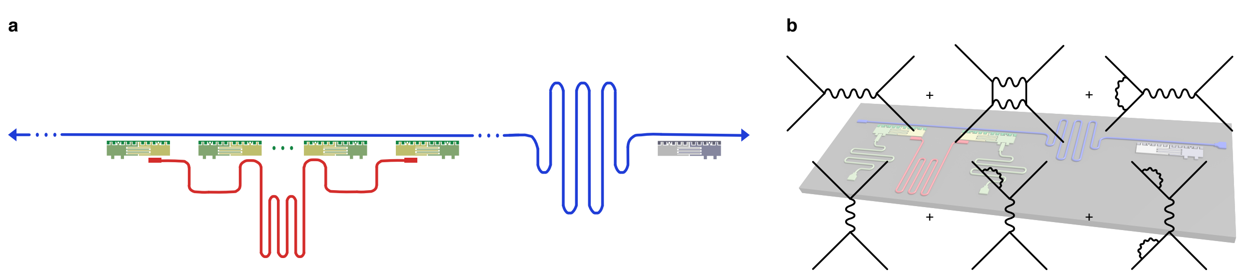
Trapped ions

Holstein Models
Mezzacapo et al., PRL 2012



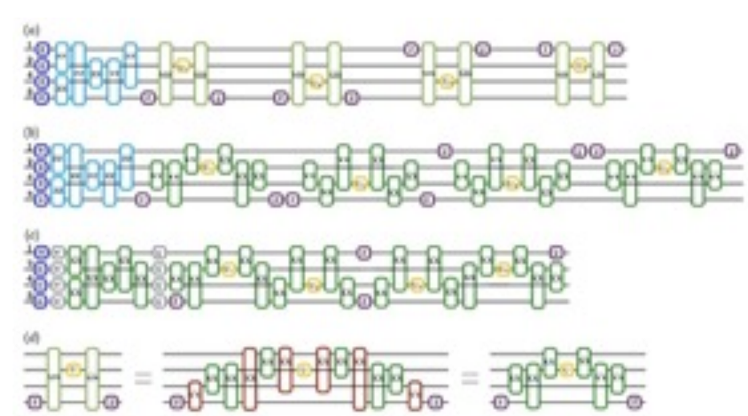
Trapped ions

Quantum field theory models
L. García-Álvarez et al., PRL 2015

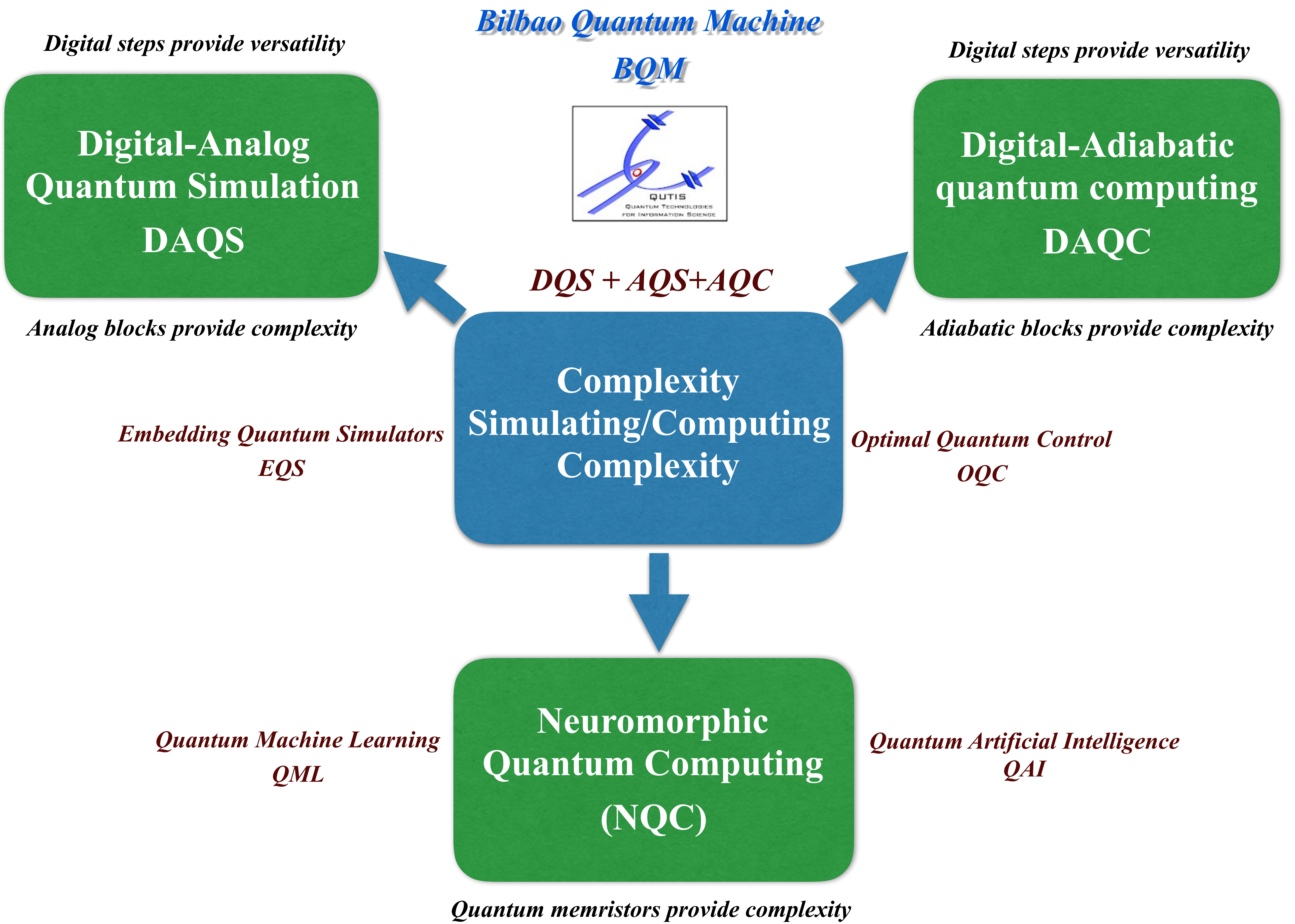


Superconducting circuits

Quantum chemistry models
L. García-Álvarez et al., arXiv 2015



Superconducting circuits


Bilbao Quantum Machine
BQM
QUTIS
QUANTUM TECHNOLOGIES FOR INFORMATION SCIENCE
Digital steps provide versatility
Digital-Analog Quantum Simulation
DAQS
Analog blocks provide complexity
Digital steps provide versatility
Digital-Adiabatic quantum computing
DAQC
Adiabatic blocks provide complexity
DQS + AQS+AQC
Complexity Simulating/Computing Complexity
Embedding Quantum Simulators
EQS
Optimal Quantum Control
OQC
Neuromorphic Quantum Computing
(NQC)
Quantum Machine Learning
QML
Quantum Artificial Intelligence
QAI
Quantum memristors provide complexity