Quantum Simulations of Fermions and Bosons with Trapped Ions

Lucas Lamata

University of the Basque Country UPV/EHU, Bilbao, Spain

Quantum Simulations, Benasque, 30 September 2013

QUTIS
Quantum Technologies for Information Science

Our group develops interdisciplinary research in

Quantum optics

Quantum information

Relativistic quantum mechanics

Circuit quantum electrodynamics

Quantum Biomimetics

Laura García-Álvarez (M. Sc. student)

Urtzi Las Heras (M. Sc. student)

Julen S. Pedernales (PhD student)

Unai Alvarez-Rodriguez (PhD student)

Antonio Mezzacapo (PhD, European SOLID grant)

Simone Felicetti (PhD, CCQED Marie Curie grant)

Roberto Di Candia (PhD, CCQED Marie Curie grant)

Mikel Sanz (Postdoc, European PROMISCE grant)

Jorge Casanova (Postdoc, European PROMISCE grant)

Guillermo Romero (Postdoc, European PROMISCE grant)

Lucas Lamata (Ramón y Cajal Fellow since 2014)

Enrique Solano (Group Leader and Ikerbasque Professor)

http://sites.google.com/site/enriquesolanogroup/

Universidad del País Vasco

ikerbasque
Basque Foundation for Science

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

EUSKO JAURLARITZA
GOBIERNO VASCO

PROMISCE

SOLID

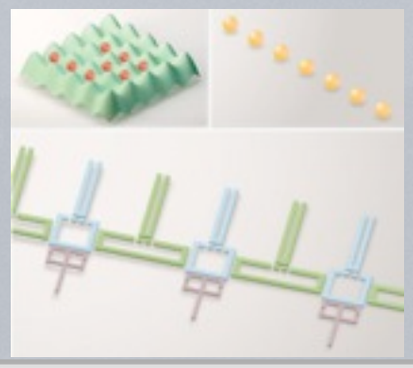
scaleQIT

QED
CIRCUIT AND CAVITY
QUANTUM ELECTRODYNAMICS

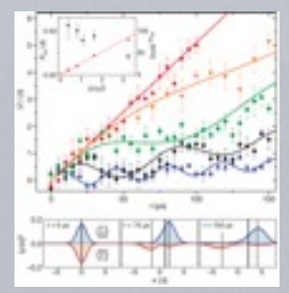
MARIE CURIE ACTIONS

Outline

Quantum Simulations



Overview of Bilbao Proposals



Fermions + Bosons in Ions

$$\{b, b^\dagger\} = 1 \qquad [a, a^\dagger] = 1$$

Future Lines

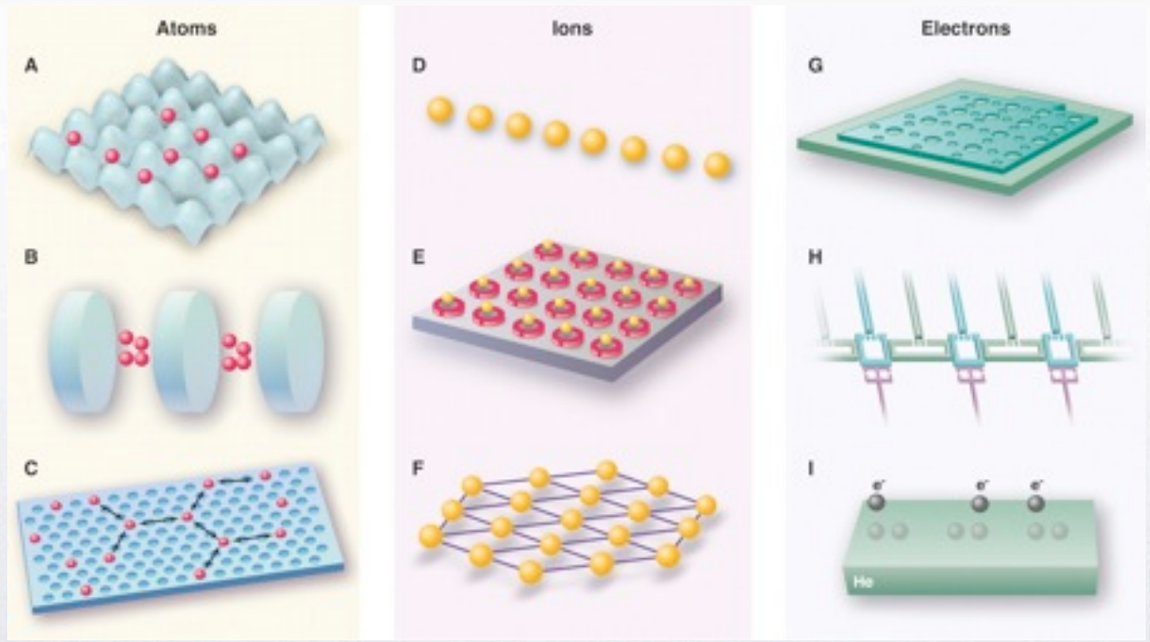
Quantum Simulations

Simulating efficiently quantum systems

Simulating unreproducible physics

Feynman ’82

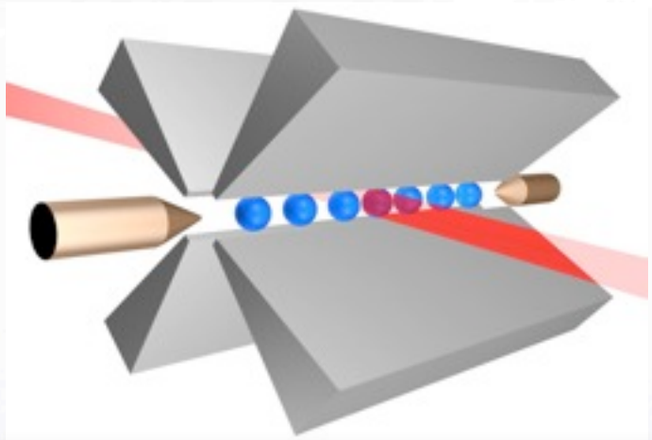
Lloyd ’96



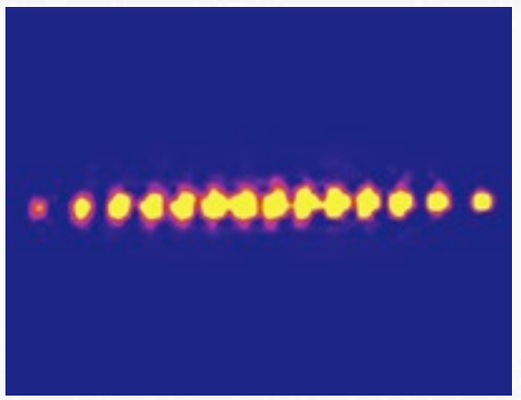
Buluta and Nori Science 326, 108 (2009)

Trapped Ions

Highly controllable



Efficient 2-qubit gates
F>99%



Good initialization and measurement
F>99%

14-qubit entanglement and 140-gate simulator (Innsbruck), 300-ion simulator (NIST)

Trapped Ions in Bilbao

PRL **98,** 253005 (2007) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2007

Dirac Equation and Quantum Relativistic Effects in a Single Trapped Ion

L. Lamata,[1] J. León,[1] T. Schätz,[2] and E. Solano[3,4]

[1]*Instituto de Matemáticas y Física Fundamental, CSIC, Serrano 113-bis, 28006 Madrid, Spain*
[2]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
[3]*Physics Department, ASC, and CeNS, Ludwig-Maximilians-Universität, Theresienstrasse 37, 80333 Munich, Germany*
[4]*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado Postal 1761, Lima, Peru*

(Received 27 March 2007; published 22 June 2007)

We present a method of simulating the Dirac equation in 3 + 1 dimensions for a free spin-1/2 particle in a single trapped ion. The Dirac bispinor is represented by four ionic internal states, and position and momentum of the Dirac particle are associated with the respective ionic variables. We show also how to simulate the simplified 1 + 1 case, requiring the manipulation of only two internal levels and one motional degree of freedom. Moreover, we study relevant quantum-relativistic effects, like the *Zitterbewegung* and Klein's paradox, the transition from massless to massive fermions, and the relativistic and nonrelativistic limits, via the tuning of controllable experimental parameters.

nature Vol 463|7 January 2010|**doi:10.1038/nature08688**

LETTERS

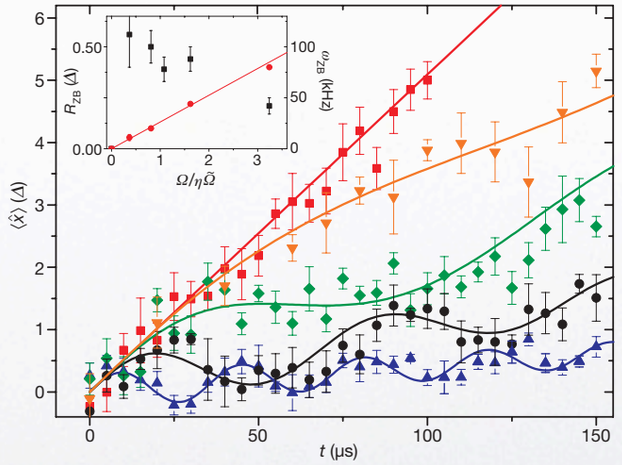
Quantum simulation of the Dirac equation

R. Gerritsma[1,2], G. Kirchmair[1,2], F. Zähringer[1,2], E. Solano[3,4], R. Blatt[1,2] & C. F. Roos[1,2]

The Dirac equation[1] successfully merges quantum mechanics with special relativity. It provides a natural description of the electron spin, predicts the existence of antimatter[2] and is able to reproduce accurately the spectrum of the hydrogen atom. The realm of the Dirac equation—relativistic quantum mechanics—is considered to be the natural transition to quantum field theory. However, the Dirac equation also predicts some peculiar effects, such as Klein's paradox[3] and 'Zitterbewegung', an unexpected quivering motion of a free relativistic quantum particle[4]. These and other predicted phenomena are key fundamental examples for understanding

easily accessed experimentally, while allowing parameter tunability over a wide range. The difficulties in observing real quantum relativistic effects have generated significant interest in the quantum simulation of their dynamics. Examples include black holes in Bose–Einstein condensates[5] and Zitterbewegung for massive fermions in solid-state physics[6], neither of which have been experimentally realized so far. Also, graphene is studied widely in connection to the Dirac equation[15–17].

Trapped ions are particularly interesting for the purpose of quantum simulation[18–20], as they allow exceptional control of experi-



Trapped Ions in Bilbao

PRL **98,** 253005 (2007) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2007

Dirac Equation and Quantum Relativistic Effects in a Single Trapped Ion

L. Lamata,[1] J. León,[1] T. Schätz,[2] and E. Solano[3,4]

[1]*Instituto de Matemáticas y Física Fundamental, CSIC, Serrano 113-bis, 28006 Madrid, Spain*
[2]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
[3]*Physics Department, ASC, and CeNS, Ludwig-Maximilians-Universität, Theresienstrasse 37, 80333 Munich, Germany*
[4]*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado Postal 1761, Lima, Peru*

(Received 27 March 2007; published 22 June 2007)

We present a method of simulating the Dirac equation in 3 + 1 dimensions for a free spin-1/2 particle in a single trapped ion. The Dirac bispinor is represented by four ionic internal states, and position and momentum of the Dirac particle are associated with the respective ionic variables. We show also how to simulate the simplified 1 + 1 case, requiring the manipulation of only two internal levels and one motional degree of freedom. Moreover, we study relevant quantum-relativistic effects, like the *Zitterbewegung* and Klein's paradox, the transition from massless to massive fermions, and the relativistic and nonrelativistic limits, via the tuning of controllable experimental parameters.

nature Vol 463|7 January 2010|doi:10.1038/nature08688

LETTERS

Quantum simulation of the Dirac equation

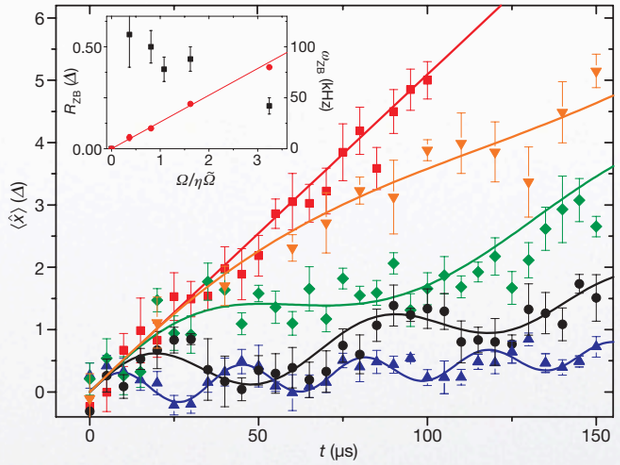
R. Gerritsma[1,2], G. Kirchmair[1,2], F. Zähringer[1,2], E. Solano[3,4], R. Blatt[1,2] & C. F. Roos[1,2]

The Dirac equation[1] successfully merges quantum mechanics with special relativity. It provides a natural description of the electron spin, predicts the existence of antimatter[2] and is able to reproduce accurately the spectrum of the hydrogen atom. The realm of the Dirac equation—relativistic quantum mechanics—is considered to be the natural transition to quantum field theory. However, the Dirac equation also predicts some peculiar effects, such as Klein's paradox[3] and 'Zitterbewegung', an unexpected quivering motion of a free relativistic quantum particle[4]. These and other predicted phenomena are key fundamental examples for understanding

easily accessed experimentally, while allowing parameter tunability over a wide range. The difficulties in observing real quantum relativistic effects have generated significant interest in the quantum simulation of their dynamics. Examples include black holes in Bose–Einstein condensates[5] and Zitterbewegung for massive fermions in solid-state physics[6], neither of which have been experimentally realized so far. Also, graphene is studied widely in connection to the Dirac equation[15–17].

Trapped ions are particularly interesting for the purpose of quantum simulation[18–20], as they allow exceptional control of experi-

- Klein (theory)
- Klein (experiment)
- Majorana equation
- Unphysical operations



Trapped Ions in Bilbao

PRL **98,** 253005 (2007) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2007

Dirac Equation and Quantum Relativistic Effects in a Single Trapped Ion

L. Lamata,[1] J. León,[1] T. Schätz,[2] and E. Solano[3,4]

[1]*Instituto de Matemáticas y Física Fundamental, CSIC, Serrano 113-bis, 28006 Madrid, Spain*
[2]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
[3]*Physics Department, ASC, and CeNS, Ludwig-Maximilians-Universität, Theresienstrasse 37, 80333 Munich, Germany*
[4]*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado Postal 1761, Lima, Peru*

(Received 27 March 2007; published 22 June 2007)

We present a method of simulating the Dirac equation in 3 + 1 dimensions for a free spin-1/2 particle in a single trapped ion. The Dirac bispinor is represented by four ionic internal states, and position and momentum of the Dirac particle are associated with the respective ionic variables. We show also how to simulate the simplified 1 + 1 case, requiring the manipulation of only two internal levels and one motional degree of freedom. Moreover, we study relevant quantum-relativistic effects, like the *Zitterbewegung* and Klein's paradox, the transition from massless to massive fermions, and the relativistic and nonrelativistic limits, via the tuning of controllable experimental parameters.

nature Vol 463|7 January 2010|doi:10.1038/nature08688

LETTERS

Quantum simulation of the Dirac equation

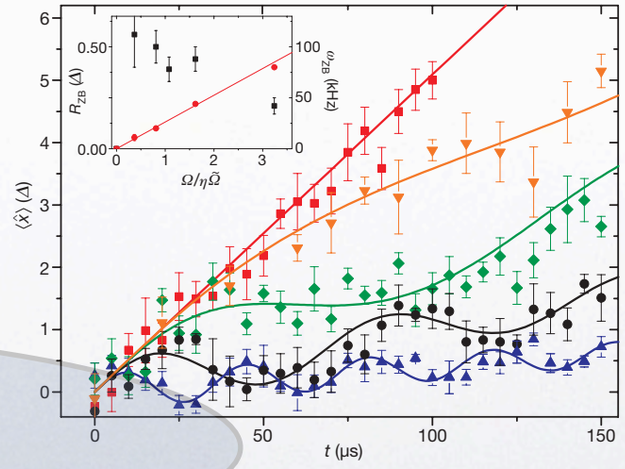
R. Gerritsma[1,2], G. Kirchmair[1,2], F. Zähringer[1,2], E. Solano[3,4], R. Blatt[1,2] & C. F. Roos[1,2]

The Dirac equation[1] successfully merges quantum mechanics with special relativity. It provides a natural description of the electron spin, predicts the existence of antimatter[2] and is able to reproduce accurately the spectrum of the hydrogen atom. The realm of the Dirac equation—relativistic quantum mechanics—is considered to be the natural transition to quantum field theory. However, the Dirac equation also predicts some peculiar effects, such as Klein's paradox[3] and 'Zitterbewegung', an unexpected quivering motion of a free relativistic quantum particle[4]. These and other predicted phenomena are key fundamental examples for understanding

easily accessed experimentally, while allowing parameter tunability over a wide range. The difficulties in observing real quantum relativistic effects have generated significant interest in the quantum simulation of their dynamics. Examples include black holes in Bose–Einstein condensates[5] and Zitterbewegung for massive fermions in solid-state physics[6], neither of which have been experimentally realized so far. Also, graphene is studied widely in connection to the Dirac equation[15–17].

Trapped ions are particularly interesting for the purpose of quantum simulation[18–20], as they allow exceptional control of experi-

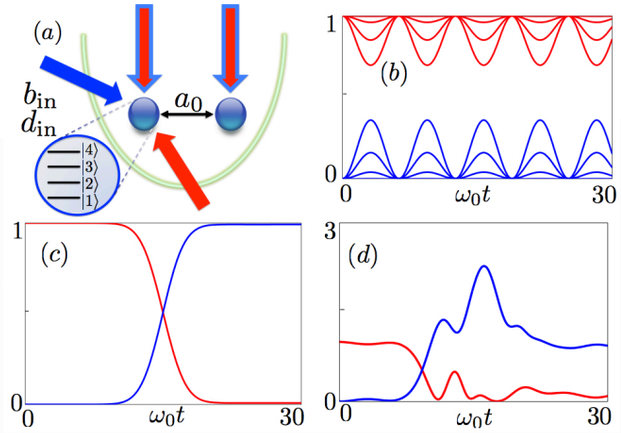
- Klein (theory)
- Klein (experiment)
- Majorana equation
- Unphysical operations



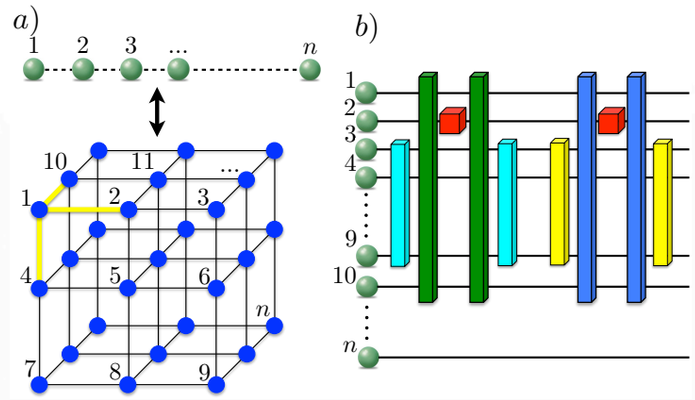
See J. Casanova's talk Tuesday

Trapped Ions in Bilbao

Quantum Field Theories,
Casanova, Lamata, ..., Solano, PRL '11

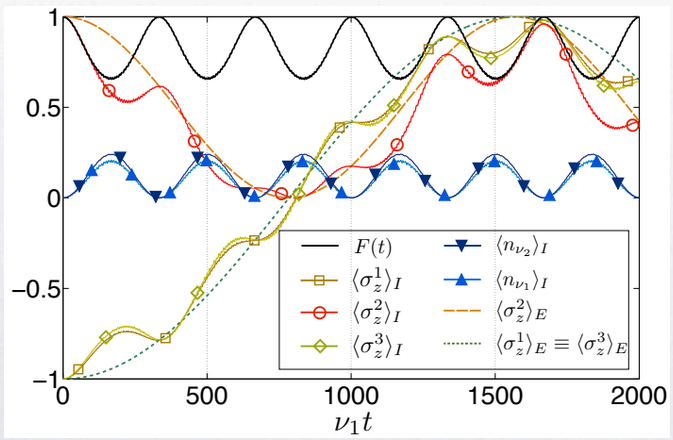


Fermion Lattice Models,
Casanova, Mezzacapo, Lamata, Solano, PRL '12



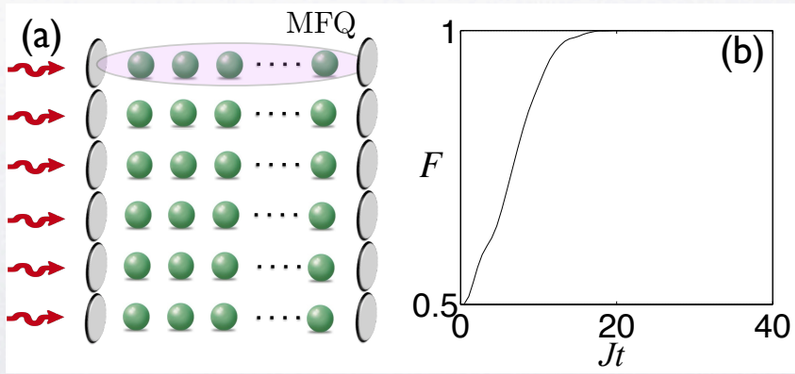
Holstein Model and unbounded Hs

Mezzacapo, Casanova, Lamata, Solano, PRL '12

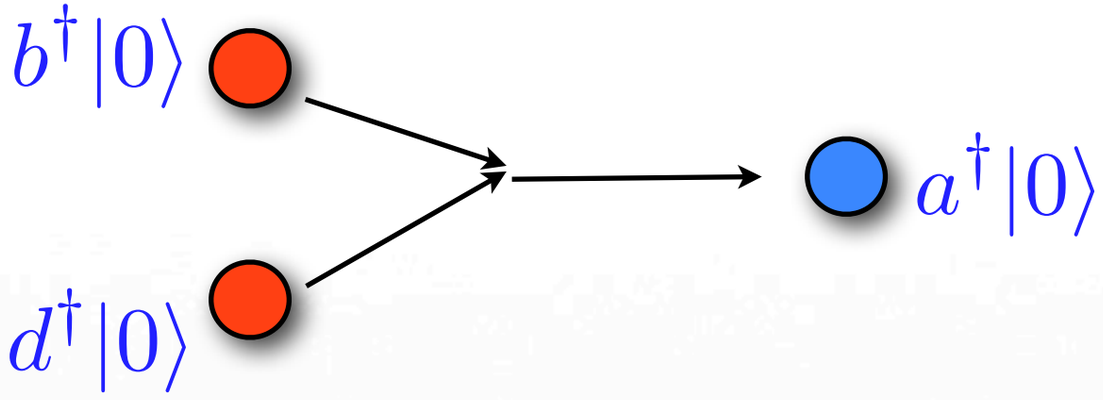


Majorana fermions and protected qubits

Mezzacapo, Casanova, Lamata, Solano, NJP '13

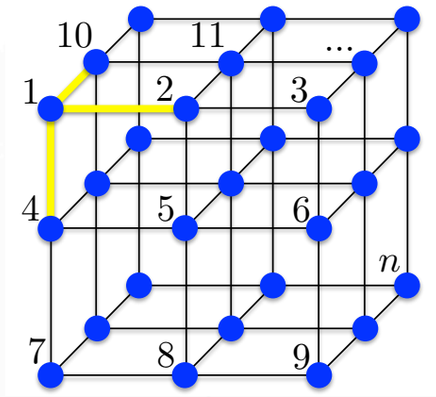


Fermions and Bosons in Trapped Ions



QFT Scattering

Casanova, Lamata, ..., Solano, PRL '11
Casanova, Mezzacapo, Lamata, Solano, PRL '12
Mezzacapo, Casanova, Lamata, Solano, PRL '12



Fermion Lattices

$$\{b, b^\dagger\} = \{d, d^\dagger\} = 1 \qquad [a, a^\dagger] = 1$$

Interacting fermions+bosons

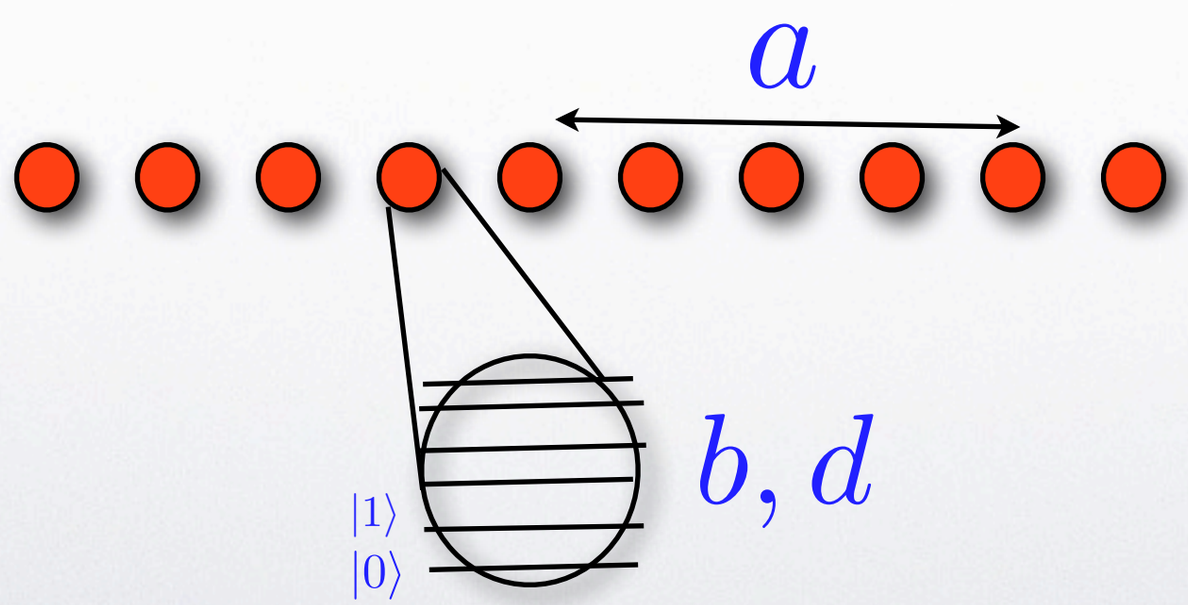
Efficiently implementable!!

Fermions and Bosons in Trapped Ions

Fermionic modes: internal levels

Bosonic modes: motional d.o.f.

digital-analog simulator, *polynomial time*



Fermions and Bosons in Trapped Ions

Fermionic interactions:

i) Jordan Wigner

$$b_i^\dagger = I \otimes I \otimes \ldots \otimes \sigma_i^+ \otimes \sigma_{i-1}^z \otimes \ldots \otimes \sigma_1^z$$

$$\{b_i, b_j^\dagger\} = \delta_{i,j}$$

ii) Trotter expansion

$$e^{-iHt} \simeq (e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_m t/n})^n$$

iii) Efficient implementation spin operators

$$H = \sum_{i=1}^{m} H_i, H_i = g_i \sigma_{i_1} \otimes \sigma_{i_2} \otimes \ldots \otimes \sigma_{i_N}$$

Casanova, Mezzacapo, Lamata, Solano, PRL '12
Mezzacapo, Casanova, Lamata, Solano, PRL '12

Fermions and Bosons in Trapped Ions

$$H = \sum_{n=2}^{\alpha} \left[\sum_{i_1 \ldots i_n = 1}^{N} g_{i_1 \ldots i_n} c_{i_1} \cdots c_{i_n} + \text{H.c.} \right],$$

Fermion Hamiltonian

$$\{c_{i_l}, c^{\dagger}_{i_{l'}}\} = \delta_{l,l'}$$

Fermions and Bosons in Trapped Ions

$$H = \sum_{n=2}^{\alpha} \Big[\sum_{i_1 \ldots i_n = 1}^{N} g_{i_1 \ldots i_n} c_{i_1} \cdots c_{i_n} + \text{H.c.} \Big],$$

Fermion Hamiltonian

$$\downarrow \quad \{c_{i_l}, c^{\dagger}_{i_{l'}}\} = \delta_{l,l'}$$

$$H = \sum_{i=1}^{m} H_i \qquad H_i = g_i \sigma_{i_1} \otimes \sigma_{i_2} \otimes \ldots \otimes \sigma_{i_N}$$

Fermions and Bosons in Trapped Ions

$$H = \sum_{n=2}^{\alpha} \Big[\sum_{i_1 \ldots i_n = 1}^{N} g_{i_1 \ldots i_n} c_{i_1} \cdots c_{i_n} + \text{H.c.} \Big],$$

Fermion Hamiltonian

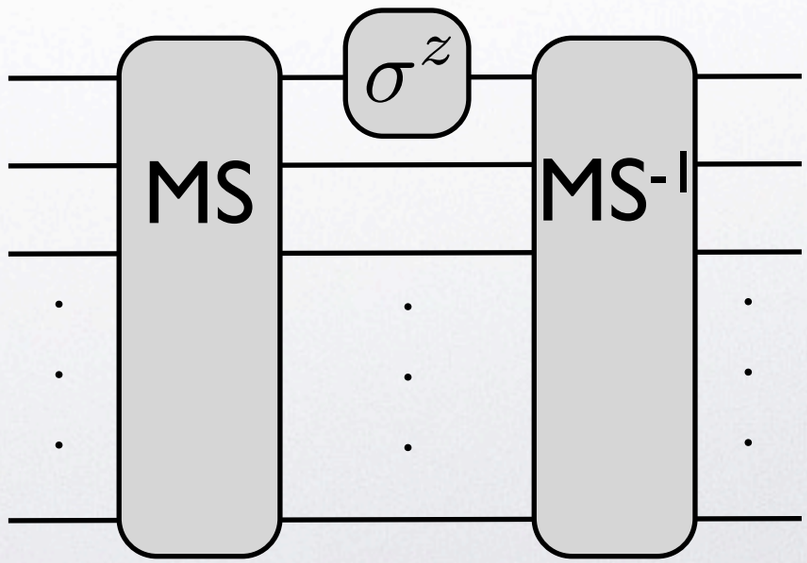
$$\downarrow \quad \{c_{i_l}, c^{\dagger}_{i_{l'}}\} = \delta_{l,l'}$$

$$H = \sum_{i=1}^{m} H_i \qquad H_i = g_i \sigma_{i_1} \otimes \sigma_{i_2} \otimes \ldots \otimes \sigma_{i_N}$$

Trapped-ion implementation: Mølmer-Sørensen gates (highly efficient)

Müller,...,Zoller, NJP'11

Casanova, Mezzacapo, Lamata, Solano, PRL '12

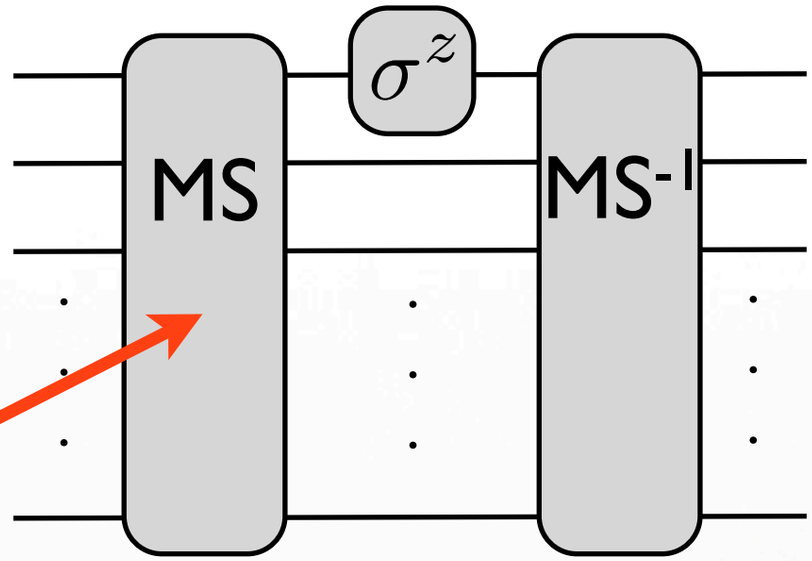


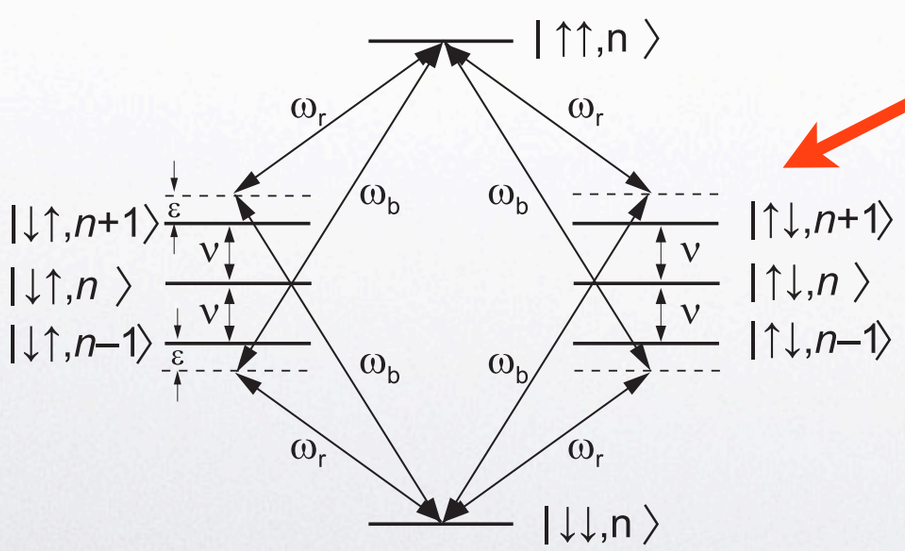
Fermions and Bosons in Trapped Ions

Trapped-ion implementation:
Mølmer-Sørensen gates (highly efficient)

Müller,...,Zoller, NJP'11

Casanova, Mezzacapo, Lamata, Solano, PRL'12





Mølmer and Sørensen, PRL'99, PRA'00

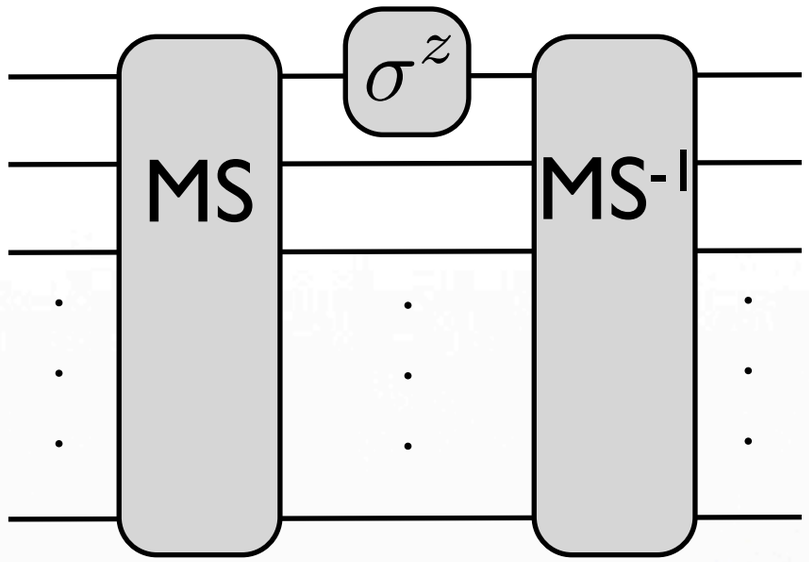
$$H = H_o + H_{\rm int},$$
$$H_0 = \nu(a^\dagger a + 1/2) + \omega_{eg}\sum_i \sigma_{zi}/2,$$
$$H_{\rm int} = \sum_i \frac{\Omega_i}{2}(\sigma_{+i}e^{i(\eta_i(a+a^\dagger)-\omega t)} + H.c.),$$
$$\omega_{b,r} = \omega_{eg} \pm (\nu + \epsilon)$$

F>99%

Fermions and Bosons in Trapped Ions

$$\mathcal{U} = \mathcal{U}_{\rm MS}(-\pi/2, 0)\mathcal{U}_{\sigma_z}(\phi)\mathcal{U}_{\rm MS}(\pi/2, 0)$$
$$= \exp\left[i\phi\ \sigma_1^z \otimes \sigma_2^x \otimes \sigma_3^x \otimes \cdots \sigma_k^x\right],$$

$$\mathcal{U}_{\rm MS}(\theta, \phi) = \exp[-i\theta(\cos\phi S_x + \sin\phi S_y)^2/4]$$



$$S_{x,y} = \sum_{i=1}^{k} \sigma_i^{x,y} \qquad \mathcal{U}_{\sigma_z}(\phi) = \exp(i\phi'\sigma_1^z) \qquad \phi' = \pm\phi$$

Arbitrary number Pauli matrices with 3 gates!!

Trotter errors

$$\mathcal{U} = \exp(-iHt), H = \sum_{j=1}^{m} H_j \qquad \tilde{\mathcal{U}} = \prod_{l=1}^{N_e} e^{-iH_{j_l} t_l},$$

$$||\mathcal{U} - \tilde{\mathcal{U}}|| < \epsilon$$

$$N_e \leq m 5^{2k} (m||H||t)^{1+1/2k} / \epsilon^{1/2k},$$

D. Berry, G. Ahokas, R. Cleve and B. Sanders, Commun. Math. Phys.'07

N_e polynomial in number of modes, error and time

Trotter errors

$$\mathcal{U} = \exp(-iHt), H = \sum_{j=1}^{m} H_j \qquad \tilde{\mathcal{U}} = \prod_{l=1}^{N_e} e^{-iH_{j_l} t_l},$$

$$||\mathcal{U} - \tilde{\mathcal{U}}|| < \epsilon$$

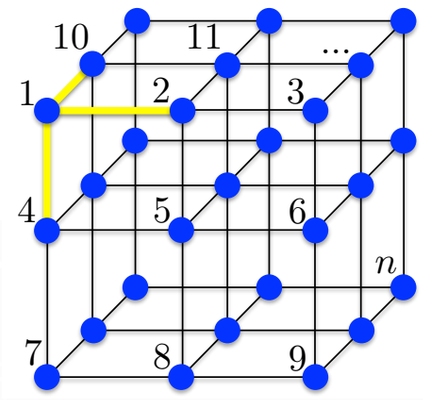
$$N_e \leq m 5^{2k} (m||H||t)^{1+1/2k} / \epsilon^{1/2k},$$

D. Berry, G. Ahokas, R. Cleve and B. Sanders, Commun. Math. Phys.'07

N_e polynomial in number of modes, error and time

Efficient implementation!!

Fermions and Bosons in Trapped Ions

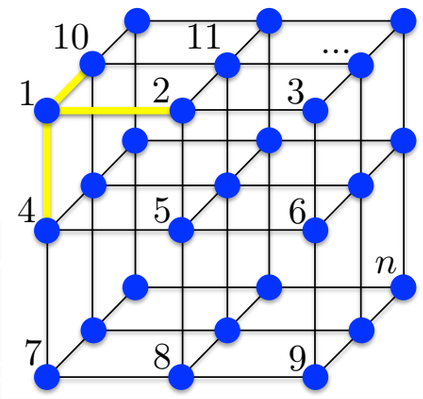


Fermion lattices in 3D, *efficient!*

$b_1^\dagger b_{10} + b_{10}^\dagger b_1$

$2^{10} \times 2^{10} = 2^{20} \simeq 10^6$ **gates**

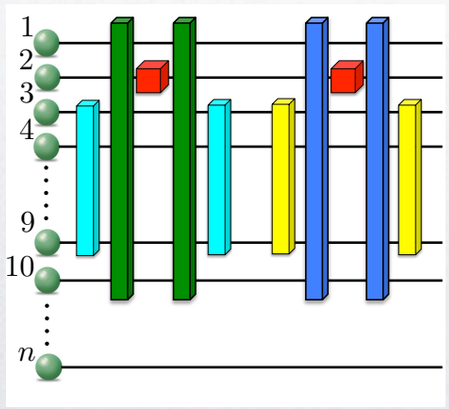
Fermions and Bosons in Trapped Ions



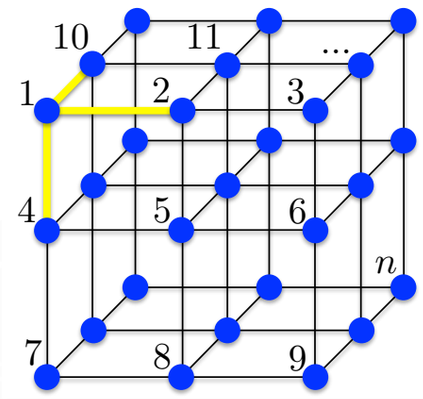
Fermion lattices in 3D, *efficient!*

$b_1^\dagger b_{10} + b_{10}^\dagger b_1$ $\qquad 2^{10} \times 2^{10} = 2^{20} \simeq 10^6$ **gates**

With our protocol: 10 gates/Trotter step!



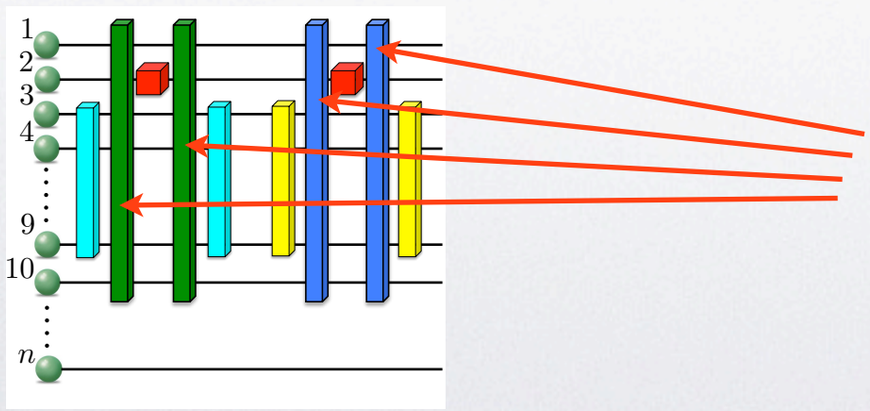
Fermions and Bosons in Trapped Ions



Fermion lattices in 3D, *efficient!*

$b_1^\dagger b_{10} + b_{10}^\dagger b_1$ $\qquad 2^{10} \times 2^{10} = 2^{20} \simeq 10^6$ gates

With our protocol: 10 gates/Trotter step!



MS gates

Fermions and Bosons in Trapped Ions

Possible to simulate:

i) Kondo

$$H = \sum_{p\sigma} \epsilon_p b^\dagger_{p\sigma} b_{p\sigma} - J \sum_{pp'j} e^{iR_j\cdot(p-p')}[(b^\dagger_{p\uparrow} b_{p'\uparrow} - b^\dagger_{p\downarrow} b_{p'\downarrow})\sigma^z_j + b^\dagger_{p\uparrow} b_{p'\downarrow}\sigma^-_j + b^\dagger_{p\downarrow} b_{p'\uparrow}\sigma^+_j].$$

ii) Hubbard

$$H = w \sum_{\delta i\sigma} b^\dagger_{i\sigma} b_{i+\delta\sigma} + U \sum_j b^\dagger_{j\uparrow} b_{j\uparrow} b^\dagger_{j\downarrow} b_{j\downarrow},$$

iii) Fröhlich

$$H = \sum_p \frac{p^2}{2m} b^\dagger_p b_p + \omega_0 \sum_q a^\dagger_q a_q + \sum_{qp} M(q) b^\dagger_{p+q} b_p (a_q + a^\dagger_{-q}),$$

Fermions and Bosons in Trapped Ions

- **Quantum Chemistry with Ions** arXiv 1307.4326

From transistor to trapped-ion computers for quantum chemistry

M.-H. Yung,[1,2,*] J. Casanova,[3,*] A. Mezzacapo,[3] J. McClean,[1] L. Lamata,[3] A. Aspuru-Guzik,[1,†] and E. Solano[3,4,‡]

[1] *Department of Chemistry and Chemical Biology, Harvard University, Cambridge MA, 02138, USA*
[2] *Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, 100084, P. R. China*
[3] *Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain*

(Dated: July 17, 2013)

Over the last few decades, quantum chemistry has progressed through the development of computational methods based on modern digital computers. However, these methods can hardly fulfill the exponentially-growing resource requirements when applied to large quantum systems. As pointed out by Feynman, this restriction is intrinsic to all computational models based on classical physics. Recently, the rapid advancement of trapped-ion technologies has opened new possibilities for quantum control and quantum simulations. Here, we present an efficient toolkit that exploits both the internal and motional degrees of freedom of trapped ions for solving problems in quantum chemistry, including molecular electronic structure, molecular dynamics, and vibronic coupling. We focus on applications that go beyond the capacity of classical computers, but may be realizable on state-of-the-art trapped-ion systems. These results allow us to envision a new paradigm of quantum chemistry that shifts from the current transistor to a near-future trapped-ion-based technology.

Fermions and Bosons in Trapped Ions

- **Quantum Chemistry with Ions** arXiv 1307.4326

From transistor to trapped-ion computers for quantum chemistry

M.-H. Yung,[1,2,*] J. Casanova,[3,*] A. Mezzacapo,[3] J. McClean,[1] L. Lamata,[3] A. Aspuru-Guzik,[1,†] and E. Solano[3,4,‡]

[1] *Department of Chemistry and Chemical Biology, Harvard University, Cambridge MA, 02138, USA*
[2] *Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, 100084, P. R. China*
[3] *Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36, 48011 Bilbao, Spain*

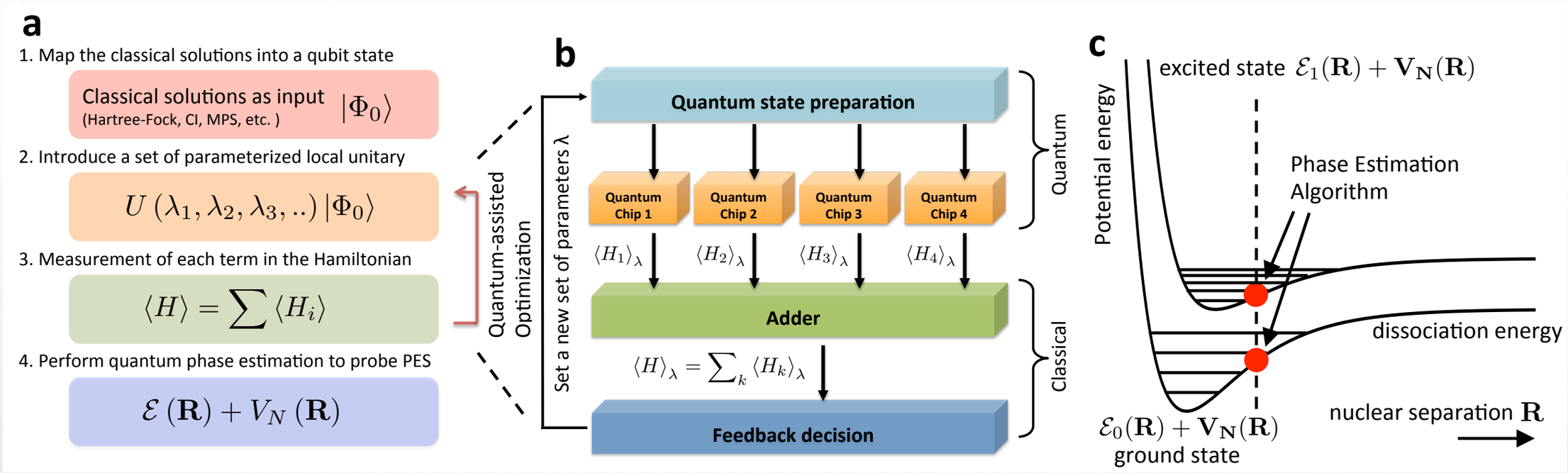
(Dated: July 17, 2013)

Over the last few decades, quantum chemistry has progressed through the development of computational methods based on modern digital computers. However, these methods can hardly fulfill the exponentially-growing resource requirements when applied to large quantum systems. As pointed out by Feynman, this restriction is intrinsic to all computational models based on classical physics. Recently, the rapid advancement of trapped-ion technologies has opened new possibilities for quantum control and quantum simulations. Here, we present an efficient toolkit that exploits both the internal and motional degrees of freedom of trapped ions for solving problems in quantum chemistry, including molecular electronic structure, molecular dynamics, and vibronic coupling. We focus on applications that go beyond the capacity of classical computers, but may be realizable on state-of-the-art trapped-ion systems. These results allow us to envision a new paradigm of quantum chemistry that shifts from the current transistor to a near-future trapped-ion-based technology.

10 ions, 10 modes, 7 excitations/mode: overcome classical computers!

Fermions and Bosons in Trapped Ions

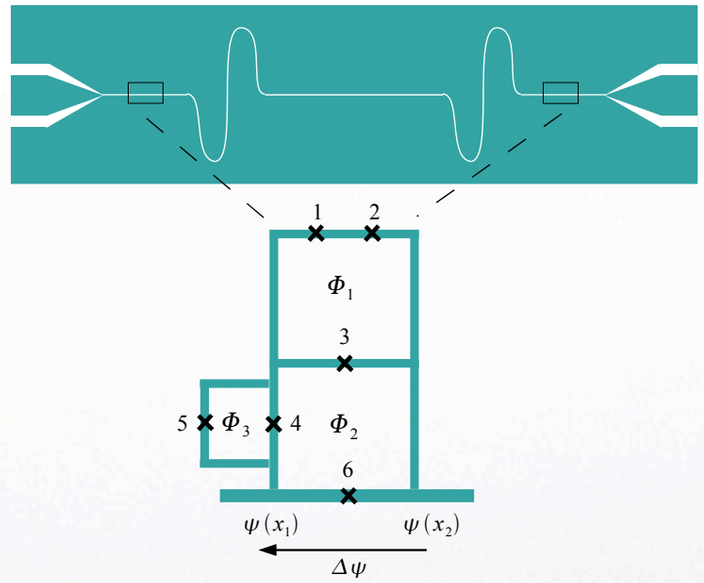
- Quantum Chemistry with Ions arXiv 1307.4326



Quantum Simulations in Bilbao

Circuit QED: Different context, different technology

- Access to continuum
- Strong/Ultrastrong coupling regime
- Quantum propagating mw

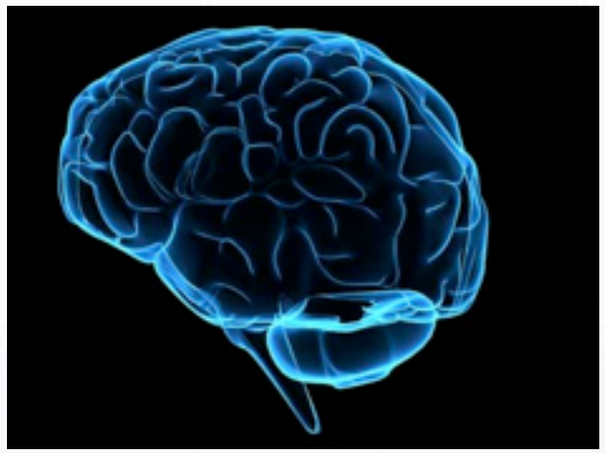


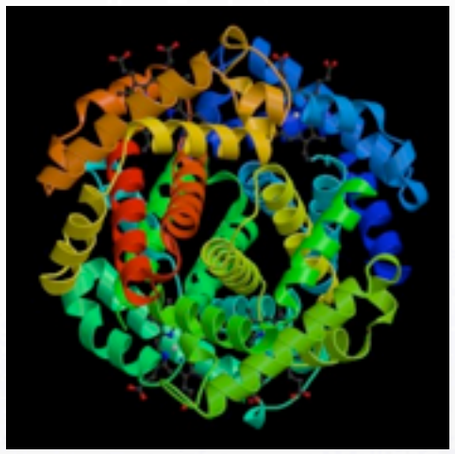
→ Future in the field!

Quantum Biomimetics

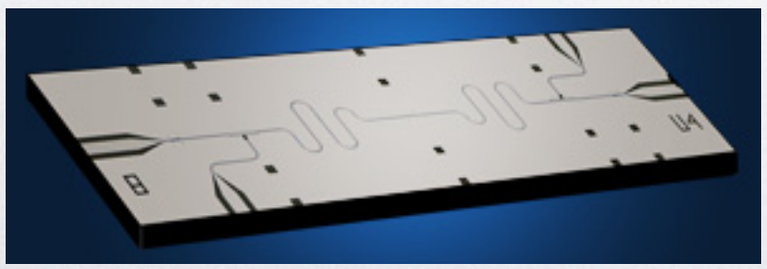
Our new contribution: Quantum Biomimetics

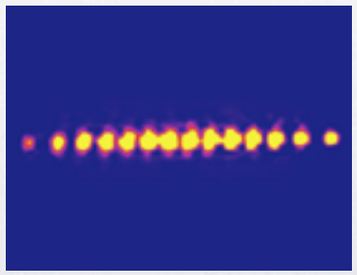
Study biological systems + mimic them in quantum models

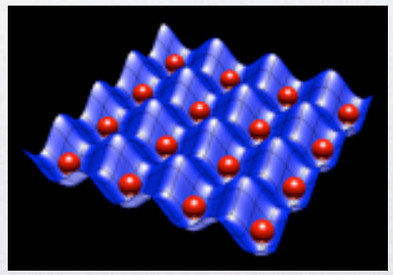




Aim: reproduce biological behaviours in quantum controllable systems







QUTIS Posters

- Roberto Di Candia: Embedding quantum simulators
- Antonio Mezzacapo: Digital Quantum Simulation of the Holstein Model
- Simone Felicetti: Entanglement via Dynamical Casimir effect
- Julen Pedernales: Quantum simulations in cQED
- Unai Alvarez-Rodriguez: Bio-Inspired Cloning of Quantum Information
- Laura García-Álvarez: Quantum field theories in cQED
- Urtzi Las Heras: Digital Quantum Simulation of Spin Models in cQED
- Paul Pfeiffer: Brain inspired Quantum Networks

Thank you for your attention!