Universidad del País Vasco · Euskal Herriko Unibertsitatea

ikerbasque
Basque Foundation for Science

Quantum simulations and quantum information

E. Solano

Universidad del País Vasco & Fundación Ikerbasque, Bilbao

IWQCD1, Cali, September 2012

My group develops interdisciplinary research in

Quantum optics

Quantum information

Circuit quantum electrodynamics

Condensed matter physics

Quantum biomimetics

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

Laura García (Master student)

Urtzi Las Heras (Master student)

Julen S. Pedernales (PhD, UPV/EHU grant)

Unai Alvarez-Rodriguez (PhD, Basque Government grant)

Antonio Mezzacapo (PhD, European SOLID grant)

Jorge Casanova (PhD, Basque Government grant)

Simone Felicetti (PhD, CCQED Marie Curie grant)

Roberto Di Candia (PhD, CCQED Marie Curie grant)

Guillermo Romero (Postdoc, Juan de la Cierva grant)

Daniel Ballester (Postdoc, European SOLID grant)

Lucas Lamata (Postdoc, European Marie Curie grant)

Enrique Solano (Professor, UPV/EHU & Ikerbasque)

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EUSKO JAURLARITZA GOBIERNO VASCO

SOLID

QED CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS

PROMISCE

Lectures on “Quantum simulations and quantum information”

Syllabus

1) Quantum simulations and quantum technologies (1h)

- Introduction and motivation
- Quantum platforms: trapped ions, optical lattices, quantum photonics, circuit QED and superconducting qubits

2) Quantum simulations in trapped ions (1h)

- Trapped ions, quantum computing, and quantum simulations
- Dirac equation: Zitterbewegung and Klein paradox
- Outlook

3) Quantum simulations in circuit QED (1h)

- Quantum optics and circuit QED
- Quantum Rabi model and relativistic quantum mechanics
- Outlook

LECTURE 1

What is a quantum simulation?

Definition

Quantum simulation is the intentional reproduction of a quantum dynamics of a physical system onto another quantum system, typically more controllable.

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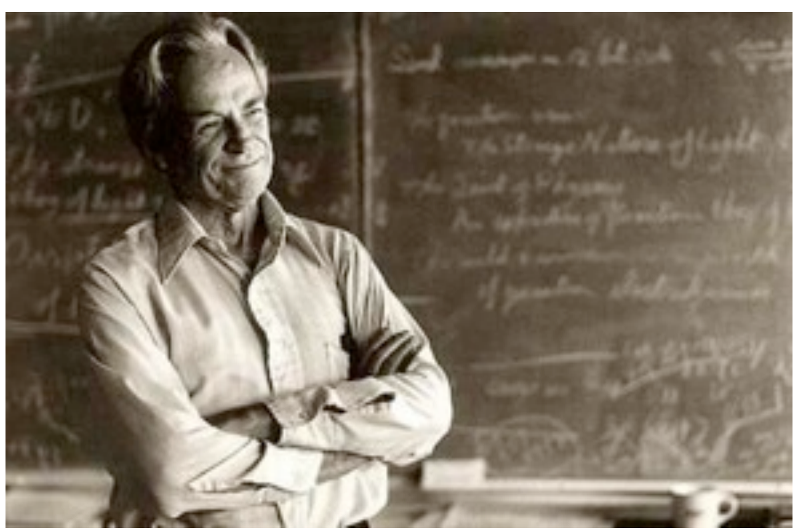
Richard Feynman



Let nature calculate for us

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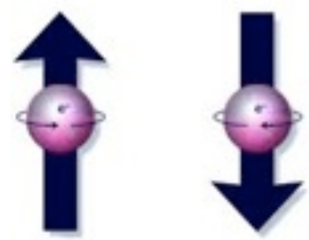
Greek theatre

Mimesis or imitation is always partial,
this is the origin of creativity and arts

Quantum simulation <=> Quantum theatre

An example of a successful quantum simulation

- An electron is a quantum system with two internal spin levels.
- An atom is a quantum system with infinite energy levels.



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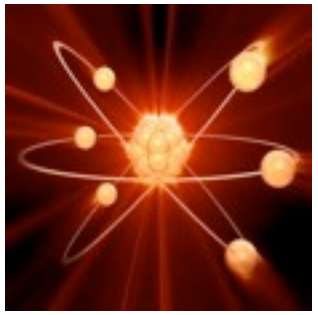

It is possible to engineer two levels of an atom such that it behaves as a spin 1/2 system.

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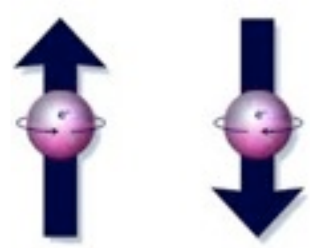

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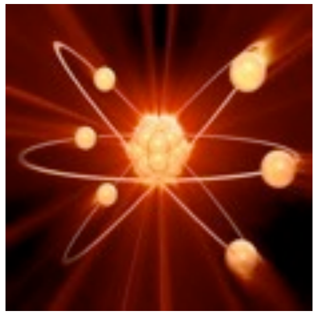
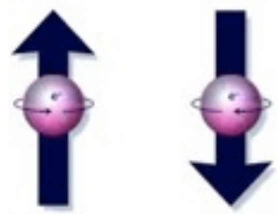


It is possible to engineer two levels of an atom such that it behaves as a spin 1/2 system.

An example of a failed quantum simulation

- A top is a physical system with a classical macroscopic behaviour.
- Can a top mimic the quantum aspects of an electron spin?



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Although the top is a system whose microscopic description is intrinsically quantum, its macroscopic dynamics is classical and cannot reproduce quantum features.

Is it possible to implement a quantum simulation of impossible physics?

The operation "complex conjugation of a wavefunction" is forbidden by quantum physics. However, it is possible to simulate it quantum mechanically with a suitable codification.

$$\psi \not\Longrightarrow \psi^*$$

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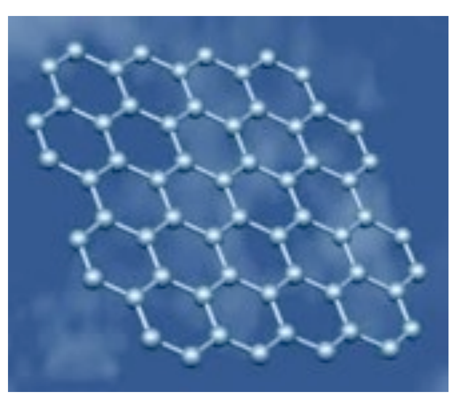
$$\psi \not\Longrightarrow \psi^{*}$$

An example of what looks like a quantum simulation but maybe not

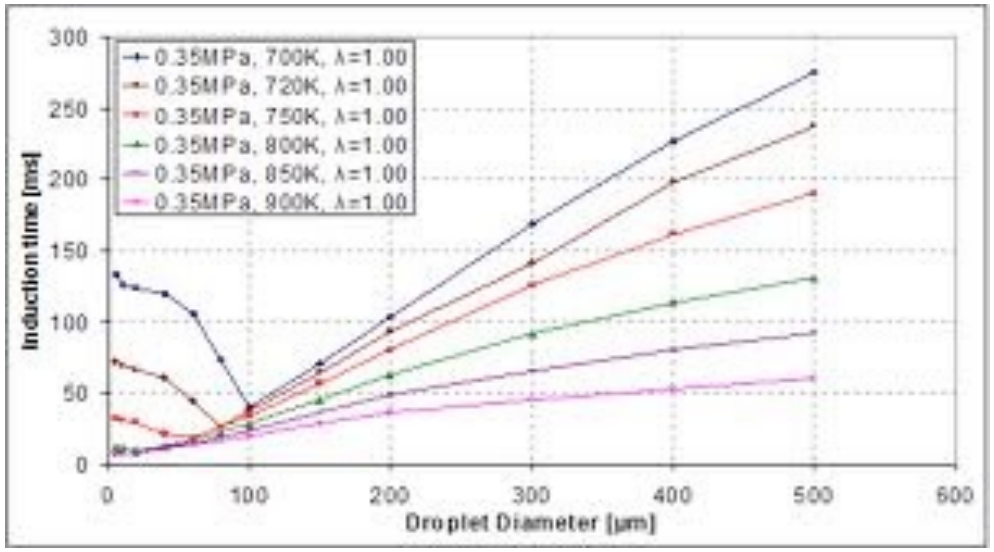
Graphene is described by the 2+1 massless Dirac equation,
but it is not a quantum simulation because it is not intentional.



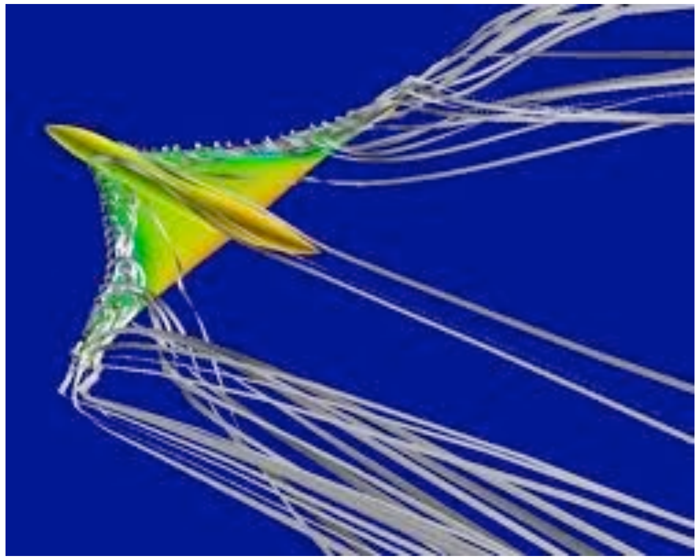
? $\Longleftrightarrow$

$$i\hbar \frac{\partial \psi}{\partial t} = (c\boldsymbol{\alpha}\cdot\hat{\mathbf{p}} + \beta mc^2)\psi$$

An example of classical simulations



Use of classical computers to simulate
complex physical behaviours
as the turbulences in an airplane



A ludic example of a classical simulation that turned quantum

A photography: classical simulation of a starred night over the Rhone river, France

A ludic example of a classical simulation that turned quantum

A photography: classical simulation of a starred night over the Rhone river, France

A painting: "quantum simulation" of the same starred night over the Rhones river, van Gogh (1888)

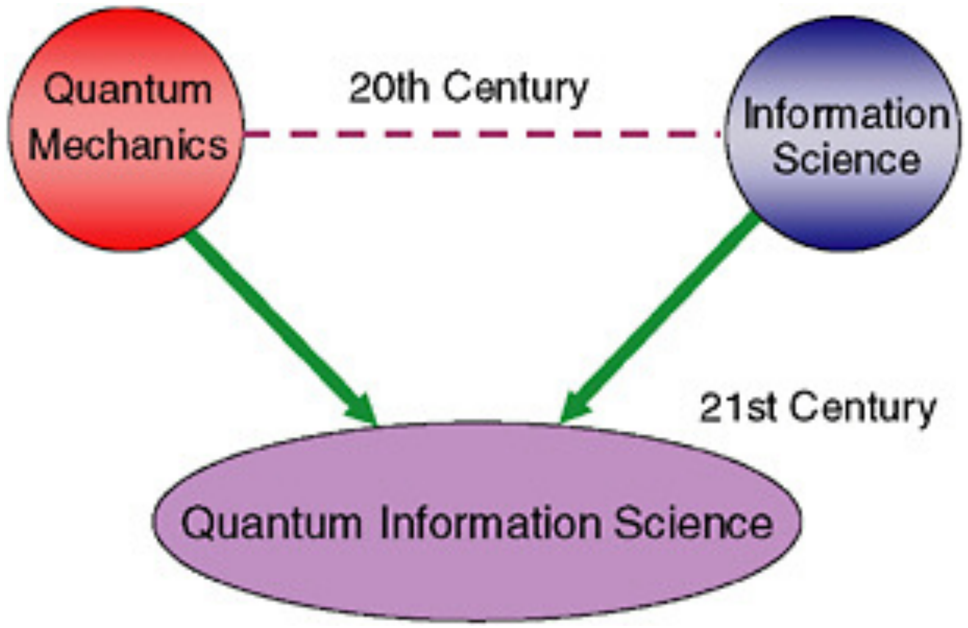
More serious consequence of reflecting on these topics

Conjecture

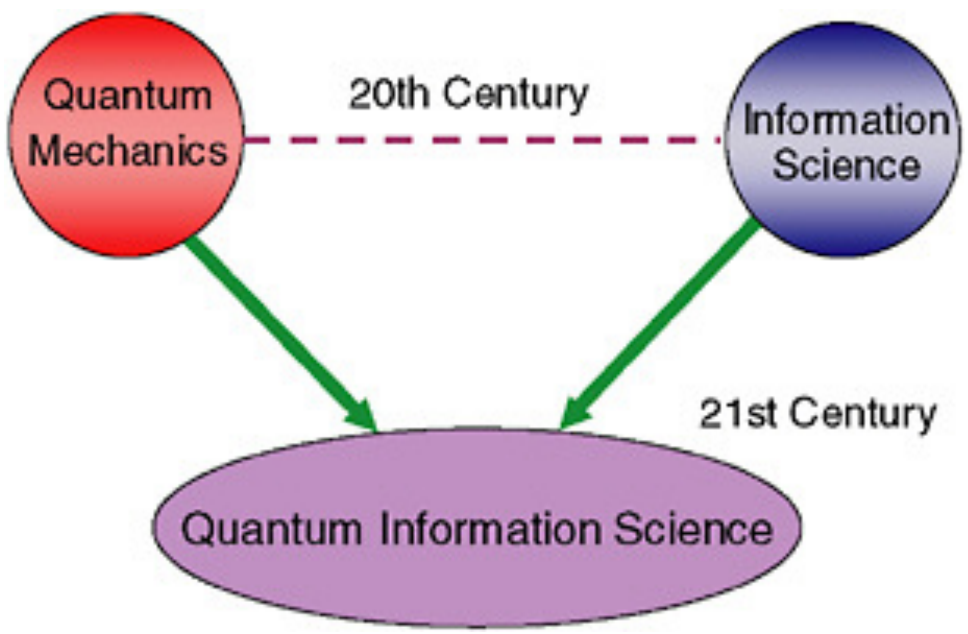
Imitation or simulation can only be partially achieved

and it is condemned to imperfection.

This is the origin of artistic and scientific creativity, therefore of new physics.



Quantum information should be able to deliver future quantum technologies



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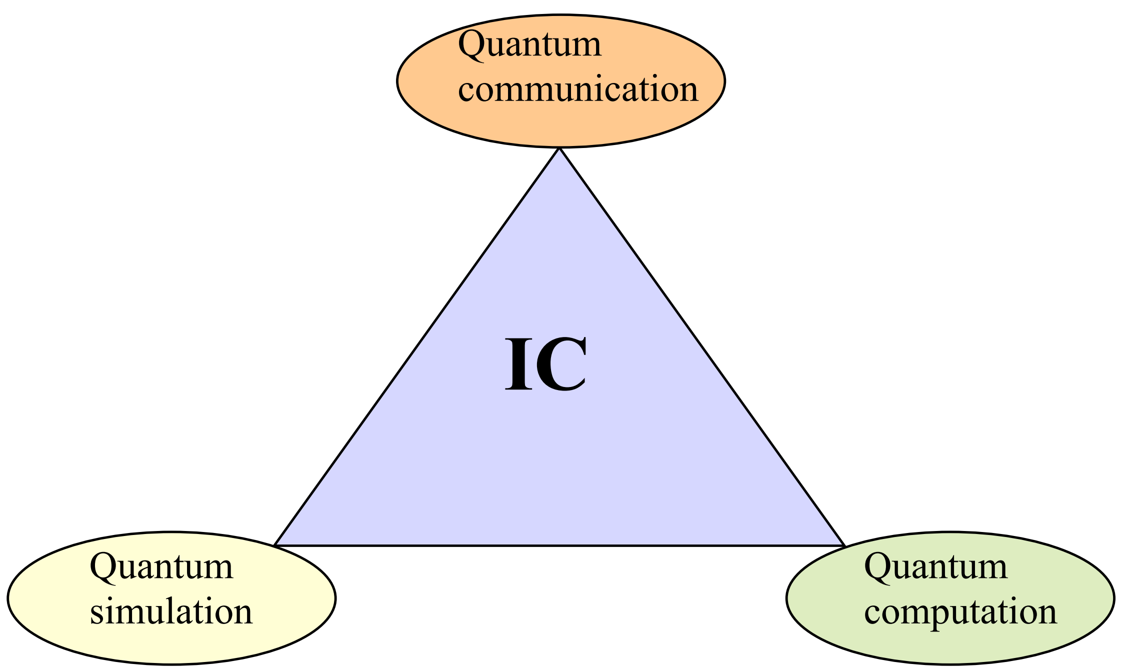

Quantum simulations are able to bring arts and aesthetics to quantum science, but also new scientific knowledge

Why are quantum simulations interesting?

a) Because we can discover analogies between unconnected fields, producing a flood of knowledge in both directions, e.g. black hole physics and Bose-Einstein condensation.

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c) Because we can predict novel physics without manipulating the original systems, experiments could make calculations beyond classical capabilities, e.g., spin models,QFTs.

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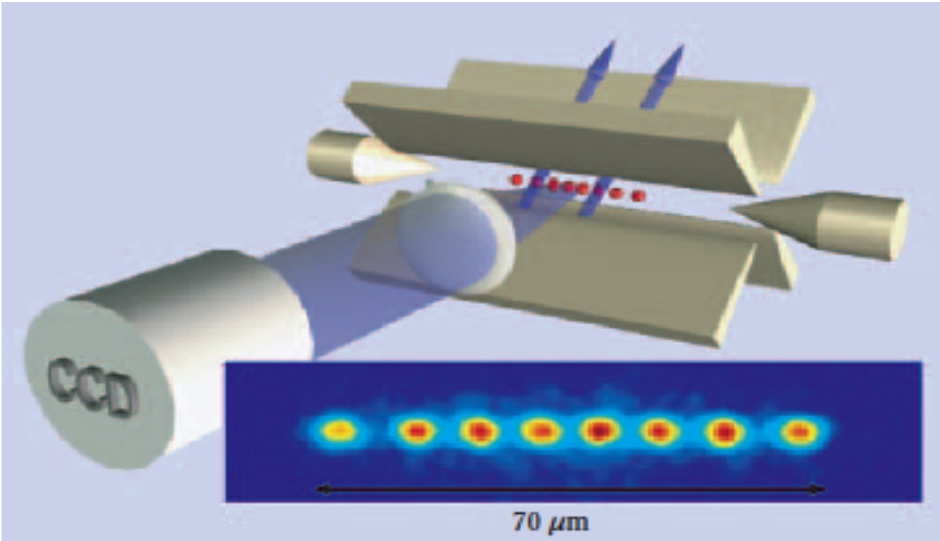
c) Because we can predict novel physics without manipulating the original systems, experiments could make calculations beyond classical capabilities, e.g., spin models,QFTs.

d) Because we are unhappy with reality, we enjoy arts and fiction in all its forms: literature, music, theatre, painting, quantum physics.

Quantum technologies for quantum simulations

Trapped ions



a) Trapped ions can be cooled down to the motional ground state

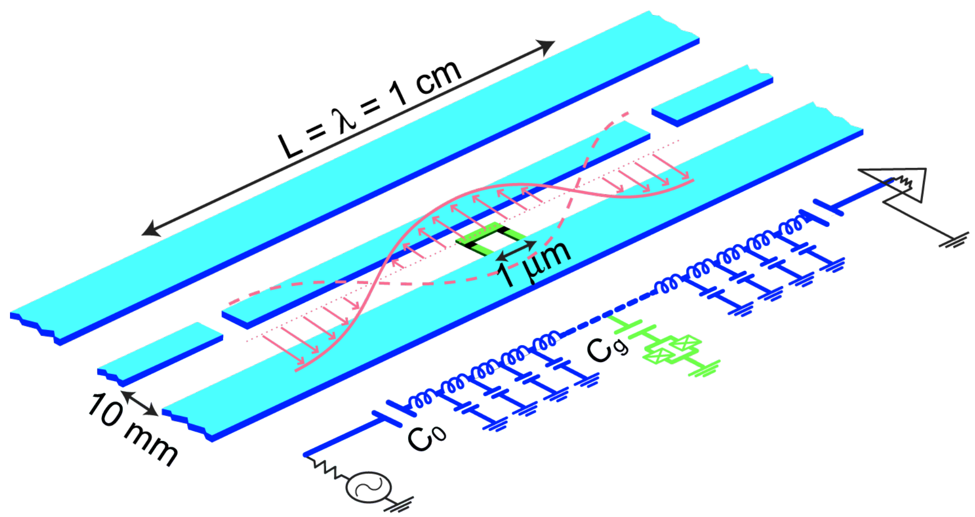
b) Trapped ions enjoy long-lived internal states to form a qubit

c) Trapped ions emulate the Jaynes-Cummings model of cavity QED

d) Trapped ions allow for high-fidelity one and two-qubit gates

e) Trapped ions are considered as the most promising quantum platform for quantum information processing and quantum simulations

Superconducting qubits and circuit QED



a) Superconducting qubits have long coherence times.

b) SC qubits can be coupled to high-Q coplanar waveguide cavities.

c) SC qubits simulate the Jaynes-Cummings model of cavity QED

d) SC qubits allow for high-fidelity one and two-qubit gates

e) SC qubits are considered as a promising quantum platform
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Optical lattices

Quantum photonics

Quantum dots

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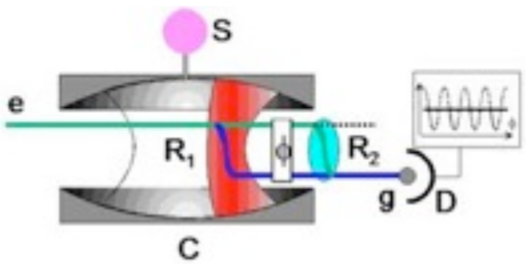
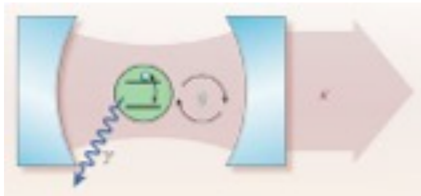
Early examples of quantum simulations

a) The simplest and most fundamental model describing the coupling between light and matter is the Jaynes-Cummings (JC) model in cavity QED (CQED).



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



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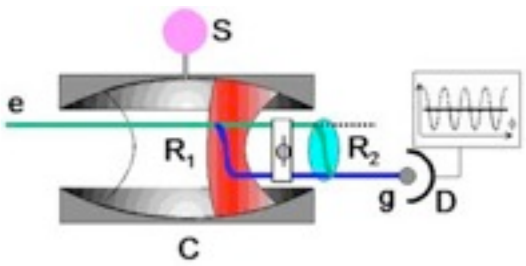

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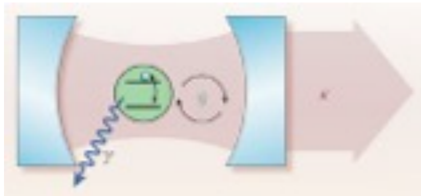
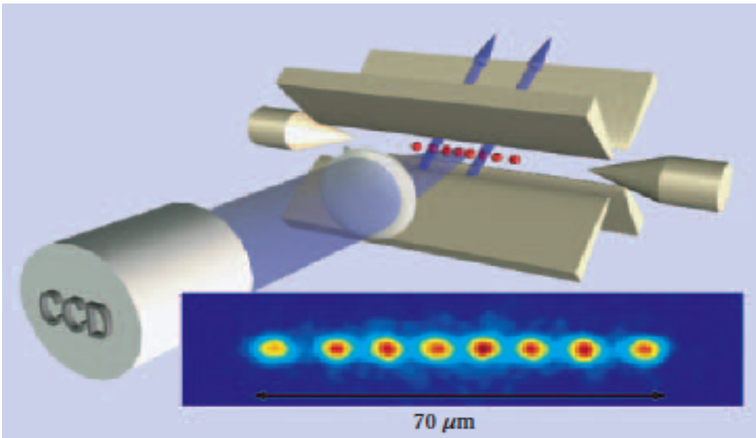


We could consider the implementation of the JC model in trapped ions as one of the first nontrivial quantum simulations.



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

The quantized electromagnetic field is replaced by quantized ion motion

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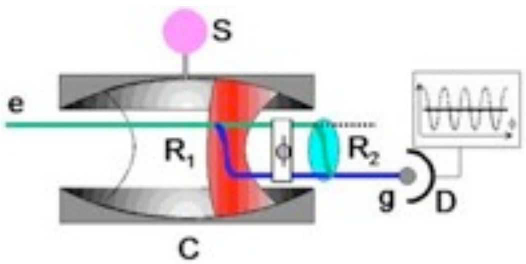

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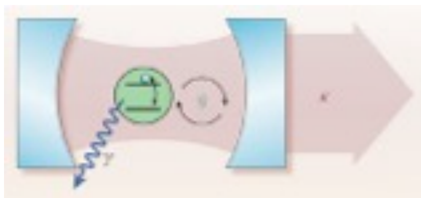

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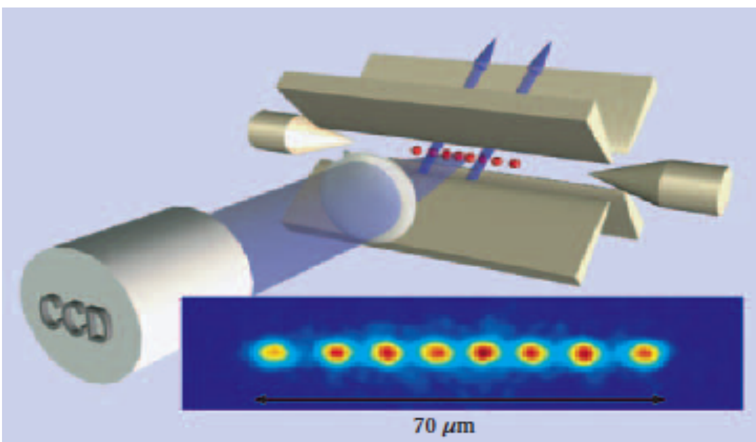

$$H_r = \hbar\eta\tilde{\Omega}_r\left(\sigma^+ a e^{i\phi_r} + \sigma^- a^\dagger e^{-i\phi_r}\right)$$

Red sideband excitation of the ion = JC interaction

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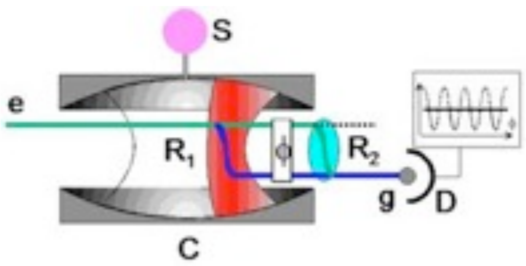

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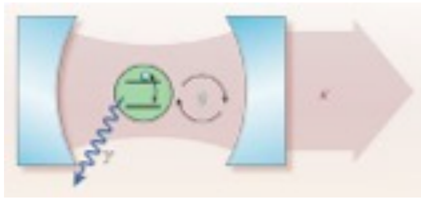

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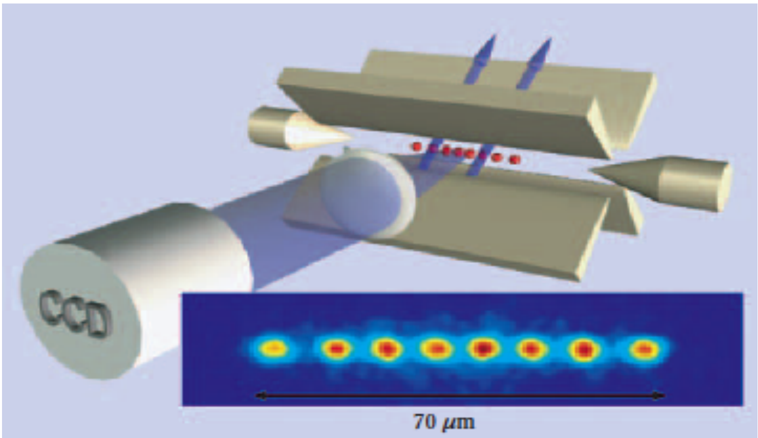

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$$H_r = \hbar\eta\tilde{\Omega}_r\left(\sigma^+ a e^{i\phi_r} + \sigma^- a^\dagger e^{-i\phi_r}\right)$$

Red sideband excitation of the ion = JC interaction

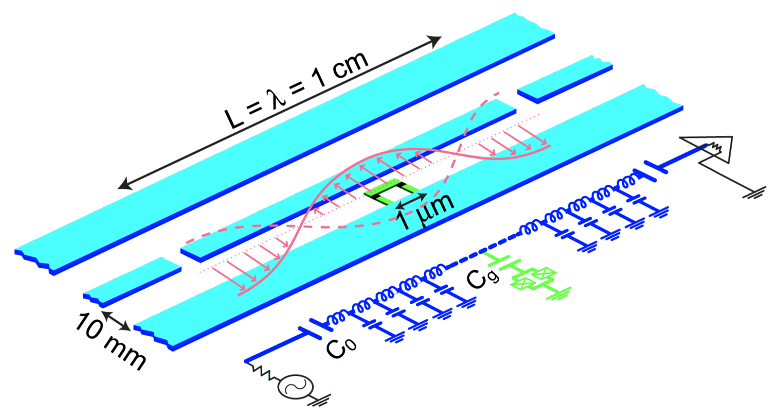
$$H_b = \hbar\eta\tilde{\Omega}_b\left(\sigma^+ a^\dagger e^{i\phi_b} + \sigma^- a e^{-i\phi_b}\right)$$

Blue sideband excitation of the ion = anti-JC interaction

The quantized electromagnetic field is replaced by quantized ion motion

b) We could see the JC model in circuit QED (cQED) as a quantum simulation;
the two-level atom is replaced by a superconducting qubit, also called artificial atom.

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



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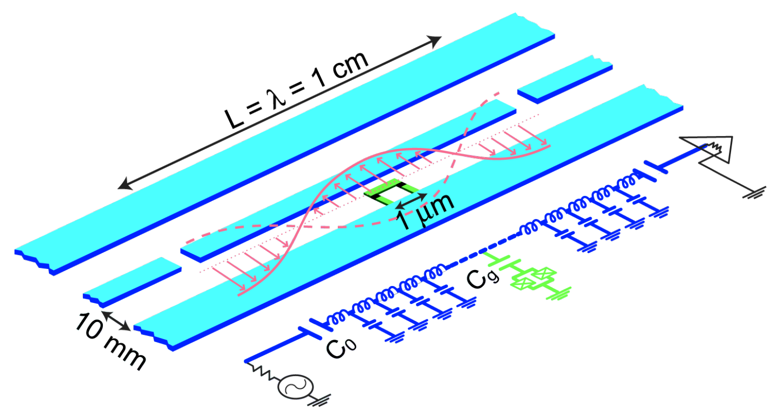
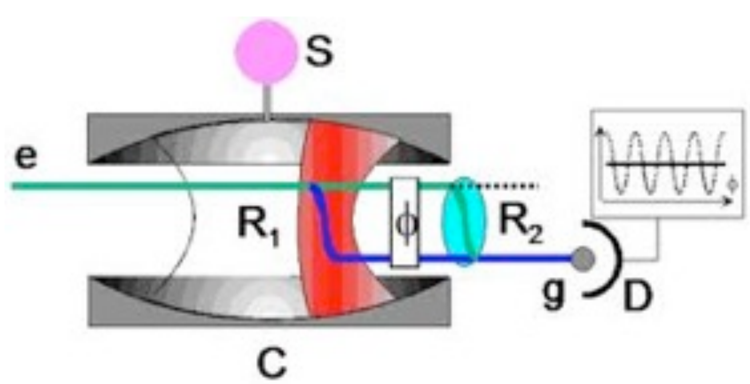
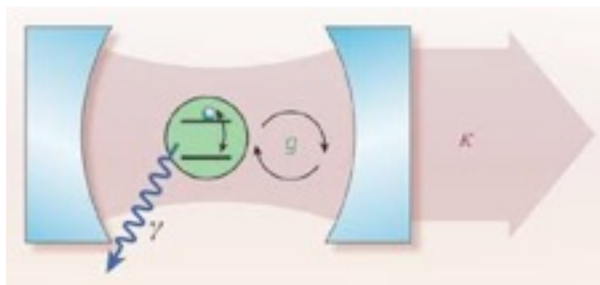


Quantum simulations are never a plain analogy, cQED has advantages in atomic control as in microwave CQED, but also longitudinal and transversal driving as in optical CQED.





QUTIS
Quantum Technologies for Information Science

QUTIS Group

Workshop Home

Application

Accomodation

Travel

Important Dates

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aqute

Workshop on Quantum Simulations

Universidad del País Vasco UPV/EHU, Bilbao, Spain

22nd-25th October 2012

Organizers: Göran Wendin and Enrique Solano
Local Organizers: Lucas Lamata and Guillermo Romero

End of LECTURE 1

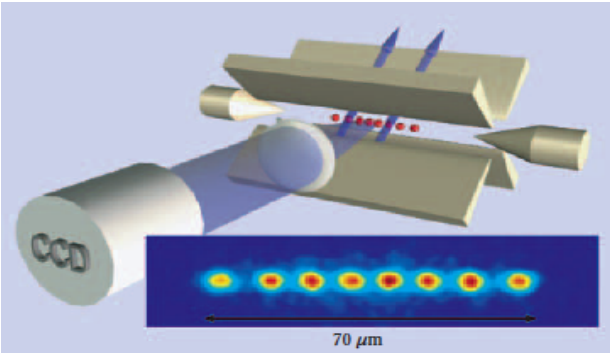
LECTURE 2

Quantum simulations in trapped ions

Basic interactions in trapped ions

a) The carrier excitation:

$$H_{\sigma_\phi} = \hbar\Omega\sigma_\phi = \hbar\Omega\left(\sigma^+ e^{i\phi} + \sigma^- e^{-i\phi}\right) \quad \begin{cases} \phi = 0 \rightarrow H_{\sigma_x} = \hbar\Omega\sigma_x \\ \phi = -\dfrac{\pi}{2} \rightarrow H_{\sigma_y} = \hbar\Omega\sigma_y \end{cases}$$

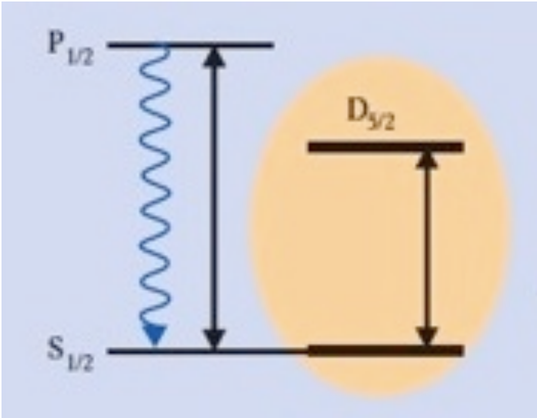


b) The red sideband excitation:

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

c) The blue sideband excitation:

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



d) The linear superposition of red and blue sideband excitations:

$$H_{r+b} = \hbar\eta\tilde{\Omega}\sigma_\phi\left(\alpha x + \beta p_x\right) \quad \text{with} \quad \begin{aligned} x &= \sqrt{\frac{\hbar}{2M\nu}}\left(a^\dagger + a\right) = \Delta\left(a^\dagger + a\right) \\ p_x &= i\sqrt{\frac{\hbar M\nu}{2}}\left(a^\dagger - a\right) = \frac{i\hbar}{2\Delta}\left(a^\dagger - a\right) \end{aligned}$$

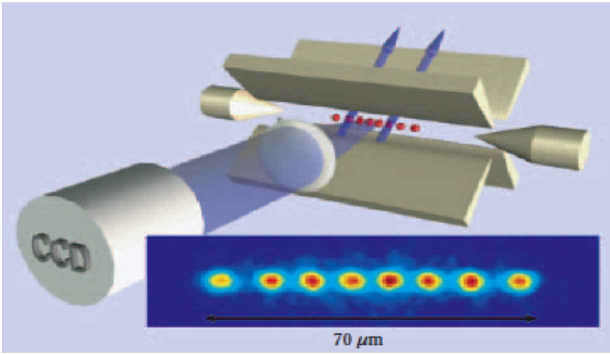
Dirac equation in trapped ions

a) The linear superposition of carrier, red and blue sideband excitations, yield an effective Hamiltonian corresponding to the 1+1 Dirac Hamiltonian for a free particle:

$$i\hbar\frac{\partial}{\partial t}\phi = H_D^{ion}\phi = \left(2\eta\Delta\tilde{\Omega}\sigma_x p_x + \hbar\Omega\sigma_z\right)\phi = \begin{pmatrix} \hbar\Omega & 2\eta\Delta\tilde{\Omega}\, p_x \\ 2\eta\Delta\tilde{\Omega}\, p_x & -\hbar\Omega \end{pmatrix}\phi,$$

to be compared with the original:

$$i\hbar\frac{\partial}{\partial t}\phi = H_D\phi = \left(c\sigma_x p_x + mc^2\sigma_z\right)\phi = \begin{pmatrix} mc^2 & c\,p_x \\ c\,p_x & -mc^2 \end{pmatrix}\phi$$



producing the parameter correspondence:

$$\begin{cases} \hbar\Omega = mc^2 \\ 2\eta\Delta\tilde{\Omega} = c \end{cases}$$

b) Similar steps produce the quantum simulation of higher dimensional Dirac equations

L. Lamata, J. León, T. Schätz, and E. Solano, PRL **98**, 253005 (2007)

c) If we consider the relativistic limit, $mc^2 \ll cp_x \; (m \rightarrow 0)$, the Dirac dynamics produces constantly growing Schrödinger cats as in quantum optical systems:

$$H_D^{ion} = 2\eta\Delta\tilde{\Omega}\sigma_x p_x + \hbar\Omega\sigma_z \rightarrow H_D^{rel} = 2\eta\Delta\tilde{\Omega}\sigma_x p_x$$

See, for example, Solano et al., PRL (2001), Solano et al., PRL (2003), Haljan et al., PRL (2005), and Zähringer et al., PRL (2010).

d) If we consider now the nonrelativistic limit, $mc^2 \gg cp_x$, the Dirac dynamics would be happy to have a quantum optician calculating the second-order effective Hamiltonian:

$$H_D^I = 2\eta\Delta\tilde{\Omega}\left(\sigma^+ e^{2i\Omega t} + \sigma^- e^{-2i\Omega t}\right)p_x \rightarrow H_{\text{eff}} = \sigma_z \frac{p_x^2}{\left(\frac{\hbar\Omega}{2\eta^2\Delta^2\tilde{\Omega}^2}\right)} = \sigma_z \frac{p_x^2}{2m}$$

with simulated mass $\quad m = \frac{\nu\Omega}{2\eta^2\tilde{\Omega}^2} M$

This is a free Schrödinger dynamics derived from the nonrelativistic limit of the Dirac equation!

e) The *Zitterbewegung* (ZB) is a jittering motion of the expectation value of the position operator $\langle x(t) \rangle$.
It appears as a consequence of the superposition of positive and negative energy components.

In the Heisenberg picture, we can write the evolution of the Dirac position operator

$$x(t) = x(0) + \frac{c^2 p_x}{H_D} t + \frac{i\hbar c}{2H_D}\left(e^{2iH_D t/\hbar} - 1\right)\left(\sigma_x - \frac{cp_x}{H_D}\right)$$

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f) The prediction of ZB is considered controversial, see several papers appeared in the last few years questioning existence/absence. The predicted ZB frequency/amplitude for our "relativistic" ion are

$$\omega_{ZB} \sim 2\left|\bar{E}_D\right| / \hbar = 2\sqrt{p_0^2 c^2 + m^2 c^4} \,/\, \hbar \equiv 2\sqrt{\left(2\eta\Delta\tilde{\Omega}p_0\right)^2 / \hbar + \Omega^2}$$

$$x_{ZB} \sim \frac{\hbar}{2mc}\left(\frac{mc^2}{\bar{E}_D}\right)^2 \equiv \frac{\eta\hbar^2\tilde{\Omega}\Omega\Delta}{4\eta^2\tilde{\Omega}^2\Delta^2 p_0^2 + \hbar^2\Omega^2} \sim \Delta$$

$$\omega_{ZB} \sim 0 - 10^6\,\text{Hz}$$

$$x_{ZB} \sim 0 - 10^3\,\text{Å}$$

From a theoretical point of view, the quantum simulation of the ZB looked cool!

However, the ZB amplitude was disappointing: how can one measure in the lab the ion position as a function of the interaction time with a resolution beyond the width of the motional ground state?

g) The answer to the previous question is: designing a highly precise measurement of the ion position!

We had proposed in 2006 such a method called “instantaneous” measurements for CQED and trapped ions.

If the initial state of the probe qubit and the unknown motional system is

$$\rho_{at-m}(0) = |+\rangle\langle+|\rho_m \quad \text{where} \quad |+\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)$$

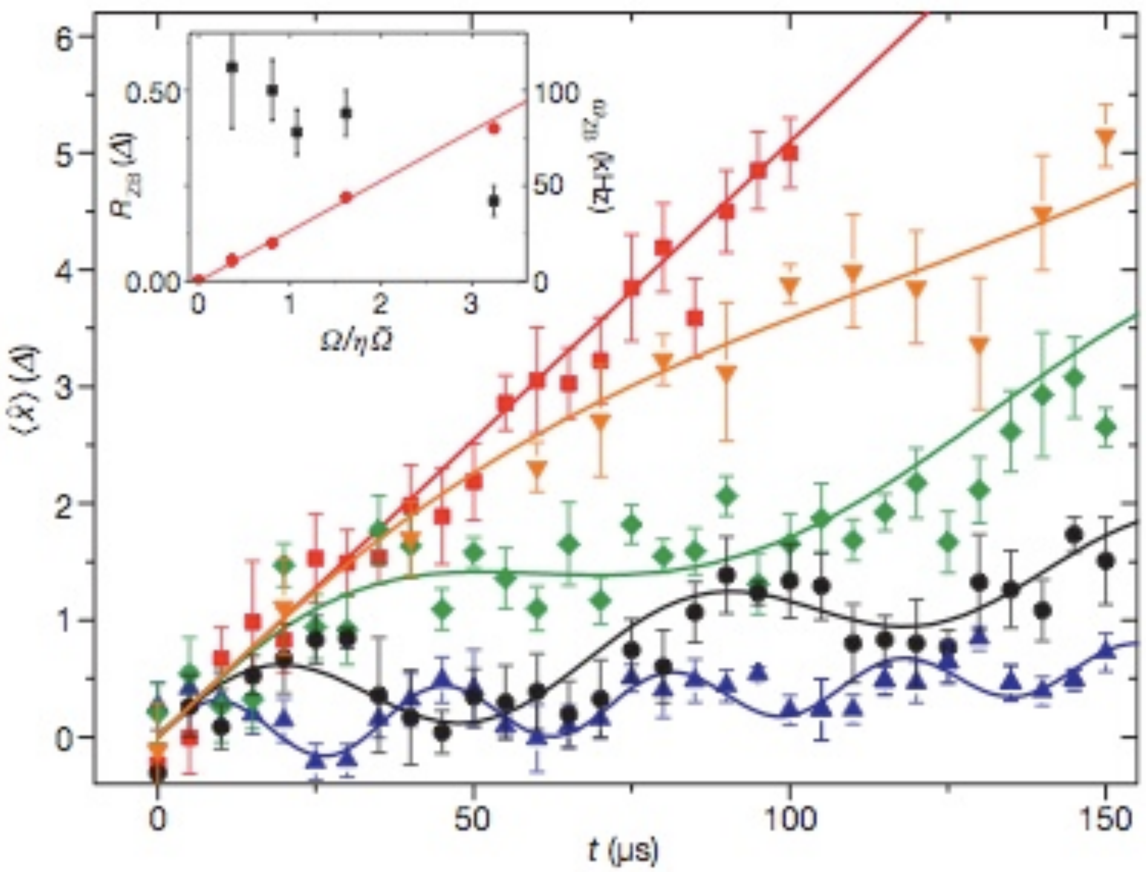
it can be proved that after a red-sideband excitation during an interaction time “t”

$$\langle x(t)\rangle = \left.\frac{dP_e(t)}{dt}\right|_{t=0} \quad \text{where} \quad P_e(t) = Tr\left[\rho_{at-m}(t)|e\rangle\langle e|\right]$$

It is possible to encode relevant motional system observables in the short-time dynamics of the probe qubit, in fact we can get the full wavefunction from the first and second derivatives at t=0!

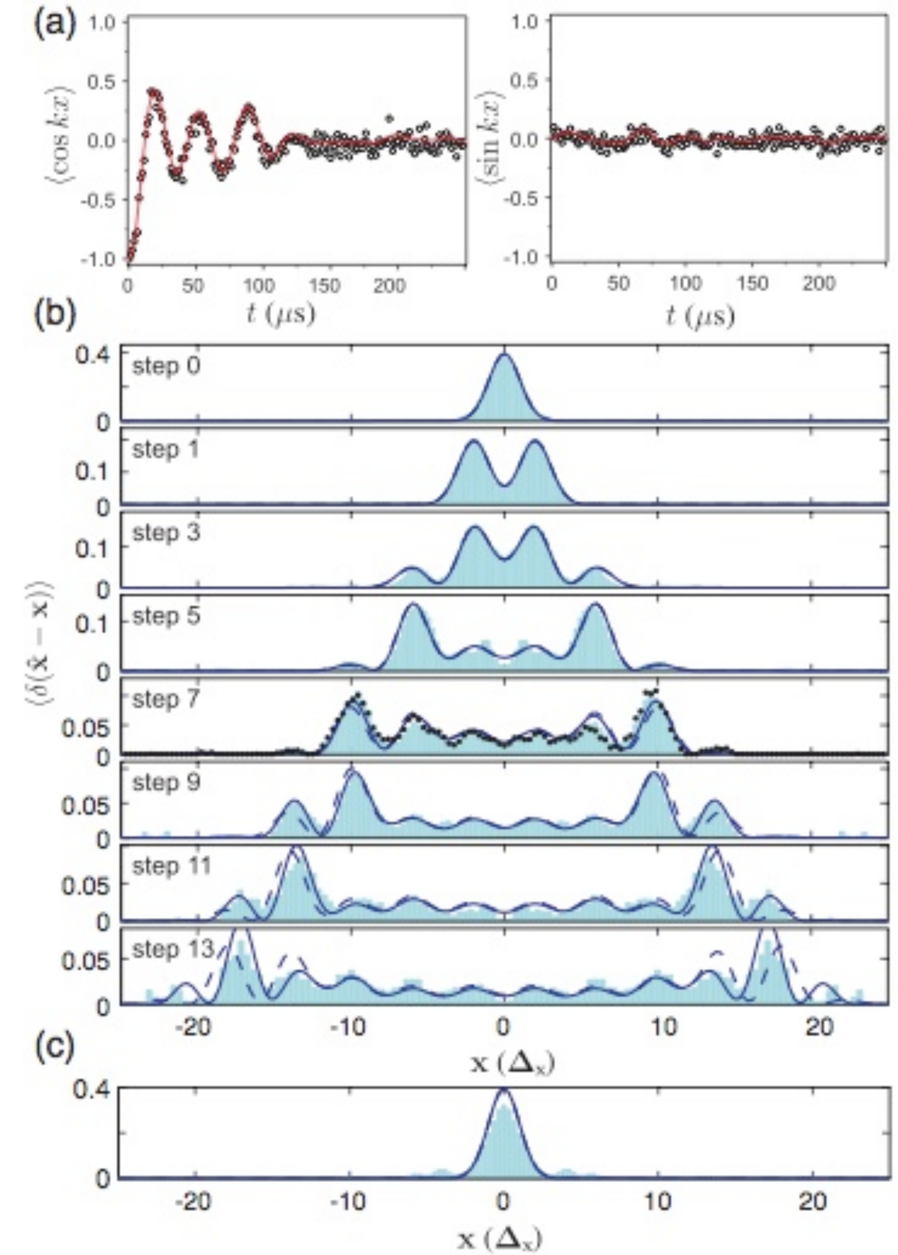
We have produced several papers studying different results for the “instantaneous” measurements. Some of them are theoretical and some of them have already seen the light of experiments.

Lougovski et al., Eur. Phys. J. D (2006); Bastin et al., J. Phys. B: At. Mol. Opt. Phys. (2006); Franca Santos et al., PRL (2006); Gerritsma et al., Nature (2010), Zähringer et al., PRL (2010); Casanova et al., PRA 81, 062126 (2010).



“Instantaneous” measurements of ZB
with sub-Δ resolution and beyond the diffraction limit.

R. Gerritsma et al., Nature (2010)

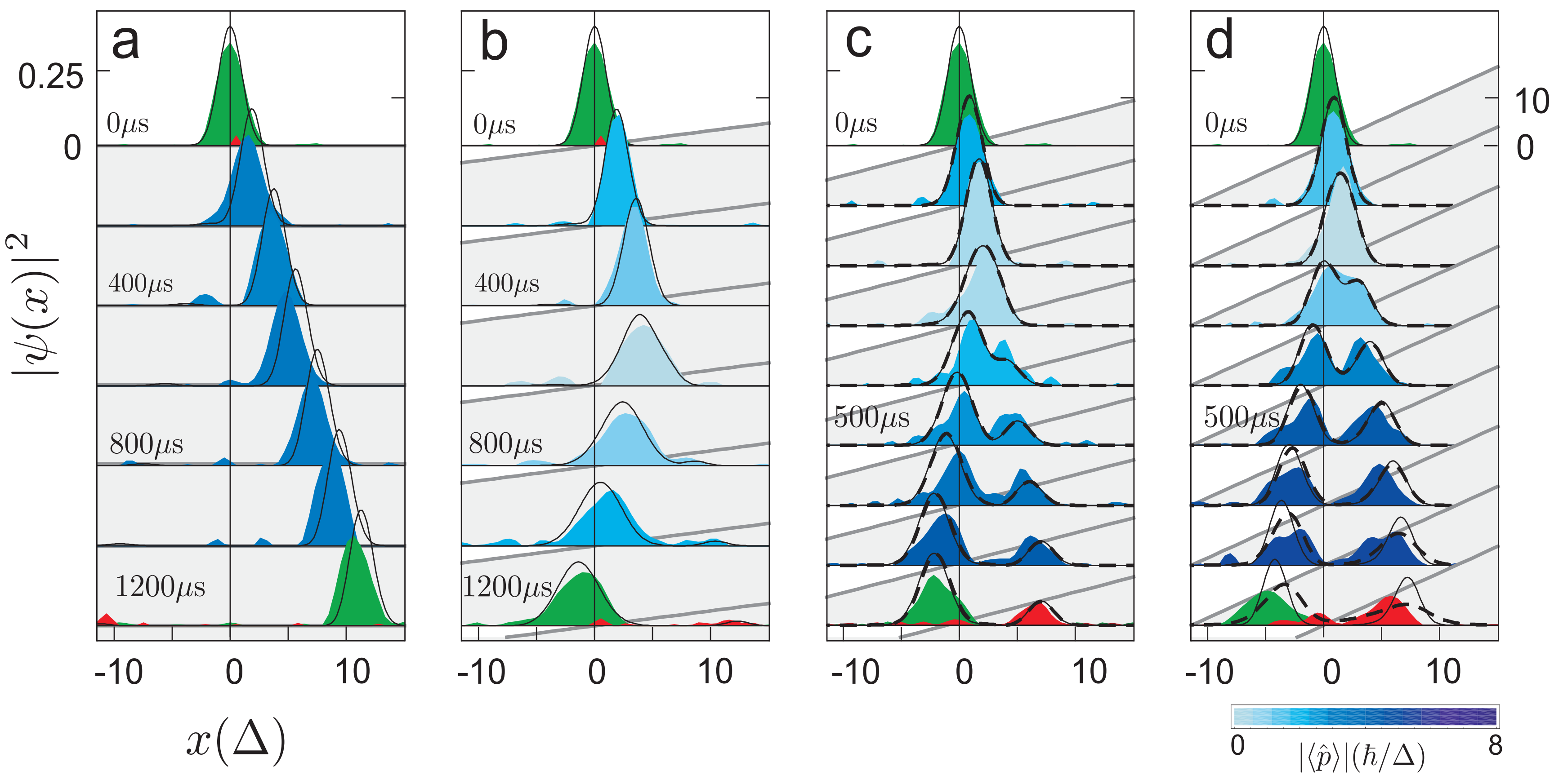


Reconstruction of absolute square wavefunction
of quantum walks in trapped ions.

F. Zähringer et al., PRL (2010)

h) We have also proposed the quantum simulation of the Klein Paradox

$$i\hbar \frac{\partial}{\partial t}\Phi = H_{DLP}\Phi = \left(c\sigma_x p_x + \alpha x + mc^2\sigma_z\right)\Phi$$



The Dirac Linear Potential is not always reflecting the particle. This amounts to a Klein Paradox behavior, where the particle can move from positive to negative energy components via tunneling.

J. Casanova et al., PRA **82**, 020101(R) (2010); R. Gerritsma et al., PRL **106**, 060503 (2011).

End of LECTURE 2

LECTURE 3

The quantum Rabi model

The quantum Rabi model (QRM) describes, in fact, the dipolar light-matter coupling.
The JC model is the QRM after RWA, it is the SC regime of cavity/circuit QED.

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

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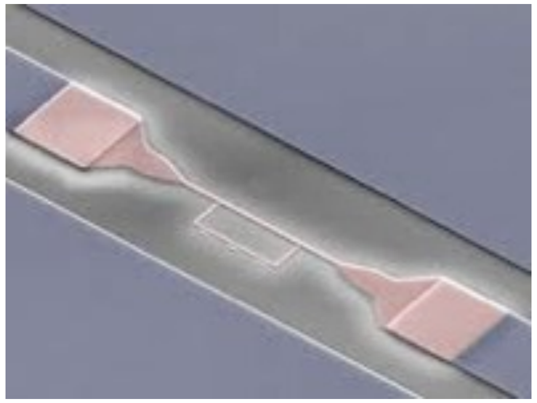
However, we have recently seen the advent of the ultrastrong coupling (USC) regime of light-matter interactions in cQED, where 0.1< g/w < 1, and RWA cannot be applied.



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

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

- Current experimental efforts are trying to approach USC regimes where g/w ~ 0.5-1.0
- Recently, the analytical solutions of the QRM were presented: D. Braak, PRL **107**, 100401 (2011).

There are interesting and novel physical phenomena in the USC regime of the QRM:

a) Physics beyond RWA: Bloch-Siegert shifts, entangled ground states, counter-intuitive results that do not violate energy conservation, etc.

$$\sigma^{\dagger} a + \sigma a^{\dagger} + \sigma^{\dagger} a^{\dagger} + \sigma a$$

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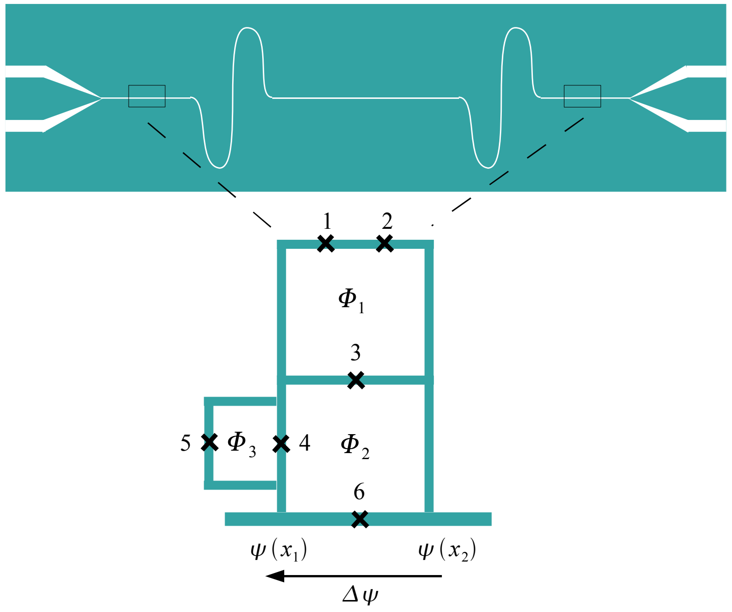
b) Faster and stronger quantum operations

b.1) Ultrafast quantum gates (CPHASE) that may work at the subnanosecond scale



G. Romero, D. Ballester, et al., PRL 108, 120501 (2012)

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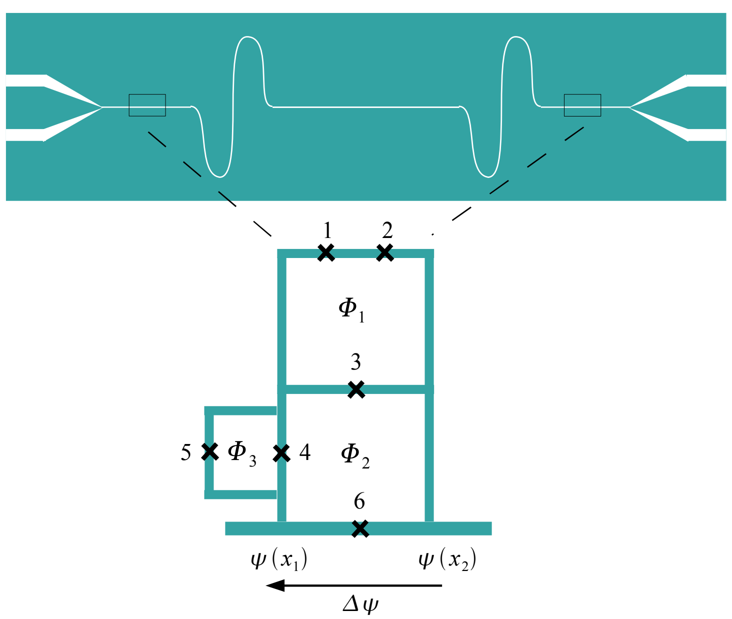

G. Romero, D. Ballester, et al., PRL 108, 120501 (2012)

b.2) New regimes of light-matter coupling: Deep strong coupling (DSC) regime of QRM.

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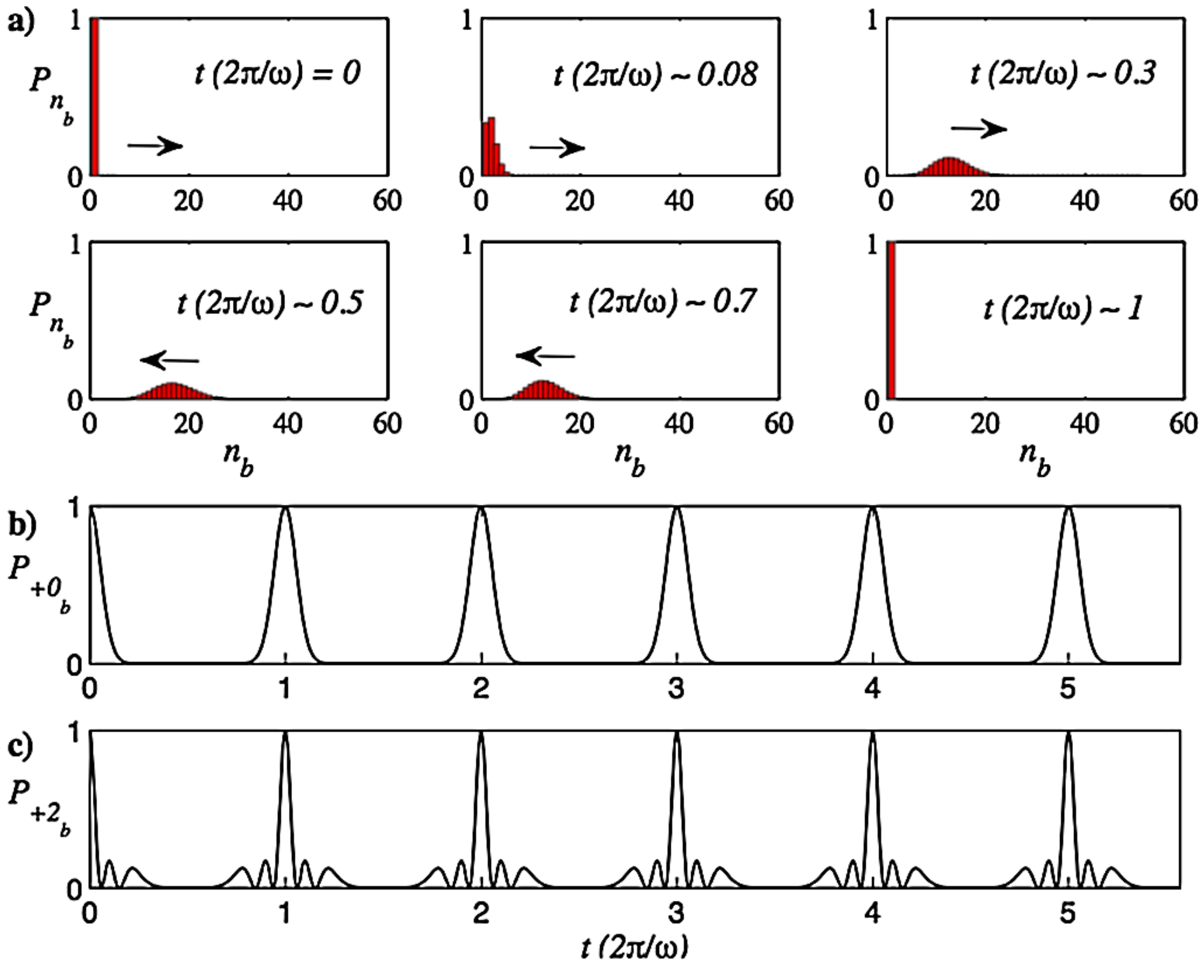
$$\Pi = -\sigma_z(-1)^{n_a} = -(|e\rangle\langle e| - |g\rangle\langle g|)(-1)^{a^\dagger a}$$

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

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



J. Casanova, G. Romero, et al., PRL **105**, 263603 (2010)

Is it possible to cheat technology or nature?

We might reach USC/DSC regimes in the lab but be unable to observe them, mainly due to the difficulty in ultrafast on/off coupling switching.

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b) We could also reveal these regimes via quantum simulations.

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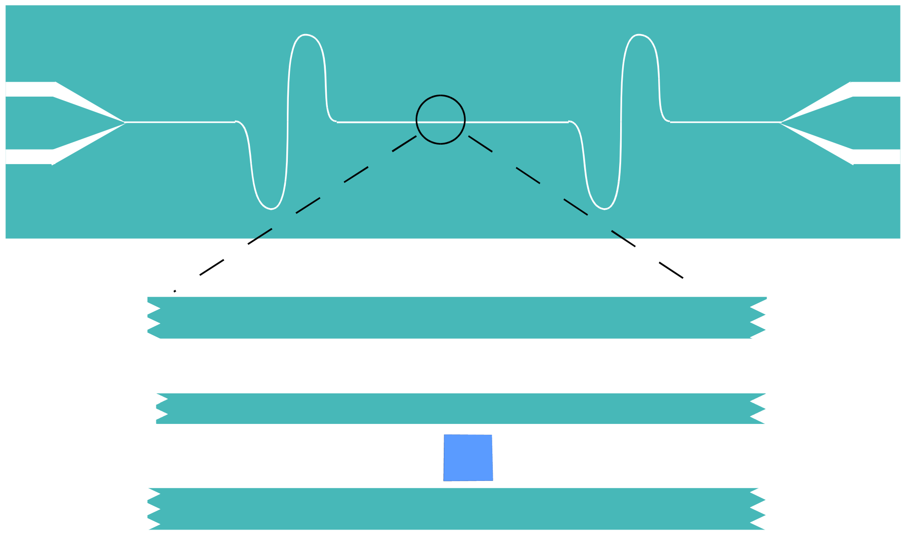
b.2) A quantum simulation of the QRM with access to all regimes?

Quantum simulation of the QRM in circuit QED



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

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, G. Romero, et al., PRX **2**, 021007 (2012)

Quantum simulation of the Dirac equation in circuit QED

1+1 Dirac equation $$i\hbar\frac{d\psi}{dt} = (c\sigma_x p + mc^2\sigma_z)\psi$$

$$\omega_{\mathrm{eff}} = \omega - \omega_1 = 0 \longrightarrow \mathcal{H}_{\mathrm{D}} = \frac{\hbar\Omega_2}{2}\sigma_z + \frac{\hbar g}{\sqrt{2}}\sigma_x p$$

$$\mathcal{H}_D = \hbar\sum_j \Omega_j(e^{i(\omega_j t+\phi)}\sigma + \mathrm{H.c.}) \qquad \phi = \pi/2$$

Zitterbewegung, via measuring $\langle X\rangle(t)$

R. Gerritsma et al., Nature **463**, 68 (2010)

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R. Gerritsma et al., Nature **463**, 68 (2010)

1+1 Dirac particle + Potential

Add a classical driving to the cavity

$$\mathcal{H} = \mathcal{H}_{JC} + \hbar\sum_{j=1,2}(\Omega_j e^{-i(\omega_j t+\phi_j)}\sigma^\dagger + \text{H.c.}) + \hbar\xi(e^{-i\omega_1 t}a^\dagger + \text{H.c.})$$

$$\mathcal{H}_{\rm eff} = \frac{\hbar\Omega_2}{2}\sigma_z - \frac{\hbar g}{\sqrt{2}}\sigma_y\hat{p} + \hbar\sqrt{2}\xi\hat{x}$$

Klein paradox

R. Gerritsma et al., PRL **106**, 060503 (2011)

Measuring $\langle X\rangle$ to observe these effects

Quadrature moments have been measured at ETH and WMI:

E. Menzel et al., PRL **105**, 100401(2010); C. Eichler et al., PRL **106**, 220503 (2011)

Conclusion and outlook

a) Scalable quantum simulations could produce novel scientific knowledge, unaccessible to classical computers and standard measurement techniques.

b) Quantum simulations could explore the limits of simulation in physics, including the allowed and forbidden quantum operations in nature.

c) Presently, optical lattices and trapped ions dominate quantum simulations. It is time for circuit QED to jump in.