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Quantum Simulations as our Quantum Theatre

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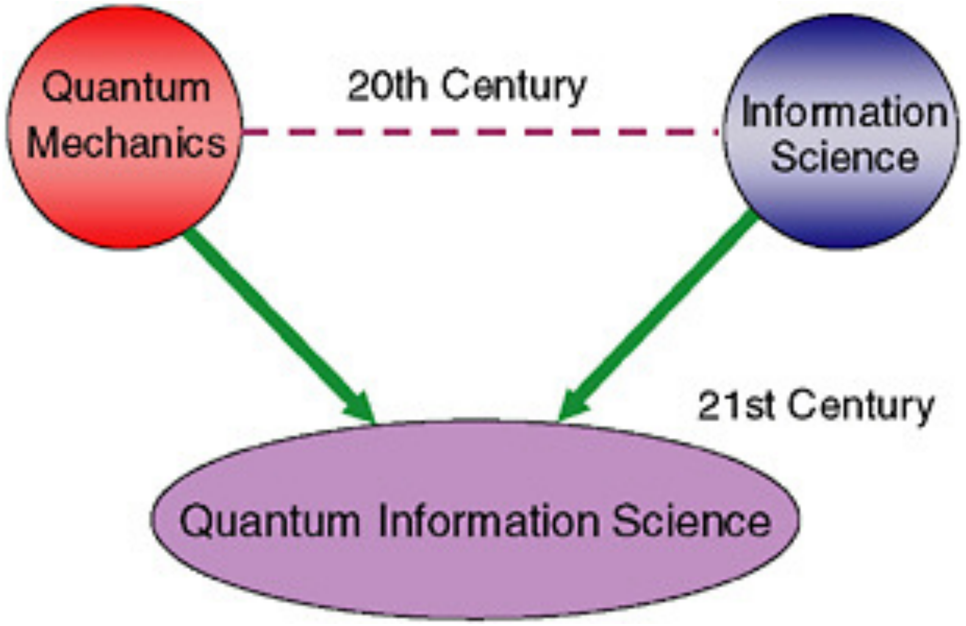
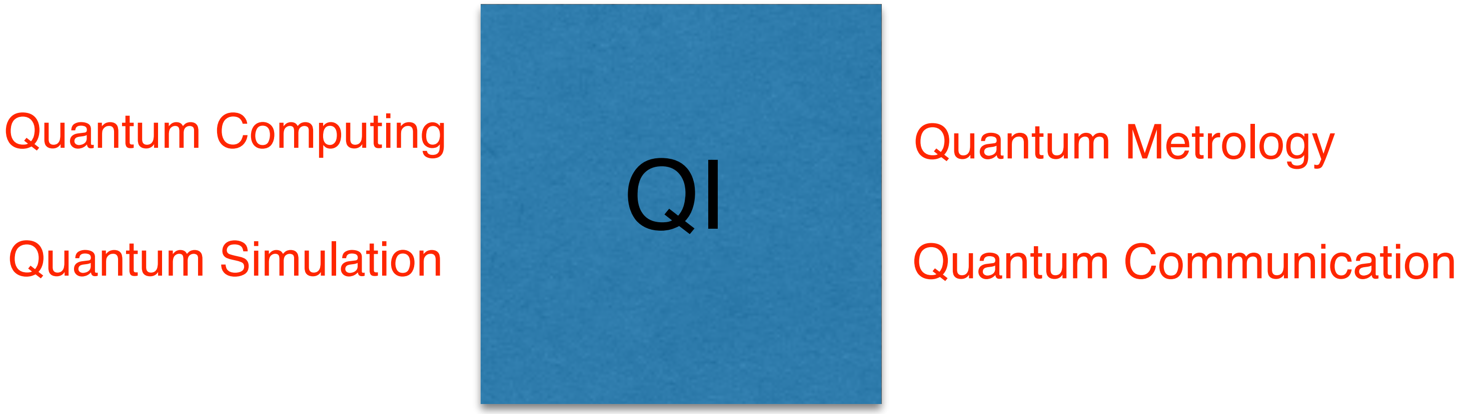




Quantum Computing

Quantum Simulation

QI

Quantum Metrology

Quantum Communication

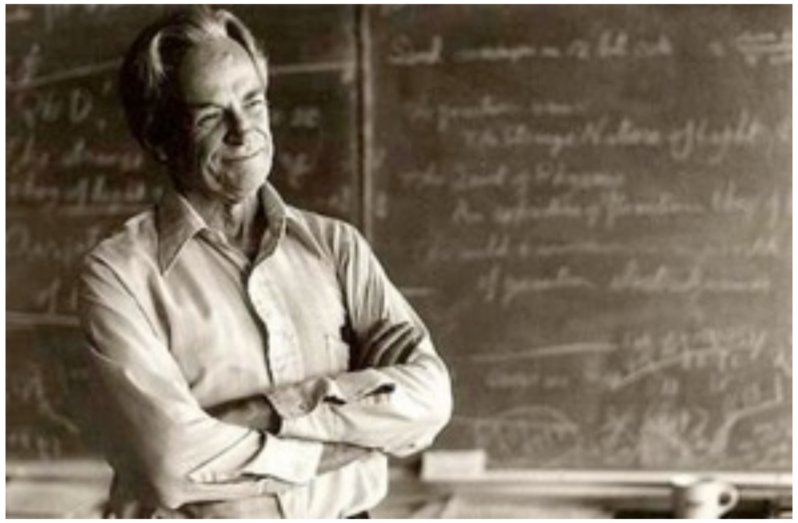
Quantum information will produce scientific knowledge
and deliver useful quantum technologies

What is a quantum simulation?

Definition

Quantum simulation is the intentional reproduction of the quantum aspects of a physical or unphysical model onto a typically more controllable quantum system.

Richard Feynman



Let nature calculate for us

<=>

Greek theatre

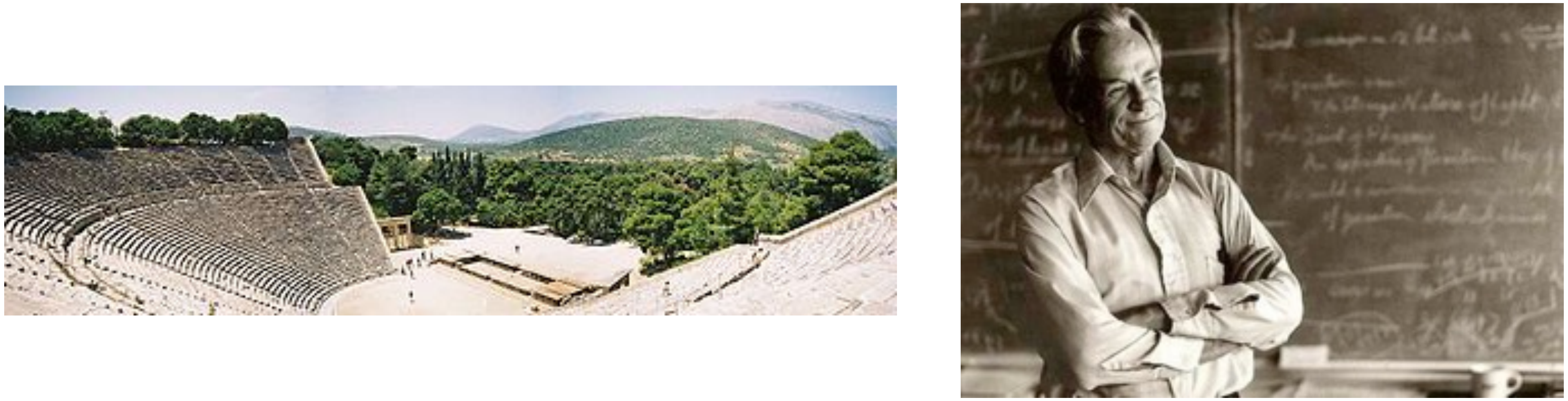
Mimesis or imitation is always partial,
this is the origin of creativity and arts

Quantum simulation <=> Quantum theatre

Conjecture on the origin of creativity

a) Imitation or simulation, be classical or quantum, may be useful but is condemned to imperfection.

b) This is the origin of artistic and scientific creativity, be for the sake of fundamental knowledge or for developing quantum technologies.



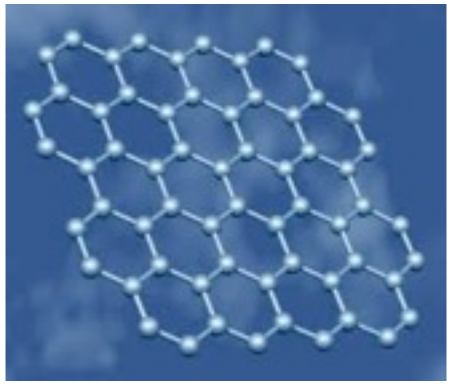
Is it possible to implement a quantum simulation of impossible physics?

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.

$$\psi \cancel{\Longrightarrow} \psi^{*}$$

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.



$$\overset{?}{\Longleftrightarrow}$$

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

Why are quantum simulations relevant and 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.

b) Because we can study phenomena that are difficult to access or even absent in nature, e.g. Dirac equation: *Zitterbewegung* & Klein Paradox, unphysical operations.

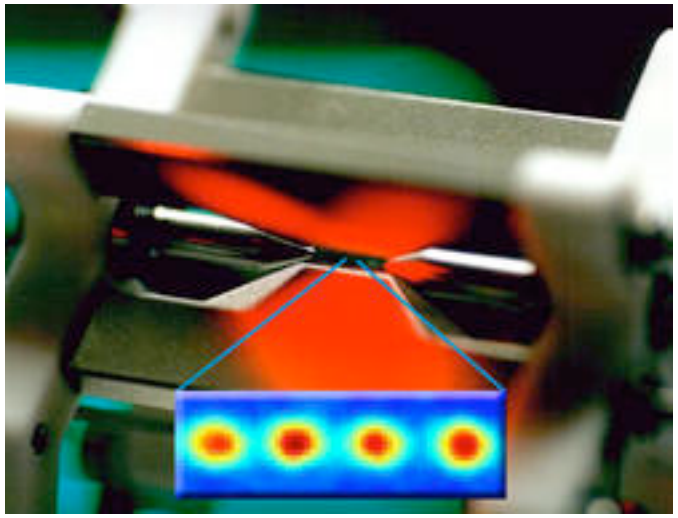
c) Because we can predict novel physics without manipulating the original systems, experiments make calculations beyond classical capabilities, e.g., fermionic models,QFTs.

d) Because we can contribute to the development of novel quantum technologies via scalable quantum simulators and their merge with quantum algorithms.

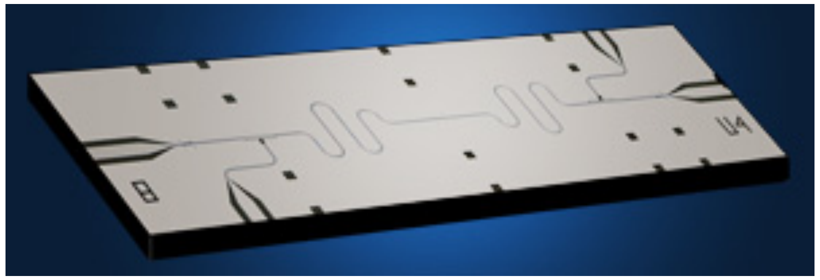
e) Because we are unhappy with reality, we enjoy arts and fiction in all its forms: literature, music, theatre, painting, quantum physics.

Quantum Technologies for Quantum Simulations

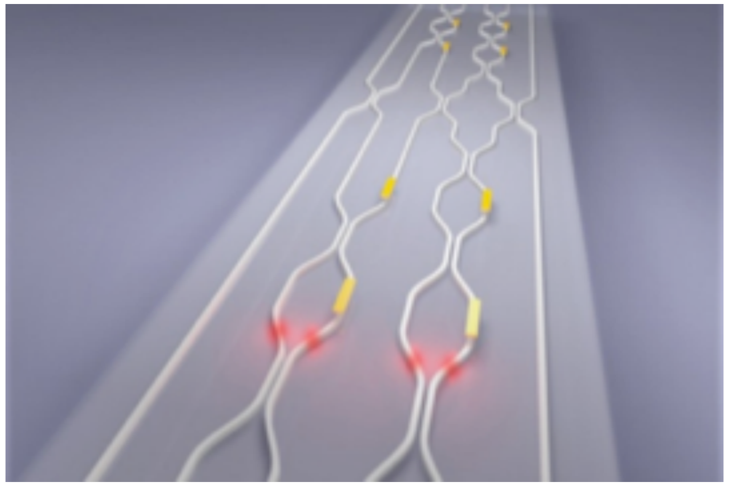
Trapped ions



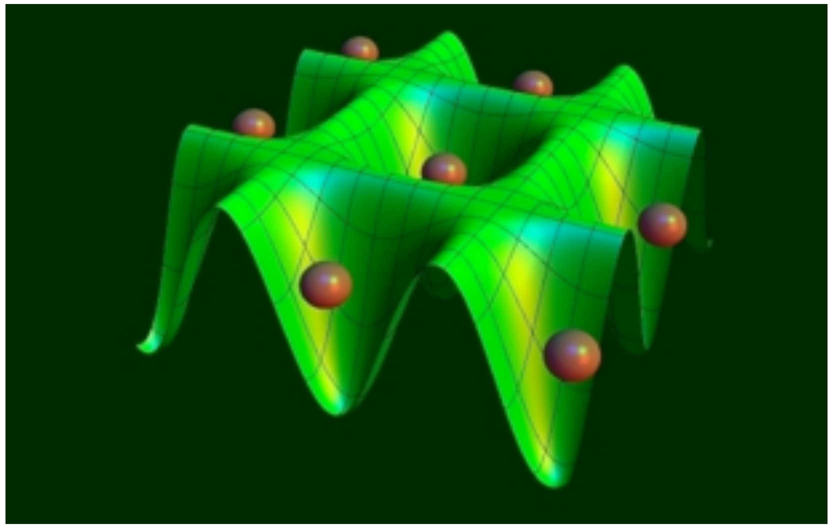
Circuit QED



Quantum photonics



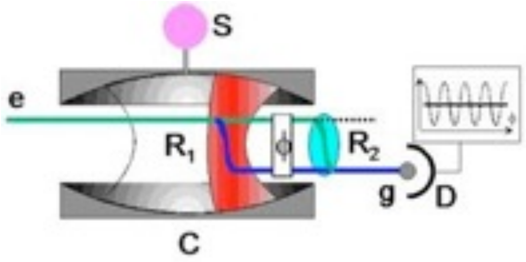
Optical lattices



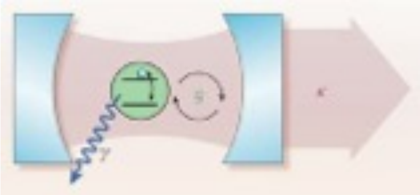
... and others are arriving!

Early examples of quantum simulations

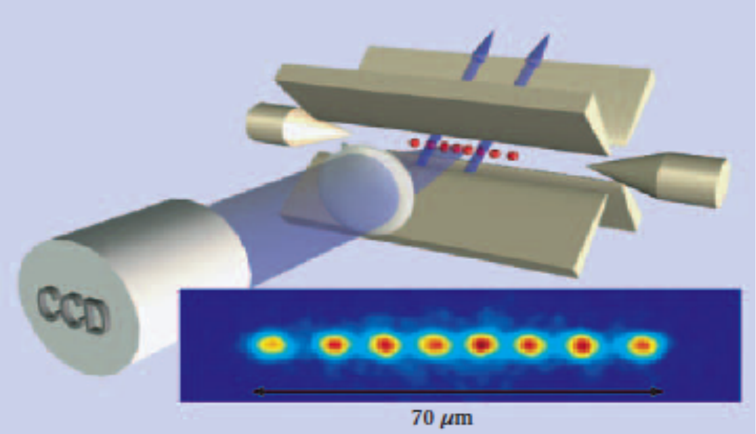
a) The simplest and most fundamental model describing the coupling between light and matter is the Jaynes-Cummings (JC) model in cavity QED (CQED).



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



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



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

Red sideband excitation of the ion = JC interaction

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

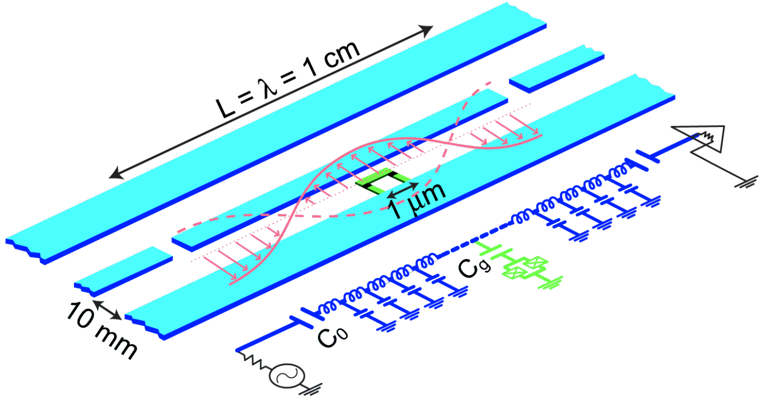
Blue sideband excitation of the ion = anti-JC interaction

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

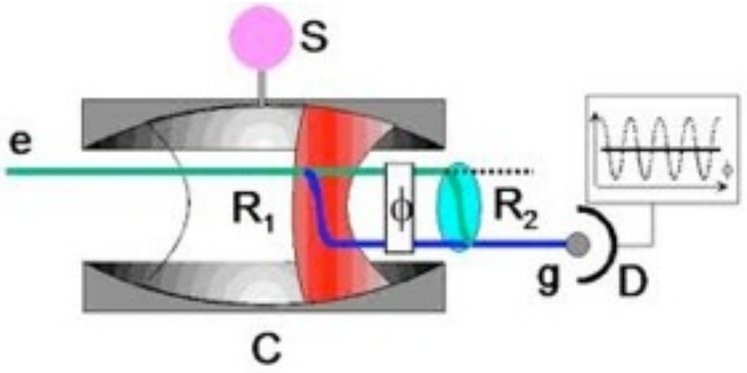
The quantized electromagnetic field is replaced by quantized ion motion

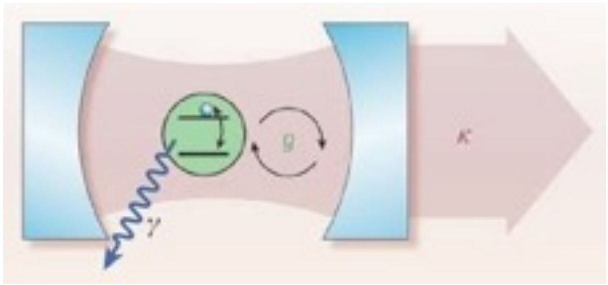
b) We could see the JC model in circuit QED (cQED) as a quantum simulation;
the two-level atom is replaced by a superconducting qubit, also called artificial atom.

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



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.



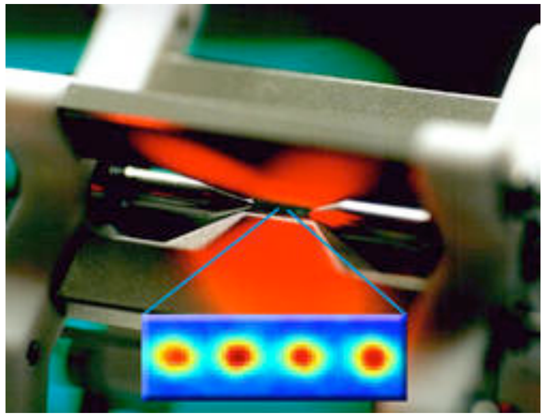


Analog or Digital Quantum Simulations?

a) Reproducing the Dirac equation in trapped ions is a good example of analog quantum simulators. Qubits map onto qubits, modes onto modes, and so on.

b) Digital quantum simulators allow us to reproduce quantum dynamics that are difficult with analog quantum simulators, enhancing our capabilities.

c) The most clever strategy should be to go for an analog-digital approach to optimize the resources provided by each quantum platform.



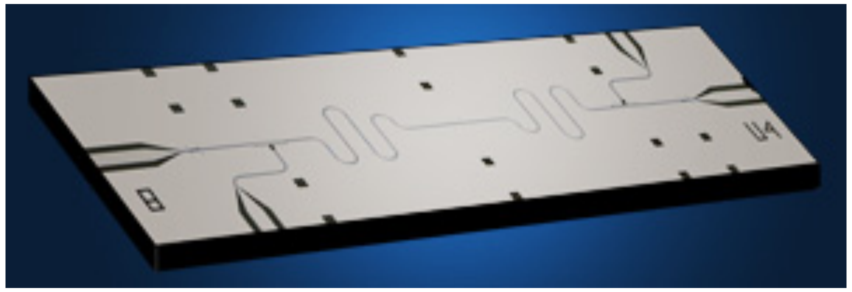
Quantum Emulation or Quantum Simulation?

a) Emulation is the process of mimicking the outwardly observable behaviour to match an existing target or model.

The internal structure of the emulating system does not have to accurately reflect the internal state of the emulated target or model.

b) Simulation consists in the effort of modelling the underlying structure of an existing target or model.

The internal structure of the emulating system tries to accurately reflect the internal state of the emulated target or model.



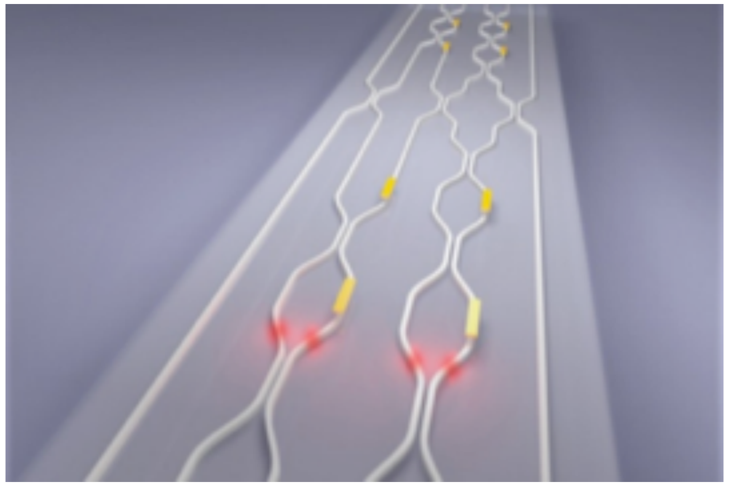
One-to-one quantum simulators or embedding quantum simulators?

a) A one-to-one quantum simulator is a device that uses a two-level system to mimic a two-level system and a harmonic oscillator to mimic a harmonic oscillator.

This may not be the clever approach when scaling up quantum simulations.

b) An embedding quantum simulator (EQS) is a device that embeds the original dynamics into an enlarged Hilbert space to enhance and optimize the extraction of information.

EQS merge the concepts of quantum simulation with quantum computing.

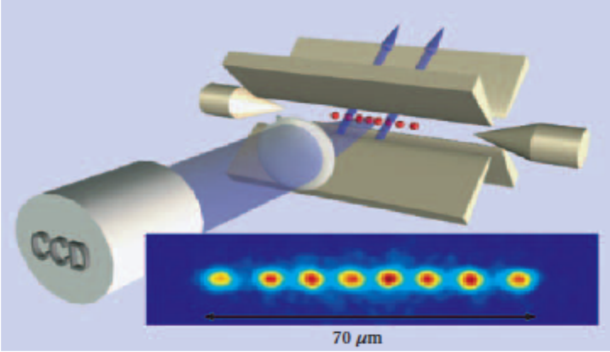


Dirac equation in trapped ions

Basic interactions in trapped ions

a) The carrier excitation:

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

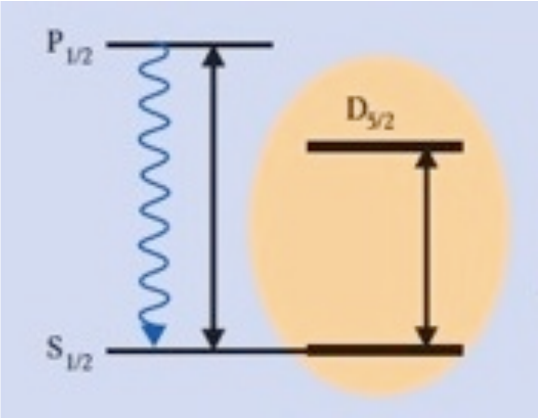


b) The red sideband excitation:

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

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:

$$H_{r+b} = \hbar\eta\tilde{\Omega}\sigma_\phi\left(\alpha x + \beta p_x\right)$$

with

$$x = \sqrt{\frac{\hbar}{2M\nu}}\left(a^\dagger + a\right) = \Delta\left(a^\dagger + a\right)$$

$$p_x = i\sqrt{\frac{\hbar M\nu}{2}}\left(a^\dagger - a\right) = \frac{i\hbar}{2\Delta}\left(a^\dagger - a\right)$$

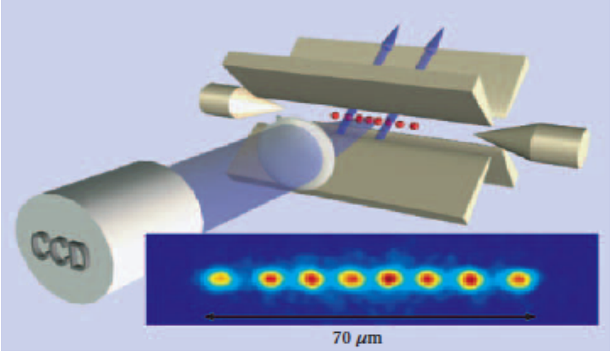
Designing the Dirac equation

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:

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

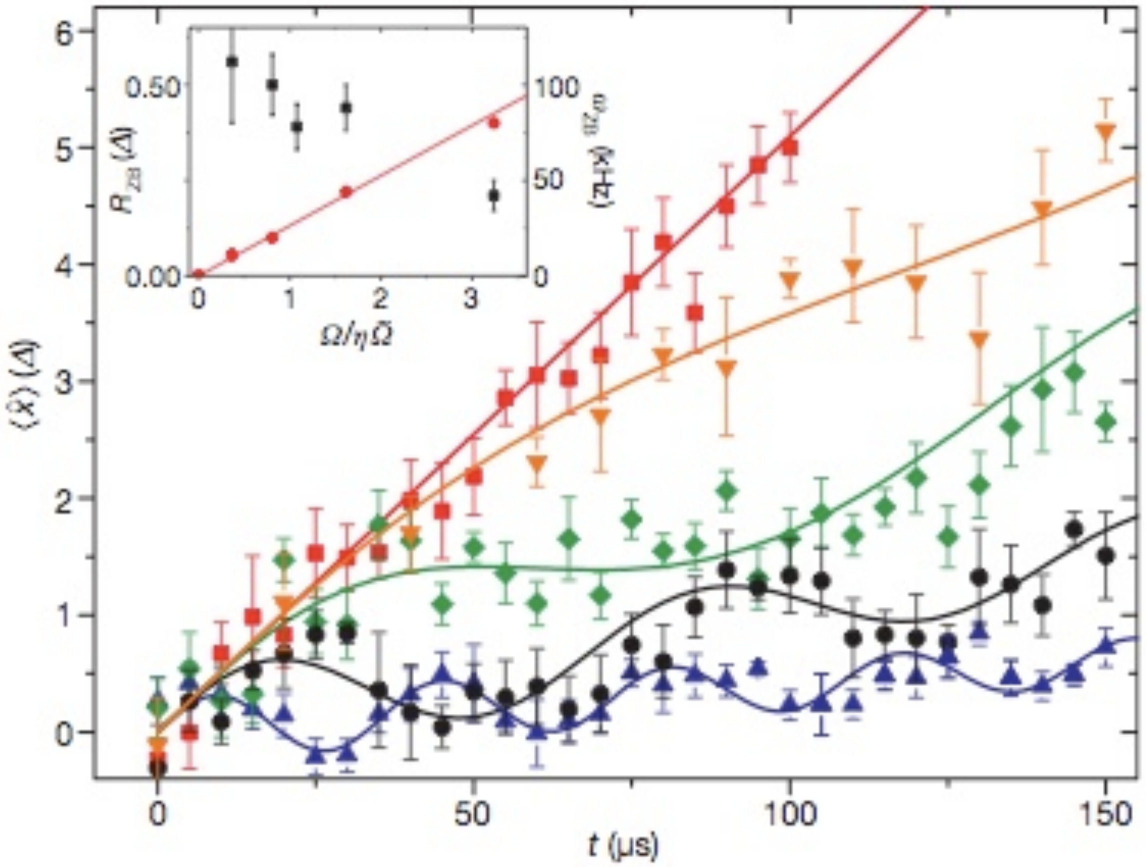


producing the parameter correspondence:

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

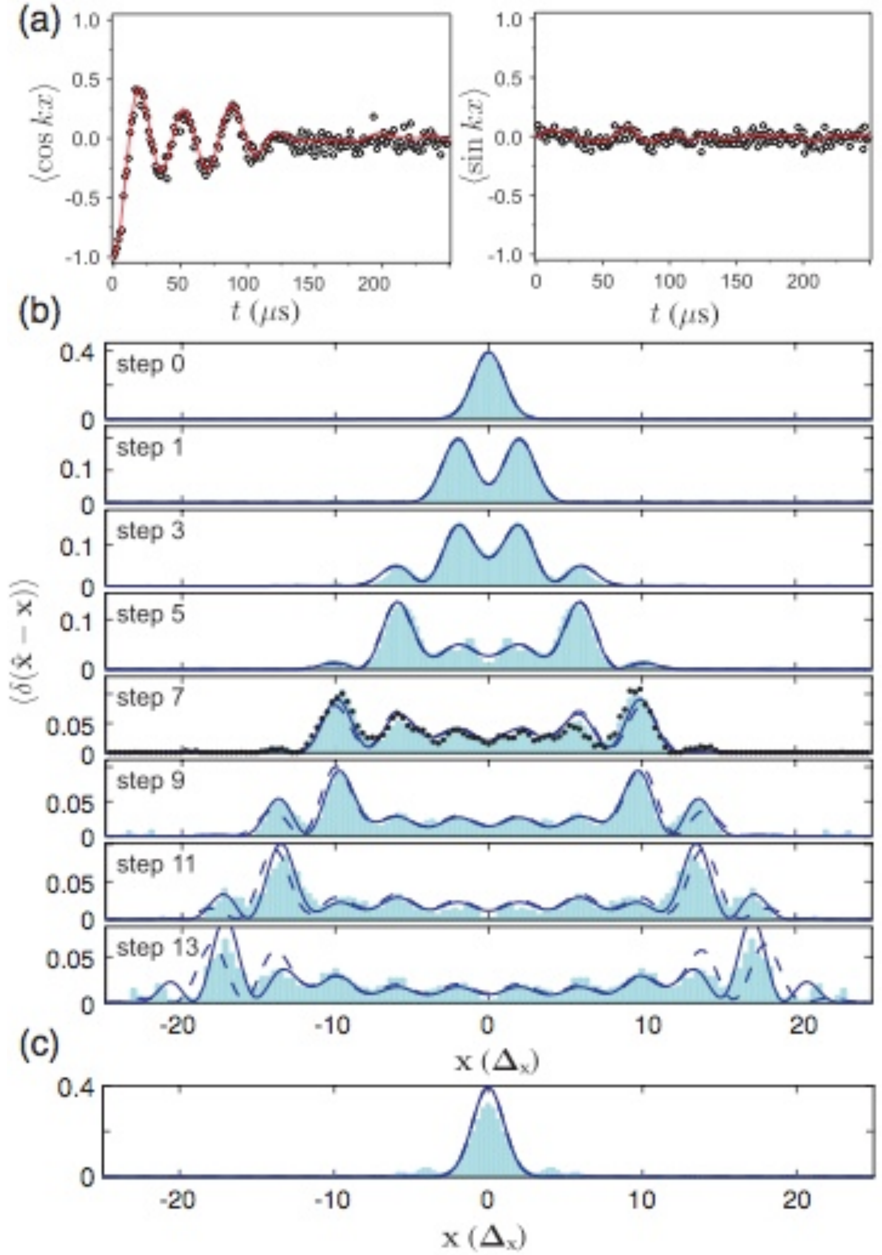
b) Similar steps produce the quantum simulation of higher dimensional Dirac equations

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



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

R. Gerritsma et al., Nature (2010)

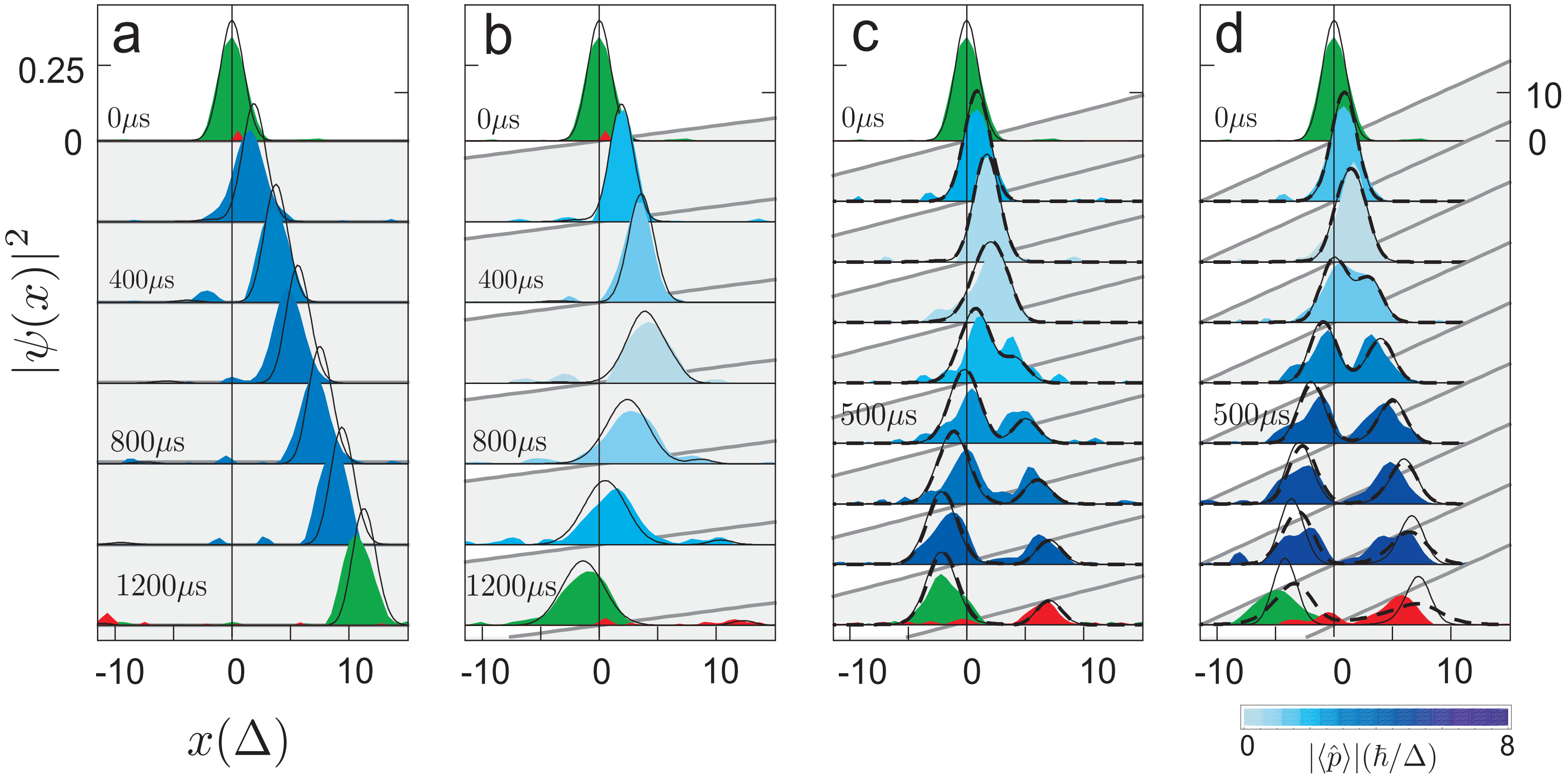


Reconstruction of absolute square wavefunction
of quantum walks in trapped ions.

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).

Quantum simulations with circuit QED

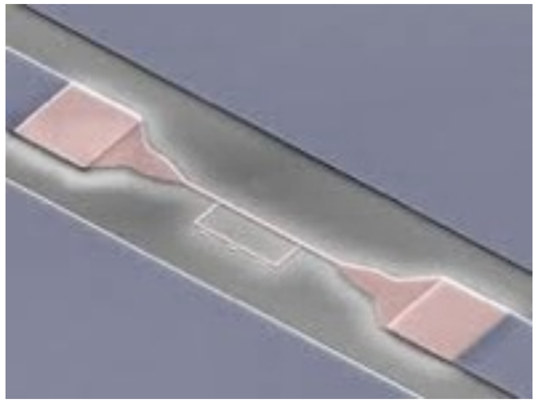
The USC regime & quantum Rabi model

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.

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

The QRM is not used for describing experiments because the RWA applies rather well in the microwave and optical regimes in quantum optics, where the JC model is enough.

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).

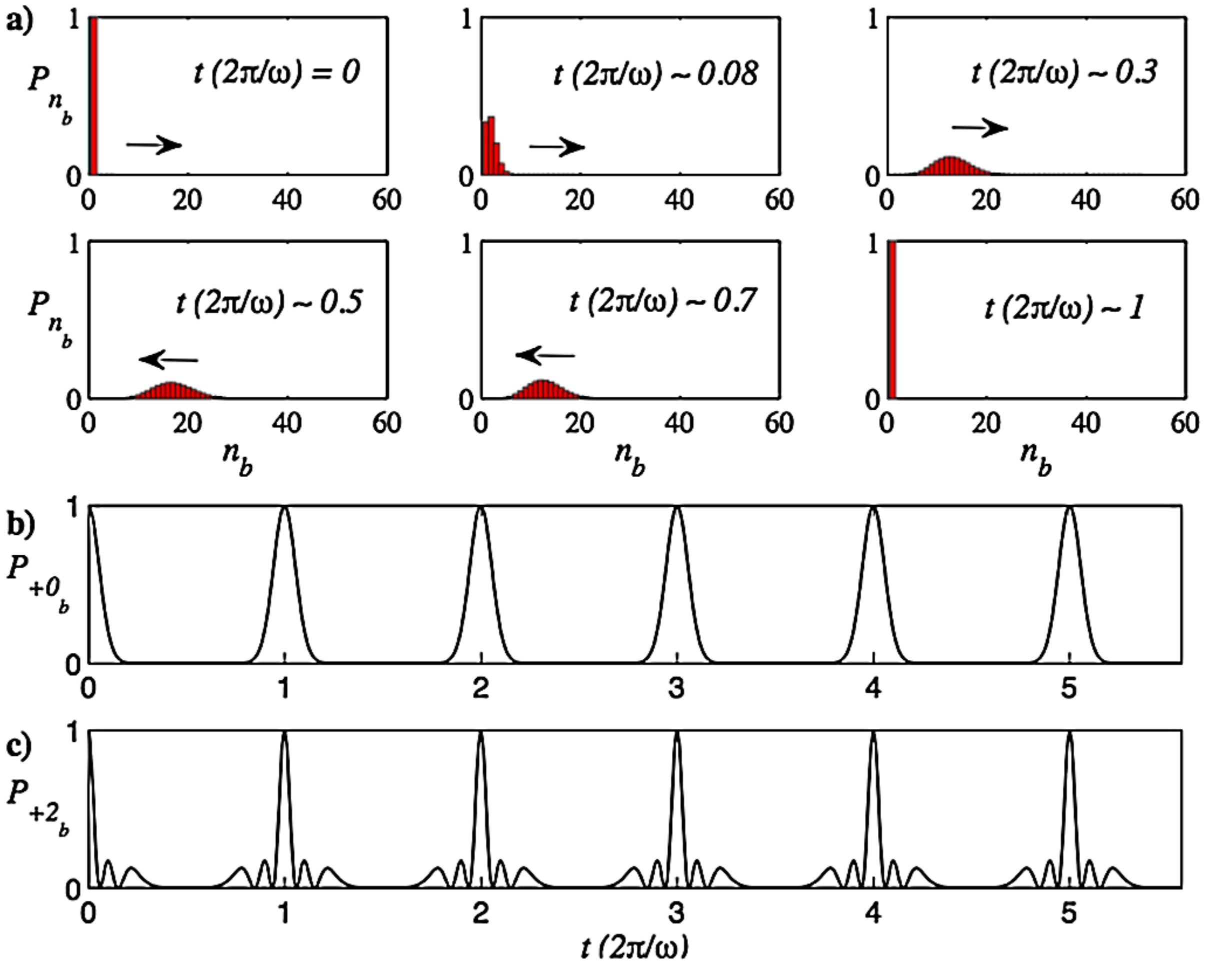
Deep strong coupling (DSC) regime of the QRM

The DSC regime of the JC model happens when g/w > 1.0, and we can ask 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, 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.

What can we do then? Here, we propose two options:

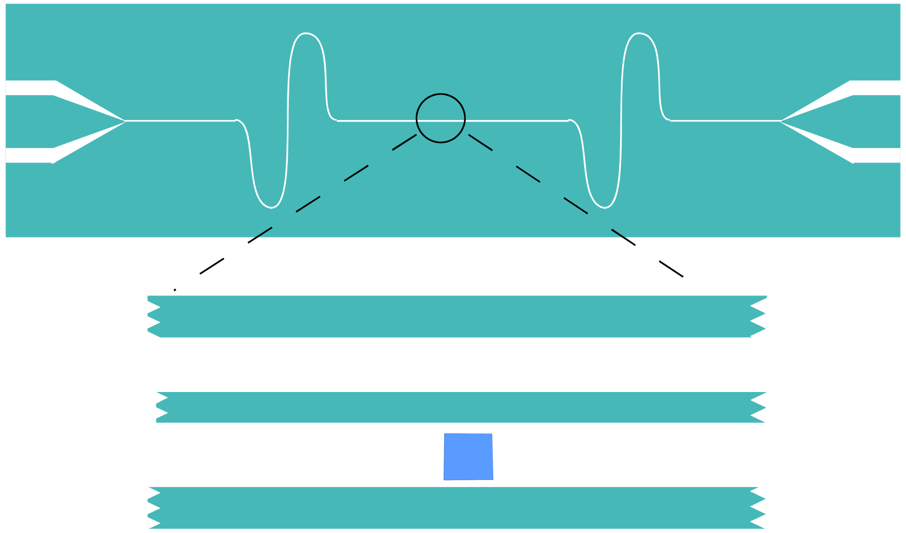
a) We go brute force and try to design ultrafast switching techniques that allow us to design a quantum measurement of relevant observables.

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

b.1) Recently appeared the first classical simulation of the QRM and DSC regime in photonic systems: A. Crespi et al., PRL **108**, 163601 (2012).

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

Simulating USC regime and quantum Rabi model



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

Two-tone microwave driving

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

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 relativistic quantum mechanics

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

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

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

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

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

1+1 Dirac particle + Potential

Add a classical driving to the cavity

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

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

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)

Disruptive concepts and techniques for QSims?

Here is my take for the next 1-5 years!

a) QSim of unphysical operations and mathematical problems

b) QSim of embedding quantum simulators for scalable models: merging quantum simulation and quantum computing concepts

c) Digital-analog techniques for scalable QSim of interacting fermions and bosons

d) Error correction and benchmarking of quantum simulators

e) QSims involving ultrastrong coupling regime of light-matter coupling

f) QSims involving a continuum of bosonic and fermionic modes

Disruptive applications of quantum simulations?

Here is my take for the next 5-10 years!

a) QSim of condensed-matter models beyond classical capabilities

b) QSim of quantum chemistry models beyond classical capabilities

c) QSim of quantum field theory models beyond classical capabilities

d) QSim of quantum metamaterials in the optical and microwave regimes

e) QSim of bimomimetic behaviours: quantum biomimetics

Conclusions and outlook

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

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

c) Presently, optical lattices and trapped ions dominate quantum simulations. Circuit QED and quantum photonics are growing too.