Title: The Fascinating, Weird World of Quantum Matter

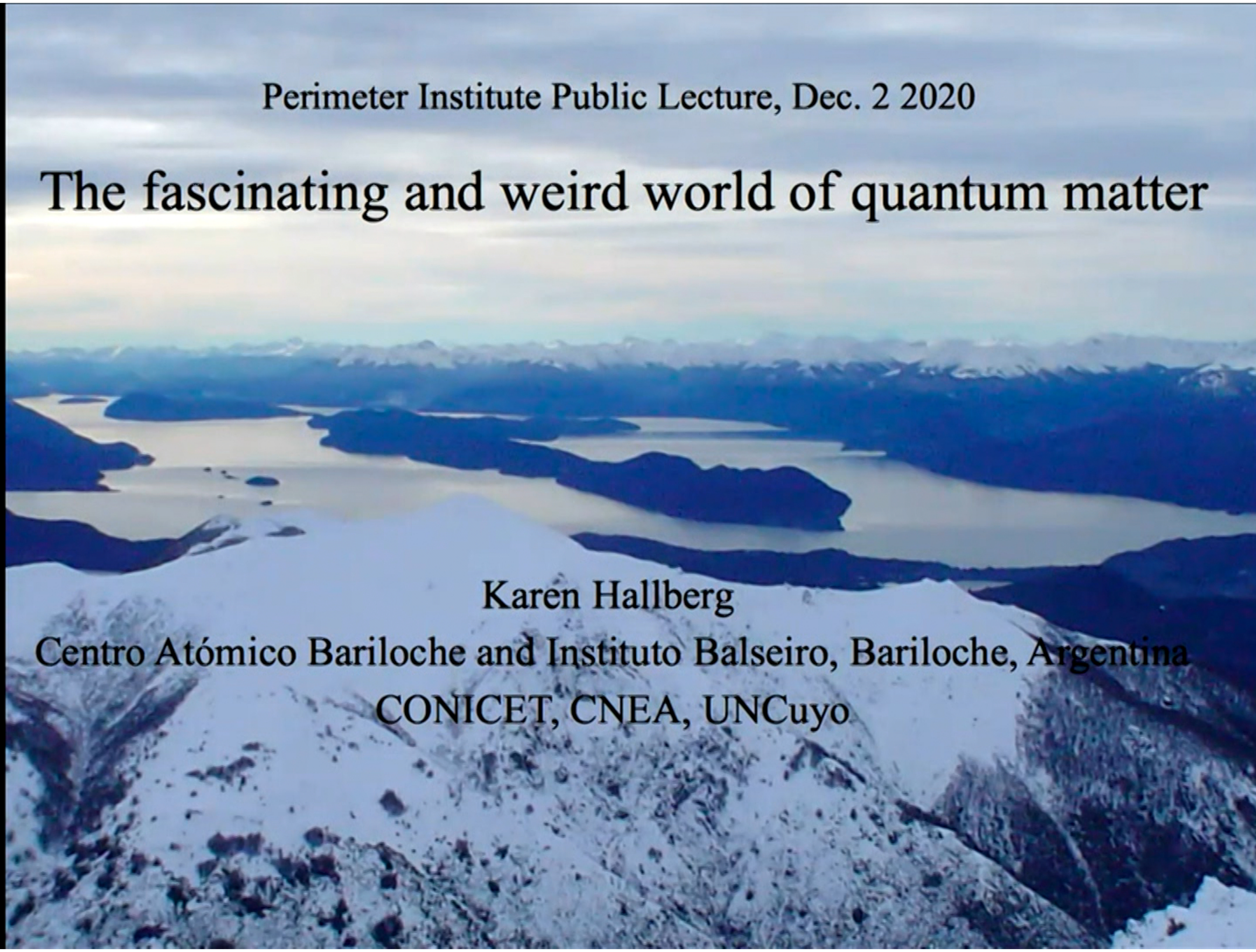
Speakers:

Collection: Perimeter Public Lectures

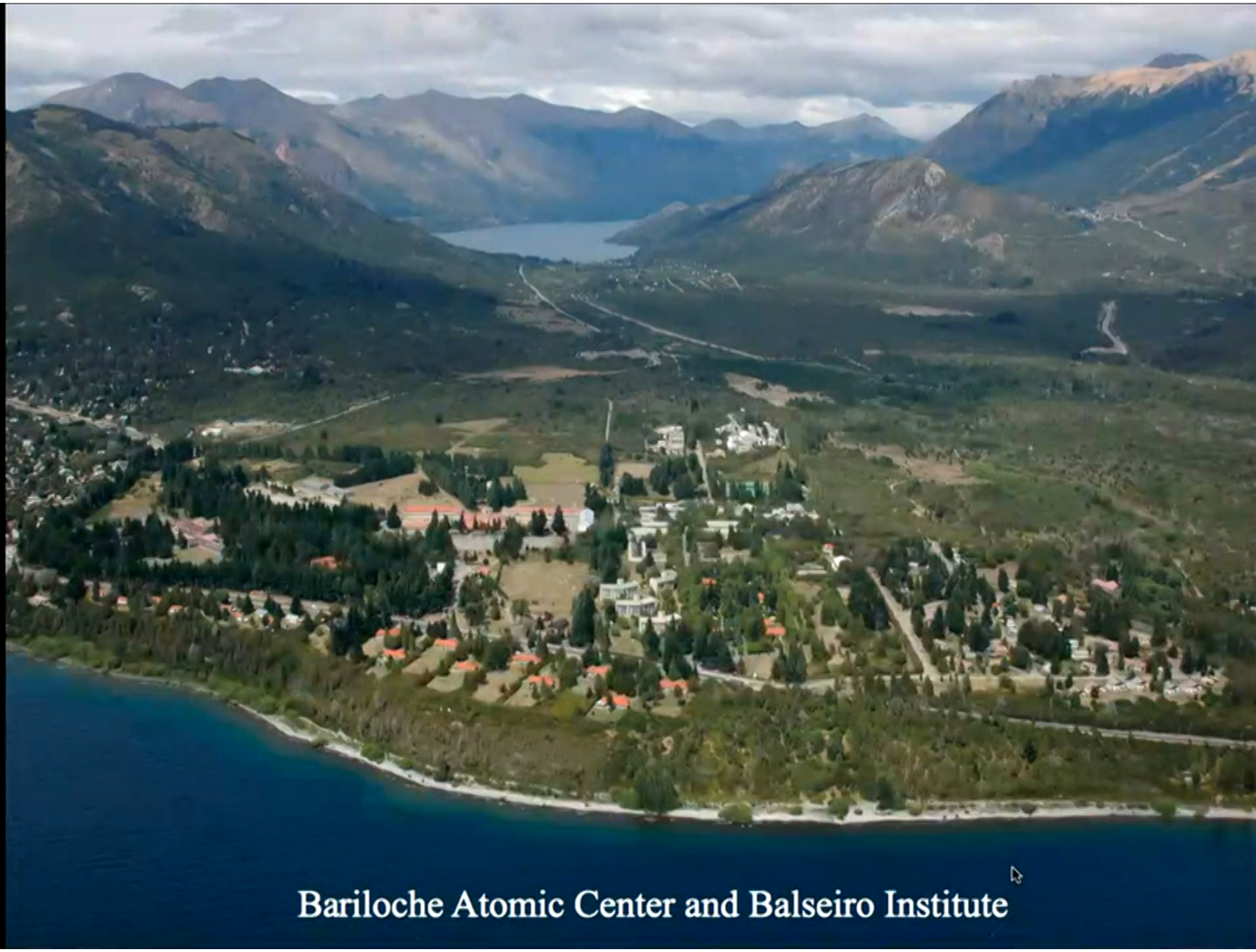
Date: December 02, 2020 - 7:00 PM

URL: http://pirsa.org/20120032

Abstract: In her December 2 Perimeter Public Lecture webcast, Hallberg will explore examples of emergent phenomena and demonstrate how we can tackle these problems using quantum information to filter the most relevant data. By advancing research in this field, we hope to seed advances with applications from medical equipment and new materials to efficient energy generation, transportation, and storage.


Perimeter Institute Public Lecture, Dec. 2 2020
The fascinating and weird world of quantum matter
Karen Hallberg
Centro Atómico Bariloche and Instituto Balseiro, Bariloche, Argentina
CONICET, CNEA, UNCuyo


Bariloche, Argentina
BRAZIL
ARGENTINA
North Atlantic Ocean
South Atlantic Ocean
South Pacific Ocean


Bariloche Atomic Center and Balseiro Institute

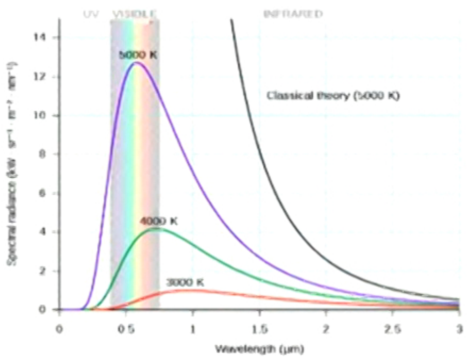
1900 black-body radiation

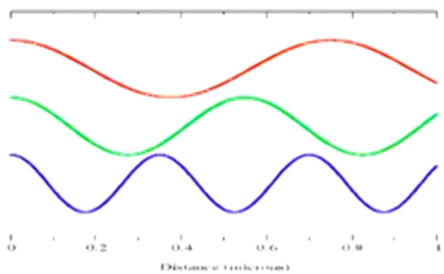
1905 photoelectric effect

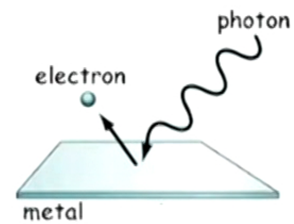
Max-Planck

Light as a particle?
Photons!

Albert Einstein







E=hν=hc/λ

$$\hbar = \frac{h}{2\pi}$$

Planck's constant h=6.626 069 934 10^{-34} kg m^2/s

1900 black-body radiation

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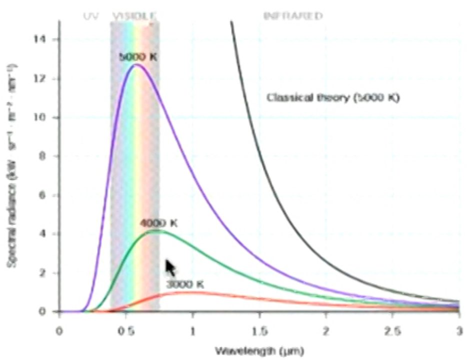
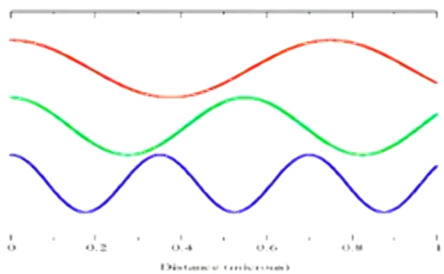
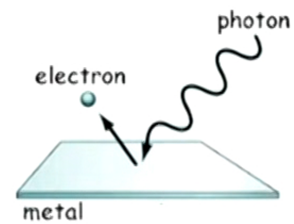




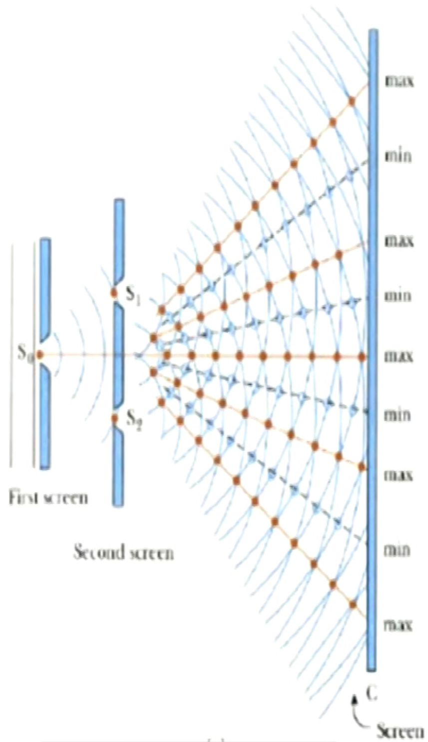


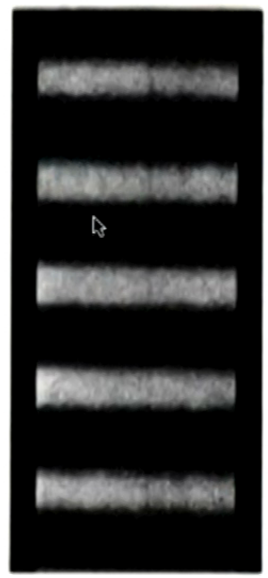
$E=h\nu=hc/\lambda$

$$\hbar = \frac{h}{2\pi}$$

Planck's constant h=6.626 069 934 10^{-34} kg m^2/s

Particles as waves?
Young's double slit experiment!





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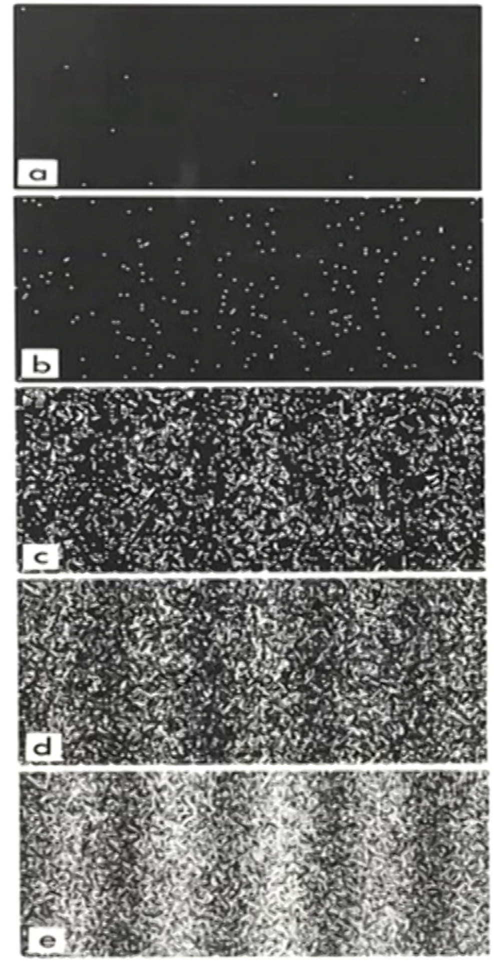
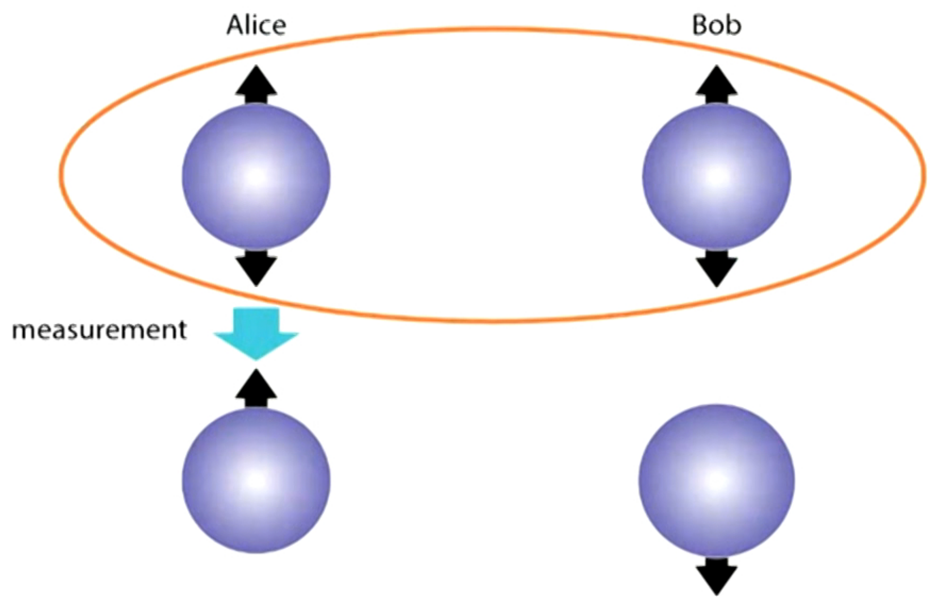


$$\lambda = \frac{h}{mv}$$

electron $\lambda \cong 0.1\text{nm}$

A. Tonomura 2007

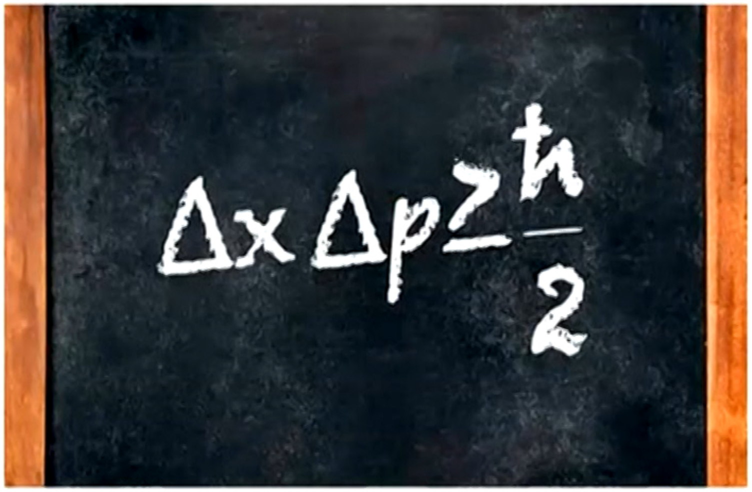
Entanglement!



Uncertainty!

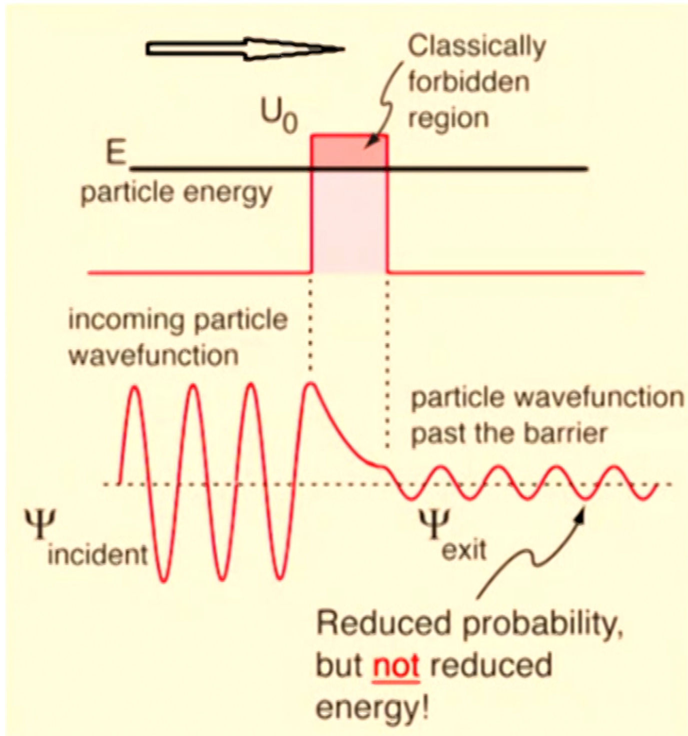
1927 Werner Heisenberg

Uncertainty!



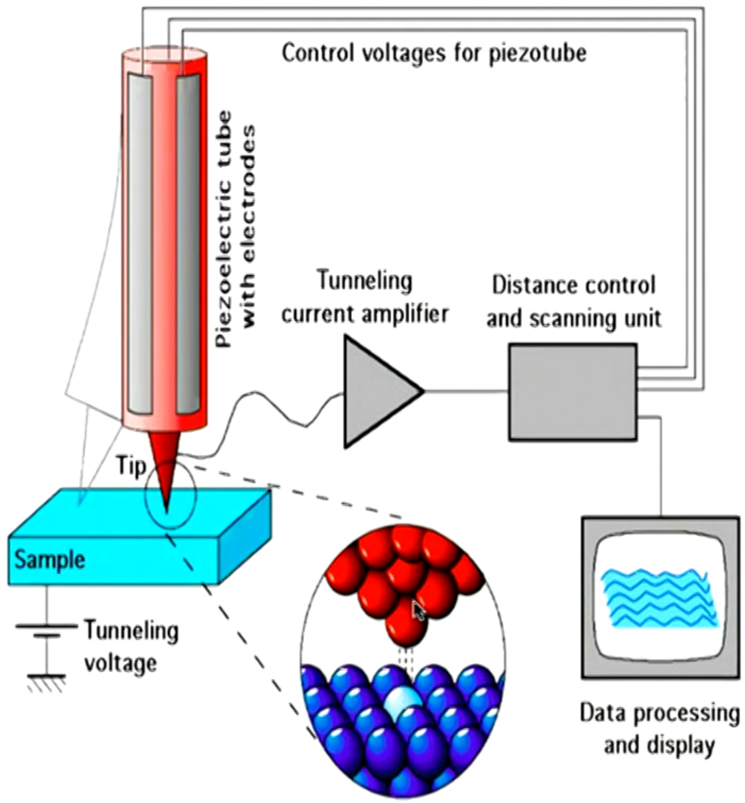
1927 Werner Heisenberg

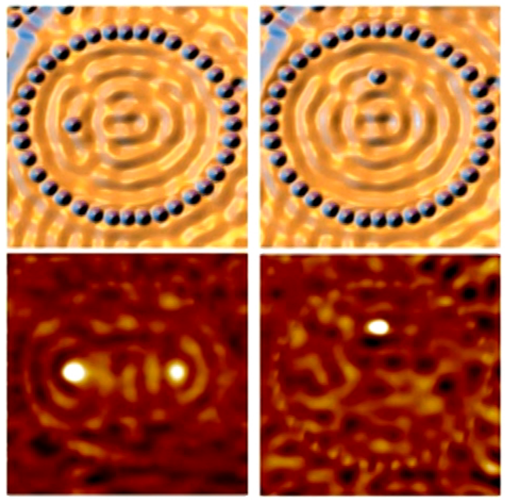
Tunneling!



Classically
forbidden
region
U_0
E
particle energy
incoming particle
wavefunction
particle wavefunction
past the barrier
$\Psi_{incident}$
Ψ_{exit}
Reduced probability,
but not reduced
energy!

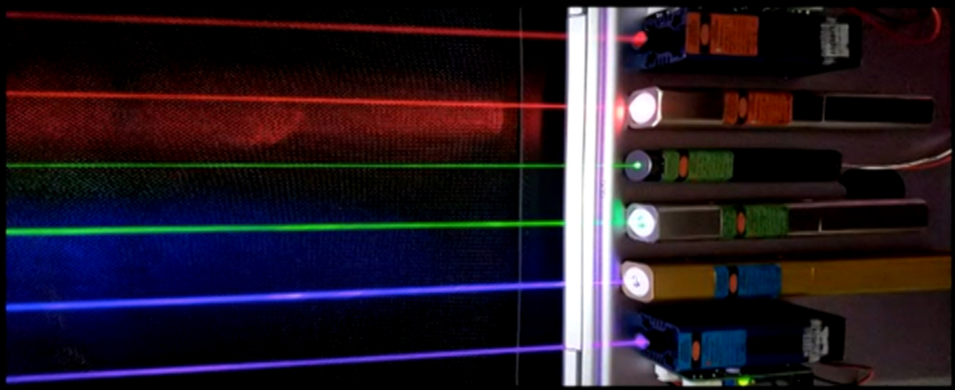
STM and electronic surface waves

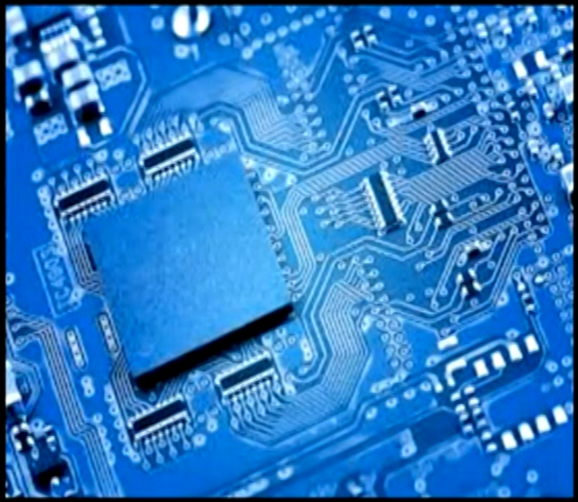


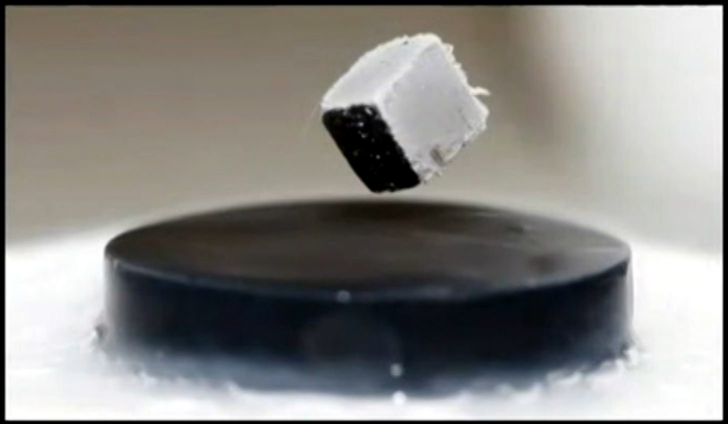


Quantum corrals, Manoharan et al, IBM

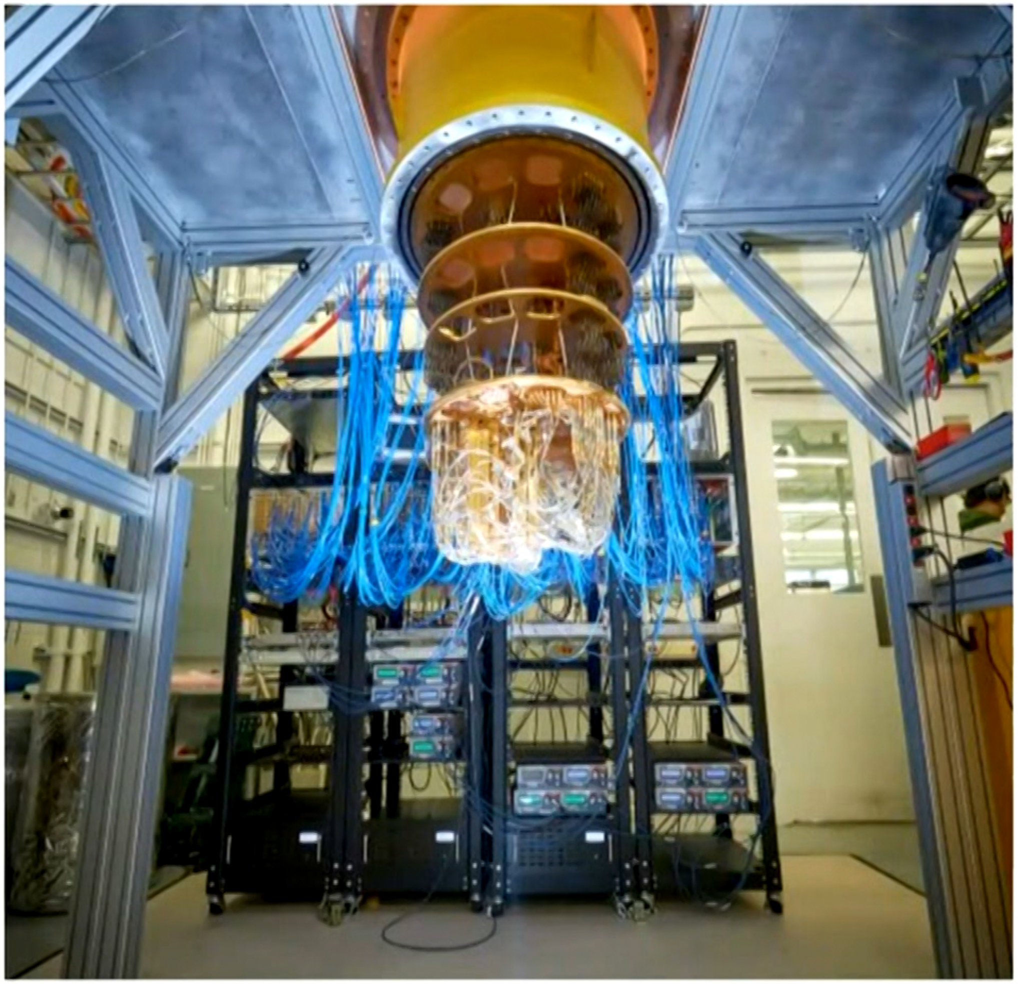
In spite of its weirdness quantum behavior is ubiquitous!







Google's Sycamore processor

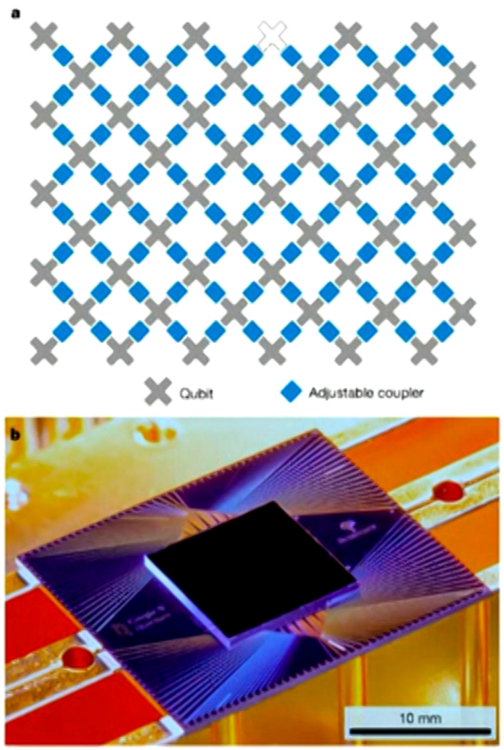


Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article



generated random number in 200s
(vs 10000yrs classical computer?)

Applications:
drug design
new materials design
climate science
finances
optimization problems
cryptography
communications

The concept of emergence

Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles. (US National Academies)

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The reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.
- P. W. Anderson*, "More is Different," Science (177), 393-396, 1972.

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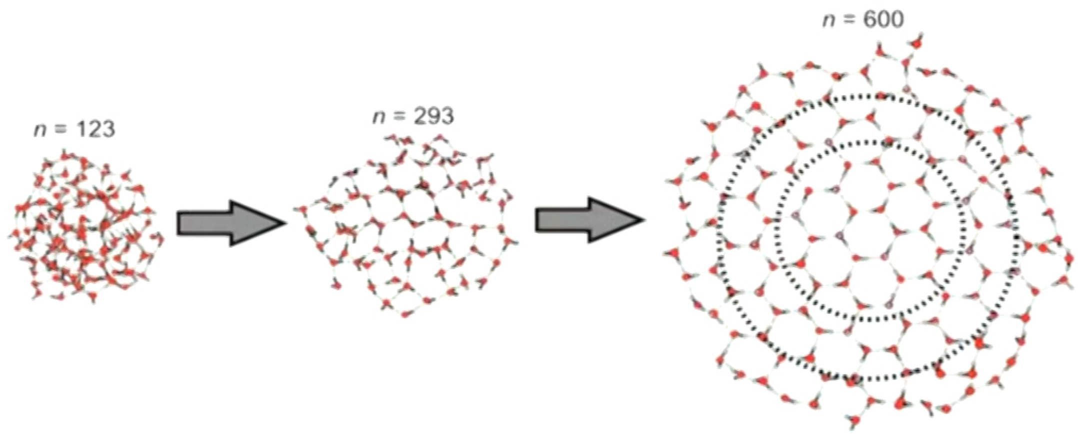
Everything that matters in science now is organisational. The reductionist (fundamental) approach has stopped from being useful. Bob Laughlin*

Topic or Phenomenon	**Individual piece**	**Interactions**
Ant colony	Ants	Pheromone trails
Consciousness	Neurons	Neural connections and firing
Crystals	Molecules	Intermolecular forces
Traffic patterns	Cars	People's reactions to car distance or brake lights
Schooling or Flocking	Fish or Birds	Fish/bird reactions to neighbor's distance and movement
City neighborhoods	People	People's and businesses' reactions to a neighborhood's reputation and flavor.
Superconductivity	Electrons	Lattice vibrations called phonons
Slime mold slug	Slime mold spores	Chemical signals
Superfluid	Atoms	Bose-Einstein statistics/quantum attraction
Crowd behavior	People	Rules for social interaction/neighbor distances
Magnetism	Magnetic domains	Magnetic coupling
Heartbeat (synchronicity of pacemaker cells)	Pacemaker cells in heart	Coupled action potentials of pacemaker cells
Synchronicity	Fireflies	Mimicry plus internal pacemaker cells
Liquid crystals	Molecules	Intermolecular interactions
Bose-Einstein Condensation	Atoms or molecules	Quantum mechanical uncertainty resulting in single wave function for all atoms
Color	Atoms	Light and atomic structure
Stock market	Investors	Transactions

Examples of emergent phenomena in quantum condensed matter



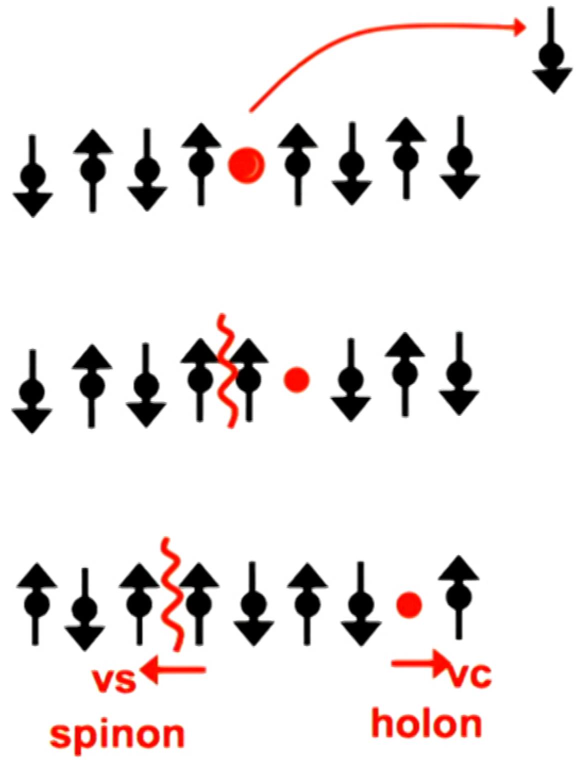
Is there a critical number above which crystal order emerges?

Pradzynski et al, Science 2012

And what if we combine quantum weirdness and complexity?

⟶ quantum condensed matter!

Emergent phenomena in low-dimensional systems:
Charge-spin fractionalisation of the electron



Haldane, Schulz, Anderson Lieb&Wu

Emergent phenomena in low-dimensional systems:
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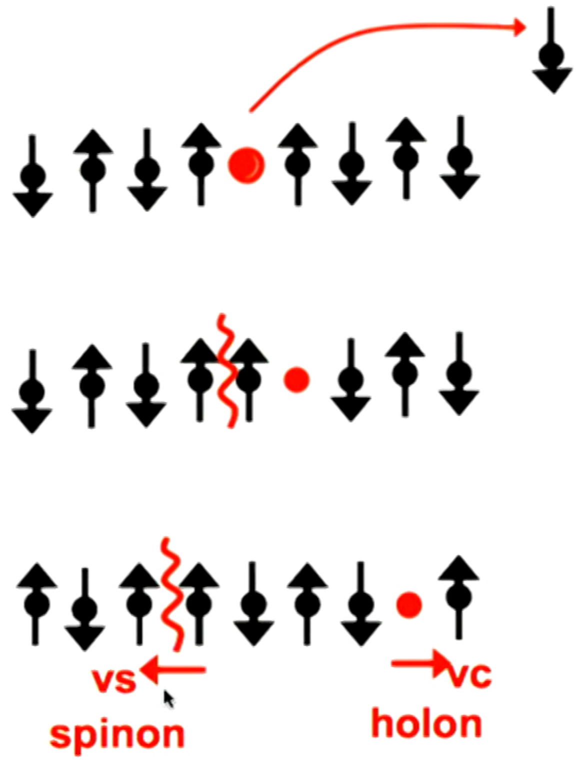


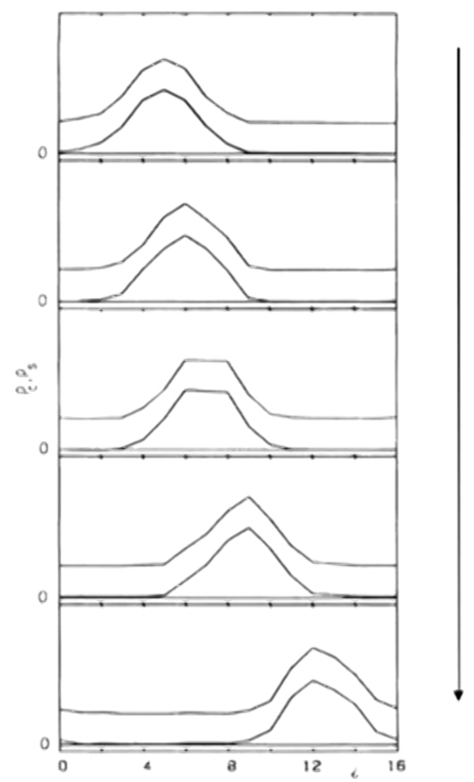
Haldane, Schulz, Anderson Lieb&Wu

PHYSICAL REVIEW B VOLUME 47, NUMBER 10 1 MARCH 1993-II

Numerical study of charge and spin separation in low-dimensional systems

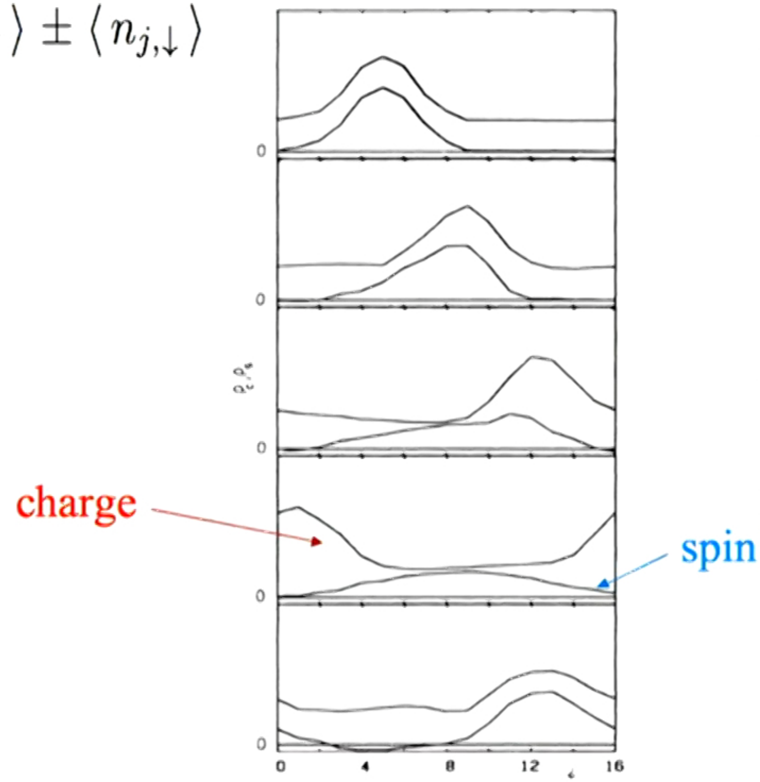
E. A. Jagla, K. Hallberg, and C. A. Balseiro
Centro Atómico Bariloche and Instituto Balseiro, 8400 S. C. de Bariloche, Argentina
(Received 16 June 1992)

U=0



$$\rho_j^{\pm} = \langle n_{j,\uparrow} \rangle \pm \langle n_{j,\downarrow} \rangle$$

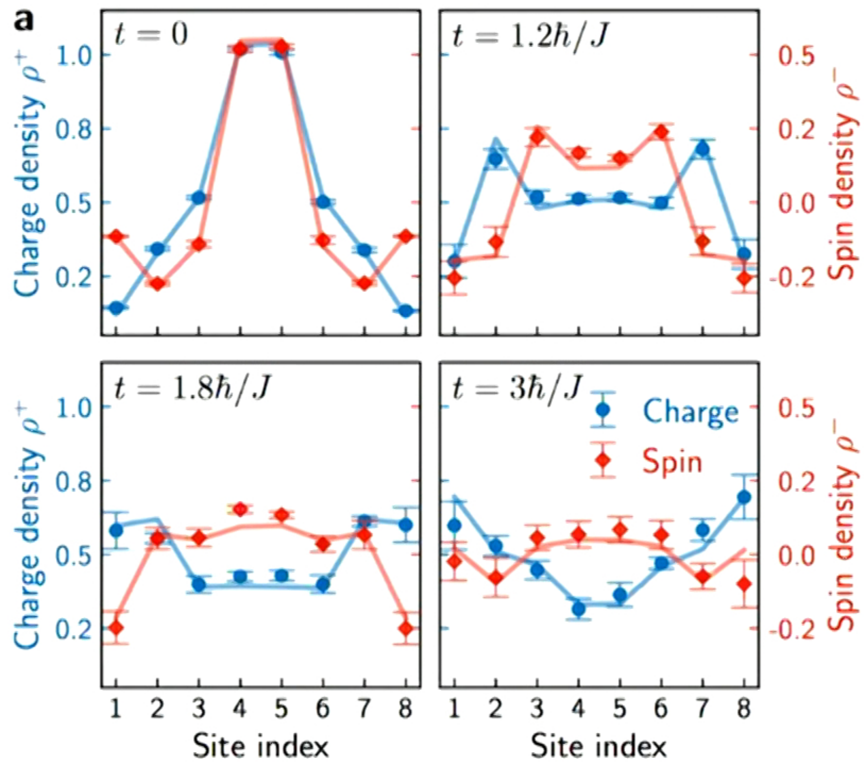
U=10t



Observation of separated dynamics of charge and spin in the Fermi-Hubbard model

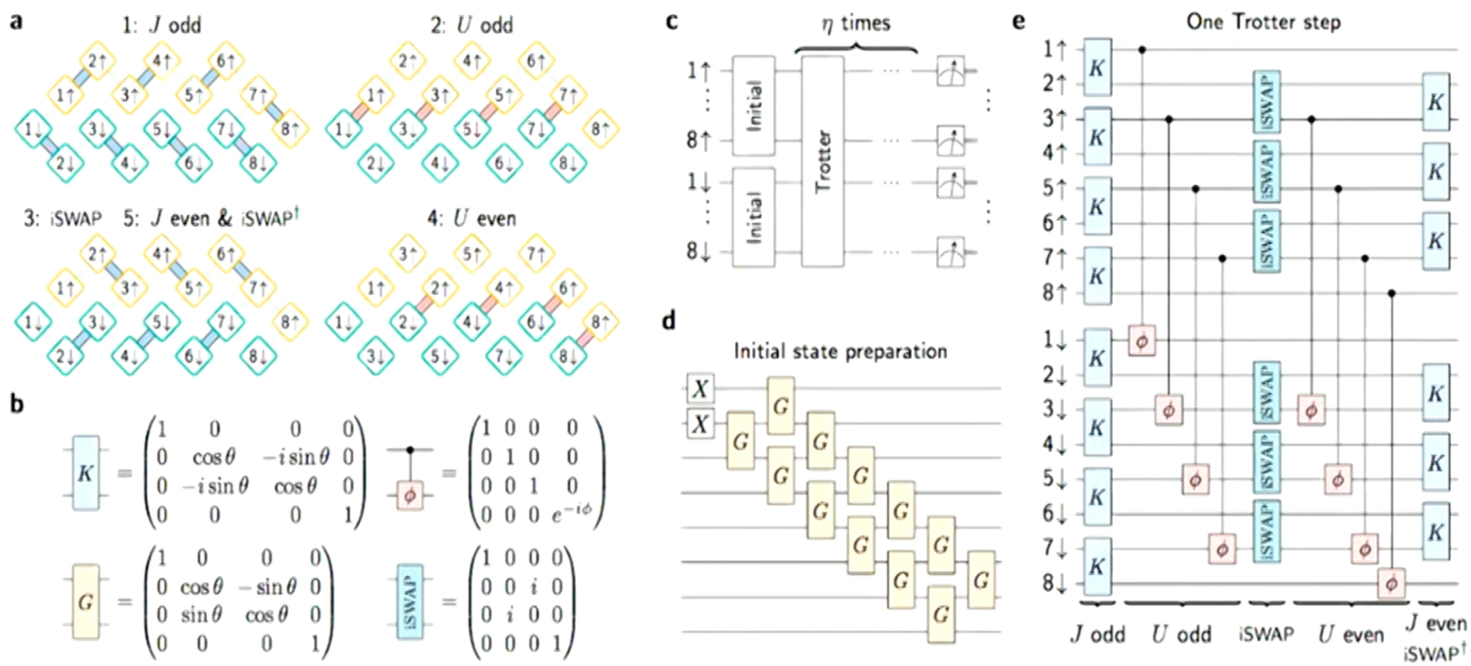
Google AI Quantum and collaborators*
(Dated: October 19, 2020)

arXiv:201007965



Simulation of correlated models using quantum computers!
QC Sycamore (google), using superconducting resonators

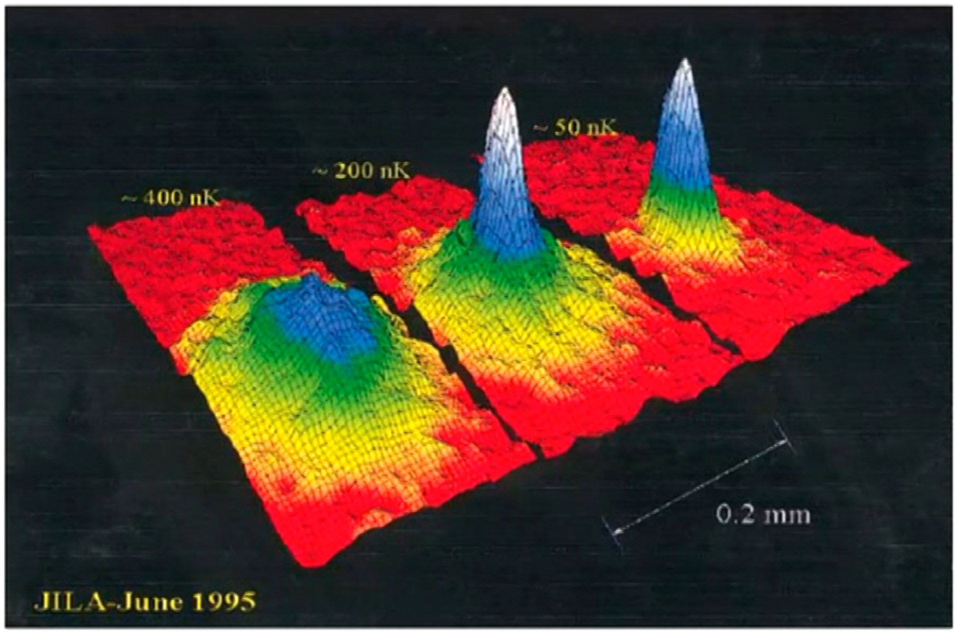
Sycamore



a
1: J odd
2: U odd
3: iSWAP 5: J even & iSWAP†
4: U even
b
c
η times
Initial
Trotter
d
Initial state preparation
e
One Trotter step
J odd
U odd
iSWAP
U even
J even
iSWAP†

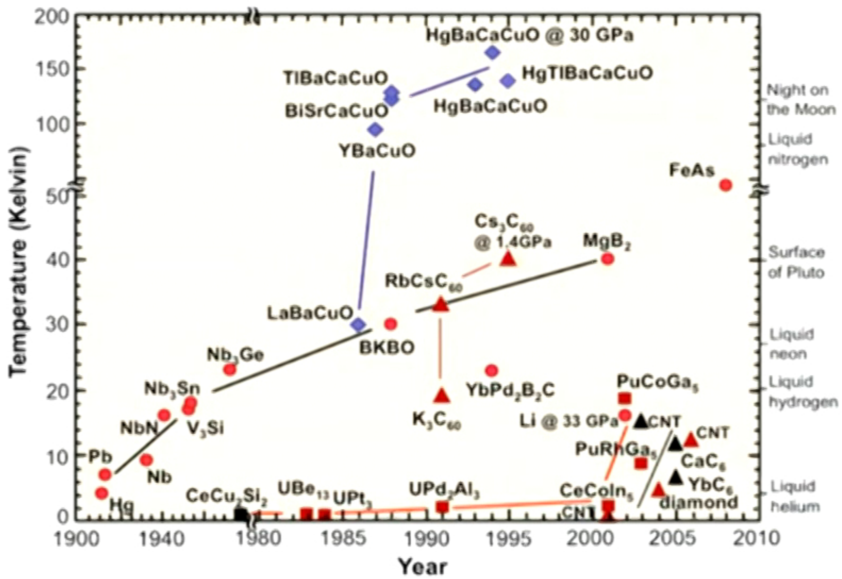
Ultracold atomic gases
(quantum simulators)

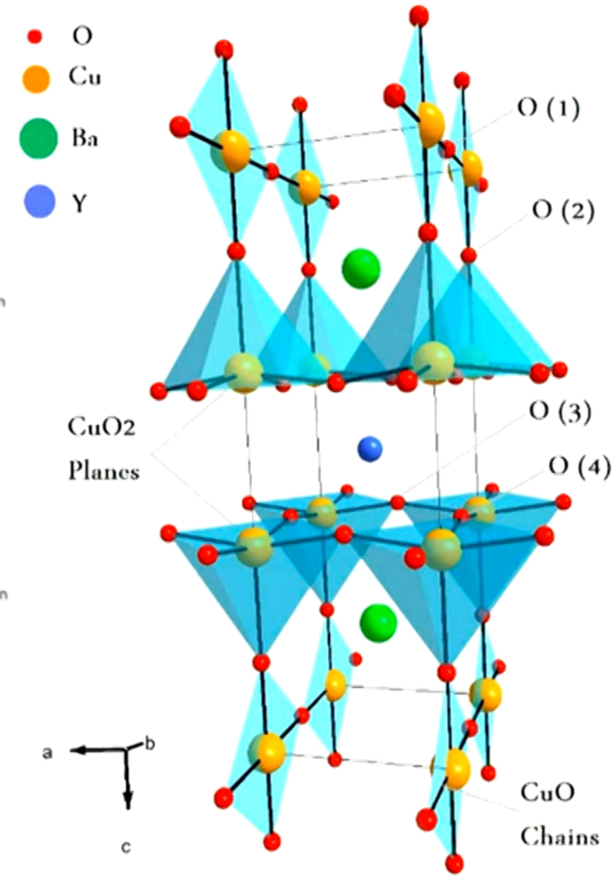
Bose-Einstein condensation (BEC) (5^{th} state of matter, macroscopic)
1995: Weimann* and Cornell* in ^{87}Rb @170nK
Ketterle* et al with ^{23}Na (Nobel Prize 2001)



In June 2020, the Cold Atom Laboratory experiment on board the International Space Station successfully created a BEC

High temperature superconductors (High Tc)
(discovered by Bednorz and Müller at IBM, Zürich in 1986)
Nobel prize 1987





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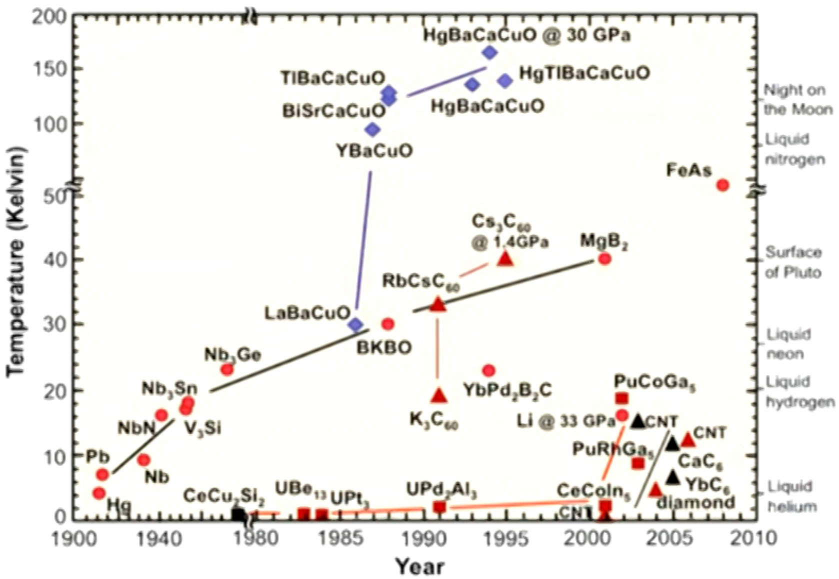
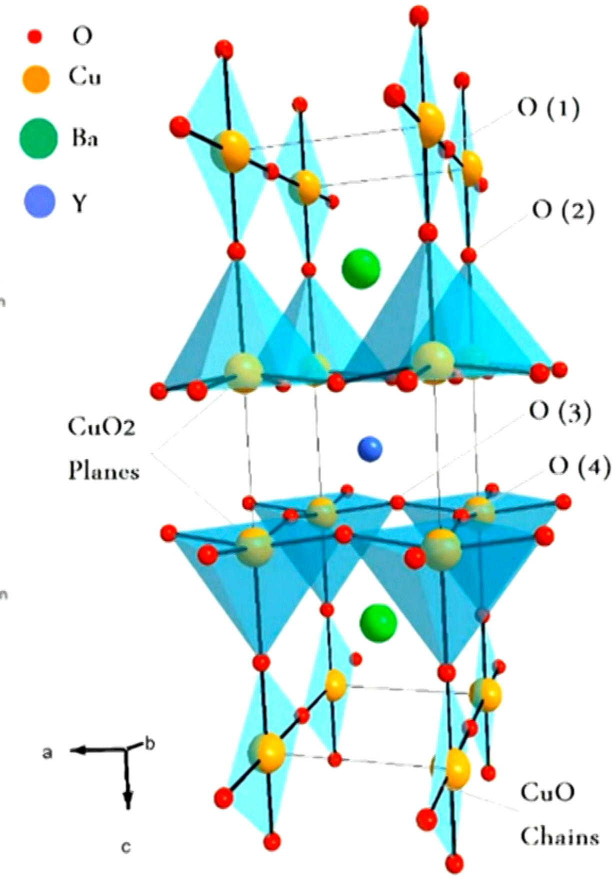




Example: Heisenberg model

$H=J \sum_{i} \mathbf{S}_i \mathbf{S}_{i+1}$ N sites (qubits), 2^N states

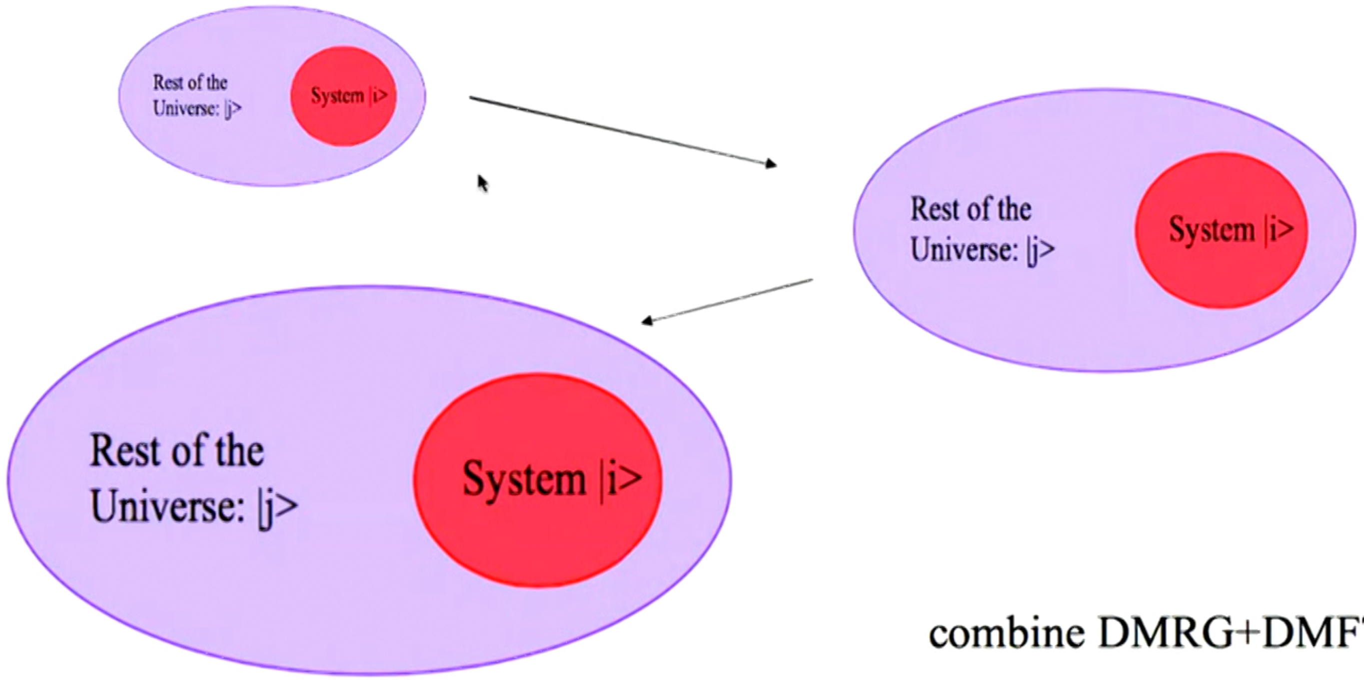
Exponential amount of configurations!

Using quantum information to optimise calculations:

An interesting new perspective on Quantum Mechanics

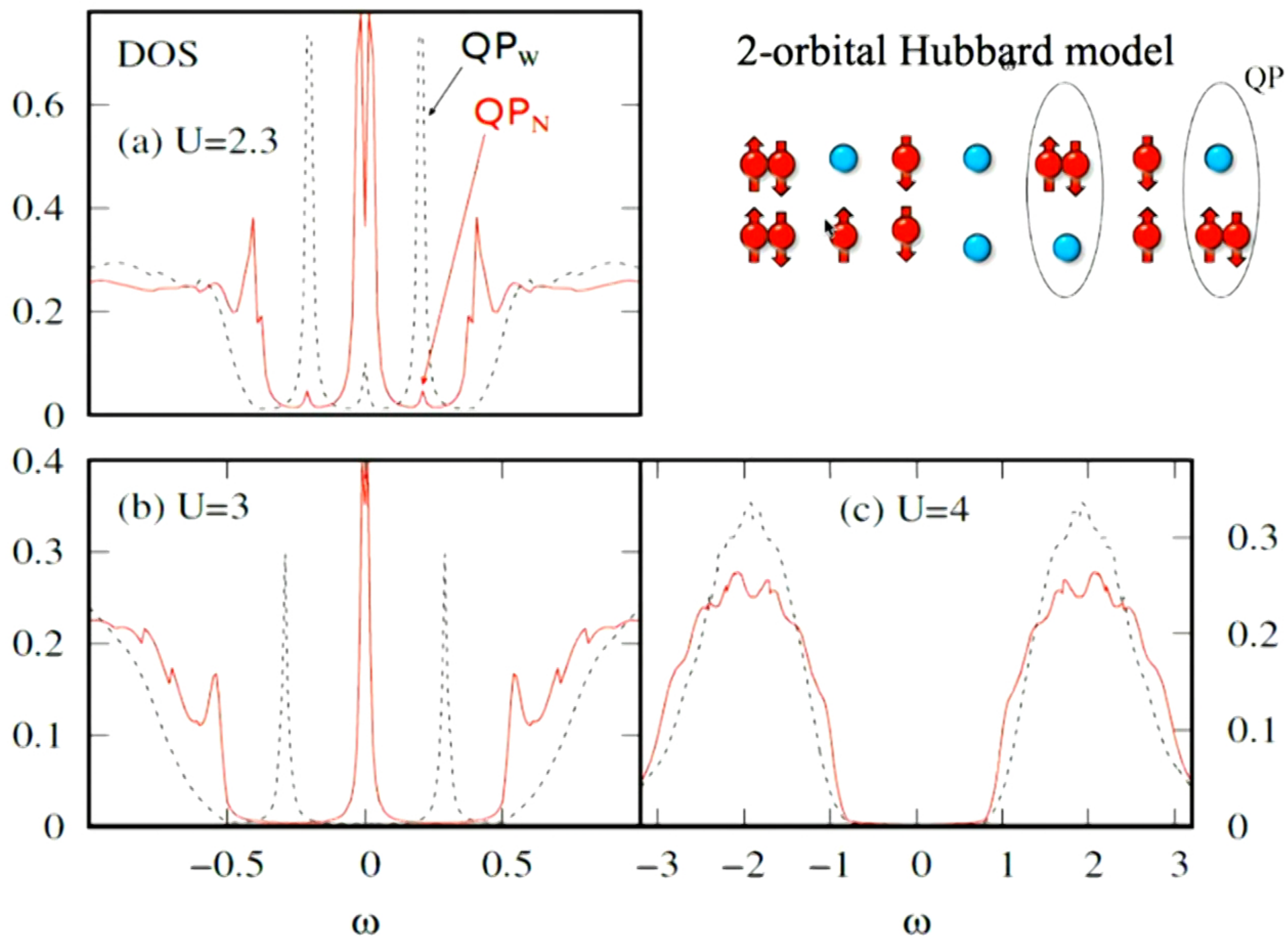
"The most challenging and interesting problems in quantum dynamics involve understanding the behaviour of strongly-coupled many-body systems... Better ways of characterizing the features of many particle entanglement may lead to new and more effective methods for understanding the dynamical behaviour of complex quantum systems." John Preskill (2000)

We use the Density Matrix Renormalisation Group (S. White 1992):
- it uses **quantum information** to keep the **most relevant quantum states**



combine DMRG+DMFT!

- García, Hallberg, Rozenberg, PRL. 2004 and PRB(RC) 2005
- Hallberg, García, Cornaglia, Facio, Núñez Fernández, EPL Perspectives 2015
- *Solving the multi-site and multi-orbital Dynamical Mean Field Theory using Density Matrix Renormalization*, Y. Núñez-Fernández and K. Hallberg, Front. Phys. 6:13 (2018)



Núñez-Fernández, Kotliar, Hallberg, PRB(R) 2018


Main collaborators:
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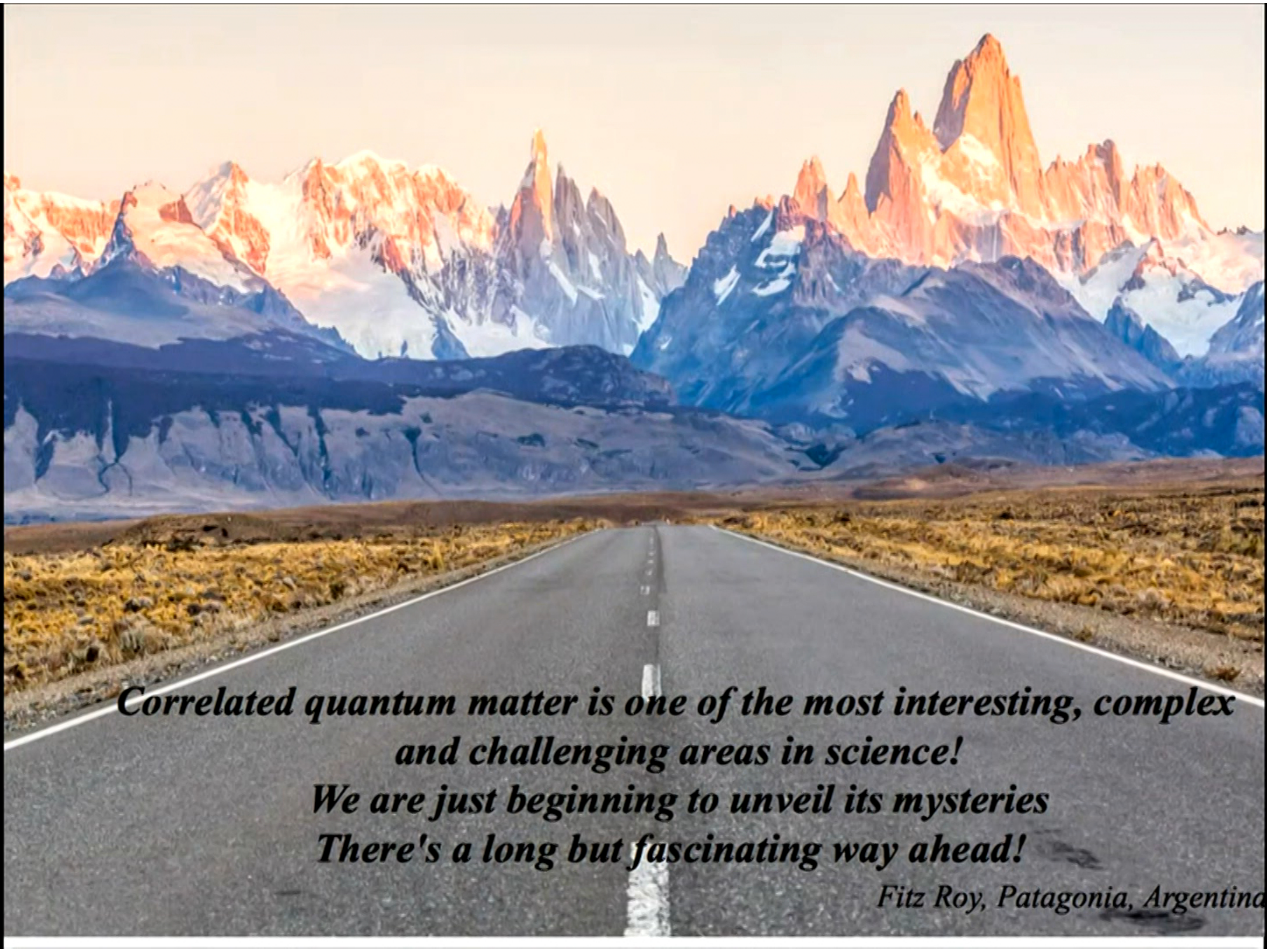
Cristian Batista (Tennessee)
Elbio Dagotto (Tennessee)
Marcelo Rozenberg (Orsay)
Michel Avignon (Grenoble)
Diego Frustaglia (Spain)
Peter Horsch (Stuttgart)
Arno Kampf (Augsburg); T. Pruschke (Göttingen)
Bruce Normand (Switzerland)
Masatoshi Imada (Tokyo)
Hiroyuki Shiba (Tokyo)
S. Ramasesha (Bangalore)
Jose d'Albuquerque e Castro (Rio)
Yuriel Núñez-Fernández (Bariloche)
Julián Rincón (Colombia)
Marco Nizama (Bariloche)
Daniel García (Bariloche)
Blas Alascio (Bariloche)
Pablo Cornaglia (Bariloche)
Carlos Balseiro (Bariloche)
Armando Aligia (Bariloche)
César Proetto (Bariloche)
Liliana Arrachea (Buenos Aires)
María E. Torio (Rosario)
Adriana Moreo (Tennessee)
Students: Nair Aucar Boidi
Hernén Fernández García


Correlated quantum matter is one of the most interesting, complex
and challenging areas in science!
We are just beginning to unveil its mysteries
There's a long but fascinating way ahead!
Fitz Roy, Patagonia, Argentina