Theory and simulation of materials and devices for quantum technologies

Procolo Lucignano
CNR-SPIN
Dipartimento di Fisica
Università di Napoli Federico II

Ph.D.
|Qu>ANTUM
|T>ECHNOLOGIES

Napoli 08/02/2019

Condensed matter theory group Napoli

University
Vittorio Cataudella
Giulio De Filippis
Carmine Antonio Perroni
Domenico Ninno
Arturo Tagliacozzo
Dario Alfè
Gabriele Campagnano
CNR
Giovanni Cantele
P.L.

From left: Loris Cangemi, Felice Conte, Pratibha Hegde, Gianluca Passarelli, Martina Minutillo

Ph.D. Students

Condensed matter theory group Napoli

University
Vittorio Cataudella
Giulio De Filippis
Carmine Antonio Perroni
Domenico Ninno
Arturo Tagliacozzo
Dario Alfè
Gabriele Campagnano
CNR
Giovanni Cantele
P.L.

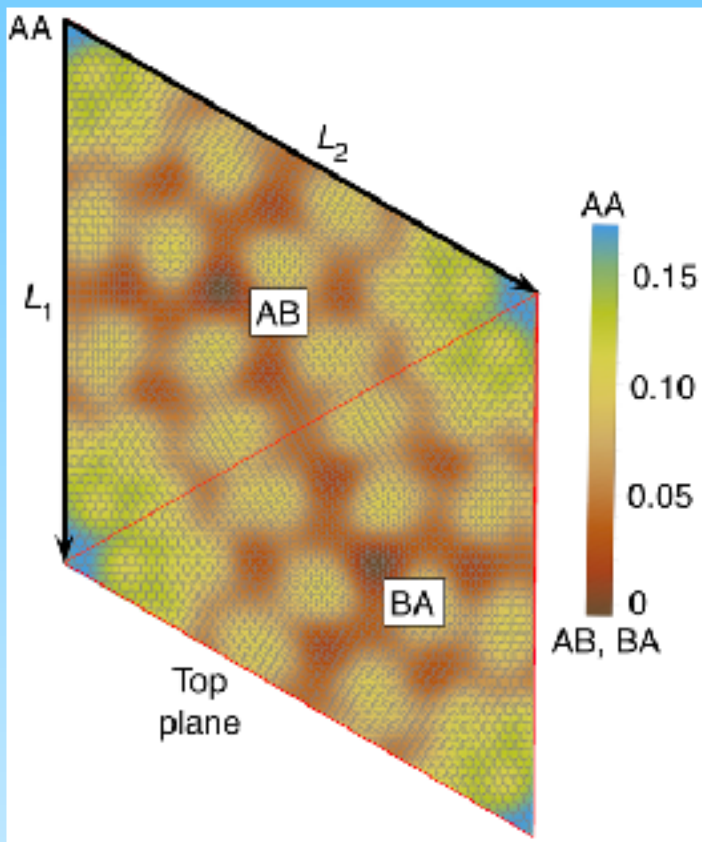
From left: Loris Cangemi, Felice Conte, Pratibha Hegde, Gianluca Passarelli, Martina Minutillo

Ph.D. Students

Quantum Technologies

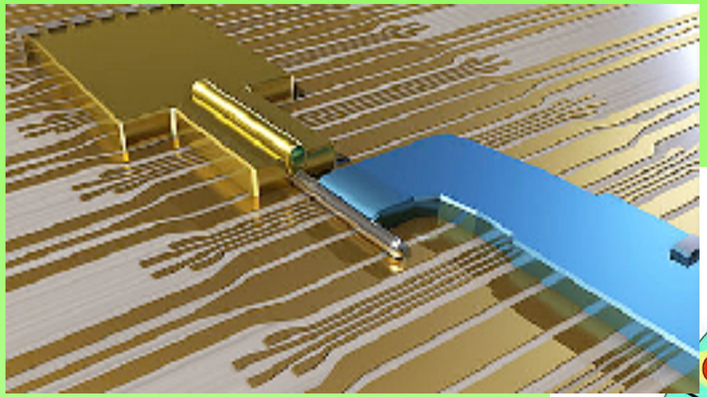
Quantum Materials

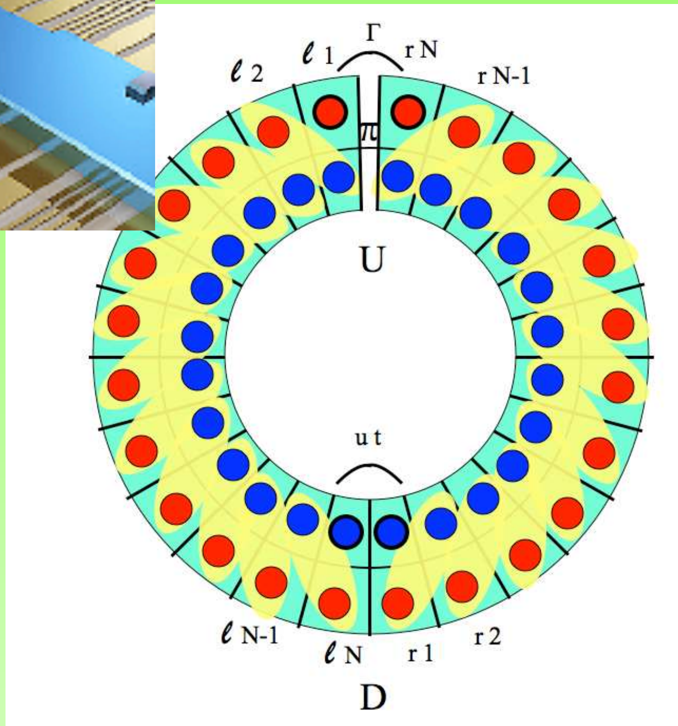
Engineer artificial materials to simulate other materials!



Topological Quantum Computation

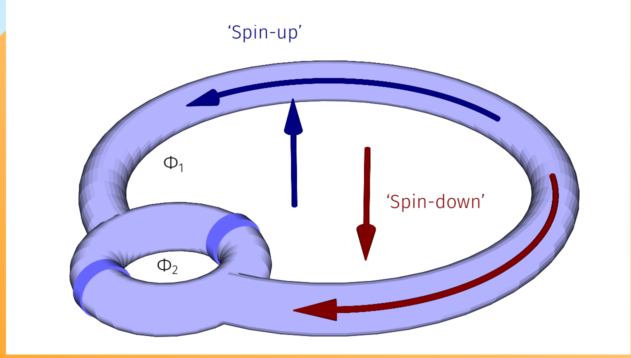
Majorana Fermions

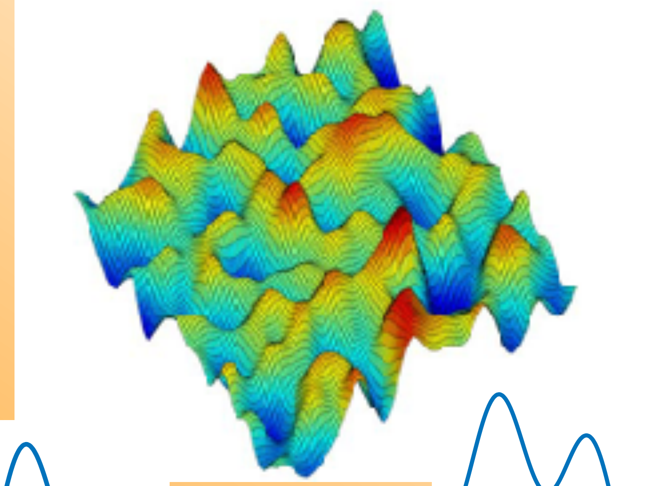


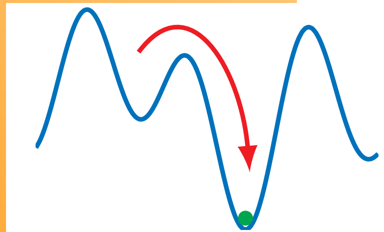


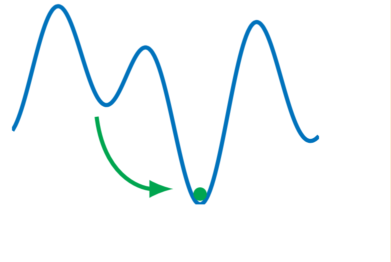
Theory and Simulation

Adiabatic quantum computation

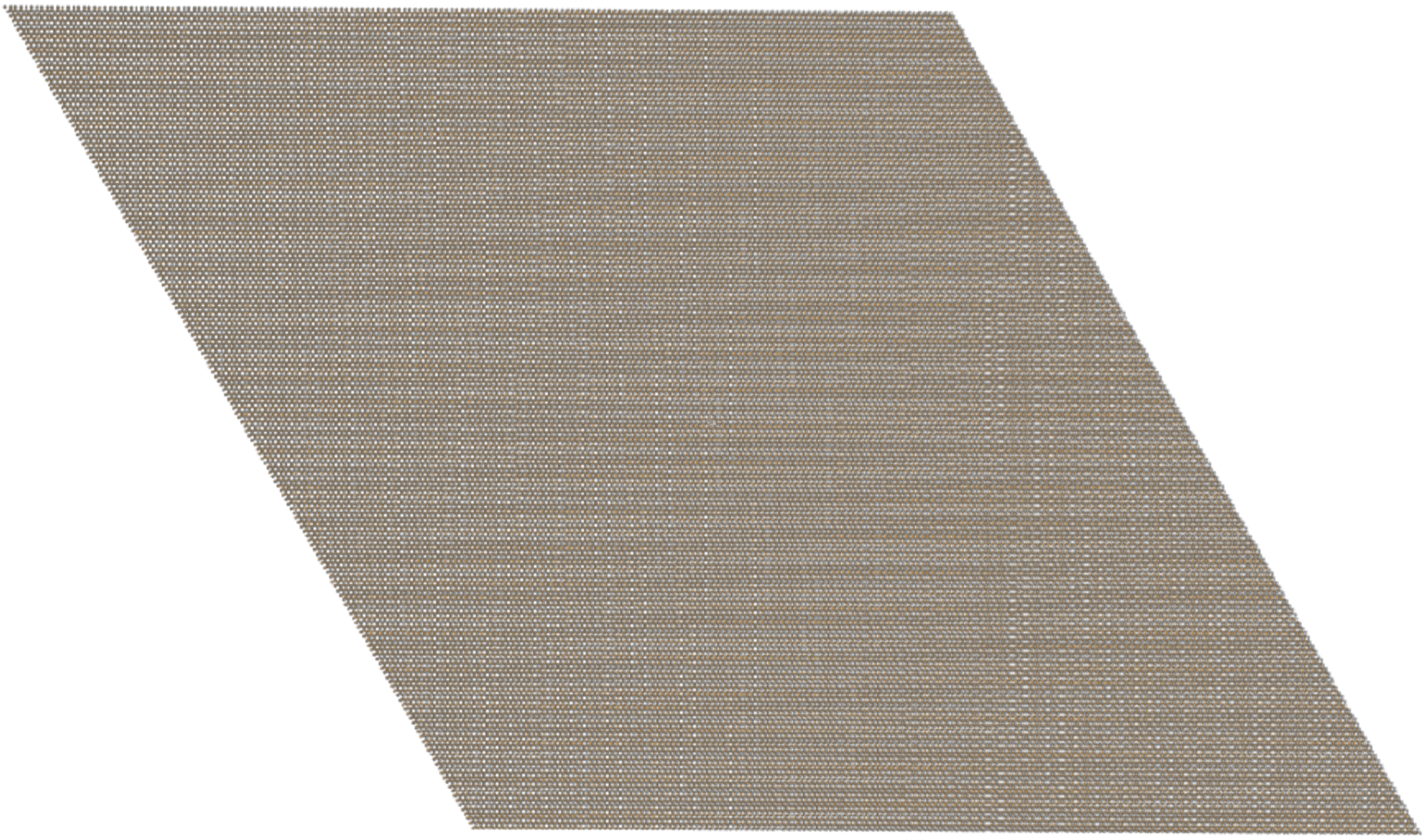




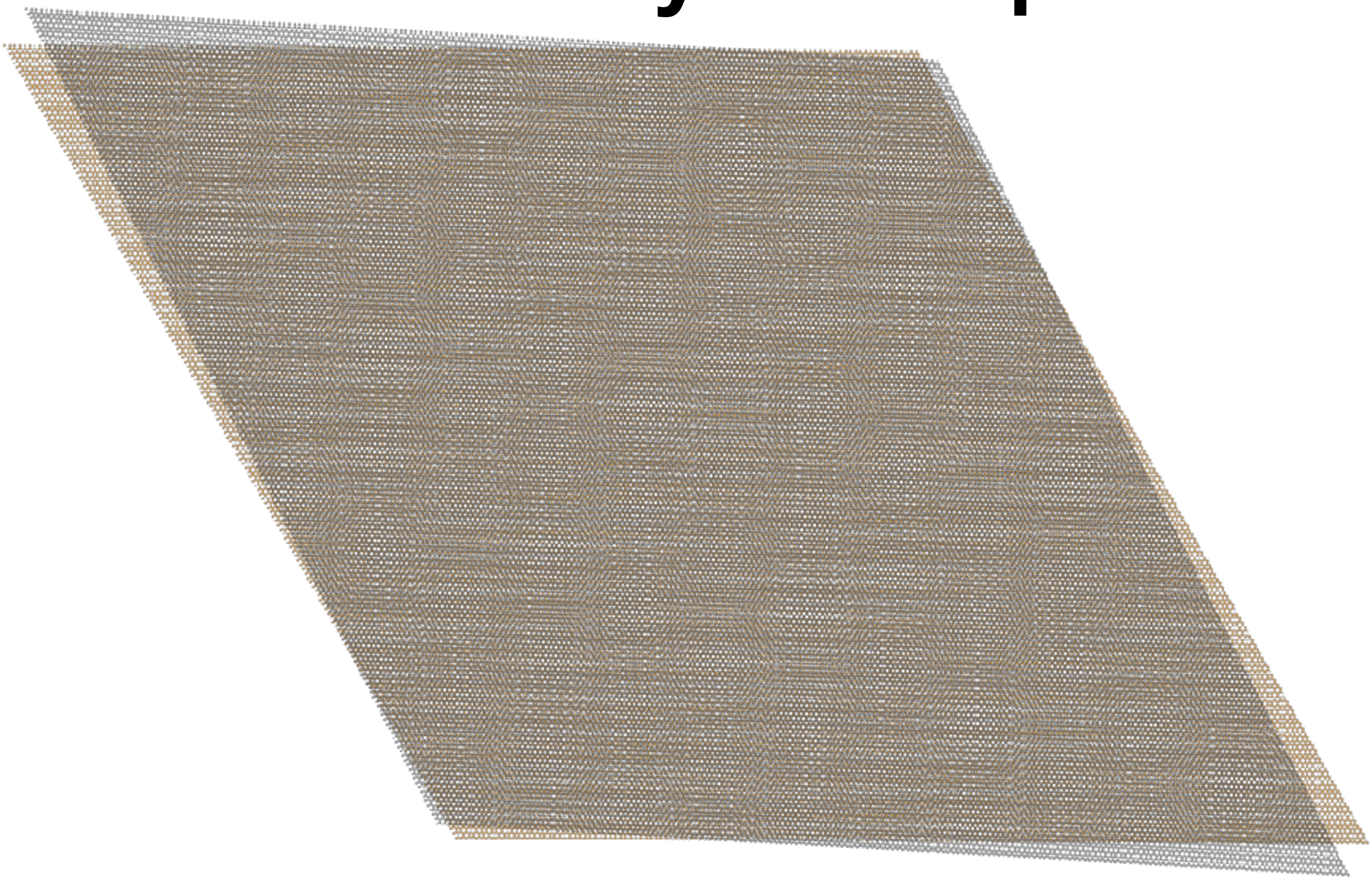




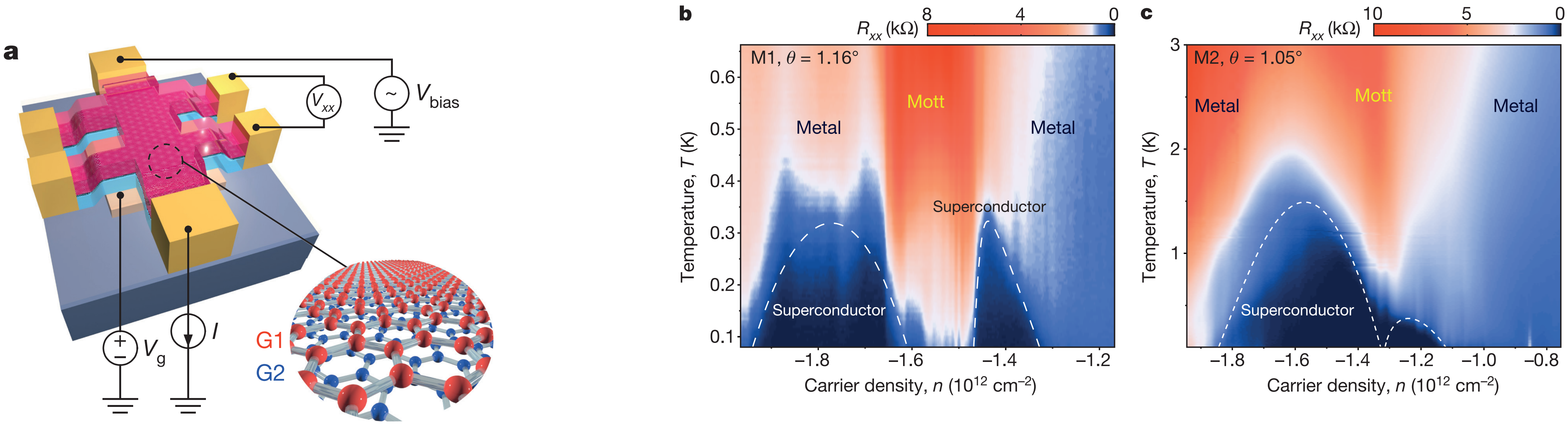
Quantum Materials: Twisted Bilayer Graphene



Quantum Materials: Twisted Bilayer Graphene



Experimental evidences

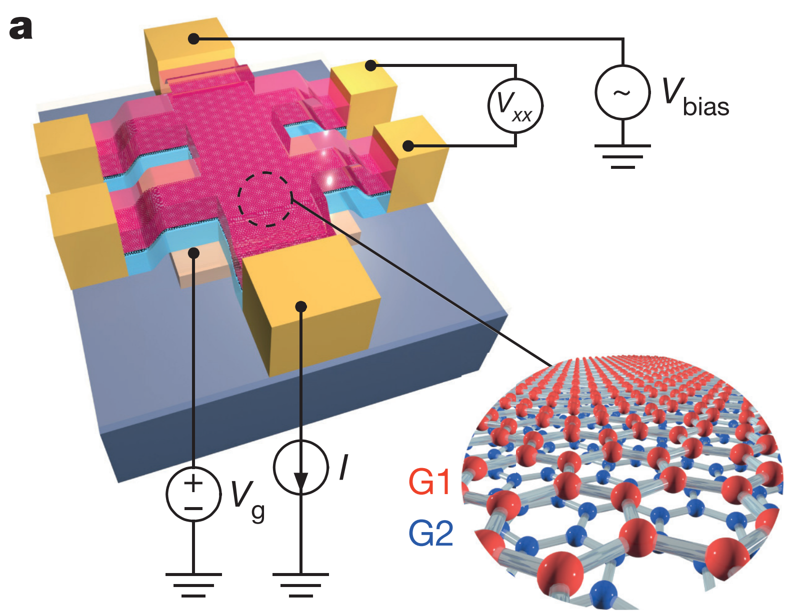


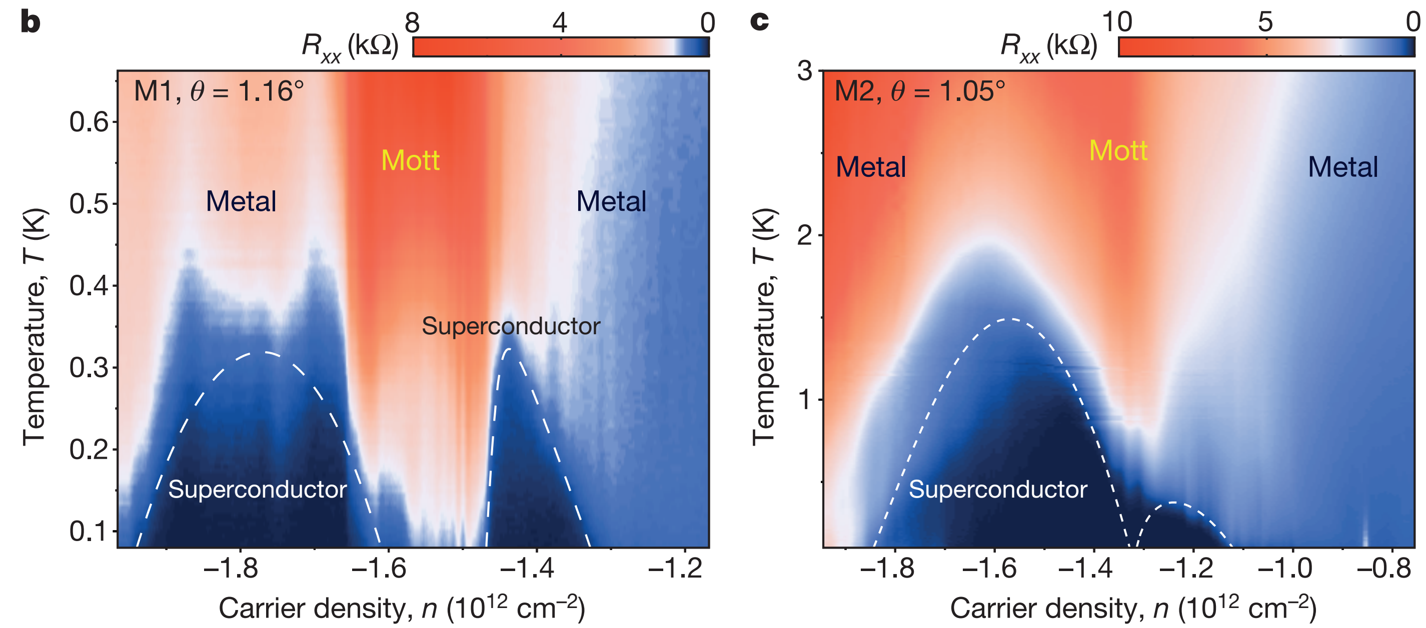
Phase diagram very similar to Cuprate superconductors

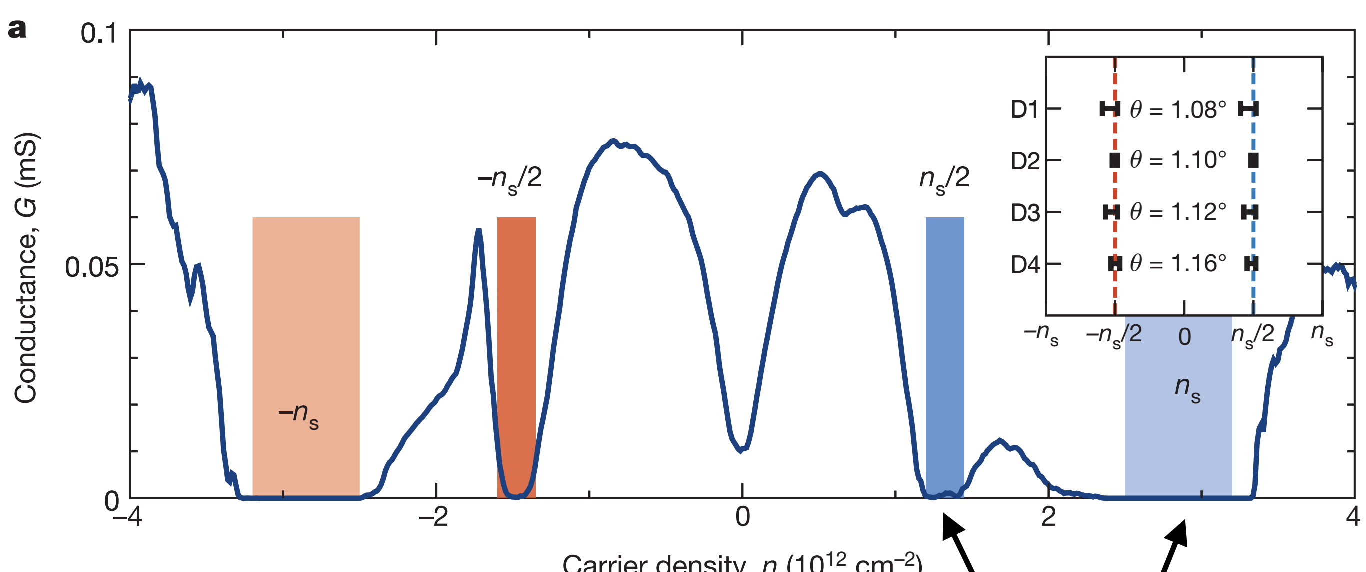
Solid state quantum simulator?

Cao et al. Nature 2018 Nature 556, 80 (2018)
Cao et al. Nature 2018 Nature 556, 43 (2018)

Experimental evidences





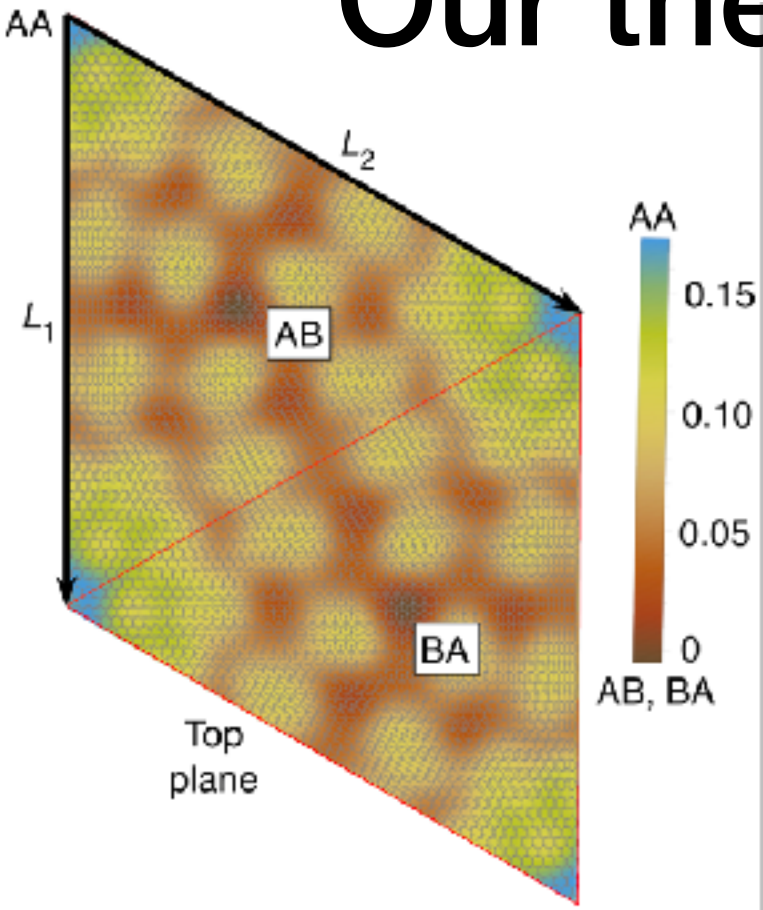


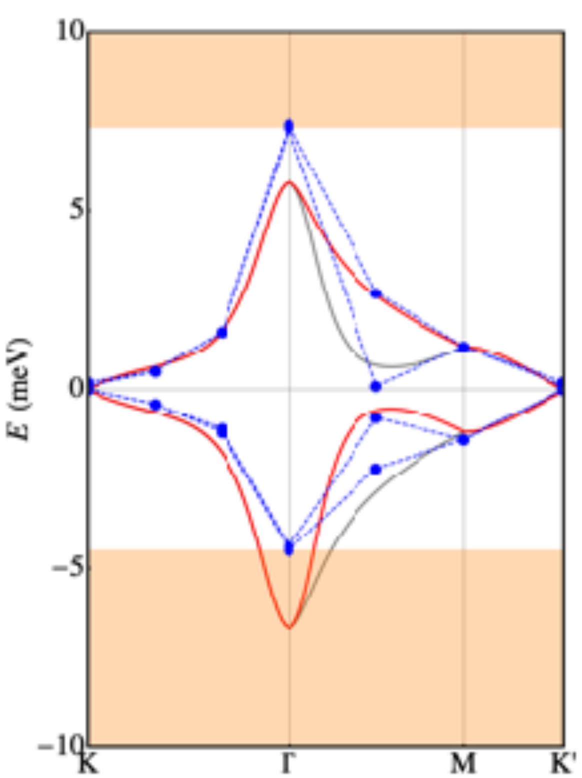
Phase diagram very similar to Cuprate superconductors
Solid state quantum simulator?

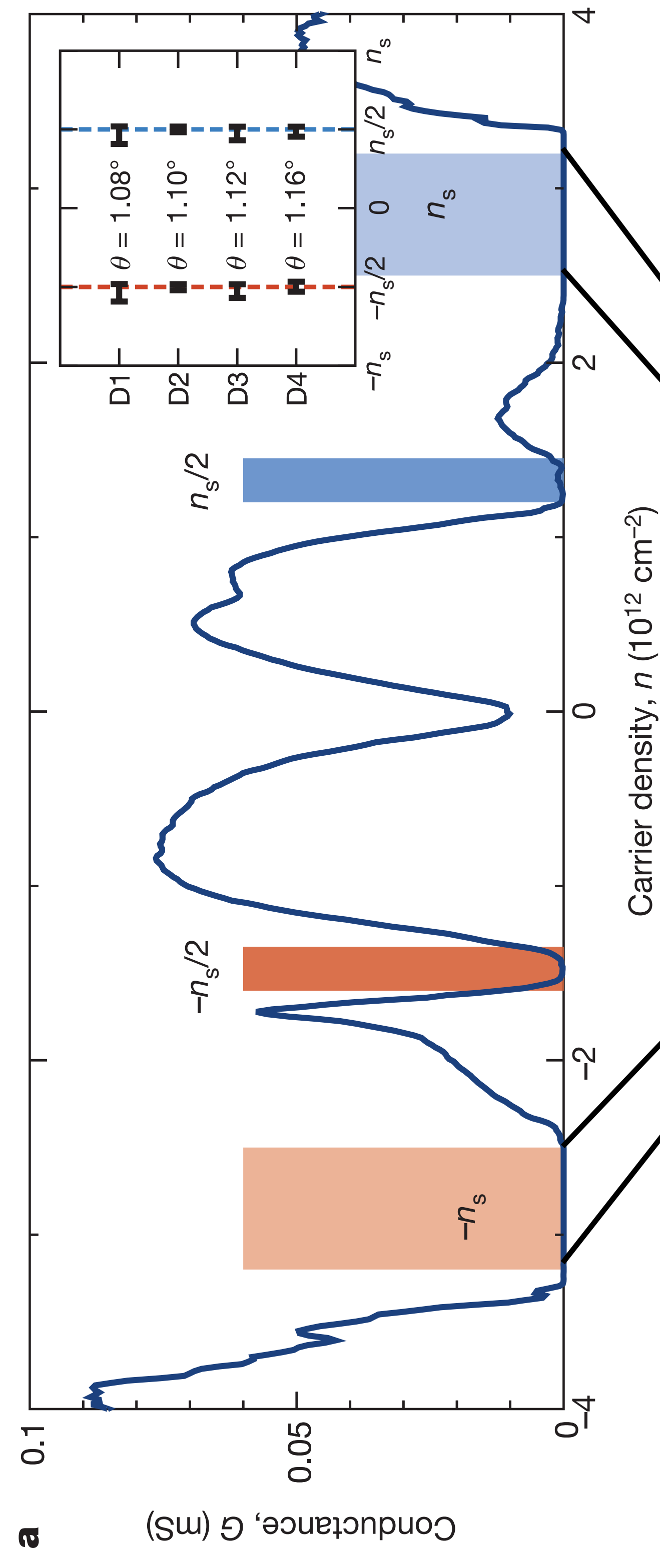
Cao et al. Nature 2018 Nature 556, 80 (2018)
Cao et al. Nature 2018 Nature 556, 43 (2018)

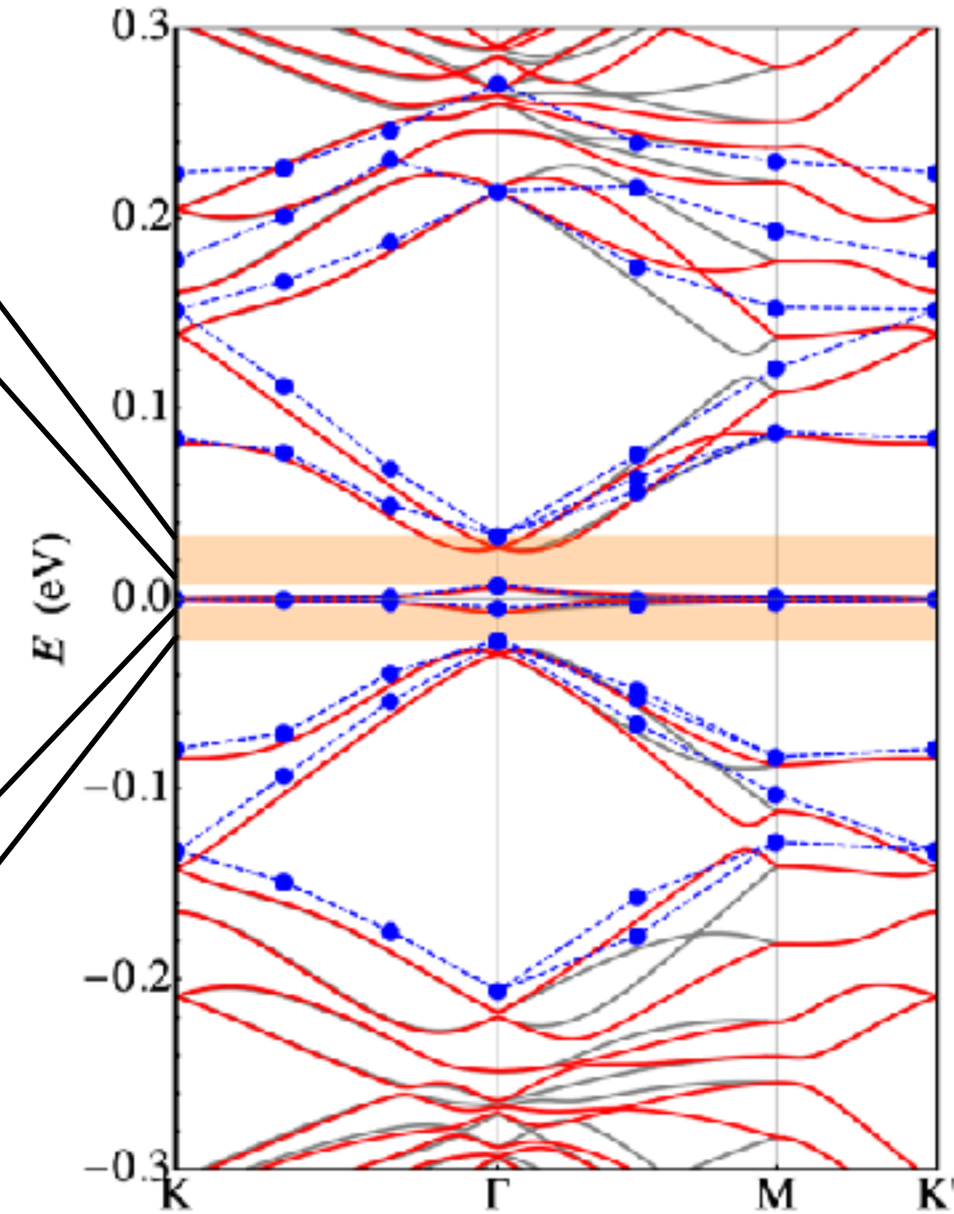
Unexpected insulating phases

Our theoretical understanding









P. Lucignano, D. Alfè, V. Cataudella, D. Ninno, G. Cantele submitted

Solid State Quantum Computation

Solid State Quantum Computation

Quantum Gates

IBM Q-experience, Rigetti and others (few tens of quits)
General purpose (Universal)
Hardly scalable (decoherence)

Solid State Quantum Computation

Quantum Gates

IBM Q-experience, Rigetti and others (few tens of quits)
General purpose (Universal)
Hardly scalable (decoherence)

Topological quantum computation

Anyonic quasiparticles (Majorana Fermions)
Topologically protected from noise and decoherence
Still speculative: many theory and experiments, no … platforms

Solid State Quantum Computation

Quantum Gates

IBM Q-experience, Rigetti and others (few tens of quits)
General purpose (Universal)
Hardly scalable (decoherence)

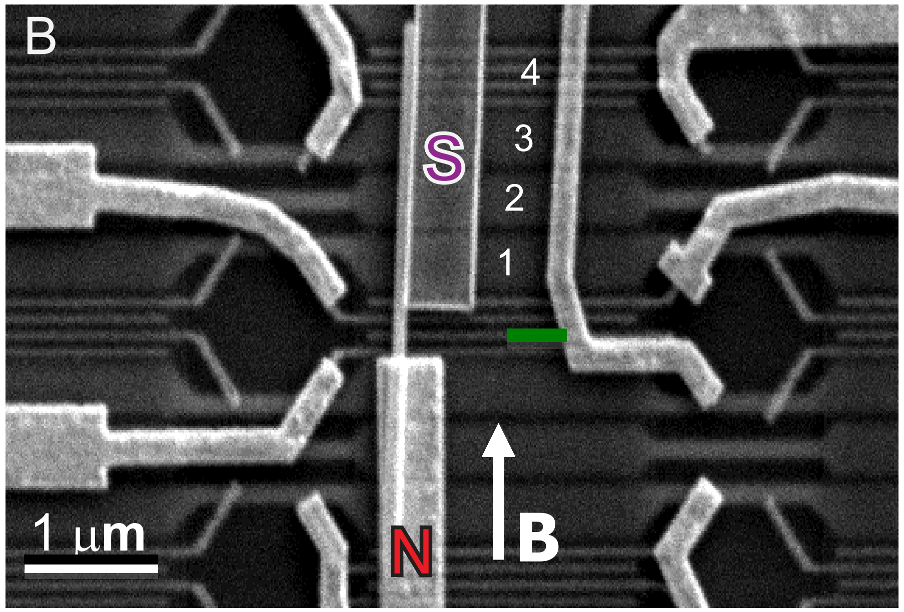
Topological quantum computation

Anyonic quasiparticles (Majorana Fermions)
Topologically protected from noise and decoherence
Still speculative: many theory and experiments, no … platforms

Adiabatic quantum computation

D-Wave 2000Q (2048 qubits)
Universal (In principle!)
In reality: **An optimizer**
Robust to decoherence

Topological quantum computation
Anyonic quasiparticles (Majorana Fermions)

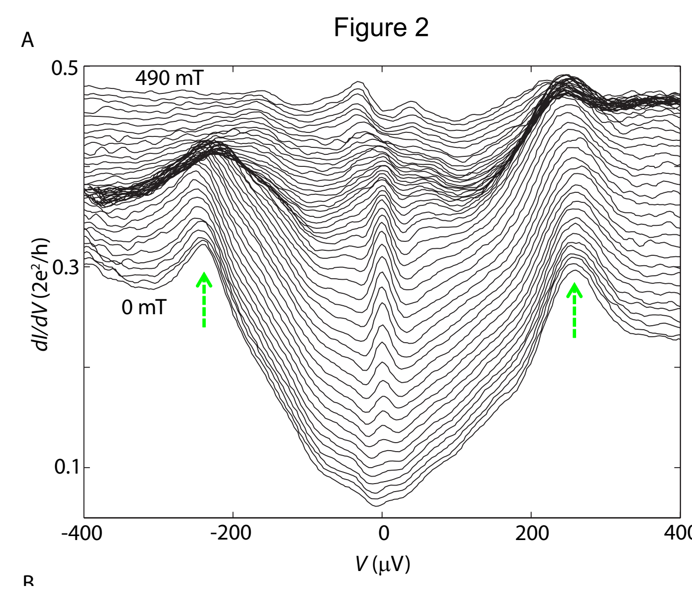


Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

Majorana fermions are particles identical to their own antiparticles. They have been theoretically predicted to exist in topological superconductors. Here, we report electrical measurements on indium antimonide nanowires contacted with one normal (gold) and one superconducting (niobium titanium nitride) electrode. Gate voltages vary electron density and define a tunnel barrier between normal and superconducting contacts. In the presence of magnetic fields on the order of 100 millitesla, we observe bound, midgap states at zero bias voltage. These bound states remain fixed to zero bias, even when magnetic fields and gate voltages are changed over considerable ranges. Our observations support the hypothesis of Majorana fermions in nanowires coupled to superconductors.

www.sciencemag.org SCIENCE VOL 336 25 MAY 2012



$\alpha \approx 0.2$ eVÅ

$E_{SO} = \alpha^2 m^* / (2\hbar^2) \approx 50\ \mu\text{eV}$ ($m^* = 0.015 m_e$).

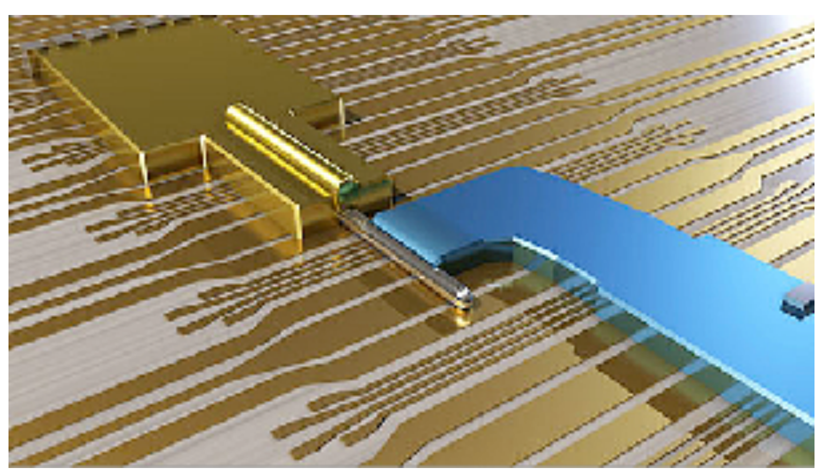
$g \approx 50$

$E_Z / B \approx 1.5$ meV/T

$\Delta \approx 250\ \mu$eV

$B > 0.15$ T where $E_Z > \Delta$

T<100mK

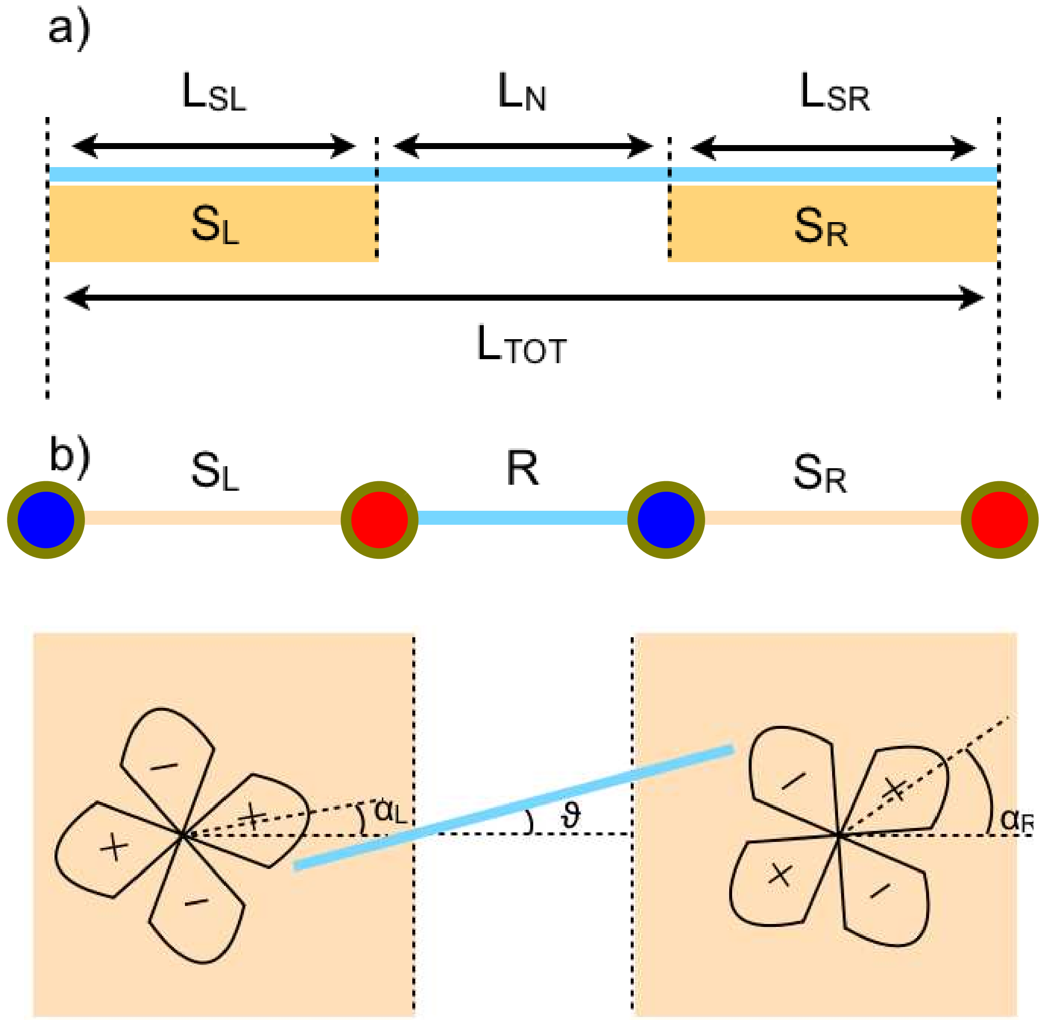


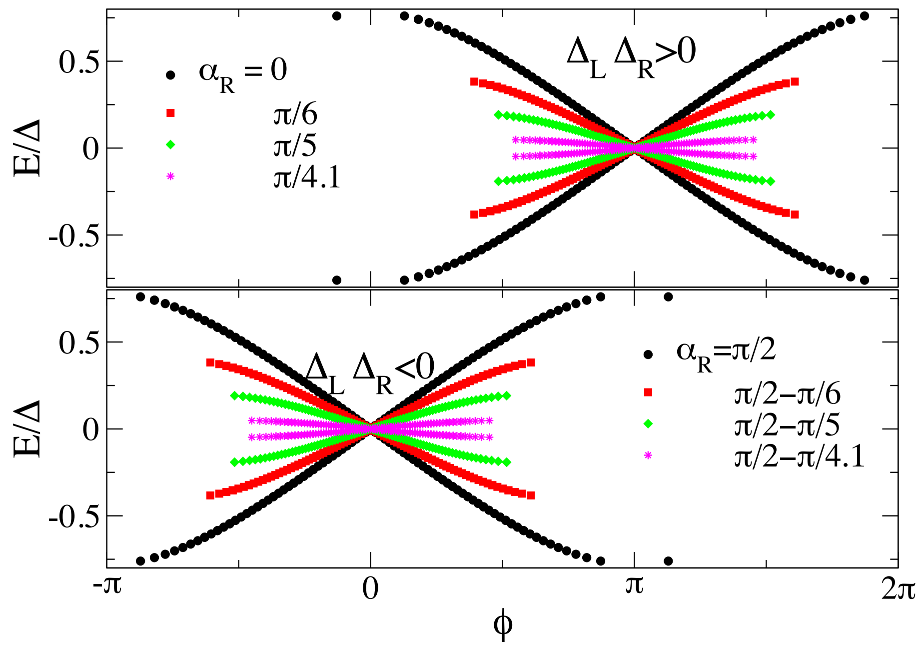
InSb, NbTiN

V. Mourik, K. Zuo, S.M. Frolov, S.R. Plissard, E.P.A.M. Bakkers, L.P. Kouwenhoven, Science 2012

OUR PROPOSAL

High T_c implementation Josephson devices



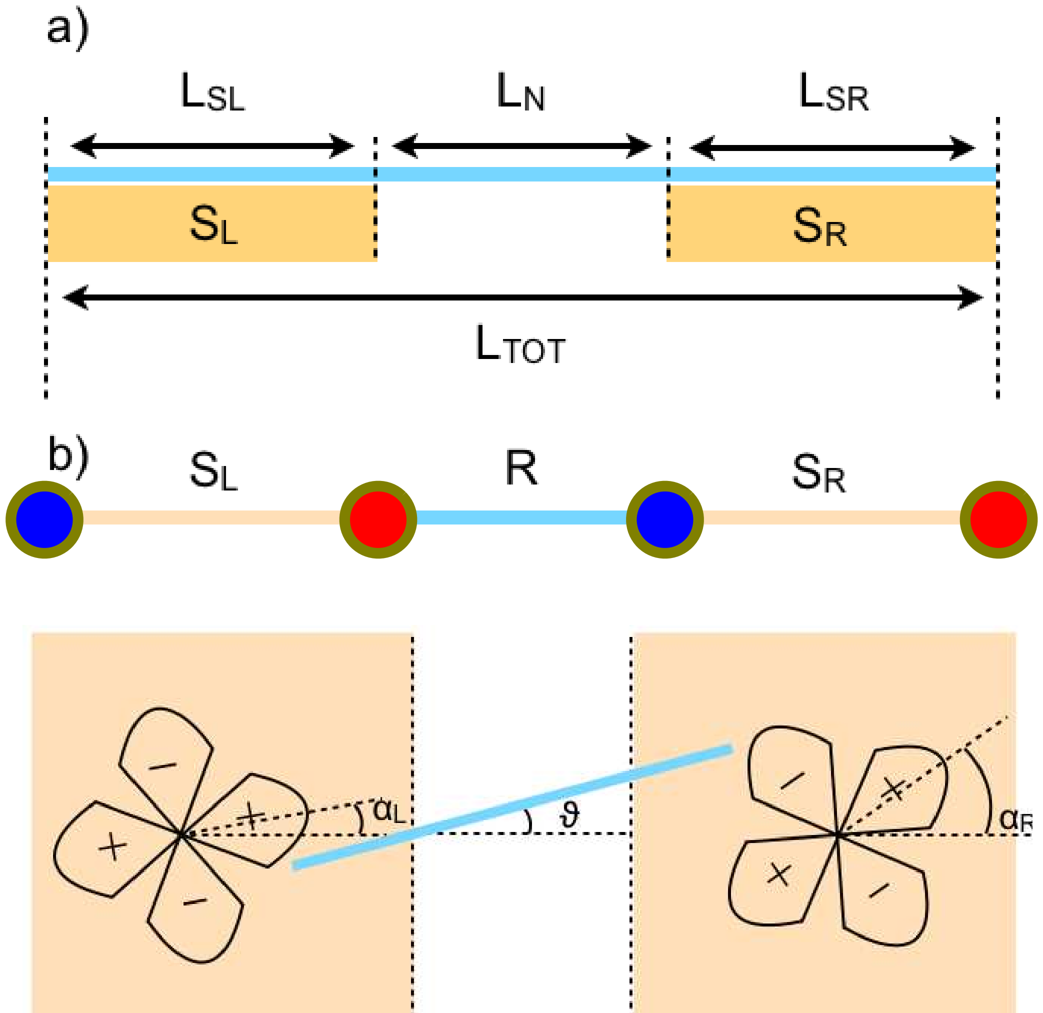


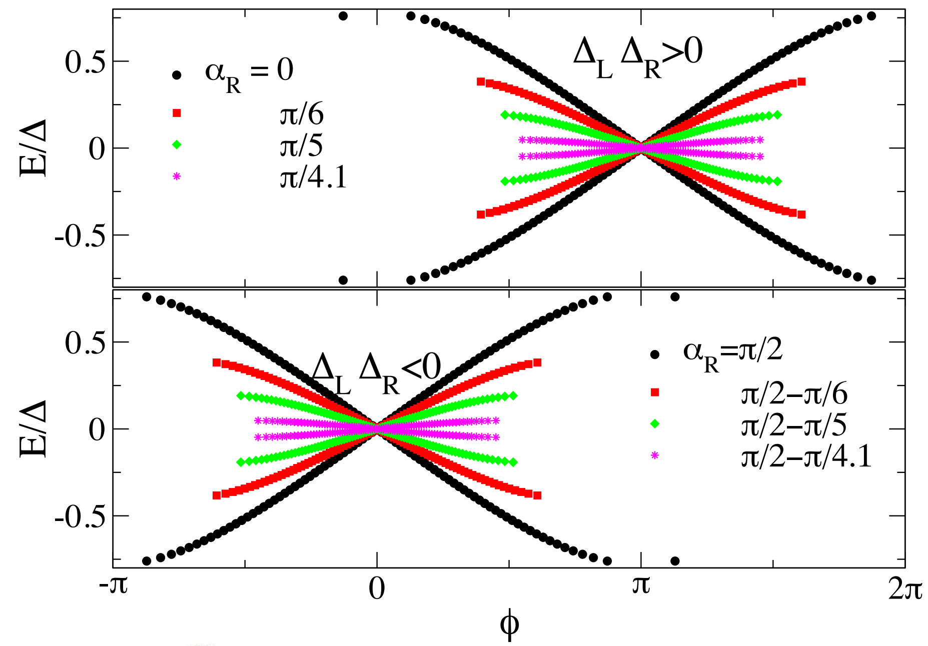
PL, A. Mezzacapo, F. Tafuri and A. Tagliacozzo PRB 2012

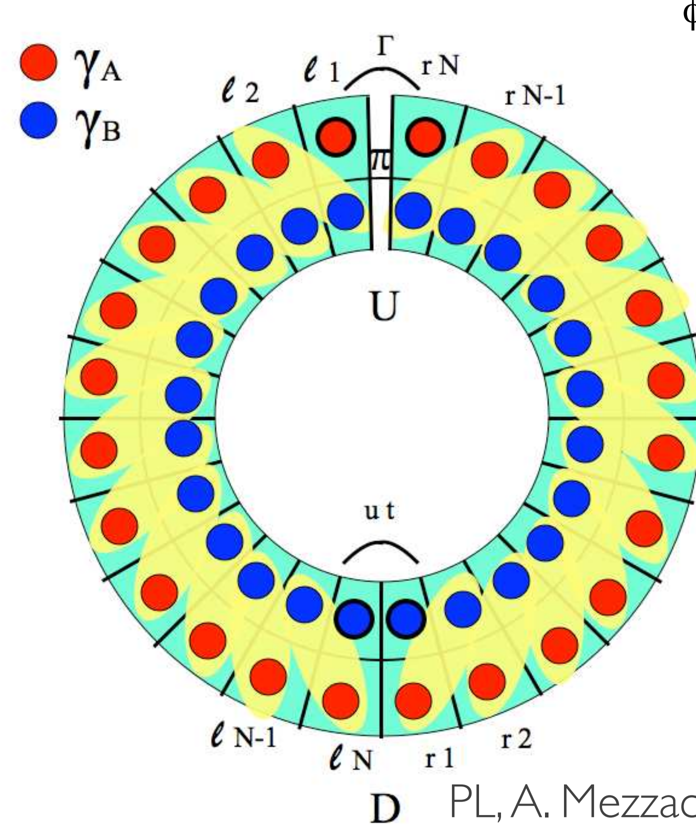
PL F. Tafuri, A. Tagliacozzo PRB 2013

OUR PROPOSAL

High T_c implementation Josephson devices





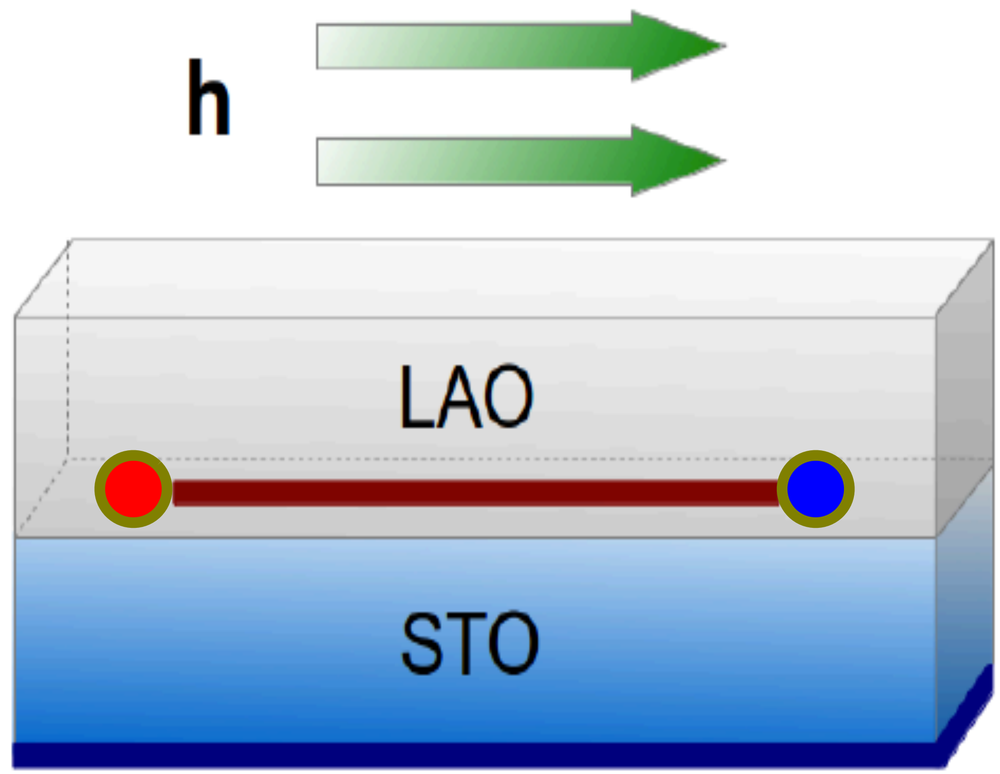


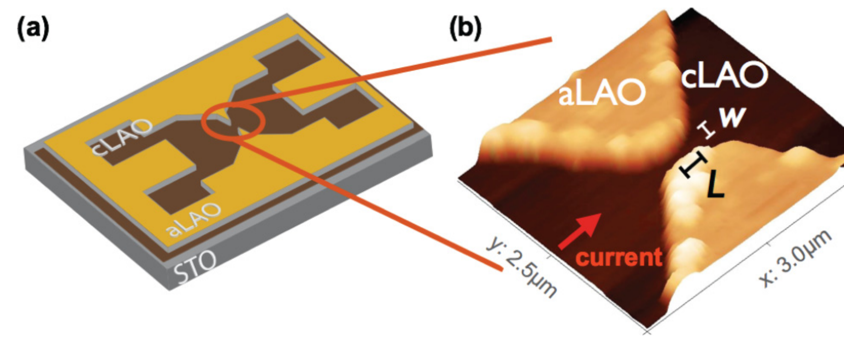
PL, A. Mezzacapo, F. Tafuri and A. Tagliacozzo PRB 2012

PL F. Tafuri, A. Tagliacozzo PRB 2013

New platforms based on oxide interfaces

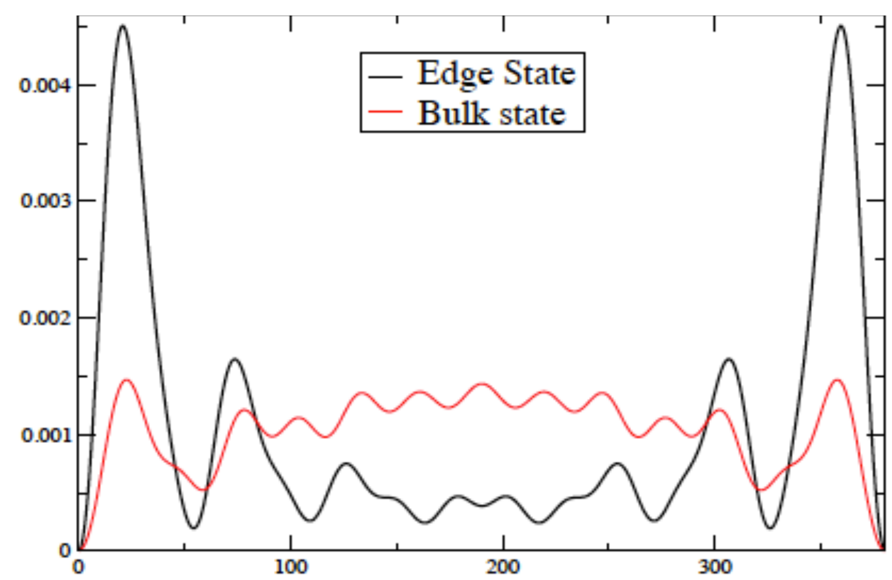
Superconductivity and strong spin orbit coupling in the same material: multifunctional oxides. The LAO/STO 2DEG interface.





D. Stornaiuolo et al PRB 2017

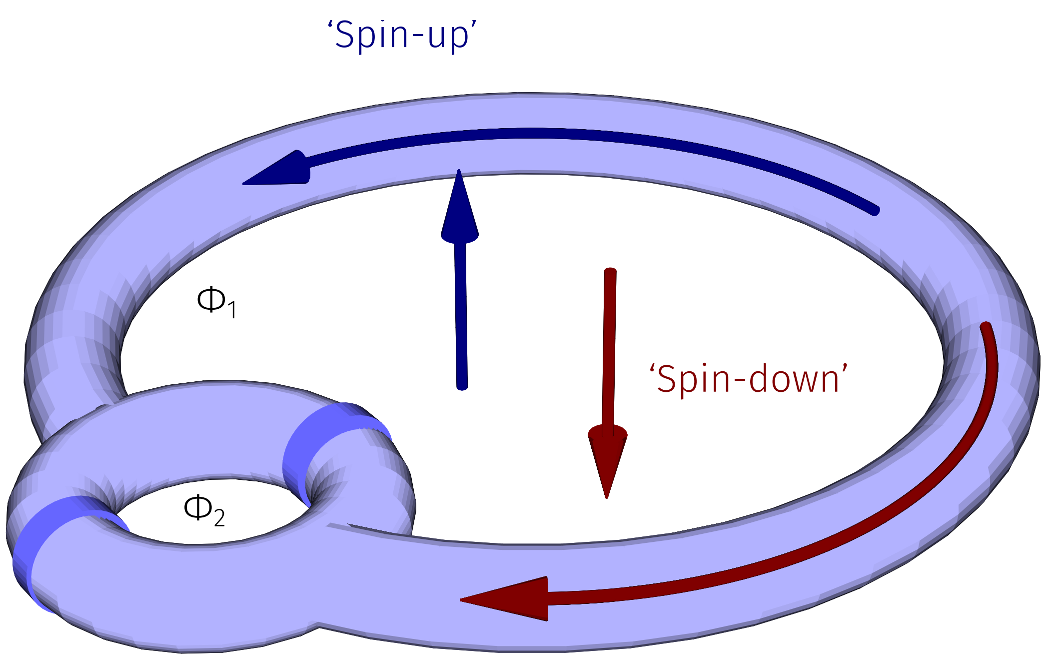
QUANTERA project Quantox
CNR-SPIN



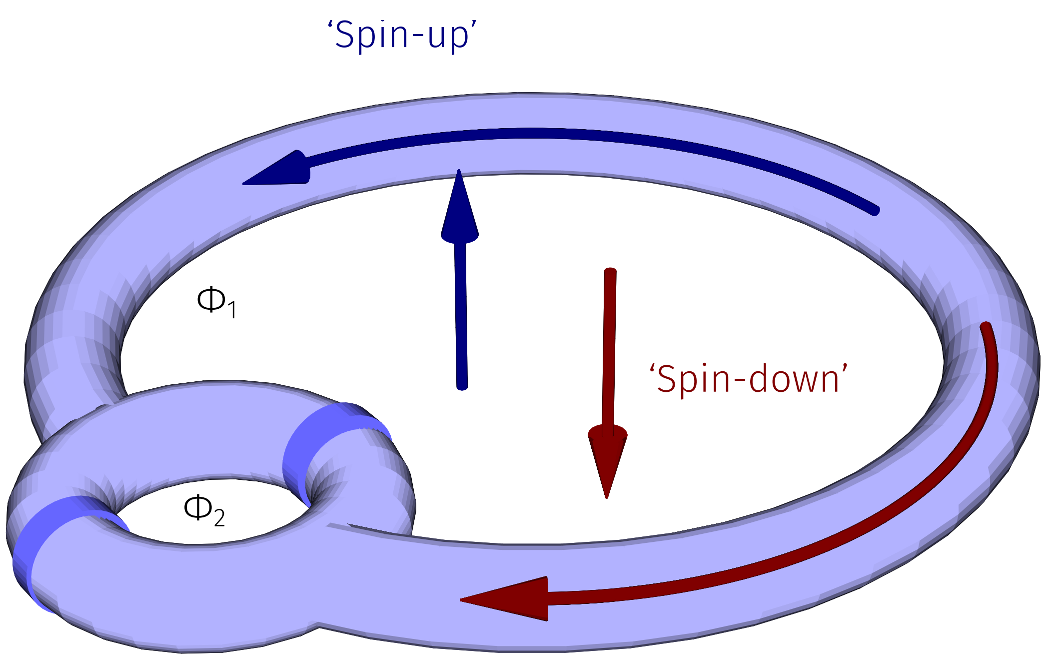
Majorana mode at the edge of the nanowire: decay length of the order of the superconducting coherence length

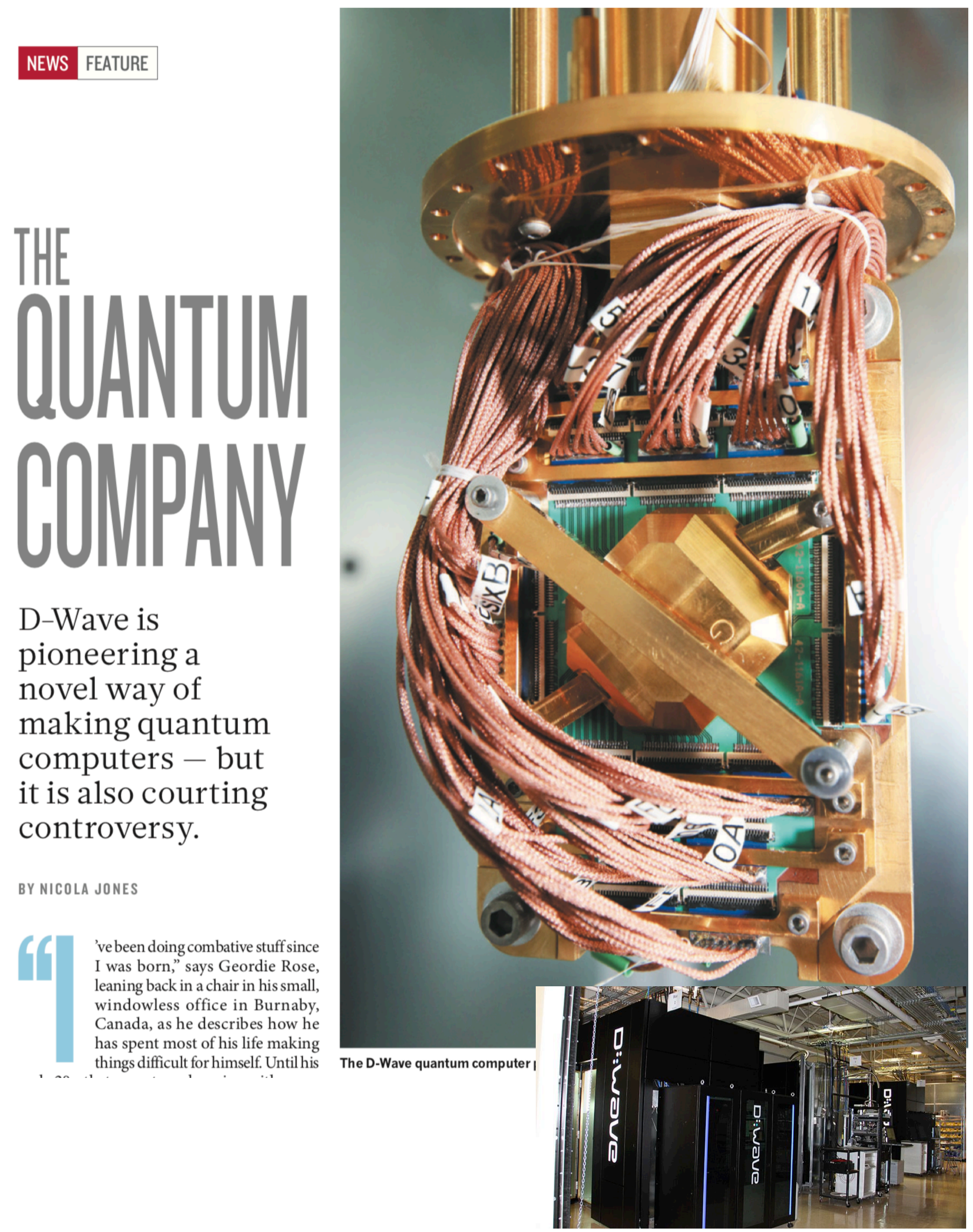
C.A. Perroni, V. Cataudella, M.Cuoco, R. Citro submitted

Annealing machines



Annealing machines





NEWS FEATURE

THE QUANTUM COMPANY

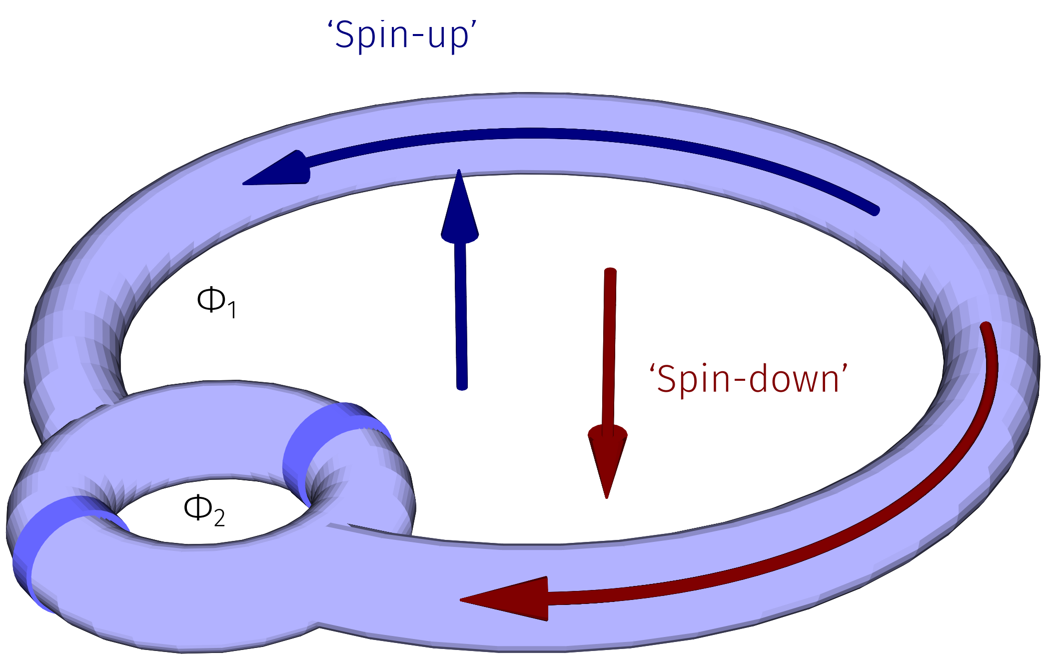
D-Wave is pioneering a novel way of making quantum computers — but it is also courting controversy.

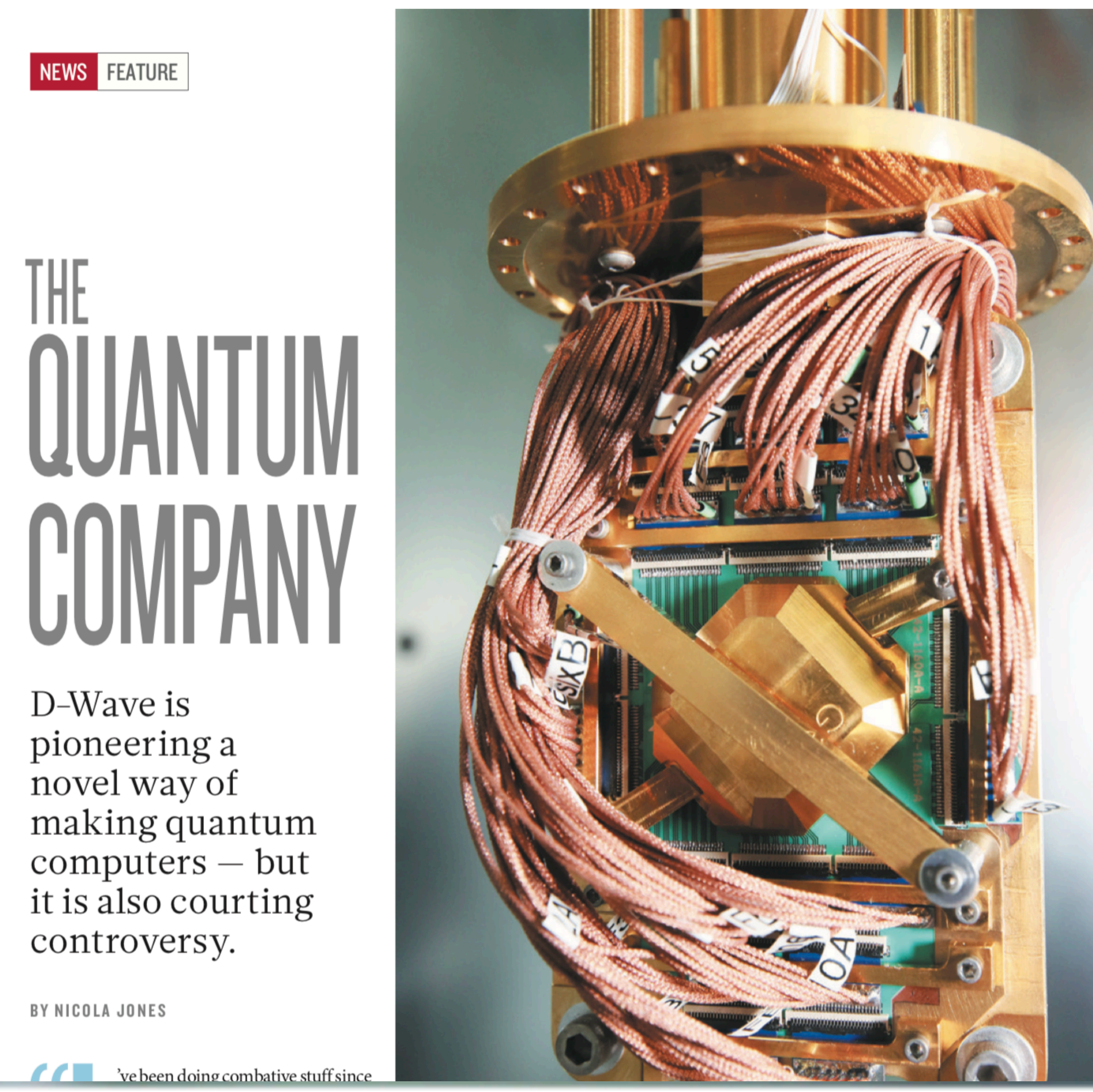
BY NICOLA JONES

"I've been doing combative stuff since I was born," says Geordie Rose, leaning back in a chair in his small, windowless office in Burnaby, Canada, as he describes how he has spent most of his life making things difficult for himself. Until his

The D-Wave quantum computer

Annealing machines





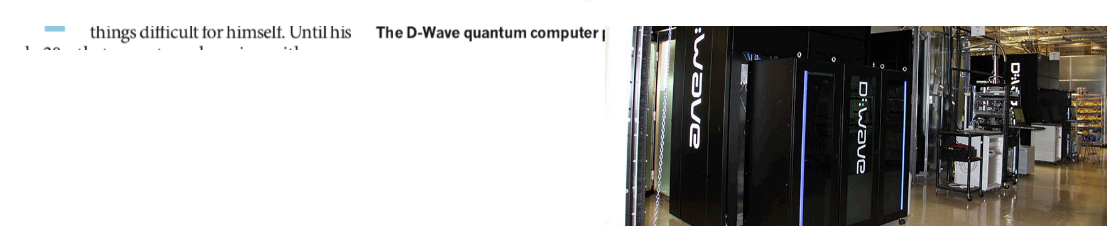
NEWS FEATURE

THE QUANTUM COMPANY

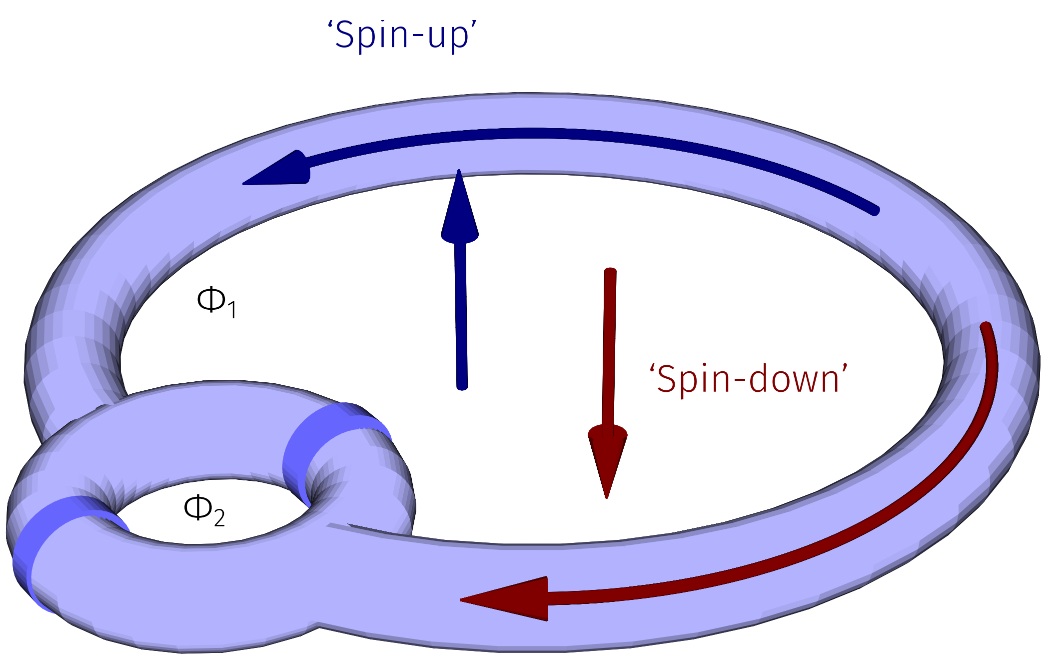
D-Wave is pioneering a novel way of making quantum computers — but it is also courting controversy.

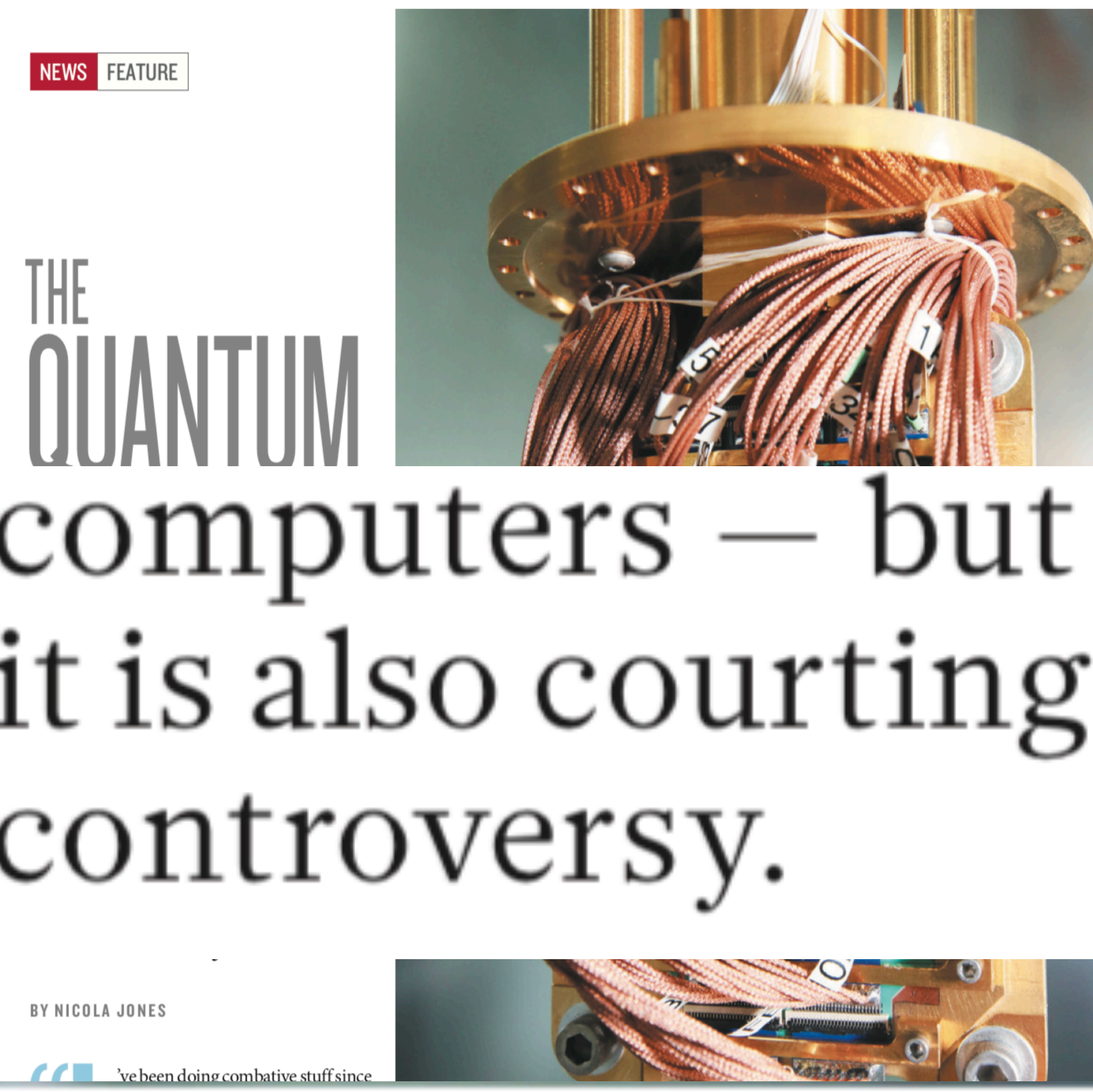
BY NICOLA JONES

The D-Wave quantum computer processor is 3,600 times faster than classical computers at some tasks.



Annealing machines



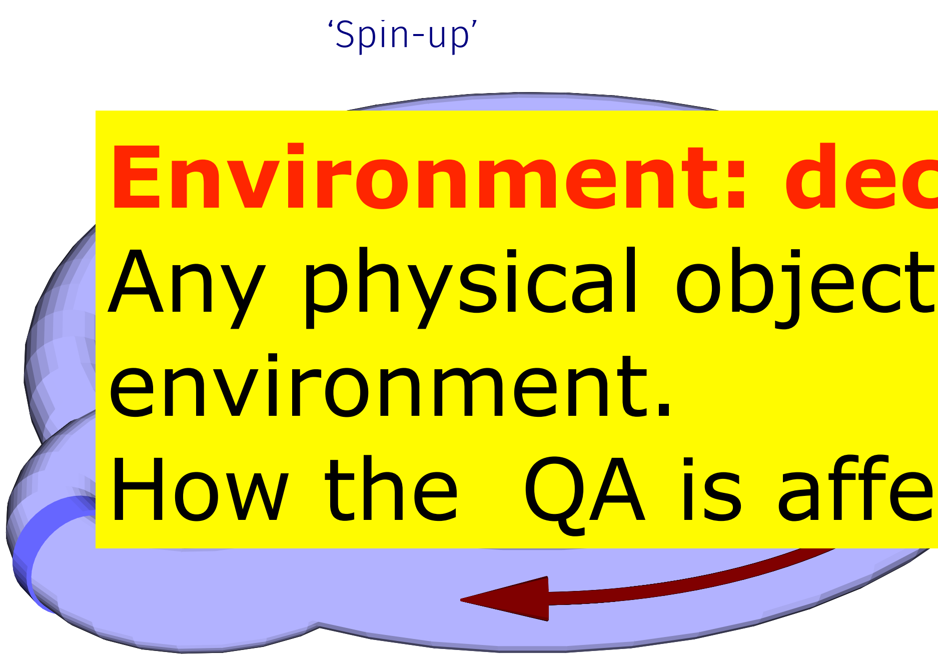

NEWS FEATURE

THE QUANTUM computers — but it is also courting controversy.

BY NICOLA JONES

The D-Wave quantum computer processor is 3,600 times faster than classical computers at some tasks.

Annealing machines

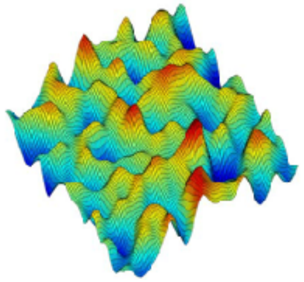


Environment: decoherence and relaxation

Any physical object interacts with the environment.

How the QA is affected by the environment?

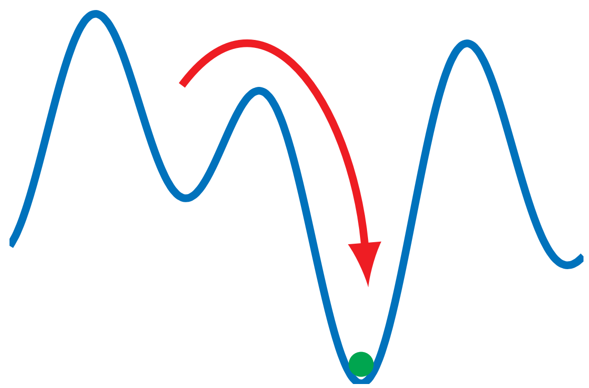
The D-Wave quantum computer processor is 3,600 times faster than classical computers at some tasks.



How to find the ground state?

Thermal annealing

Exploring the landscape **adiabatically** reducing thermal fluctuations



$$T(t) = T_0(1 - t/t_f) + T_{fin} t/t_f$$

Appropriate choice of T_0 and T_{fin} can drive the system through the GS

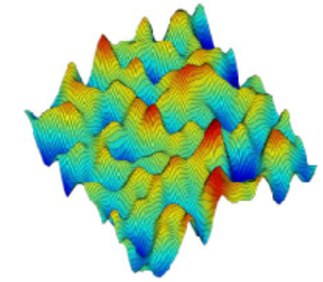
Not very efficient for NP hard problems!

- Many almost equally deep minima
- Separated by thin and high energy barriers

G. Passarelli, G. De Filippis, V. Cataudella, **PL,** PRA, 97, 022319 (2018)

L.M. Cangemi, G. Passarelli, V. Cataudella, **PL,** G. De Filippis, PRB, 98, 184306 (2018)

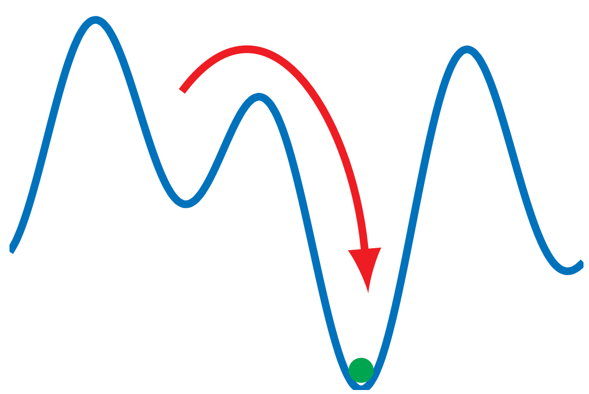
V. Vitale, G. De Filippis, A. De Candia, A. Tagliacozzo, V. Cataudella, **PL**, submitted



How to find the ground state?

Thermal annealing

Exploring the landscape **adiabatically** reducing thermal fluctuations



$$T(t) = T_0(1 - t/t_f) + T_{fin} t/t_f$$

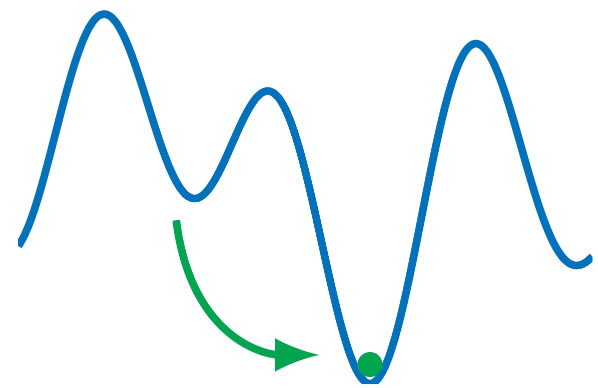
Appropriate choice of T_0 and T_{fin} can drive the system through the GS

Not very efficient for NP hard problems!

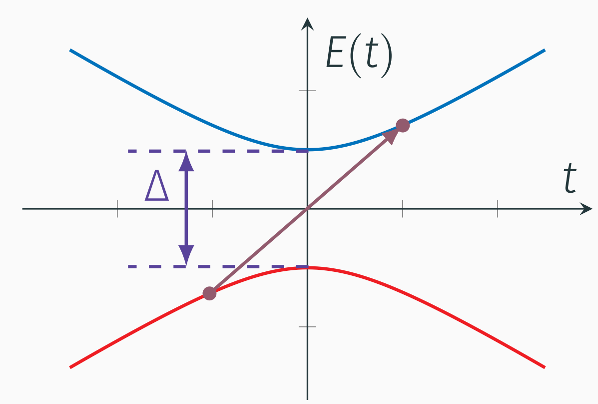
- Many almost equally deep minima
- Separated by thin and high energy barriers

Quantum annealing

Exploring the landscape **adiabatically** reducing quantum fluctuations!



$$H(t) = H_0(1 - t/t_f) + H_{fin} t/t_f$$



Landau-Zener

$$P_{LZ} = e^{-\gamma t_f \Delta^2}$$

t_f must be much longer than the inverse gap squared: $t_f \gg \Delta^{-2}$

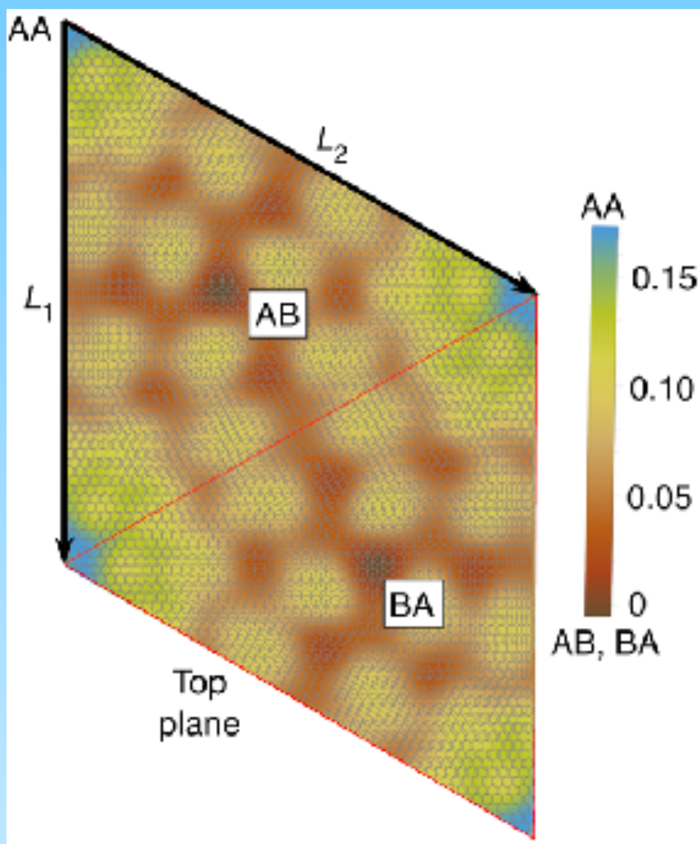
G. Passarelli, G. De Filippis, V. Cataudella, **PL,** PRA, 97, 022319 (2018)

L.M. Cangemi, G. Passarelli, V. Cataudella, **PL,** G. De Filippis, PRB, 98, 184306 (2018)

V. Vitale, G. De Filippis, A. De Candia, A. Tagliacozzo, V. Cataudella, **PL**, submitted

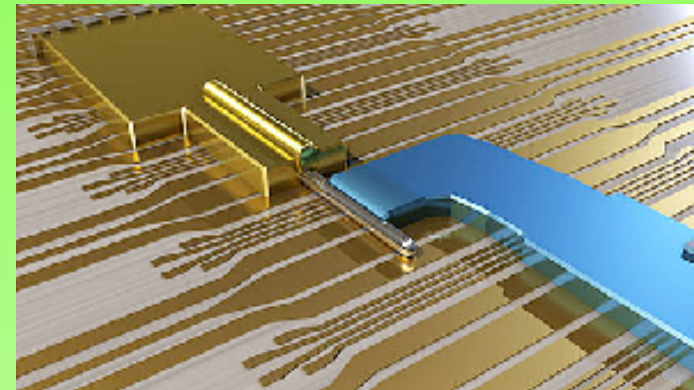
Quantum Materials

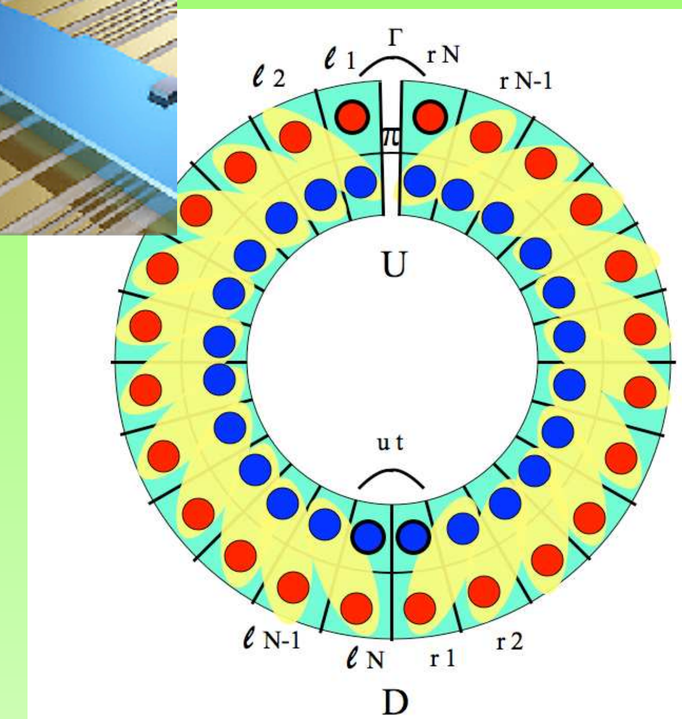
Engineer artificial materials to simulate other materials!



Topological Quantum Computation

Majorana Fermions





Theory and Simulation

Adiabatic quantum computation