Quantum Simulators

Rosario Fazio

The Abdus Salam
International Centre for Theoretical Physics,
Trieste - Italy

NEST, Scuola Normale Superiore
and Istituto Nanoscienze-CNR,
Pisa - Italy

Simulator

It is used in many contexts, such as simulation of technology for performance **optimisation** …

The act of simulating something first requires that a **model be developed** …

…it can be used to show the eventual **real effects** of **alternative conditions** …

… it is also used when the real system **cannot be engaged**, because it may not be accessible, or it may be dangerous or …

… or it is being designed but not yet built, **or it may simply not exist**.

…One can use machines and/or computers as simulators or **physical systems as simulators**

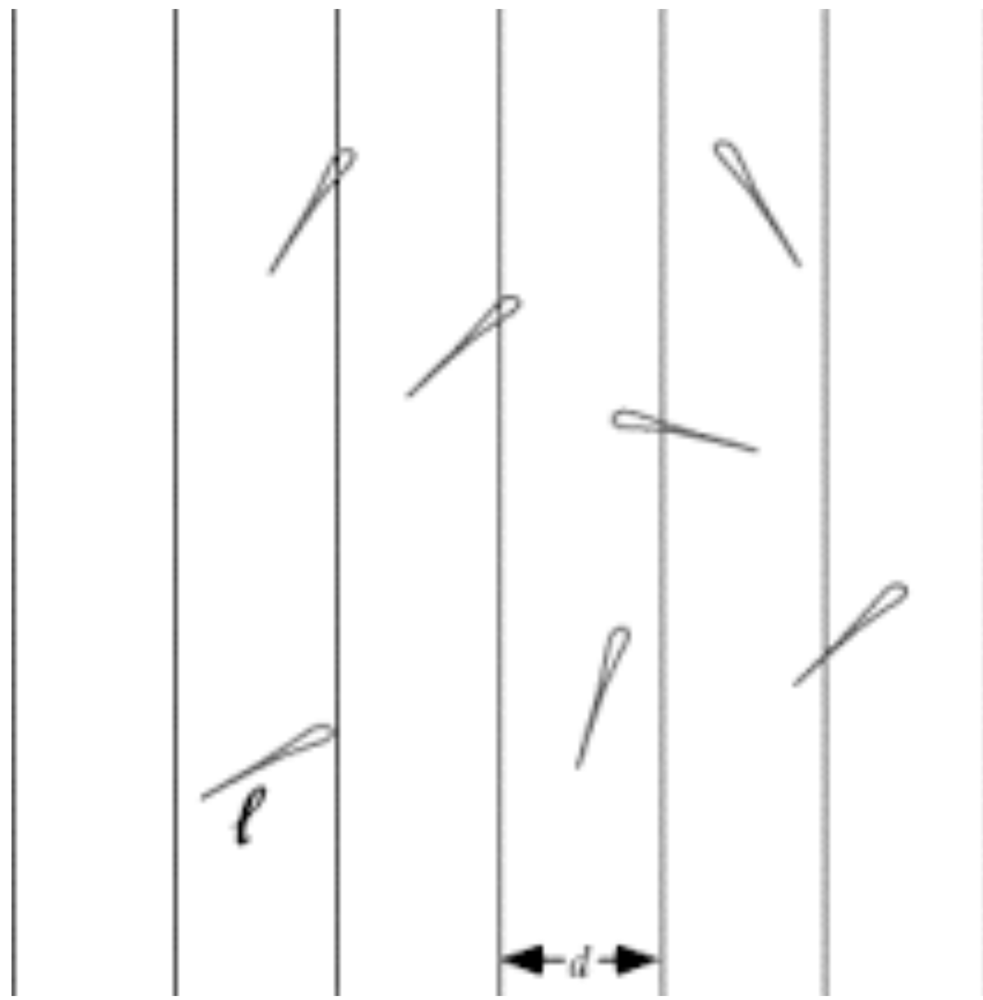
Buffon's needle

BUFFON SE BUTTATO ERA SIMULAZIONE E DOVEVA ESSERE ...
https://it-it.facebook.com/notes/il...è.../buffon...simulazione.../310984355598715/
BUFFON SE BUTTATO ERA **SIMULAZIONE** E DOVEVA ESSERE AMMONITO!! 12 dicembre 2011 alle ore 14:22 · Piace a 87 persone34 commentiCondivisioni: ...

Problema dell'ago di Buffon - UniFI - DiSIA
local.disia.unifi.it/VL/VL_IT/buffon/buffon2.html
Simulazione 1. Esegui l' esperimento dell'ago di **Buffon** con le impostazioni predefinite e osserva gli esiti sullo spazio campionario. Osserva come i punti della ...

SIMULAZIONE FINALE CHAMPIONS LEAGUE JUVENTUS ... - YouTube

https://www.youtube.com/watch?v=OvsMI5dARMU
06 giu 2015 - Caricato da ThatsAndree__
SIMULAZIONE FINALE CHAMPIONS LEAGUE JUVENTUS-BARCELLONA FIFA



Georges-Louis Leclerc, Comte de Buffon

Simulator

It is a device that allows the imitative representation of the functioning of one system or process by means of the functioning of another…

…It allows the imitation of the operation of a real-world process or system over time

A **quantum simulator** …

…for exploring reality and …

…for making “fantasy” real

- # What is a quantum simulator?

  Controlled quantum systems that allow to study specific difficult quantum problems (Feynman 1982)

- # Why do we need it?

  Classical computation may not be able to offer required performances.
  Explore “new” phenomena difficult to study elsewhere

- # How do we realise it?

  Several experimental platforms are already available

- # Where do we stand at present?

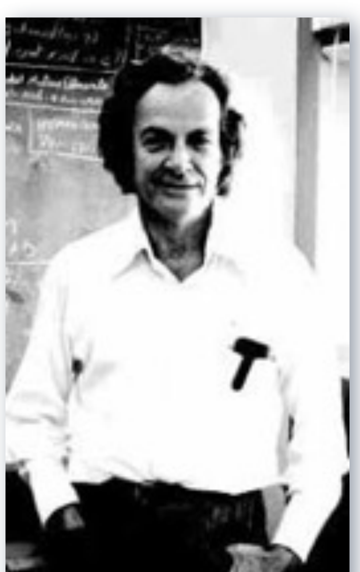
  Few examples

“What & Why”

Many-body systems … “hard to understand”:

Frustrated quantum magnets
High-Tc superconductors
…

Quantum simulator: an experimental *controllable* system that reproduces the physics of a given model Hamiltonian



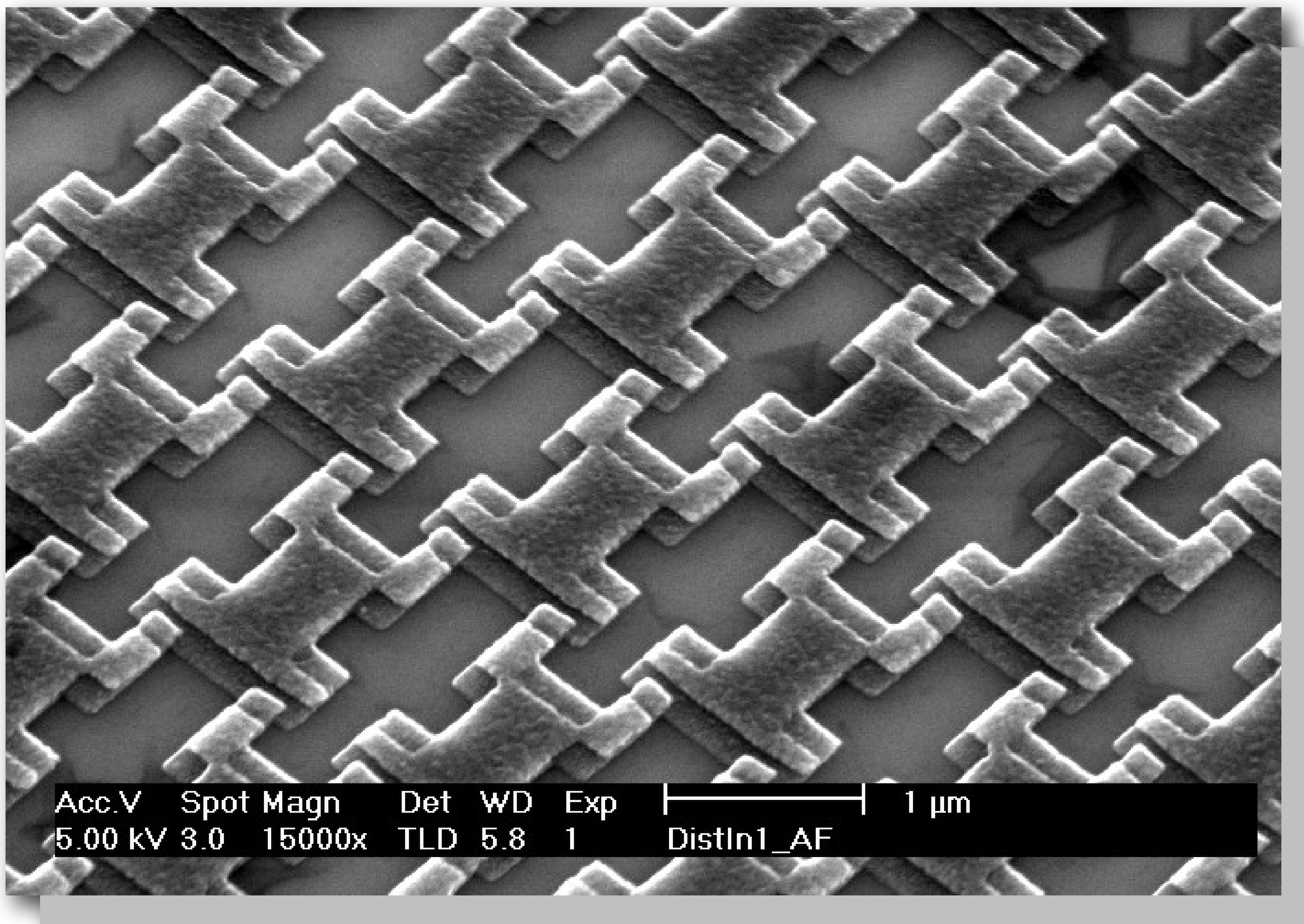
- Questions not accessible via classical computation because the exp-large dimension of the Hilbert space (e.g. complex quantum ground states or dynamics in solid state systems)
- Questions that are not directly “tractable/identified” in “nature” (e.g. thermalisation, defect formation, …)
- Refine our control on many-body systems
- New states of matter (e.g. time-crystals,exotic qp, …)

“How”

- Detailed microscopic knowledge
- Initial state preparation
- Highly tuneable
- High level of coherence over large time scales
- Good access for measurements

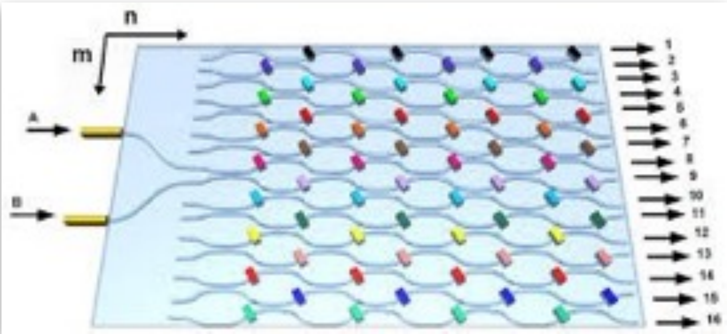
Experimental platforms (prehistory)

Josephson junction arrays in the quantum regime

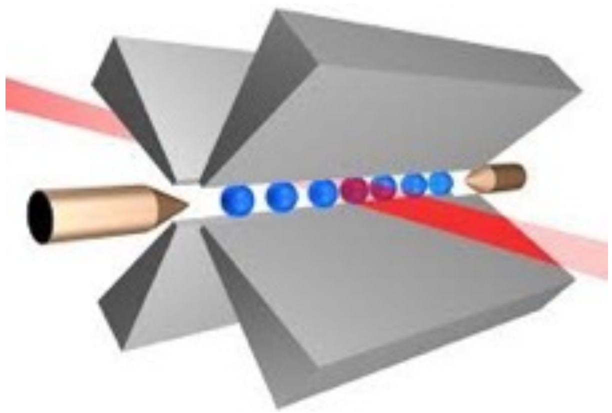


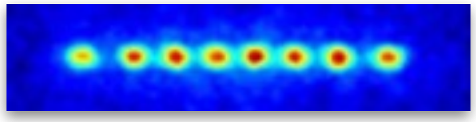
J.E. Mooij group
(TUDelft)

Exp platforms

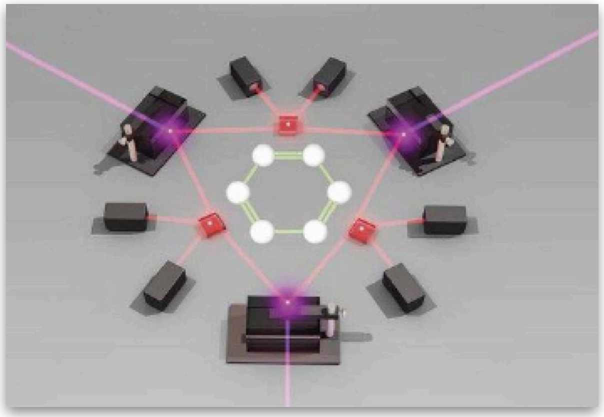


Photonic quantum simulators

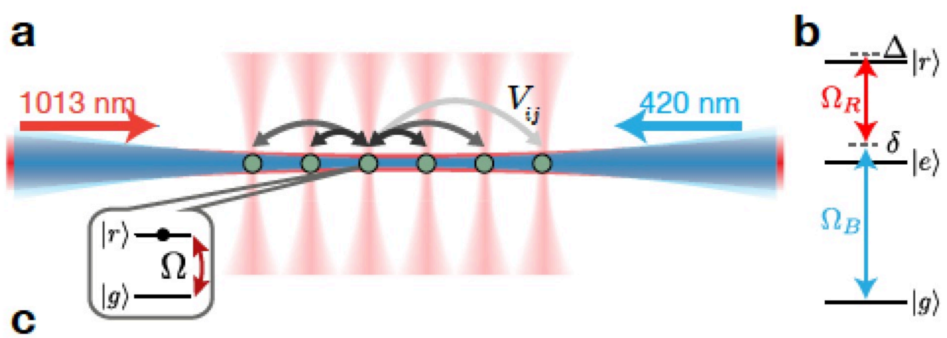


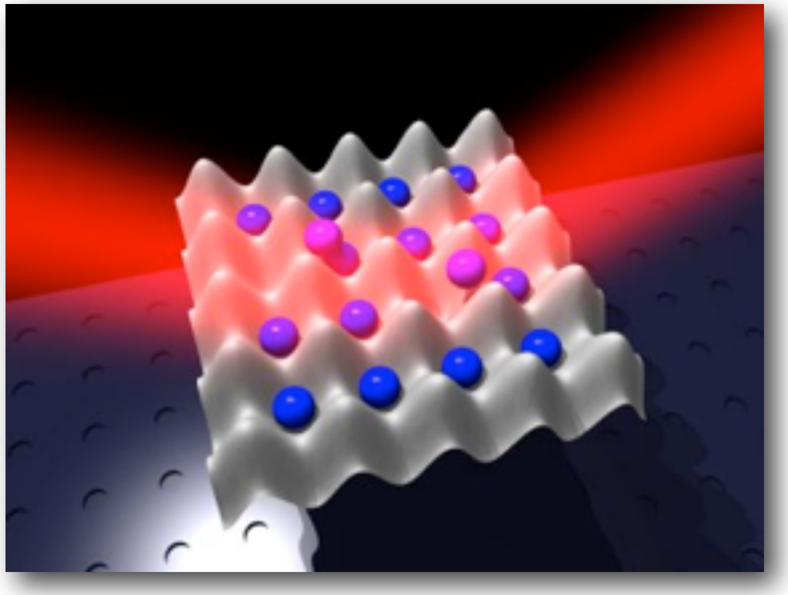


Trapped ions



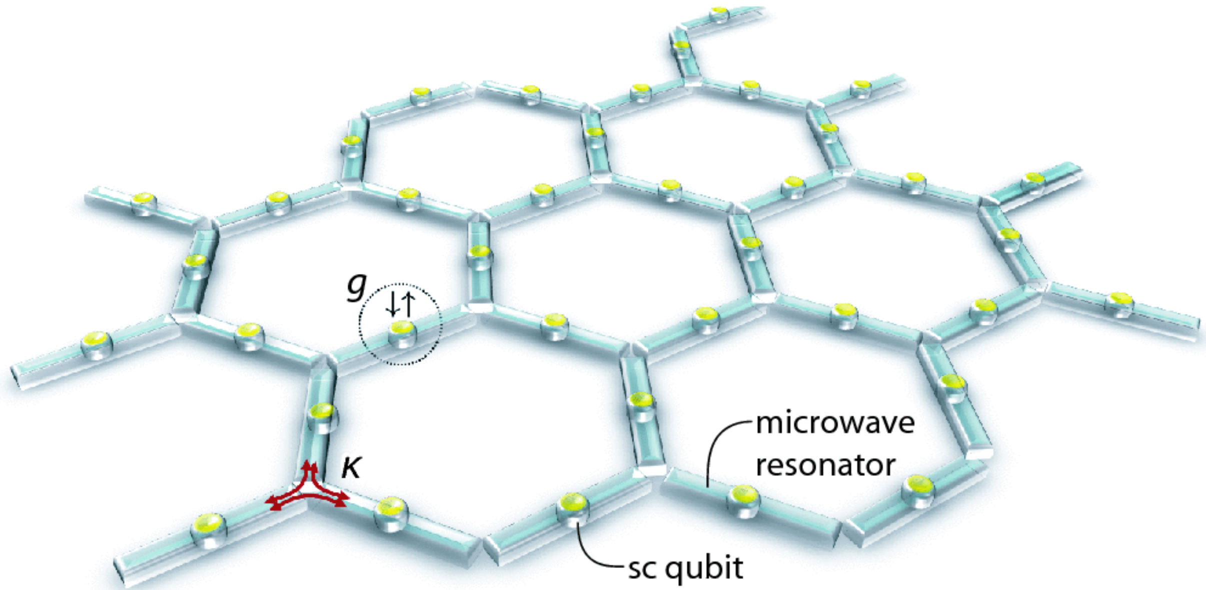
Rydberg atoms

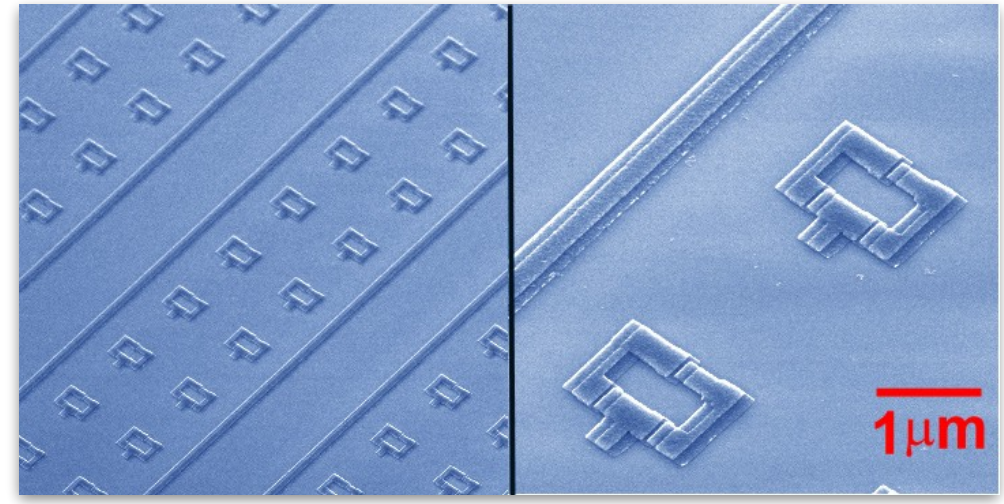




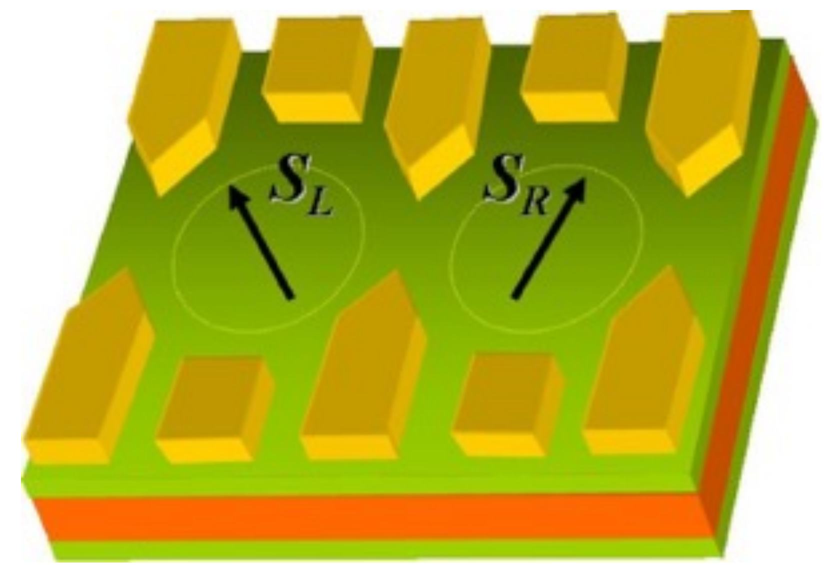
Optical lattices

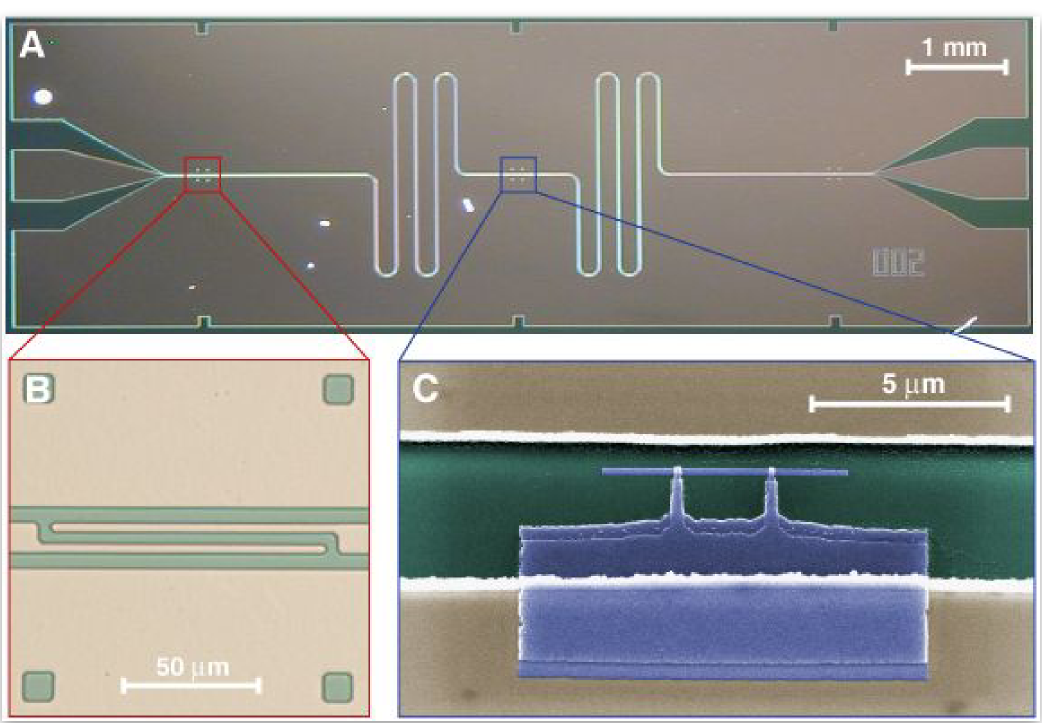
Exp platforms

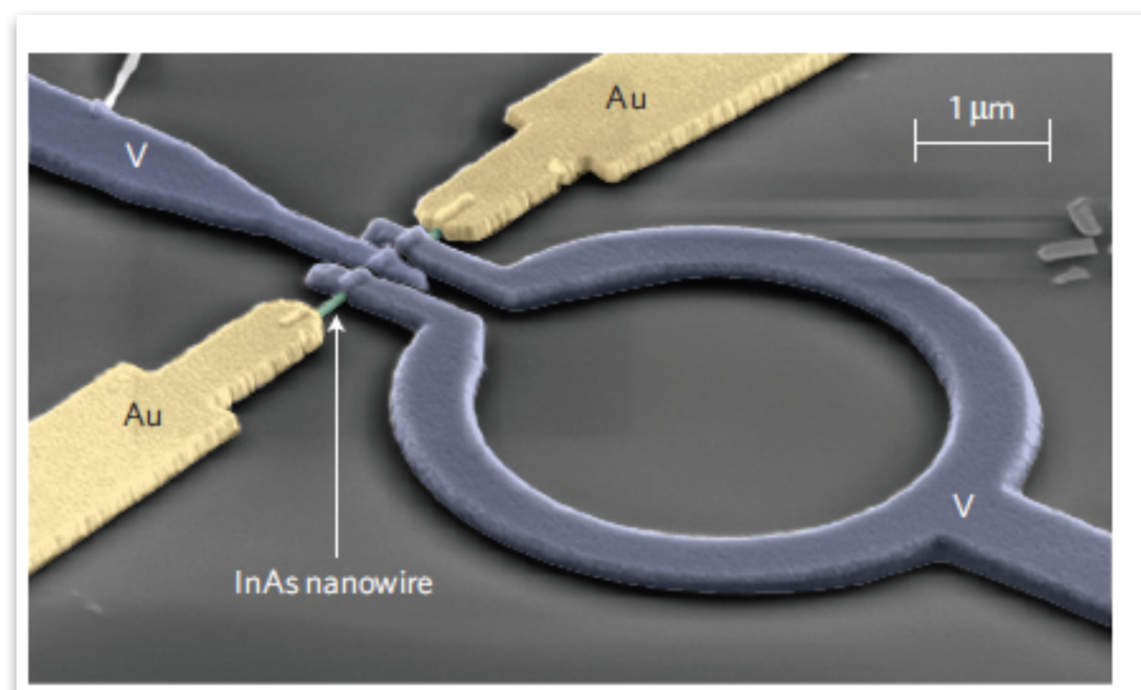




Superconducting & semiconducting nanostructures





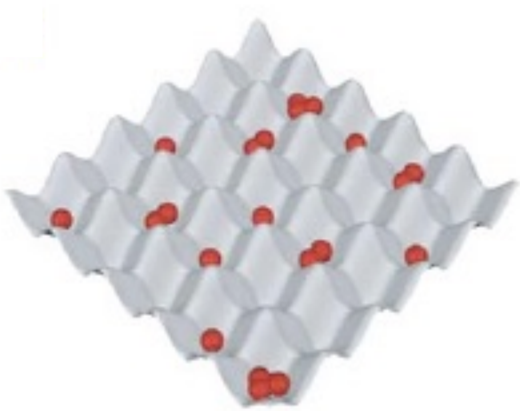


Bose-Hubbard model

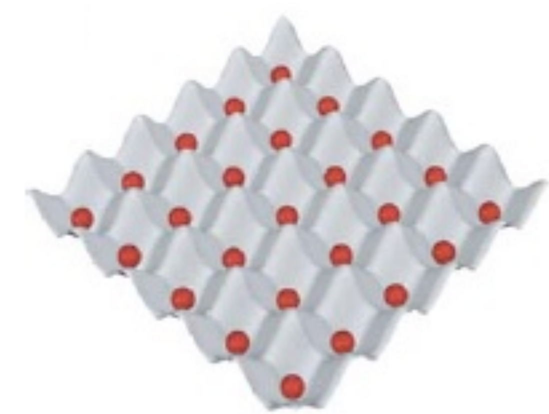
Bosons hopping on a d-dimensional lattice

$$\mathcal{H} = \underbrace{-J \sum_{\langle ij \rangle} (a_i^\dagger a_j + \mathrm{h.c.})}_{\text{hopping}} + \underbrace{U \sum_i n_i (n_i - 1)}_{\text{repulsion}}$$

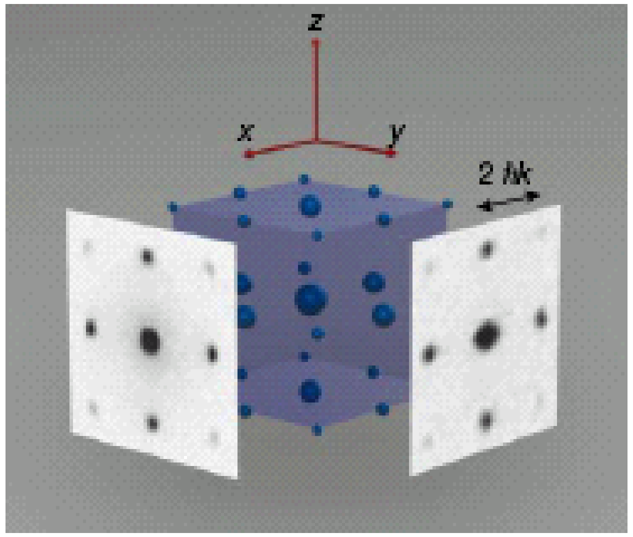
J >> U superfluid



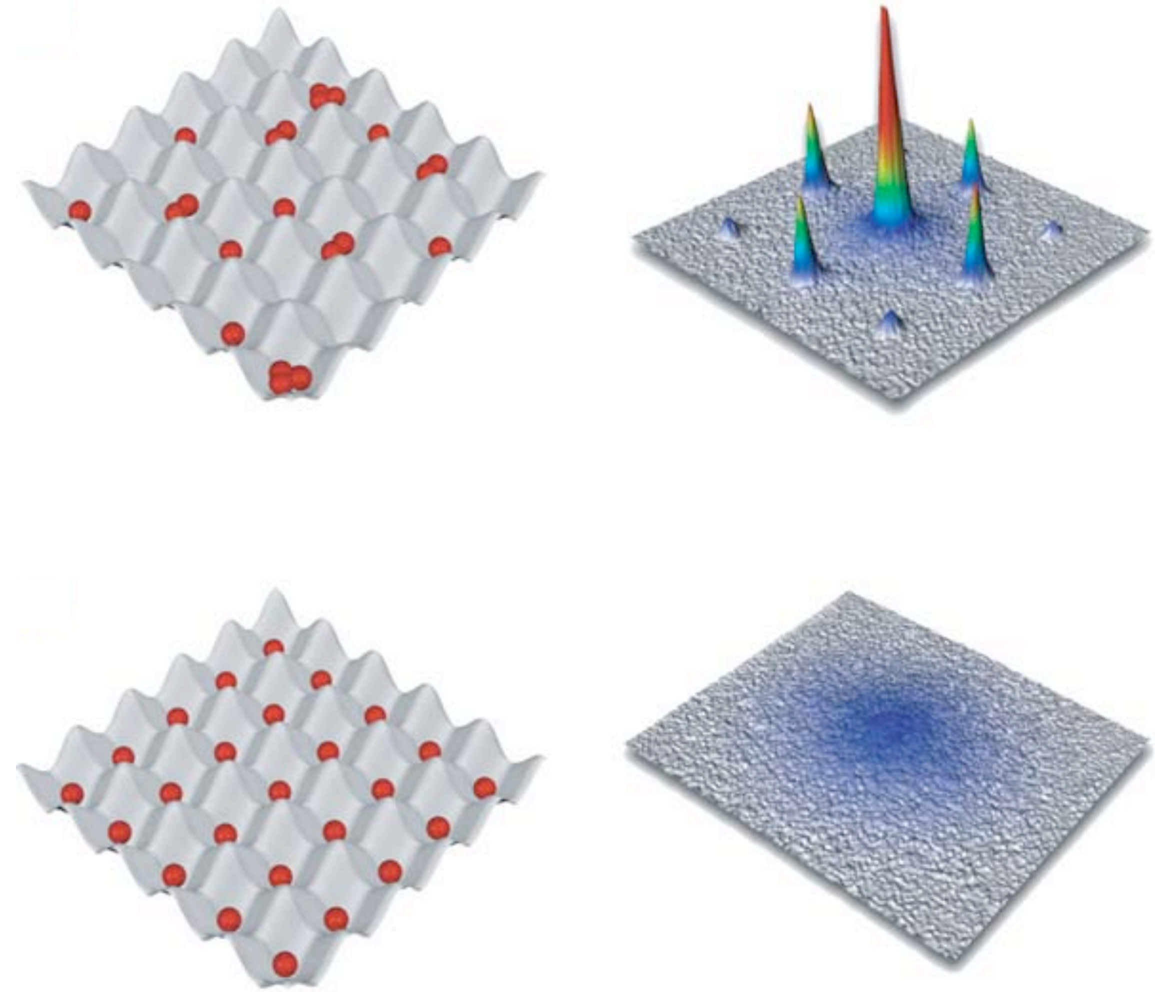
J << U Mott insulator



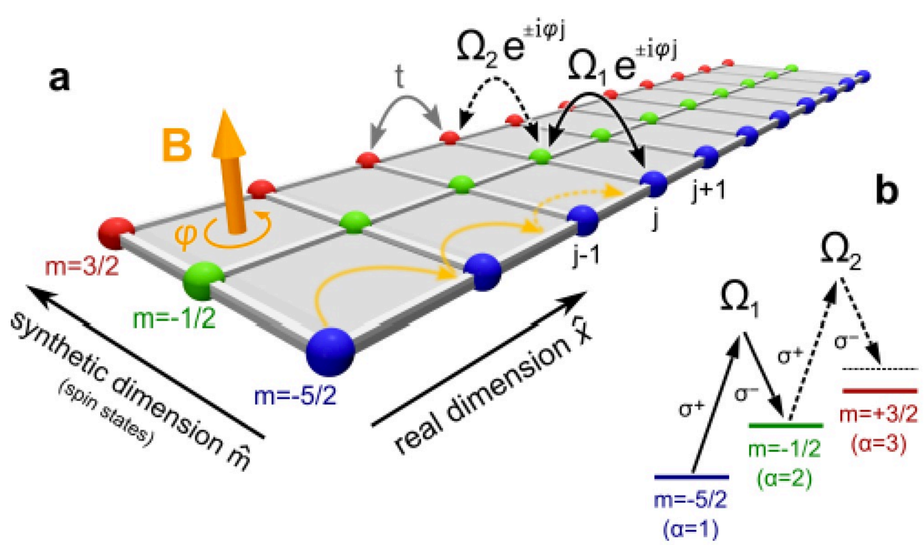
Bose-Hubbard model



M. Greiner *et al*, Nature (2002)



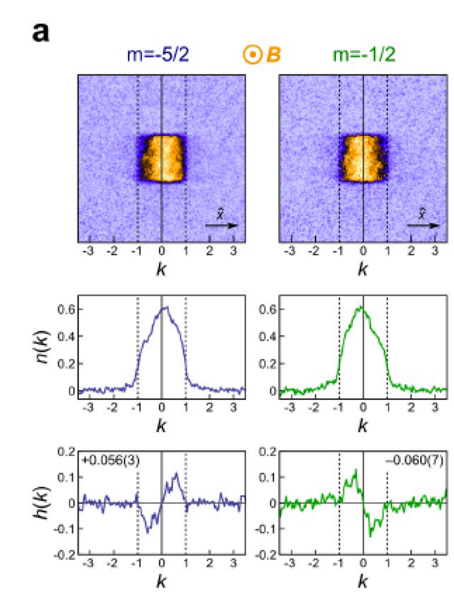
Fermi-Hubbard model



A. Mancini *et al*, Science (2015)

Different ingredients:

- fermions
- synthetic dimension
- frustration



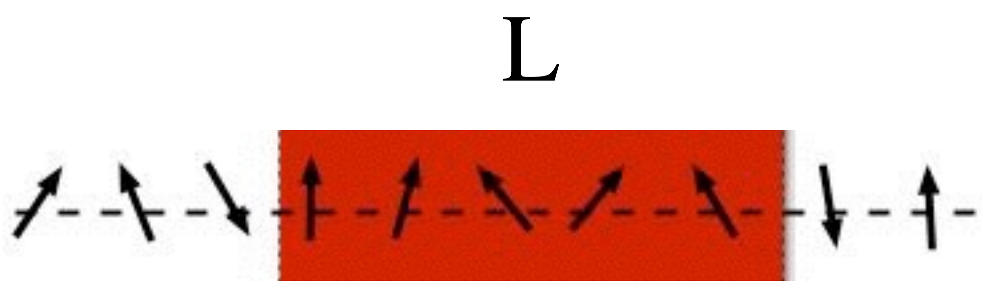
…from ground state

… to dynamics

Quantum quench

$t = 0$ $\quad | \Psi(0) \rangle$

$t > 0$ $\quad | \Psi(t) \rangle = U(t) | \Psi(0) \rangle$



$$S(\rho_L) \equiv -tr(\rho_L log \rho_L)$$

The entanglement entropy grows linearly with time saturating to a volume law

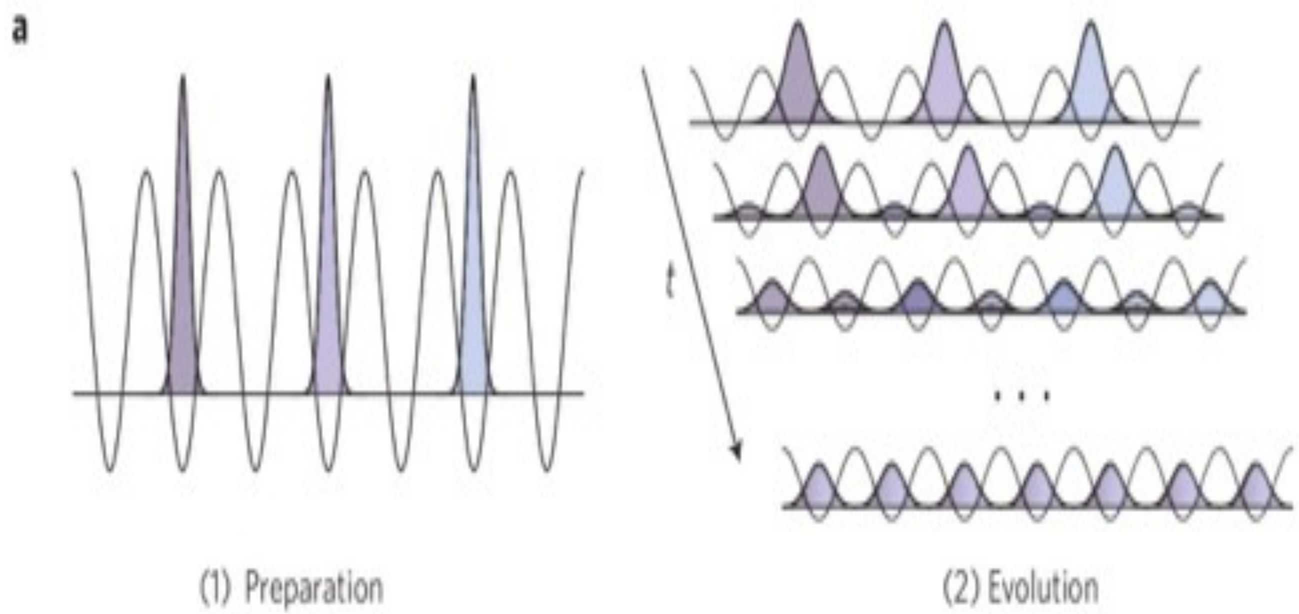
Calabrese & Cardy 2005

Our ability to simulate the system with a classical computer is spoiled

G. Vidal 2003 - 2004

Intimate connections between cond-mat stat-mech and quantum-info

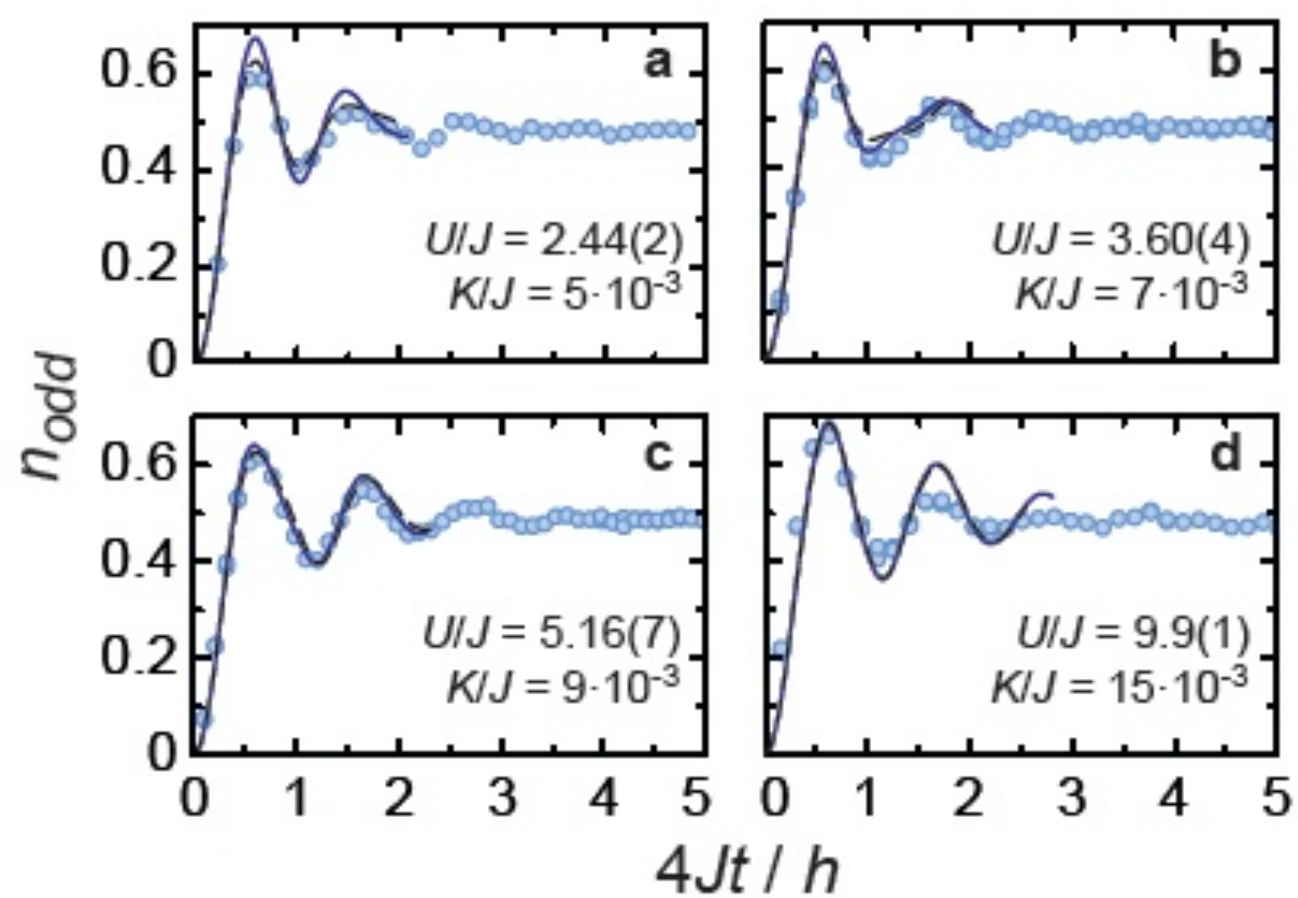
…from ground state to dynamics



$$| \Psi(0)\rangle$$

$$| \Psi(t)\rangle = U(t) \mid \Psi(0)\rangle$$

Following the dynamics, by means of numerical simulation, of a many-body quantum system becomes increasingly hard.



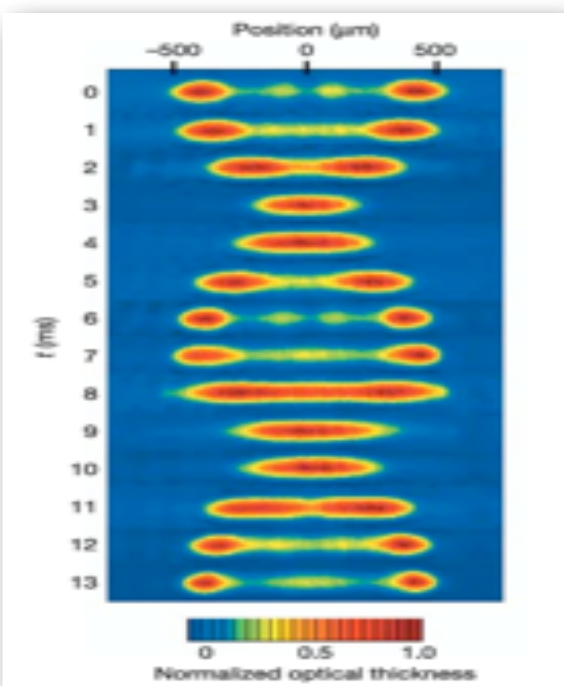
S. Trozky *et al*, Nat. Phys. (2012)

Thermalisation

Ergodicity and thermalisation in quantum systems is one of the most intriguing problems in quantum physics

An isolated many-body system should be able to reach at long times a thermal steady state compatible with the initial energy density *as far as local observables* are concerned. ***A large system acts as its own environment***

The quantum Newton's cradle:
lack of thermalization in 1D condensates



T. Kinoshita, T. Wenger, and D.S. Weiss,
Nature **440**, 900 (2006)

Integrable systems: appear to relax to a non-thermal steady state that keeps track of all the constants of motion: the generalised Gibbs ensemble

Many-body localisation

D. Basko, I. Aleiner, B. Altshuler , Ann. Phys. 2006

Breakdown of ergodicity in a generic, disordered many-body quantum system - no part of it acts as reservoir for the rest of the system.

Transport of mass/spin/energy is frozen

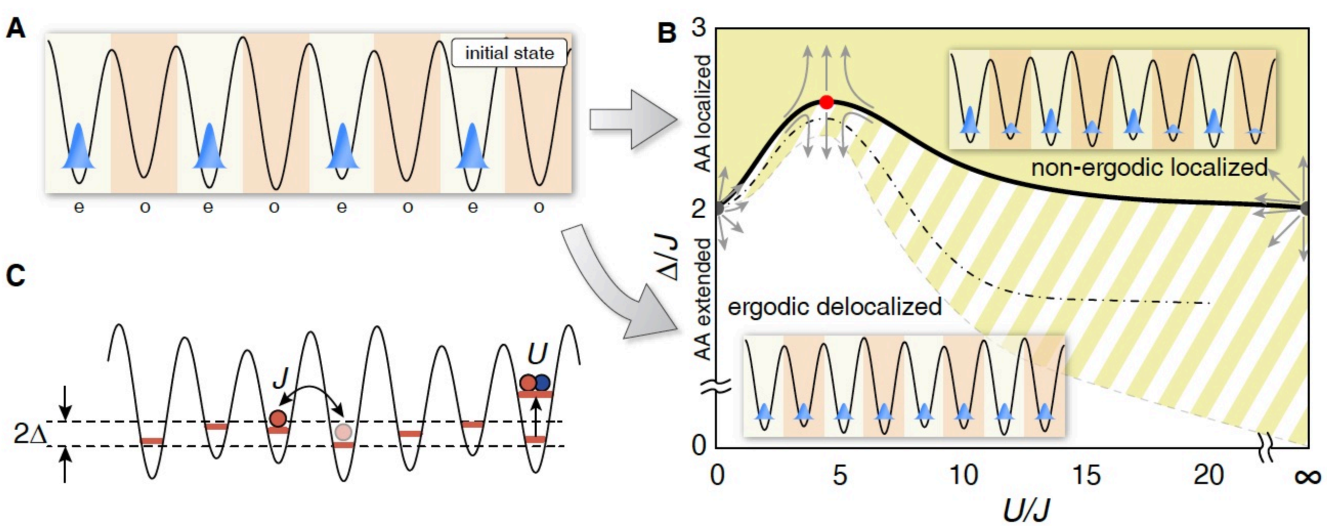
Quantum correlations (entanglement) can still propagate in the MBL phase

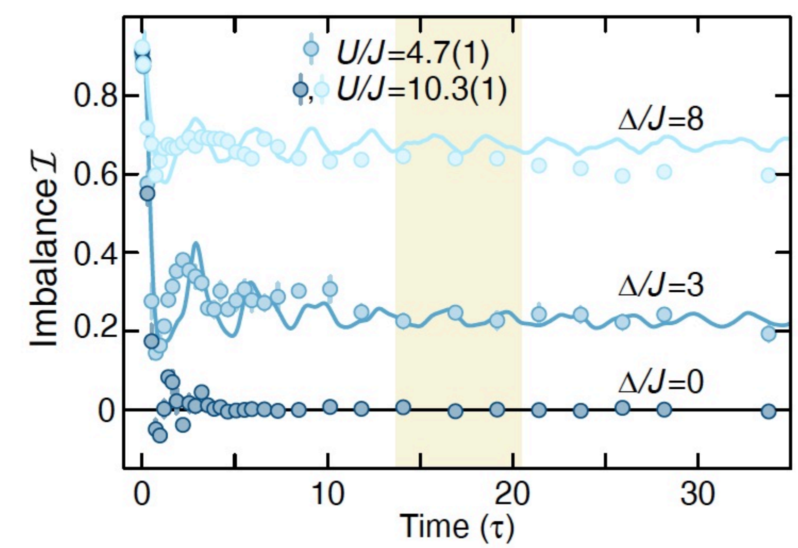
Existence of an extensive number of local integrals of motions (an effective “l-bit” Hamiltonian)

Many-body localisation

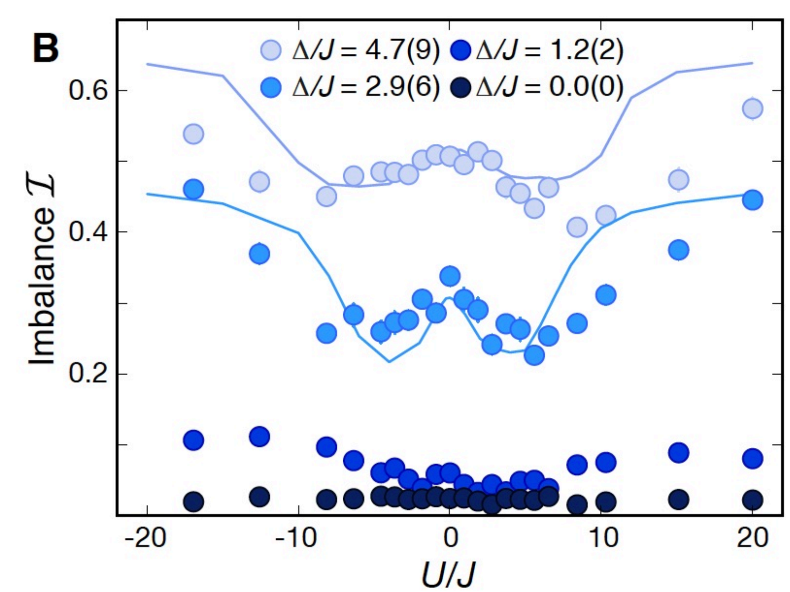
Absence of thermalisation through a measurement of imbalance in a one-dimensional interacting Fermi system in the presence of "pseudo-random" potential

M. Schreiber *et al.*, Science (2015)





The imbalance indicates the failure of the system to thermalise. It is not a direct indication of the many-body dephasing taking place in the MBL phase



…“even more” exotic …

Can time-translational invariance be spontaneously broken?

Wilczek 2013

Time-crystal

Time-crystals

Can time-translational invariance be spontaneously broken?

Wilczek 2013

A no-go theorem lead to the conclusion that systems in thermal equilibrium cannot manifest any time-crystalline behaviour.

Floquet time crystals: The time-translation symmetry breaking appears as the response of an observable which oscillates with periodicity that is a multiple of the imposed drive.

Boundary time crystals: Time-translational symmetry breaking occurs only in a fraction of the sample.

F. Iemini, *A. Russomanno, J. Keeling, M. Schirò, M. Dalmonte, and R. Fazio,* Phys. Rev. Lett. **121**, 035301 (2018)

Floquet time crystals

(TTSB in periodically driven systems)

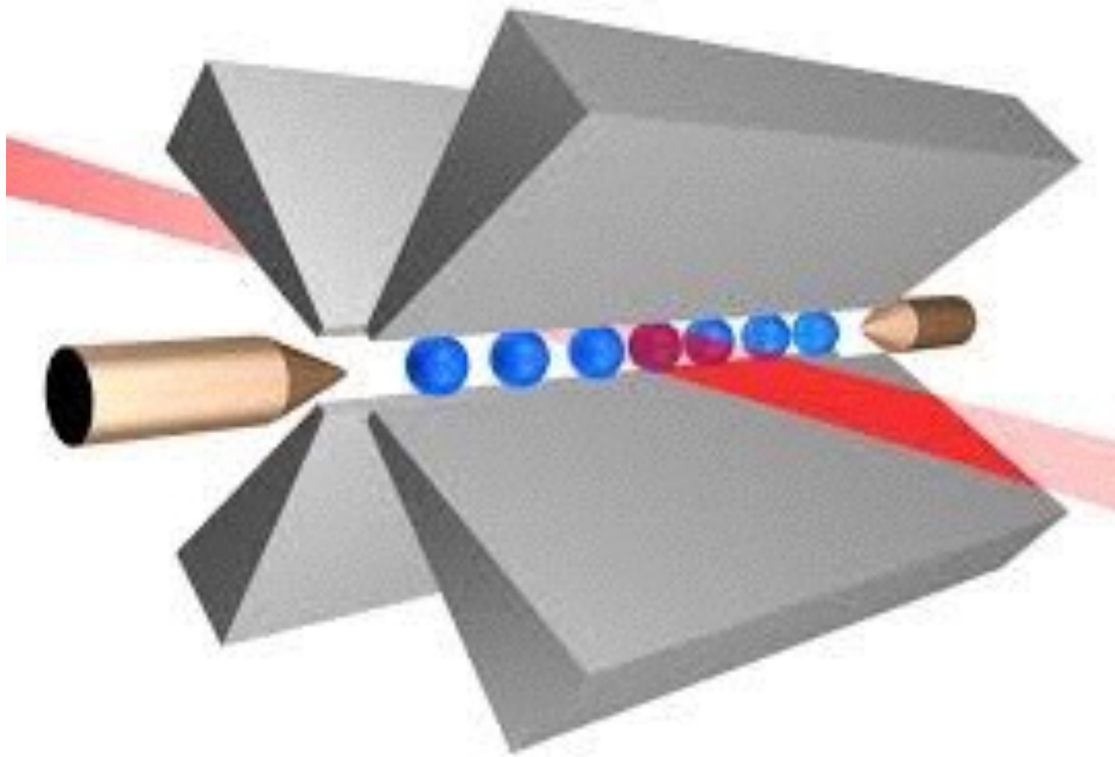
$$\mathcal{H}(t+T) = \mathcal{H}(t)$$

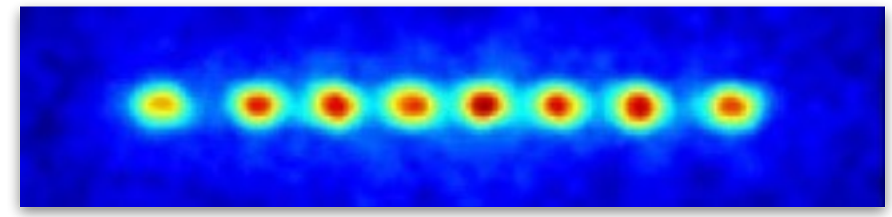
Else *et al* 2016
Khemani *et al* 2016

Hamiltonian **Period T** → **Spontaneous breaking** → Observables **Period nT**

$$f(t) = \lim_{N\to\infty} \langle \psi | \hat{O}(t) | \psi \rangle$$

$$f(t+\tau_B) = f(t) \qquad \tau_B = nT$$





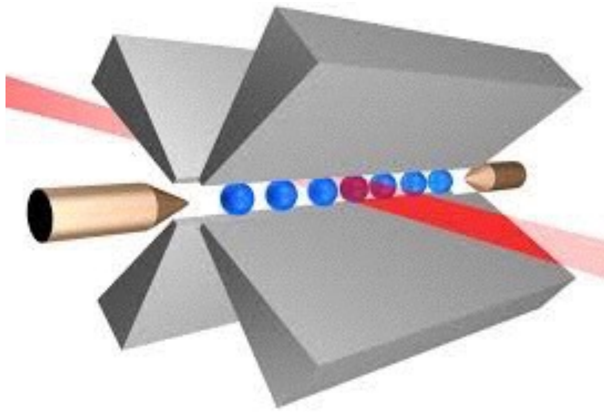
Trapped ions

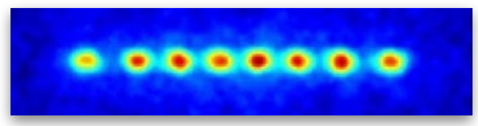
$$H = \sum J_{ij} S_i^z S_j^z - h \sum S_i^x$$

$$J_{ij} \sim \frac{1}{|i-j|^\alpha}$$

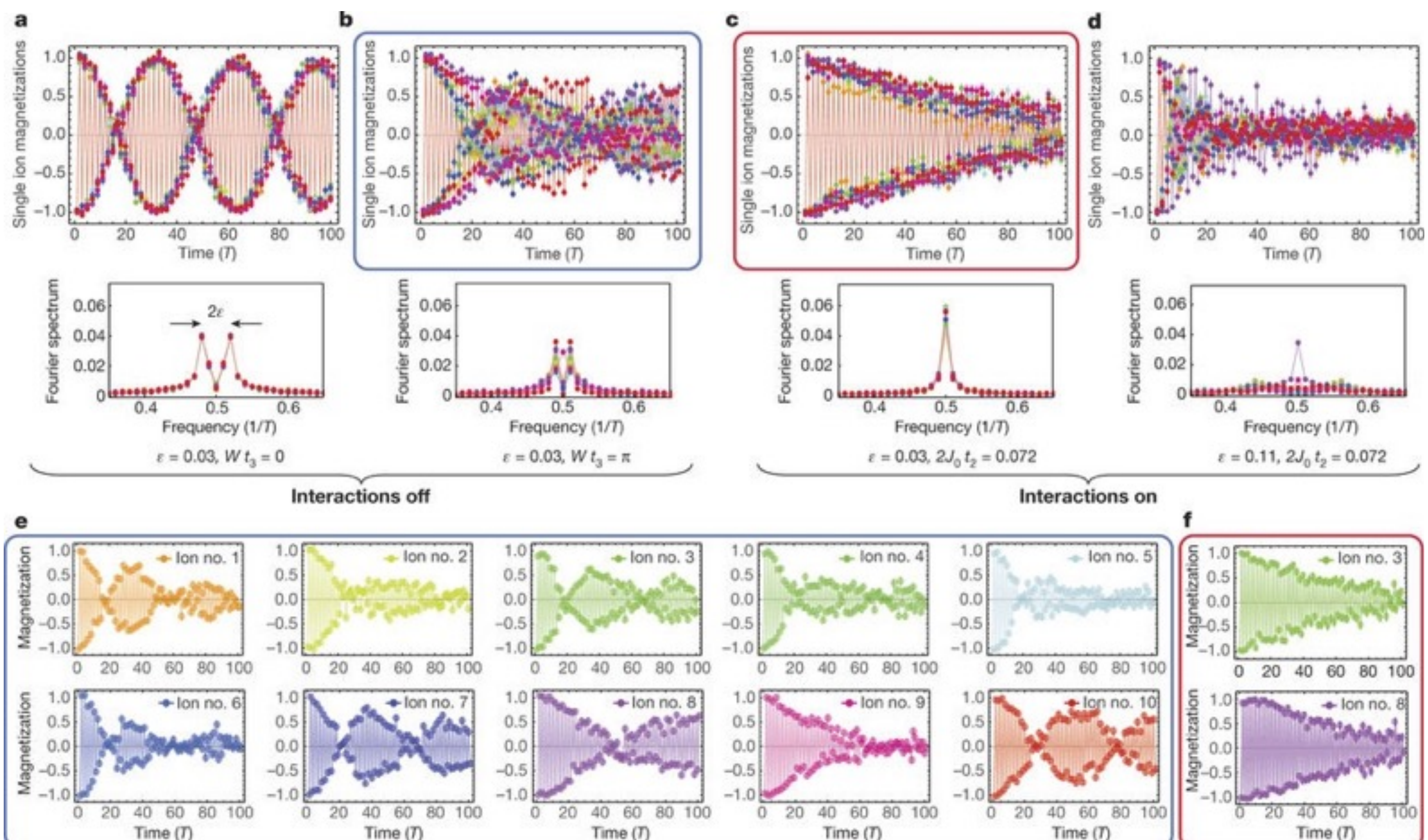
Time-crystals

Experimental realisation of Floquet time-crystals
Choi *et al* 2016
Zhang *et al* 2016





Trapped ions



- **Is it possible to have a Floquet time-crystal in the absence of disorder?**
- **How to observe direct transitions between different crystalline phases**

Floquet time-crystals in infinite-range models

A. Russomanno *et al*, Phys. Rev. B **95**, 214307 (2017)
F. Surace *et al*, in preparation

…where do we stand at present ?

51 vs 53 qubits

Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien,[1] Sylvain Schwartz,[1,2] Alexander Keesling,[1] Harry Levine,[1] Ahmed Omran,[1] Hannes Pichler,[3,1] Soonwon Choi,[1] Alexander S. Zibrov,[1] Manuel Endres,[4] Markus Greiner,[1] Vladan Vuletić,[2] and Mikhail D. Lukin[1]

[1]Department of Physics, Harvard University, Cambridge, MA 02138, USA
[2]Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[4]Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA

Controllable, coherent many-body systems provide unique insights into fundamental properties of quantum matter, allow for the realization of novel quantum phases, and may ultimately lead to computational systems that are exponentially superior to existing classical approaches. Here, we demonstrate a novel platform for the creation of controlled many-body quantum matter. Our approach makes use of deterministically prepared, reconfigurable arrays of individually controlled, cold atoms. Strong, coherent interactions are enabled by coupling to atomic Rydberg states. We realize a programmable Ising-type quantum spin model with tunable interactions and system sizes of up to 51 qubits. Within this model we observe transitions into ordered states (Rydberg crystals) that break various discrete symmetries, verify high-fidelity preparation of ordered states, and investigate dynamics across the phase transition in large arrays of atoms. In particular, we observe a novel type of robust many-body dynamics corresponding to persistent oscillations of crystalline order after a sudden quantum quench. These observations enable new approaches for exploring many-body phenomena and open the door for realizations of novel quantum algorithms.

13 Jul 2017

Thank you

Observation of a Many-Body Dynamical Phase Transition with a 53-Qubit Quantum Simulator

J. Zhang,[1] G. Pagano,[1] P. W. Hess,[1] A. Kyprianidis,[1] P. Becker,[1] H. Kaplan,[1] A. V. Gorshkov,[1] Z.-X. Gong,[1] and C. Monroe[1,2]

[1]Joint Quantum Institute and Joint Center for Quantum Information and Computer Science, University of Maryland Department of Physics and National Institute of Standards and Technology, College Park, MD 20742
[2]IonQ, Inc., College Park, MD 20740

(Dated: August 7, 2017)

A quantum simulator is a restricted class of quantum computer that controls the interactions between quantum bits in a way that can be mapped to certain difficult quantum many-body problems. As more control is exerted over larger numbers of qubits, the simulator can tackle a wider range of problems, with the ultimate limit being a universal quantum computer that can solve general classes of hard problems. We use a quantum simulator composed of up to 53 qubits to study a non-equilibrium phase transition in the transverse field Ising model of magnetism, in a regime where conventional statistical mechanics does not apply. The qubits are represented by trapped ion spins that can be prepared in a variety of initial pure states. We apply a global long-range Ising interaction with controllable strength and range, and measure each individual qubit with near 99% efficiency. This allows the single-shot measurement of arbitrary many-body correlations for the direct probing of the dynamical phase transition and the uncovering of computationally intractable features that rely on the long-range interactions and high connectivity between the qubits.

4 Aug 2017