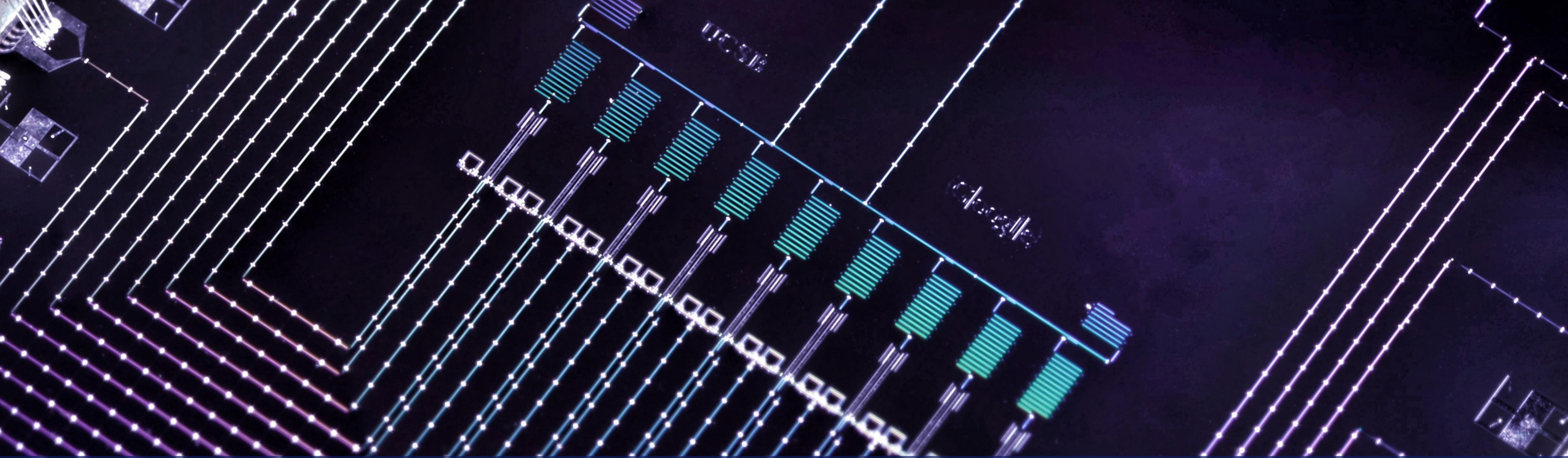


Quantum simulation with arrays of superconducting qubits

First applications in probing many-body localization

Journée Théorie du CPTGA

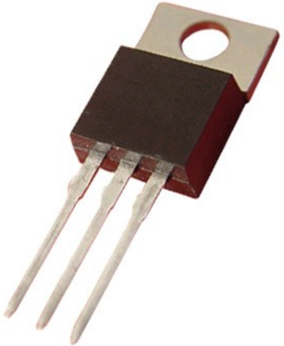
Michele Filippone

Historical

Silicon

band theory

Transistor



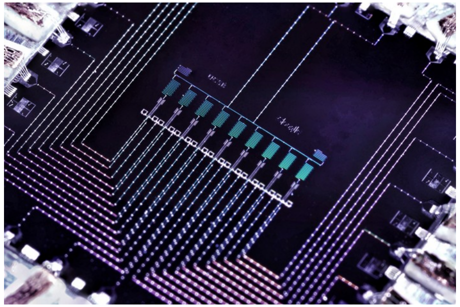
Classical bits

$01010010\ldots$

thiscatdoesnotexist.com

Will history repeat ?

Synthetic
Quantum Matter



Theory of
Quantum Matter

Miraculous
device ?

?

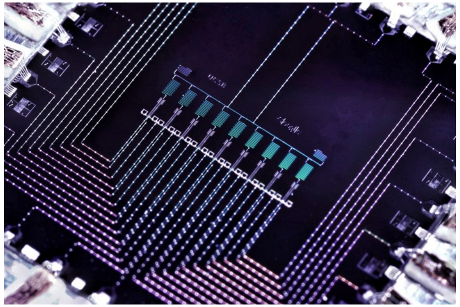
? ? ? ? ?

Quantum bits

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes \frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes |0\rangle \otimes |1\rangle \ldots$$

Will history repeat ?

Synthetic
Quantum Matter



Theory of
Quantum Matter

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Quantum bits

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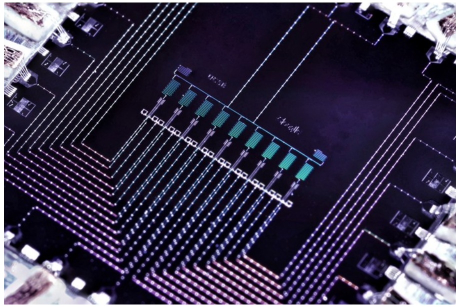
? ? ? ? ?

Will history repeat ?

CPTGA - 2021

Synthetic
Quantum Matter



Theory of
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?

Quantum bits

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes \frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes |0\rangle \otimes |1\rangle \ldots$$

? ? ? ? ?

Last two years ...

Article

Quantum supremacy using a programmable superconducting processor

Nature | Vol 574 | 24 OCTOBER 2019 | **505**

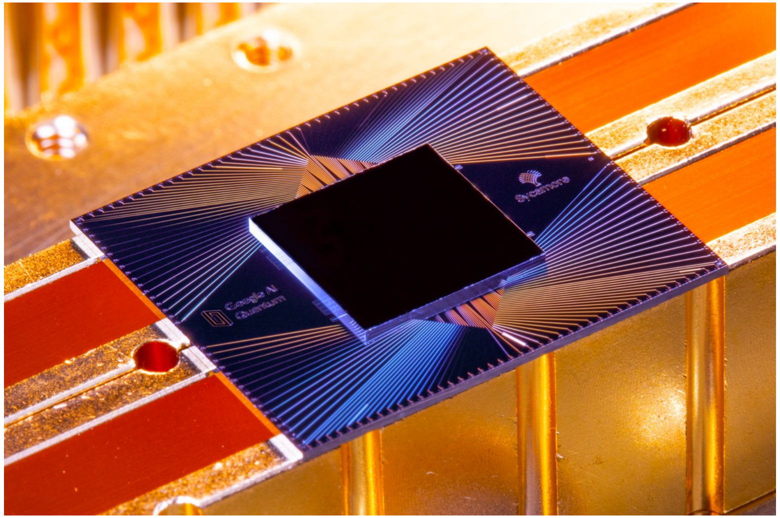

Photo credit: Eric Lucero

Google

RESEARCH

QUANTUM COMPUTING

Quantum computational advantage using photons

Zhong *et al.*, *Science* **370**, 1460–1463 (2020)

Photo credit: PhysicsWorld

Last two years …

Article

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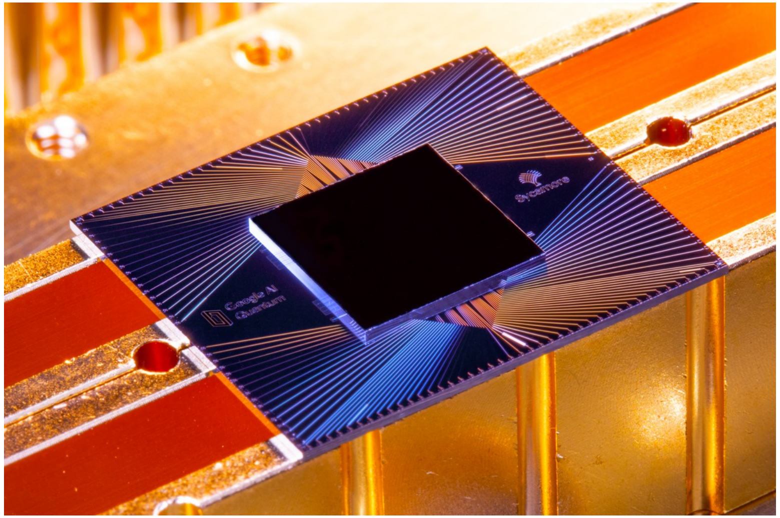

Photo credit: Eric Lucero

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RESEARCH

QUANTUM COMPUTING

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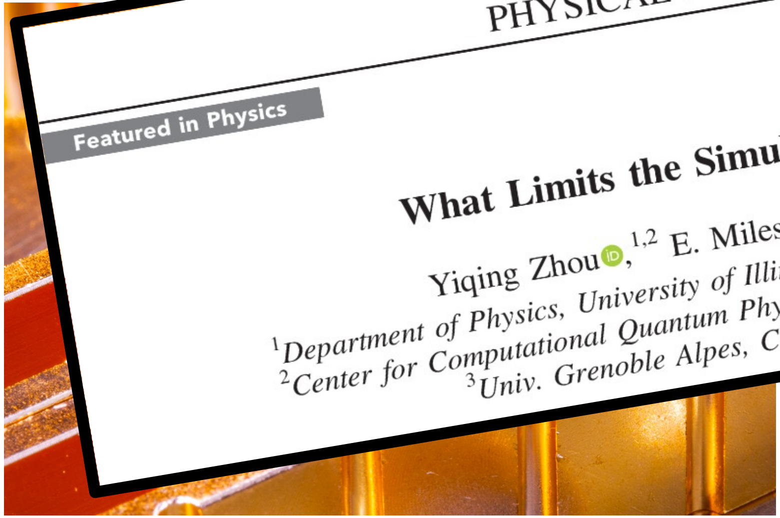
Photo credit: PhysicsWorld

1958
University of Science and Technology of China

Last two years ...

Article

Quantum supremacy using a programmable superconducting processor



PHYSICAL REVIEW X 10, 041038 (2020)

Featured in Physics

What Limits the Simulation of Quantum Computers?

Yiqing Zhou,[1,2] E. Miles Stoudenmire,[2] and Xavier Waintal[3]

[1]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
[2]Center for Computational Quantum Physics, Flatiron Institute, New York, New York 10010, USA
[3]Univ. Grenoble Alpes, CEA, IRIG-Pheliqs, 38054 Grenoble, France

RESEARCH

...hotons

...370, 1460–1463 (2020)

Photo credit: Eric Lucero

Photo credit: PhysicsWorld

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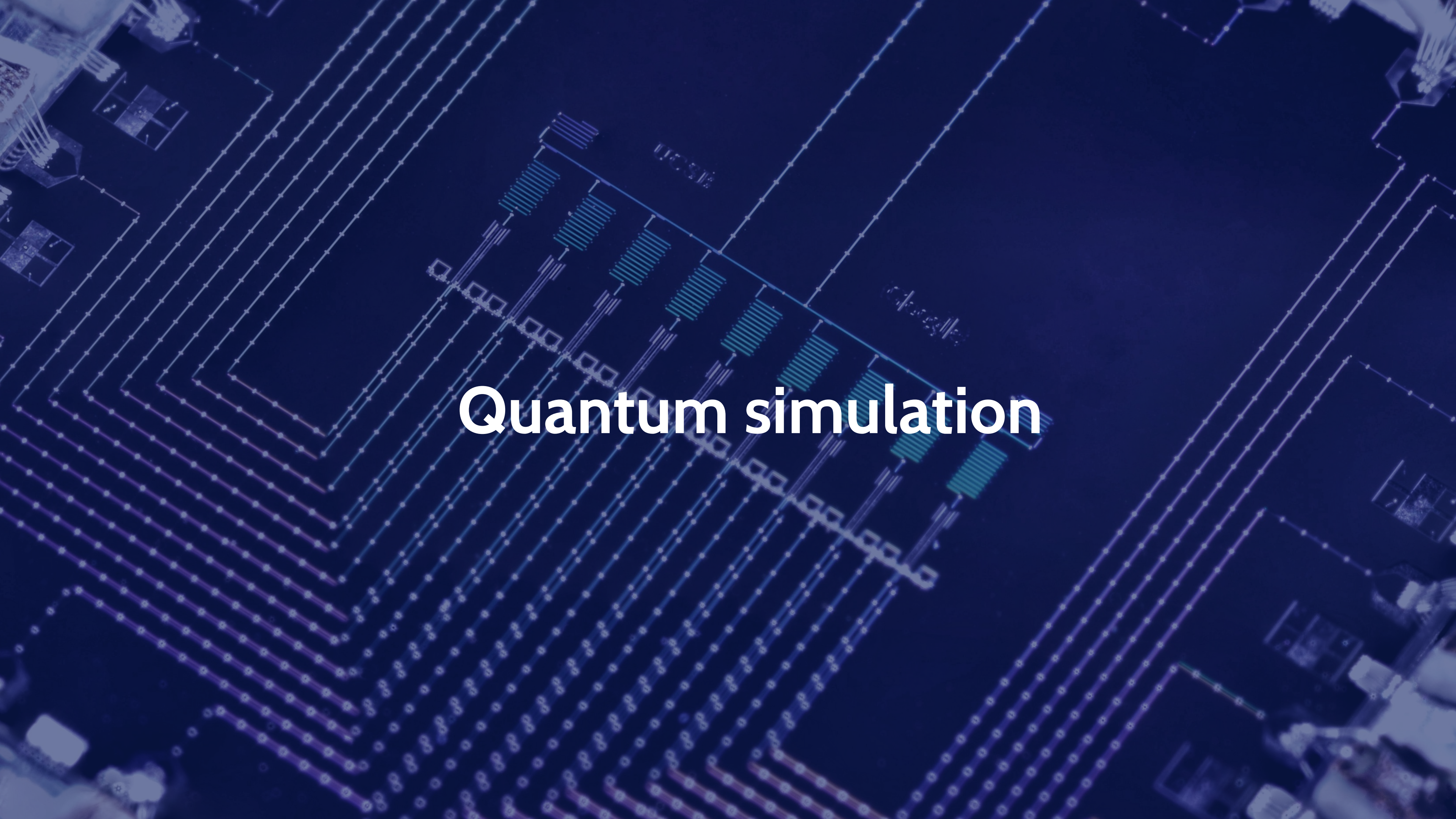
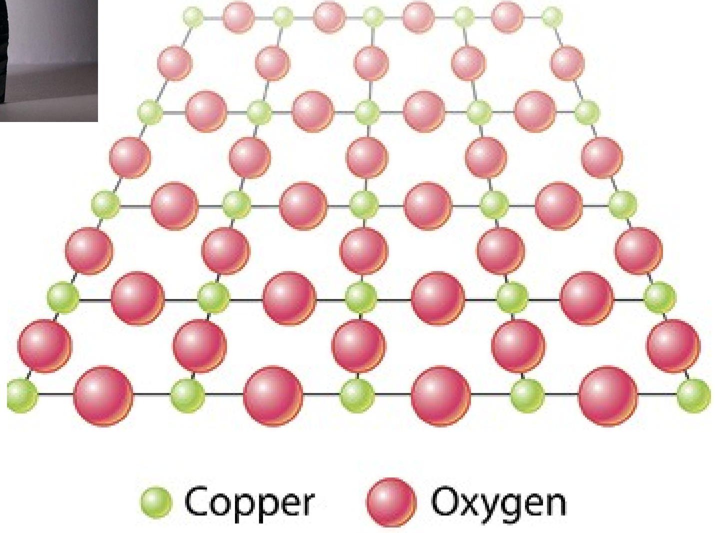
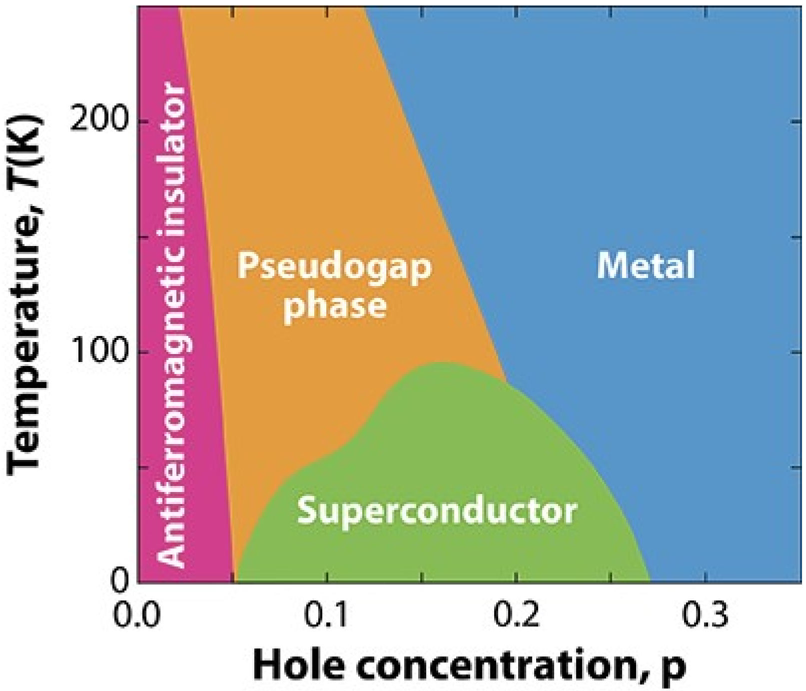
Quantum simulation



Does the Fermi-Hubbard model describe High-Tc Superconductors?



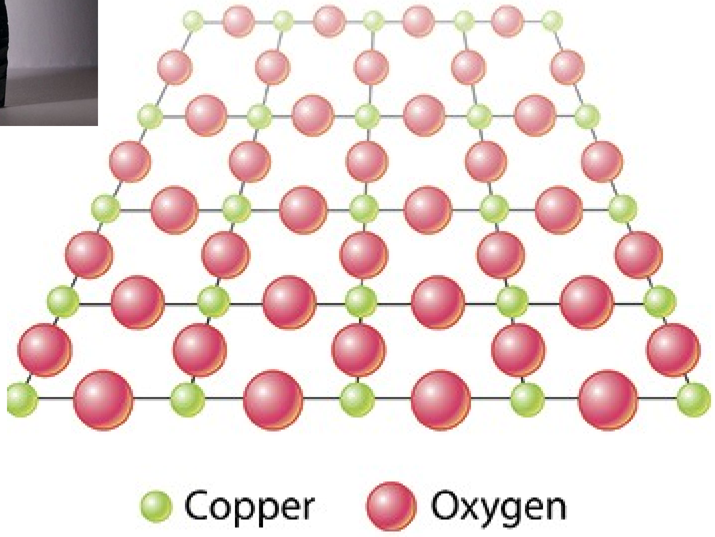
Electrons hop between the copper ions via the oxygen bonds



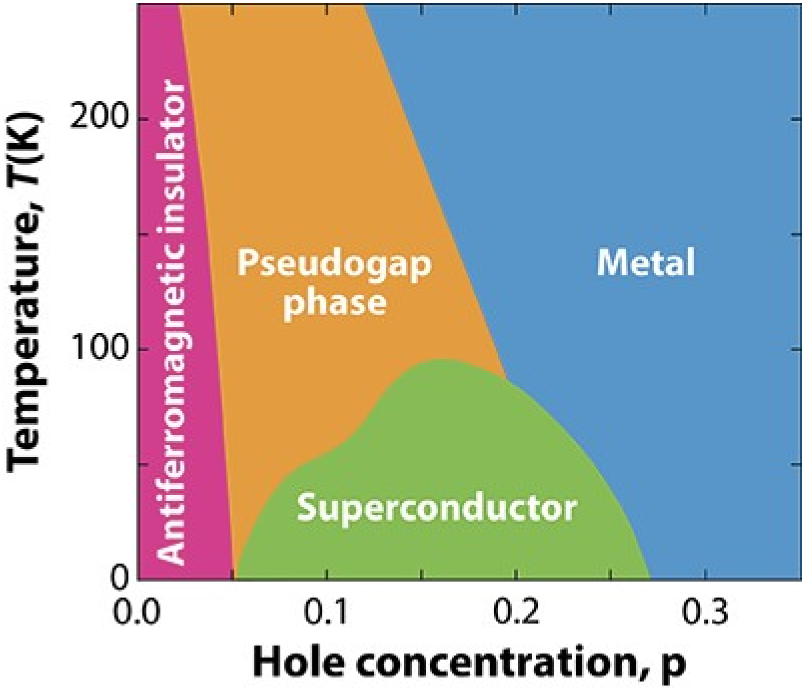
$$H_{\mathrm{FH}} = t \sum_{<i,j>,\sigma} \left[c^{\dagger}_{i,\sigma} c_{j,\sigma} + \mathrm{h.c.} \right] + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

APS/Carin Cain

Does the Fermi-Hubbard model describe High-Tc Superconductors?



Electrons hop between the copper ions via the oxygen bonds



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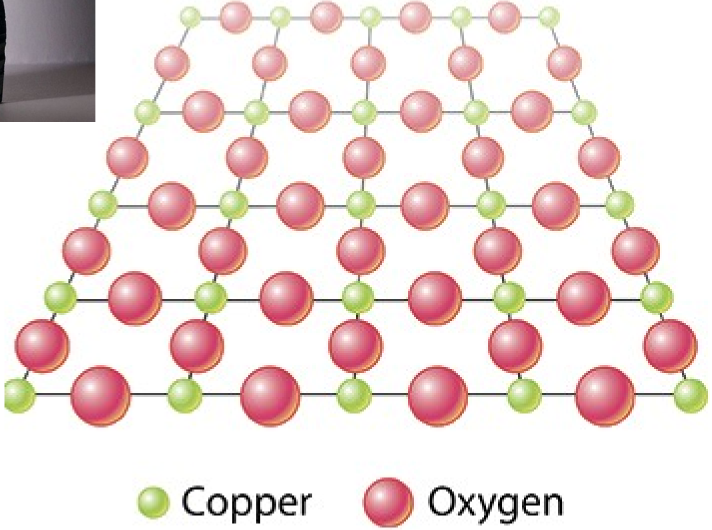
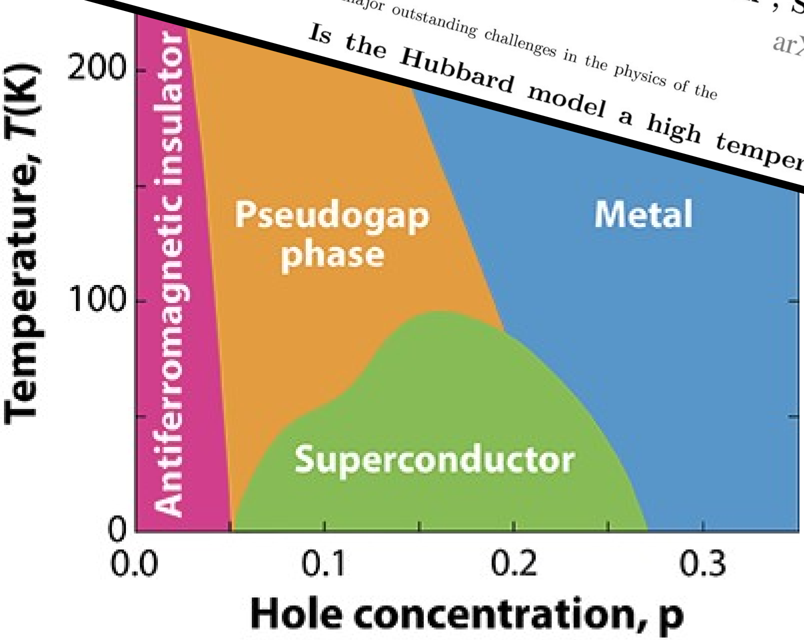
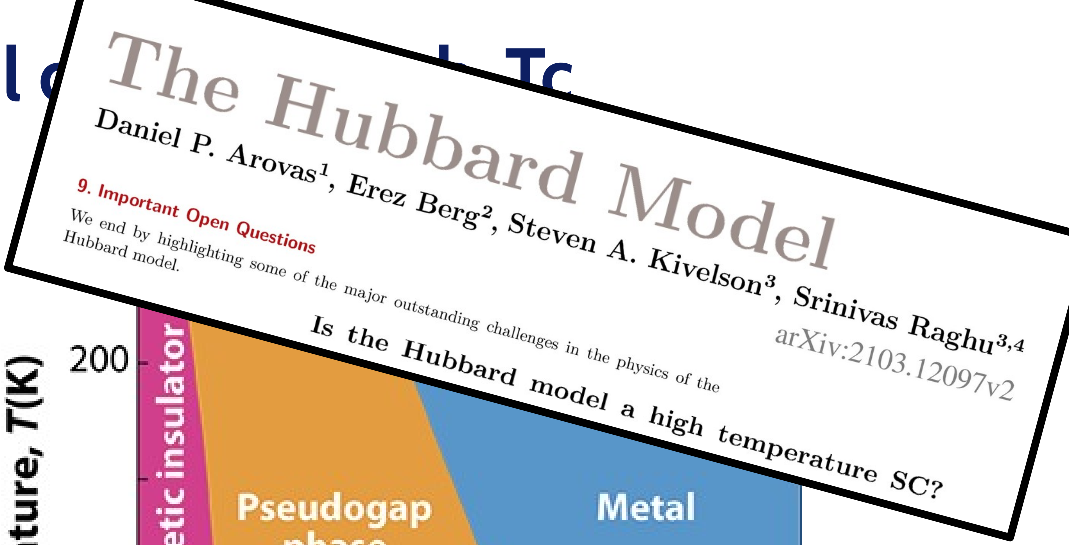
APS/Carin Cain

Does the Fermi-Hubbard model c … h Tc Superconductors?



Electrons hop between the copper ions via the oxygen bonds




The Hubbard Model

Daniel P. Arovas[1], Erez Berg[2], Steven A. Kivelson[3], Srinivas Raghu[3,4]

arXiv:2103.12097v2

9. Important Open Questions

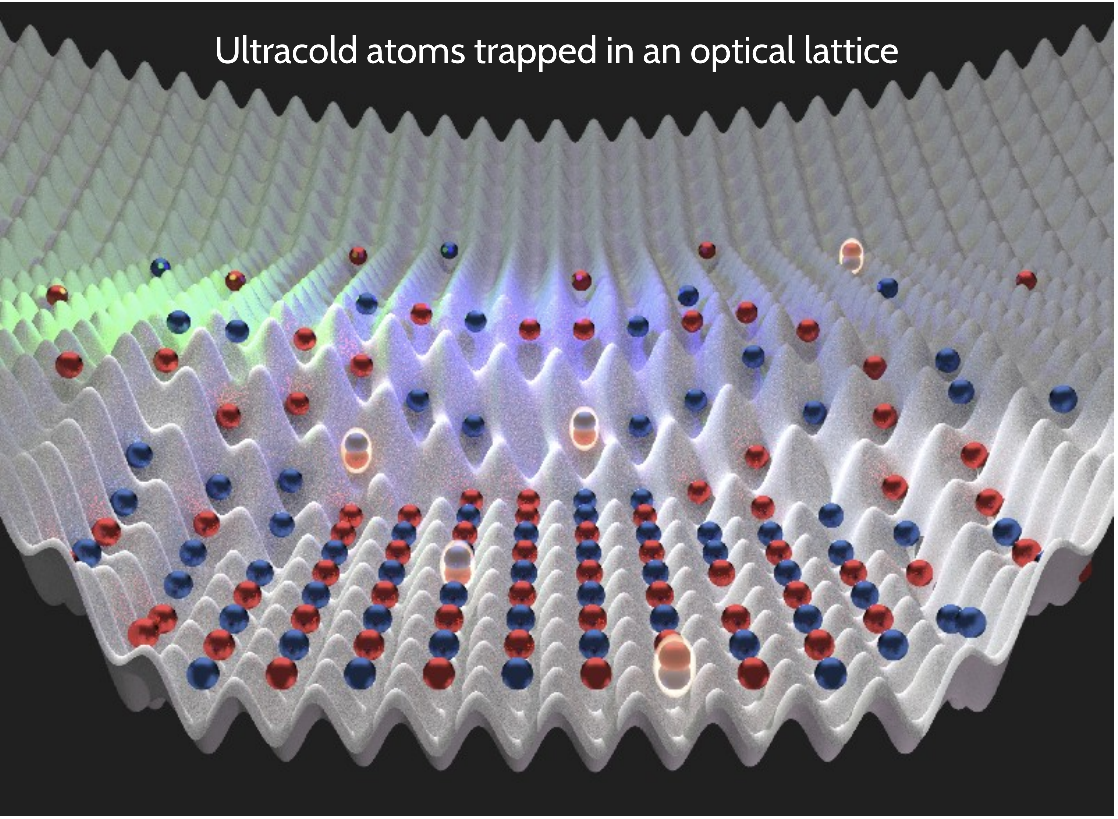
We end by highlighting some of the major outstanding challenges in the physics of the Hubbard model.

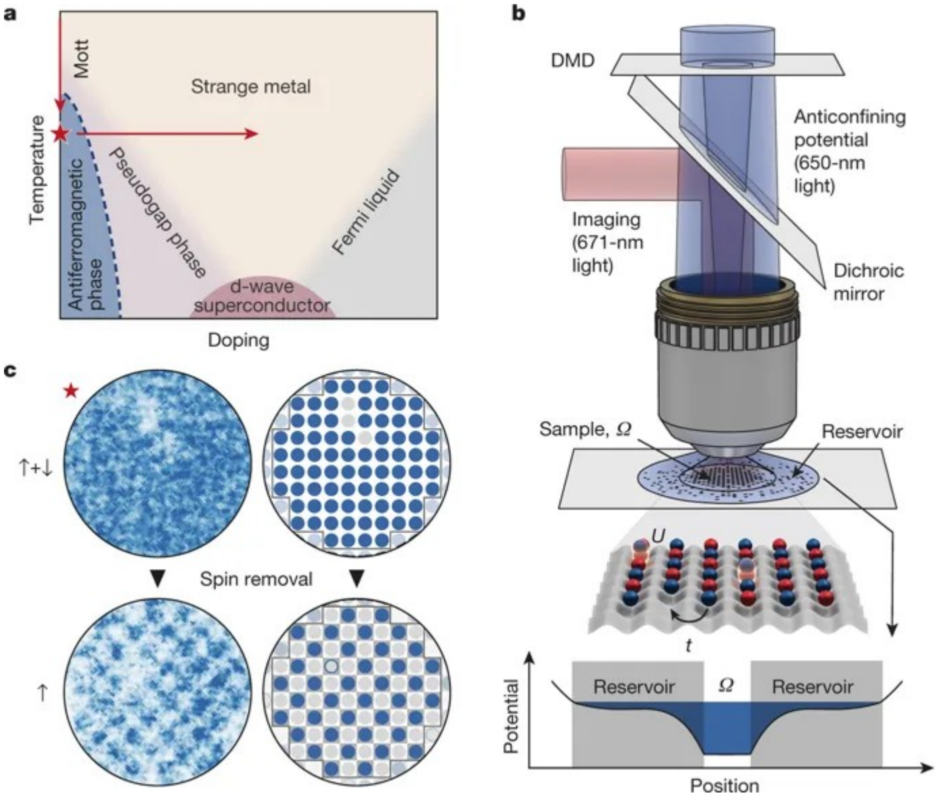
Is the Hubbard model a high temperature SC?

$$H_{\mathrm{FH}} = t \sum_{<i,j>,\sigma} \left[c^{\dagger}_{i,\sigma} c_{j,\sigma} + \mathrm{h.c.} \right] + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

APS/Carin Cain

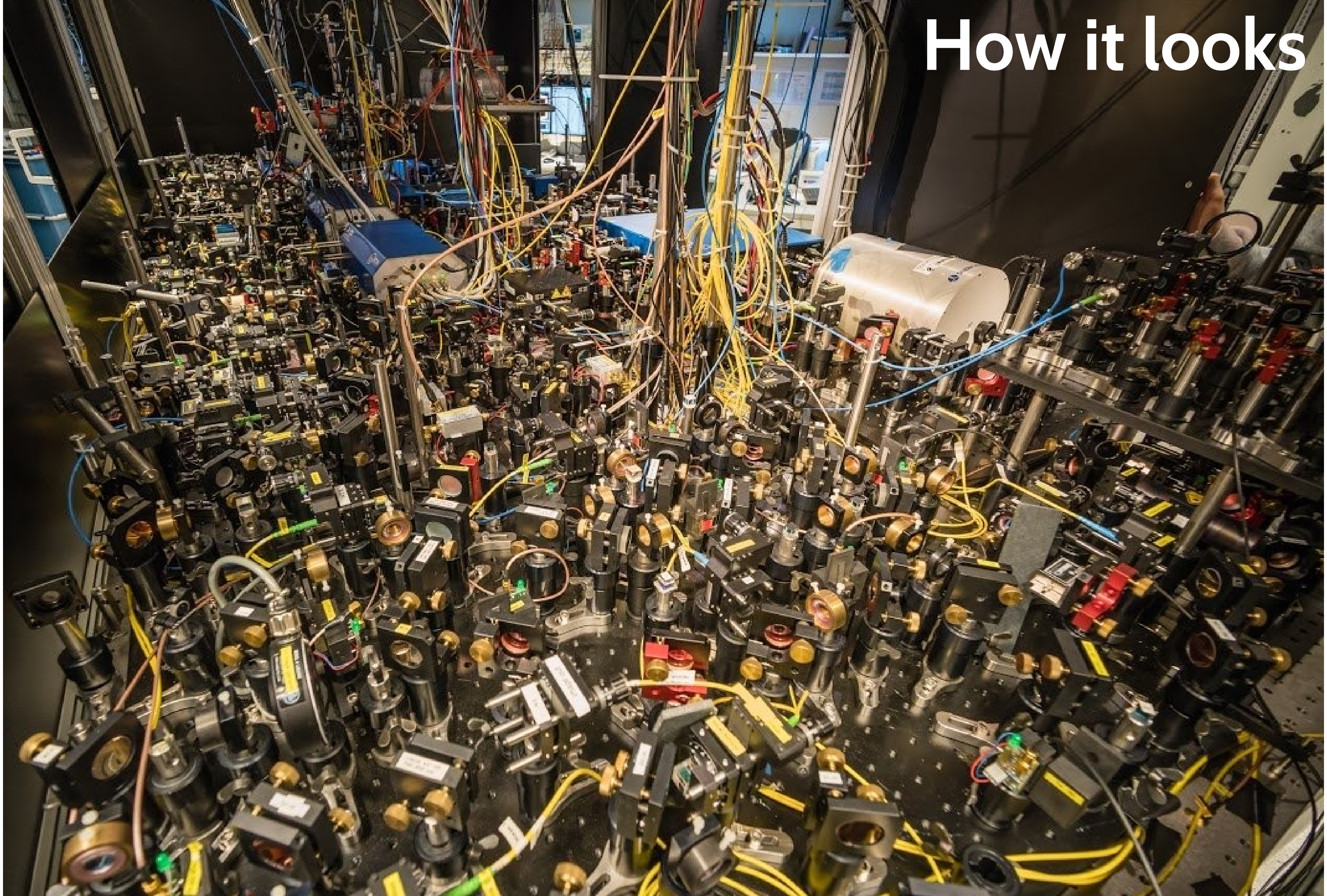
Quantum simulation with cold atoms



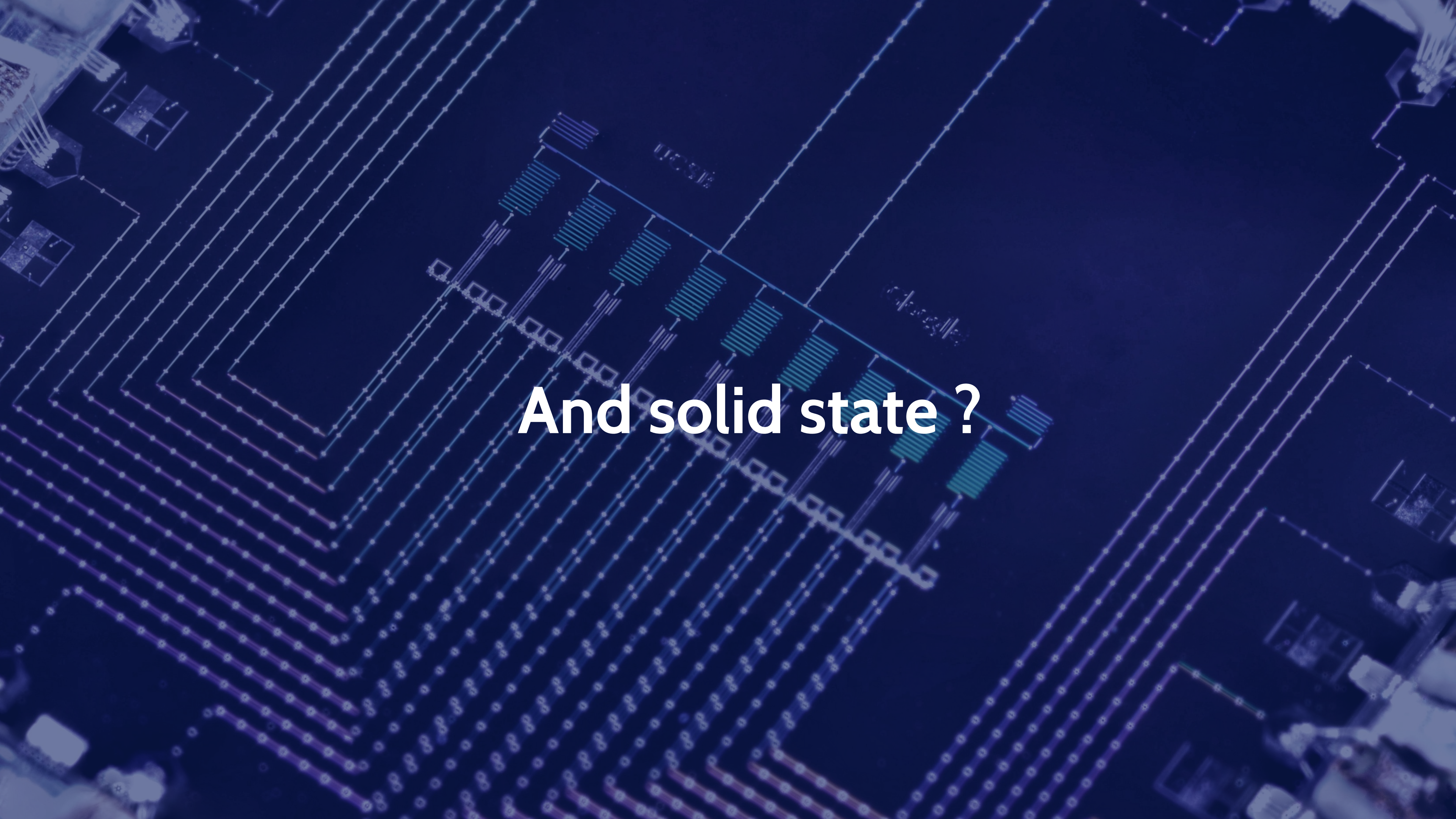


Greiner's group – Nature 2017

How it looks



And solid state ?



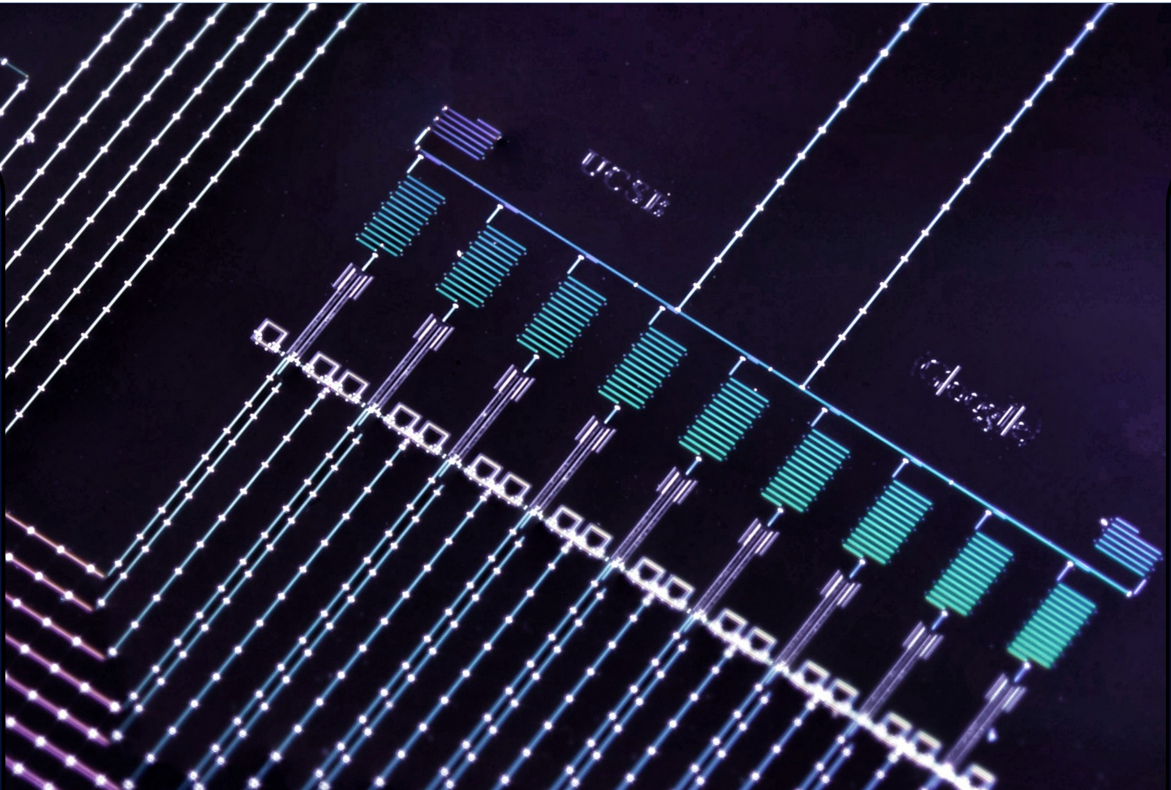
UNIVERSITÉ DE GENÈVE

DQMP Department of Quantum Matter Physics

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

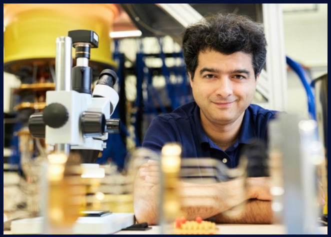
Google

“Many”-body localization in a superconducting quantum simulator



Ben Chiaro

Pedram Roushan



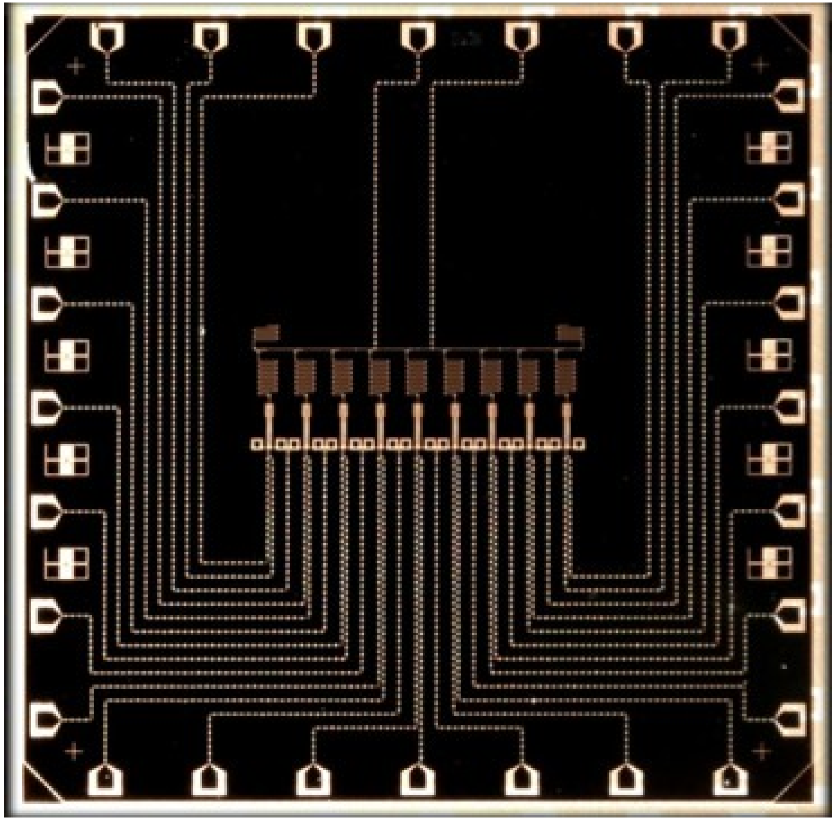
Annabelle Bohrdt

Michael Knap

Sarang Golapakrishnan

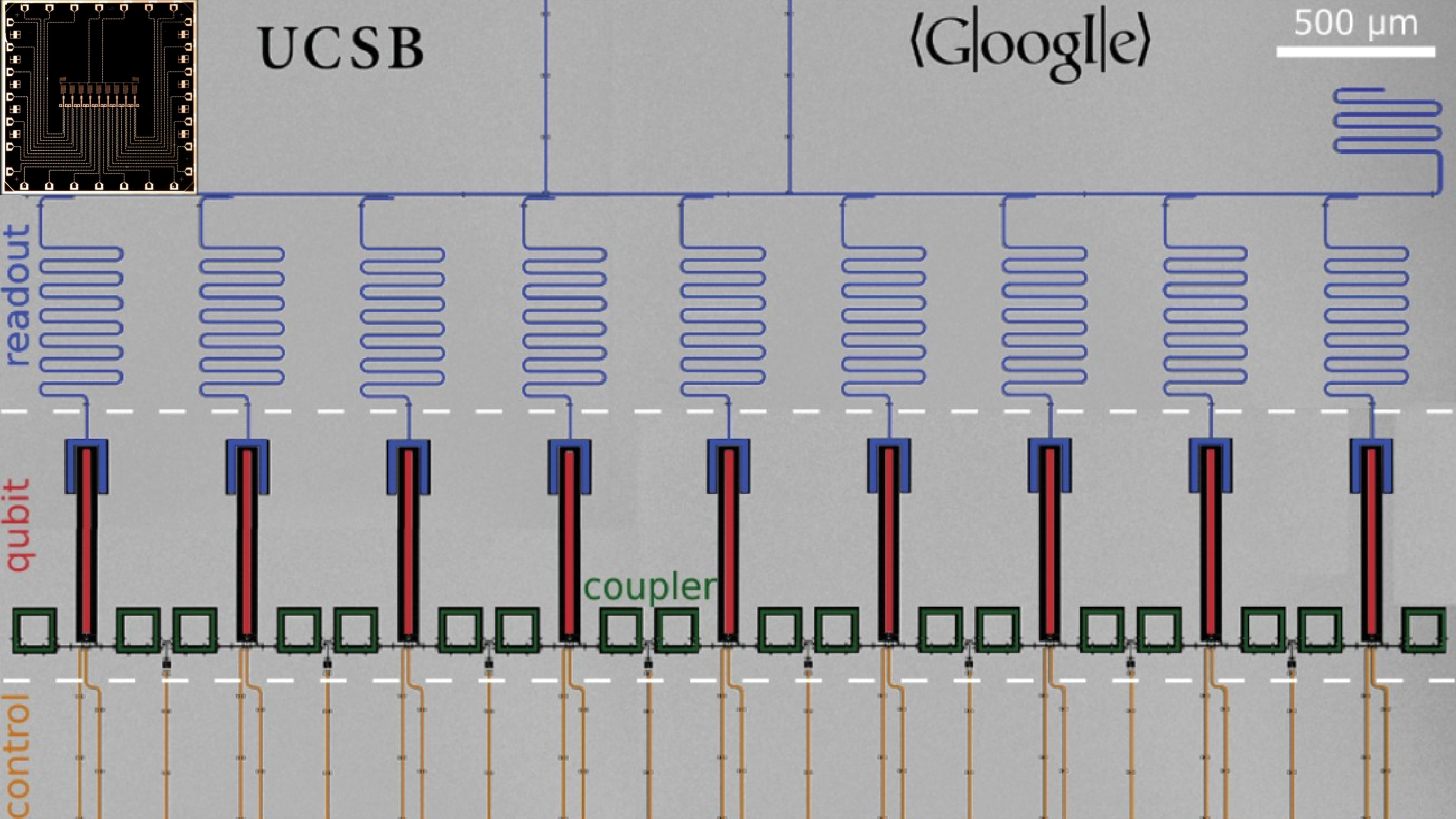
Dmitry A. Abanin

Quantum simulation in a 9-Qubit system



TODAY's QUESTION:

Probing the exotic dynamics of disordered interacting systems (Many-Body Localization)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coupler
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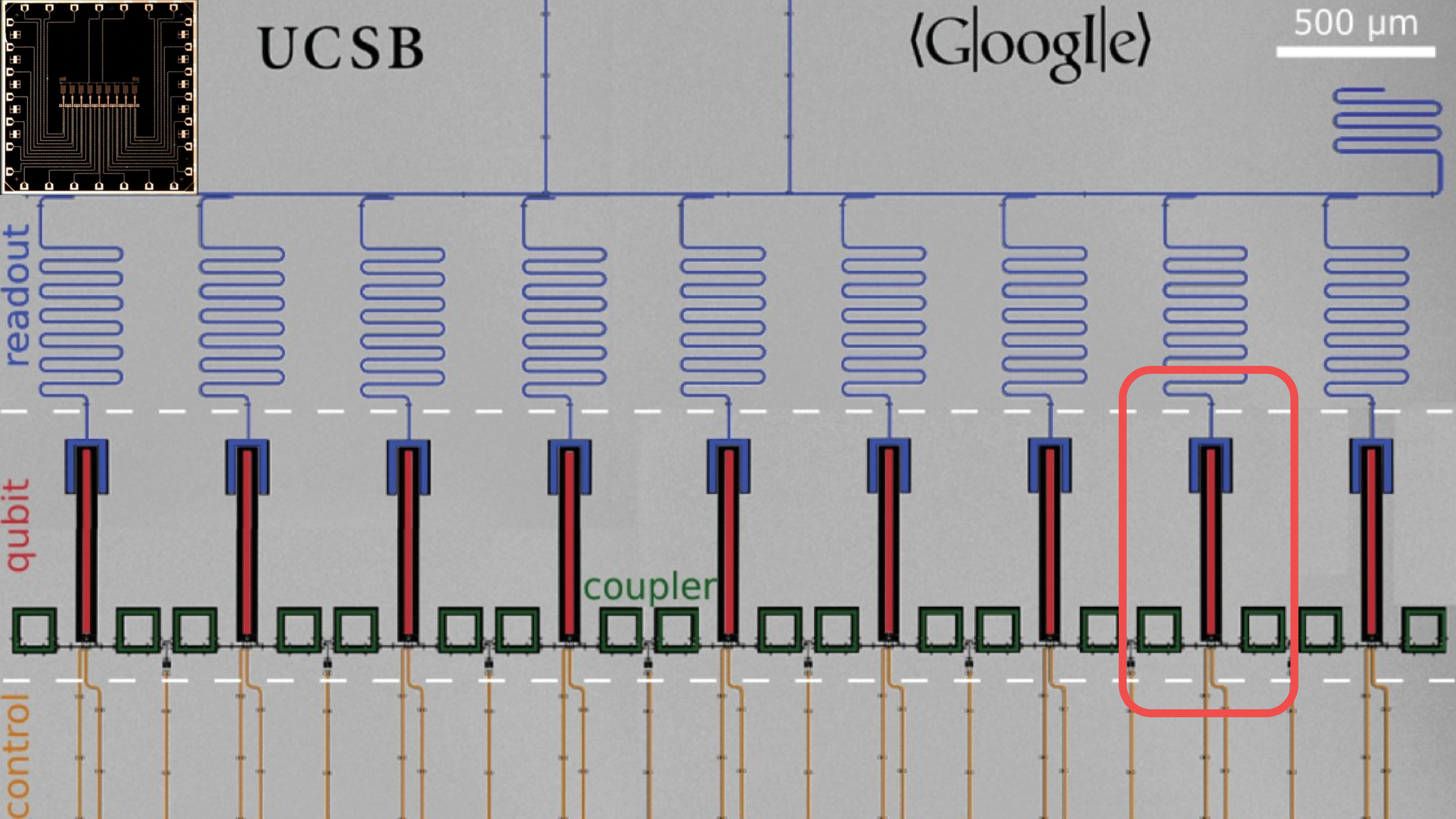
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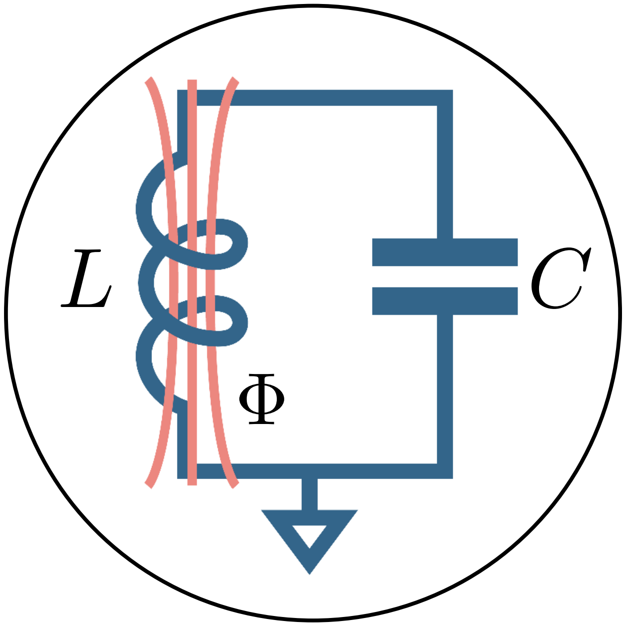
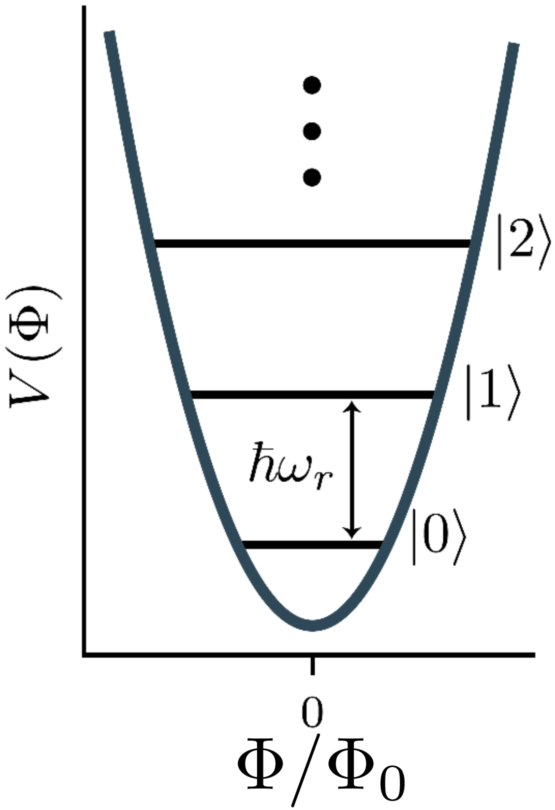
Building artificial atoms with superconductors



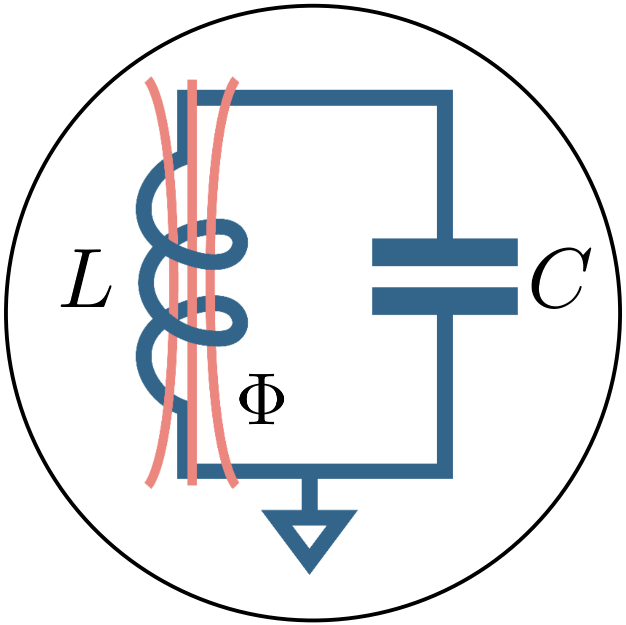


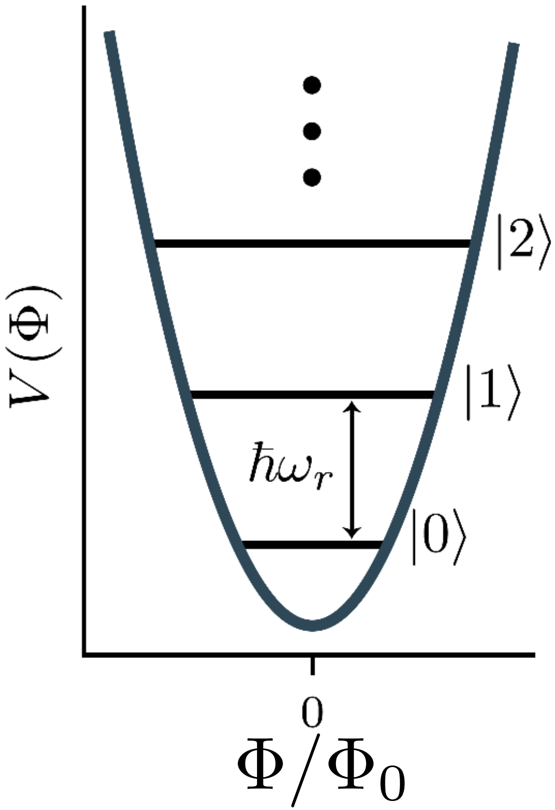
$$H_{LC} = \frac{Q^2}{2C} + \frac{1}{2}C\omega_r^2\Phi^2$$

$$\omega_r = \frac{1}{\sqrt{LC}} \qquad [\Phi, Q] = i\hbar$$

Blais, Grimsmo, Girvin and Wallraff **Rev. Mod. Phys. (2021)**

Building artificial atoms with superconductors



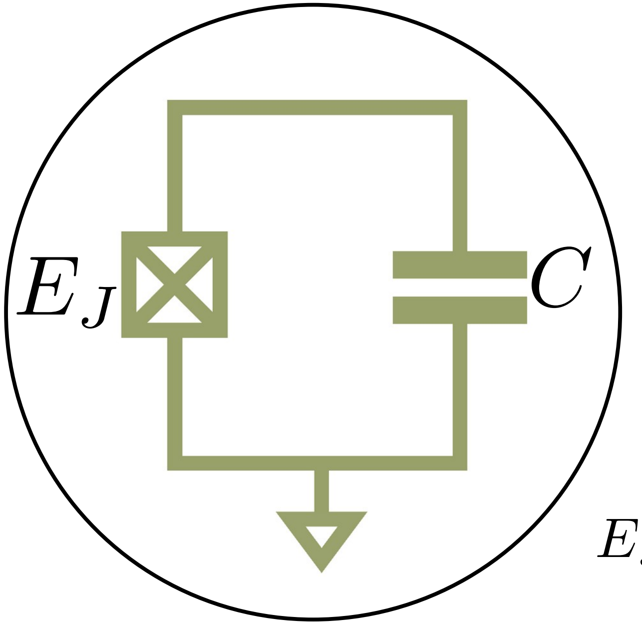


$$H_{LC} = \hbar\omega_r a^\dagger a = \hbar\omega_r n$$

$$\omega_r = \frac{1}{\sqrt{LC}} \qquad [a, a^\dagger] = 1$$

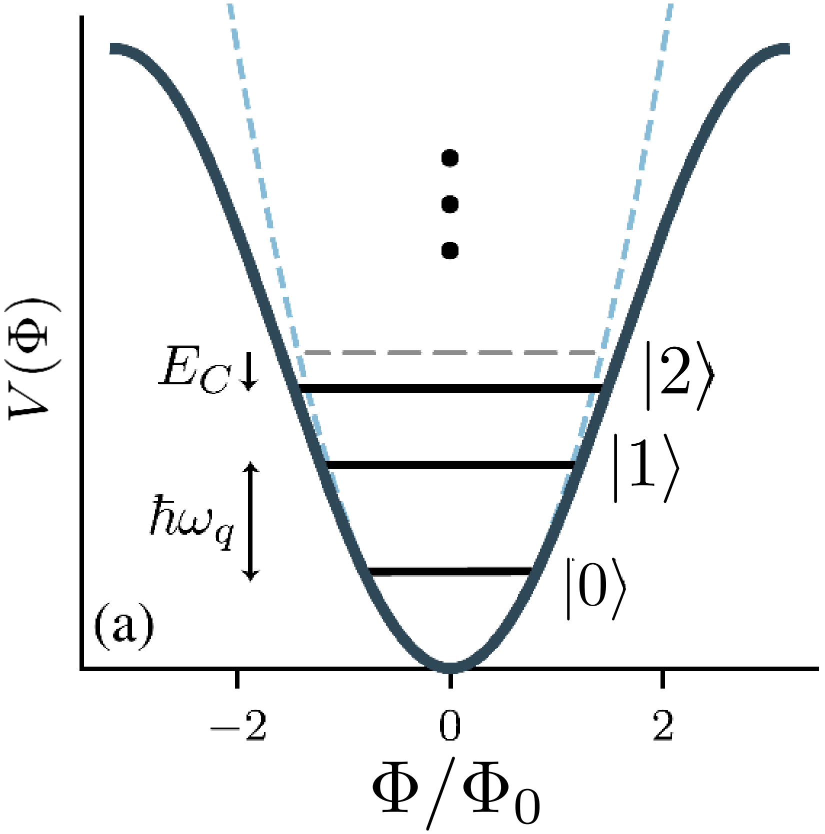
Blais, Grimsmo, Girvin and Wallraff **Rev. Mod. Phys. (2021)**

Building artificial atoms with superconductors



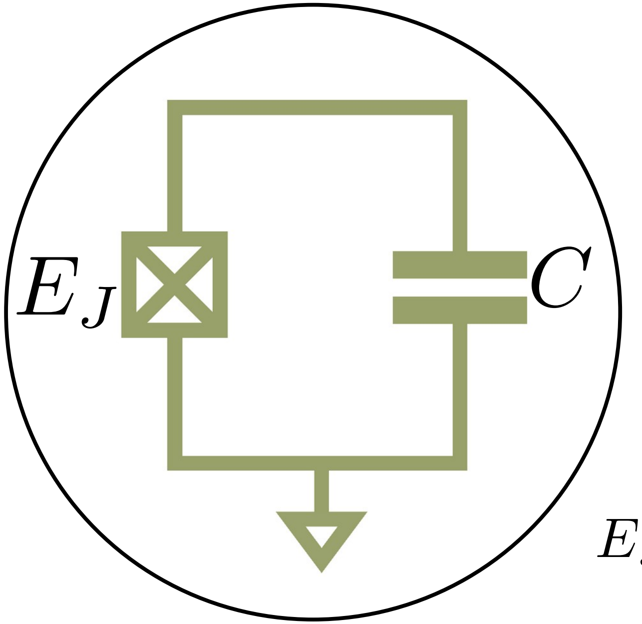
$$E_J = \frac{\Phi_0 I_c}{2\pi}$$

$$H = \frac{Q^2}{2C} - E_J \cos\left(2\pi \frac{\Phi}{\Phi_0}\right)$$



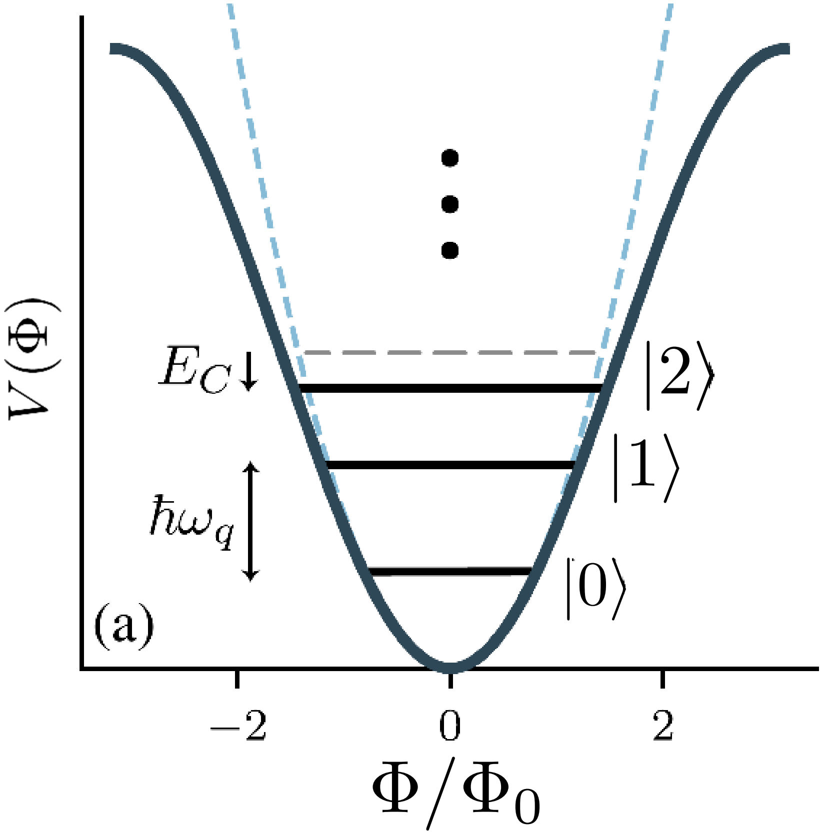
Blais, Grimsmo, Girvin and Wallraff **Rev. Mod. Phys. (2021)**

Building artificial atoms with superconductors

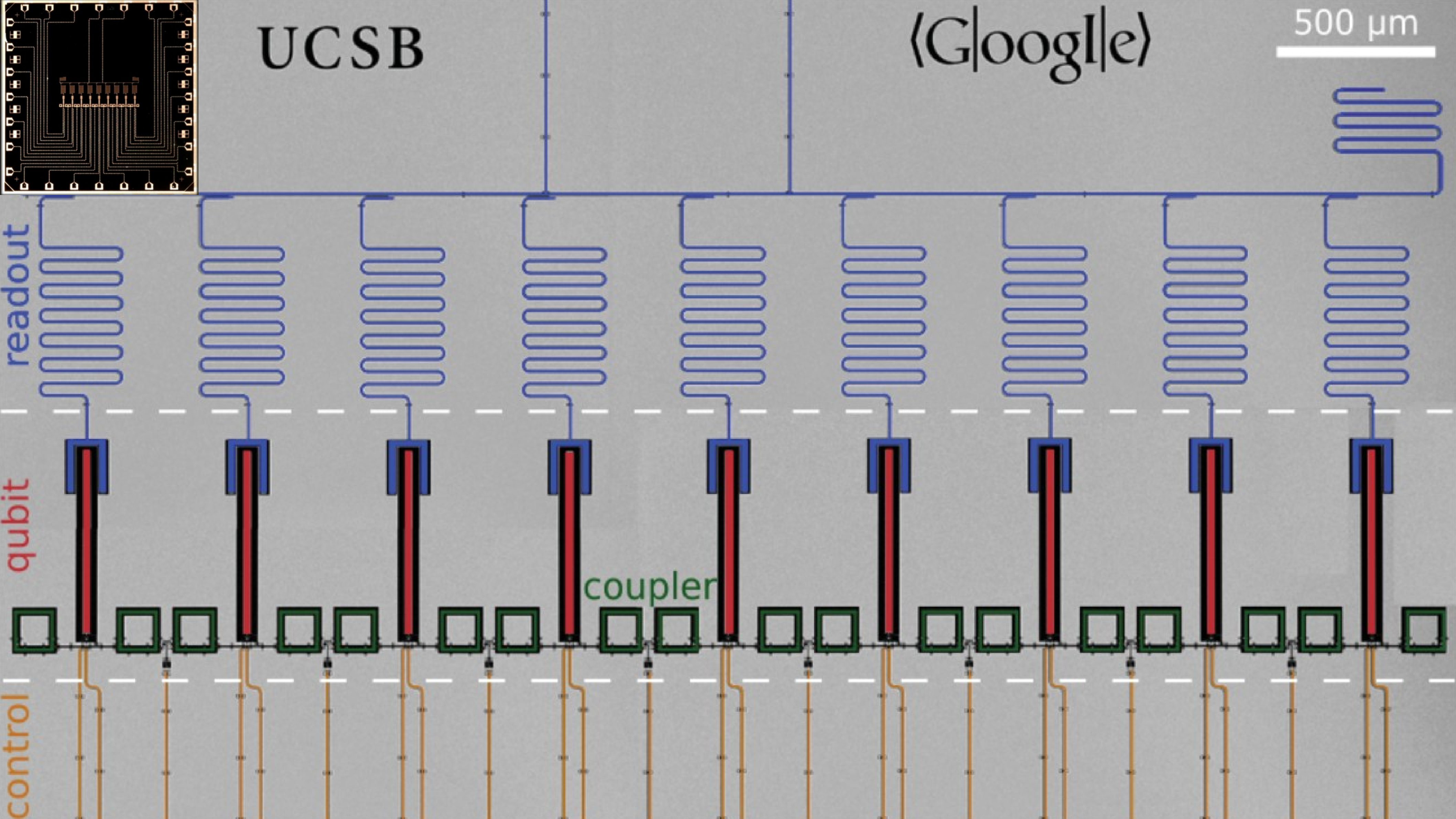


$$E_J = \frac{\Phi_0 I_c}{2\pi}$$

$$H \simeq \hbar\omega_r n + \frac{U}{2} n(n-1)$$



Blais, Grimsmo, Girvin and Wallraff **Rev. Mod. Phys. (2021)**



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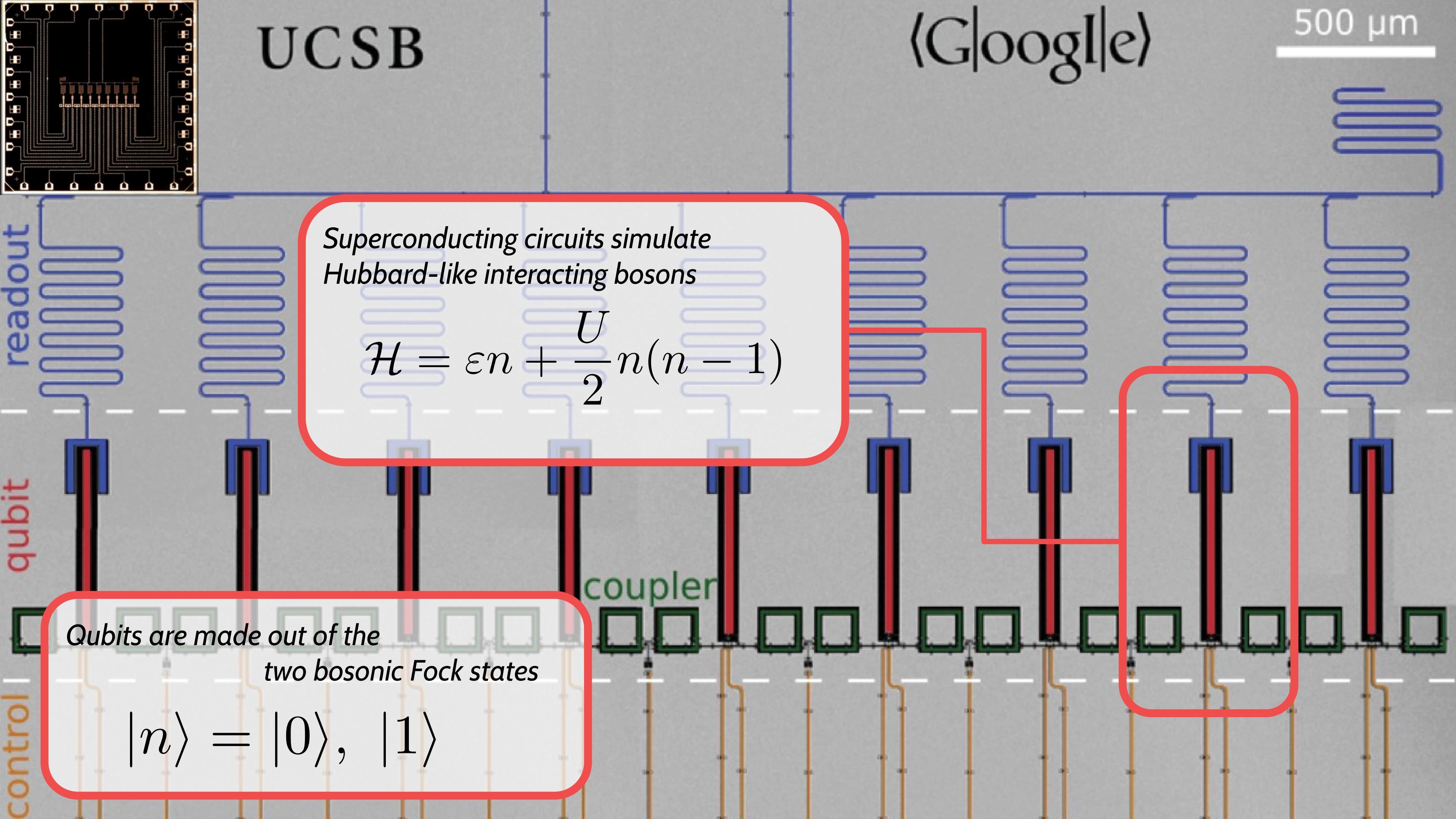


Superconducting circuits simulate Hubbard-like interacting bosons

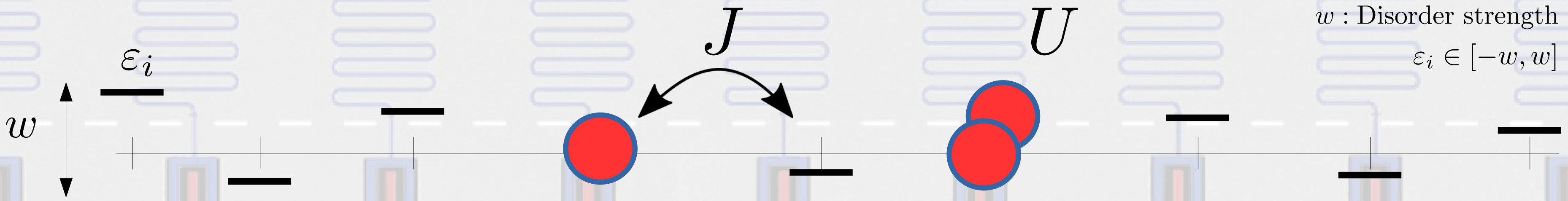
$$\mathcal{H} = \varepsilon n + \frac{U}{2} n(n-1)$$

Qubits are made out of the two bosonic Fock states

$$|n\rangle = |0\rangle,\ |1\rangle$$

Bose-Hubbard model

$$\mathcal{H}_{\mathrm{BH}} = \sum_{i}^{N_{\mathrm{Q}}} \varepsilon_i n_i + J \sum_{\langle i,j \rangle} \left(a_i^\dagger a_j + \mathrm{h.c} \right) + \frac{U}{2} \sum_{i}^{N_{\mathrm{Q}}} n_i (n_i - 1)$$



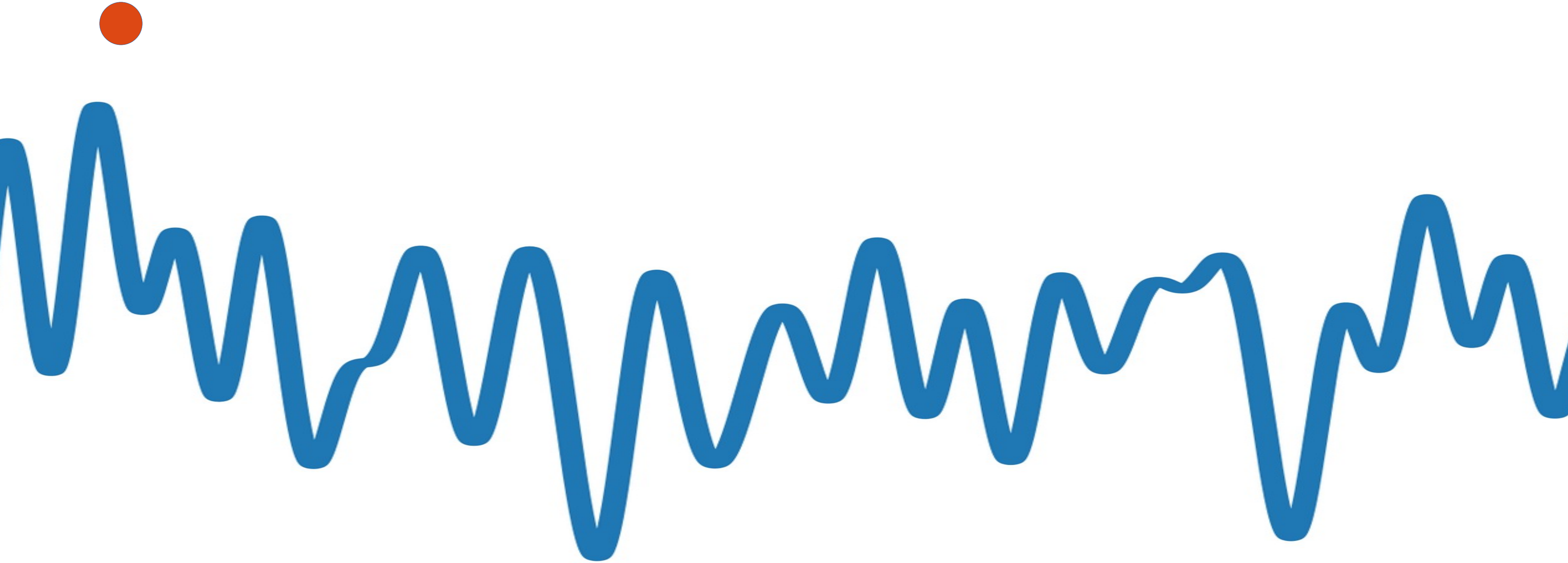
Quantum evolution of controlled initial states

$$|\Psi_0\rangle = |1\rangle \otimes |0\rangle \otimes |1\rangle \otimes |0\rangle \otimes \dots$$

$$|\Psi_0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes |0\rangle \otimes |1\rangle \otimes |0\rangle \otimes \dots$$

Absence of Diffusion in Certain Random Lattices

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)



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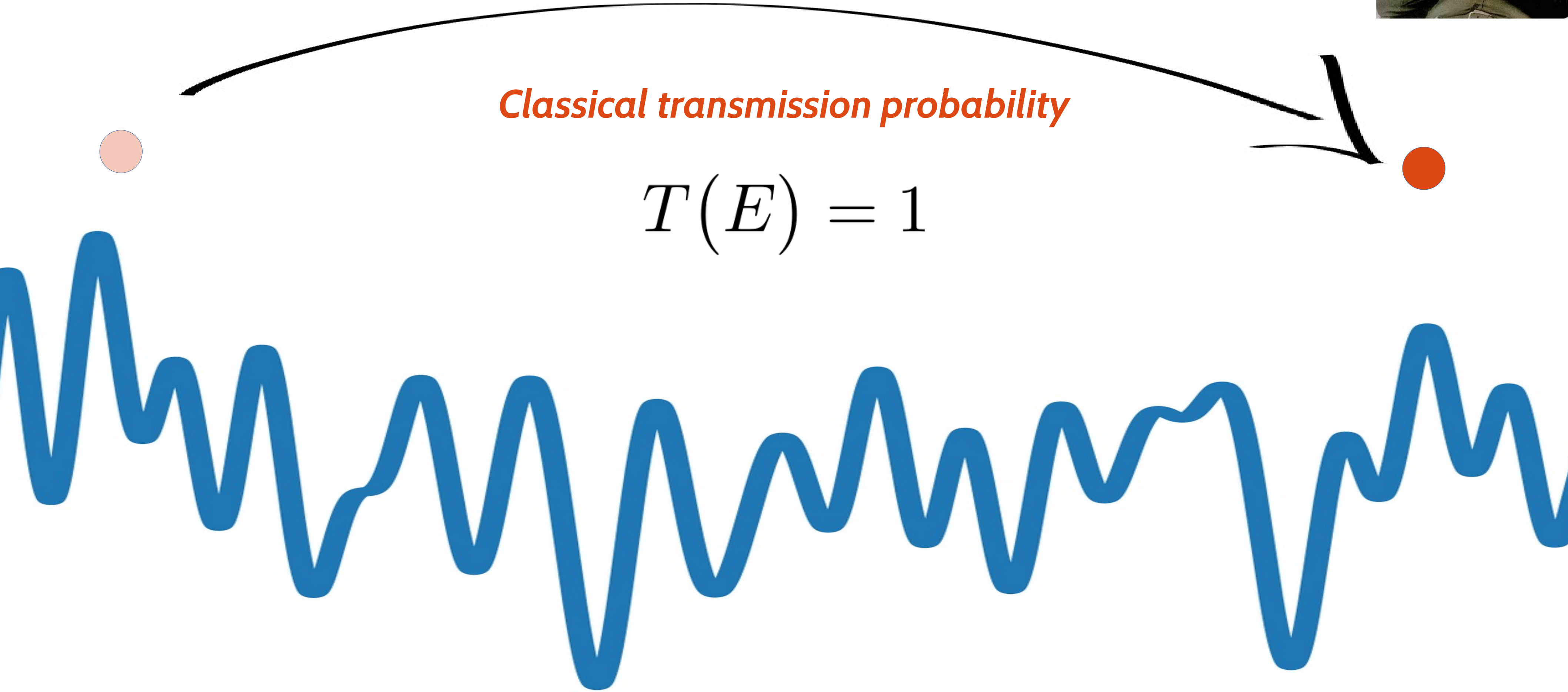

$$T(E) = 1$$

Absence of Diffusion in Certain Random Lattices

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Bell Telephone Laboratories, Murray Hill, New Jersey
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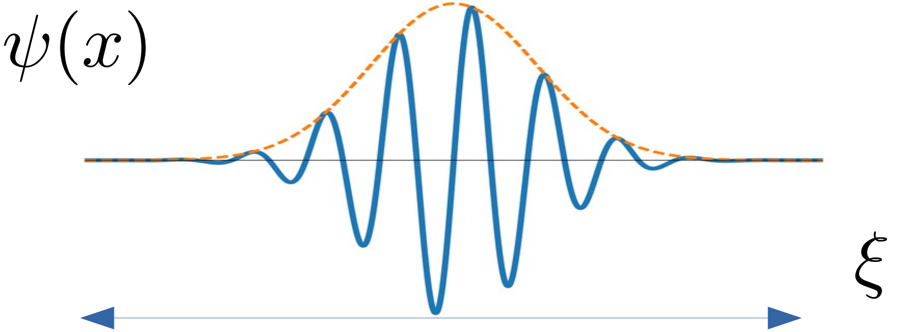
Quantum interference leads to particle localization



$$T(E) = 0$$

Is localization stable in the presence of interactions?

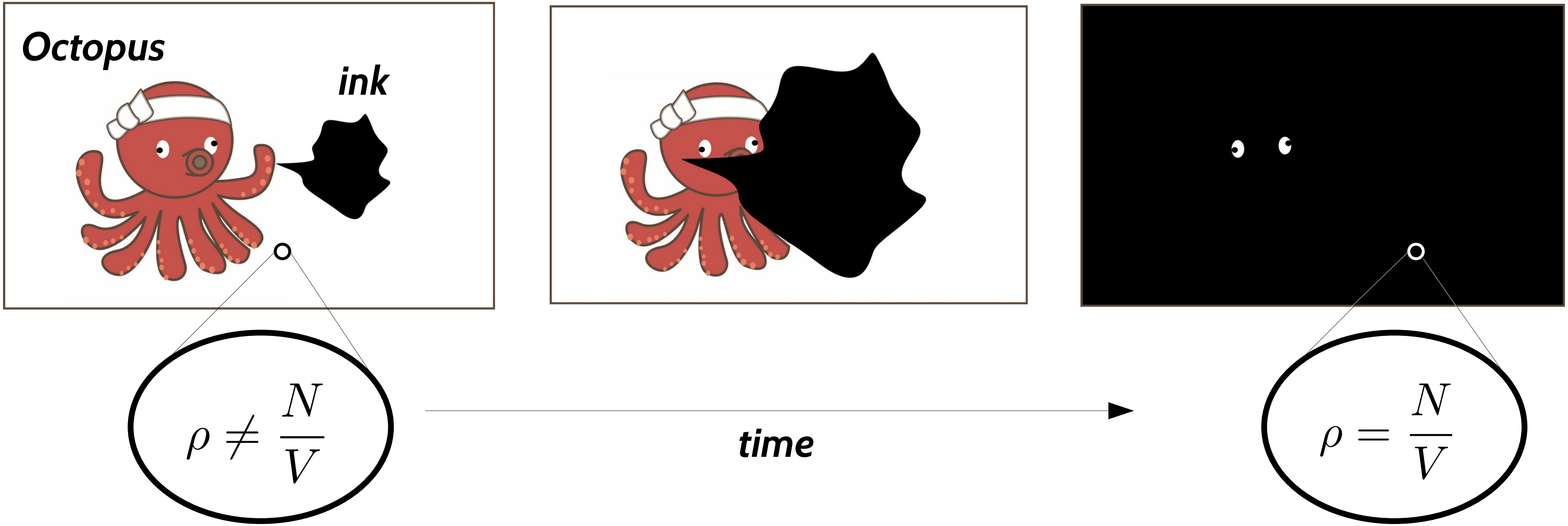
Giamarchi, Schulz (1988)
Basko, Aleiner, Altshuler, Annals of Physics (2006)
Pal, Huse, PRB (2010)

Diffusion in interacting systems

"Interacting systems explore all (micro) states allowed by energy conservation, they forget about their initial conditions and thermalize"

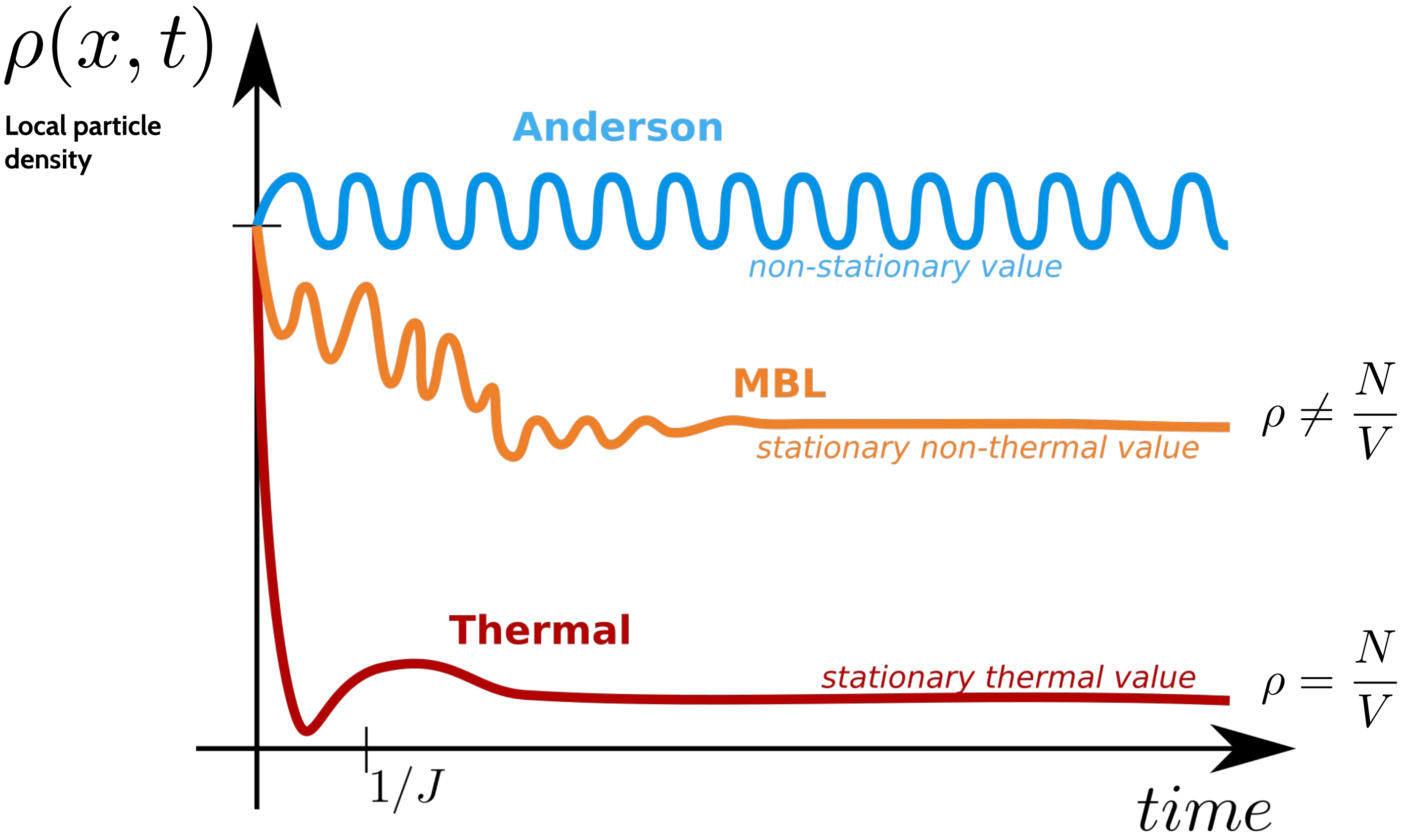
Ludwig E. Boltzmann

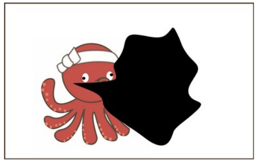
Octopus in a box (Diffusion)

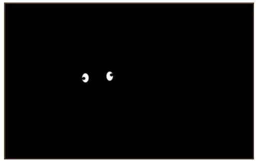


Many-Body Localization (MBL)

MBL systems relax towards "non-thermal" states and keep memory about the initial state

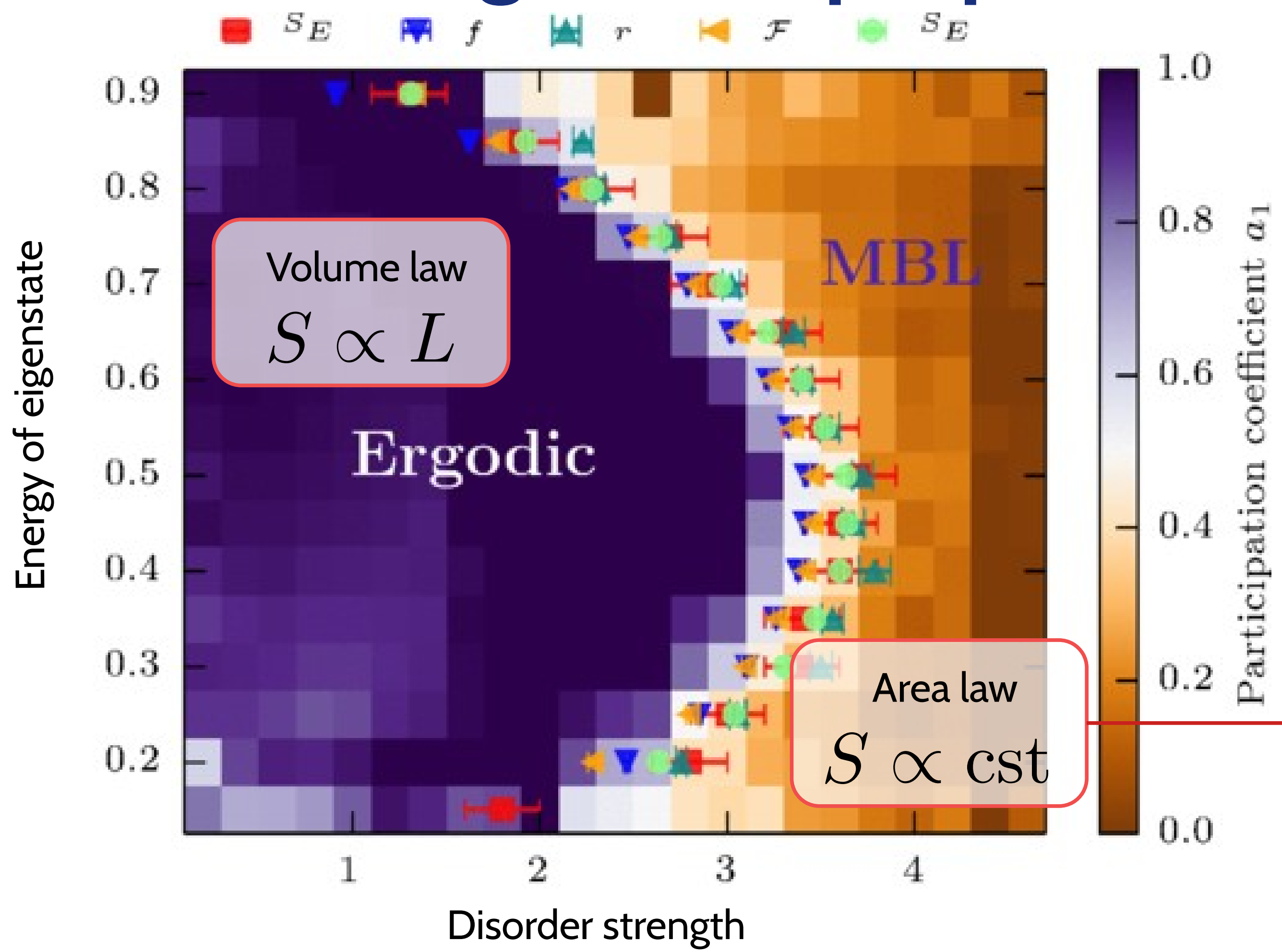


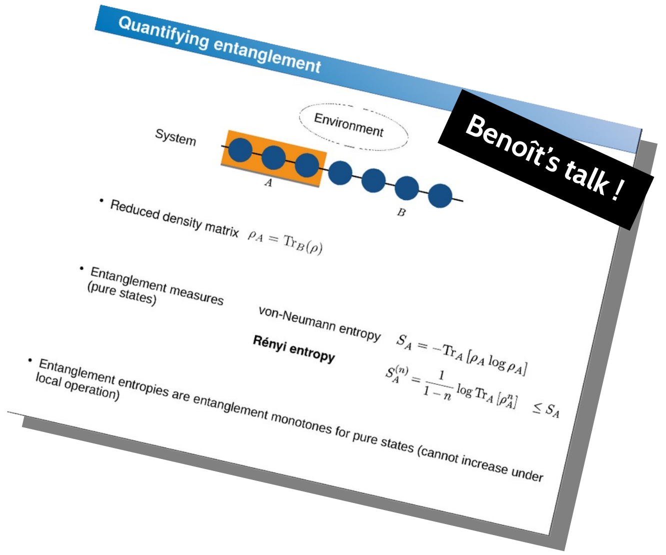




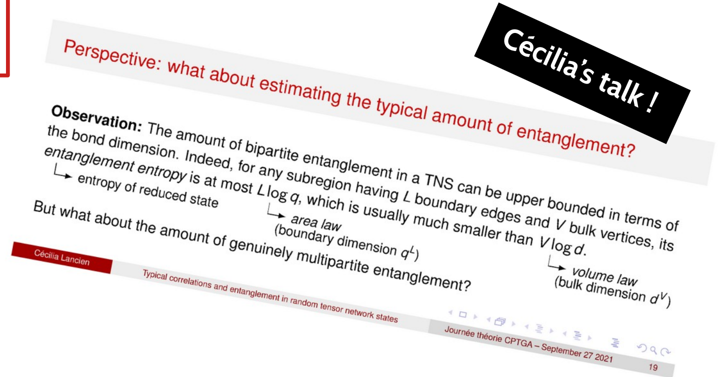
M. Serbyn, Z. Papic and D. Abanin **PRB** (2014)

Exotic entanglement properties



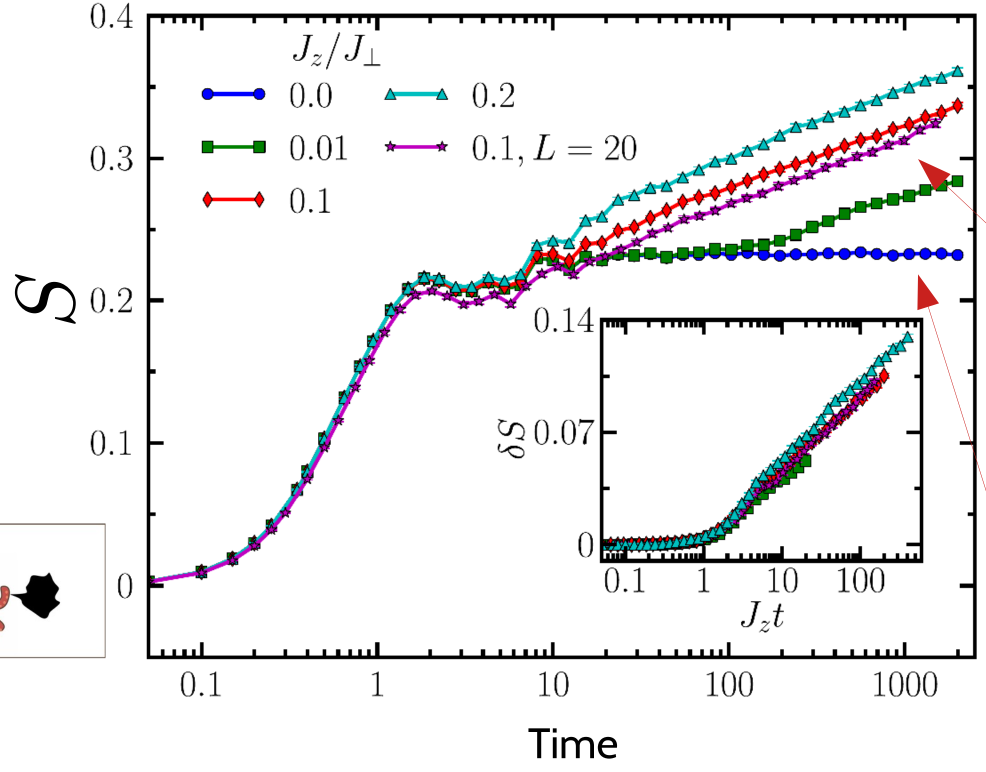


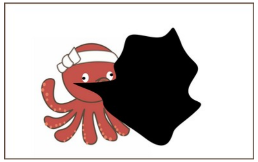
The many-body eigenstates are well described by Matrix Product States (MPS)

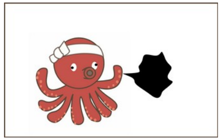


Luitz, Laflorencie, Alet **PRB (2015)**

Exotic entanglement properties







Logarithmic entanglement growth

$$S \propto \ln(t)$$

Anderson Insulator

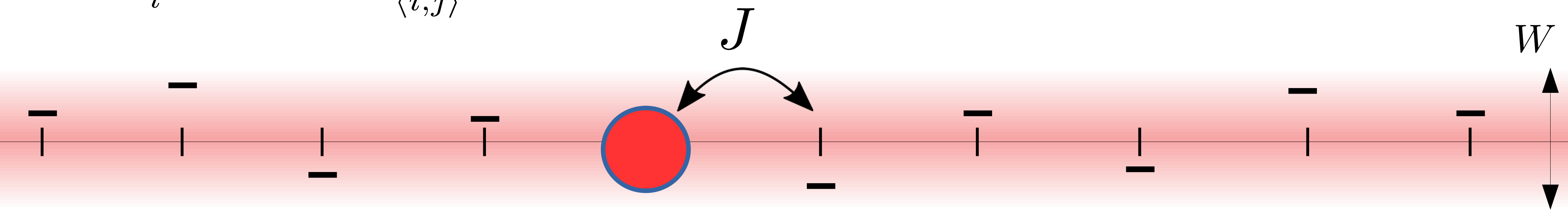
Bardarson, Pollmann, Moore **PRB (2012)**

Emergent integrability : Local Integrals of Motion

$$H = \sum_i \varepsilon_i a_i^\dagger a_i + J \sum_{\langle i,j \rangle} \left(a_i^\dagger a_j + \mathrm{h.c} \right)$$

W : Disorder strength

$\varepsilon_i \in [-W, W]$



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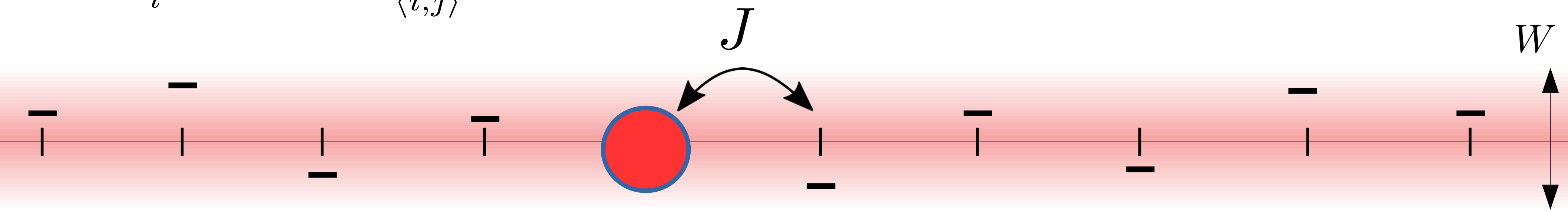
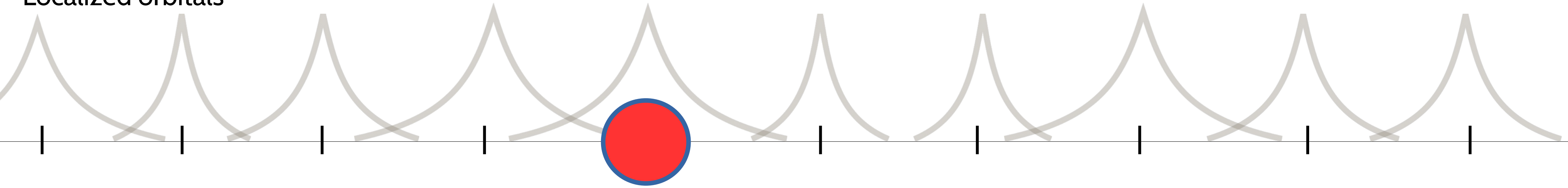


Anderson localization

$$H = \sum_i \tilde{\epsilon}_i \tilde{n}_i$$

Localized orbitals



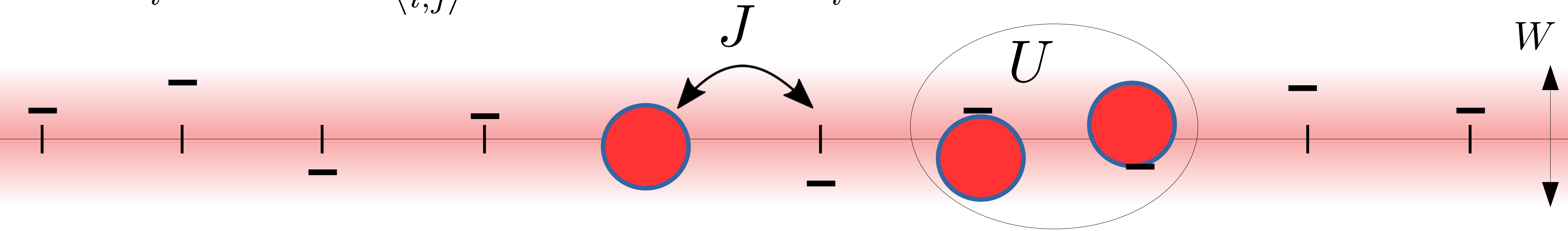
M. Serbyn, Z. Papic and D. Abanin **PRL** (2013)

Emergent integrability : Local Integrals of Motion

$$H = \sum_i \varepsilon_i a_i^\dagger a_i + J \sum_{\langle i,j \rangle} \left(a_i^\dagger a_j + \text{h.c} \right) + U \sum_i a_i^\dagger a_i a_{i+1}^\dagger a_{i+1}$$

W : Disorder strength

$\varepsilon_i \in [-W, W]$

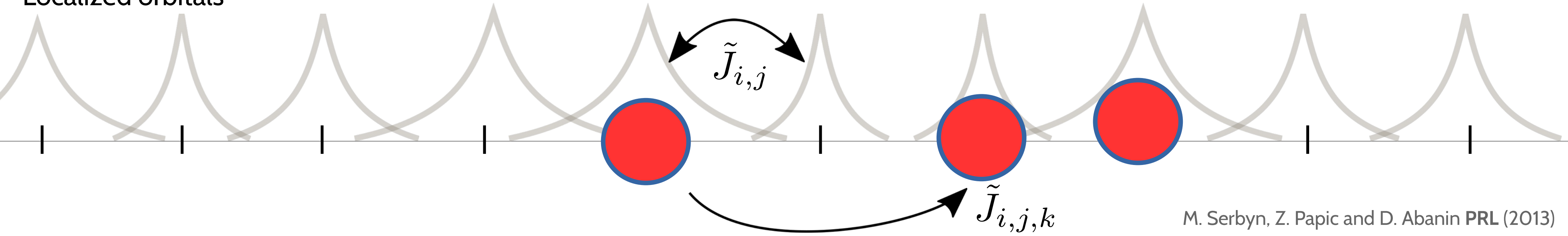


$$H = \underbrace{\sum_i \tilde{\epsilon}_i \tilde{n}_i}_{\text{Anderson localization}} + \underbrace{\sum_{i,j} \tilde{J}_{i,j} \tilde{n}_i \tilde{n}_j + \sum_{i,j,k} \tilde{J}_{i,j,k} \tilde{n}_i \tilde{n}_j \tilde{n}_k + \dots}_{\text{Non-local interactions}}$$

$\tilde{n}_i$: Local Integral of Motion

$[\tilde{n}_i, H] = 0 \quad \text{(LIOM)}$

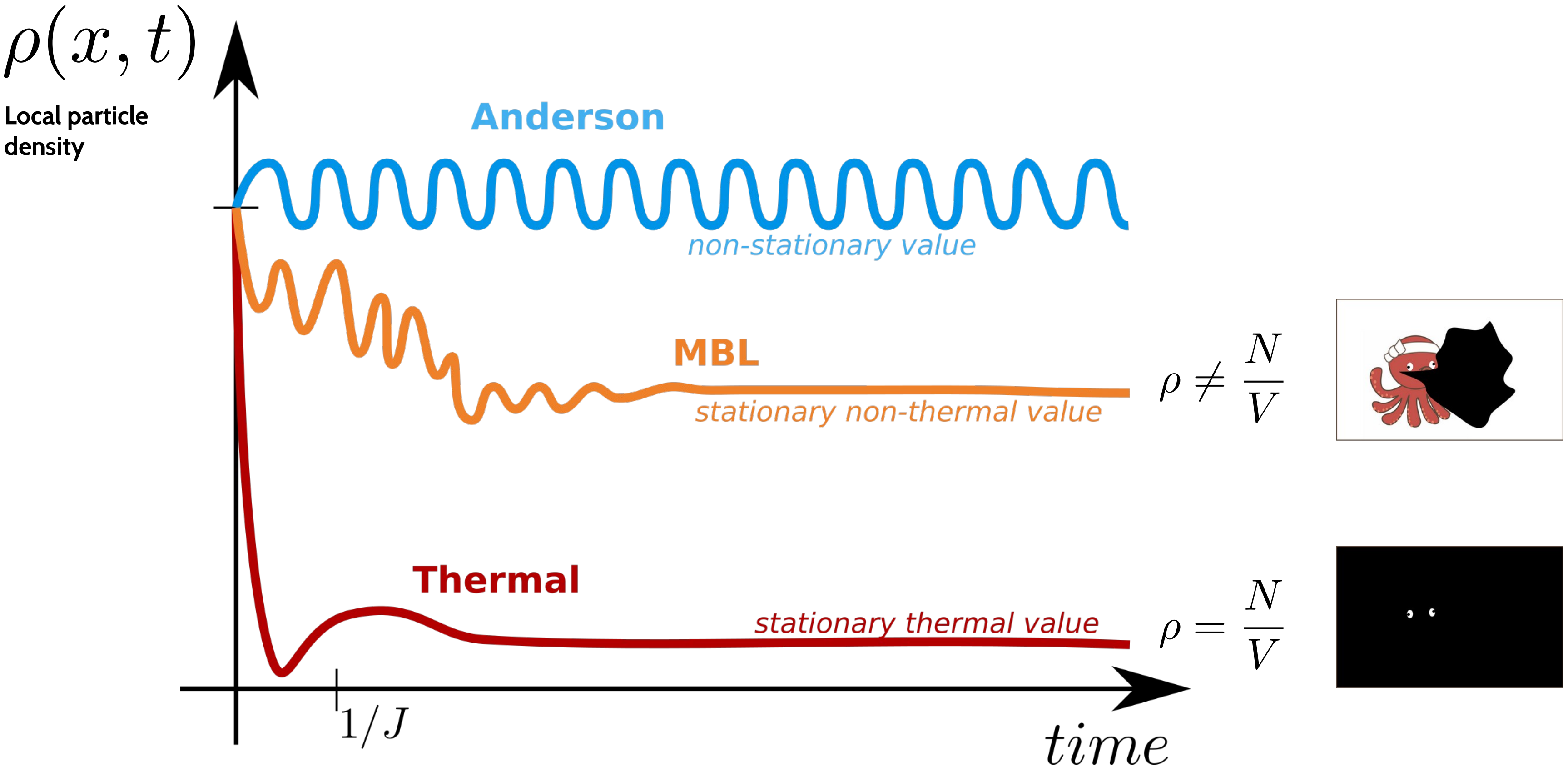
Localized orbitals



M. Serbyn, Z. Papic and D. Abanin **PRL** (2013)

Many-Body Localization (MBL)

MBL systems relax towards "non-thermal" states and keep memory about the initial state

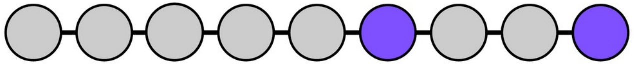


M. Serbyn, Z. Papic and D. Abanin **PRB** (2014)

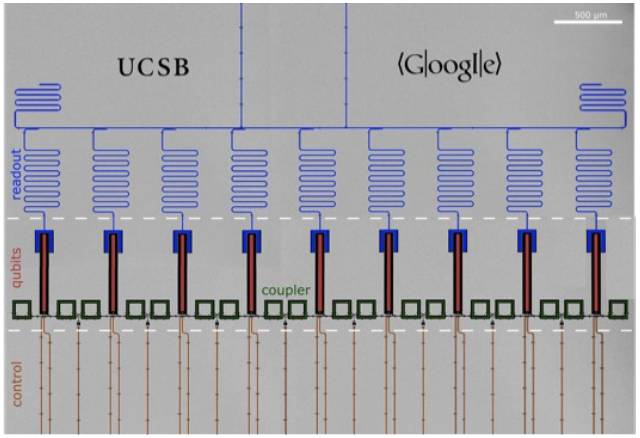
Boson transport : Diffusion vs Localization

Initial state

$$|\Psi_0\rangle = |0\rangle \otimes |0\rangle \otimes |0\rangle \otimes |0\rangle \otimes |0\rangle \otimes |1\rangle \otimes |0\rangle \otimes |0\rangle \otimes |1\rangle$$



Measure density here



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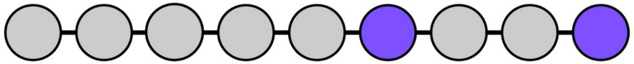
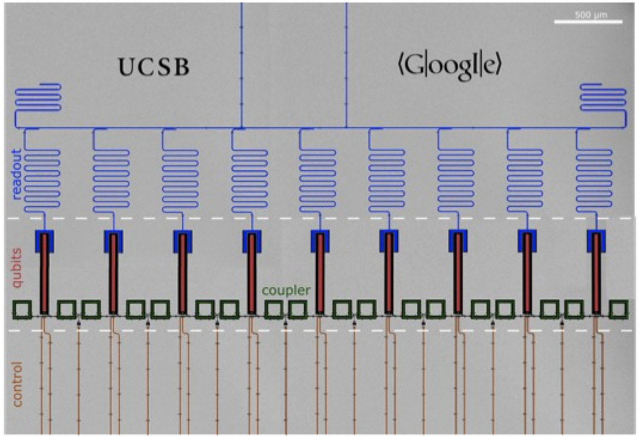
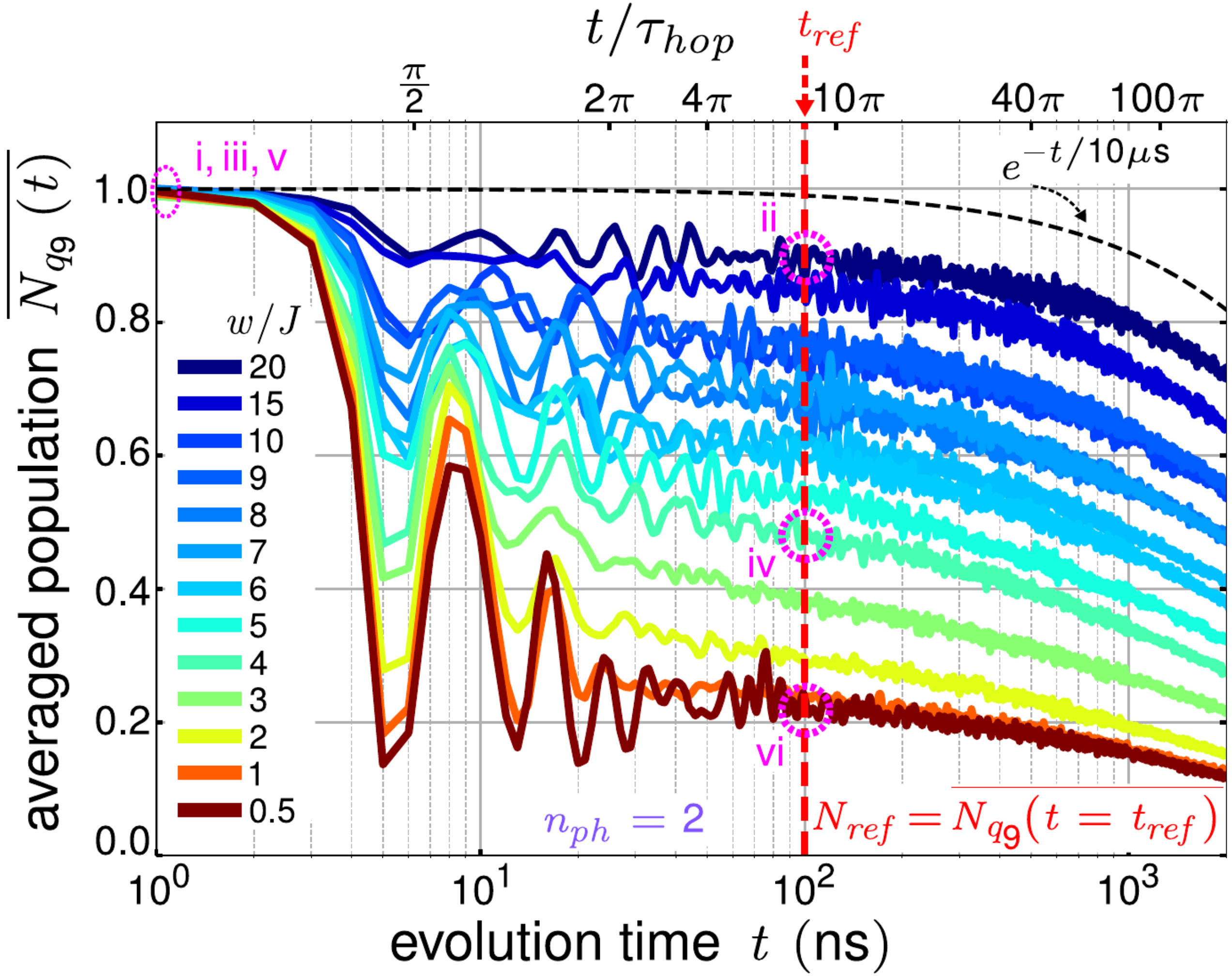


Measure density here

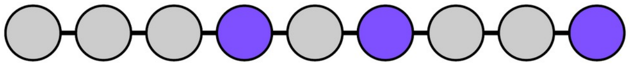


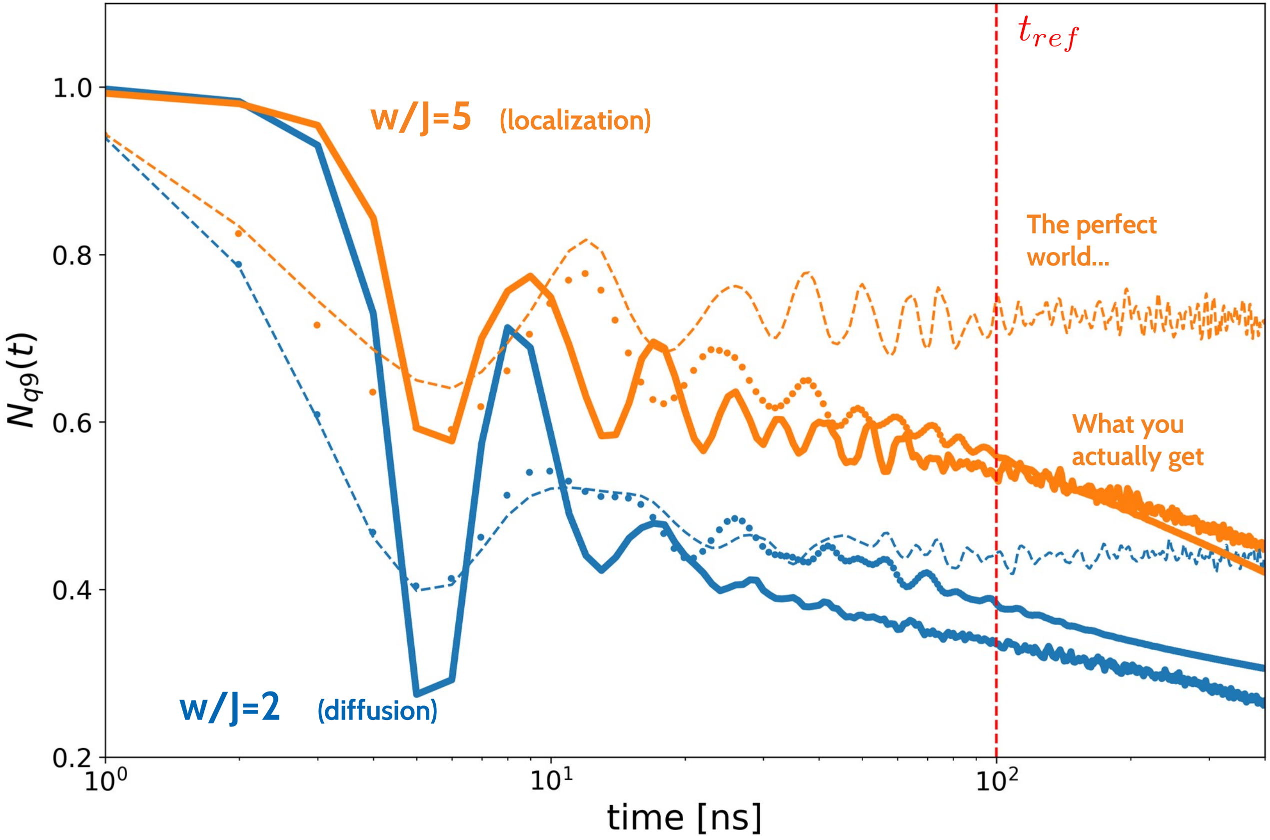


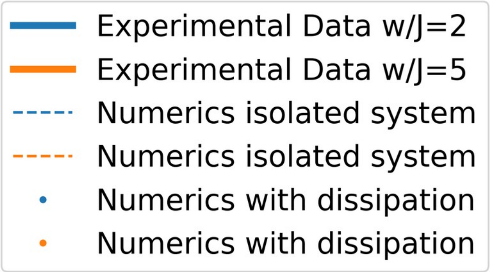
The presence of dephasing and losses

Initial state

$$|\Psi_0\rangle = |0\rangle \otimes |0\rangle \otimes |0\rangle \otimes |1\rangle \otimes |0\rangle \otimes |1\rangle \otimes |0\rangle \otimes |0\rangle \otimes |1\rangle$$

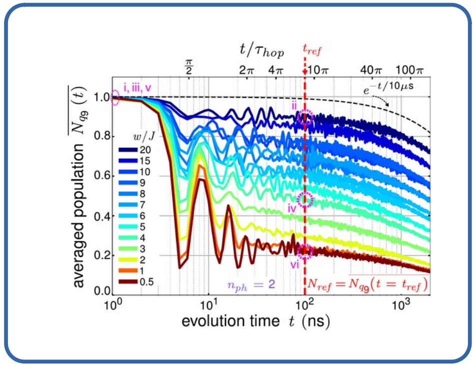


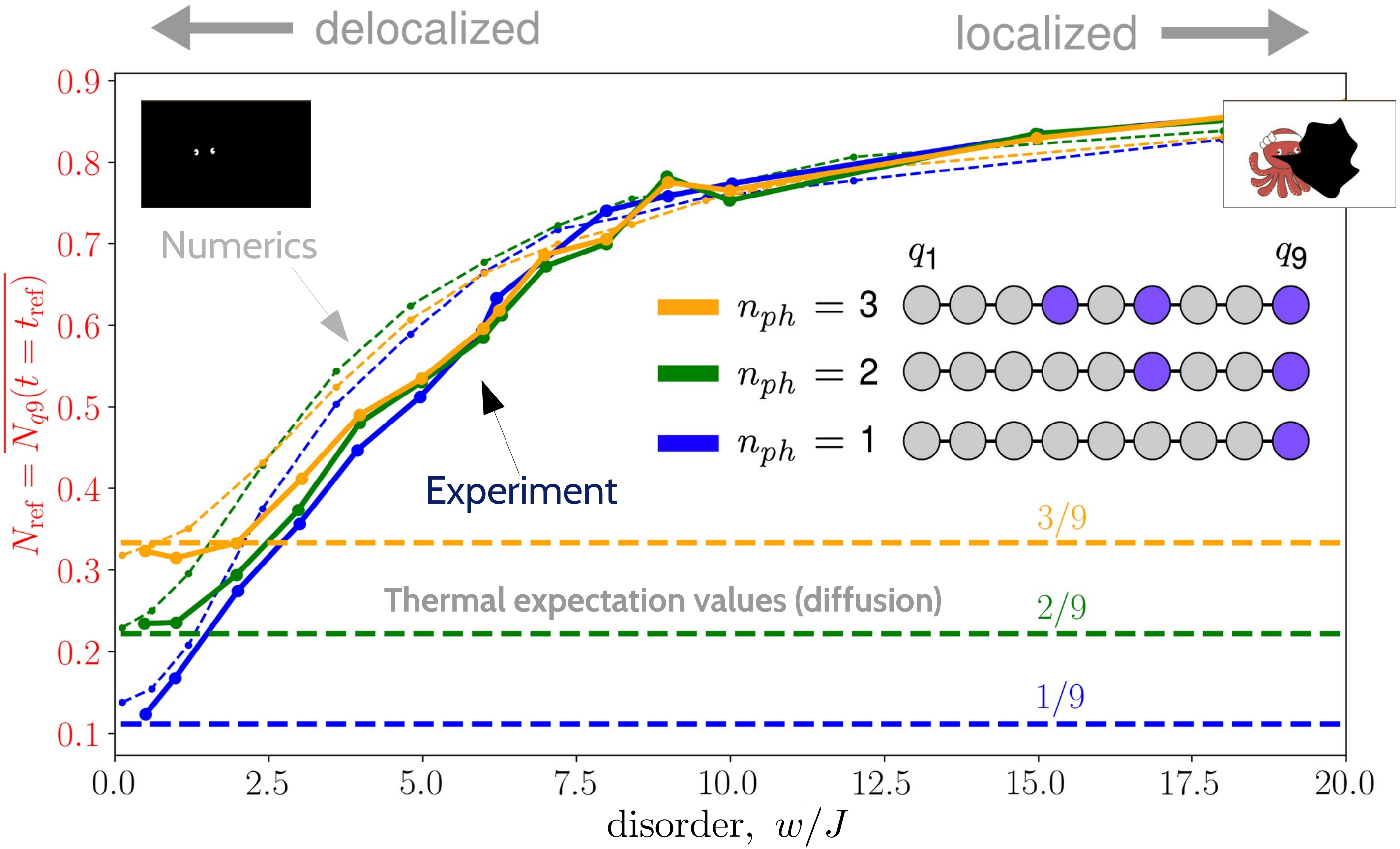




$$T_2 \sim 10\mu s$$

Localization





Slow dynamics in 2D

Sycamore circuit

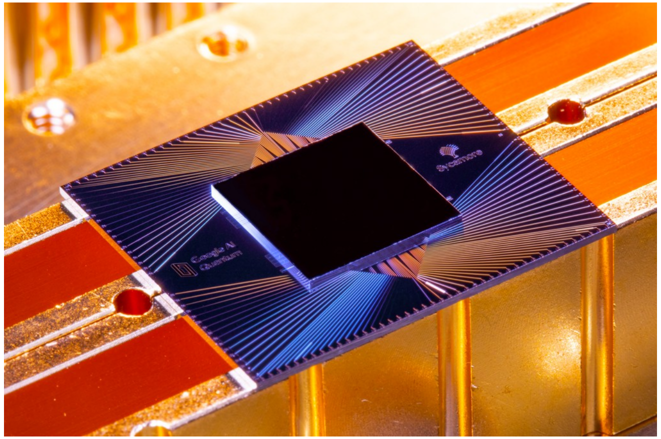
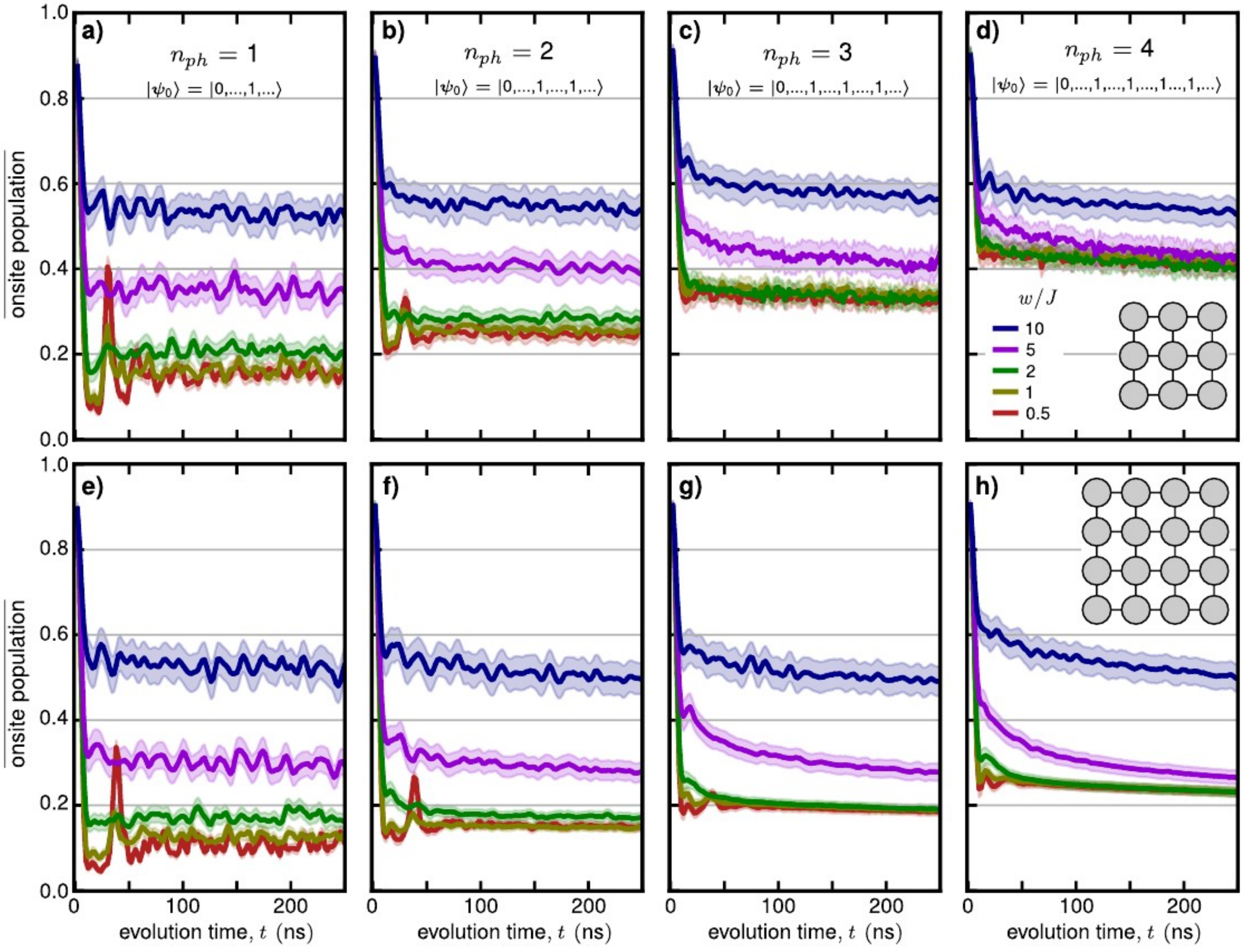


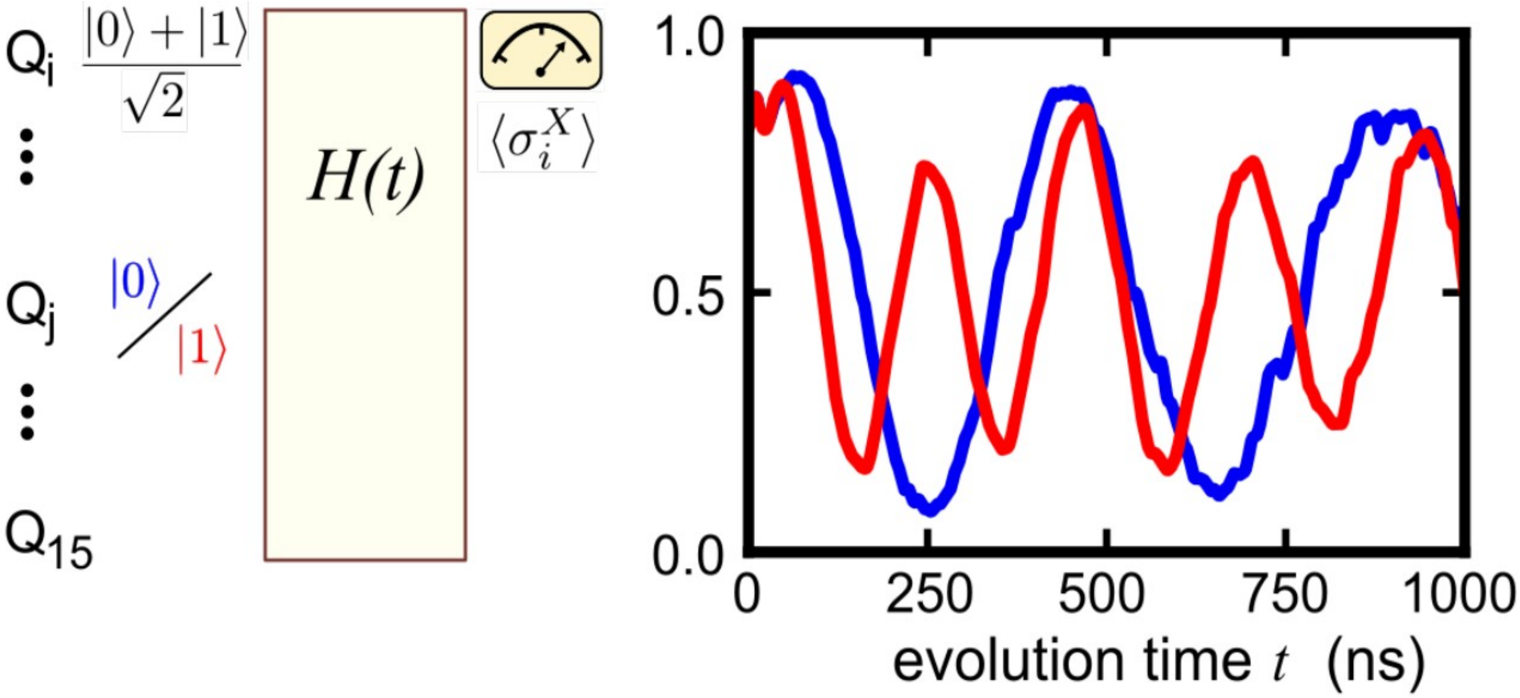
Photo credit: Eric Lucero

Arute, F. et al. "Quantum supremacy using a programmable superconducting processor", Nature (2019)



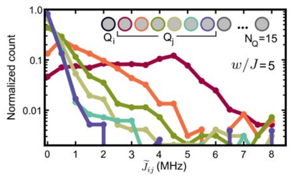
Direct measurement of LIOMs

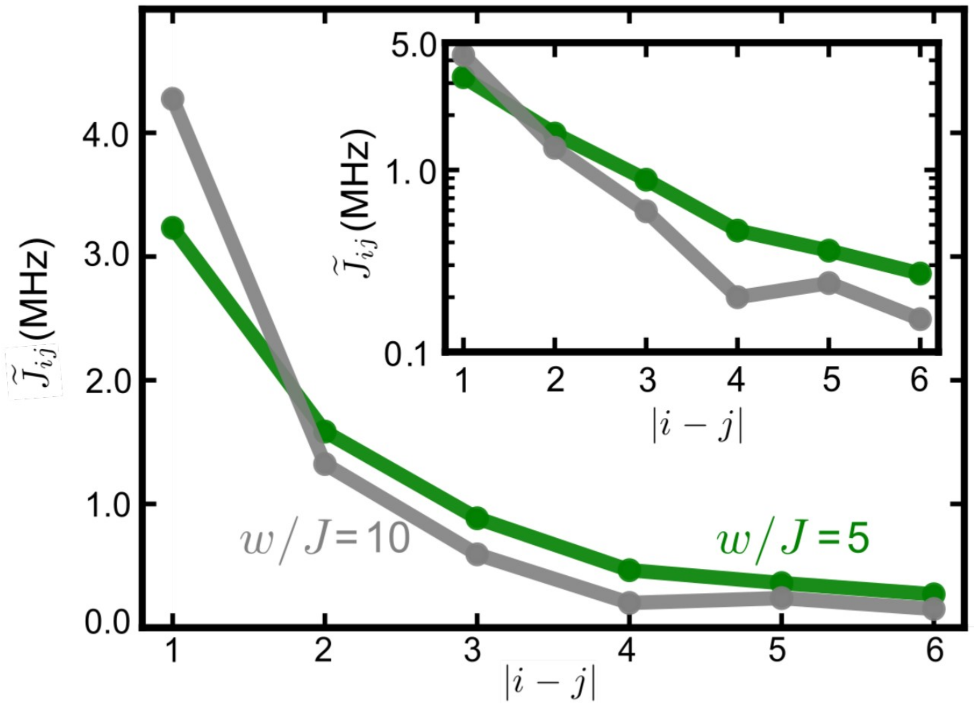
$$H = \sum_i \tilde{\epsilon}_i \tilde{n}_i + \sum_{i,j} \tilde{J}_{i,j} \tilde{n}_i \tilde{n}_j + \sum_{i,j,k} \tilde{J}_{i,j,k} \tilde{n}_i \tilde{n}_j \tilde{n}_k + \dots$$



Exponential decay with distance

$$H = \sum_i \tilde{\epsilon}_i \tilde{n}_i + \sum_{i,j} \tilde{J}_{i,j} \tilde{n}_i \tilde{n}_j + \sum_{i,j,k} \tilde{J}_{i,j,k} \tilde{n}_i \tilde{n}_j \tilde{n}_k + \ldots$$





Growth and preservation of entanglement

Sycamore circuit

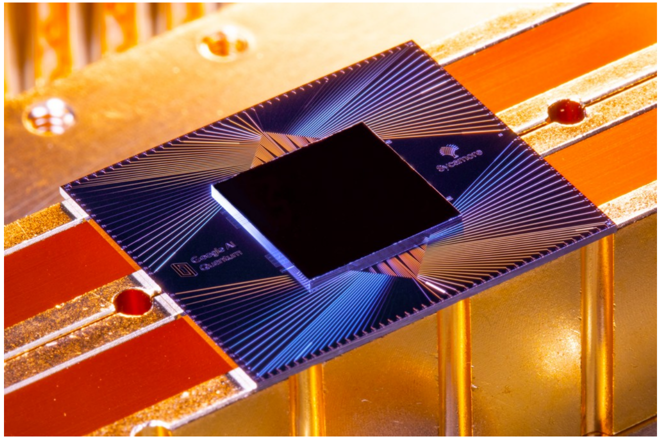
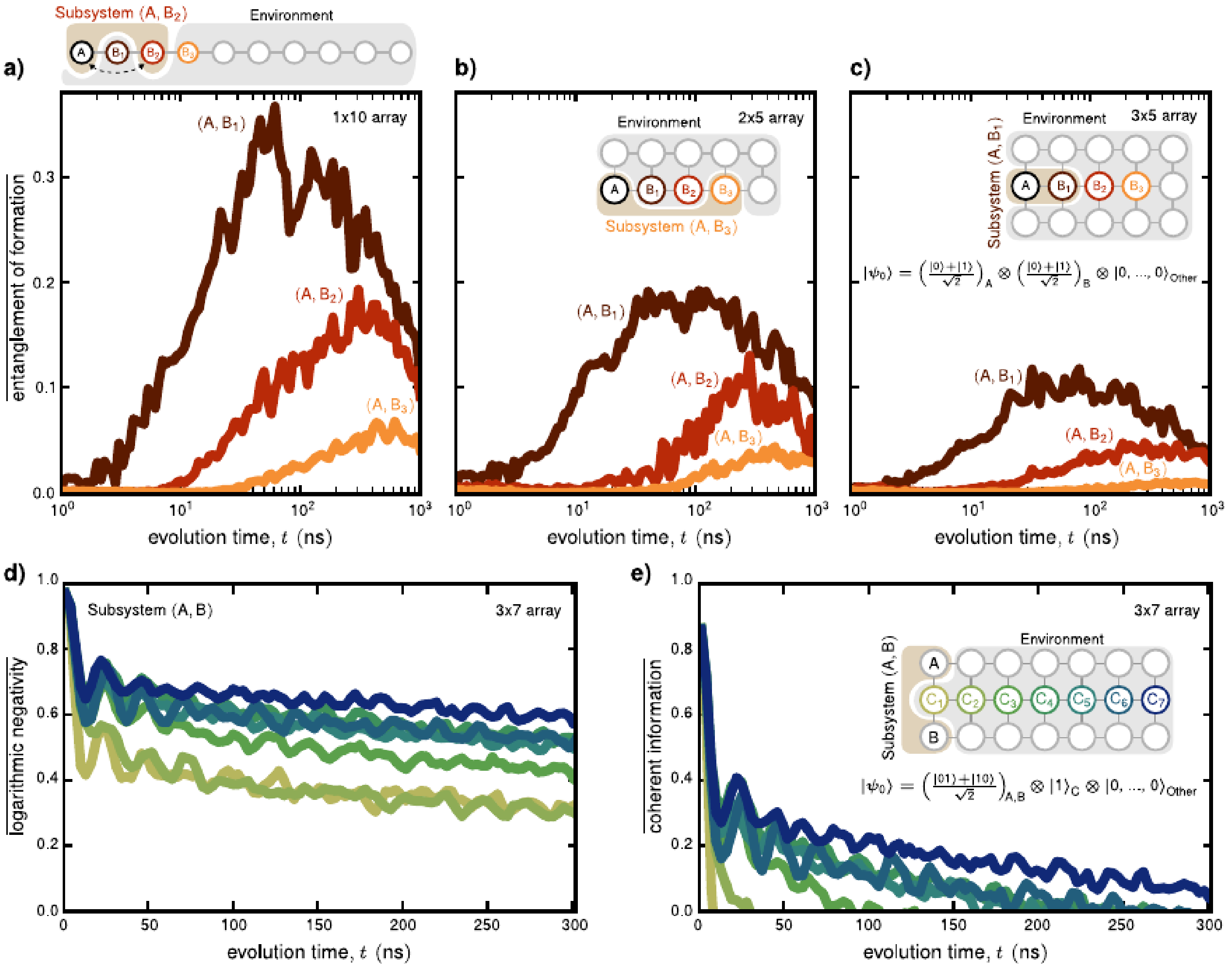


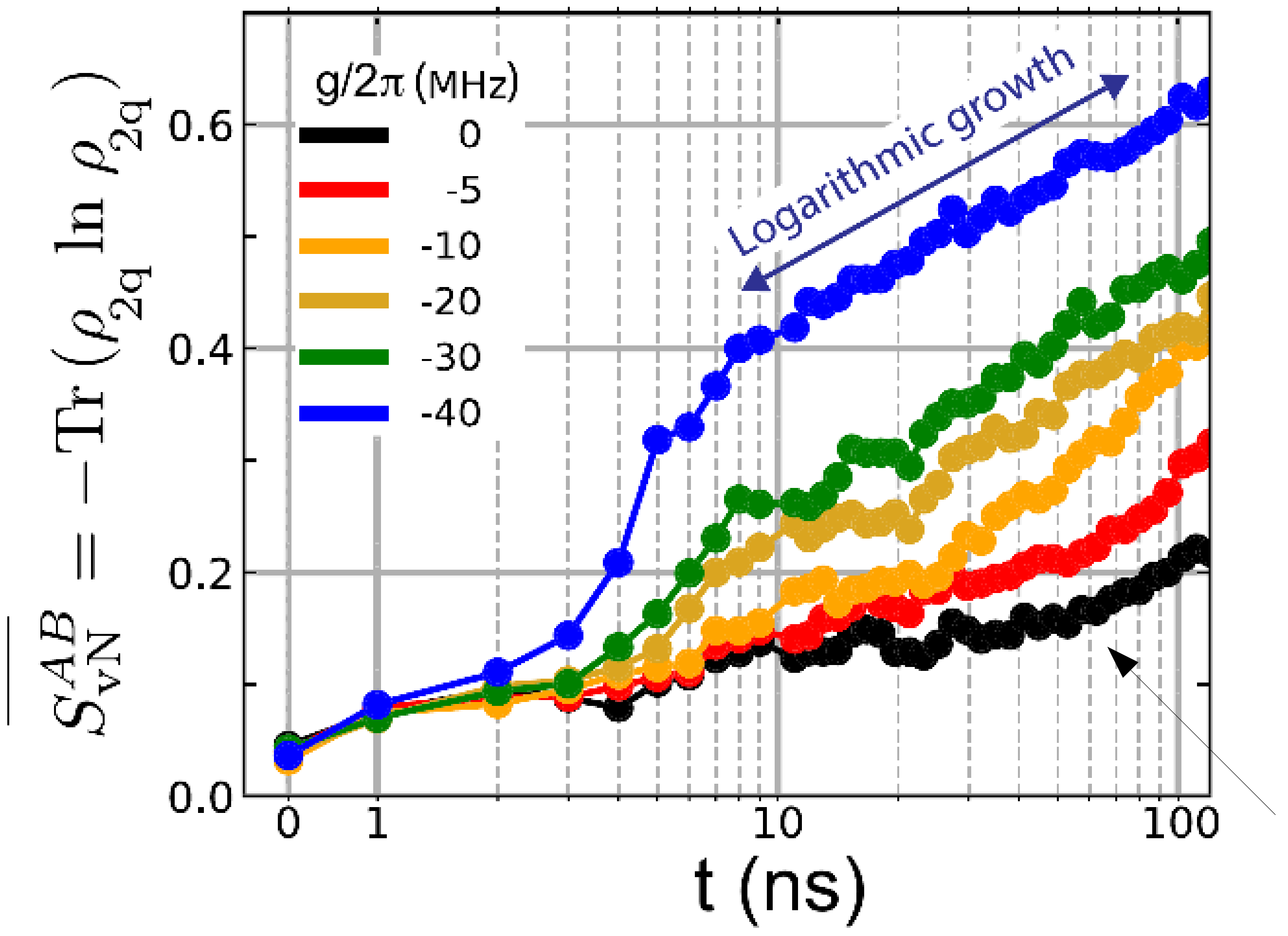
Photo credit: Eric Lucero

Arute, F. et al. "Quantum supremacy using a programmable superconducting processor", Nature (2019)



w/J = 10

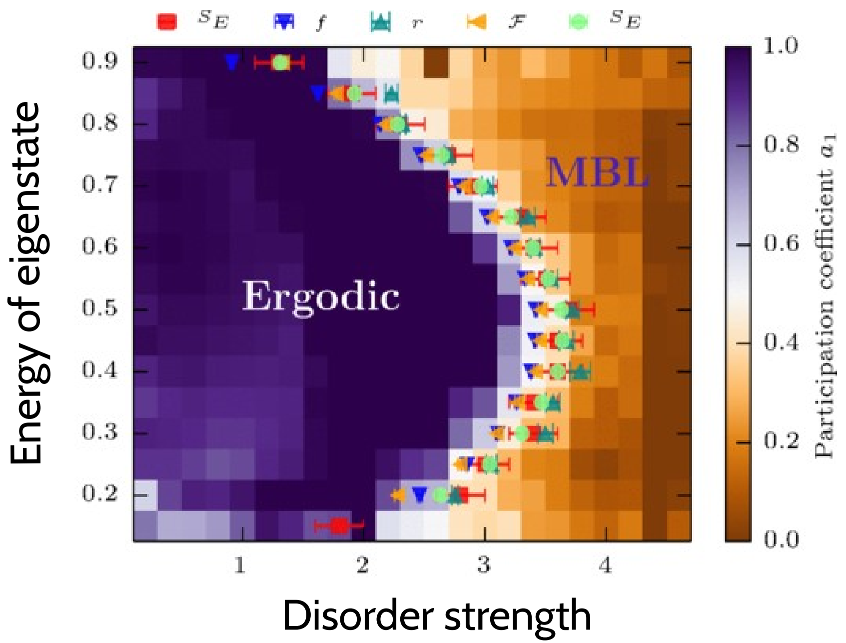
Watch out the entanglement entropy !

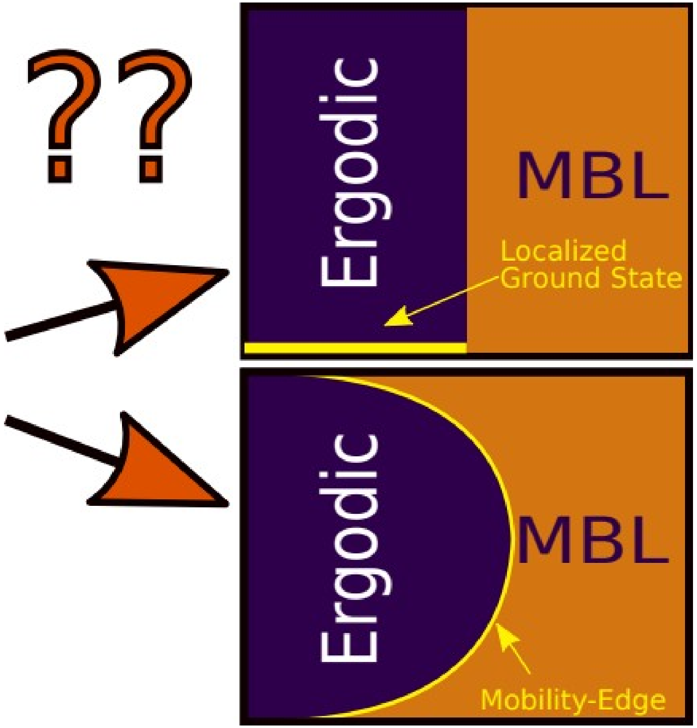


!!!!!!

Open questions about MBL

Ergodic-to-localized transition and mobility edge





Luitz, Laflorencie, Alet **PRB (2015)**

De Roeck, Huveneers, Müller, Schiulaz **PRB (2016)**

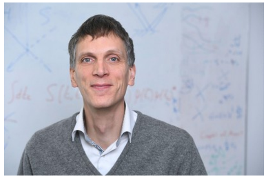
Nucleation of ergodicity by a single impurity in supercooled insulators

Ulrich Krause

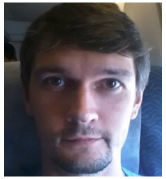
Théo Pellegrin

I asked him the photo too late :(

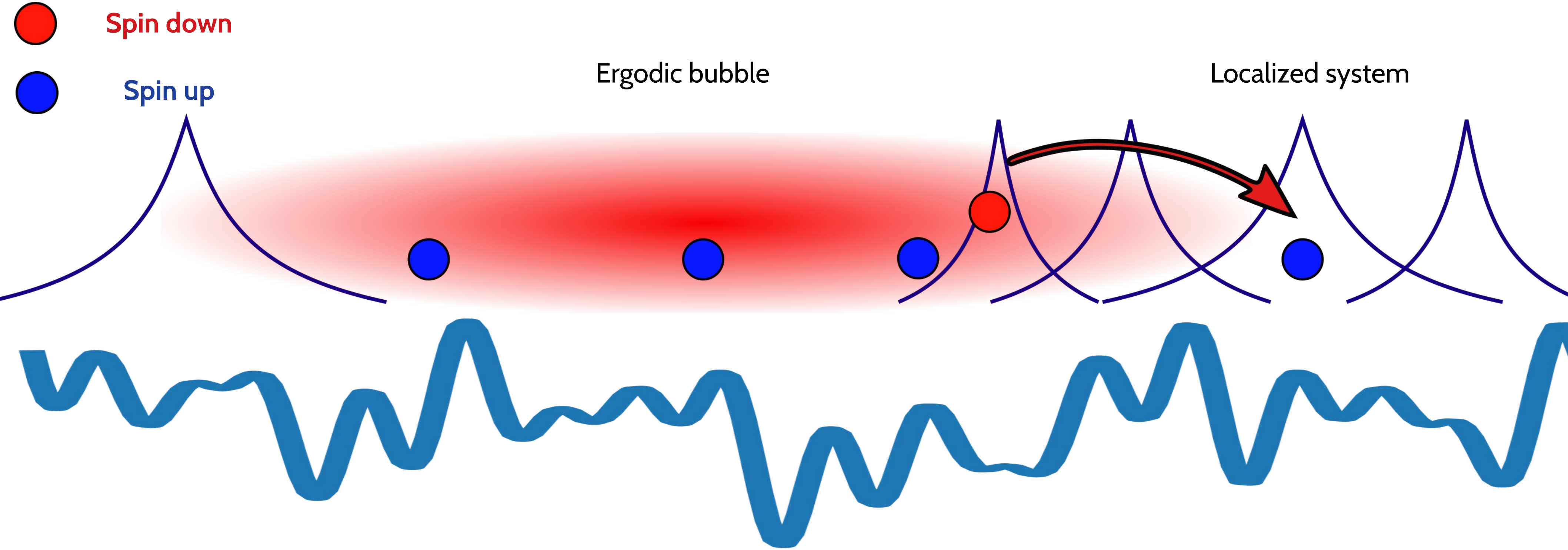
Piet W. Brouwer



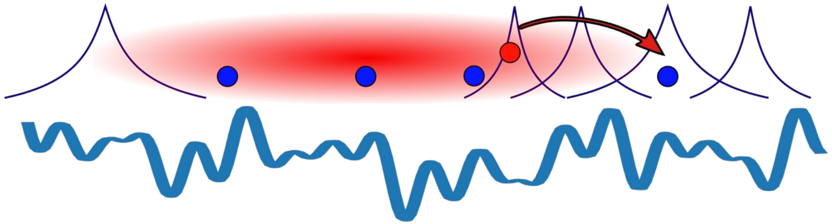
Dmitry Abanin



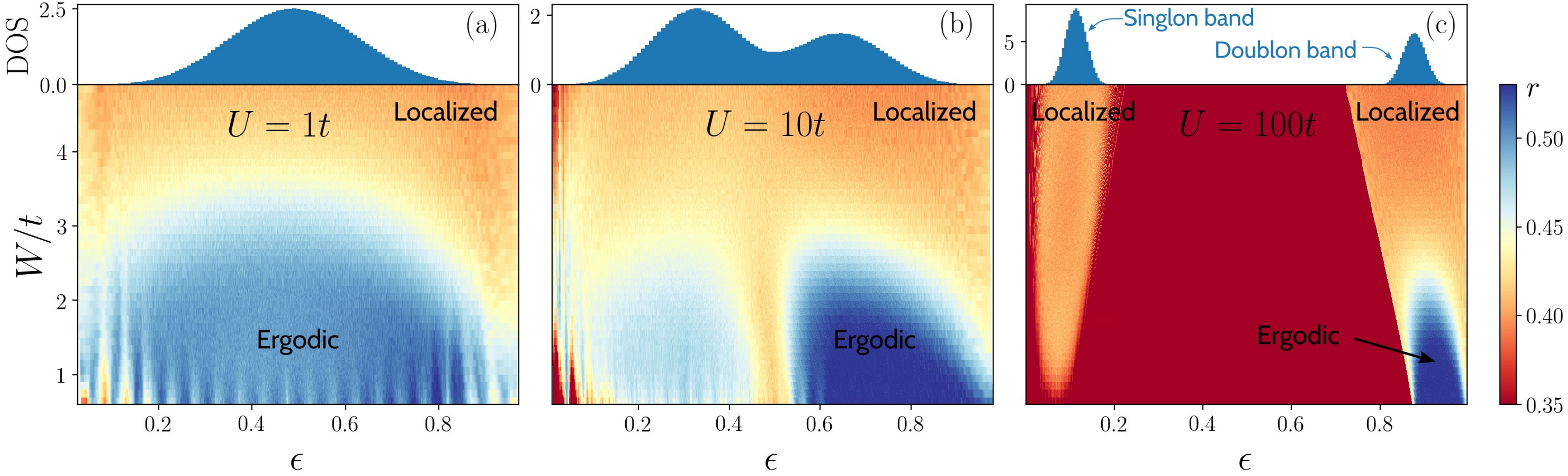
PRL 2021



Nucleation of ergodicity by a single impurity in supercooled insulators

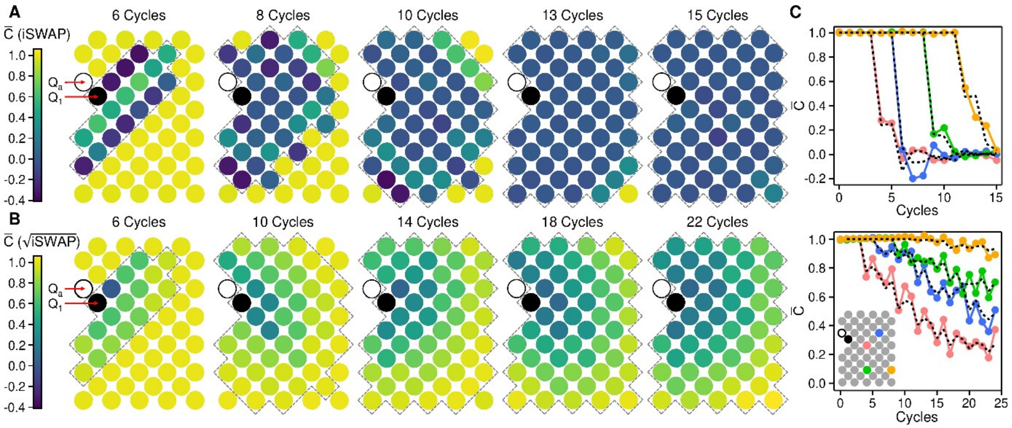


PRL 2021

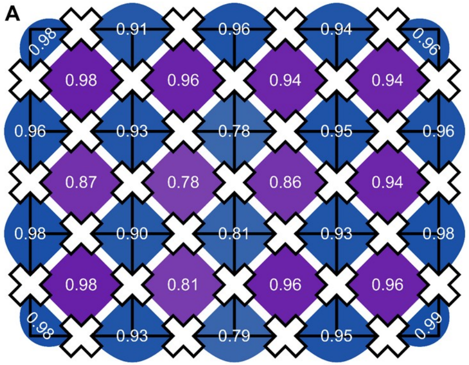


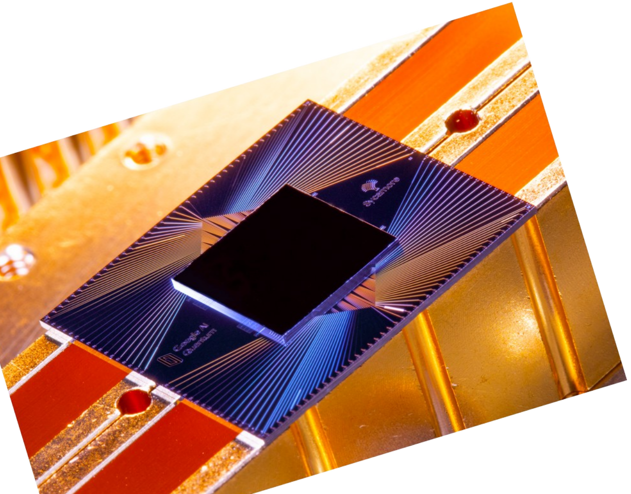
Quantum dynamics in solid state simulators

Information Scrambling in Computationally Complex Quantum Circuits

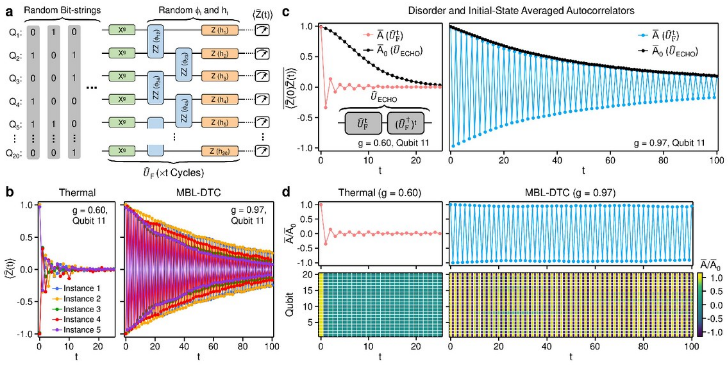


Realizing topologically ordered states on a quantum processor

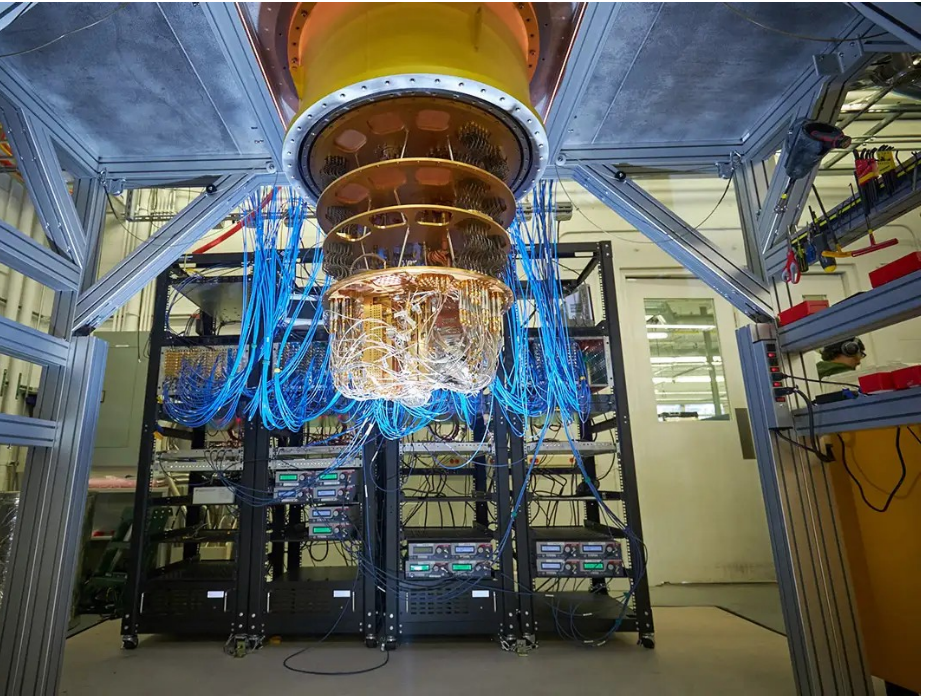




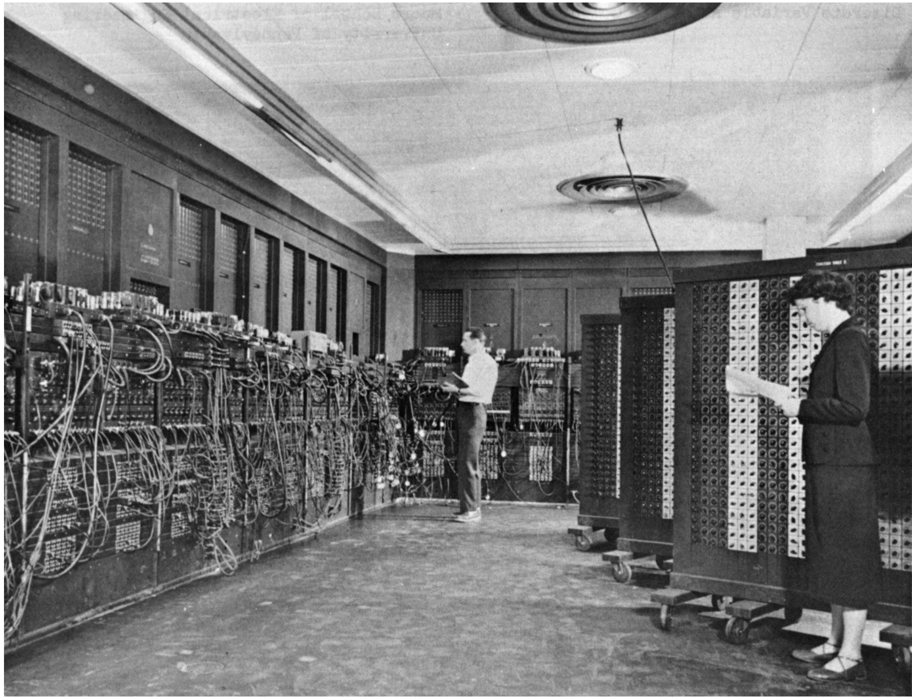
Observation of Time-Crystalline Eigenstate Order on a Quantum Processor



Google Supercomputer (2019/ ?)



Eniac Supercomputer (1946/1955)



?

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THE SIMPSONS

"I predict that within 100 years, computers will be twice as powerful, 10,000 times larger, and so expensive that only the five richest kings in Europe will own them."

Here in Grenoble …

QuantumSilicon
Grenoble

DE LA RECHERCHE À L'INDUSTRIE
cea

UNIVERSITÉ
Grenoble
Alpes

cnrs
dépasser les frontières

NÉEL
institut

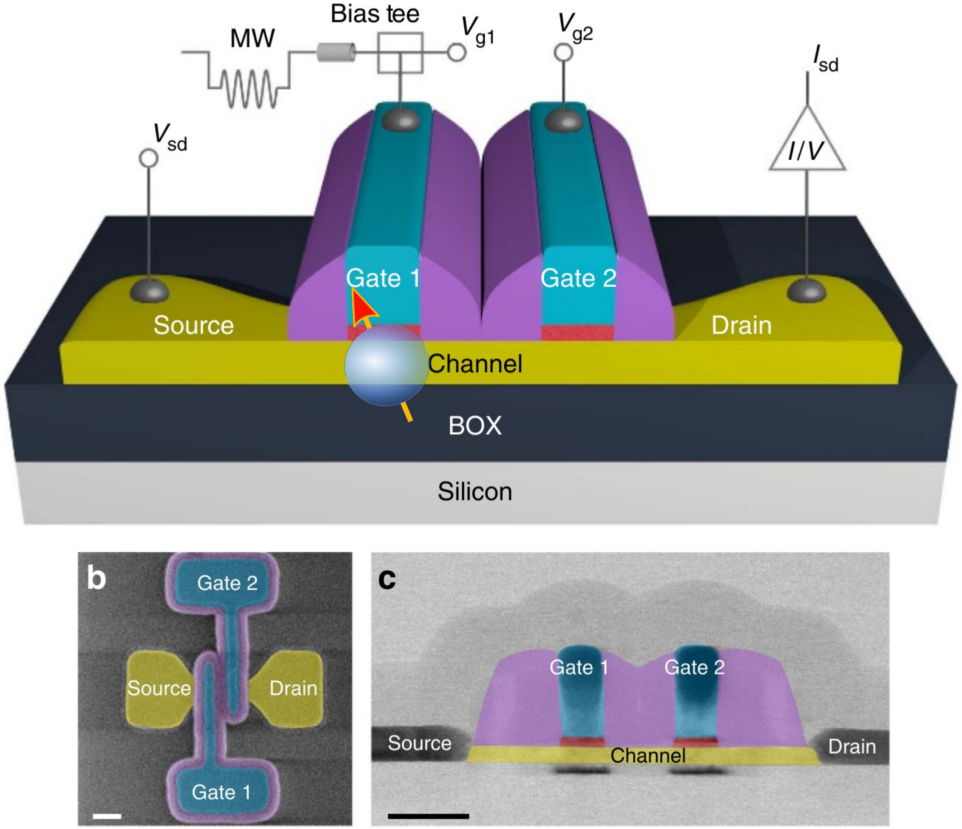
ARTICLE

Received 28 Jul 2016 | Accepted 14 Oct 2016 | Published 24 Nov 2016

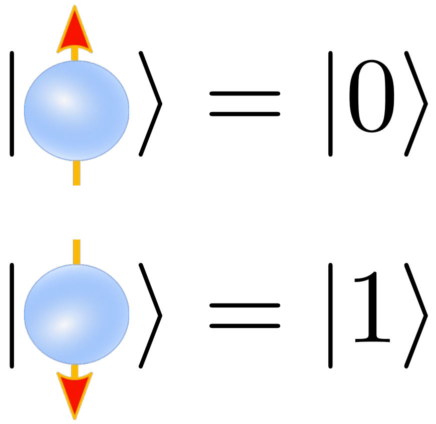
nature COMMUNICATIONS

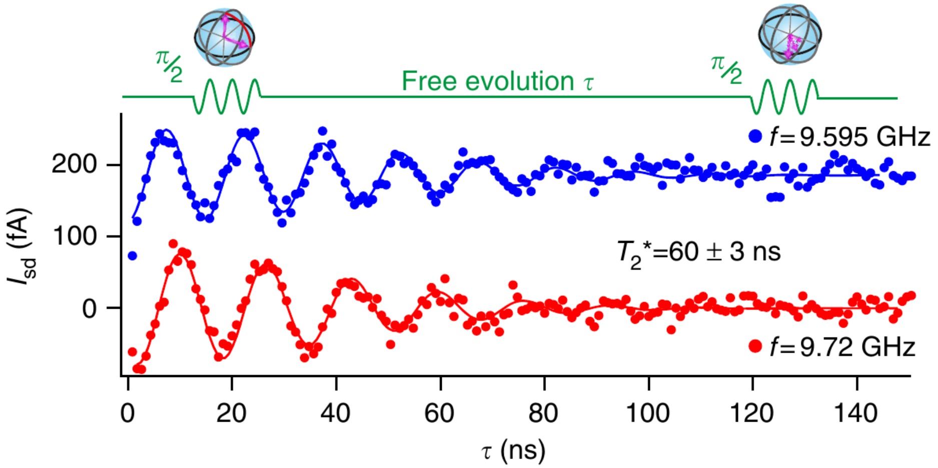
A CMOS silicon spin qubit

R. Maurand[1,2], X. Jehl[1,2], D. Kotekar-Patil[1,2], A. Corna[1,2], H. Bohuslavskyi[1,2], R. Laviéville[1,3], L. Hutin[1,3], S. Barraud[1,3], M. Vinet[1,3], M. Sanquer[1,2] & S. De Franceschi[1,2]



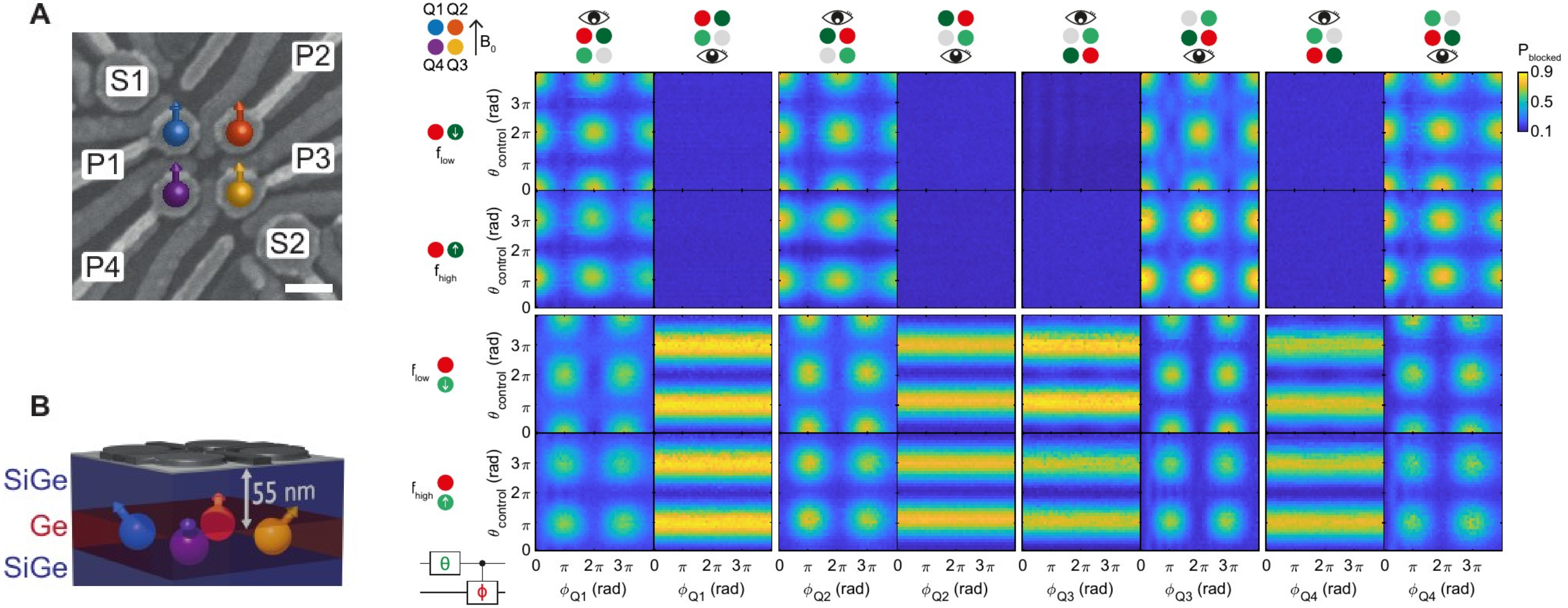
Qubits are now encoded in the spin state of single electrons confined in semiconductors





A four-qubit germanium quantum processor

Nico W. Hendrickx[1]✉, William I. L. Lawrie[1], Maximilian Russ[1], Floor van Riggelen[1], Sander L. de Snoo[1], Raymond N. Schouten[1], Amir Sammak[2], Giordano Scappucci[1] & Menno Veldhorst[1]✉

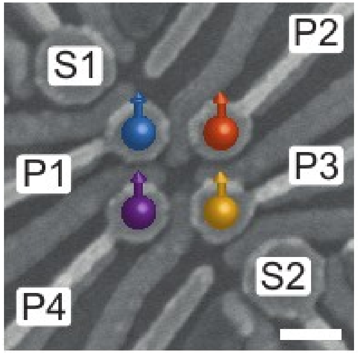


Article

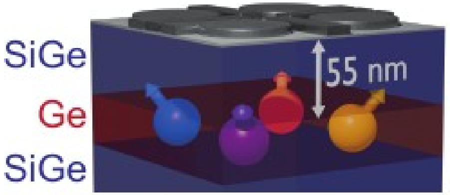
A four-qubit germanium quantum processor

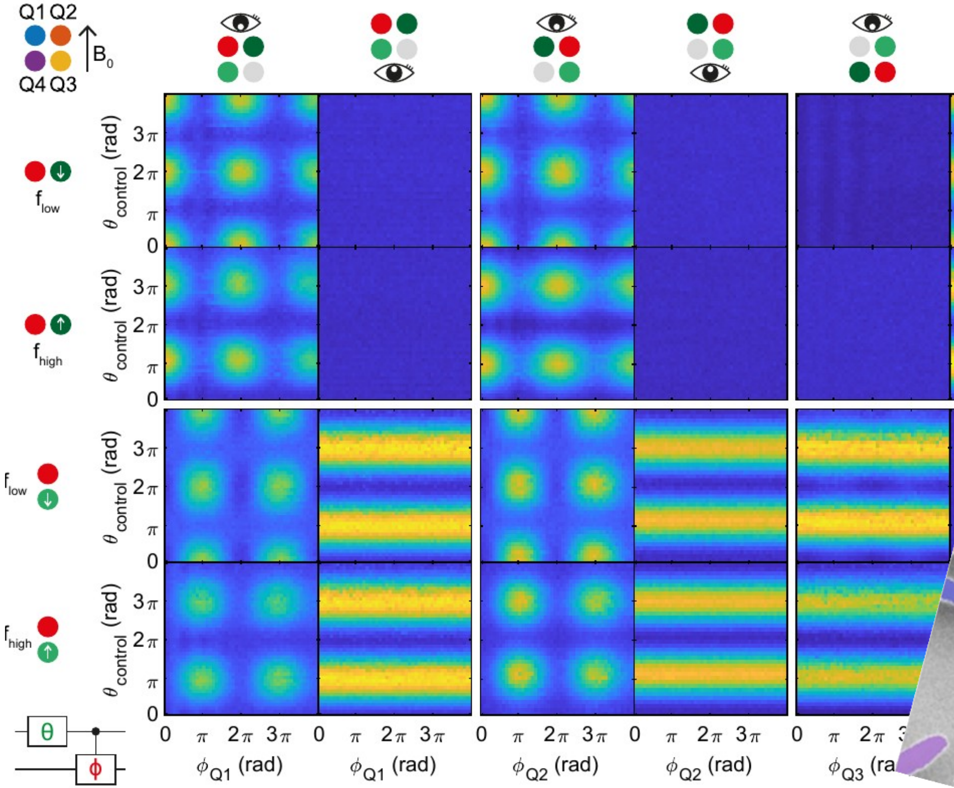
Nico W. Hendrickx[1]✉, William I. L. Lawrie[1], Maximilian Russ[1], Floor van Riggelen[1], Sander L. de Snoo[1], Raymond N. Schouten[1], Amir Sammak[2], Giordano Scappucci[1] & Menno Veldhorst[1]✉

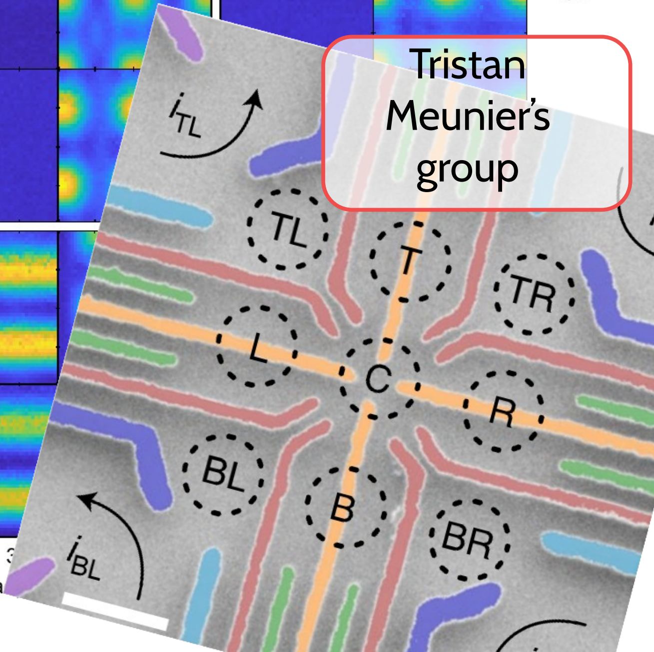
A



B







Many thanks to many people

LPMMC

Frank Hekking

Anna Minguzzi

Denis Basko

Cécile Repellin

Piet W. Brouwer

Thierry Giamarchi

Dima Abanin   Pedram Roushan   me with horrible haircut

Thank you for your attention!