



COLLÈGE  
DE FRANCE  
— 1530 —



# "FROM ATOMS TO QUANTUM MACHINES"

Michel Devoret

CHAIR OF MESOSCOPIC PHYSICS

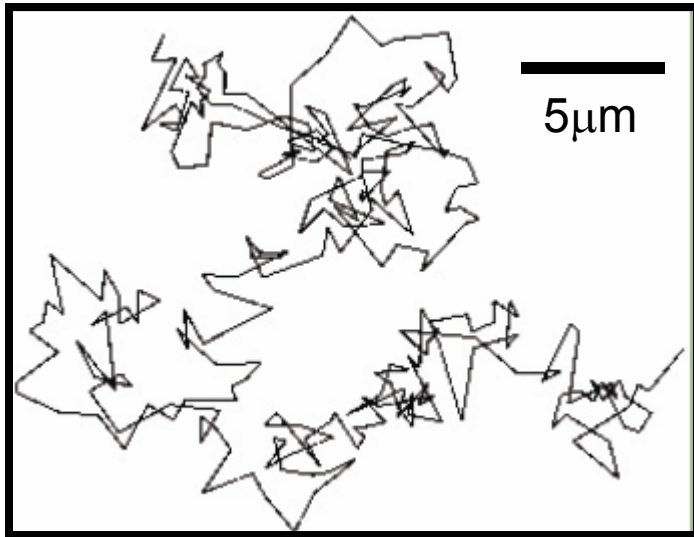
Inaugural Lecture

May 31, 2007

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# "SEEING" ATOMS

YESTERDAY....



Measurement and analysis of  
brownian motion (1908)



Jean Perrin

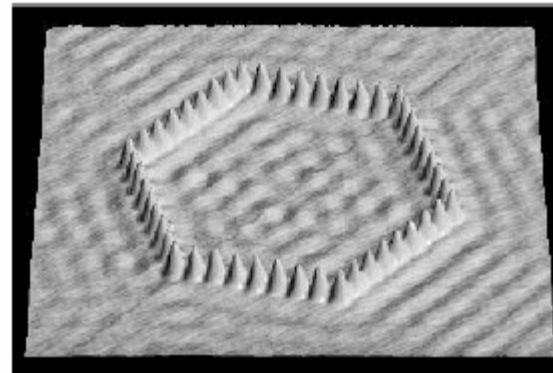


Albert Einstein



Paul Langevin

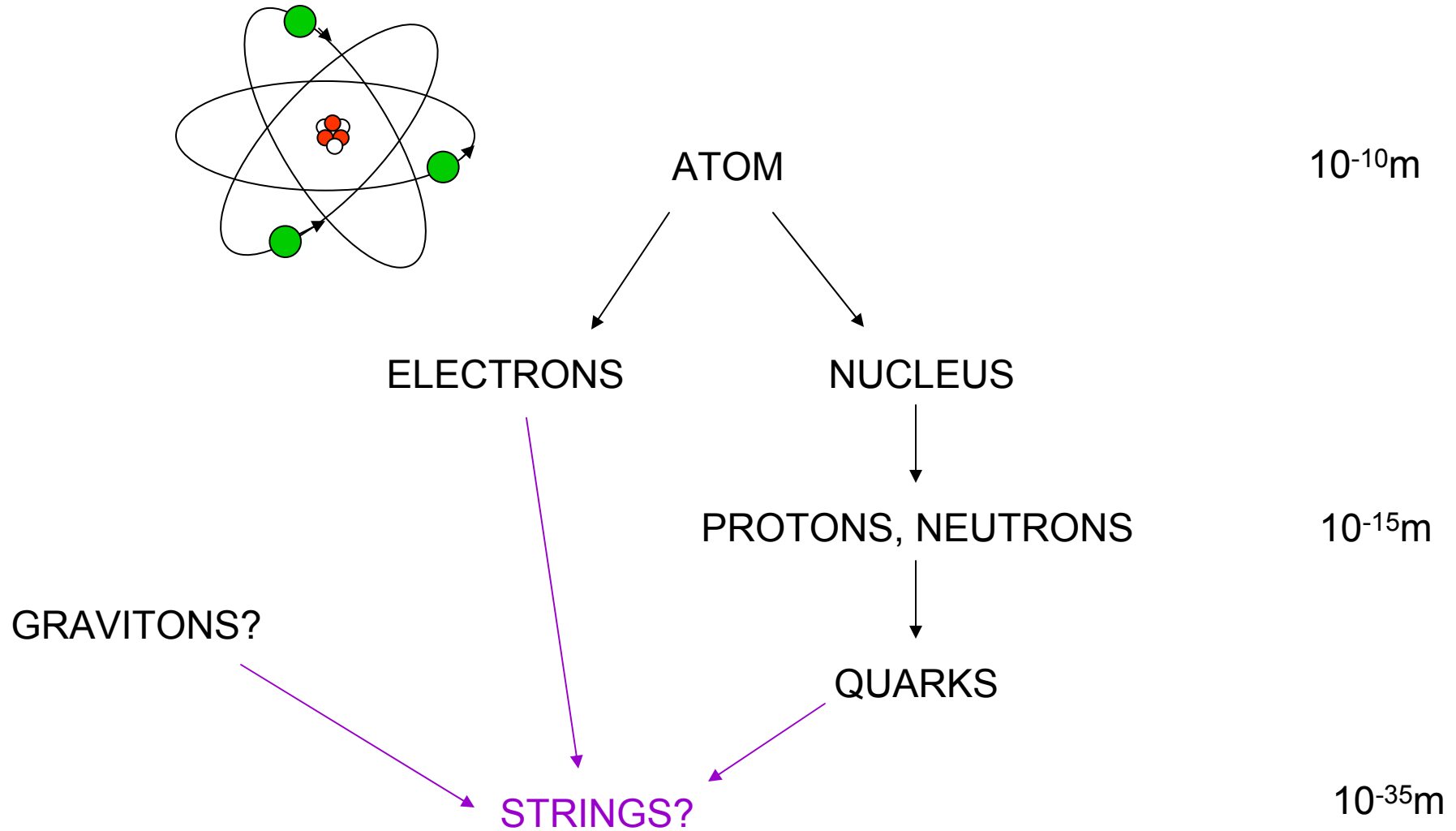
.... AND TODAY

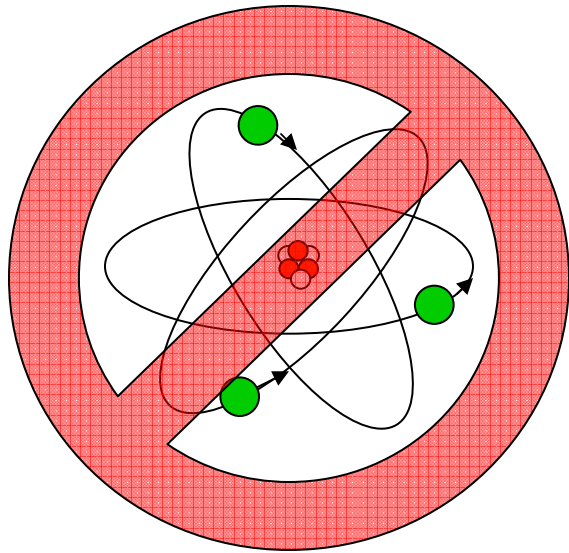


Iron atoms  
arranged on  
a copper surface  
(Eigler *et al.*)

*Surface Review and Letters* 2 (1), 127-137 (1995)

# THE ATOM IS ITSELF A WORLD OF PARTICLES

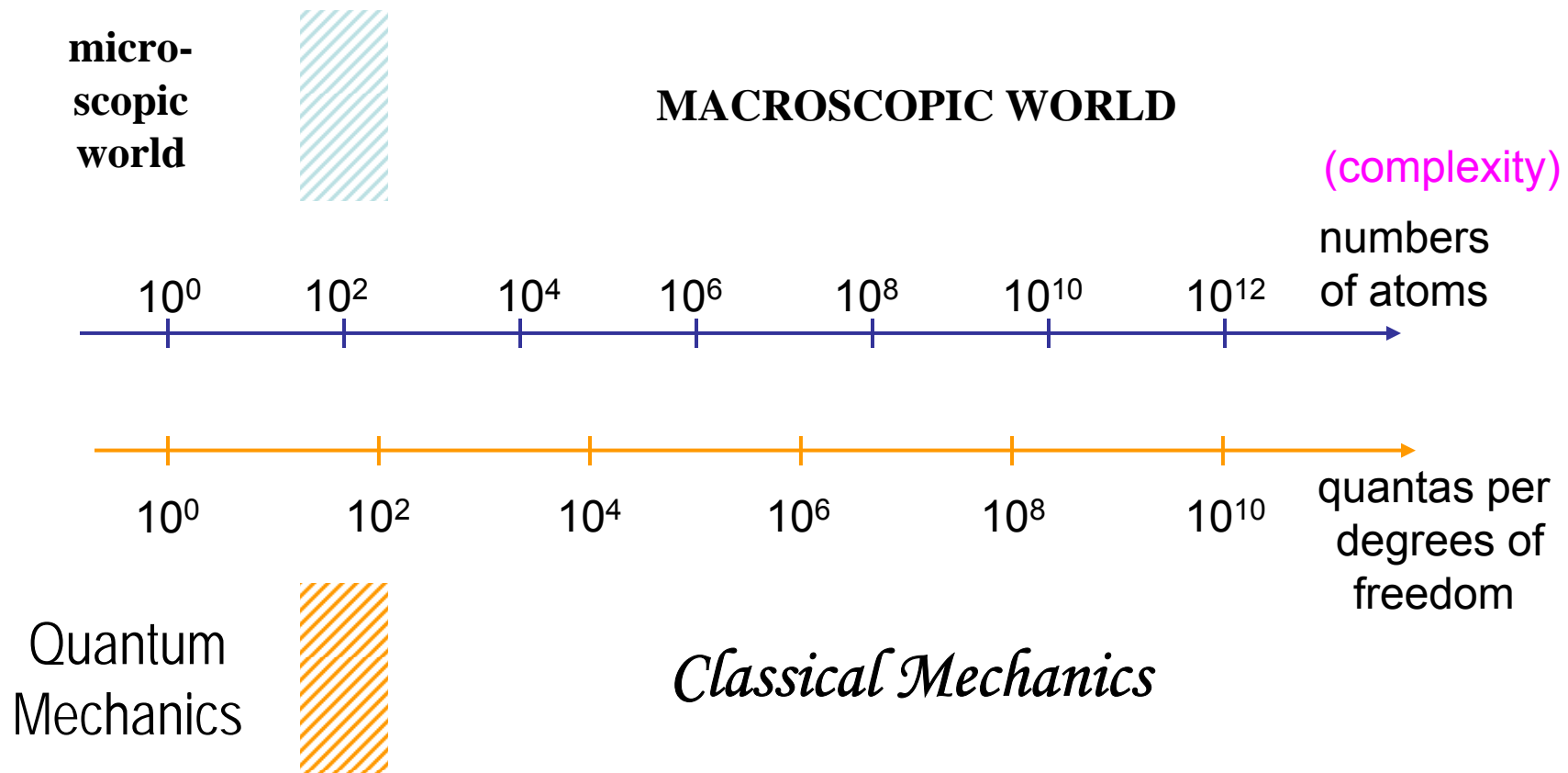




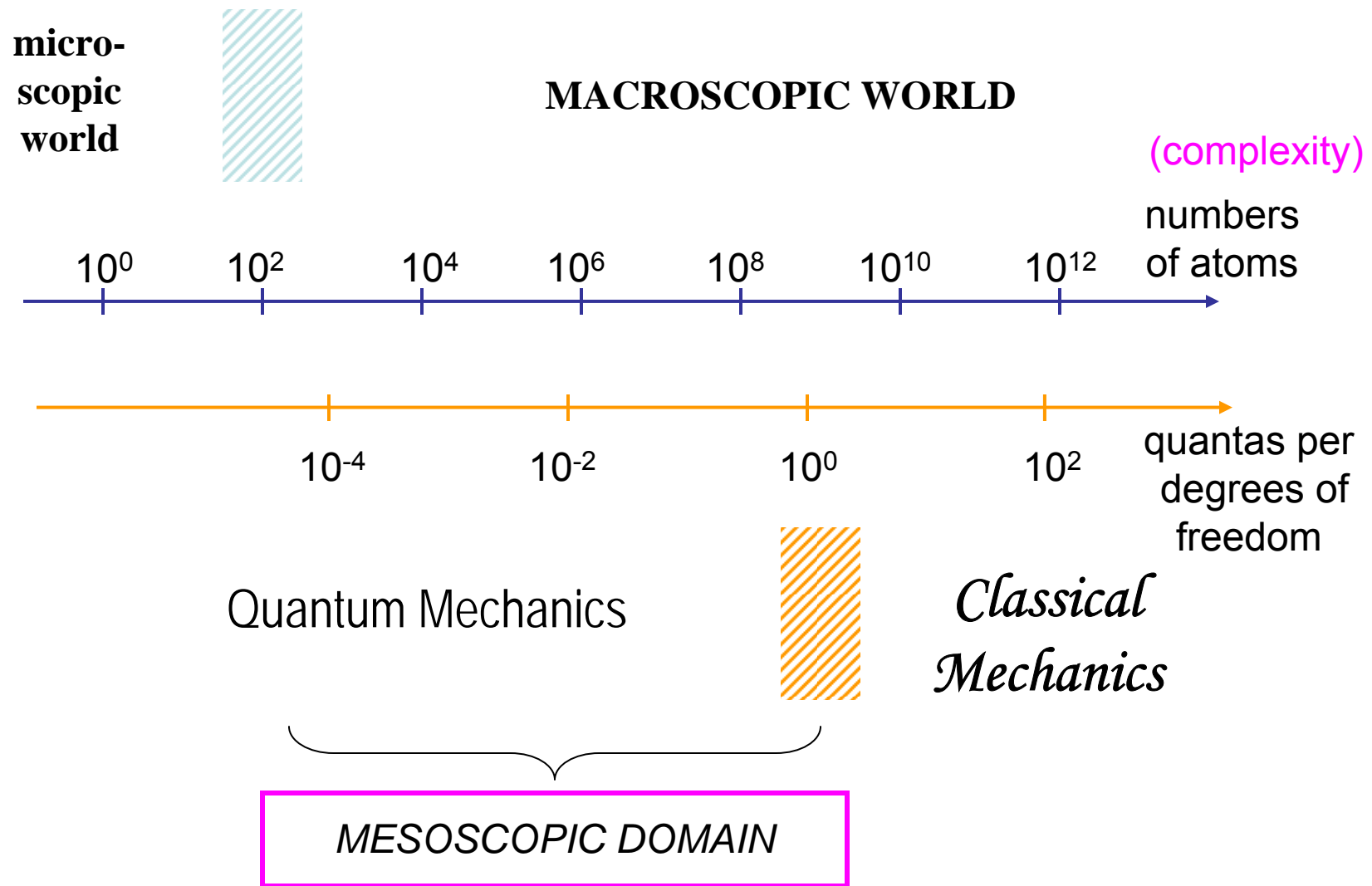
**YET,  
ATOMS ARE  
NOT  
MINIATURE  
SOLAR SYSTEMS**

IN QUANTUM MECHANICS, BASIC NOTIONS LIKE  
TRAJECTORIES AND EVENTS  
LOSE THEIR USUAL MEANING

# TWO WORLDS



# SEPARATING THE BORDERLANDS



# WHY EXPLORE MESOSCOPIC SYSTEMS?

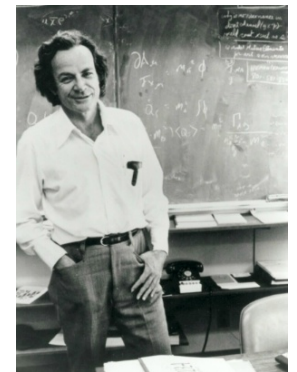
ADVANTAGES OF  
MACRO SYSTEMS:  
MODULARITY,  
FLEXIBILITY,  
ACCESSIBILITY

ADVANTAGES OF  
QUANTUM SYSTEMS:  
ORDER,  
DISCRETENESS,  
ENTANGLEMENT

MESOSCOPIC SYSTEMS:  
- PARTIALLY CONFINED QUASIPARTICLES  
- ARTIFICIAL ATOMS

QUANTUM  
LEGO SET

QUANTUM  
MACHINES?

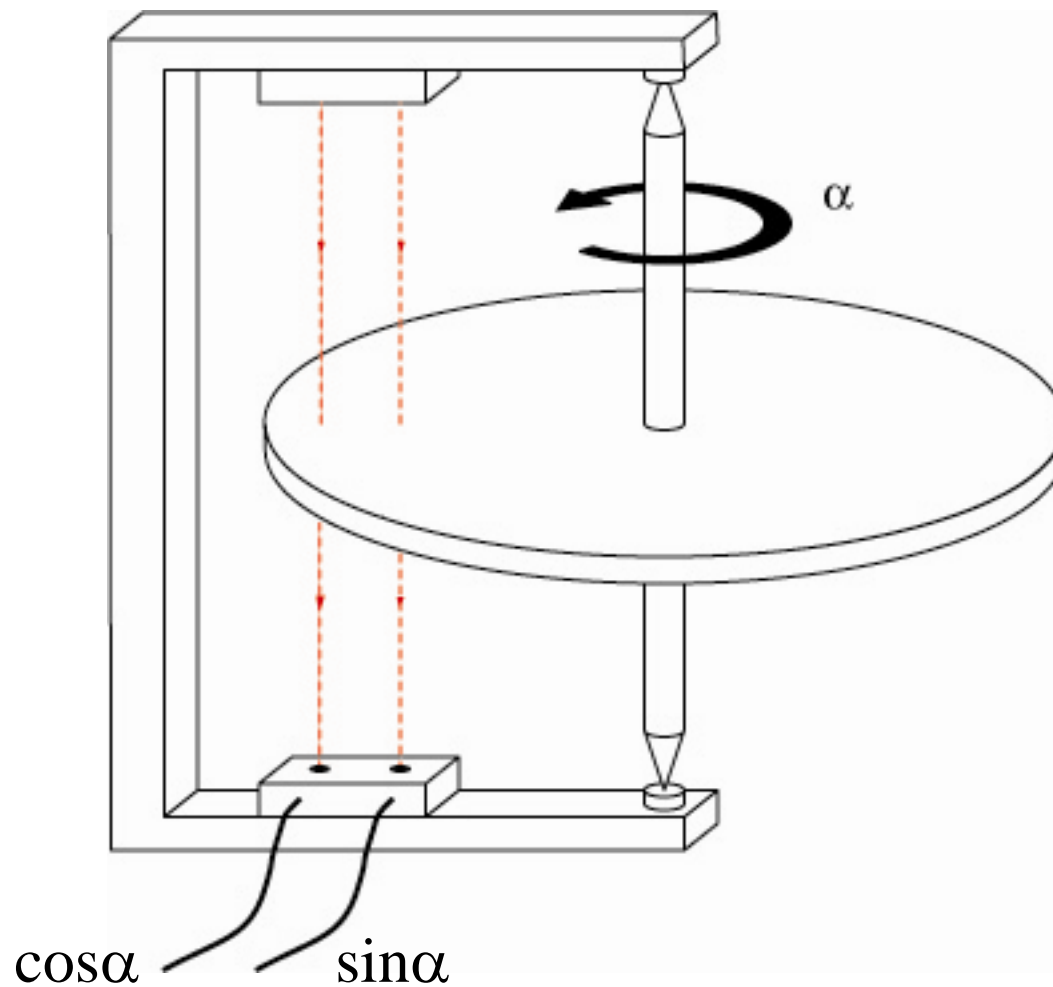


- WHAT ARE THESE QUANTAS DEFINING THE CLASSICAL-QUANTUM BORDERLAND?
- CHALLENGES OF MESOSCOPIC SYSTEMS:  
HOW DO WE MAKE, MEASURE AND CALCULATE THEM?  
THE QUANTUM POINT CONTACT
- APPLICATIONS TO METROLOGY AND QUANTUM INFORMATION PROCESSING : METROLOGICAL TRIANGLE AND SUPER-CONDUCTING QUANTUM CIRCUITS



- **WHAT ARE THESE QUANTAS DEFINING THE CLASSICAL-QUANTUM BORDERLAND?**
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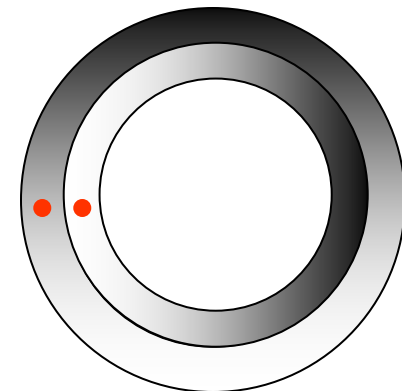
# A COMPLEX SYSTEM WITH THE SIMPLEST DEGREE OF FREEDOM



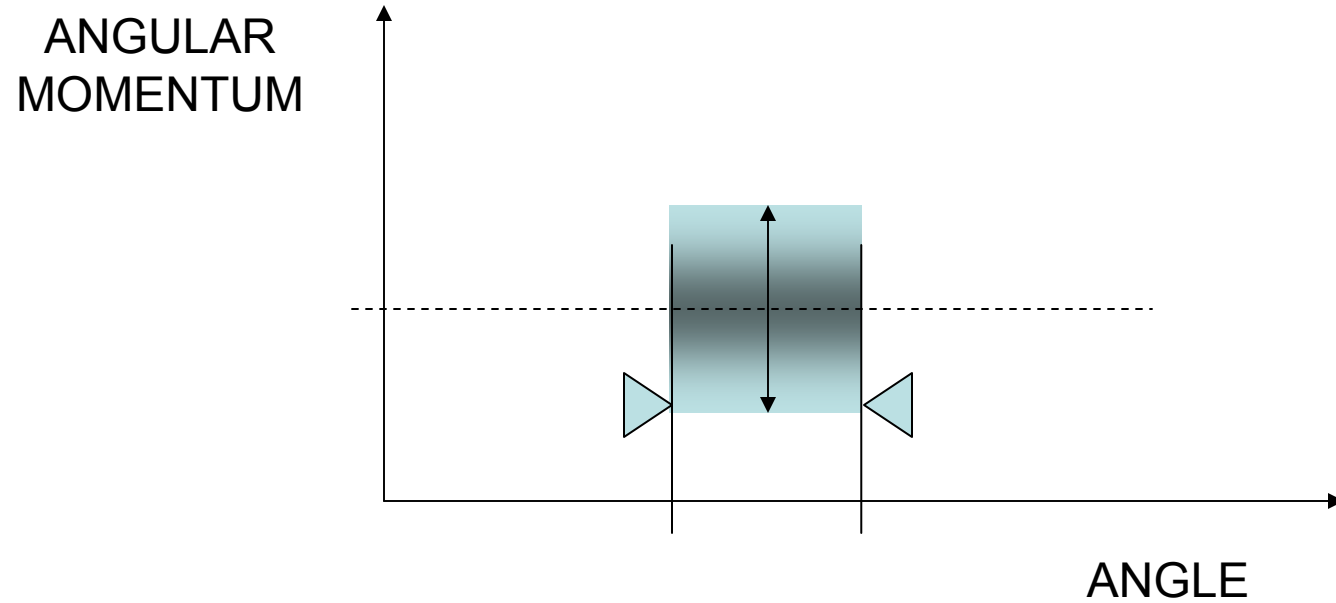
we measure:

- i) angular position  $\alpha$
- ii) angular velocity  $d\alpha/dt$

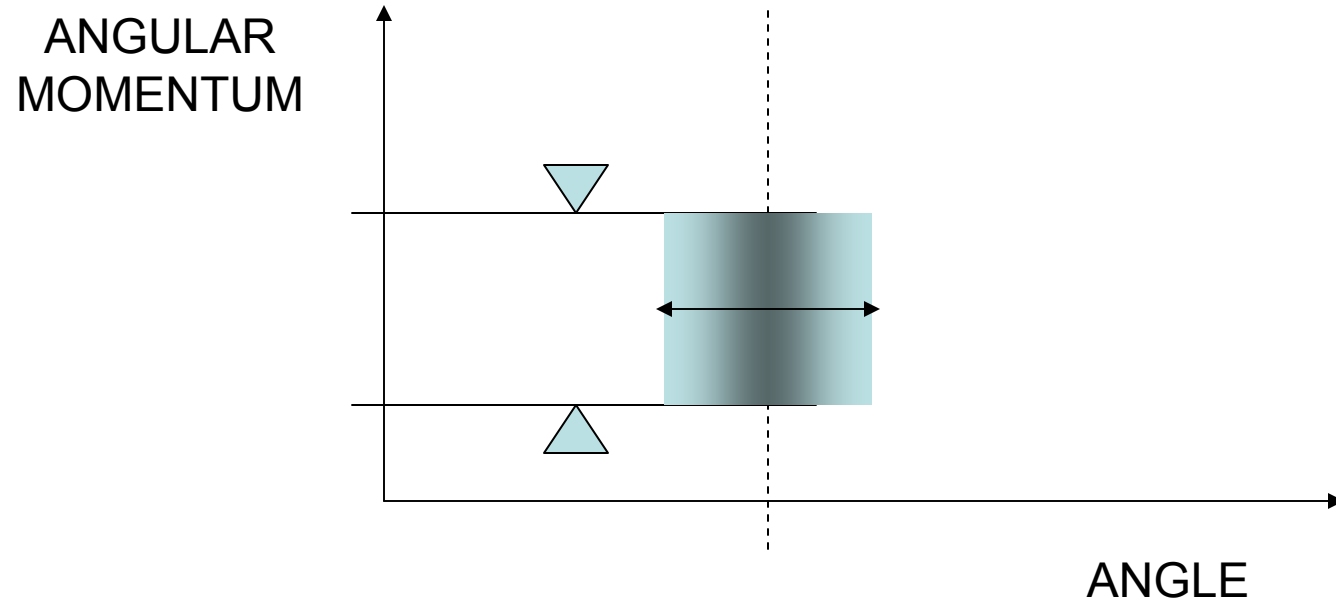
example:



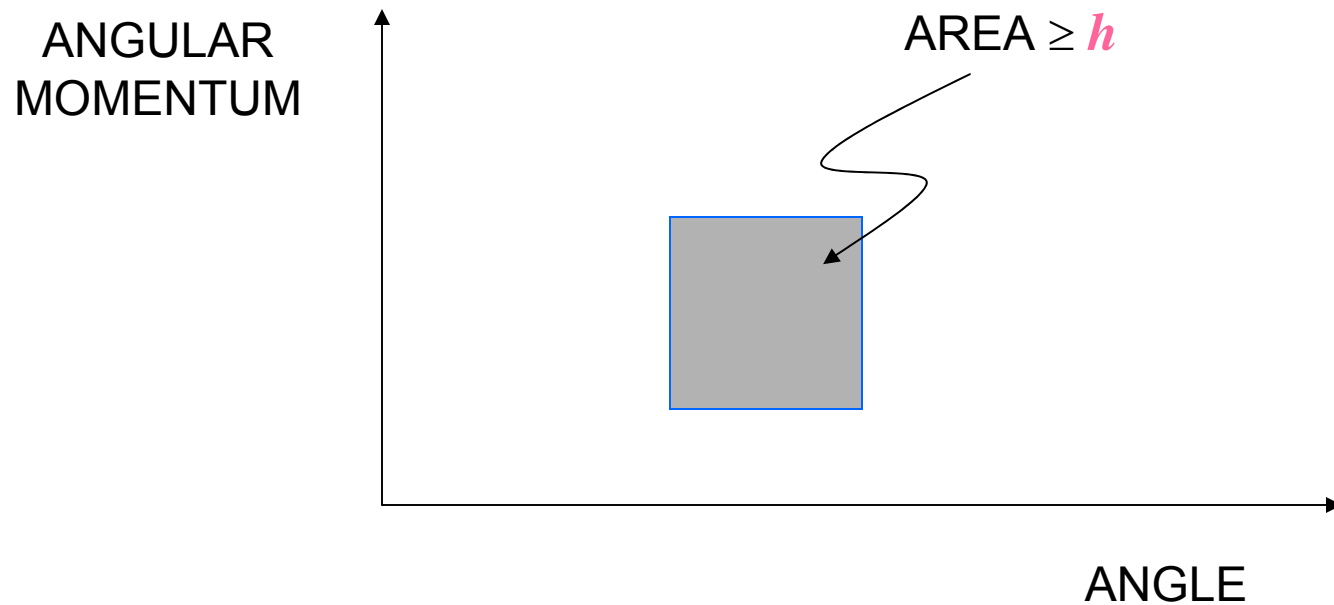
# QUANTUM LAWS RESTRICT INFORMATION ACQUISITION



# QUANTUM LAWS RESTRICT INFORMATION ACQUISITION



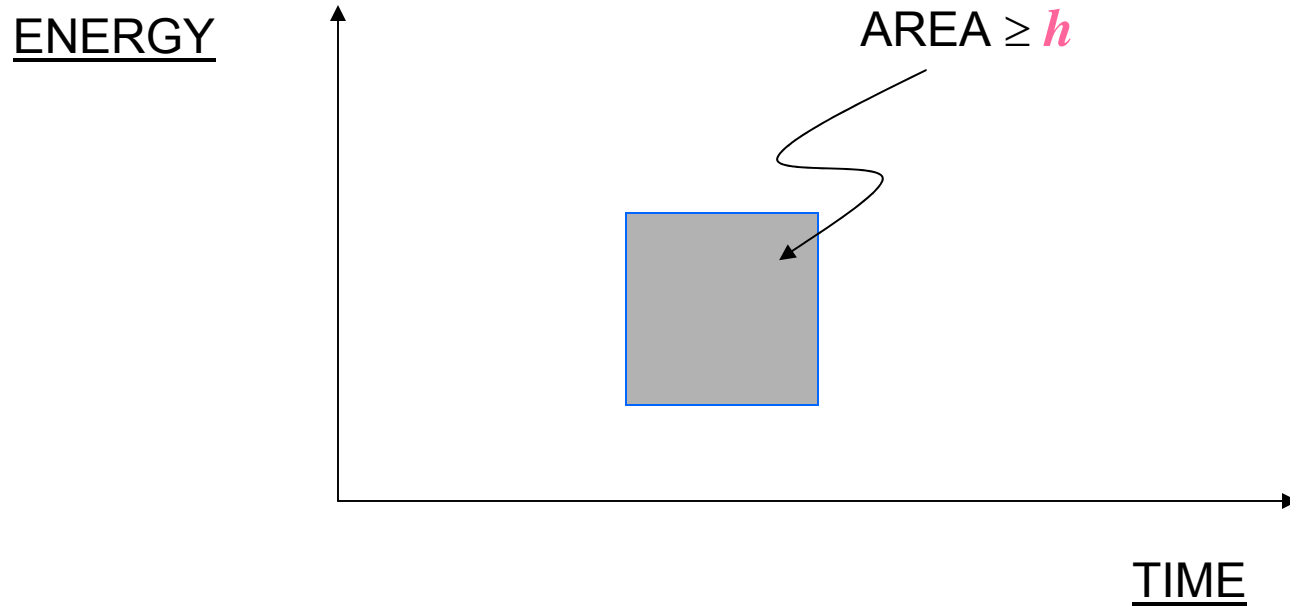
# PLANCK'S CONSTANT SETS THE ACTION QUANTUM....



$$h \approx 10^{-34} \text{ J}\cdot\text{s}$$

Measurement of angular position of hard drive with 16 bits  
→ velocity fuzz: thousandth of a turn per billion years!

# ... THE TRUE INDIVISIBLE QUANTITY OF NATURE



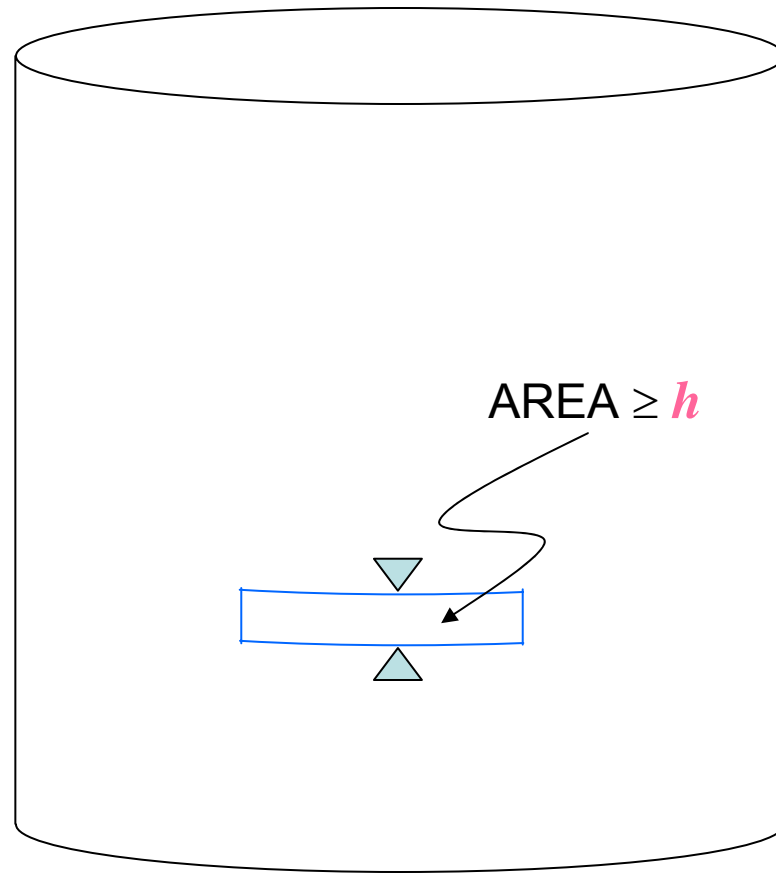

$$h \approx 10^{-34} \text{ J}\cdot\text{s}$$

ENERGY  $\rightarrow$  TEMPERATURE:

$$10\text{mK} \times 1\text{ns}$$

# DISCRETENESS OF CYCLIC SYSTEM

ANGULAR  
MOMENTUM

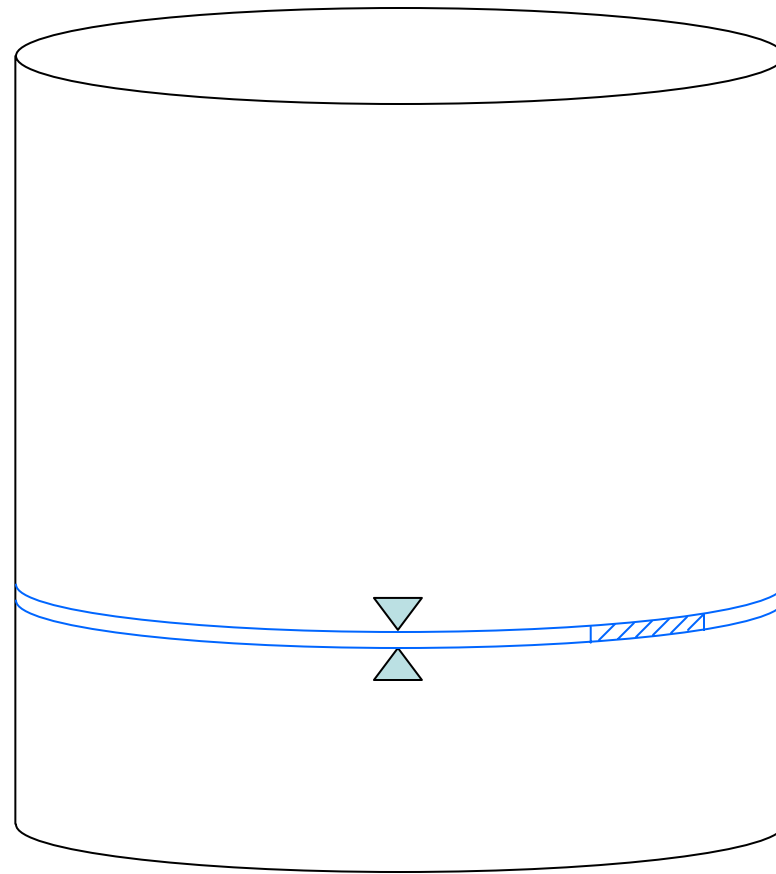



AREA  $\geq h$

ANGLE

# DISCRETENESS OF CYCLIC SYSTEM

ANGULAR  
MOMENTUM



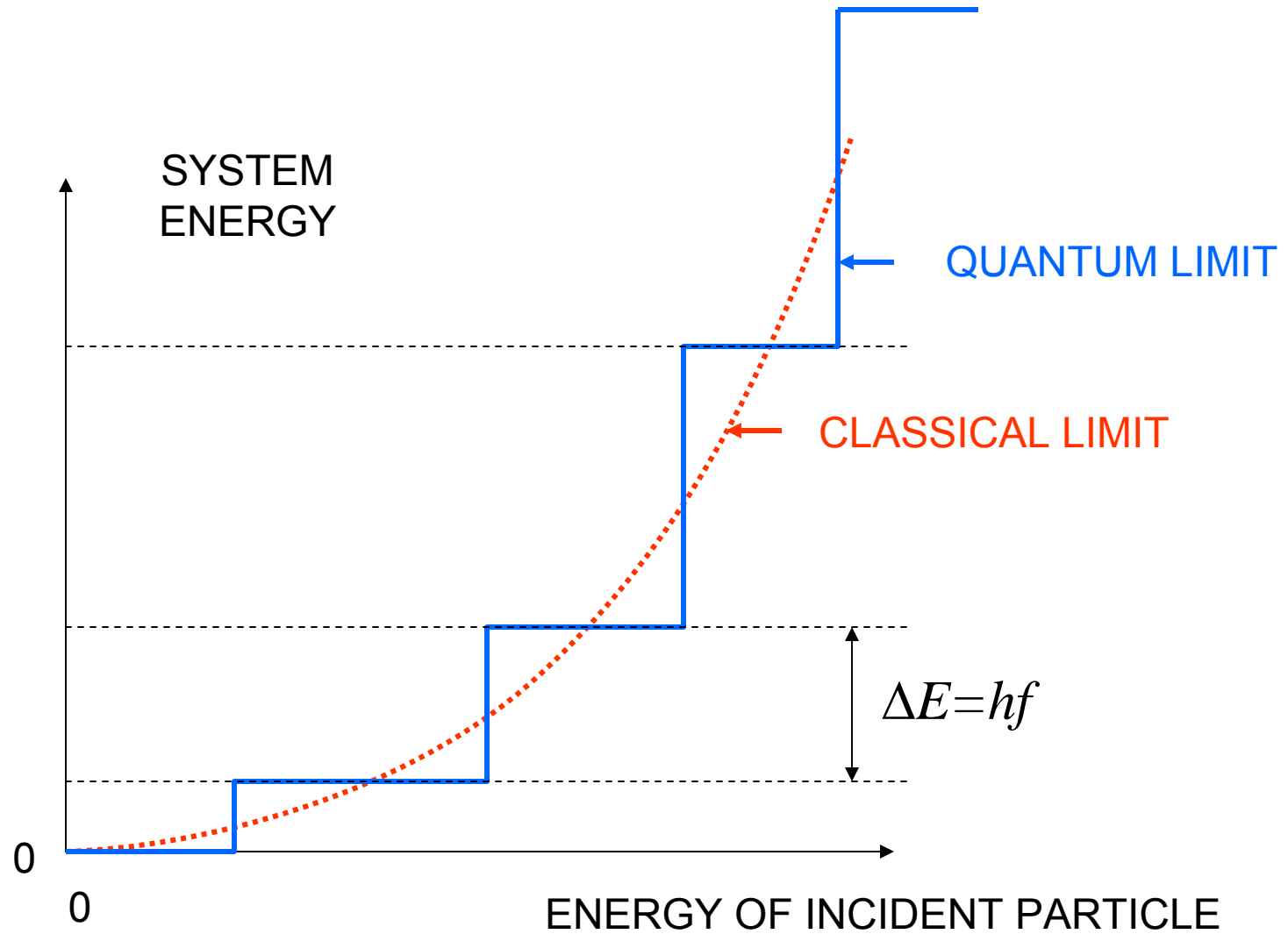
INTERFERENCE!

ANGLE



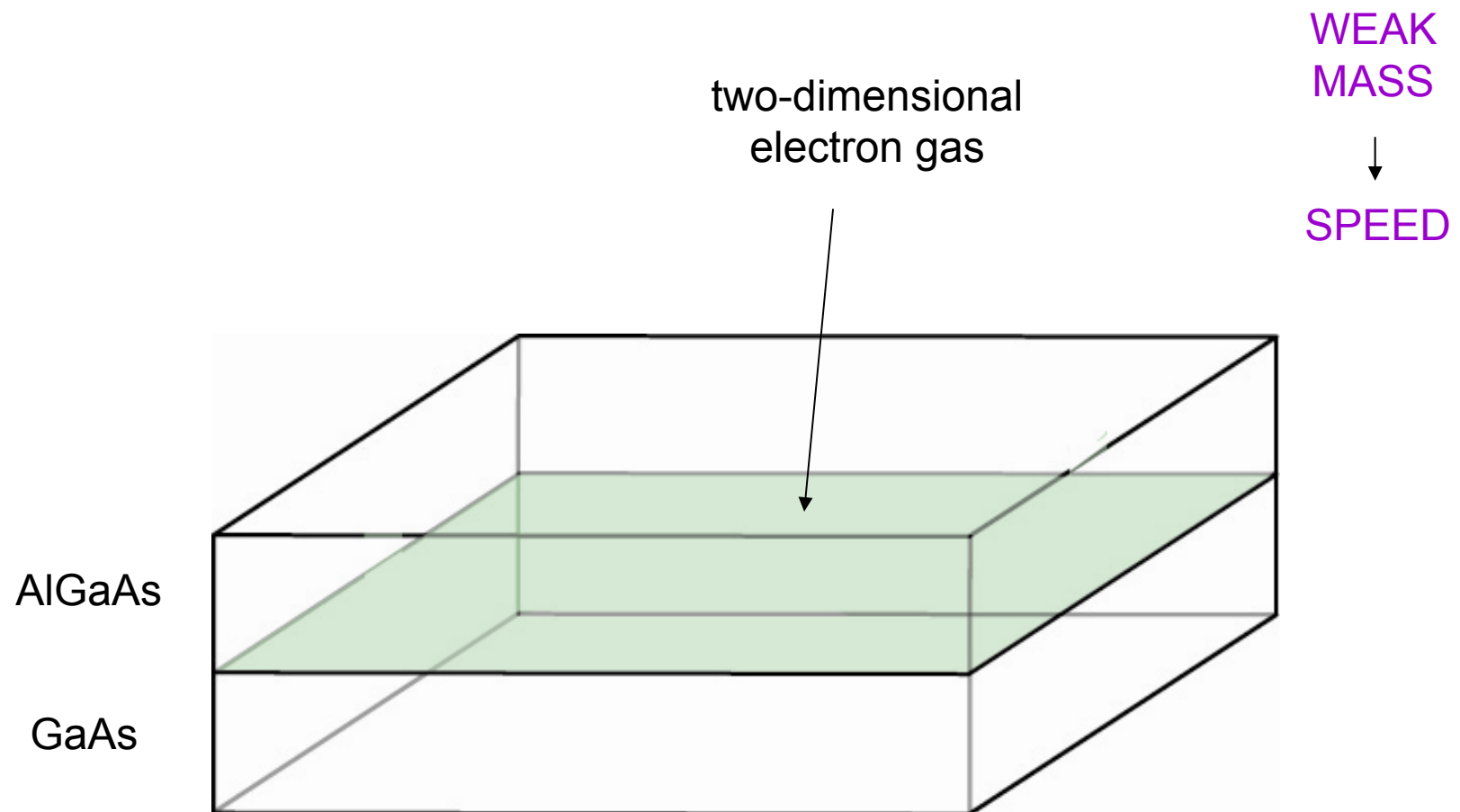


# ENERGY QUANTIZATION

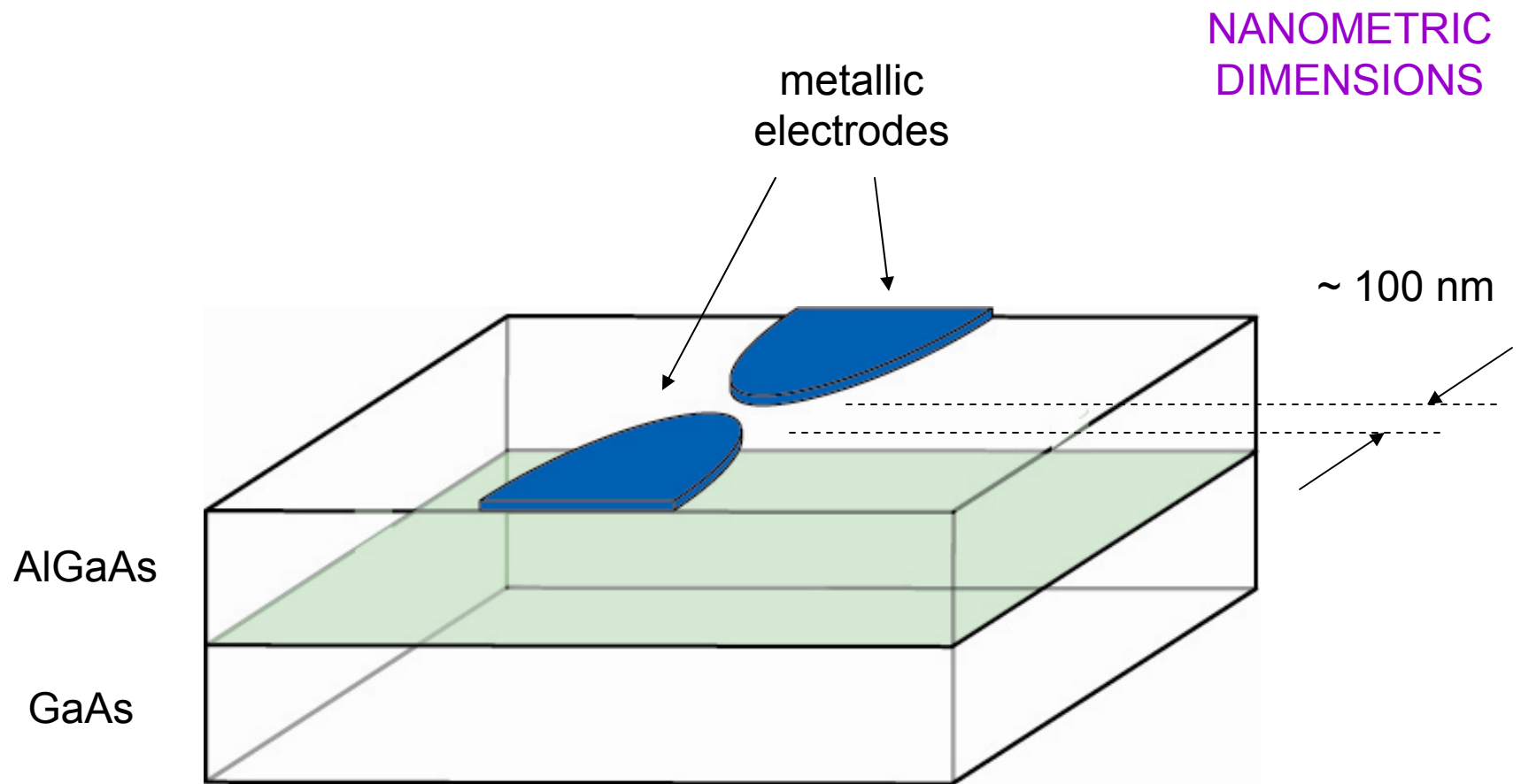


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# THE QUANTUM POINT CONTACT

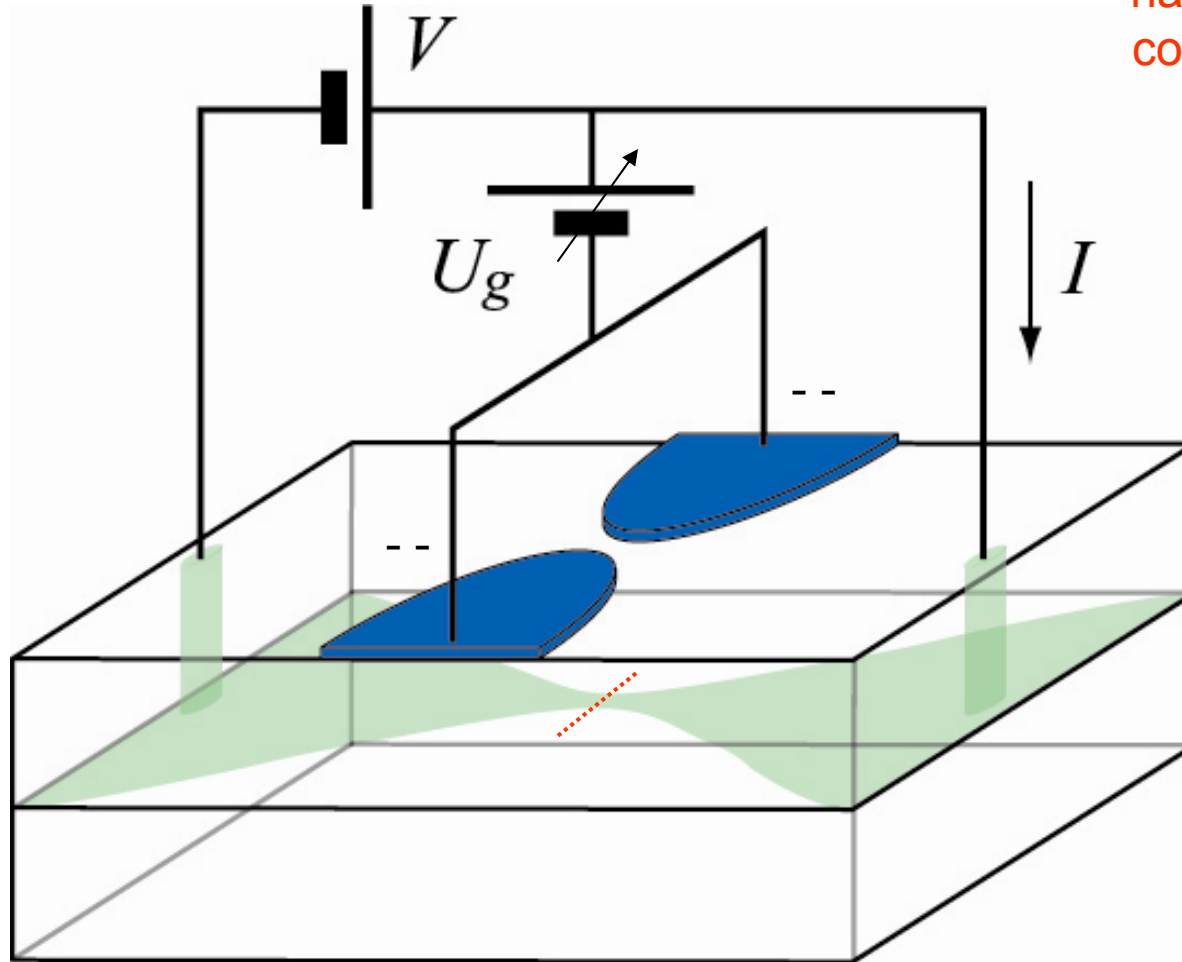


# THE QUANTUM POINT CONTACT

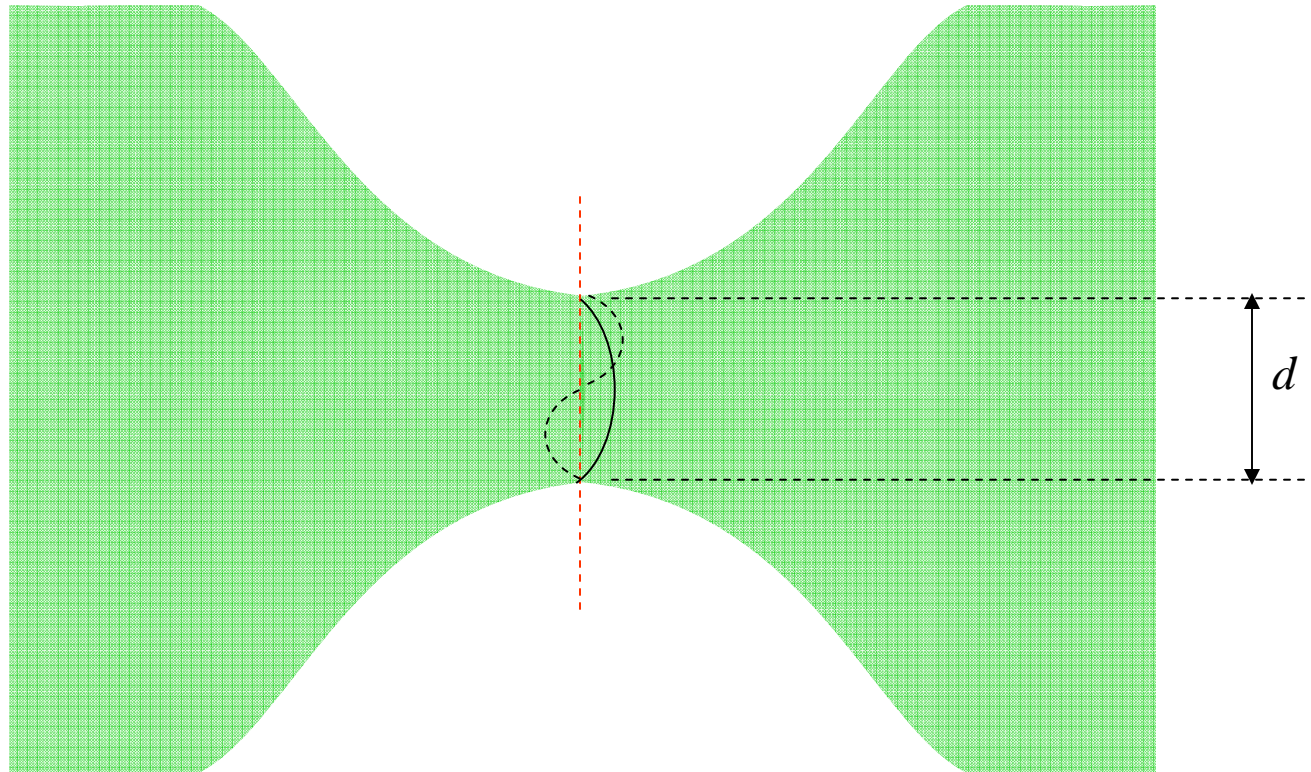


# THE QUANTUM POINT CONTACT

consider charge  
having traversed  
contact in time  $T$



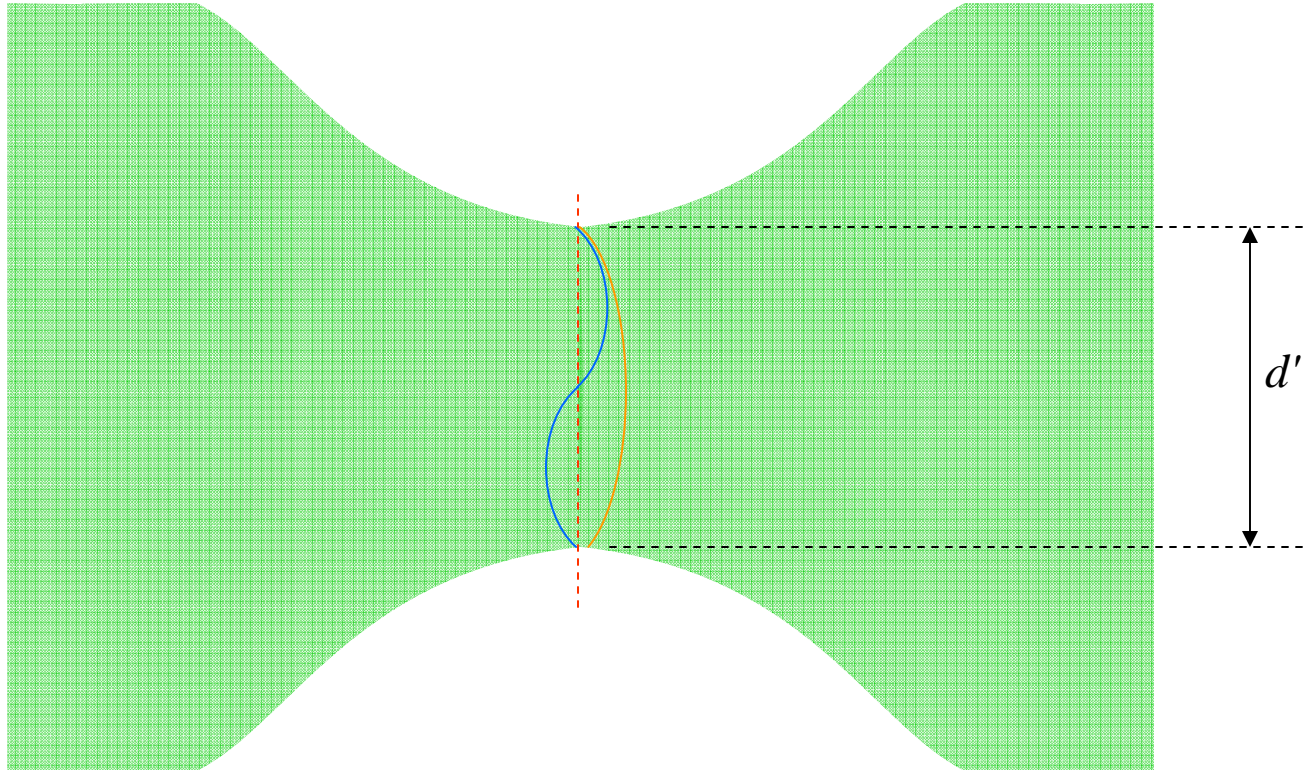
# ELECTRONIC MODES



LOW  
TEMPERATURES

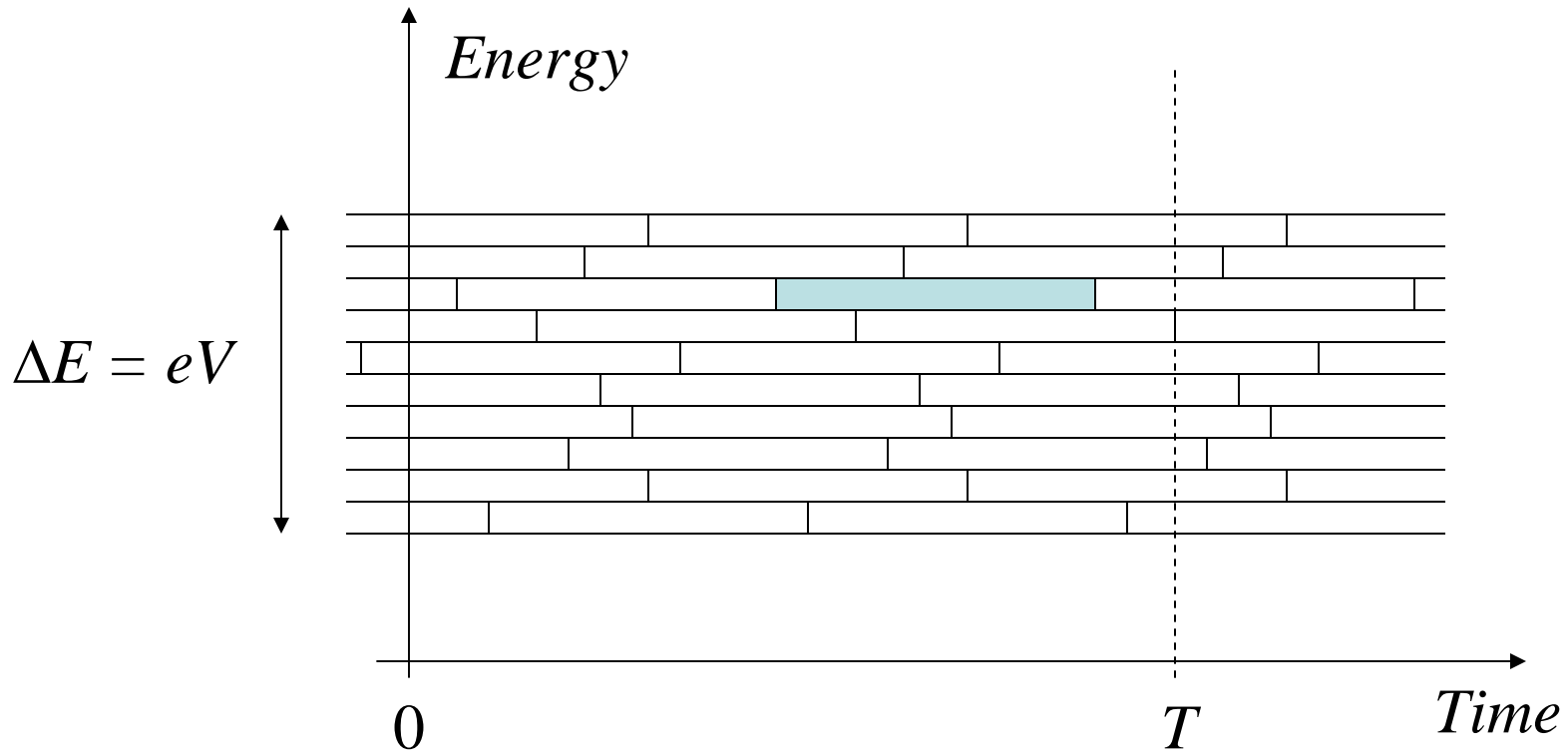
$$k_B T \ll \frac{h v_F}{d}$$

# ELECTRONIC MODES



WAVEGUIDE ANALOG

# OF MHOS AND ELECTRONS

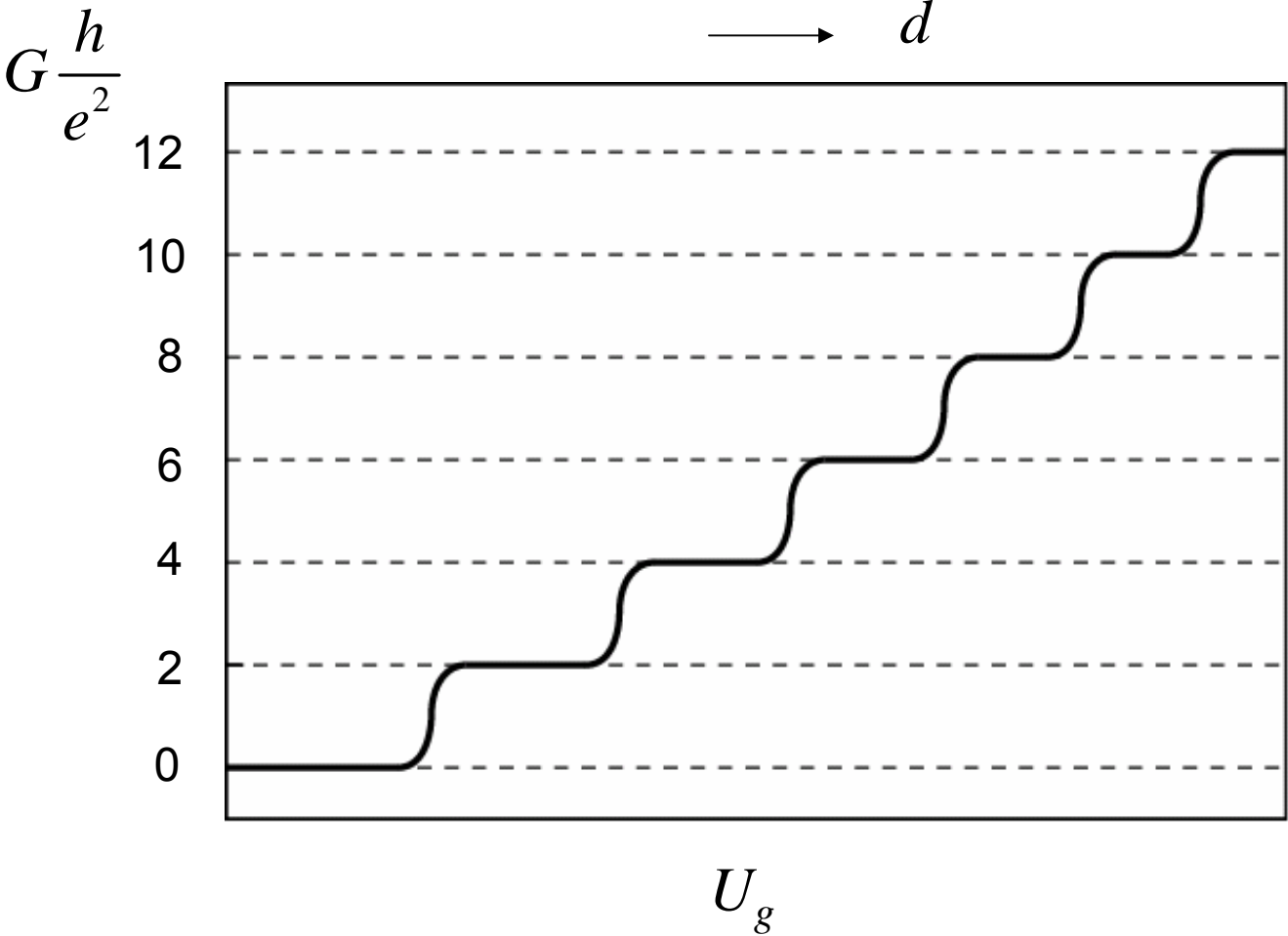


number of packets: 
$$N = \frac{ET}{h} = \frac{eVT}{h}$$

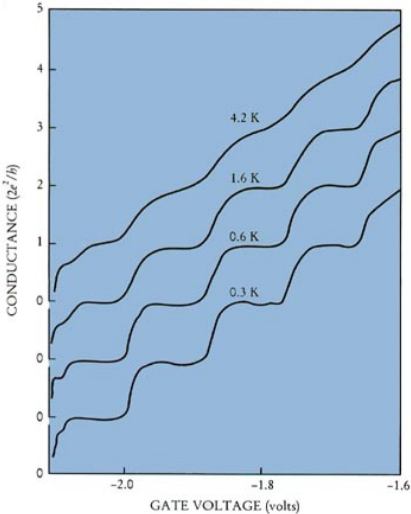
conductance: 
$$G = \frac{I}{V} = \frac{2eN}{TV} = 2 \frac{e^2}{h} \approx \frac{2}{26 \text{ k}\Omega}$$



# CONDUCTANCE QUANTIZATION



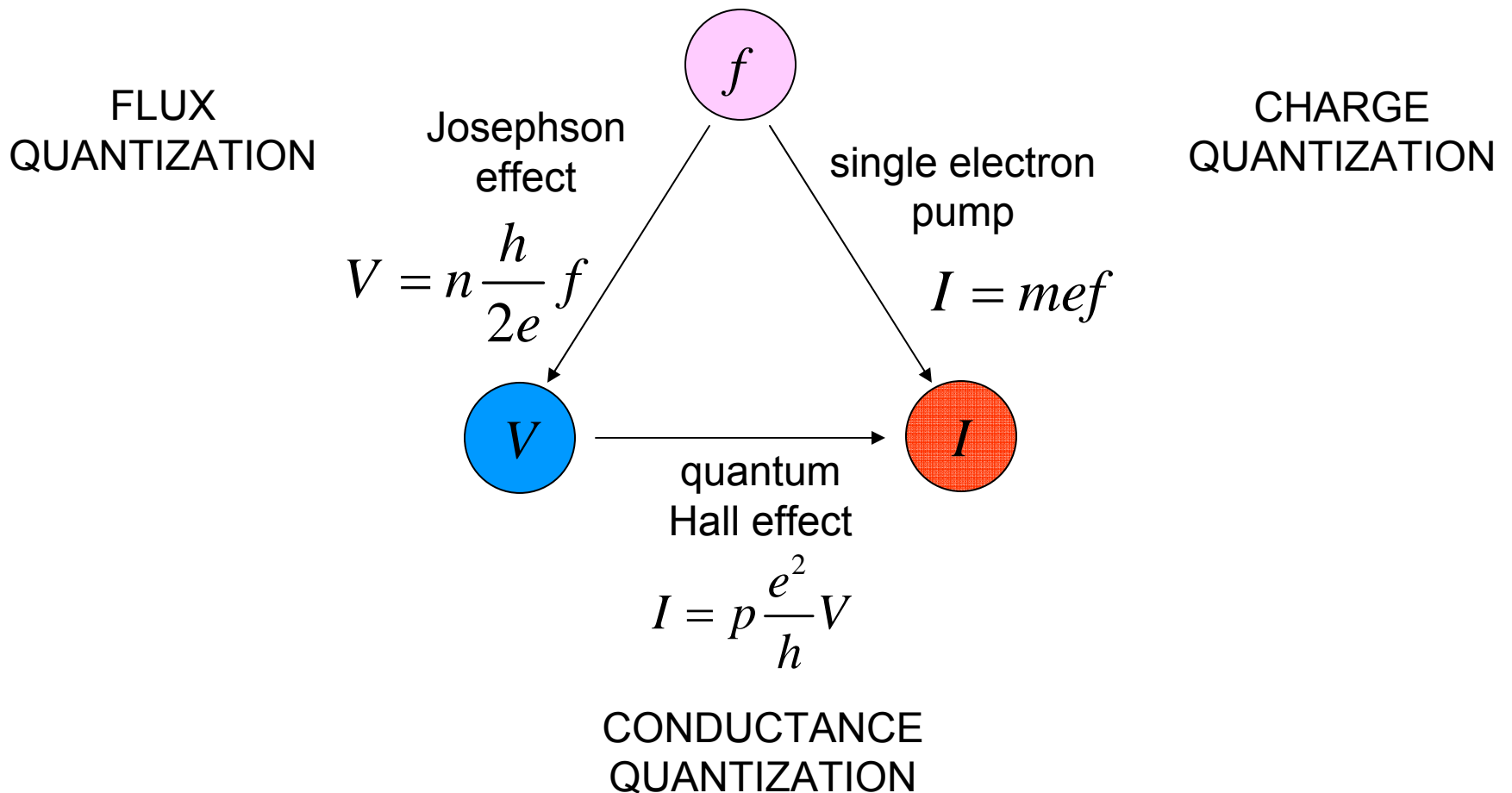
van Wees *et al.*  
1988



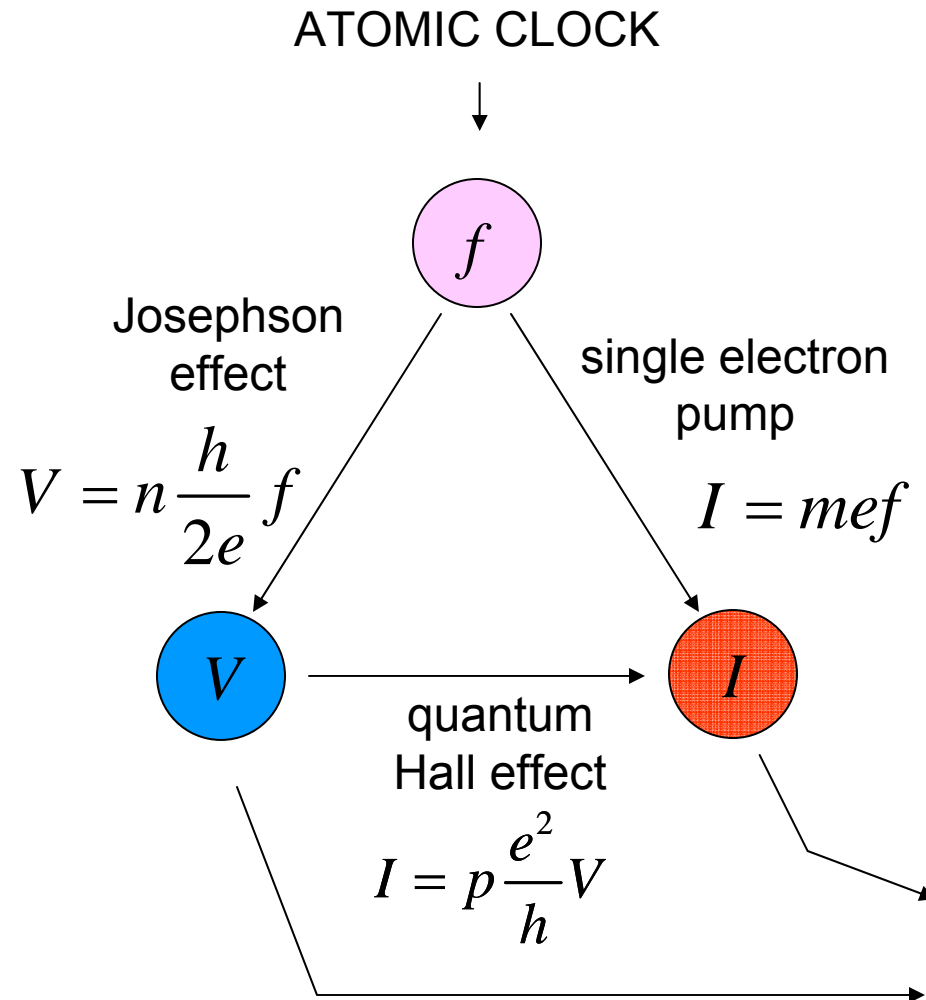
ACCESS TO A QUANTUM PHENOMENON  
WITH A SIMPLE VOLTMETER!

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# TRIANGLE OF METROLOGICAL MESOSCOPIC EFFECTS



# TRIANGLE OF METROLOGICAL MESOSCOPIC EFFECTS



revision  
of SI system



# UNIVERSAL AND MICROSCOPIC CONSTANTS

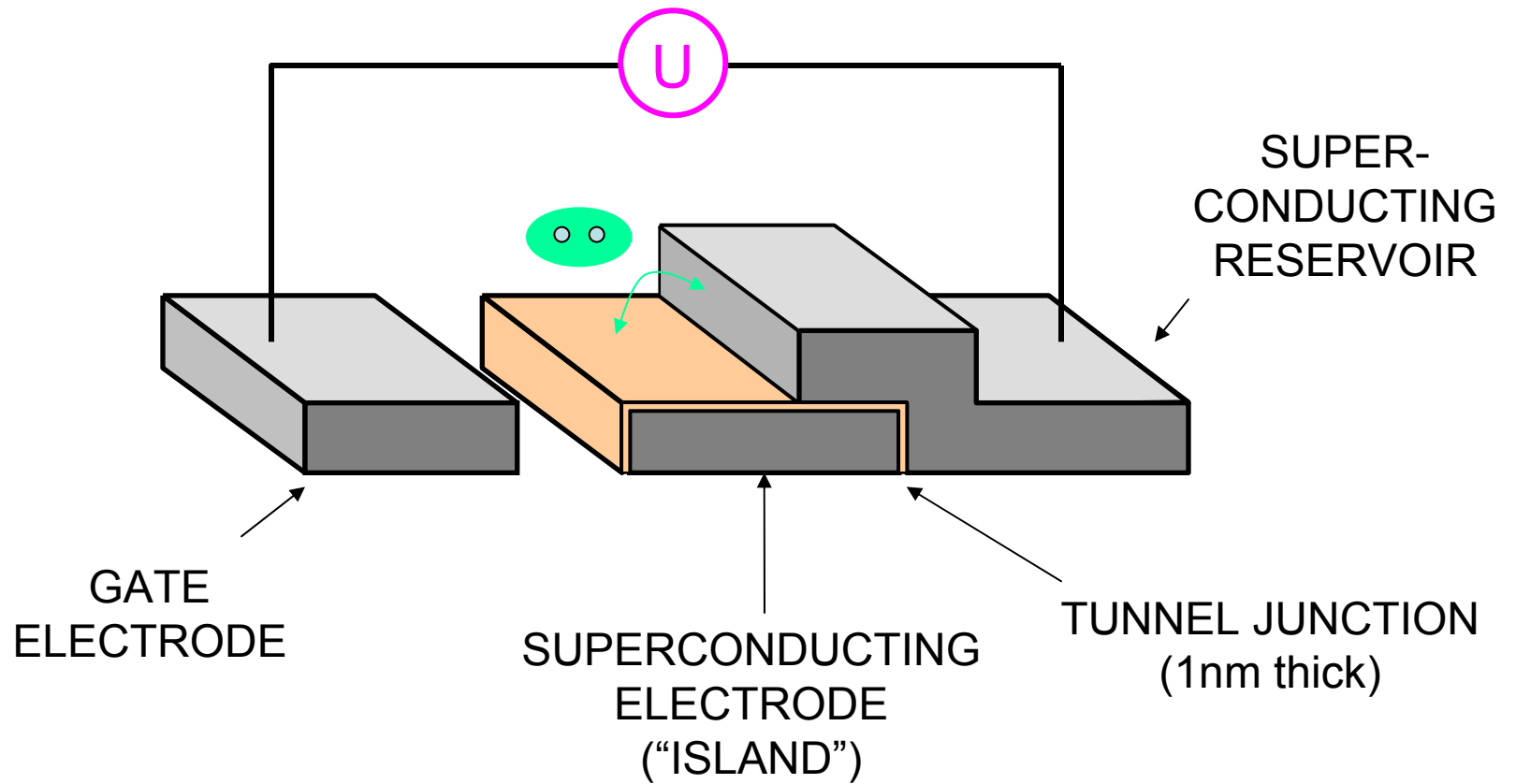


from S. Harris

UNIVERSAL  
QUANTUM  
CONSTANTS  
EMERGE  
ROBUSTLY IN  
METROLOGICAL  
TRIANGLE

ARTIFICIAL  
ATOMS?

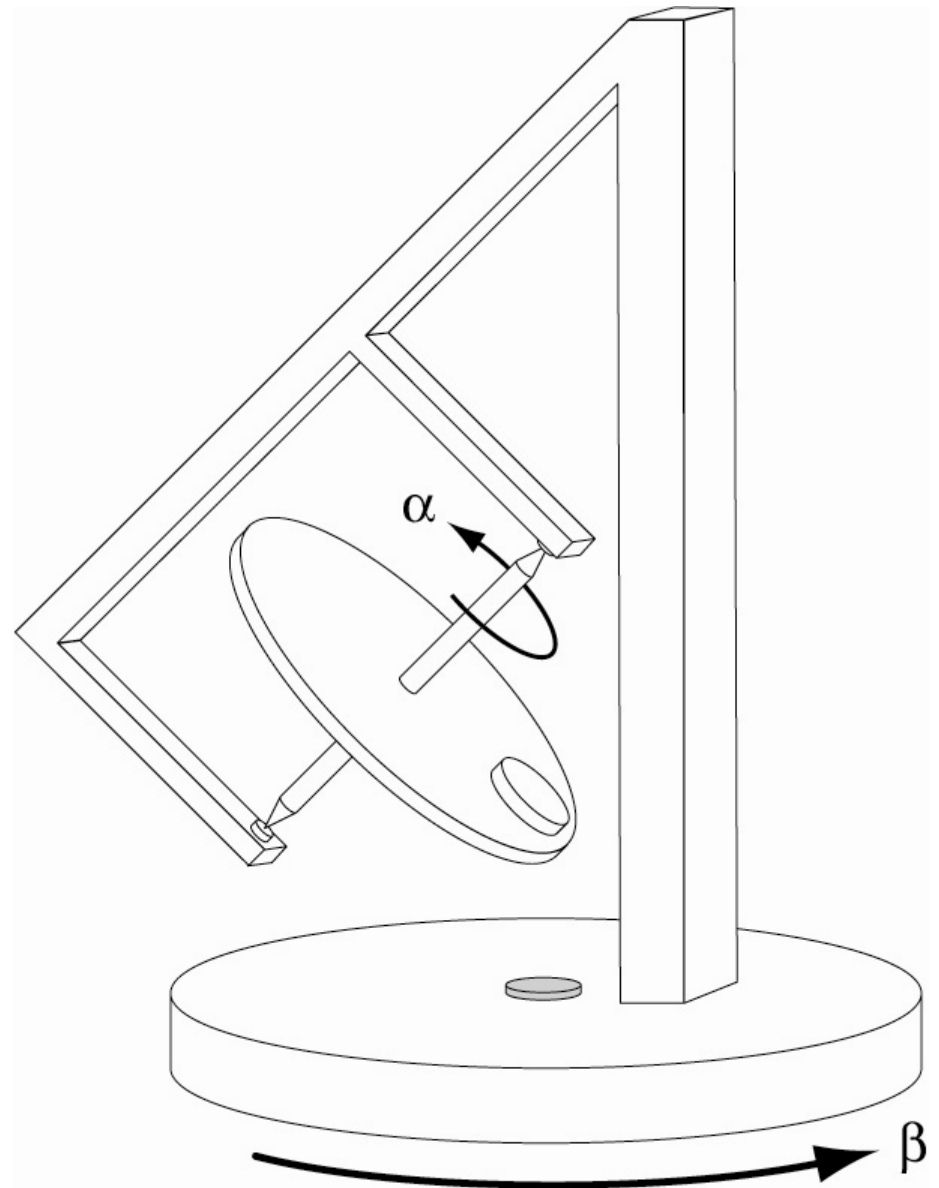
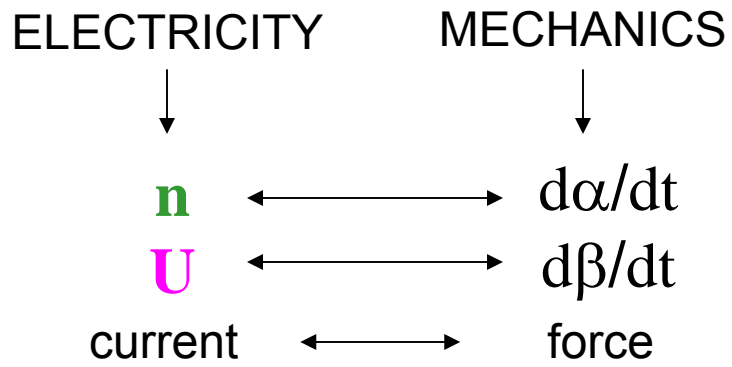
# AN ARTIFICIAL ATOM: THE COOPER PAIR BOX



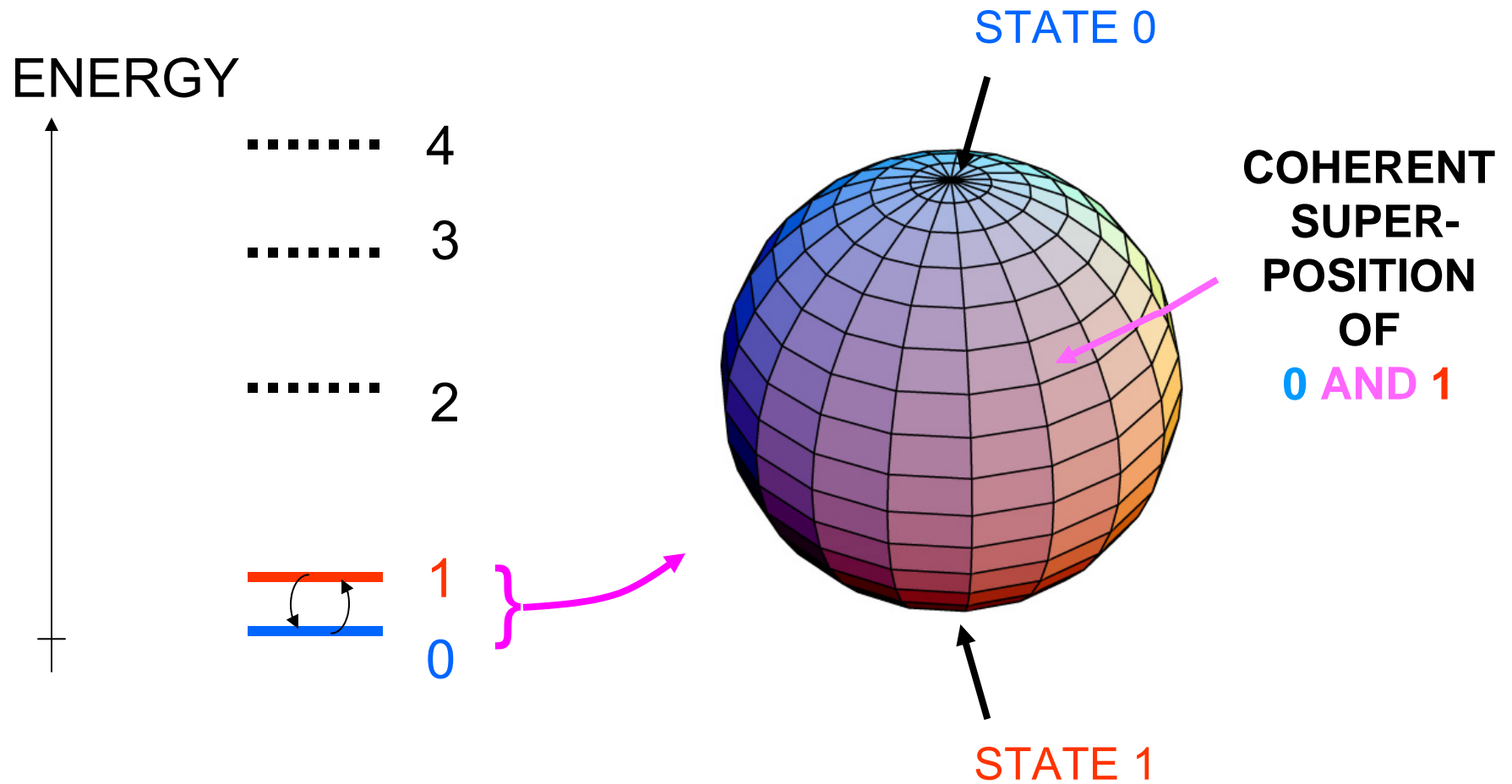
WITH  $n$  PAIRS  
OF EXCESS  
ELECTRONS

V. Bouchiat *et al.* 1997

# MECHANICAL ANALOG

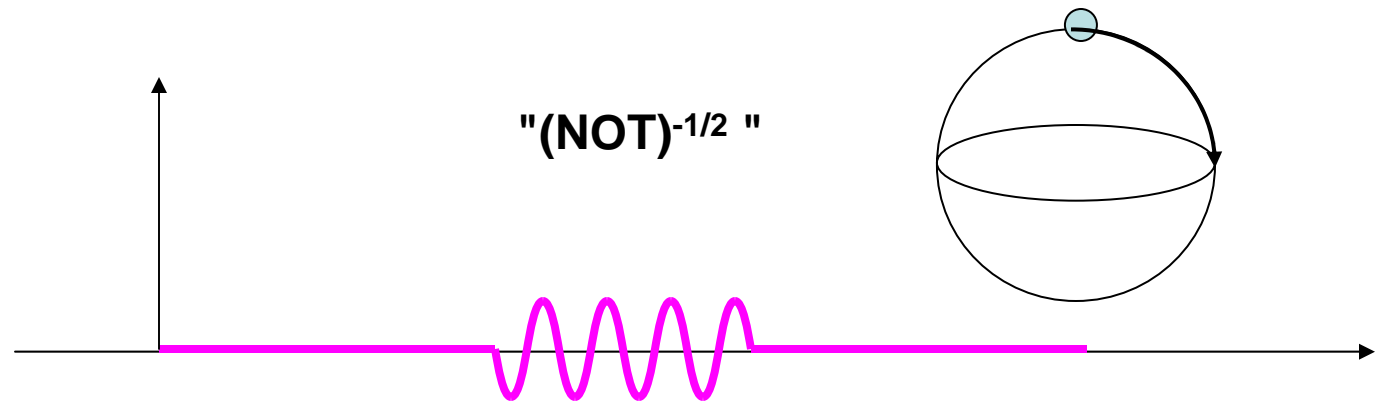
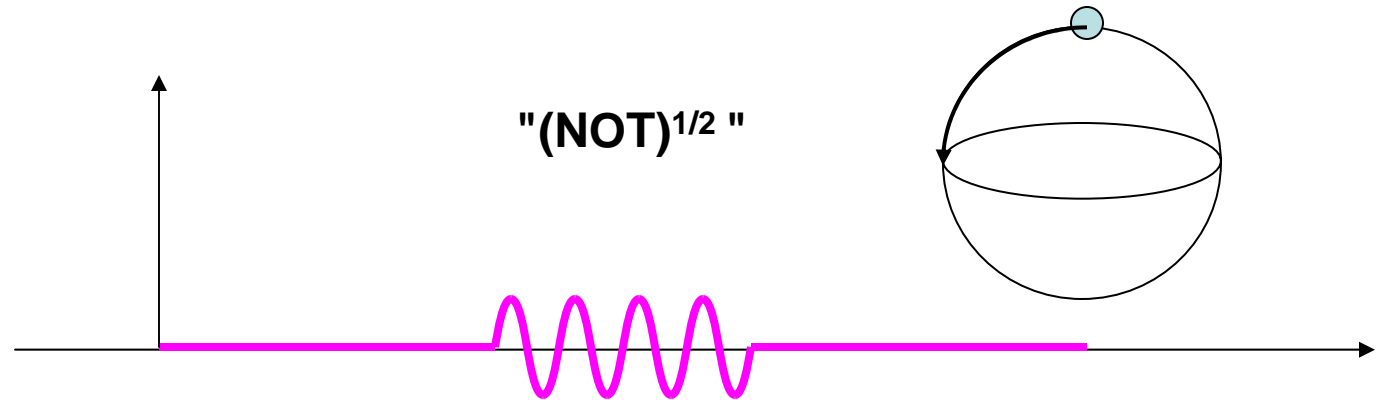
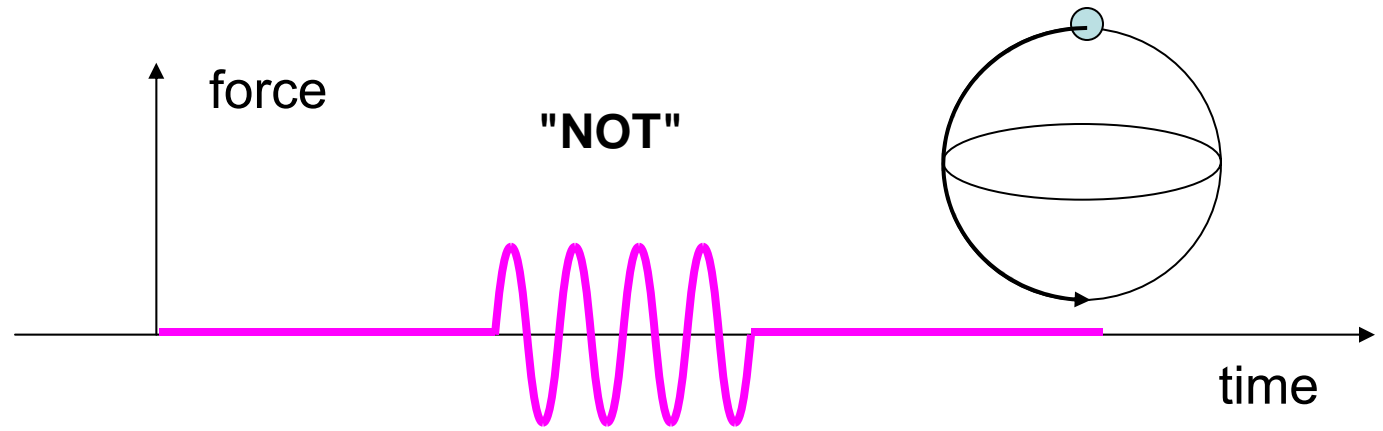


# QUBIT : QUANTUM BINARY INFORMATION UNIT

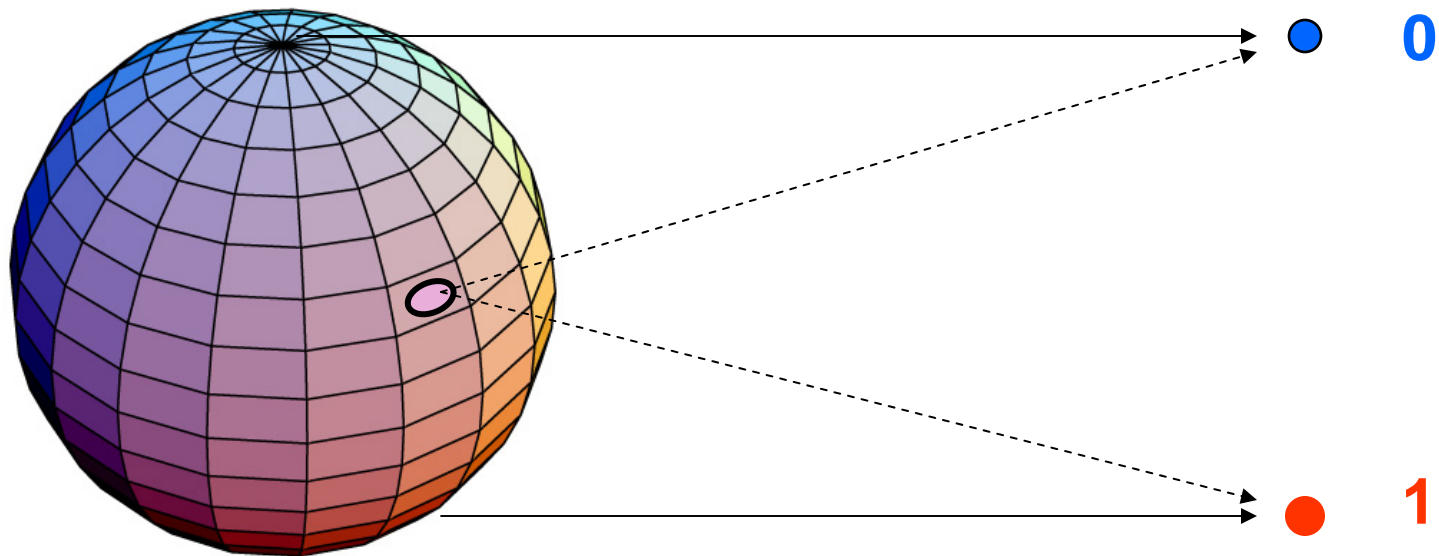




# WRITING A SUPER- POSITION

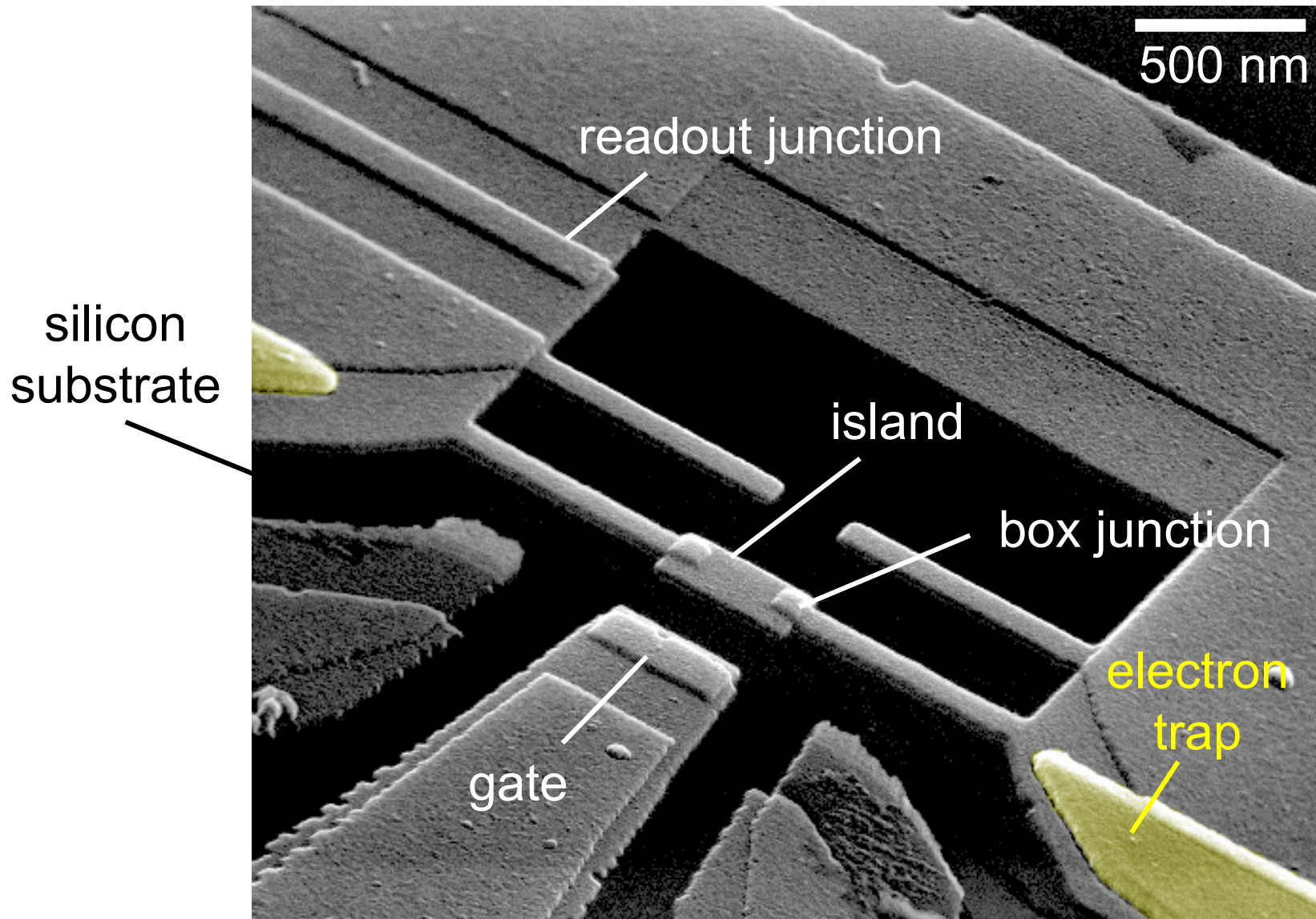


# THE PRINCIPLE OF INFORMATION RESTRICTION TAKES ITS TOLL

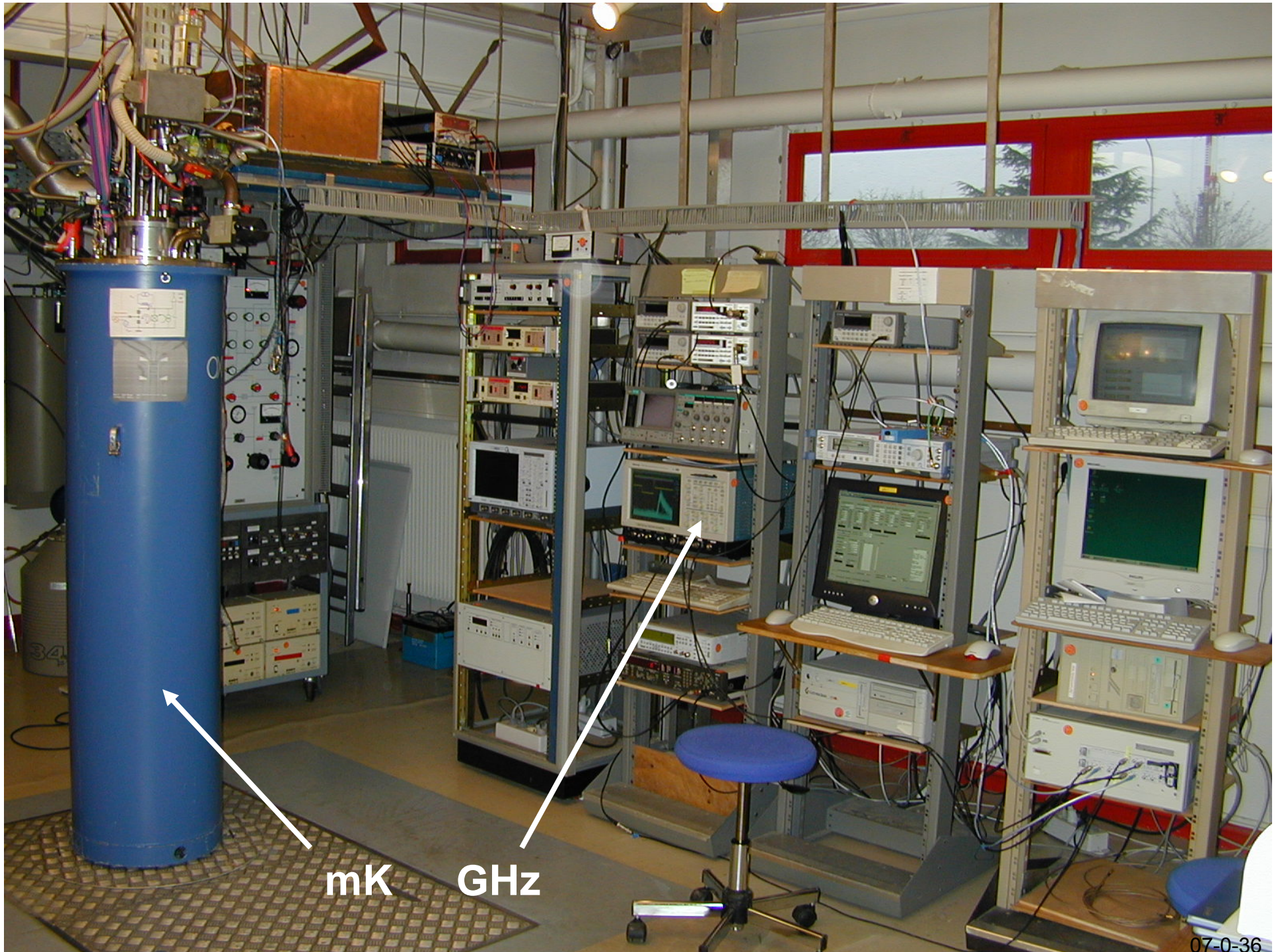


DURING READOUT,  
QUANTUM INFORMATION  
REDUCES TO  
**0 OR 1**

# 1 QUBIT NANO-CIRCUIT



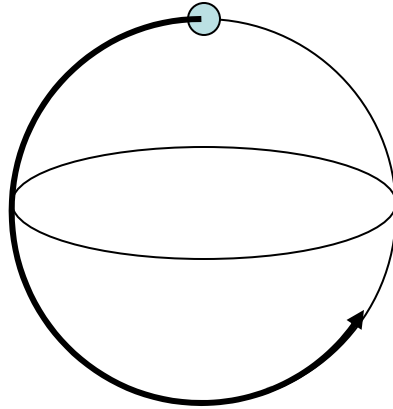
Vion *et al.*, 2002



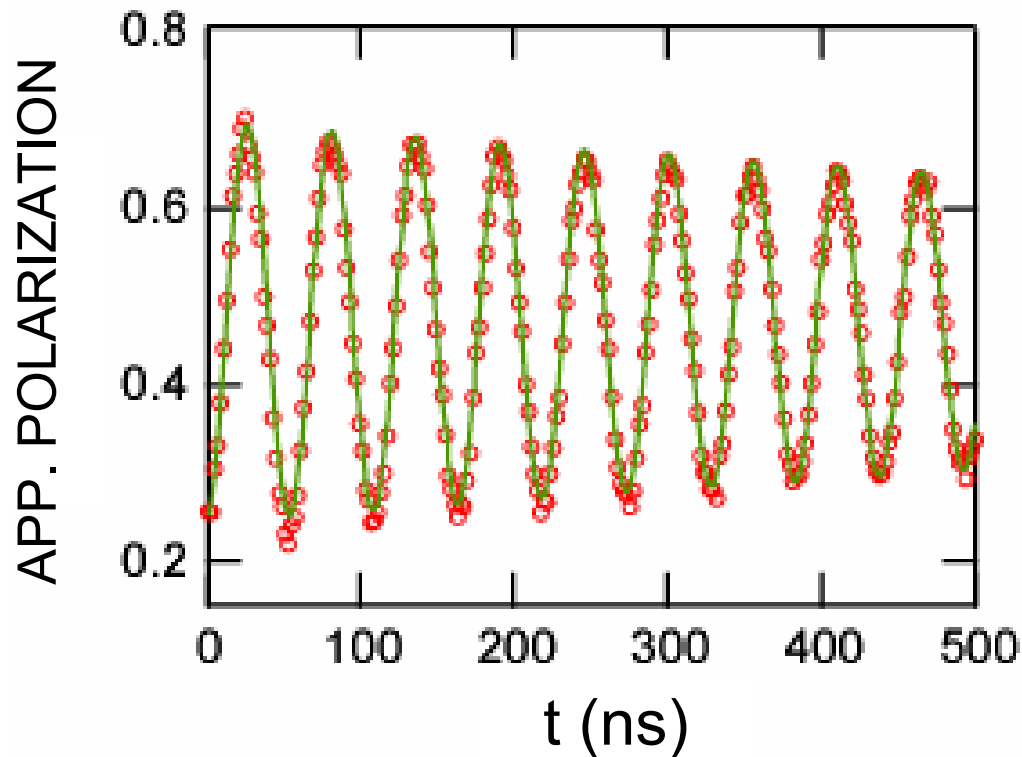
mK

GHz

# QUBIT MANIPULATION



- RESET
- IRRADIATION WHILE  $t$
- MEASUREMENT



Rabi oscillations of atomic physics and nuclear magnetic resonance observed on a single spin!

(Siddiqi *et al.*, 2006)

# CONCLUSIONS AND PERSPECTIVES

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NEW CHALLENGES : NANOMETER SCALE FABRICATION,  
MEASUREMENT OF INDIVIDUAL QUANTAS, THEORY OF COMPLEX  
QUANTUM SYSTEMS

---

NEW QUANTUM EFFECTS : FRACTIONAL CHARGES  
STRONG COUPLING BETWEEN CHARGE AND FIELD,  
LOCAL MANIPULATION OF ELECTRONIC AND NUCLEAR SPINS,  
NON-GAUSSIAN NOISE, ENTANGLEMENT OF COLLECTIVE VARIABLES....

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APPLICATIONS: REDEFINITION OF BASIC UNITS, DETECTION OF  
PARTICLES AND WEAK FORCES, INFORMATION PROCESSING

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MESOSCOPIC SYSTEMS OPEN THE WAY TO THE  
QUANTUM MACHINES IMAGINED BY RICHARD FEYNMAN

---

DISCOVERY OF A NEW COMPLEXITY AXIS  
TOWARDS WHICH QUANTUM MECHANICS  
WOULD PRESENT ANOMALIES?

# MY MENTORS AND CLOSE COLLEAGUES

## University of Orsay

John ELAND  
Sydney LEACH  
Maurice CHAPPELLIER

## CEA-Saclay

Anatole ABRAGAM  
Neil SULLIVAN  
Maurice GOLDMAN  
André LANDESMAN

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