Giuseppe A. Falci

(University of Catania, I)

Scuola Superiore di Catania, 12 Marzo, 2026

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Missione 4
Istruzione e Ricerca

Giuseppe A. Falci
University of Catania

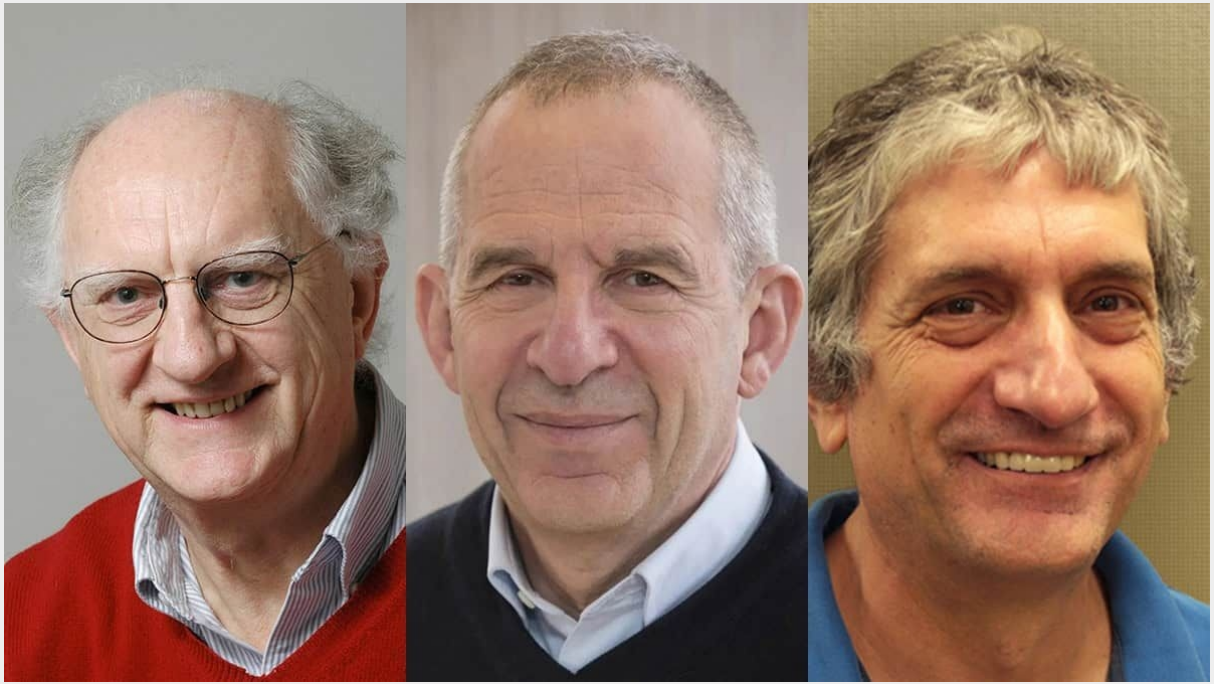
Dai gatti di Schrödinger alle Tecnologie Quantistiche il Nobel per la Fisica 2025

Uni ct FISICA E ASTRONOMIA "ETTORE MAJORANA"
INFN Istituto Nazionale di Fisica Nucleare

QuCaT Quantum Technologies at UniCT

Scuola Superiore di Catania, Novembre 14, 2025

Nobel Prize in Physics 2025
John Clarke, Michel Devoret and John Martinis



"for the discovery of **macroscopic quantum mechanical tunnelling** and **energy quantisation** in an electric circuit"

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Outline

1985 MQT

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Outline

Motivation: is "classicality" an emergent property?

1985 MQT

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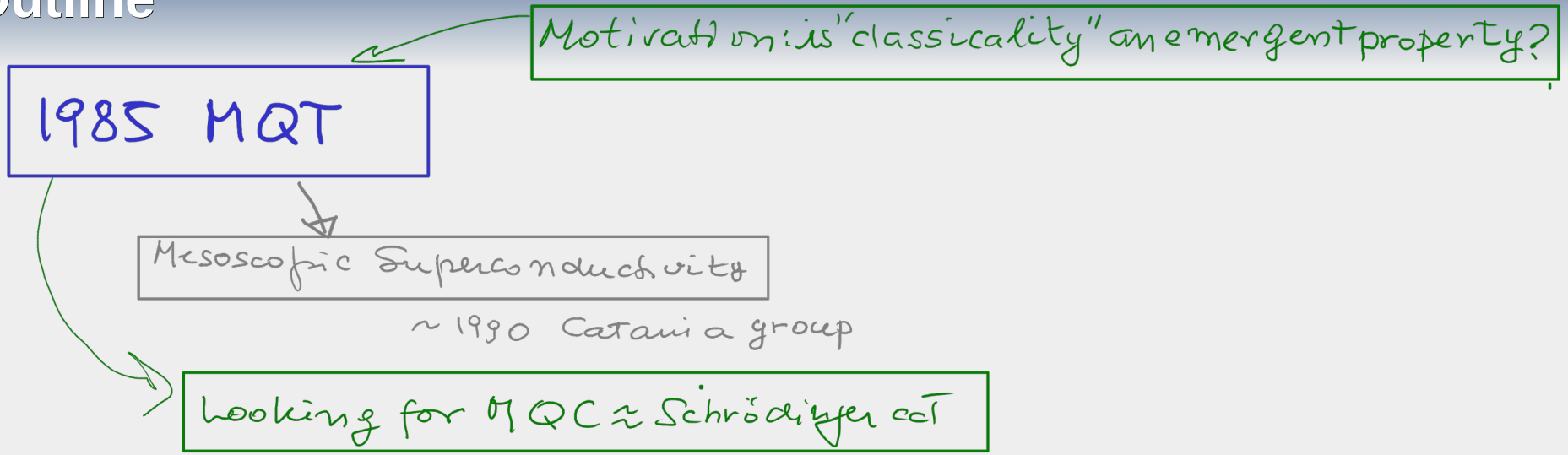
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Mesoscopic Superconductivity
~ 1990 Catania group
looking for MQC ≈ Schrödinger cat

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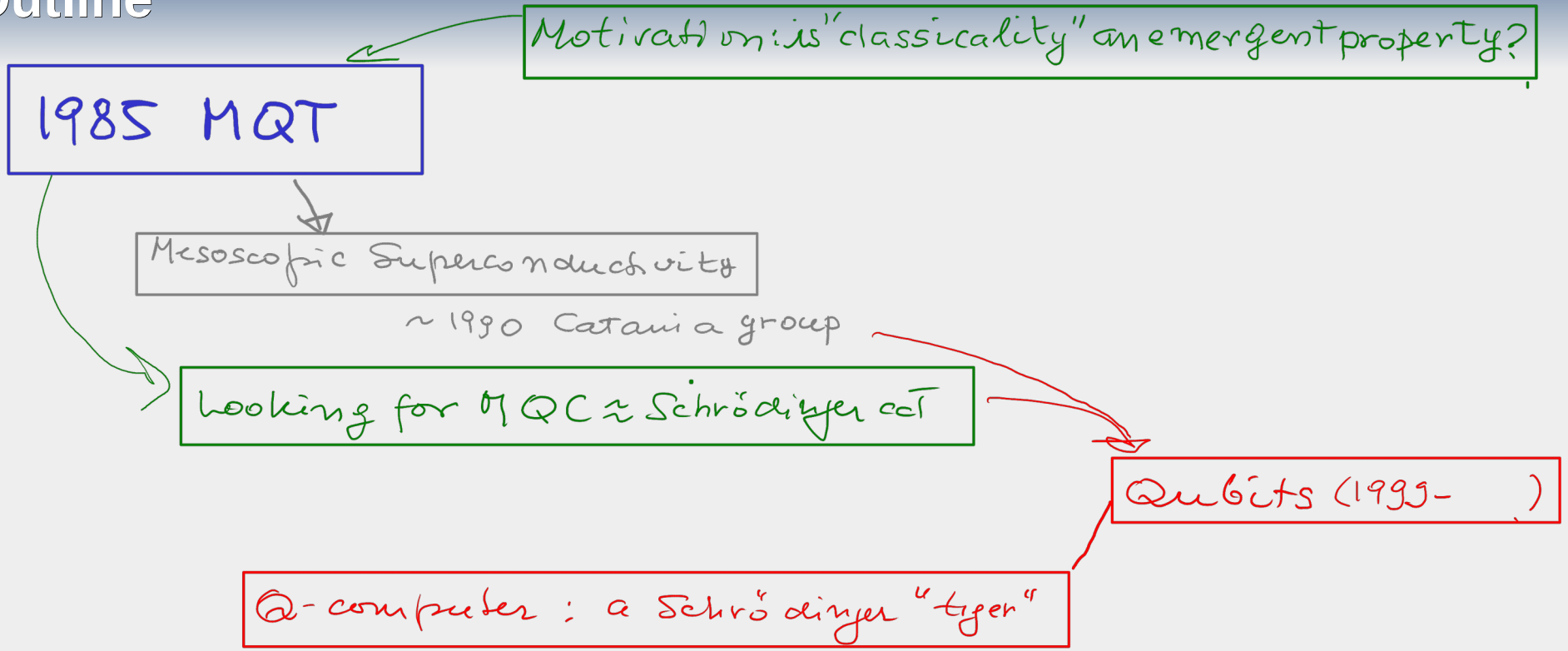
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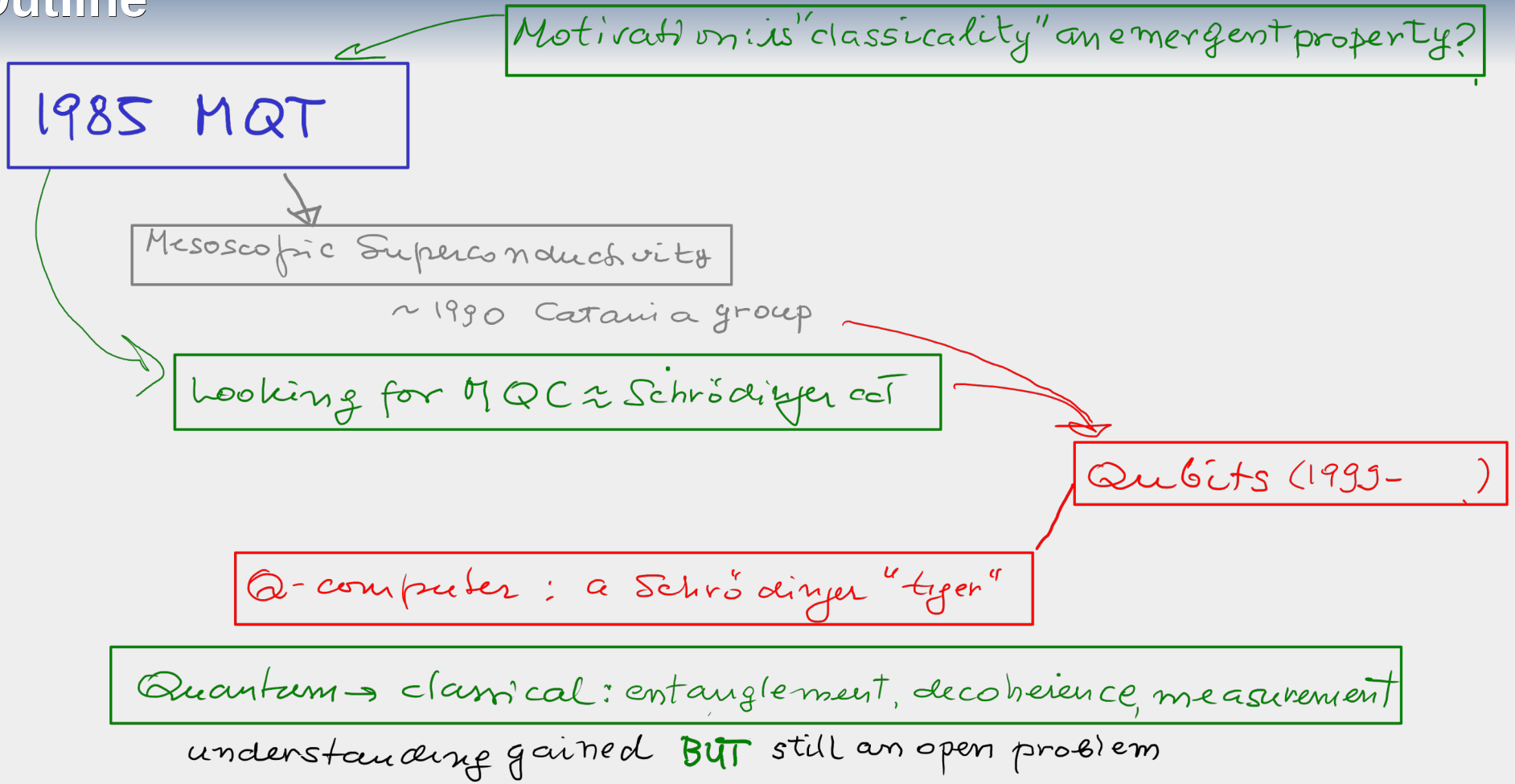
Qubits (1999-)
Q-computer : a Schrödinger "tiger"

Outline



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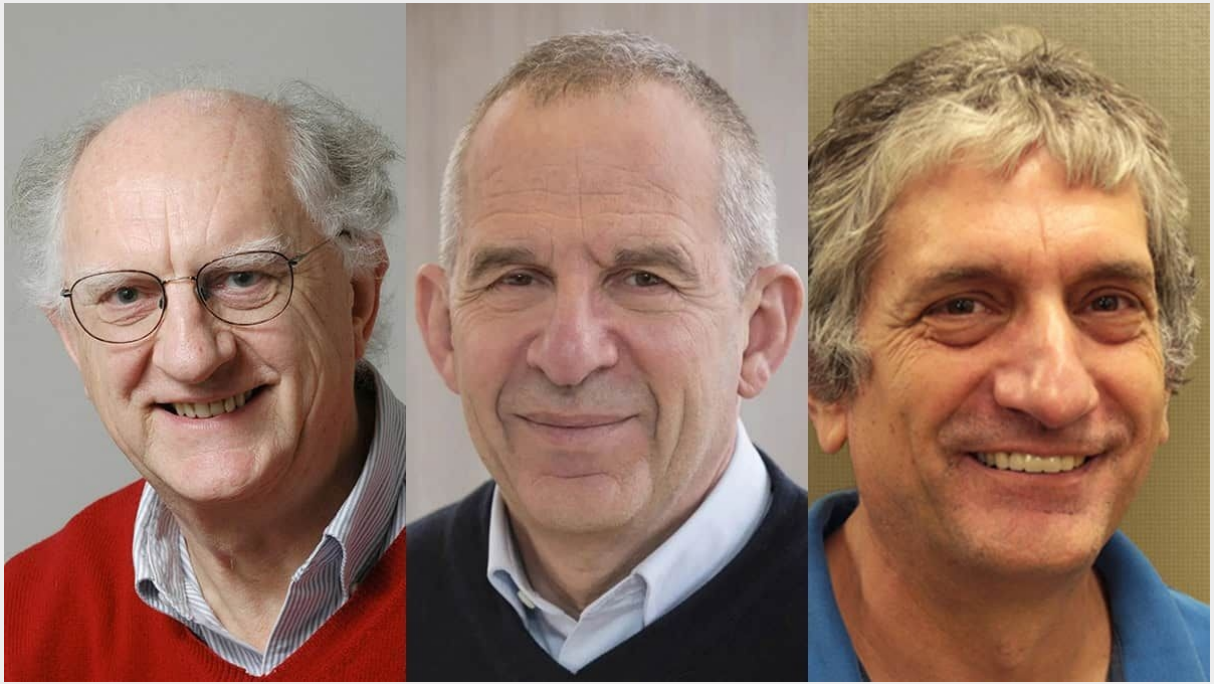

"for the discovery of macroscopic quantum mechanical tunnelling and **energy quantisation** in an electric circuit"

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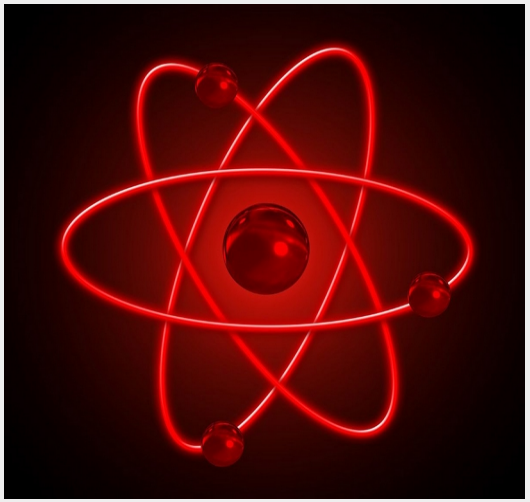
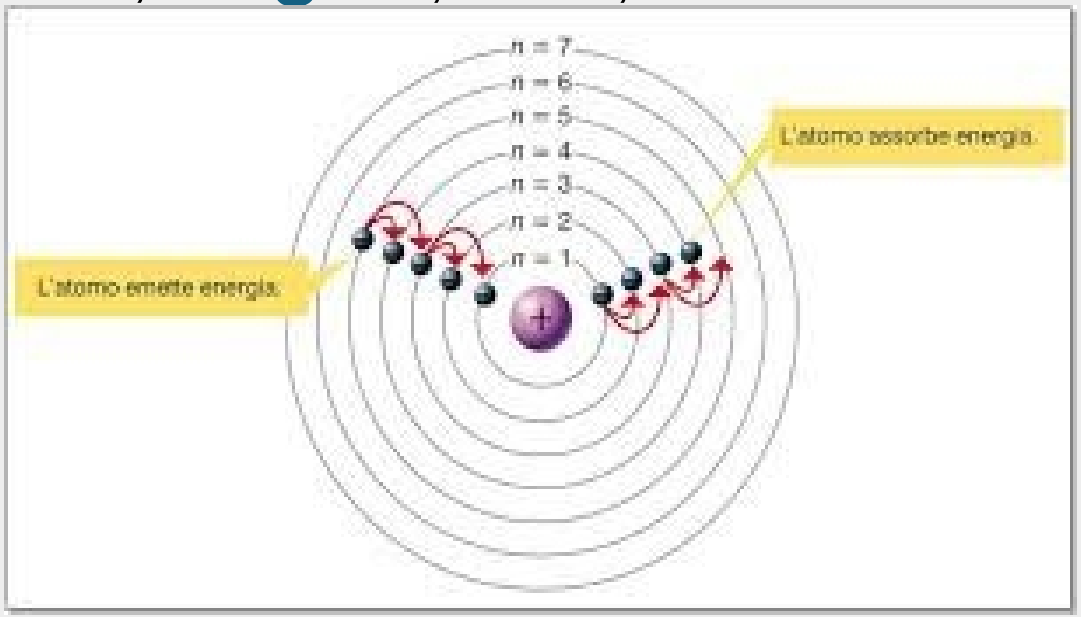
Energy Quantization

Quantizzazione dell'energia

In the **microscopic** world: atoms, molecules, nuclei, ...





According to QM:

electronic **energies** can assume only certain **discrete** values

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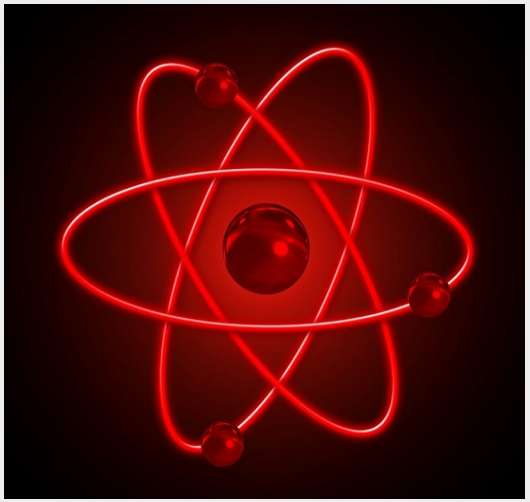
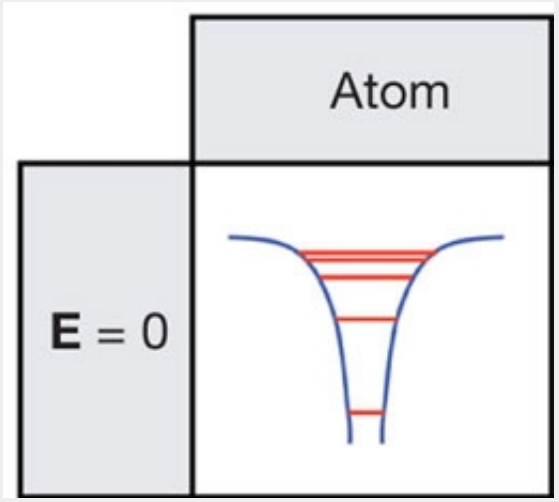
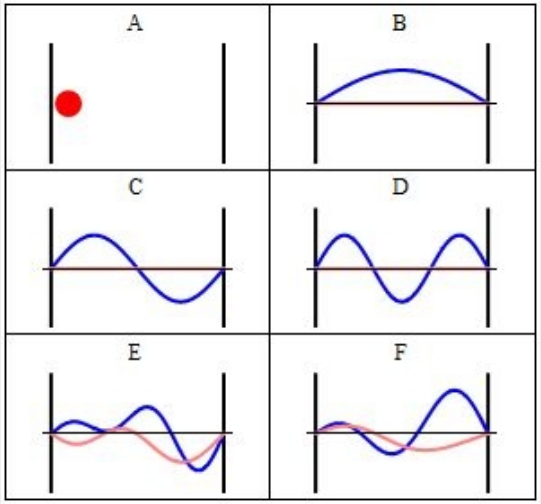






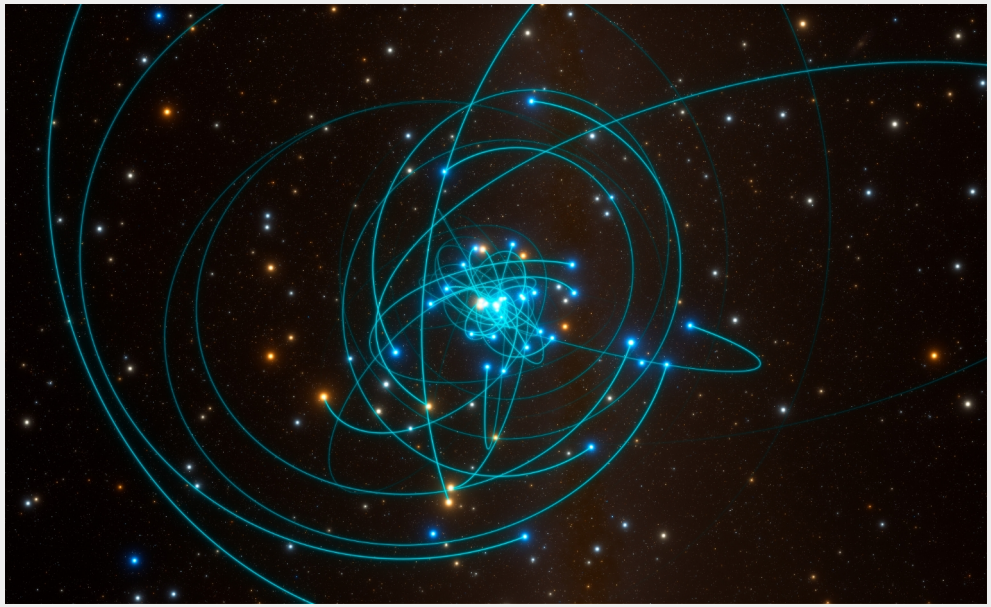
According to QM:

electronic **energies** can assume only certain **discrete** values

as the frequencies of a vibrating string confined in a **potential well**

Energy Quantization disappears in macroscopic objects

with a much larger mass



celestial bodies can follow any orbit

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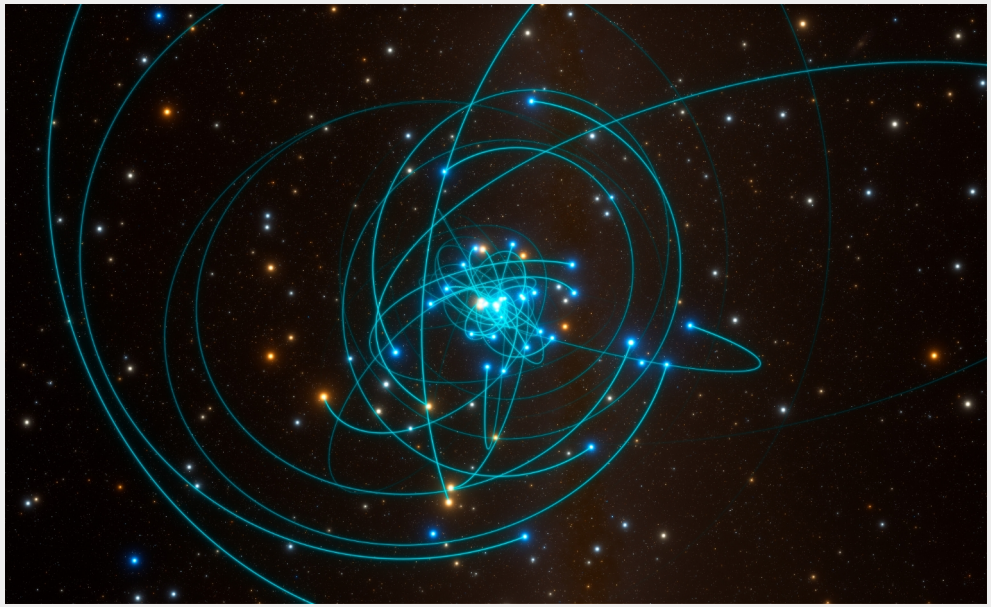

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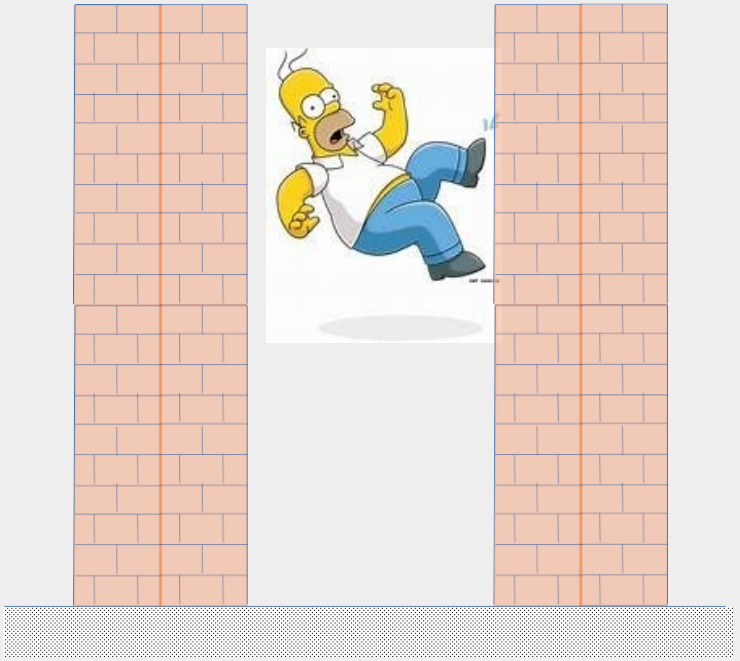

with continuous energy

Even if they are confined

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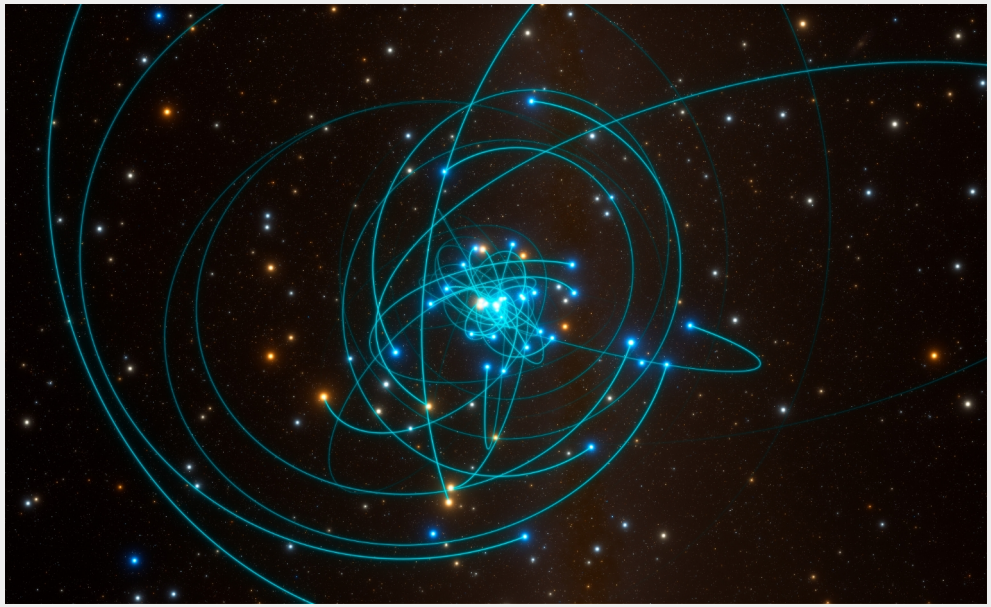

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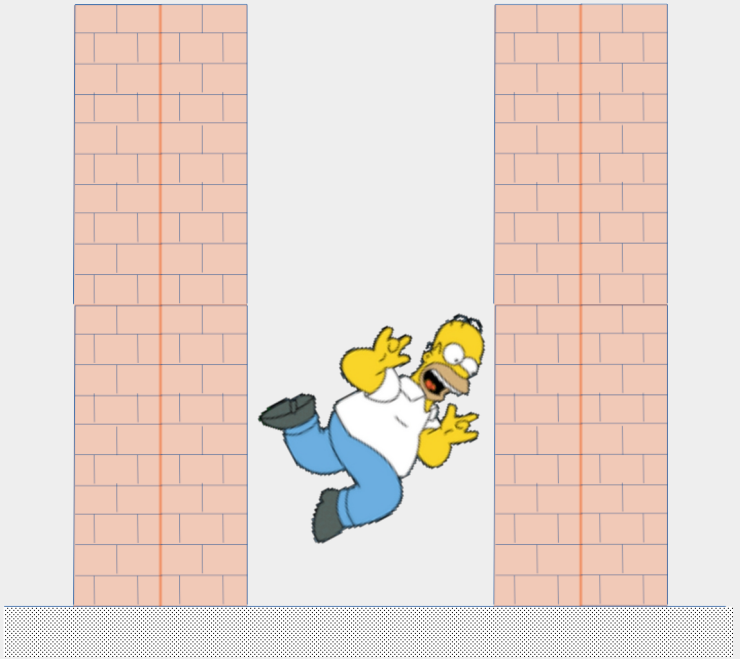

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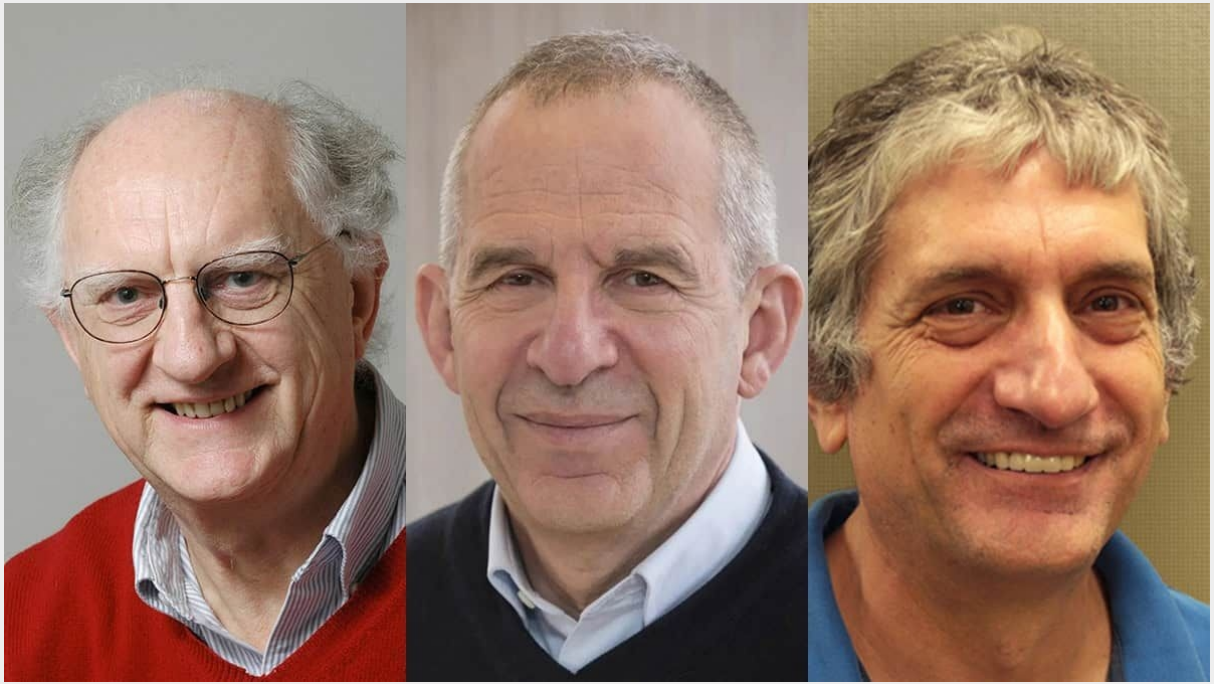

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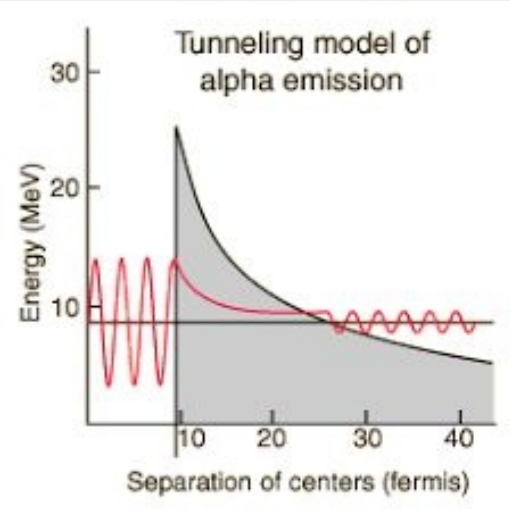
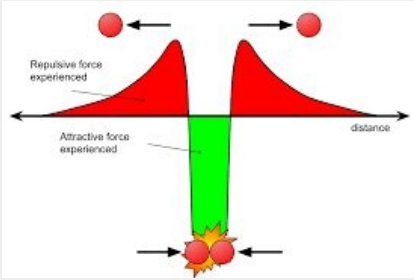
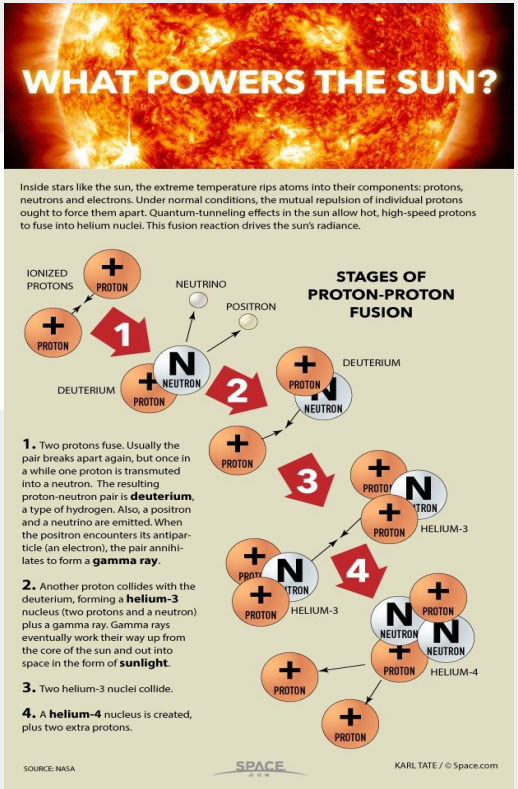
Quantum Tunneling in the microscopic world

α-particles in nuclei



nucleons in nuclear reactions





penetrate a potential barrier

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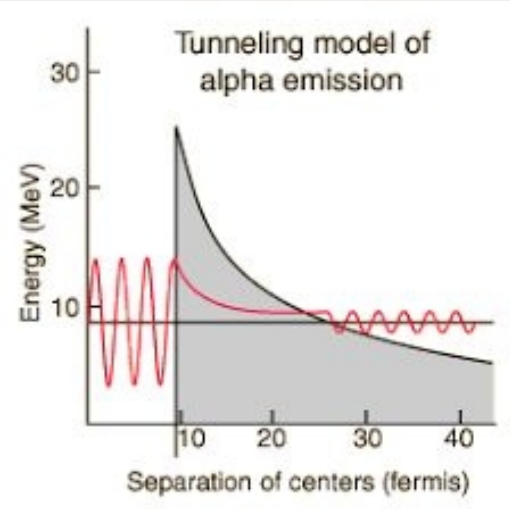

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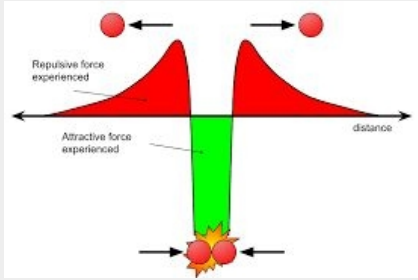
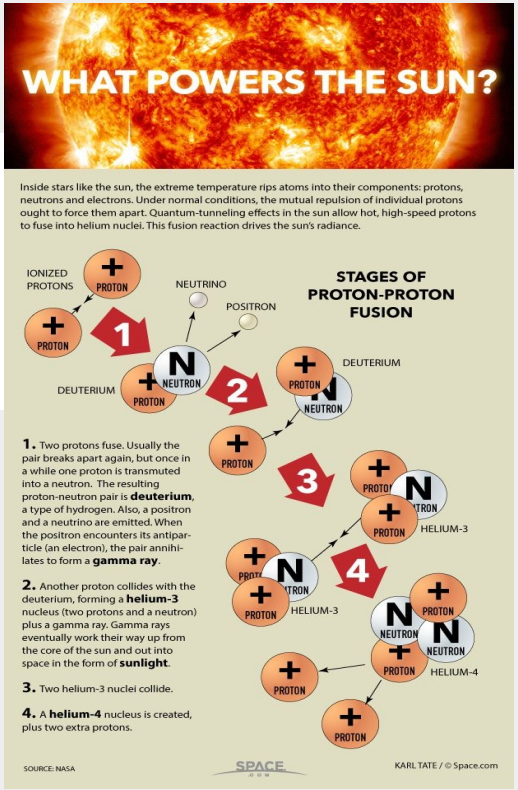
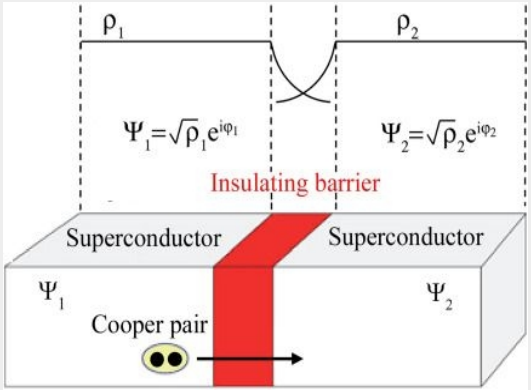




electrons in metal-insulator-metal tunnel junctions



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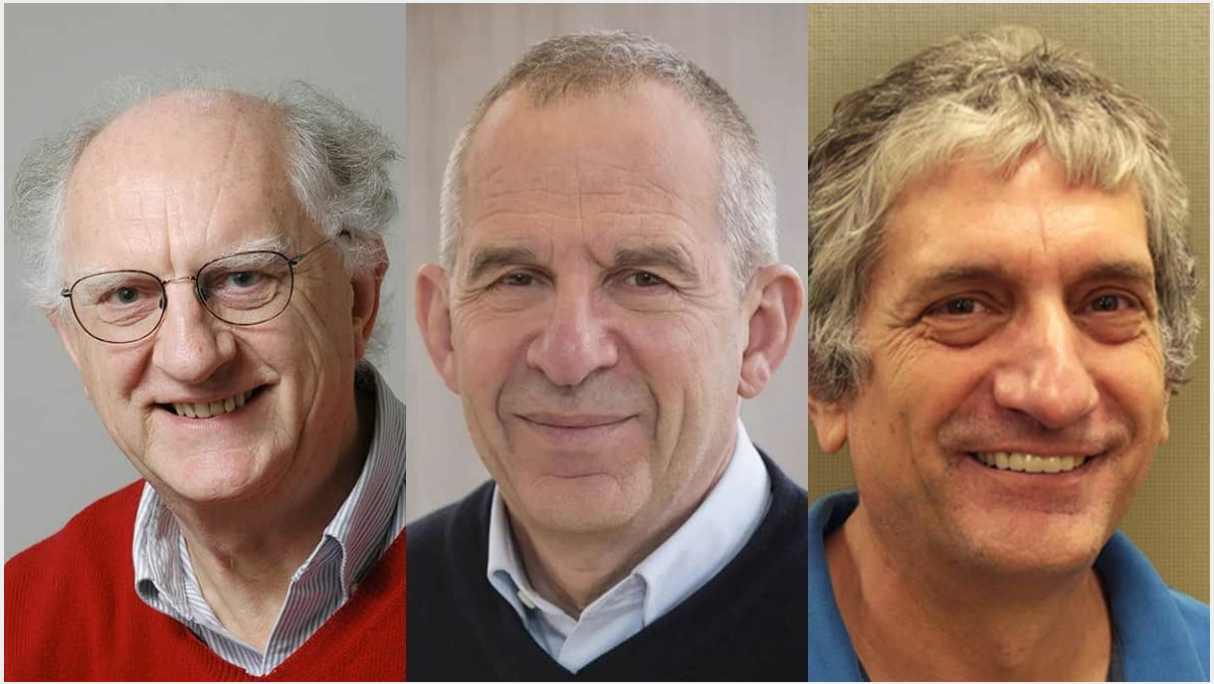

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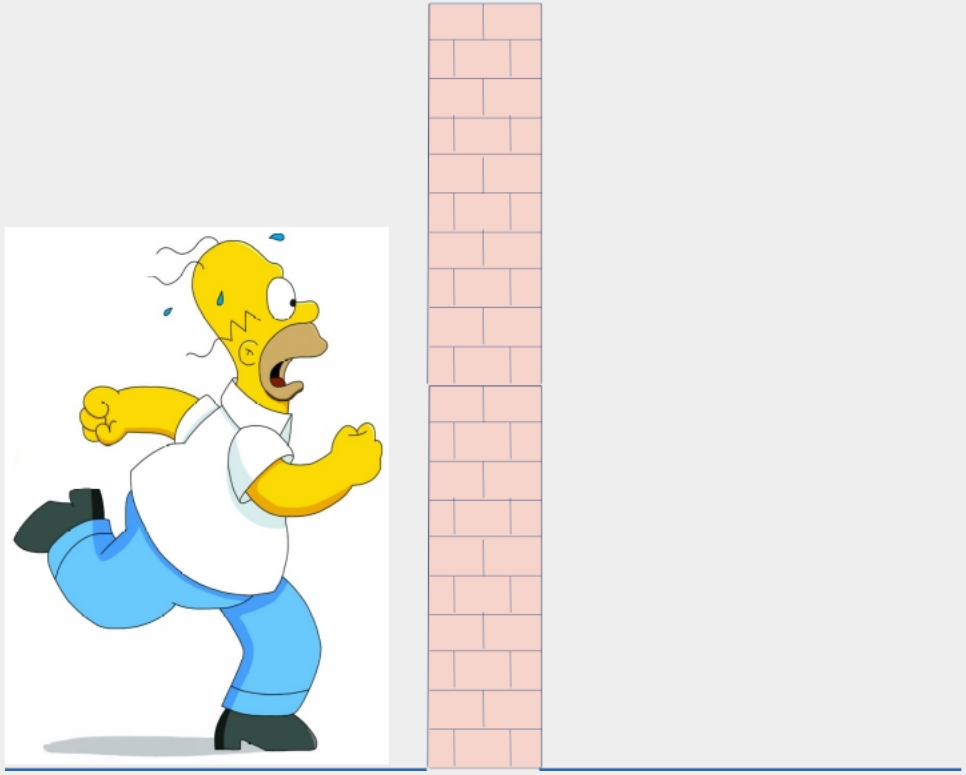
In the macroscopic world

the barrier is a hard wall



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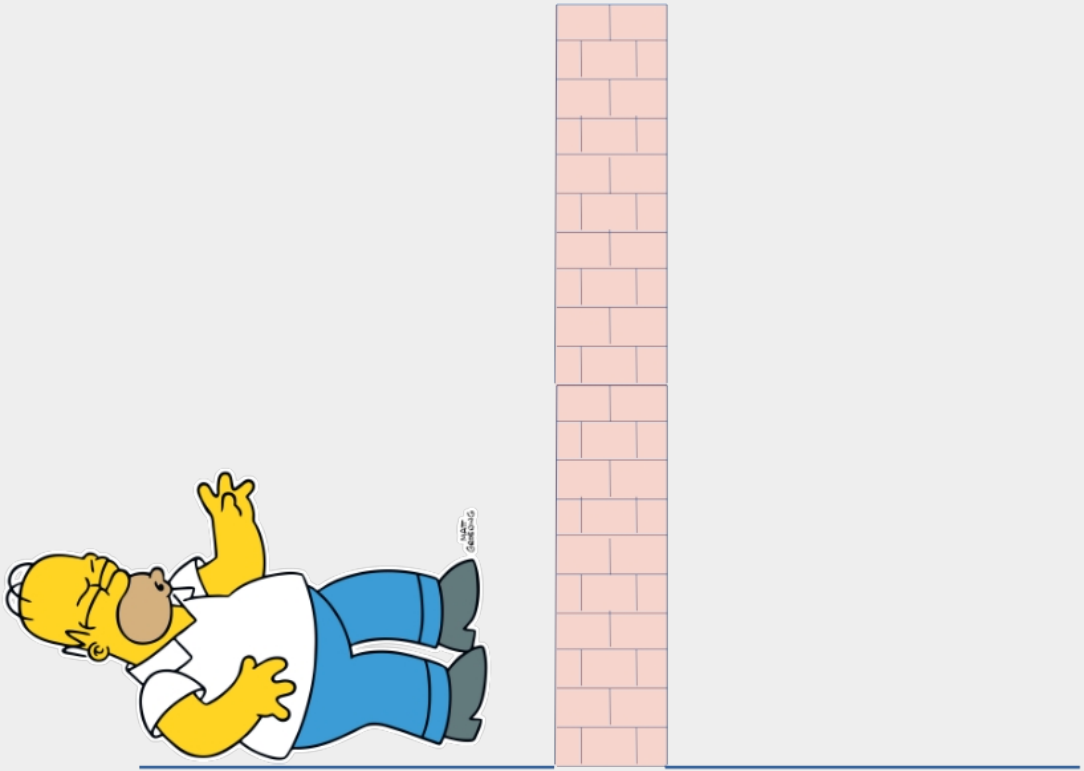
In the macroscopic world

the barrier is a hard wall

and passing through
is by no means easy



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and passing through
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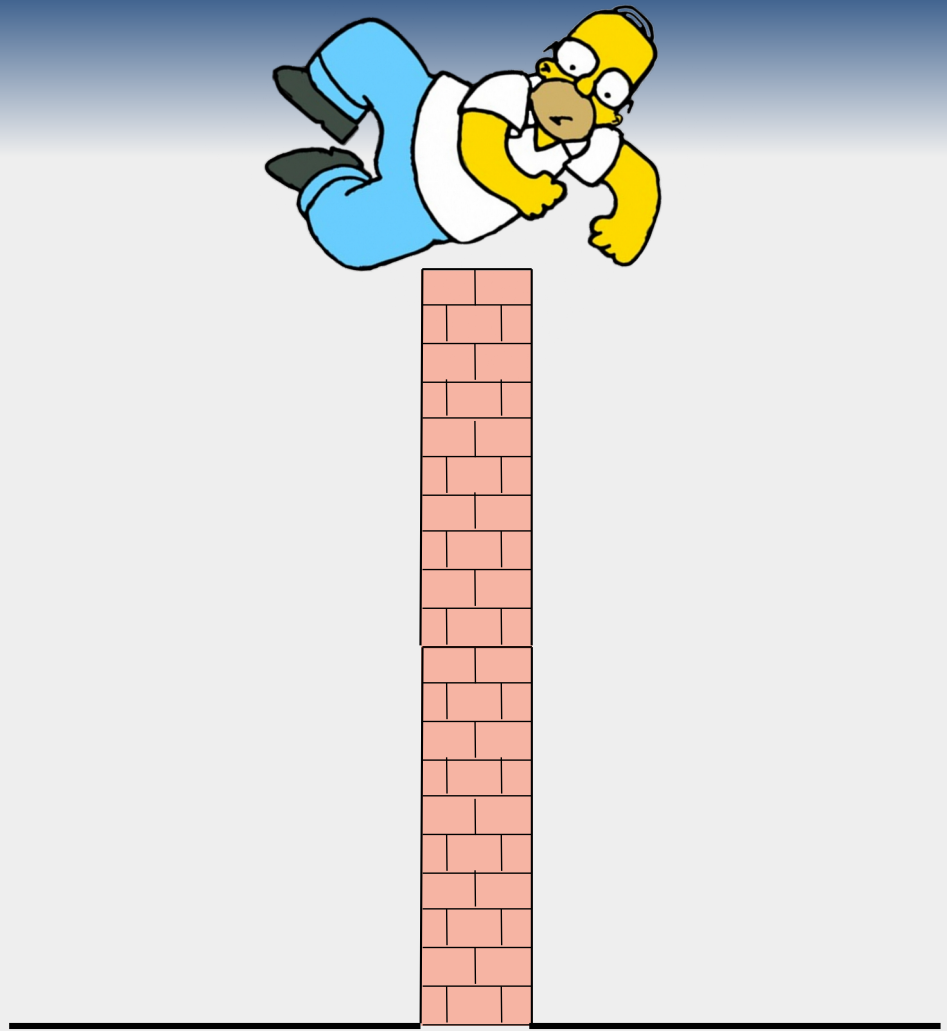
much better to jump

but energy must be spent



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In the macroscopic world

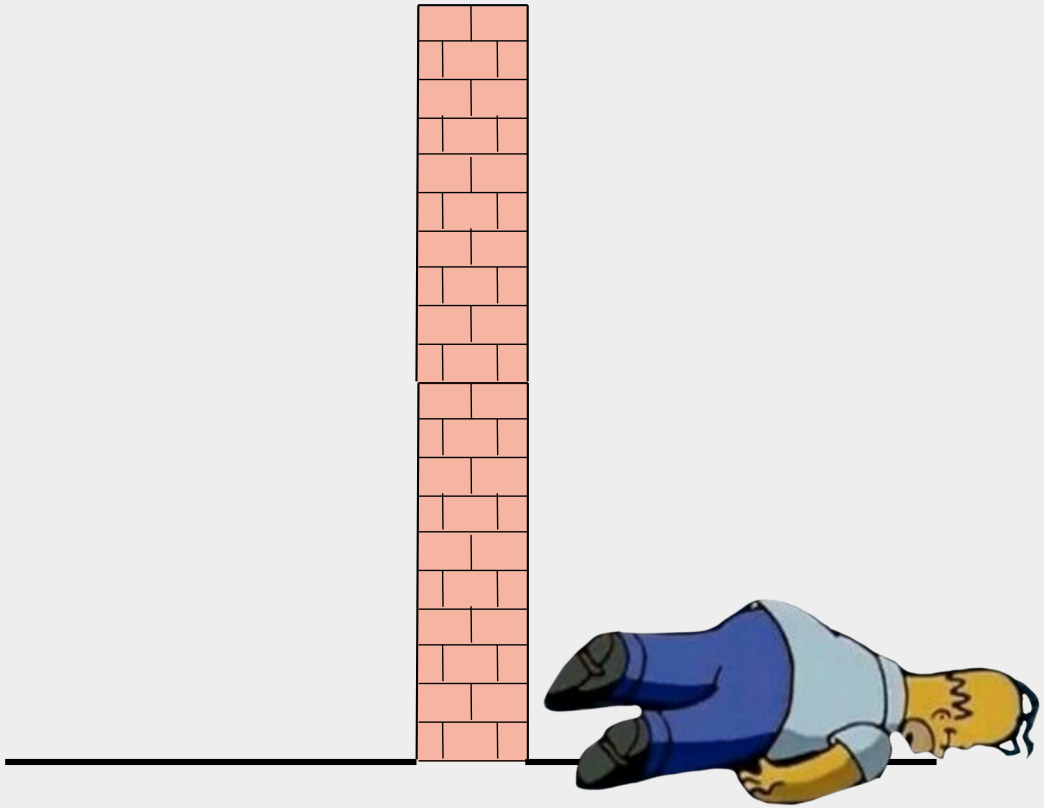
the barrier is a hard wall

and passing through
is by no means easy

much better to jump

but energy must be spent

for the successful end



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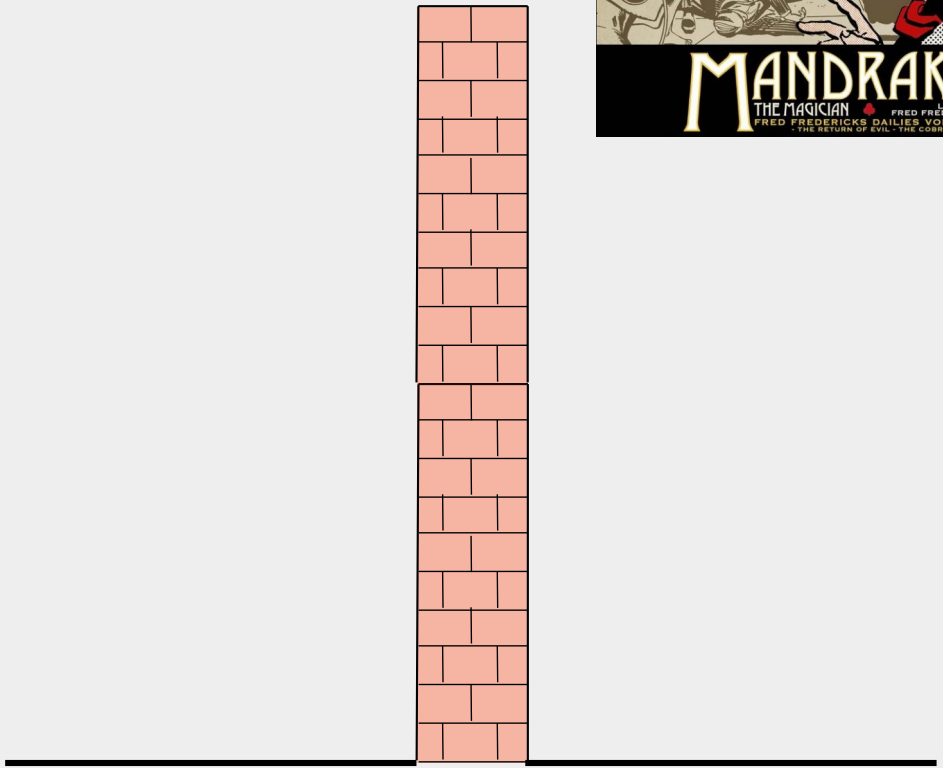
except for magicians



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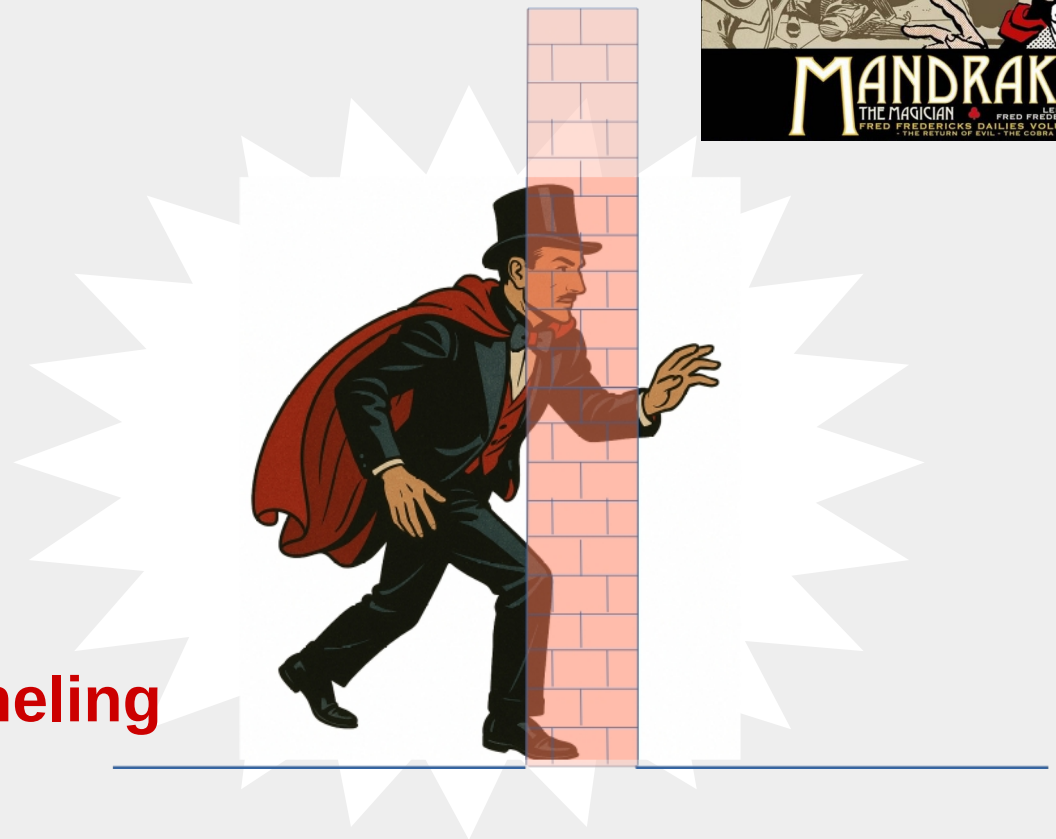

able to implement

Macroscopic Quantum Tunneling

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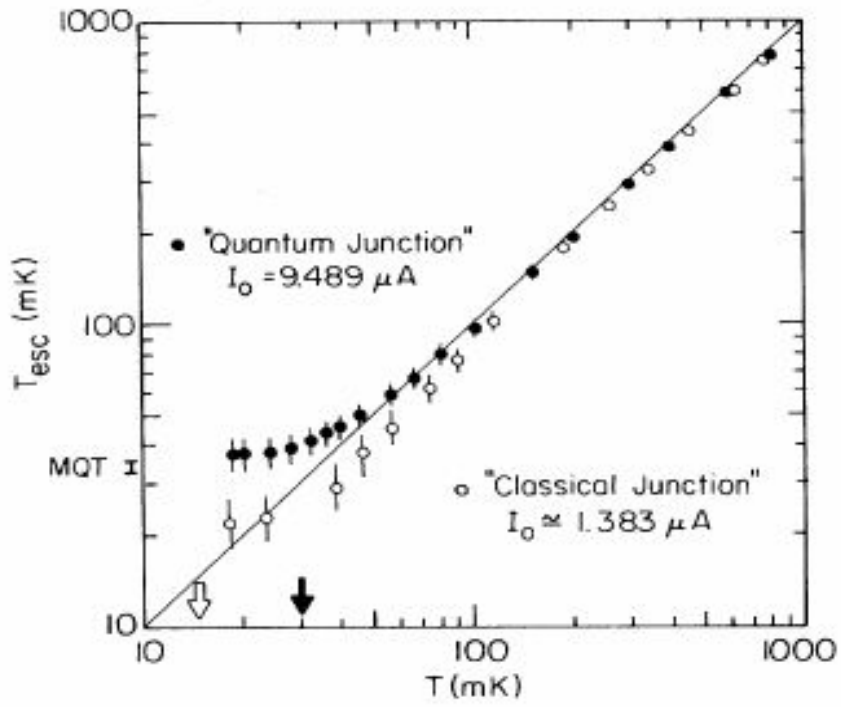
Macroscopic Quantum Tunneling

VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

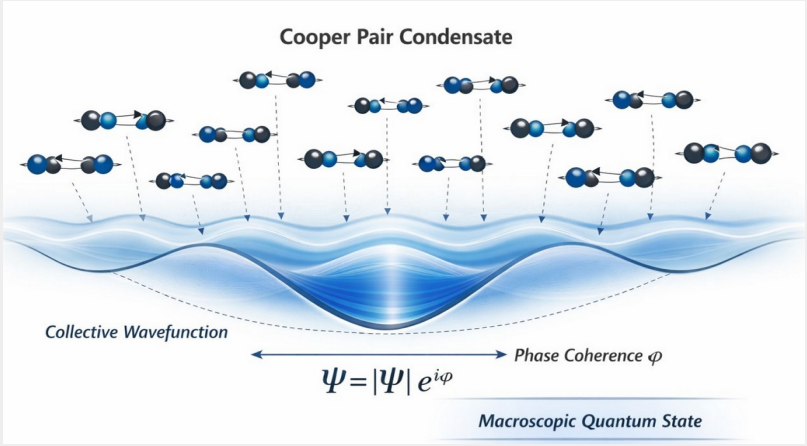
Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 26 July 1985)

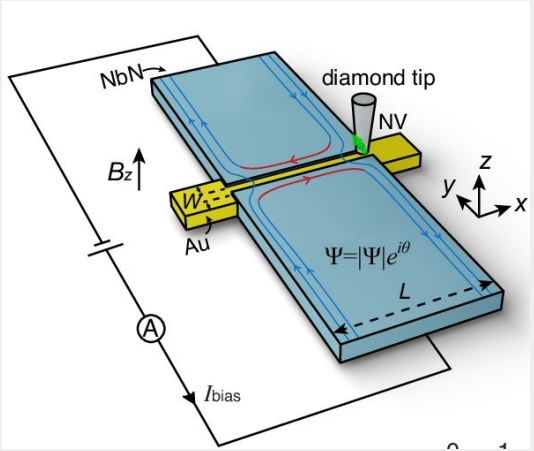


Hardware: superconducting condensate

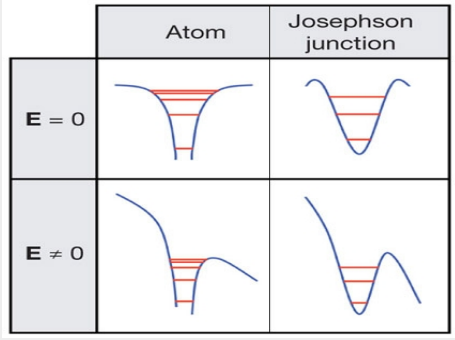
a 1D “particle” with **large mass**
made of many **pairs of**
electrons moving **coherently**



in an electrical circuit containing
a **Josephson Junction**



behaves as an
artificial atom



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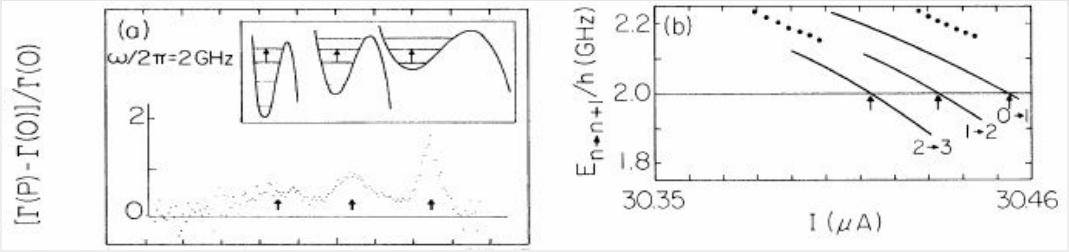
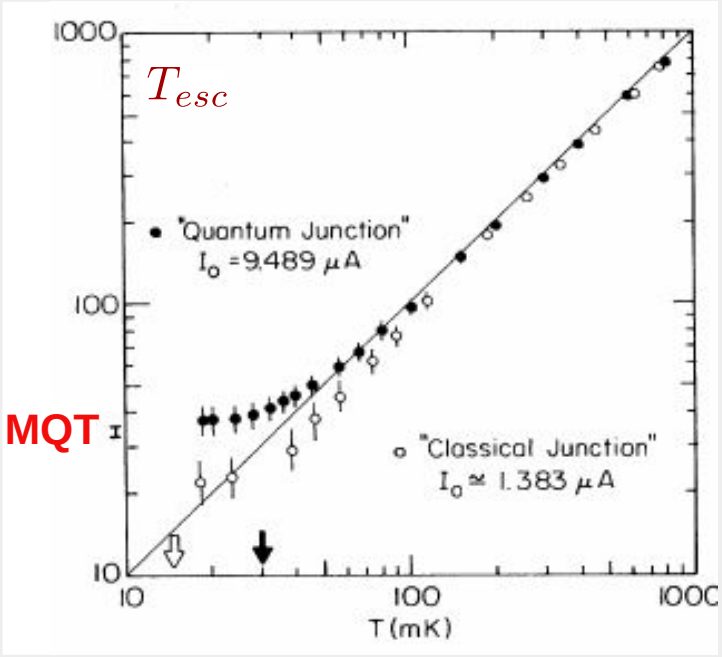
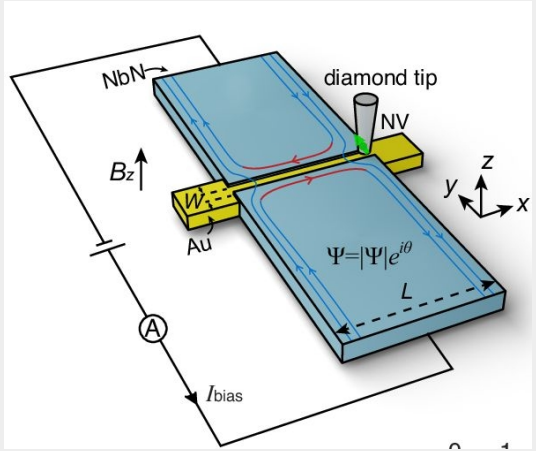
MQT and discrete energy levels in a macroscopic artificial atom



discrete energy levels



MQT



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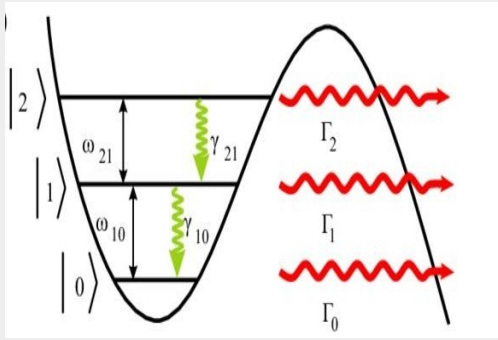

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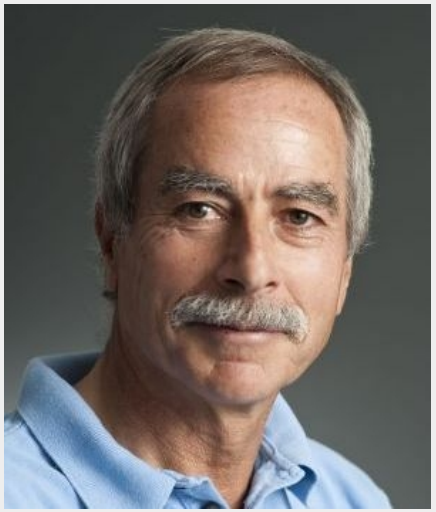
Motivation: is "classicality" an emergent property?

Schrödinger cat (1935) & measurement (1926)

1982 Caldeira-Leggett (MQC)

1984 Ambegaokar, Eckern, Schön



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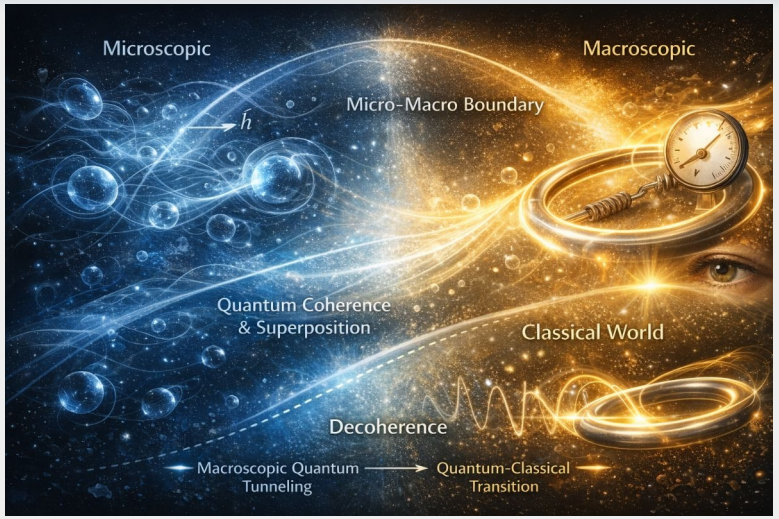
Why MQT is important?

Reasons of principle: MQ describes atoms but can it **survive in the macroscopic world?**

- **Q-mysteries** in the physics at the atomic level
  - **Superposition** (things can exist in multiple states at once)
  - Quantum measurement: the system **"collapses"**: in one of the states of the superposition.
    - Only **probabilistic** guess can be made
    - The mesaured state is **actualized only after the mesurement**



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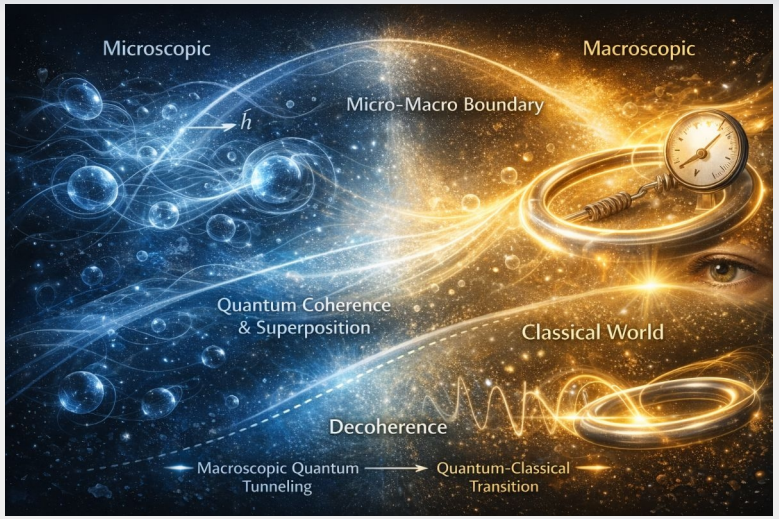

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- How things **"really"** work?
  - A **ball or a cube** ("states of shape"), either **red or blue** ("states of color")
  - In a box where we can detect either the shape or the color
    - Classically four states with well **defined shape AND color**
    - QM → two crazy states with unpredictable behavior upon measurement (Dr Jeckill and Mr Hyde)

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Why MQT is important? Schrödiger cats!

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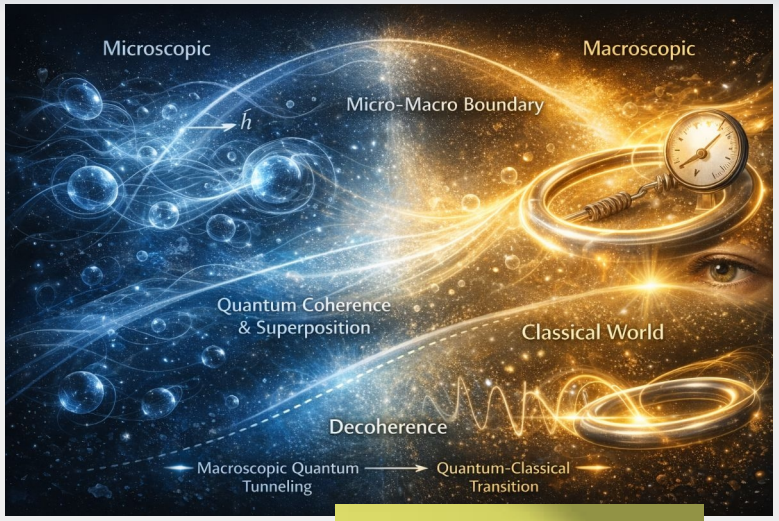
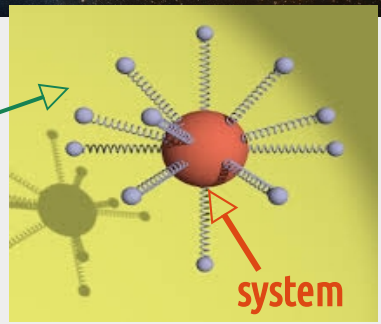


- **Q-mysteries** in the physics at the atomic level
  - **Superposition** (things can exist in multiple states at once)
  - Quantum measurement: the system **"collapses"**: in one of the states of the superposition.

- Nothing like that is seen in macroscopic systems
  - **"Decoherence"**
    - In objects with a large-mass → better: macroscopic objects interact with their **environment**



- MQT experiment supports the "heretic" idea of **Schroedinger cats**: superpositions may exist also in the macroscopic world!
  - Macroscopic Quantum Coherence (**MQC**)

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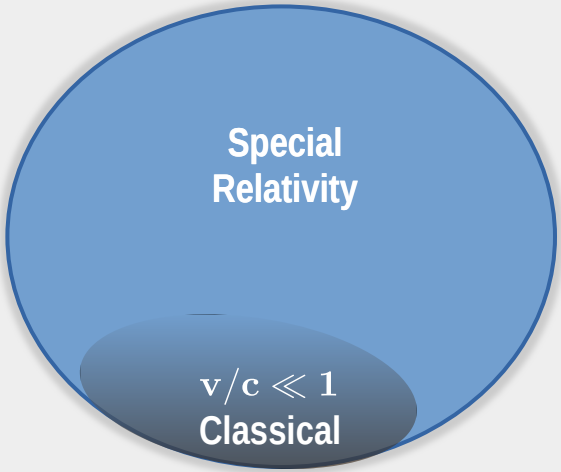
The measurement problem(s)

- It seems that “Reality” does not exist before the mesurement

- Problem with standard postulate of QM
  - Copenhagen interpretation ↔ von Neumann Rule 5
    - Bohr, Heisenberg, Born, … 99% of physicists

  - Special relativity **does not need** “classical” physics to be formulated
    - Newtonian behavior approached **continuously** for $v/c \ll 1$



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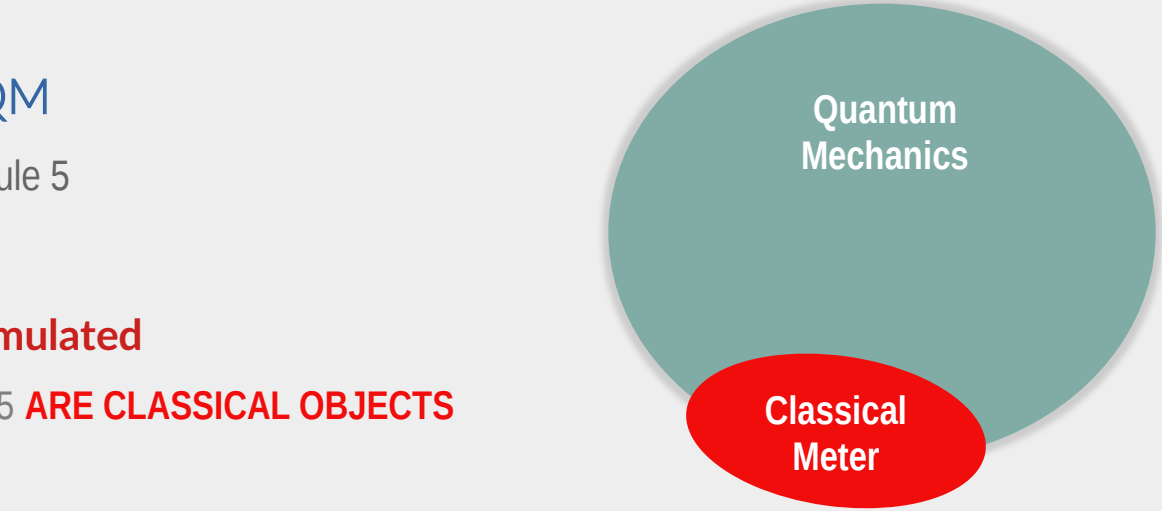
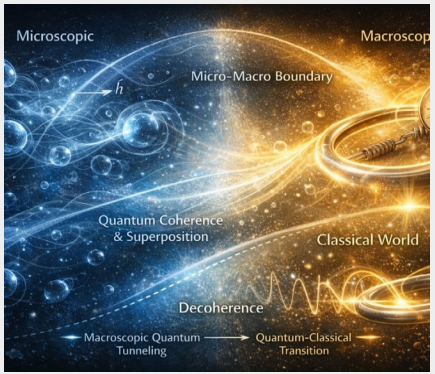
  - **QM needs “classical” physics to be formulated**
    - Measurement apparata subsumed by vNRs 4-5 **ARE CLASSICAL OBJECTS**





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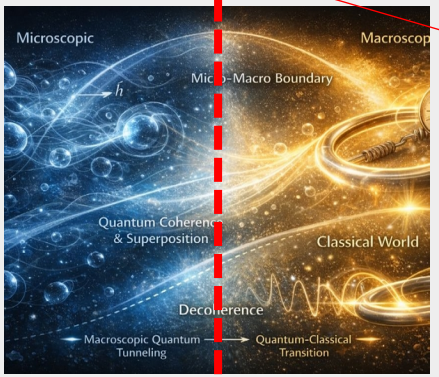

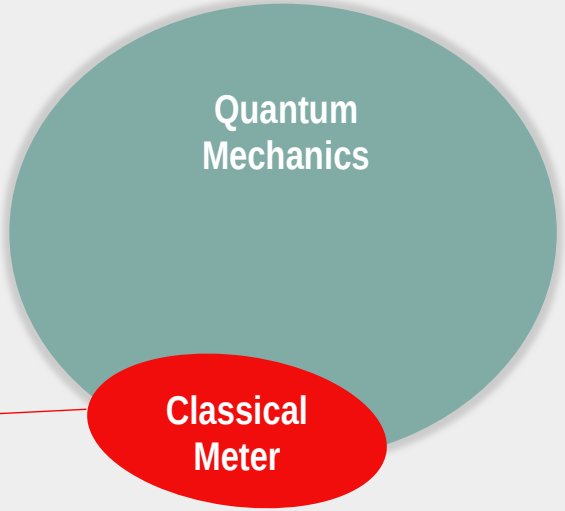

- **How classicality emerges** when going macroscopic?
  - **Abruptly** ↔ quantum phase transition?
  - As a smooth **crossover** as for Relativity?

- NB - Schrödinger cat again
  - the macroscopic meter entangled with the microscopic object

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Macroscopic QM → mesoscopic superconductivity

- Theoretical predictions of MQT
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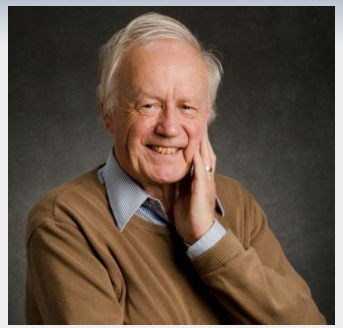
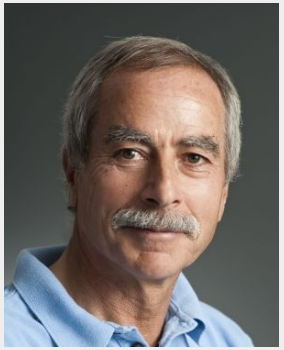
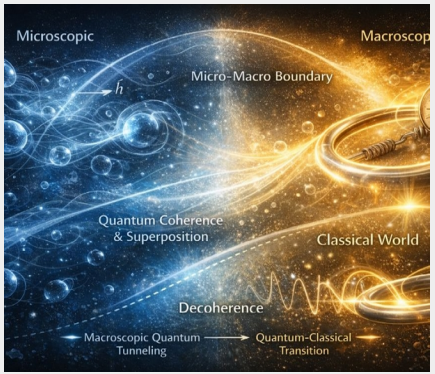
  - **Microscopic derivation**: Ambegaokar, Eckern, Schoen (1982)







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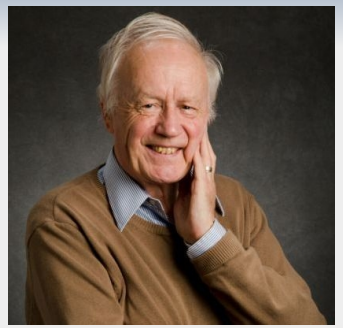
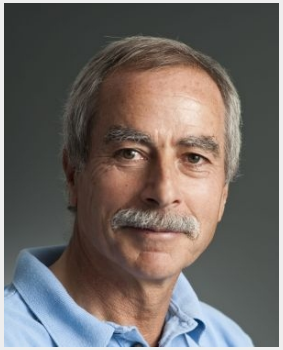




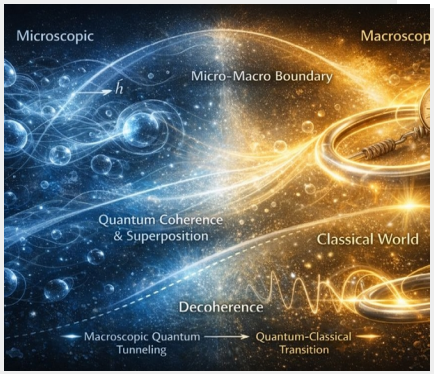
Quasiparticle and Cooper pair tunneling in small capacitance Josephson junctions

Effects of the electromagnetic environment

G. Falci*, V. Bubanja, and Gerd Schön**

Condensed Matter
Zeitschrift für Physik B
© Springer-Verlag 1991

Catania-Delft 1990-91



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MQT → Macroscopic Quantum Coherence

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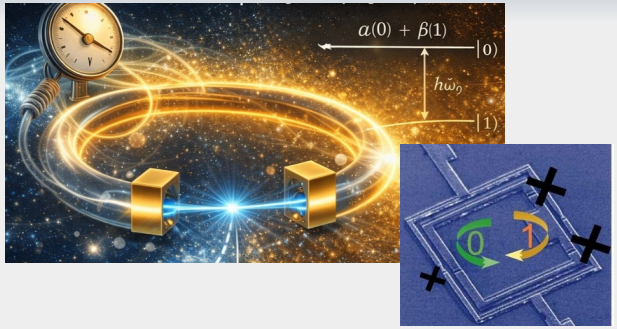

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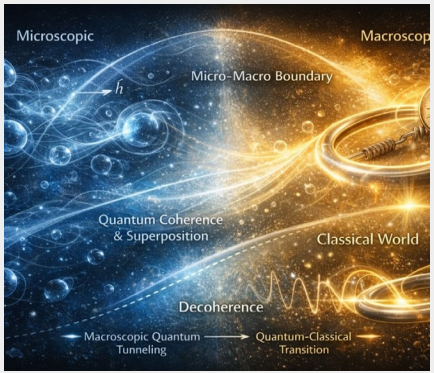

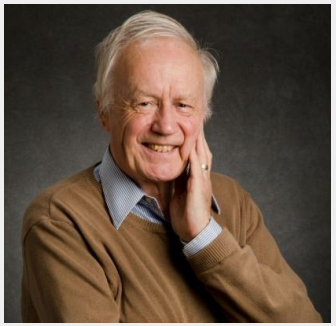

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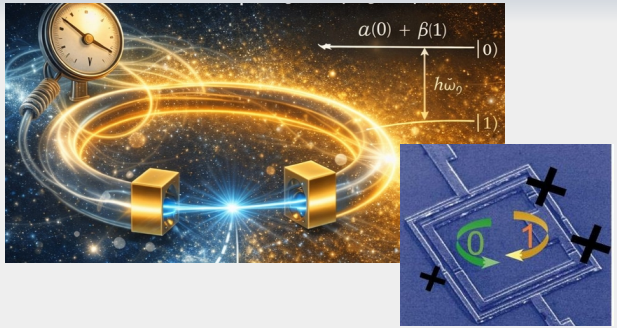

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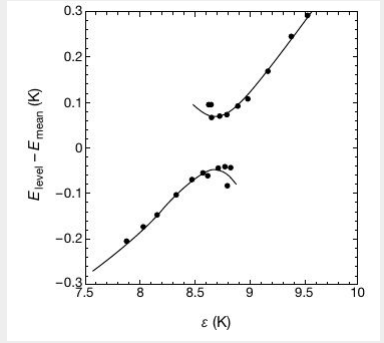

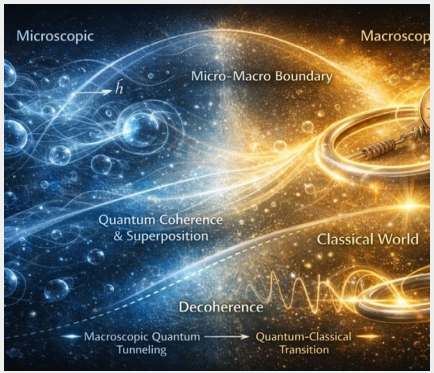

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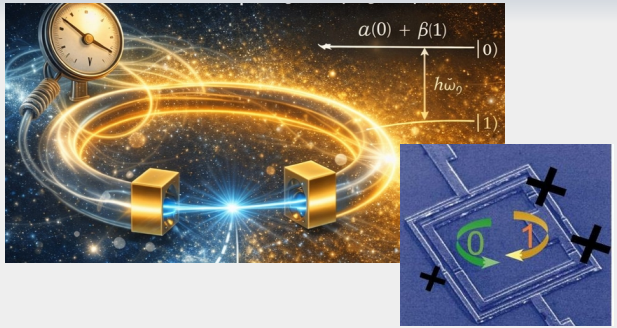

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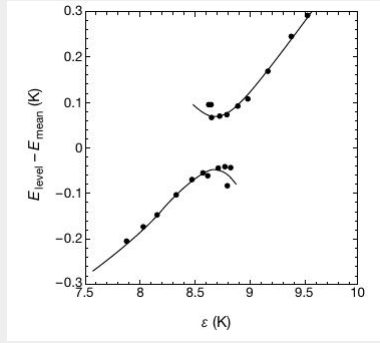
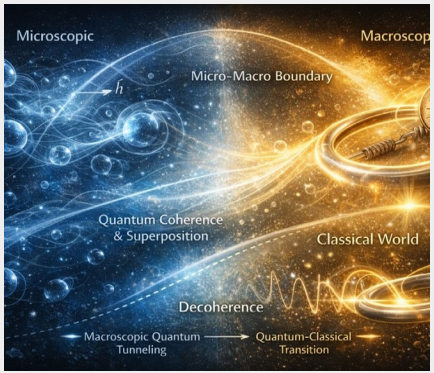
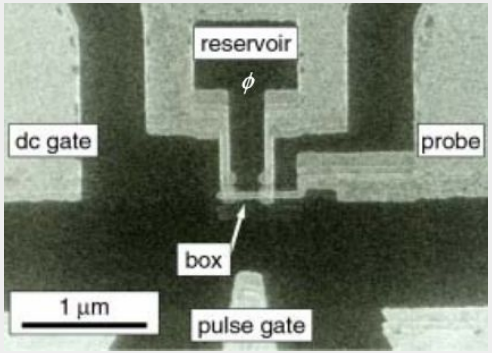
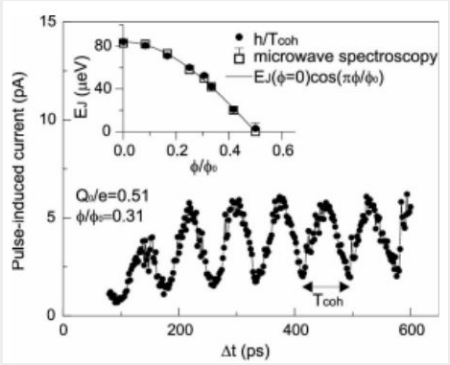
  - Dual experiment (not macroscopic) Nakamura et al. (1999)





Majorana oscillations → first **superconducting QUBIT**





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1999 "dual" exper. in CPB

→ "fluxonium"

→ "transmon"

Qubits (1999-)

Quantum mysteries lead to new technologies

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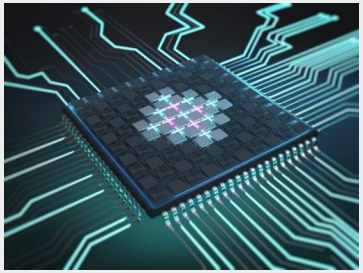
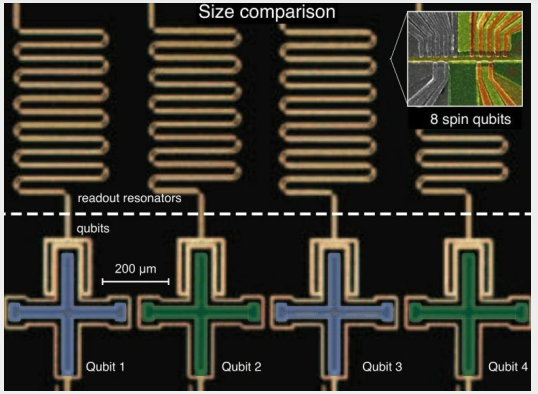
Technological importance

Qubits made of **macroscopic “atoms”**

Can be **wired** and integrated in circuits





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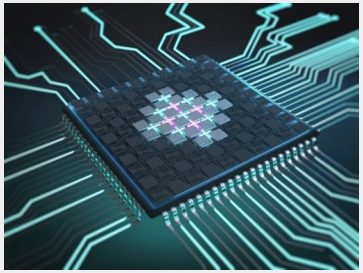
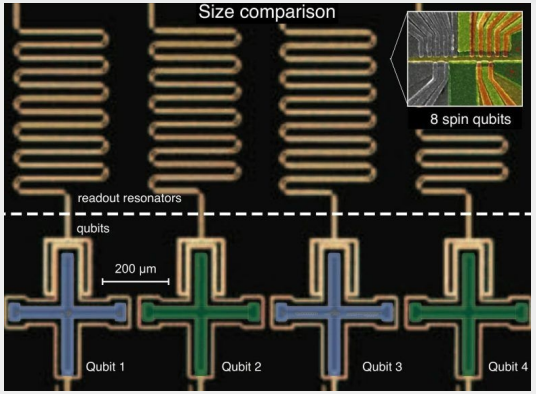
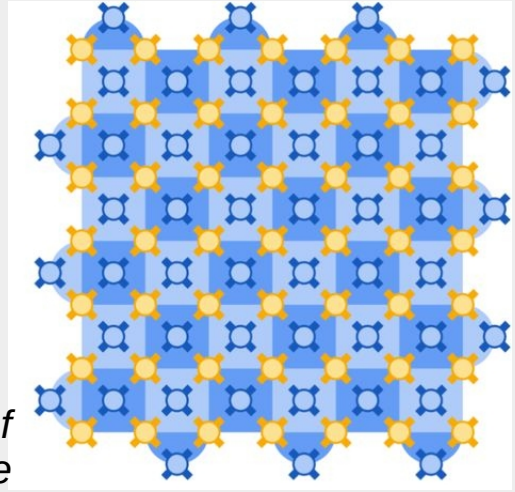




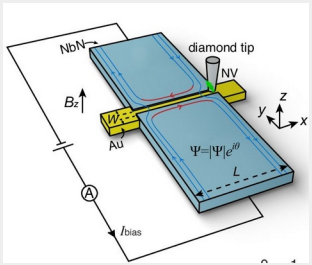
To build **quantum computers** able
to solve problems **impossible even**
for supercomupters

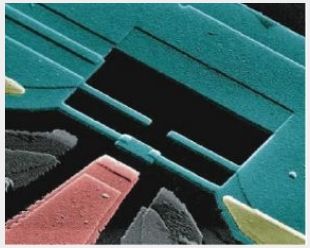


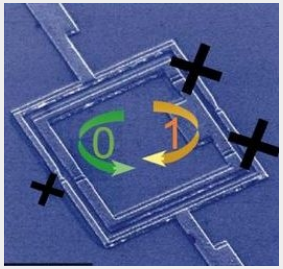
Architecture of
Google Sycamore

Technological importance: design flexibility

Manipulating phase, charge, magnetic flux → **Geometric phases**







letters to nature

NATURE | VOL 407 | 21 SEPTEMBER 2000 | www.nature.com

Detection of geometric phases in superconducting nanocircuits

Giuseppe Falci*§, Rosario Fazio*§, G. Massimo Palma†§, Jens Siewert*§ & Vlatko Vedral‡

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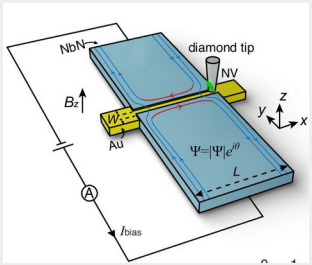

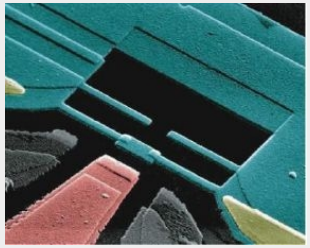

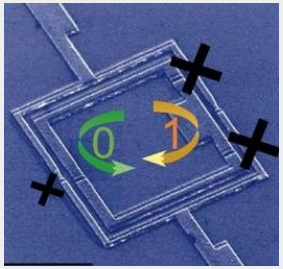

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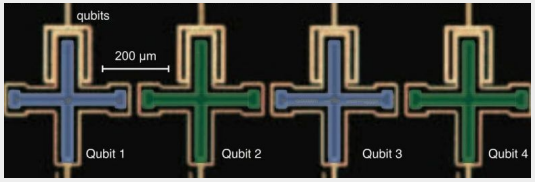
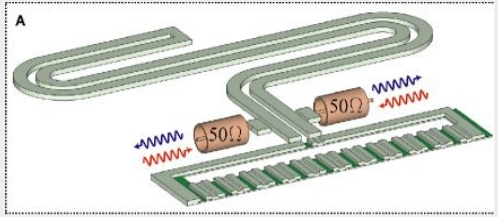
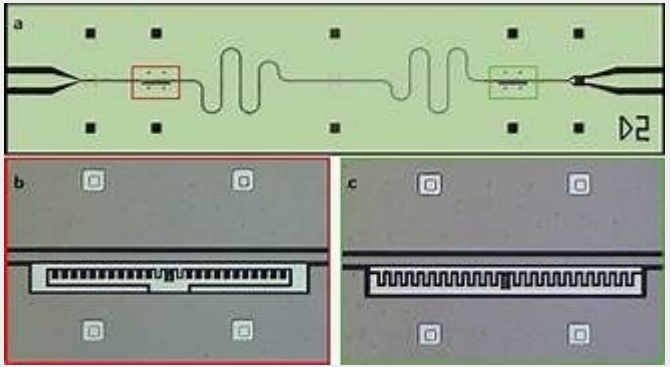
Transmon



Fluxonium



Circuit QED



1985 MQT

Motivation: is "classicality" an emergent property?

Schrödinger cat (1935) & measurement (1926)

1982 Caldeira-Leggett (MQC)

1984 Ambegaokar, Eckern, Schön

Mesoscopic Superconductivity

~1990 Catania group

Looking for MQC ≈ Schrödinger cat

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1999 "dual" exper. in CPB → "transmon"

Qubits (1999-)

Quantum mysteries lead to new technologies

Q-computer: a Schrödinger "tiger"

Defying the paradigm that macroscopic is classical

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letters to nature

NATURE | VOL 416 | 11 APRIL 2002 | www.nature.com

Scaling of entanglement close to a quantum phase transition

A. Osterloh*†, Luigi Amico*†, G. Falci*† & Rosario Fazio†‡

* *Dipartimento di Metodologie Fisiche e Chimiche (DMFCI), viale A. Doria 6, 95125 Catania, Italy*
† *NEST-INFM, Piazza dei Cavaliezi 7, I-56126 Pisa, Italy*
‡ *Scuola Normale Superiore, Piazza dei Cavaliezi 7, I-56126 Pisa, Italy*

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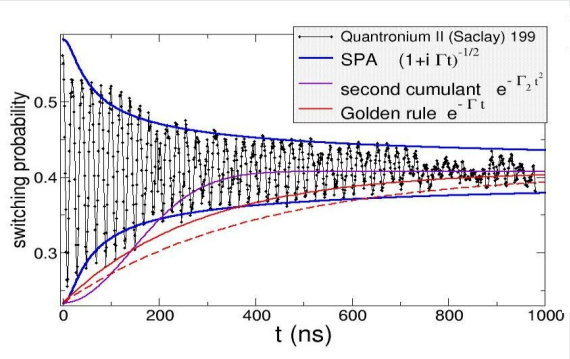
Main obstacle: decoherence



VOLUME 88, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 2002

Decoherence and 1/*f* Noise in Josephson Qubits

E. Paladino,[1] L. Faoro,[2] G. Falci,[1] and Rosario Fazio[3]

PRL **94,** 167002 (2005) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2005

Initial Decoherence in Solid State Qubits

G. Falci,* A. D'Arrigo, A. Mastellone, and E. Paladino

REVIEWS OF MODERN PHYSICS, VOLUME 86, APRIL–JUNE 2014

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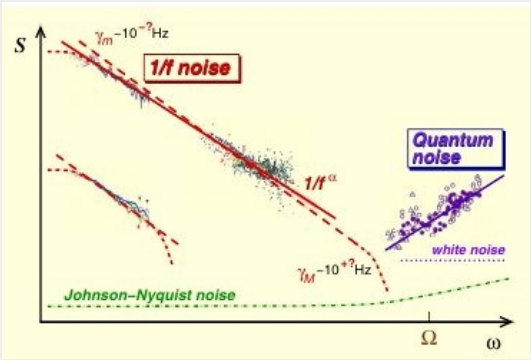

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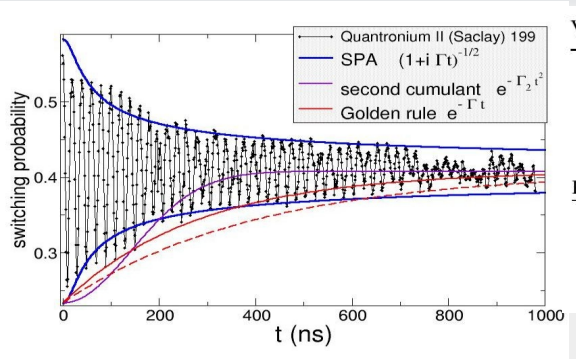

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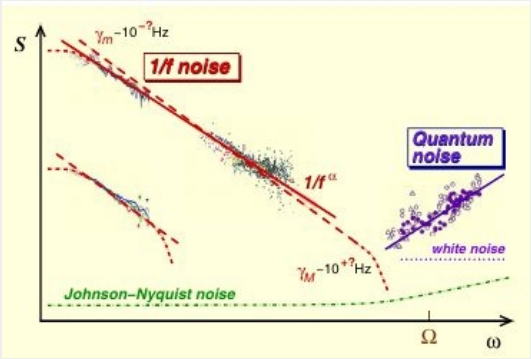

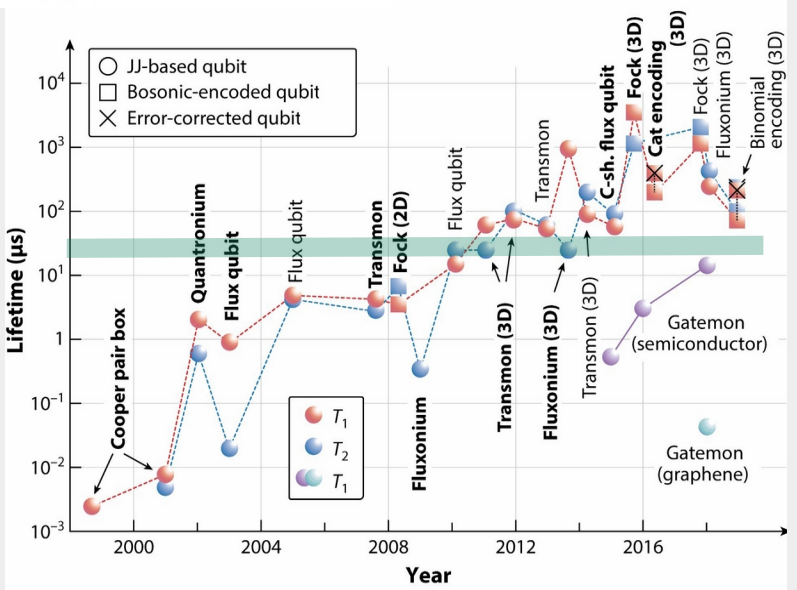

Kjaergaard et al., Annu. Rev. Condens. Matter Phys. 2020

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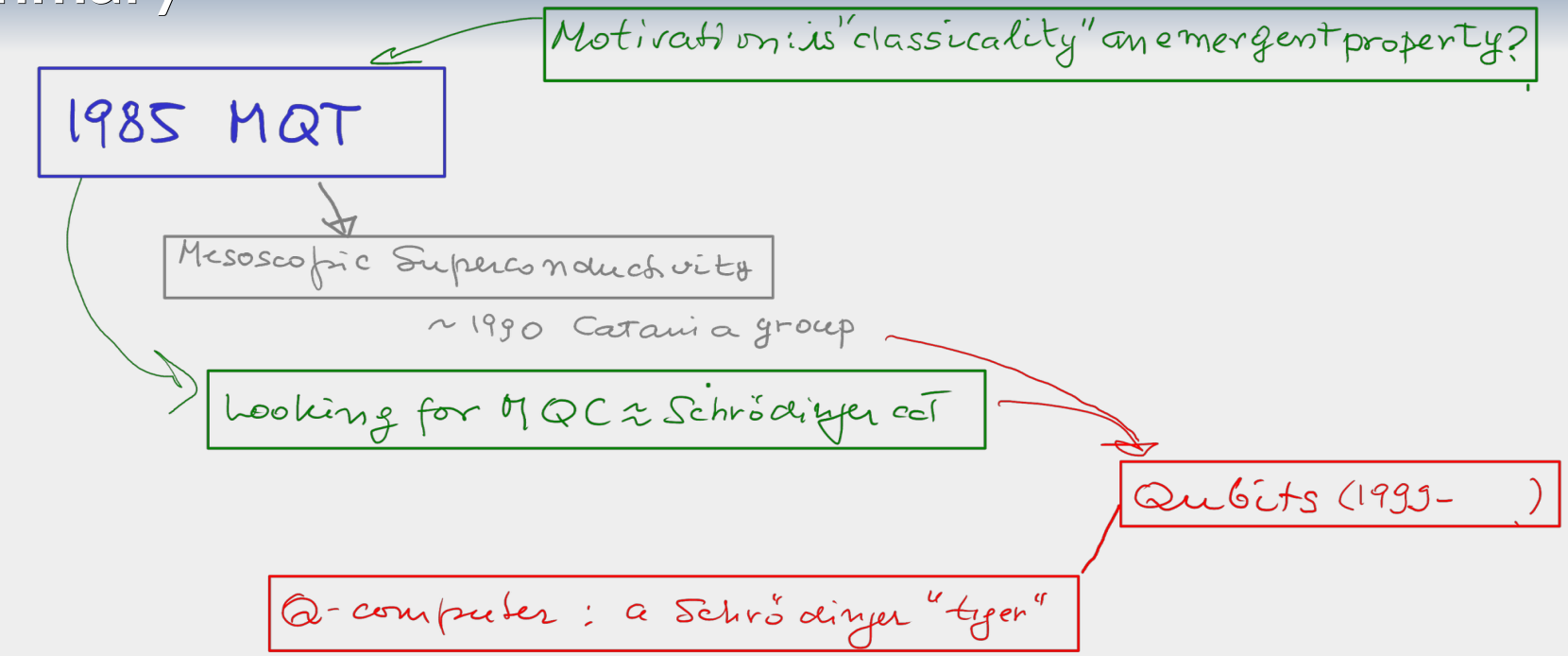
Summary



Quantum → classical: entanglement, decoherence, measurement

understanding gained **BUT** still an open problem

physical conditions

fundamental questions
(phase transition & vNRS)

Thanks for your attention!

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Quantum Technologies at UniCT

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