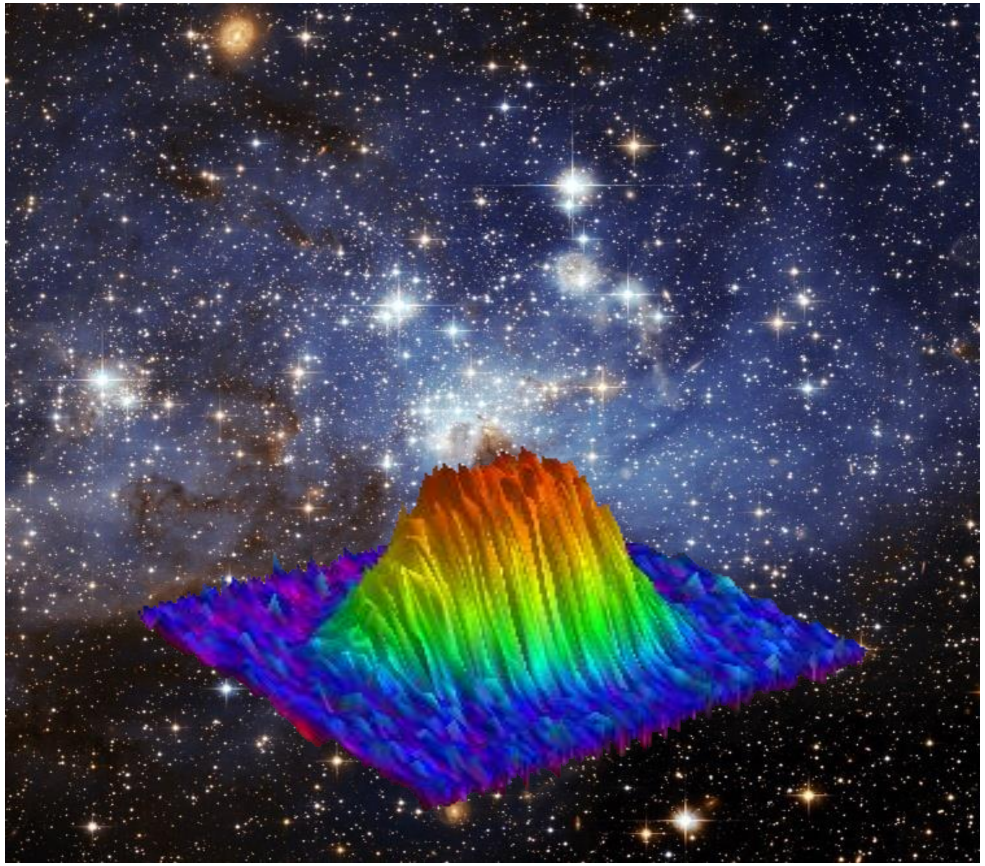
Quantum Simulation



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

Congrès annuel de la SFP, Nantes, 10 juillet, 2019

The problem

Understand Nature ! A many-body quantum systems

Examples:
high energy physics, condensed-matter, neutron stars, Chemistry; Nature is an assembly of interacting particles !

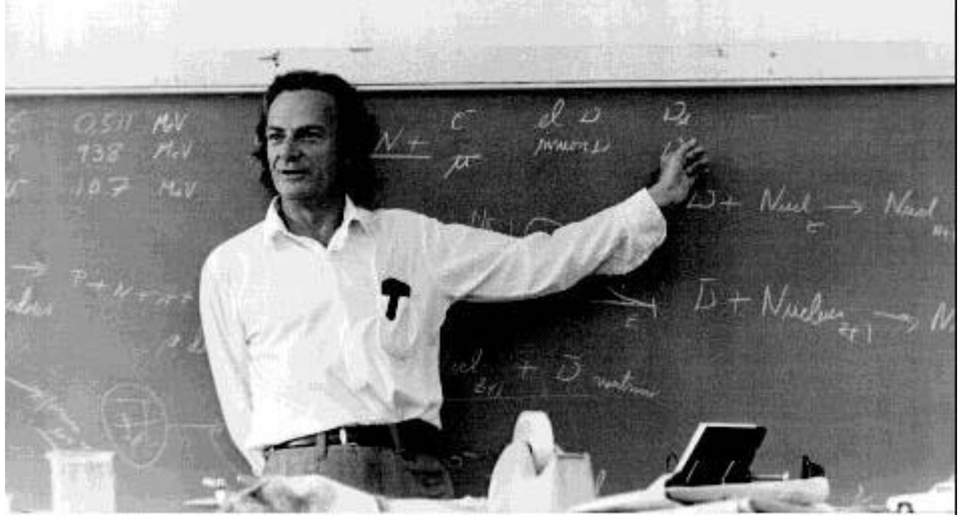
Equilibrium properties and dynamics

For instance, phase diagrams and phase transitions, time evolution,

The difficulty: exponential growth of the Hilbert space and consequently of the system's density matrix

Example: 40 spin ½, without any spatial degree of freedom has dimension 2^{40} = 1 099 511 627 776 configuration space

Approximate solutions: very often uncontrolled



The vision

Simulating Physics with Computers
Richard P. Feynman
Received May 7, 1981

Can we simulate quantum Physics with computers ?

Exponential growth of the Hilbert space when increasing the number of interacting particles: → untractable, in particular for fermions

1) Universal Quantum Computer

Ongoing research, large international effort, but extremely challenging

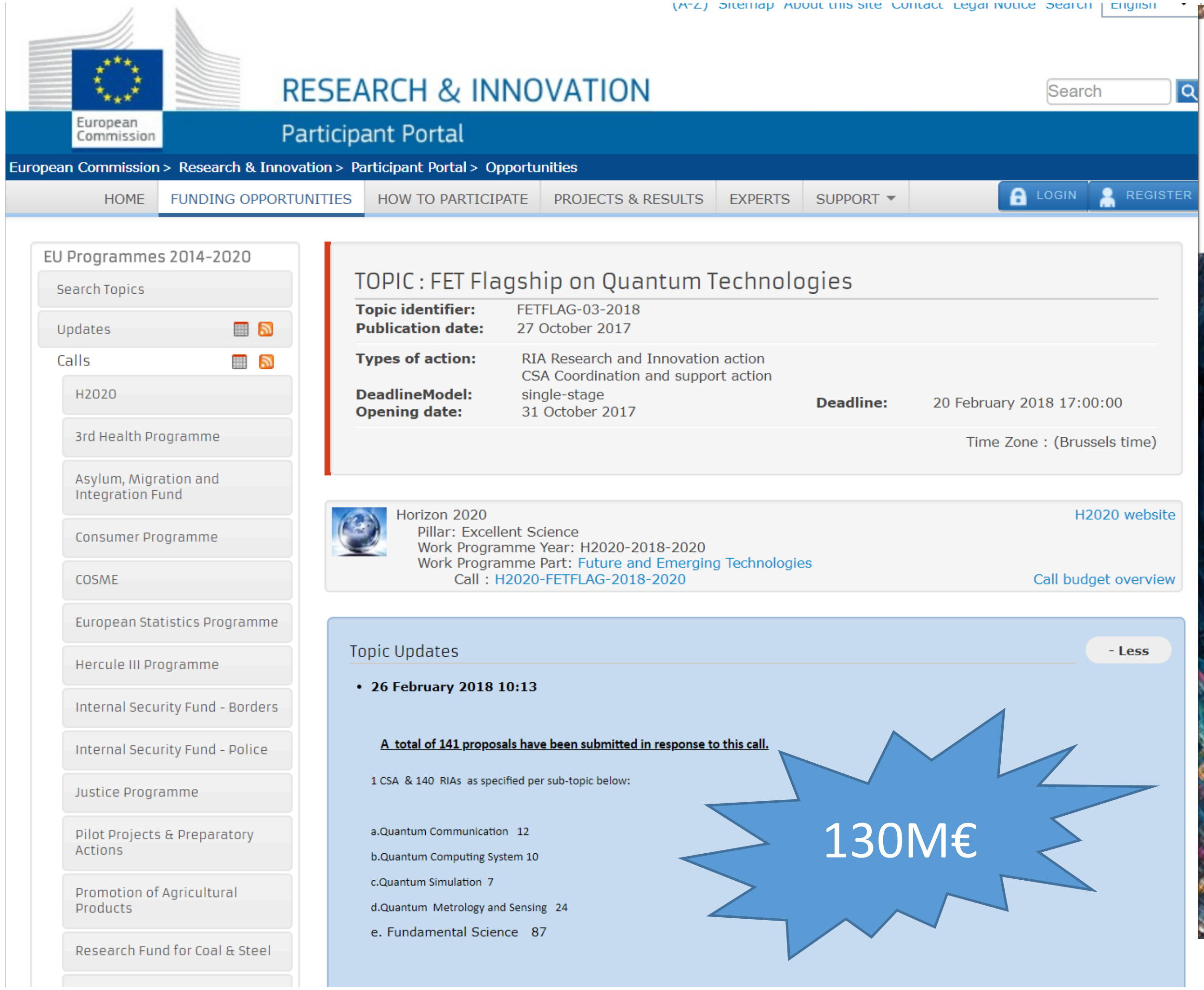
2) Quantum simulator

- Write an Hamiltonian to describe a physical system
- Find a well controlled system to simulate this Hamiltonian
- Measure the system's properties like ground state energy, excitation spectrum, collective modes,…
- non universal

Diversity of platforms to realize quantum simulators

Quantum Technology

Oct 2017: European QT Flagship



26 Sept. 2018

Similar programs in the USA, Japan, China,…

~ 20 companies: IBM, Microsoft, Google, D-Wave Honeywell, ATOS, Airbus,…..

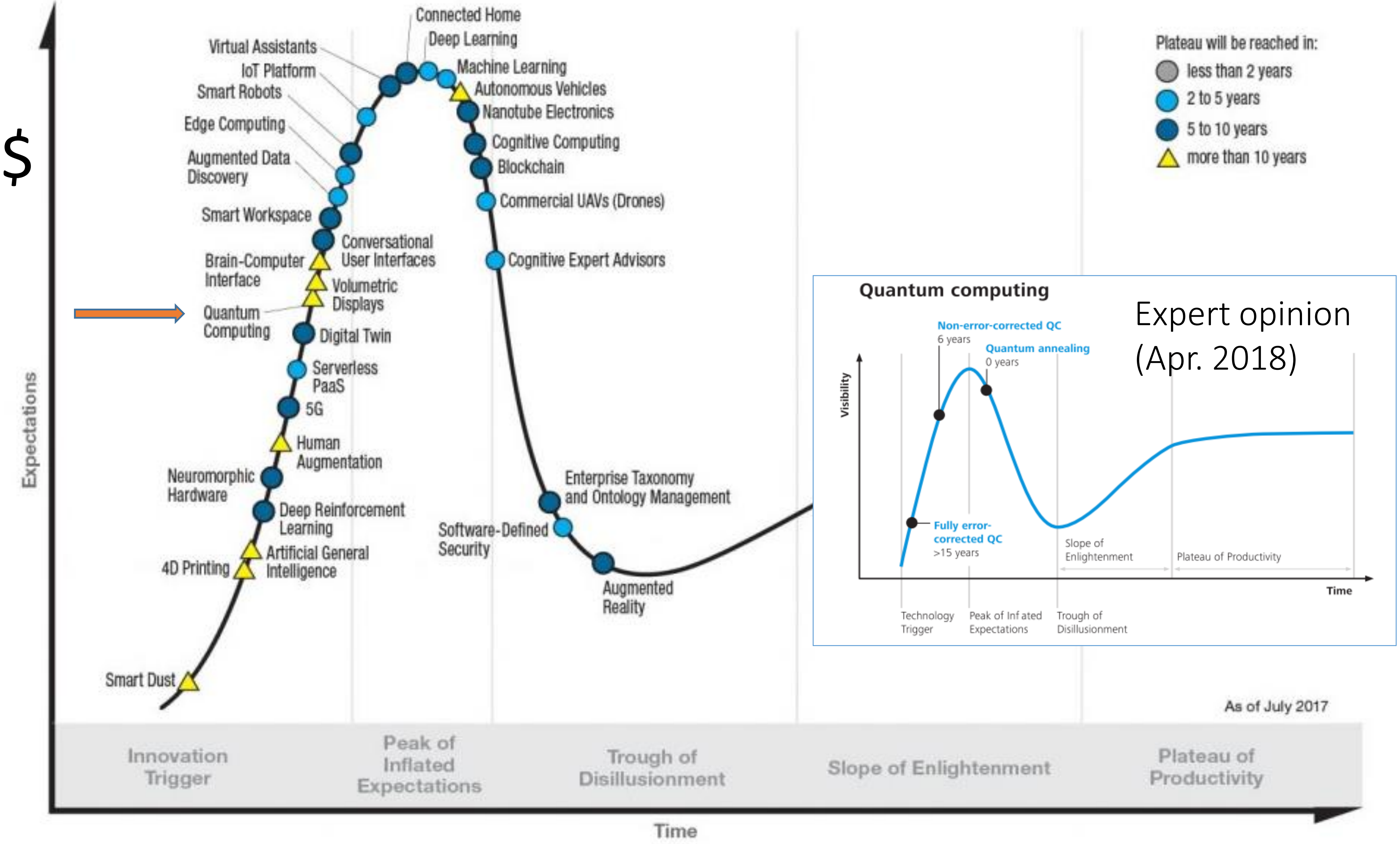
Over 70 start-ups on QC and Q-Sim in last 4 years !

See https://quantumcomputingreport.com

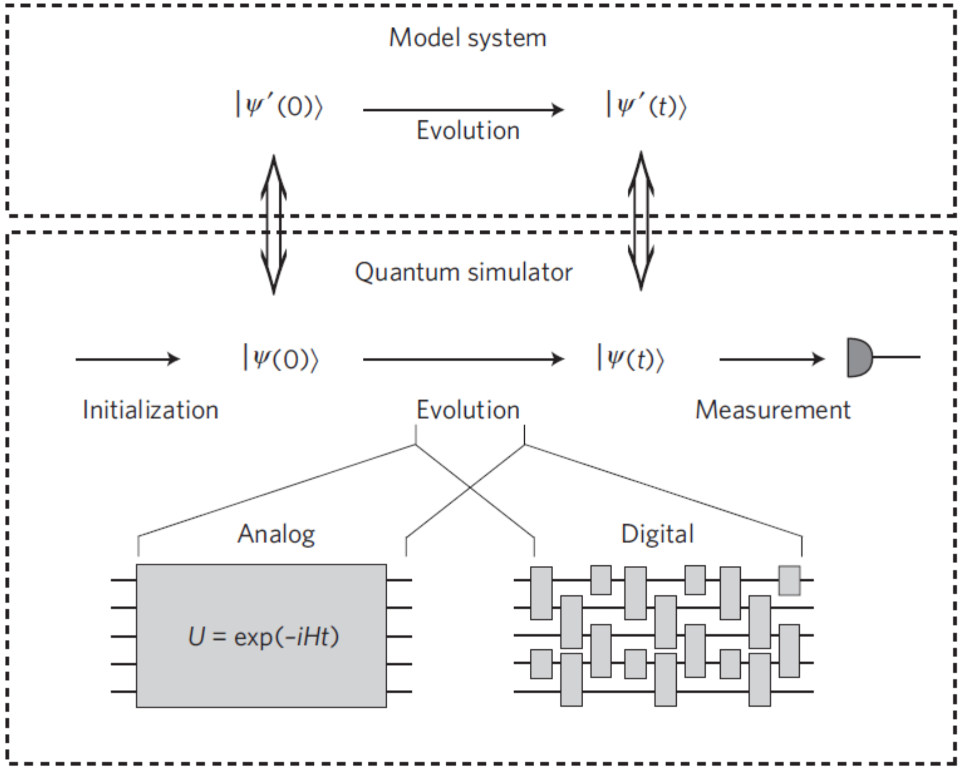
Quantum Hype or Real ?

Slide from F. Schmidt-Kaler, Natal, Nov 2018

€ or $



The goals of quantum simulation



Obtain results on the system that cannot be acquired by standard methods or numerical simulations

Explore new geometries, parameters, or configurations that are not available in the initial system

Invent novel systems or devices based on the acquired knowledge

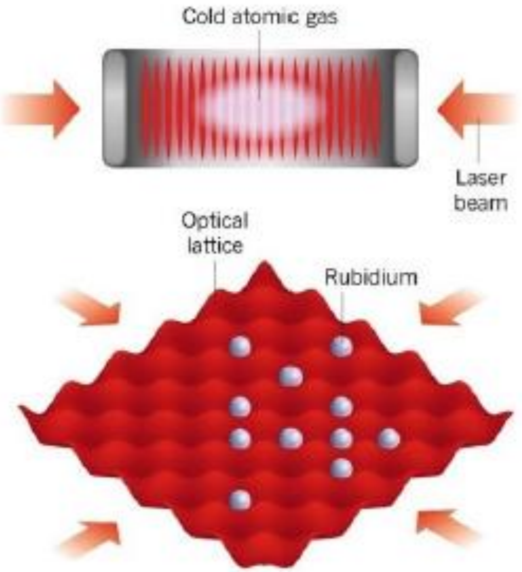
Non-trivial questions:

How to verify the simulation results ?
How to detect and correct errors ?

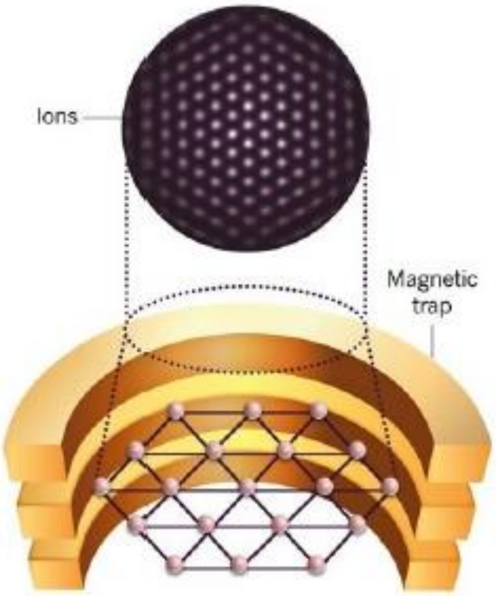
Quantum simulators

News feature, Nature, 14 Nov. 2012

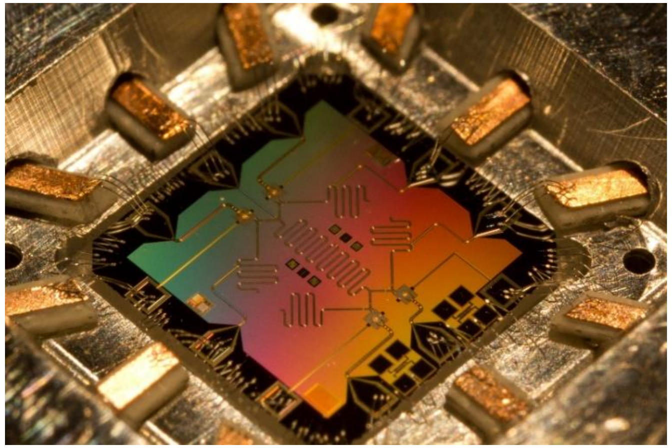
Cold atoms



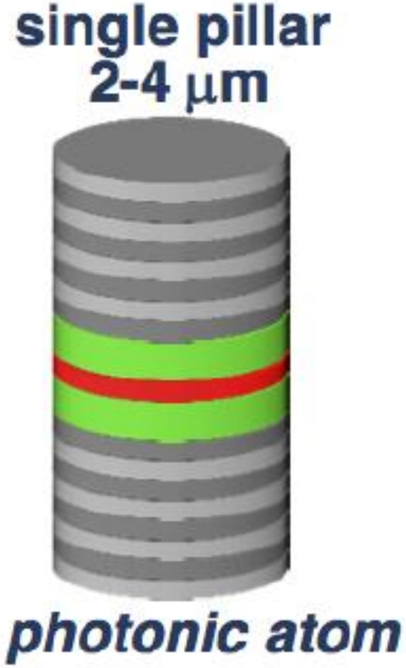
Trapped ions



Supercond circuits

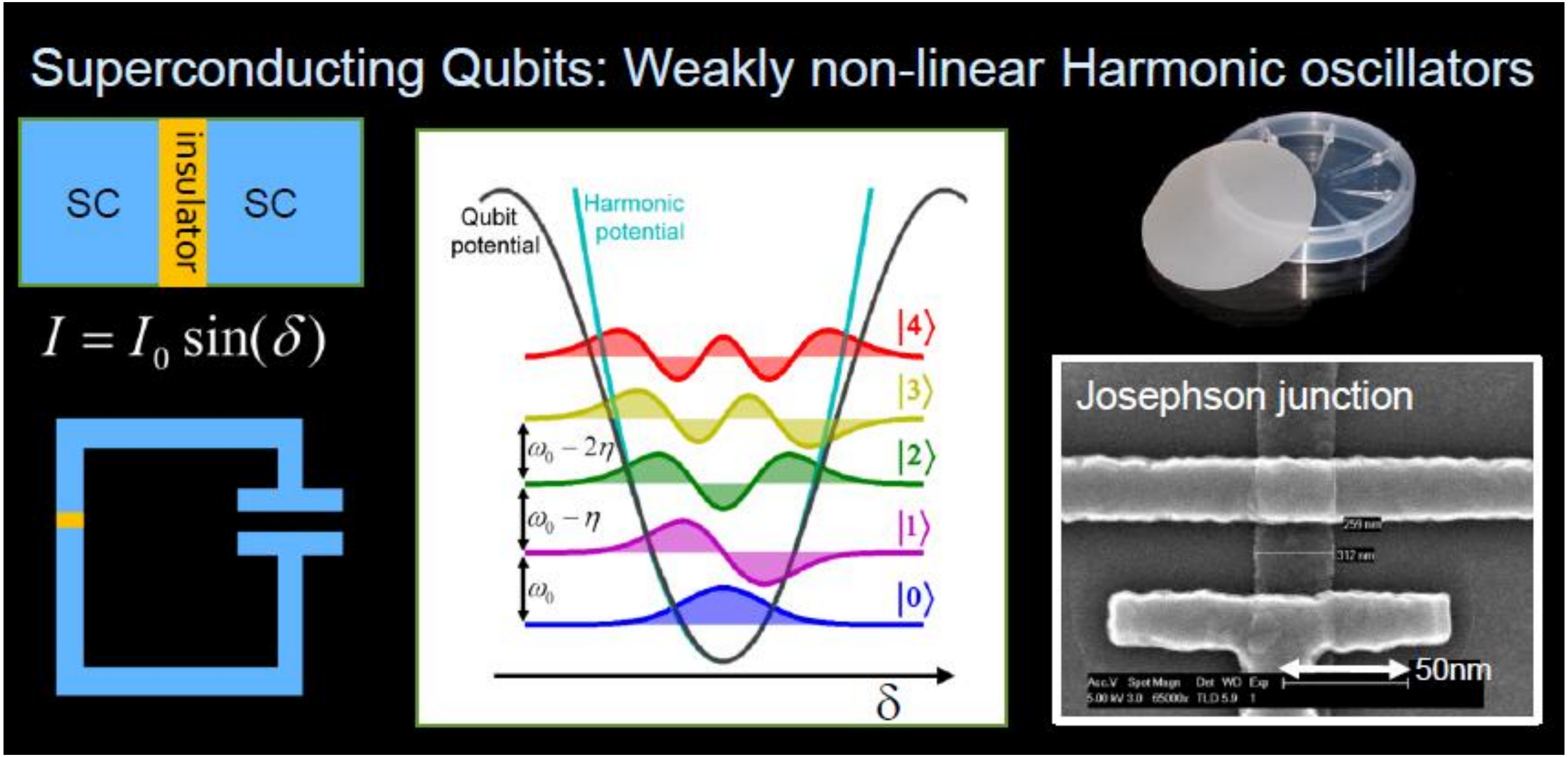


Polaritons



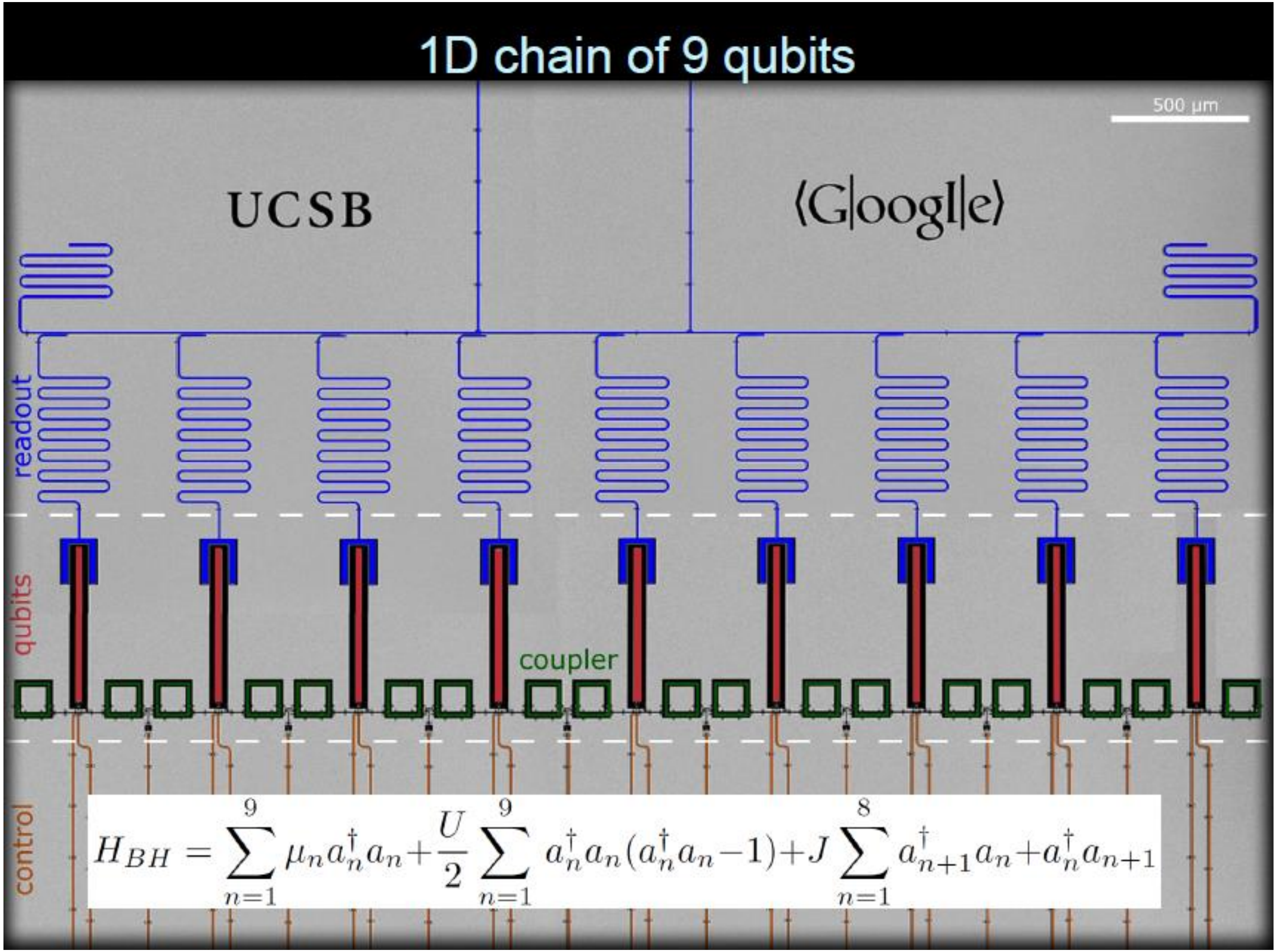
+ photons, excitons. . .

Superconducting qubits



From Pedram Roushan, Google Inc., ICQSIM, Paris, November 2017

Simulation of the Bose-Hubbard Hamiltonian

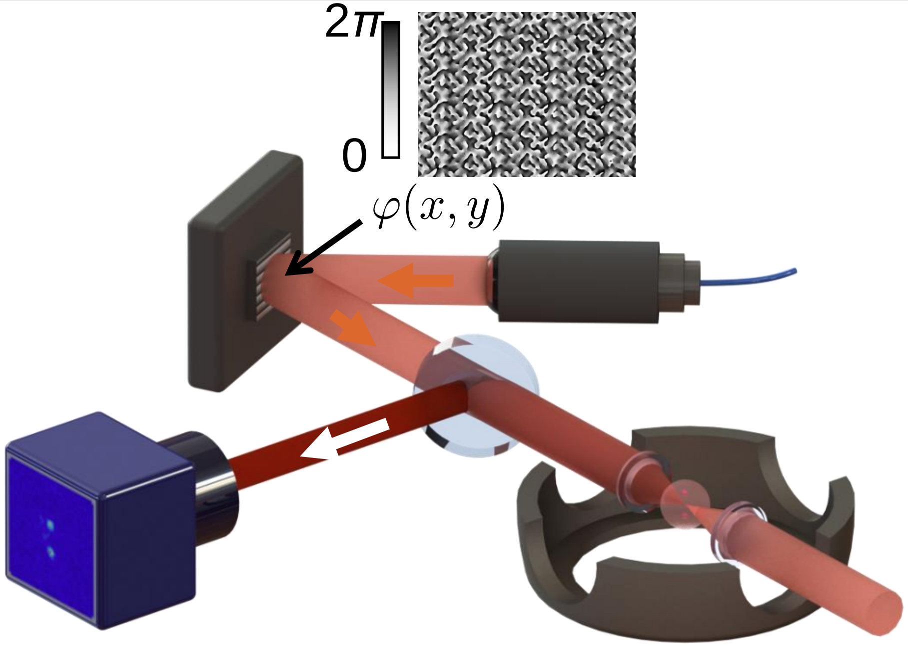


Signature of many-body Localization on energy Spectrum in a 9 qubit chain

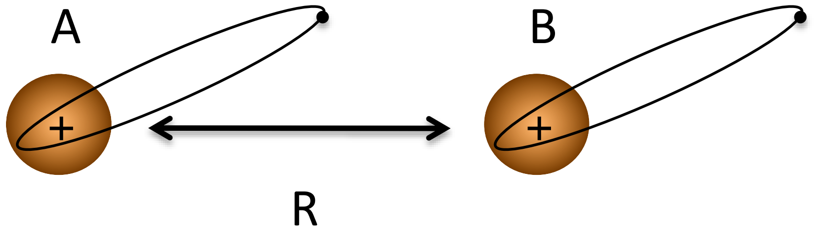
Roushan et al. Science 2017

Simulation of quantum magnetism using assembled 2D arrays of individual atoms

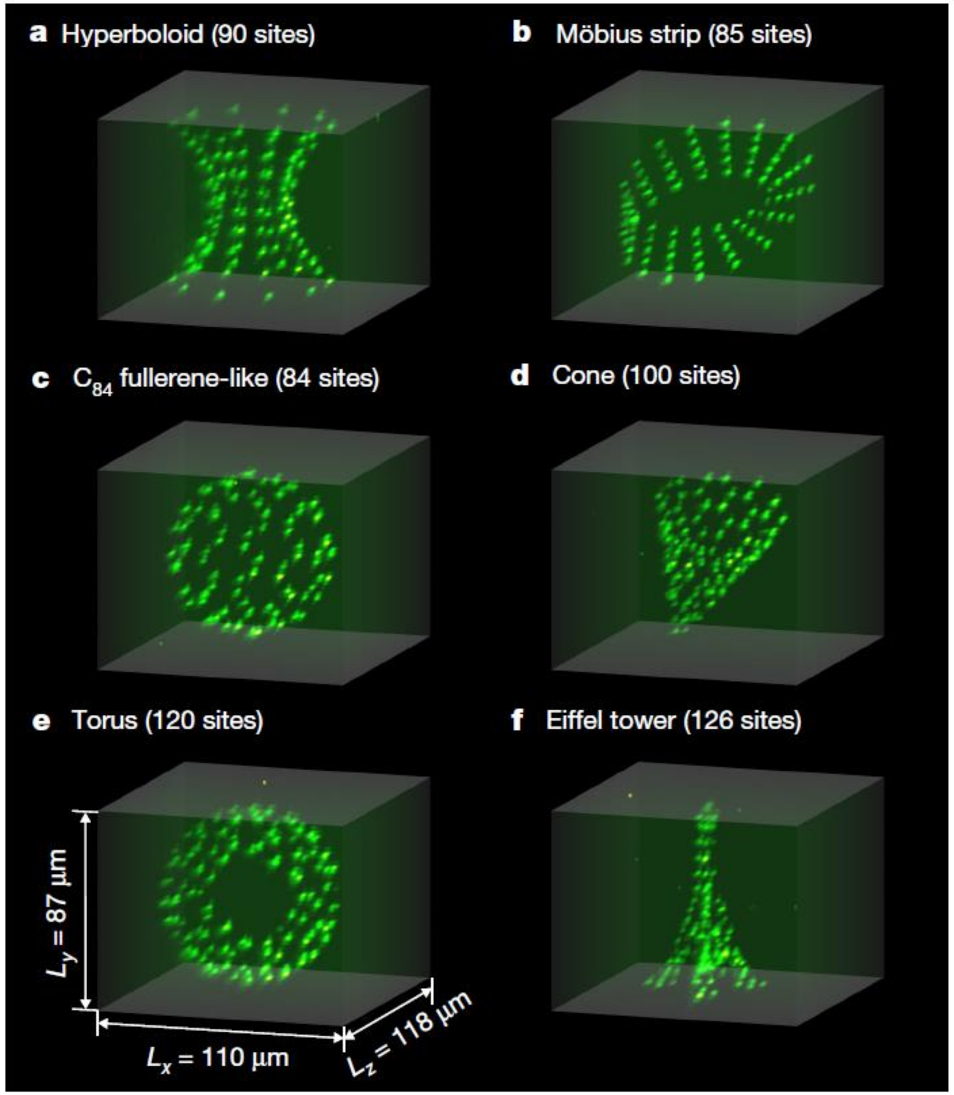
Controlled interactions: Rydberg excitation



Rydberg atoms



$$V_{AB} = 1/\,|\,r_A - r_B\,|^6$$



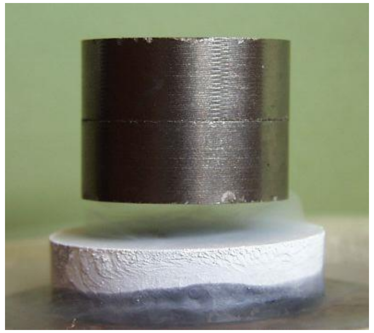
Quantum simulation with ultracold Gases

Diluteness: atom-atom interactions described by 2-body (and 3-body) physics. At low energy: a single parameter, the scattering length *a*

Control of the sign and magnitude of interaction
Control of trapping parameters:
Periodic potentials, « optical lattices »
Time dependent phenomena: out of equilibrium situations in 3D, 2D,1D
Simplicity of detection

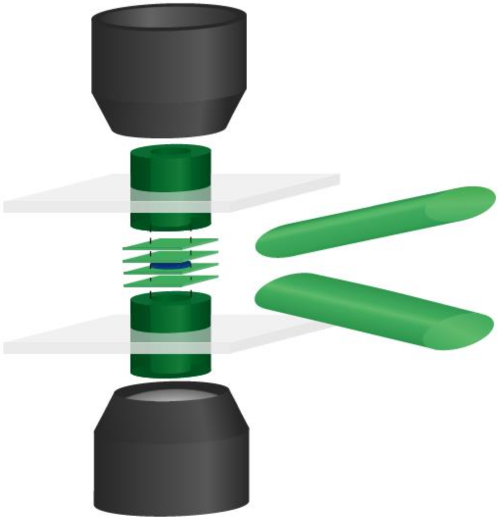
Quantitative Comparison with quantum Many-Body theories:
Gross-Pitaevskii, Bose and Fermi Hubbard models,
search for exotic phases, dipolar gases
disorder effects, Anderson localization, …

Link with condensed matter (high Tc superconductors),
astrophysics (neutron stars), Nuclear physics,
high energy physics (quark-gluon plasma)



Two-dimensional physics with quantum gases

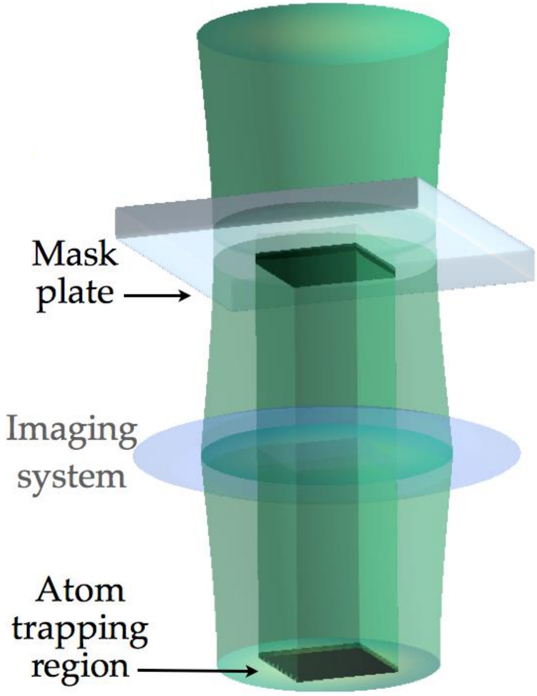
Collège de France, J. Dalibard, J. Beugnon, S. Nascimbène
Institut d'optique, T. Bourdel. LPL, H. Perrin

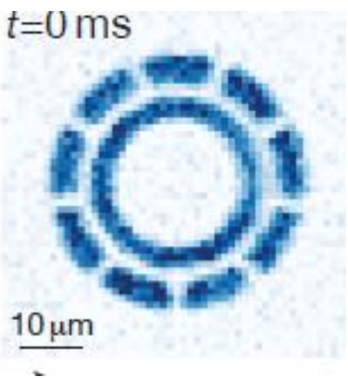


Freezing the motion along the vertical direction

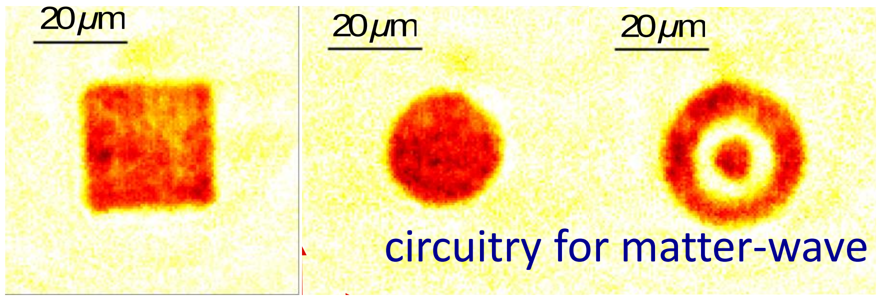
one plane of atoms

Similar to the 2D electron gas in a quantum well

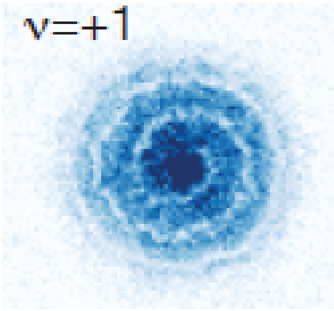




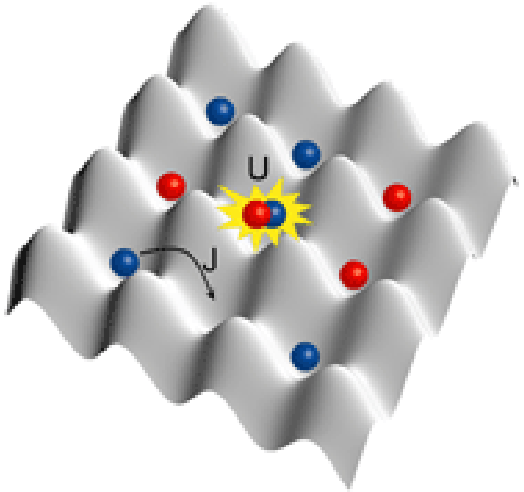
Free motion in a 2D box of arbitrary shape



circuitry for matter-wave



High Tc superconductivity and Fermi Hubbard model

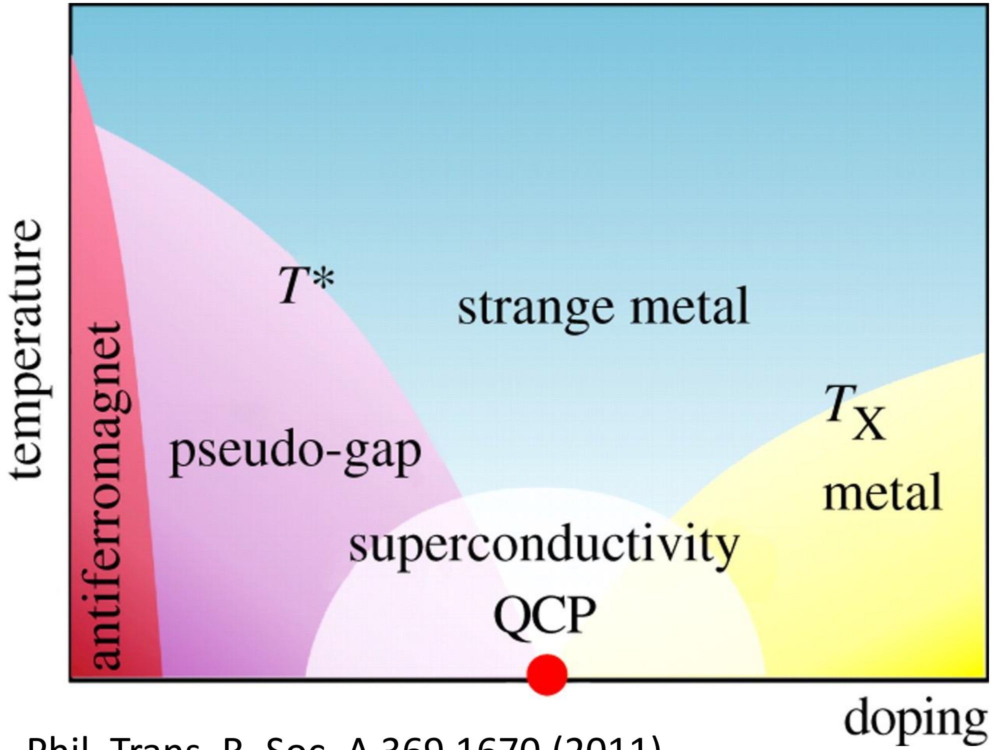


$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + c_{j,\sigma}^{\dagger} c_{i,\sigma} \right) + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

Realized naturally with cold atoms in optical lattices with fully tunable parameters.

Rich phase diagram:

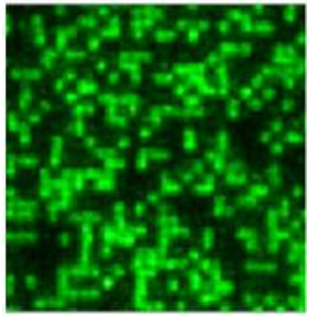
commensurate/
incommensurate AFM,
pseudogap, strange metal,
d-wave superconductivity…



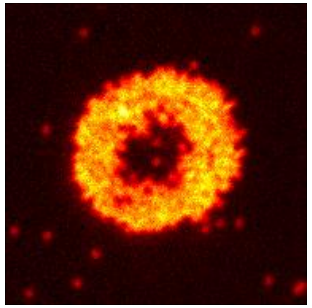
Galanakis et al., Phil. Trans. R. Soc. A 369 1670 (2011)

Quantum gas microscopy

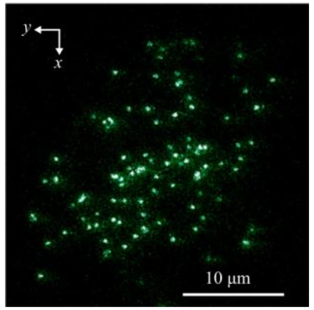
- Boson microscopes: 2010



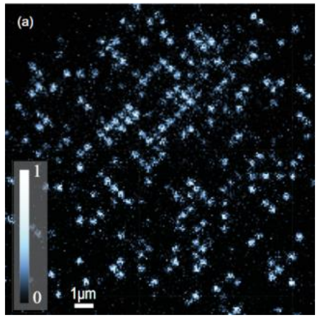
Harvard



MPQ

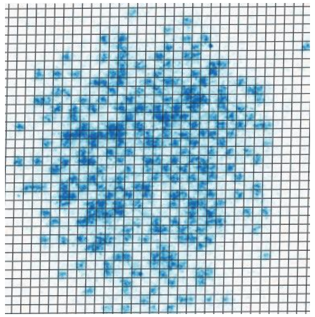


Kyoto

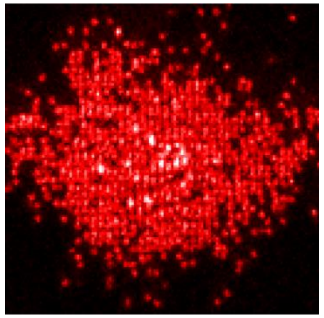


Tokyo

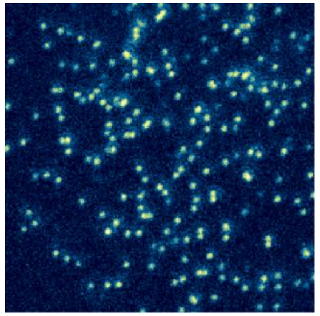
- Fermion microscopes: 2015



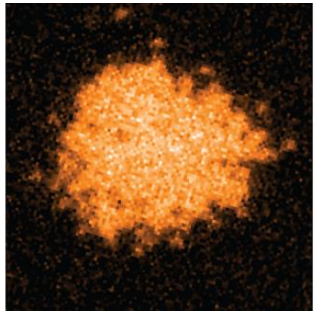
Harvard



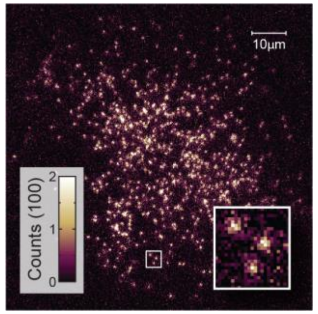
MPQ



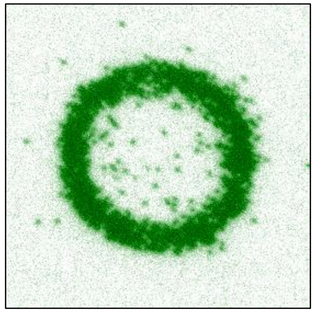
Strathclyde



MIT



Toronto

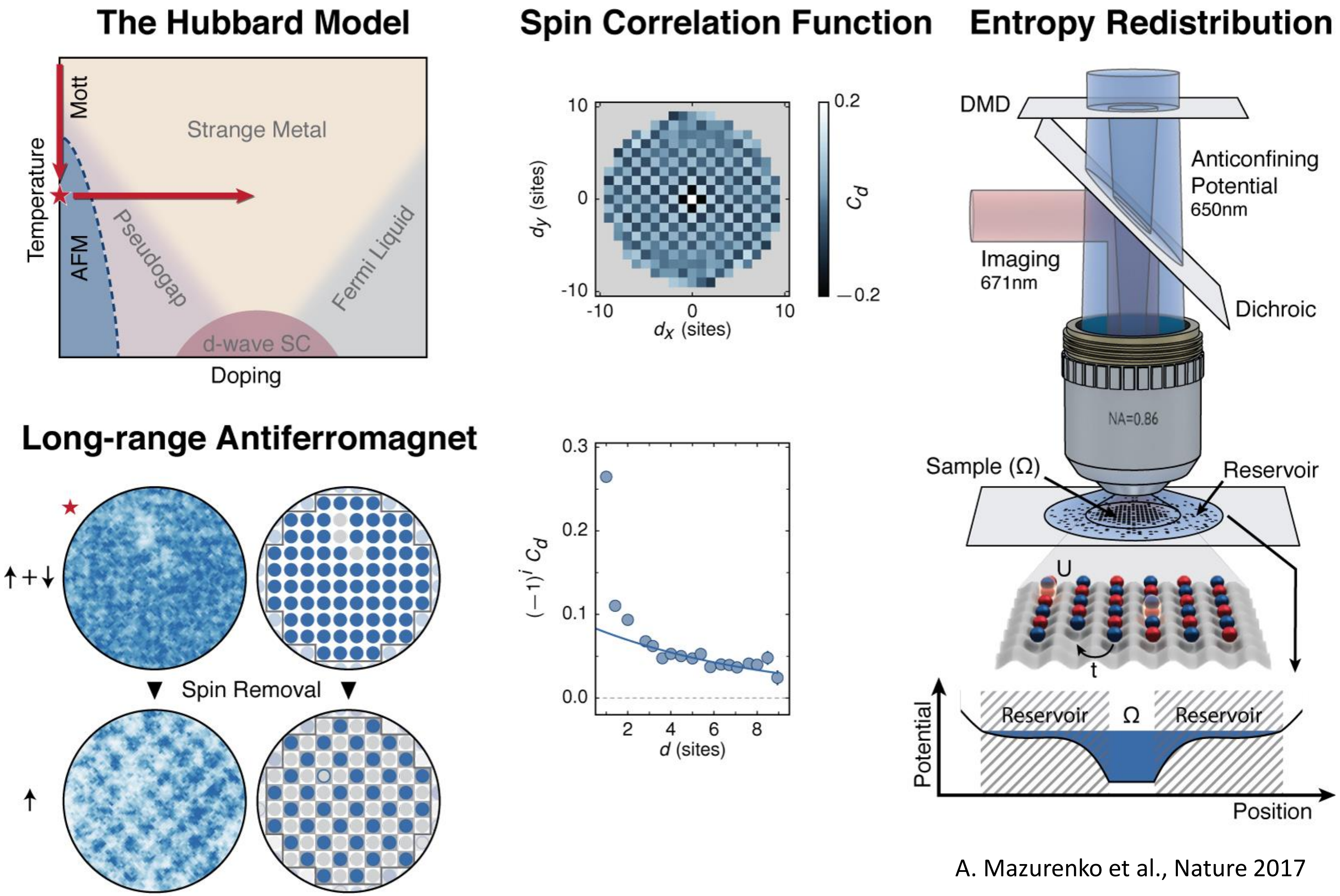


Princeton

The Fermi Hubbard model in 2D

M. Greiner, Harvard, I. Bloch, MPQ
M. Koehl, Bonn, S. Kuhr, Glasgow
M. Zwierlein MIT, J. Thywissen, Toronto

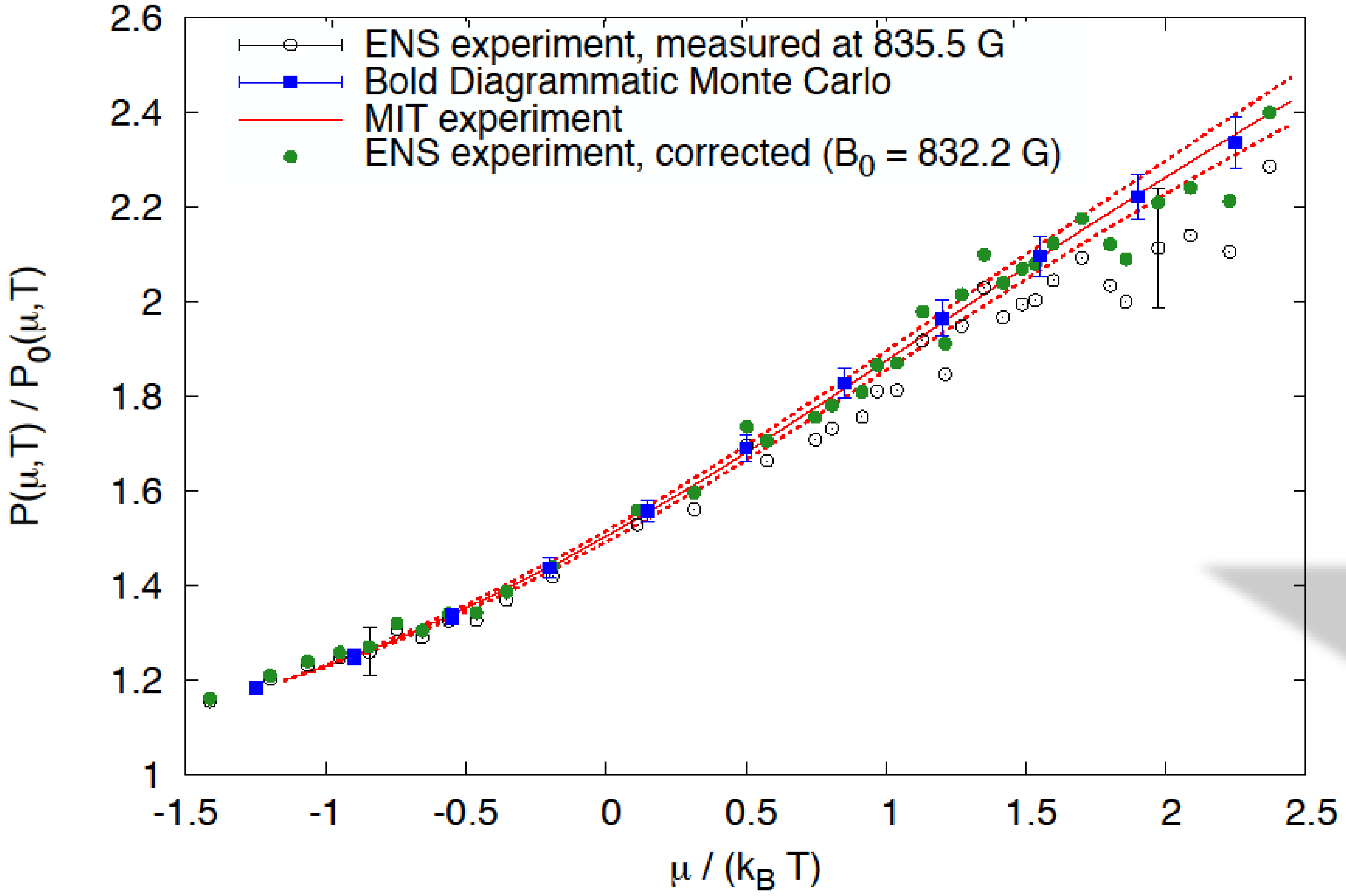
$$\hat{H} = -t \sum_{\sigma,\langle i,j\rangle \in \Omega} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U \sum_{i\in\Omega} \hat{n}_{i,\downarrow}\hat{n}_{i,\uparrow},$$



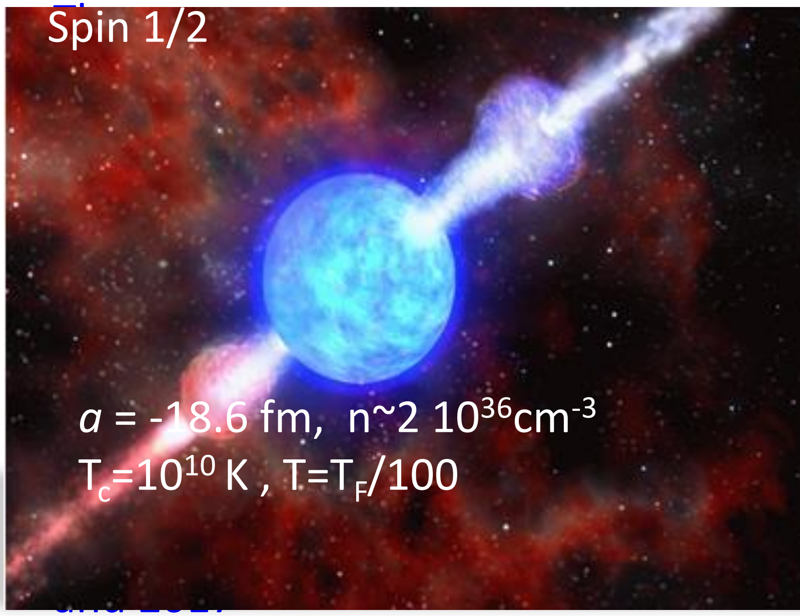
A. Mazurenko et al., Nature 2017

Equation of state of a Fermi gas with tunable interaction

S. Nascimbène, N. Navon, K. Jiang, F. Chevy, C. Salomon, Nature 2010



Unitary limit: 1/a=0



Neutron star

5% agreement with a many-body theory in strongly interacting regime

Currently explored problems

Equilibrium quantum systems, bulk or lattice

Phase diagrams, equation of state, superconductivity and spin imbalance, exotic superfluidity

Out of equilibrium systems and quantum quenches

Transport and dissipation, Kibble-Zurek scenario, many-body localization

Quantum magnetism

Individual particle detection, lattice systems, frustration, impurity problems

Topological systems

Quantum Hall effect, spin-orbit coupling, gauge fields, synthetic dimensions,
Majorana fermions and link with quant. computation

Theory

All of previous topics, preparation, measurements, use dissipation and entanglement
Thermalization of an isolated quantum system, quenches, entanglement growth