Title: Foundations and Interpretation of Quantum Theory - Lecture 20

Date: Mar 30, 2010 02:30 PM

URL: http://pirsa.org/10030008

Abstract: Macroscopic quantum coherence

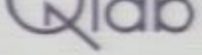
Foundations and Interpretation of Quantum Theory:
MACROSCOPIC QUANTUM PHENOMENA

Michel Devoret &
Vladimir Manucharyan,
Yale University

"ACTUALLY I STARTED OUT IN QUANTUM MECHANICS, BUT SOMEWHERE ALONG THE WAY I TOOK A WRONG TURN."

MACROSCOPIC QUANTUM PHENOMENA IN SUPERCONDUCTING CIRCUITS

QUANTUM – MECHANICAL ELECTRONICS LAB



Applied Physics and Physics, Yale University

R. VIJAY (U.C.Berkeley)
I. SIDDIQI (U.C.Berkeley)
C. RIGETTI (IBM)
M. METCALFE (NIST)
V. MANUCHARIAN

N. BERGEAL (ESPCI Paris)
F. SCHACKERT
A. KAMAL
B. HUARD (ENS Paris)
A. MARBLESTONE (MIT)

N. MASLUK
M. BRINK
K. GEERLINGS
L. FRUNZIO
M. DEVORET

Acknowledgements: R. Schoelkopf, S. Girvin, D. Prober & D. Esteve

W.M. KECK

COLLÈGE DE FRANCE 1530

Waterloo

MACROSCOPIC QUANTUM PHENOMENA IN SUPERCONDUCTING CIRCUITS

OUTLINE

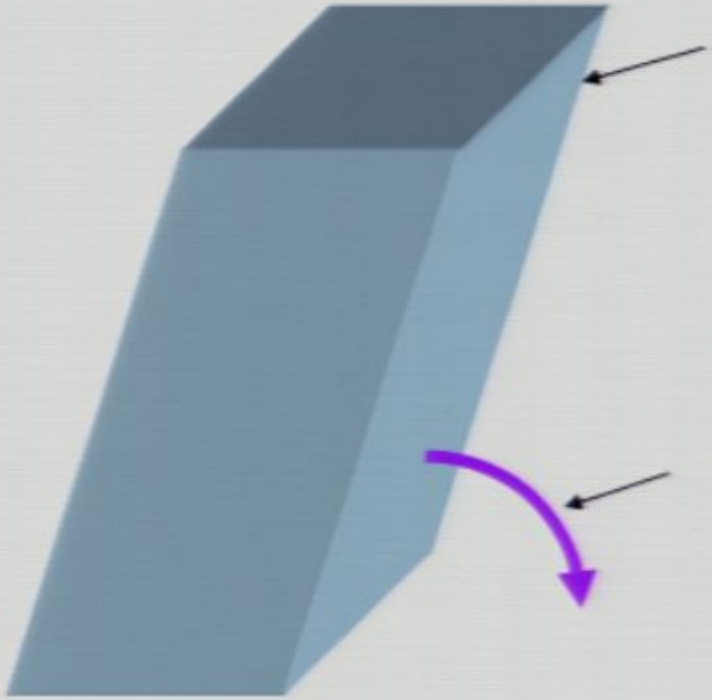
TODAY: BASIC QUESTIONS ADDRESSED BY SUPER-CONDUCTING CIRCUITS

THURSDAY: MACROSCOPIC QUANTUM EXP^{TS} ON THE FLUXONIUM ARTIFICIAL ATOM

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



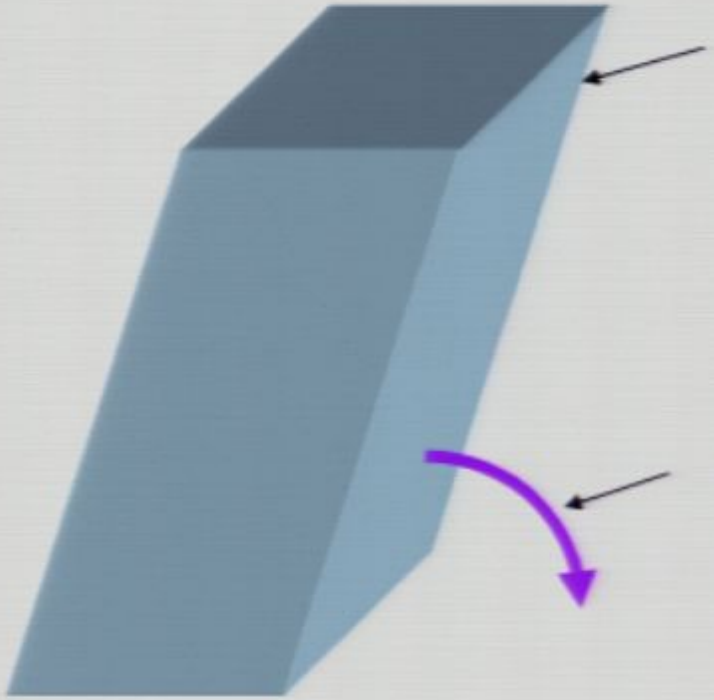
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



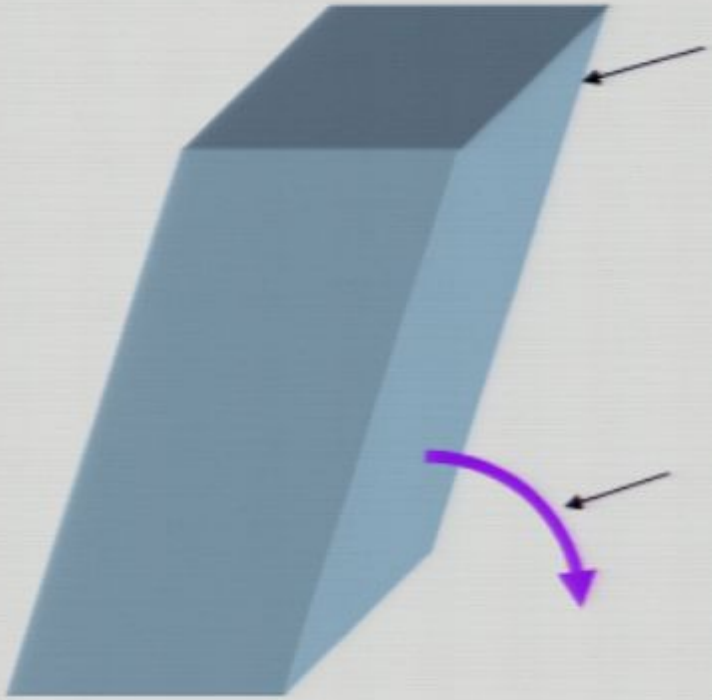
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



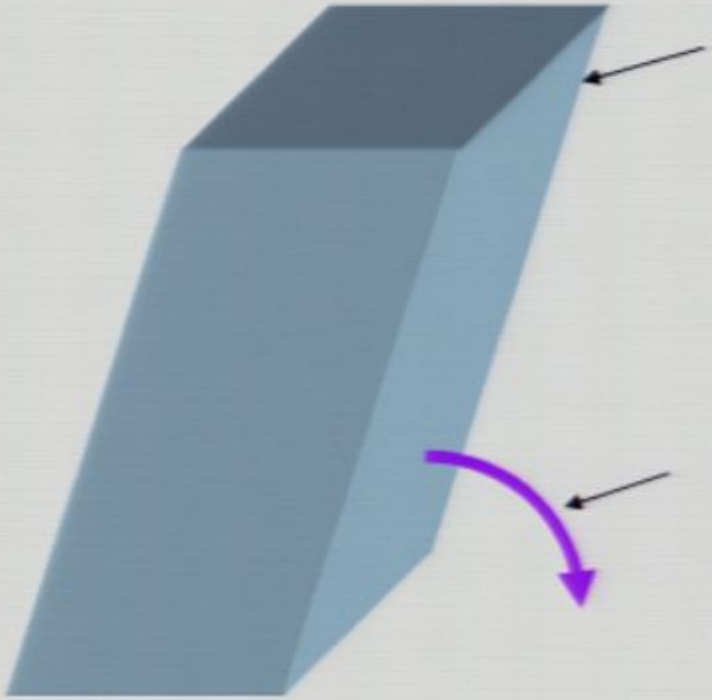
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



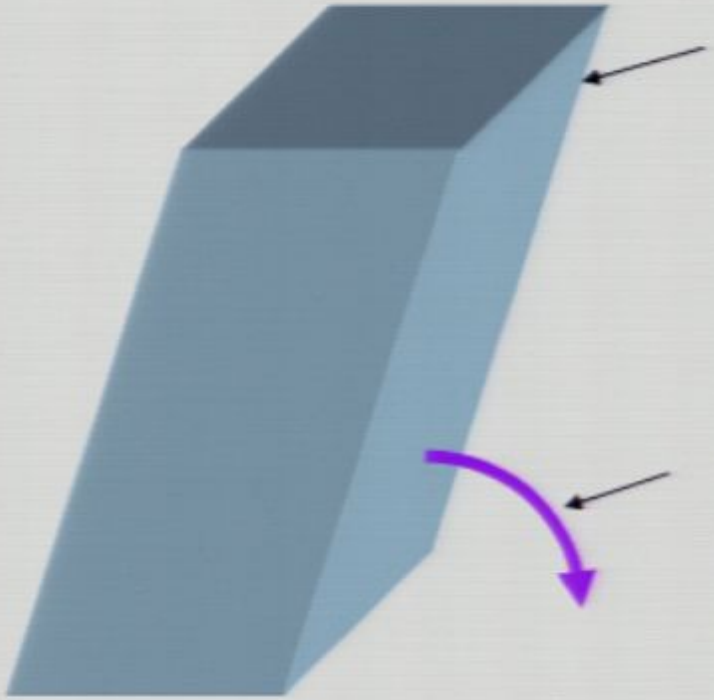
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



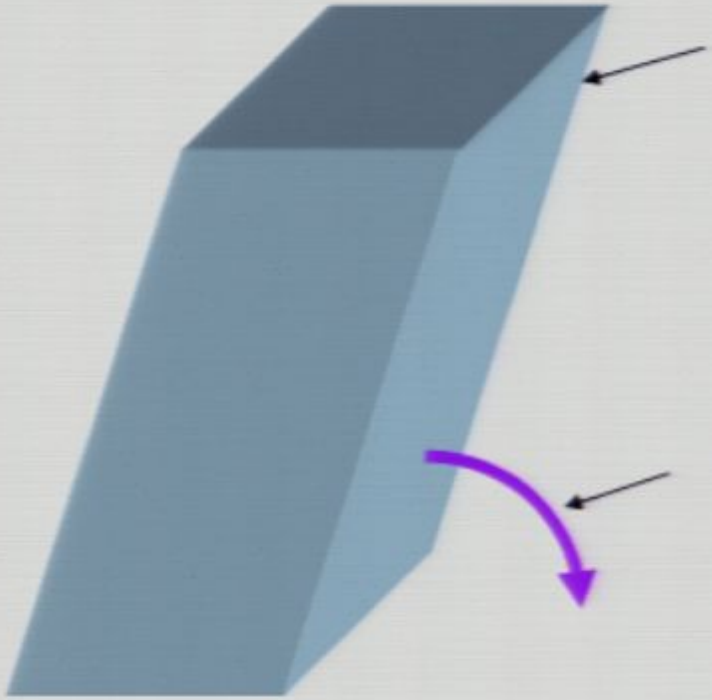
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



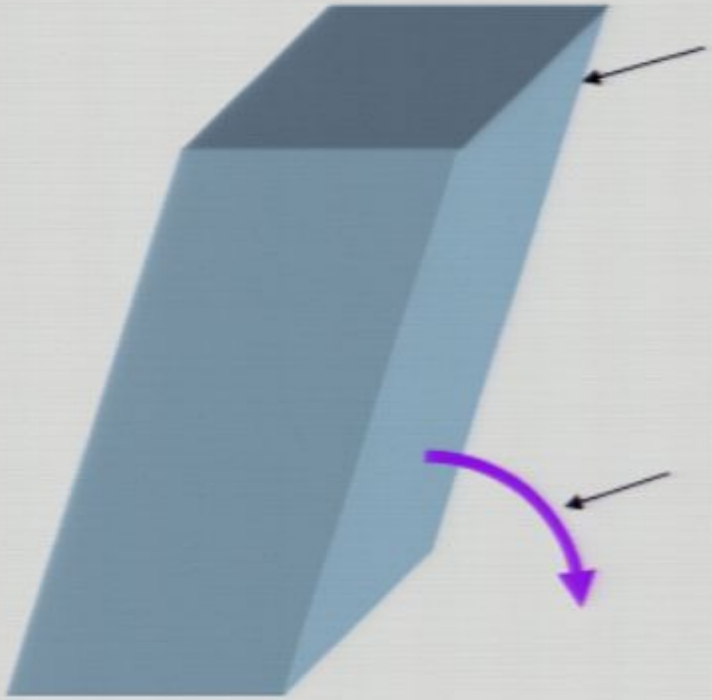
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



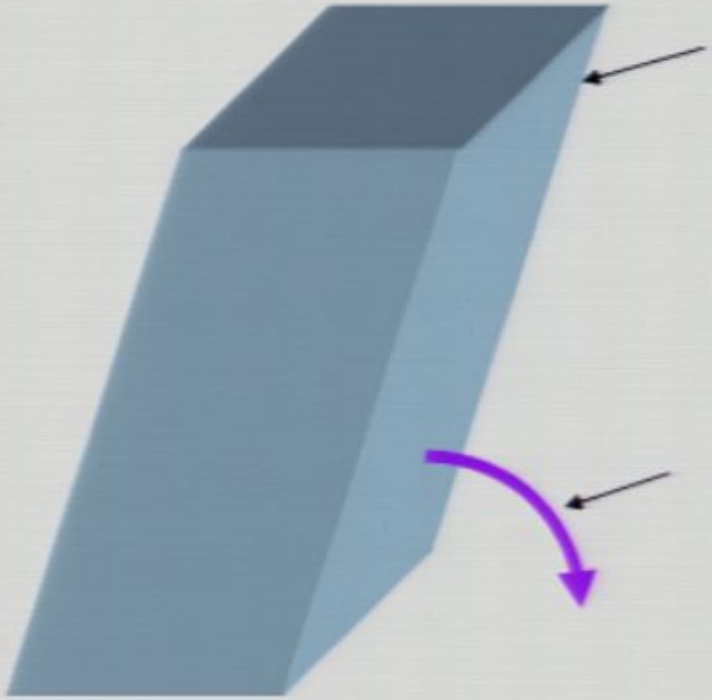
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



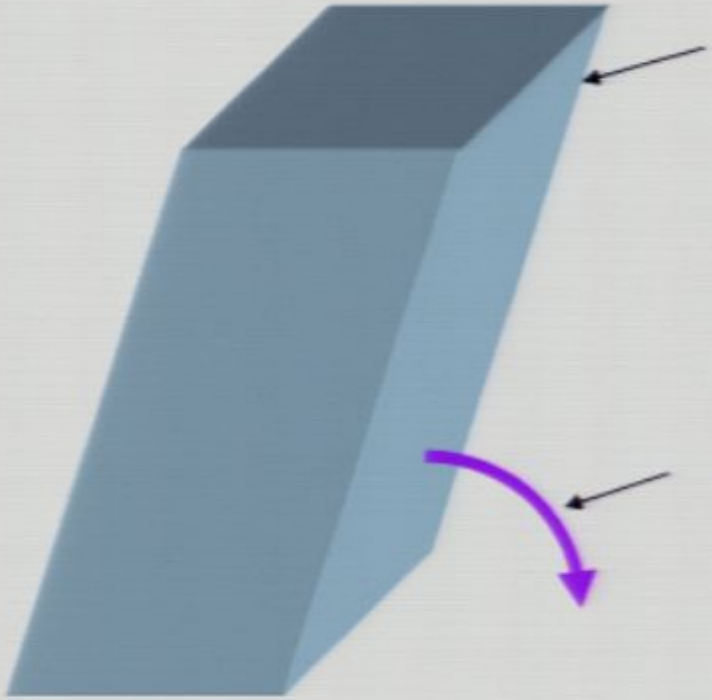
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



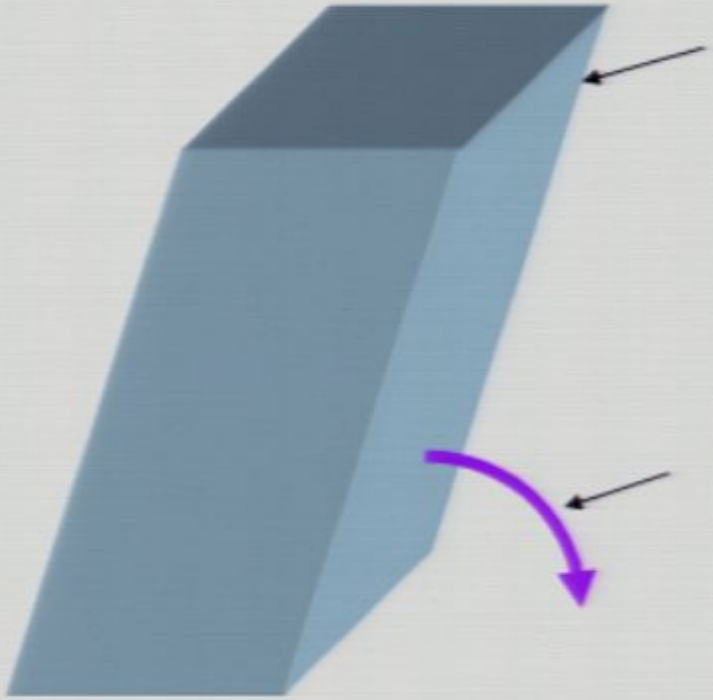
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



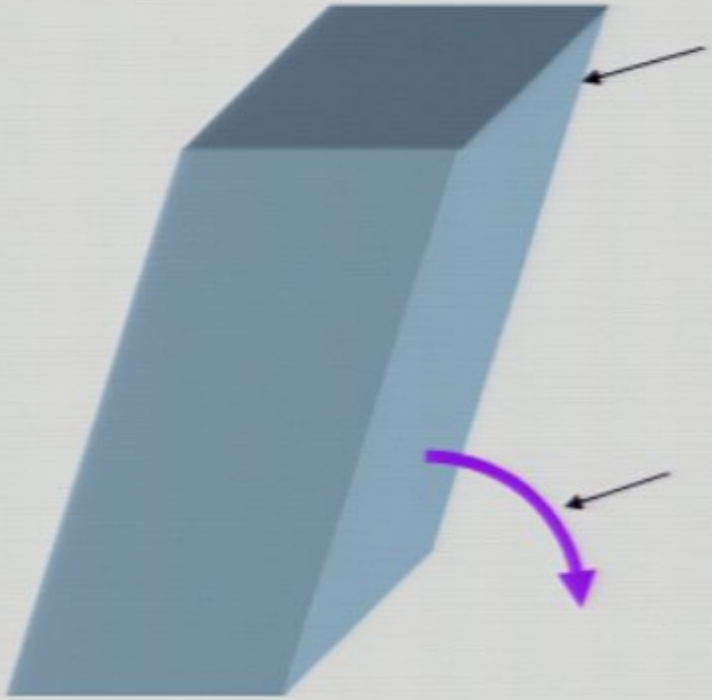
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



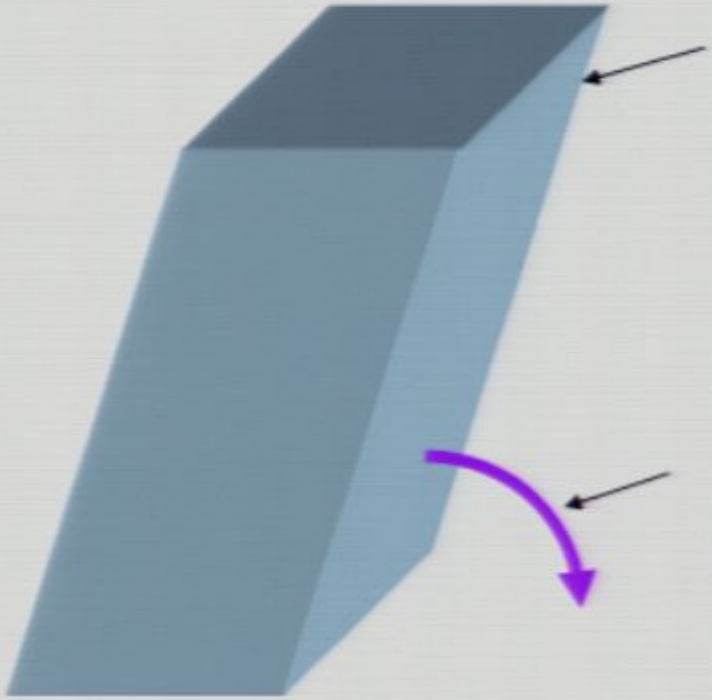
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



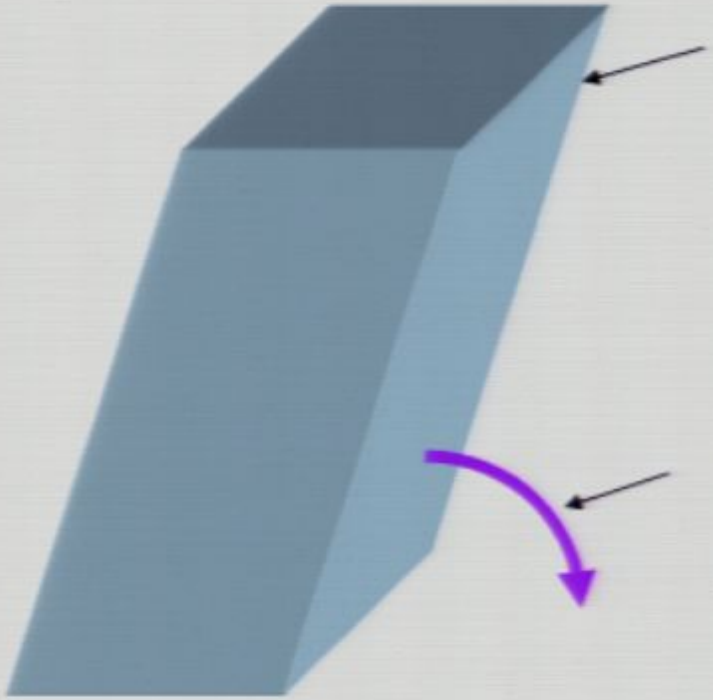
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



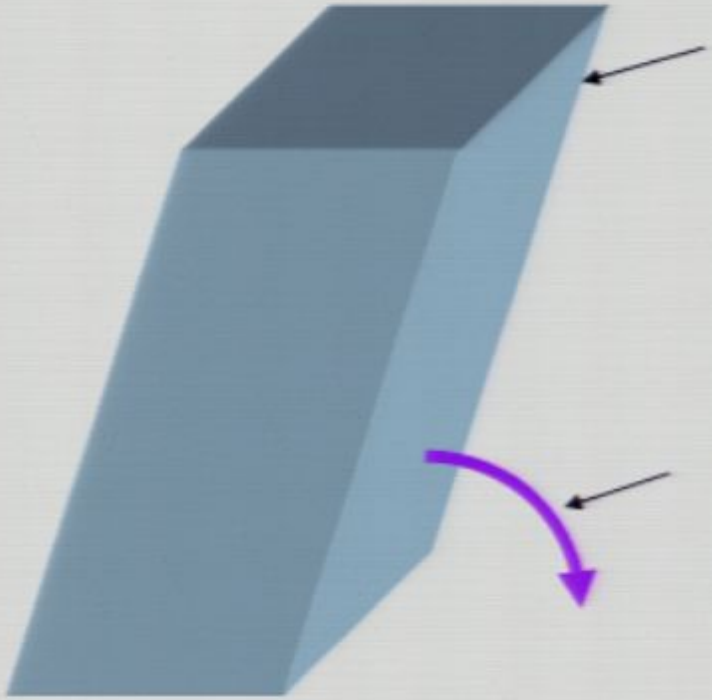
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



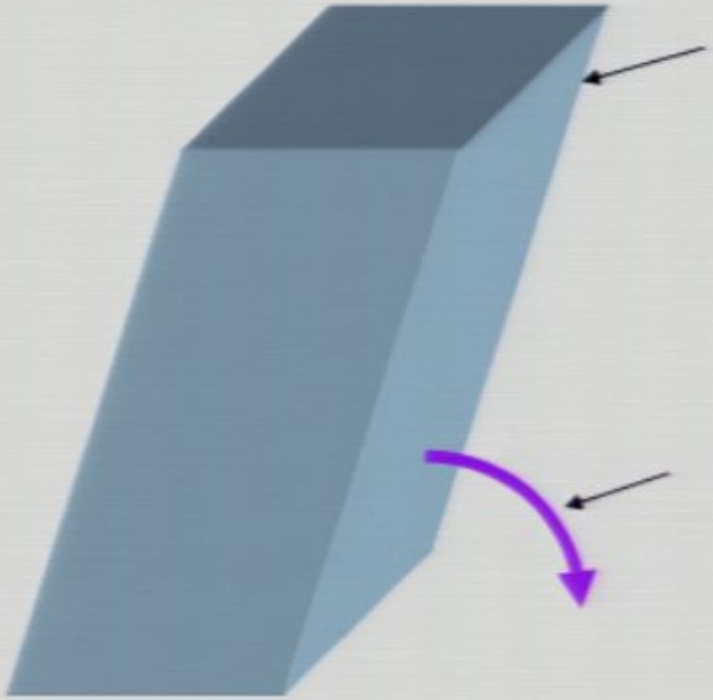
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



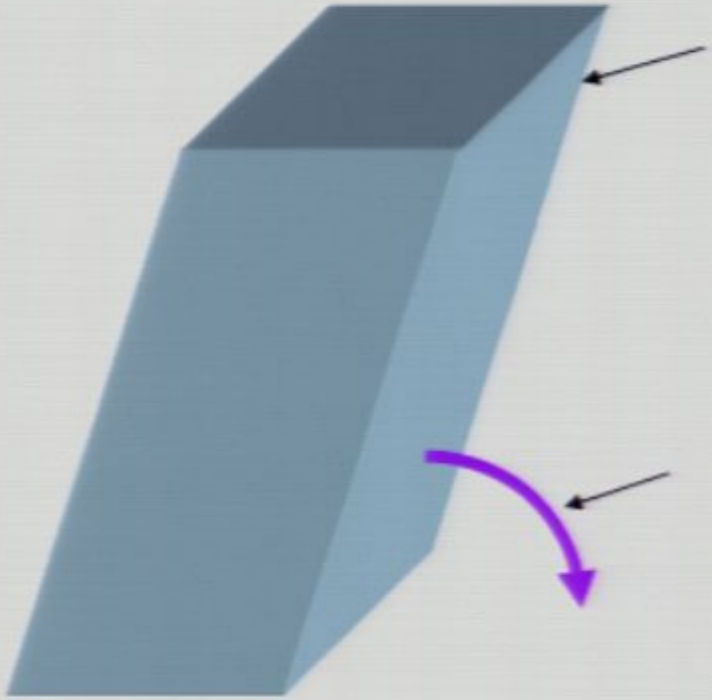
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



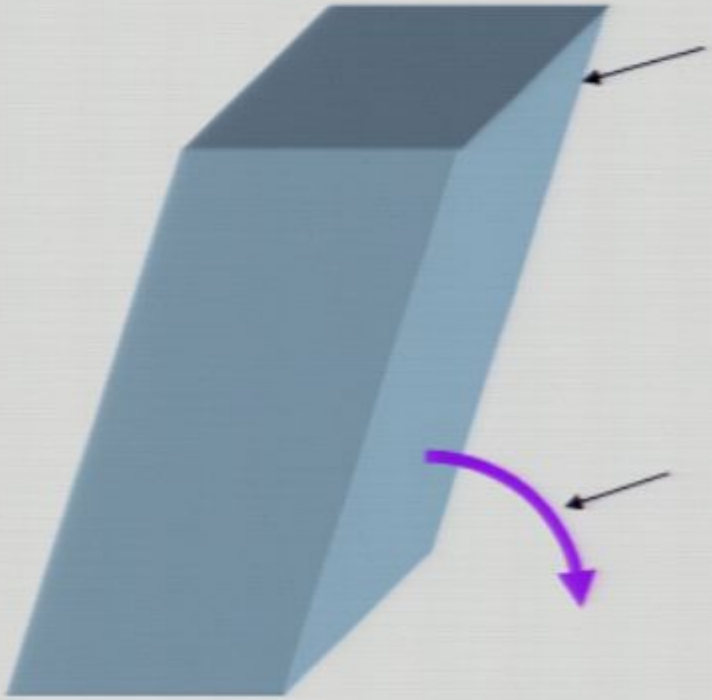
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



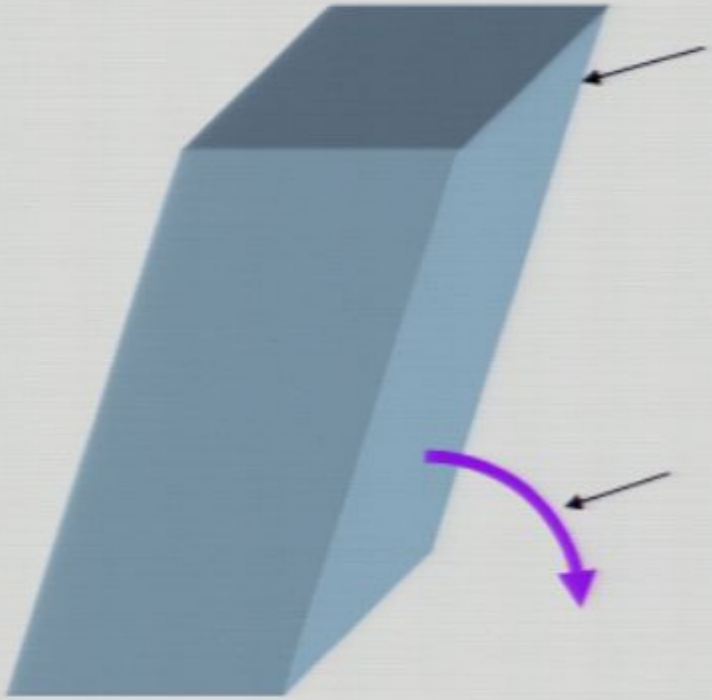
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



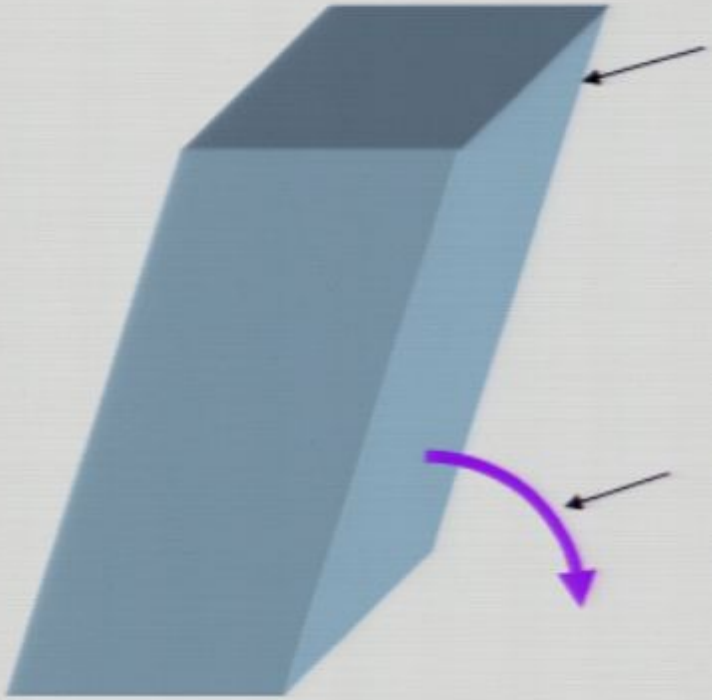
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



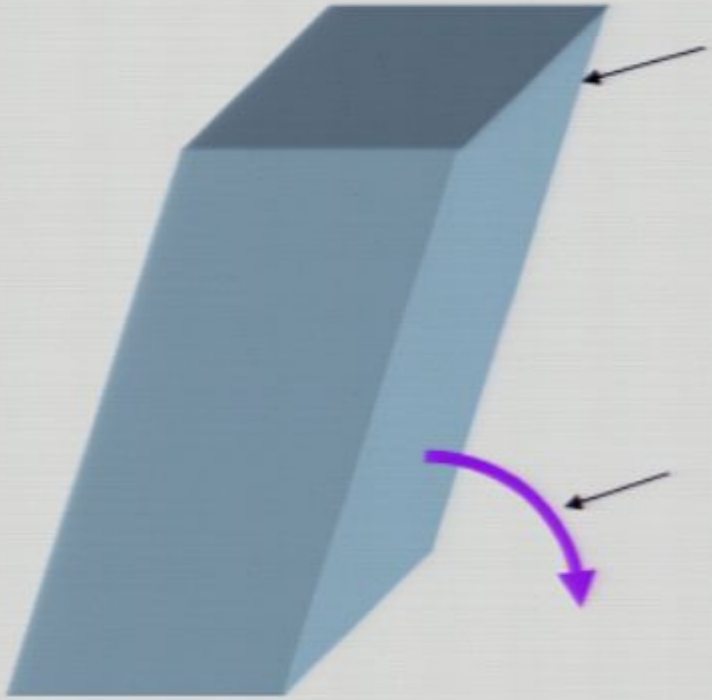
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



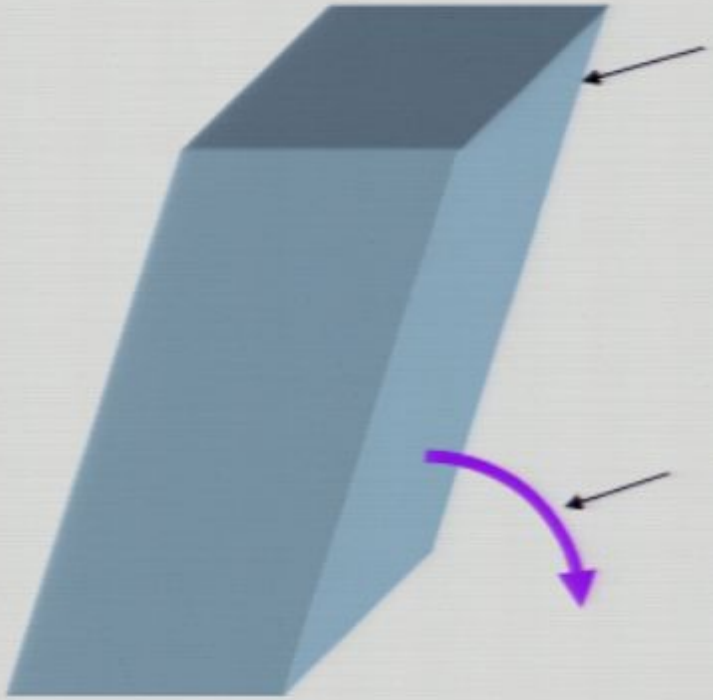
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



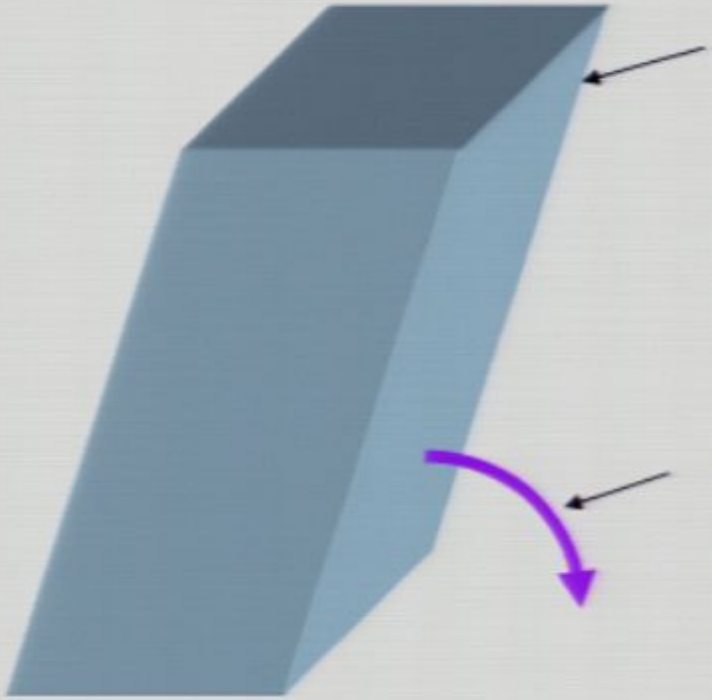
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



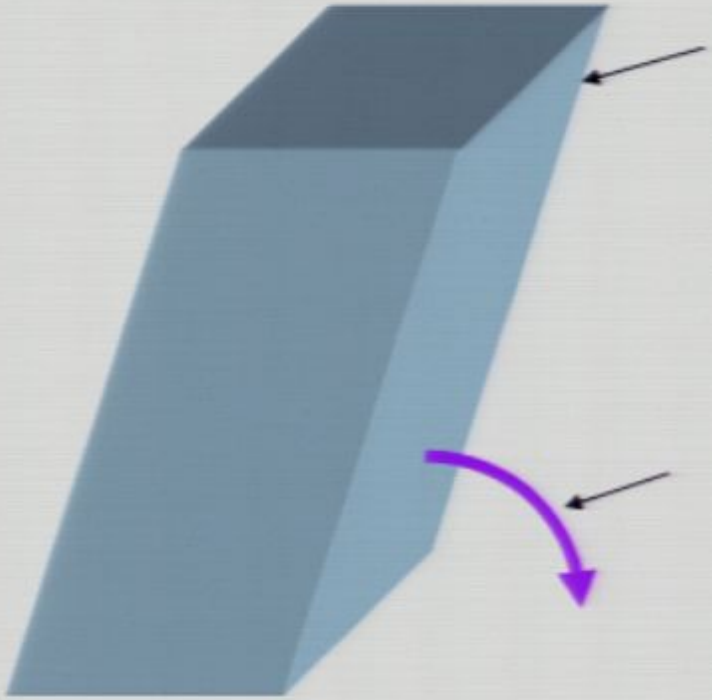
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



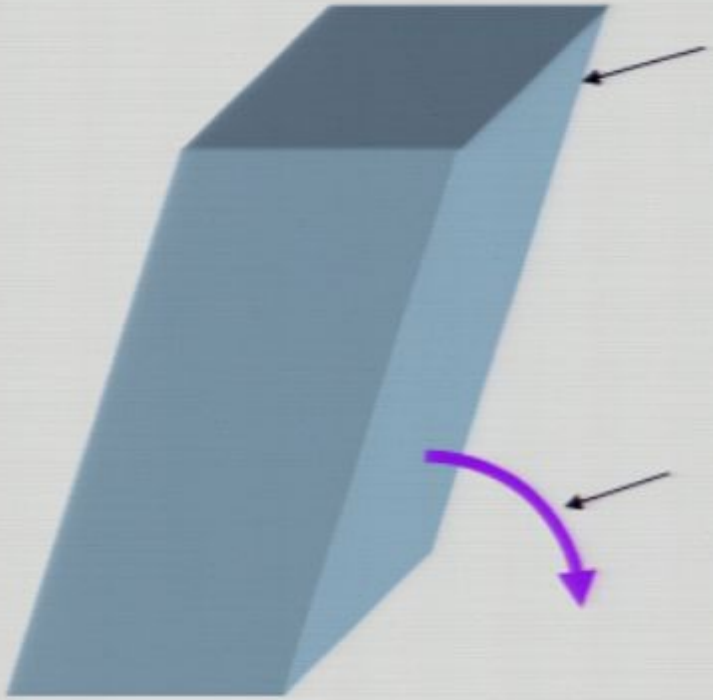
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



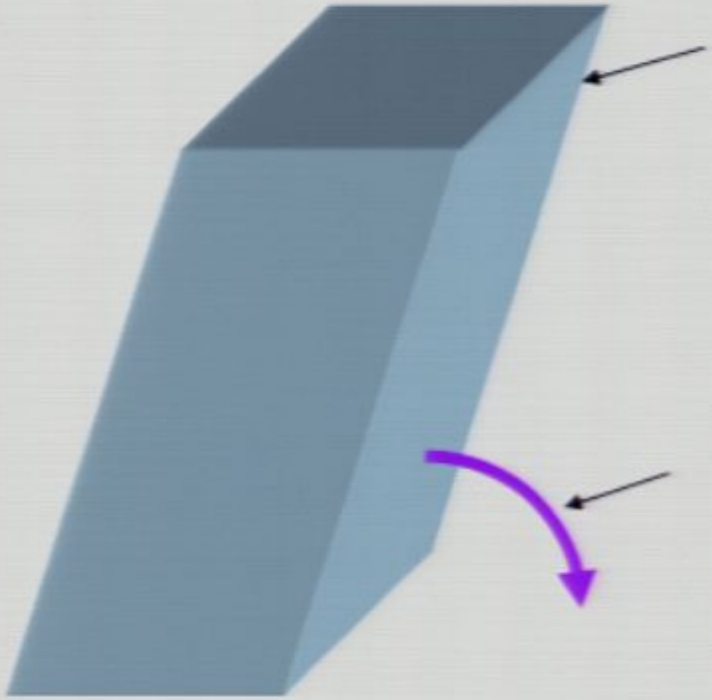
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

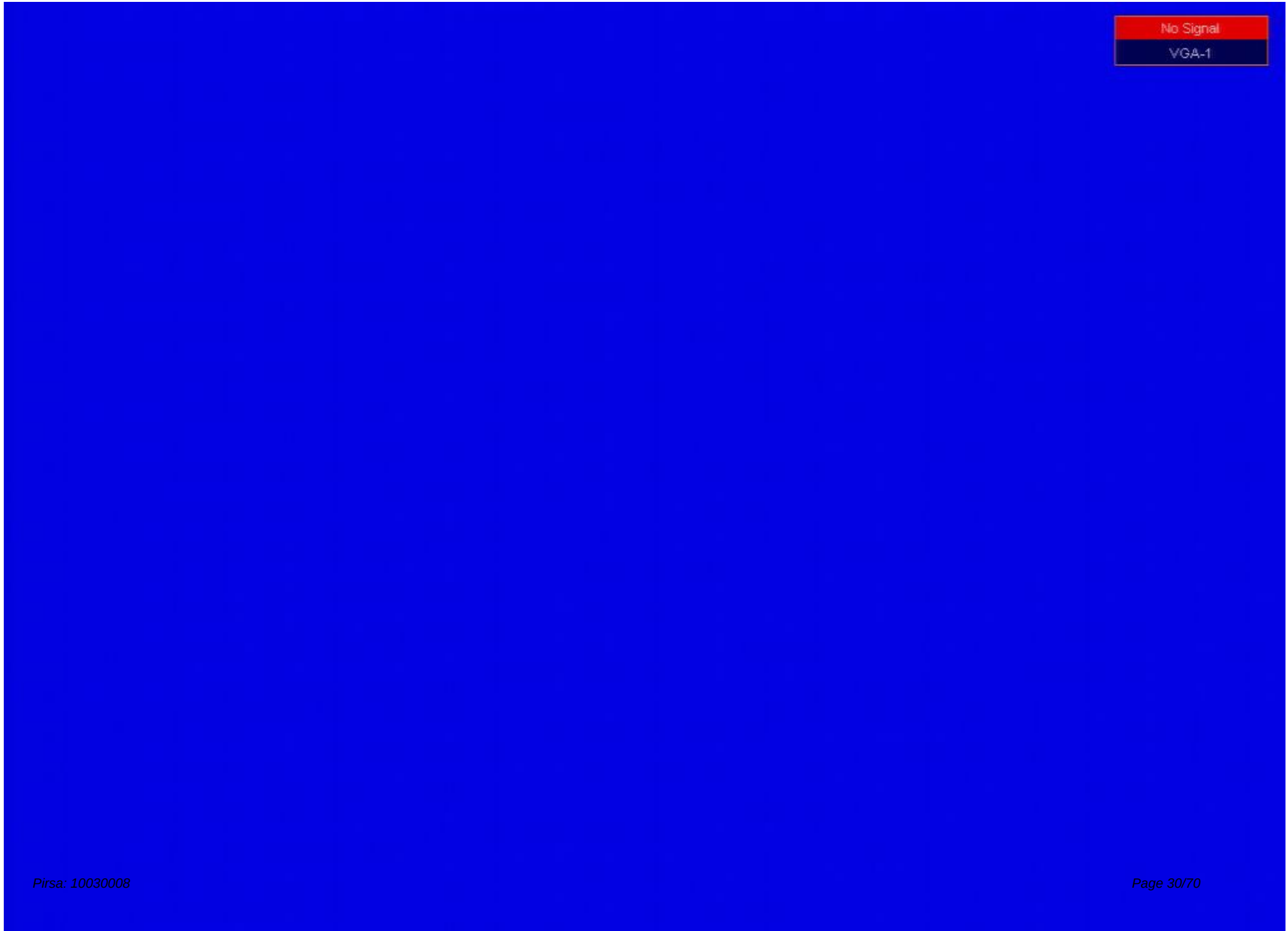
I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

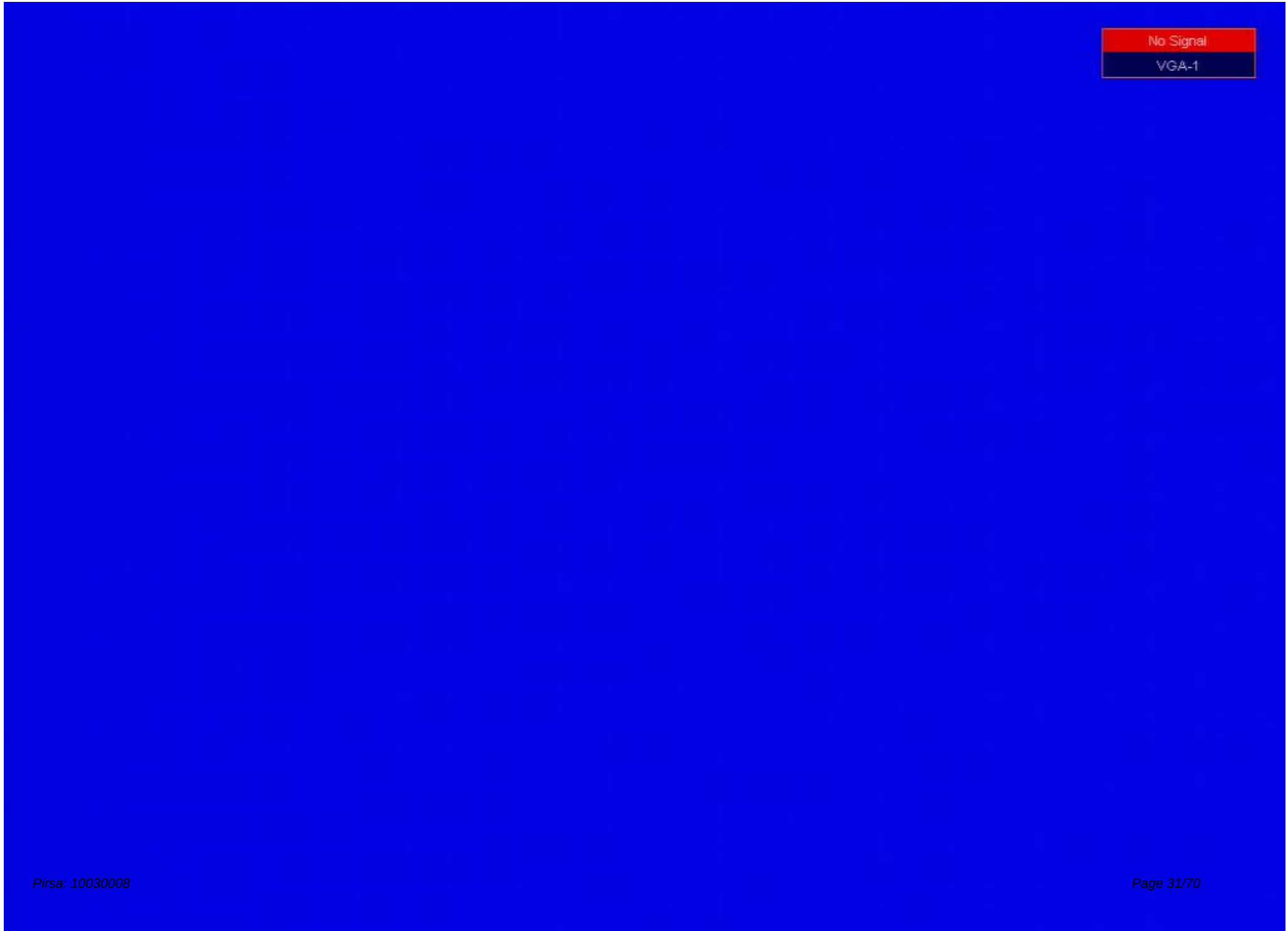
Example of single crystal in a metastable position:

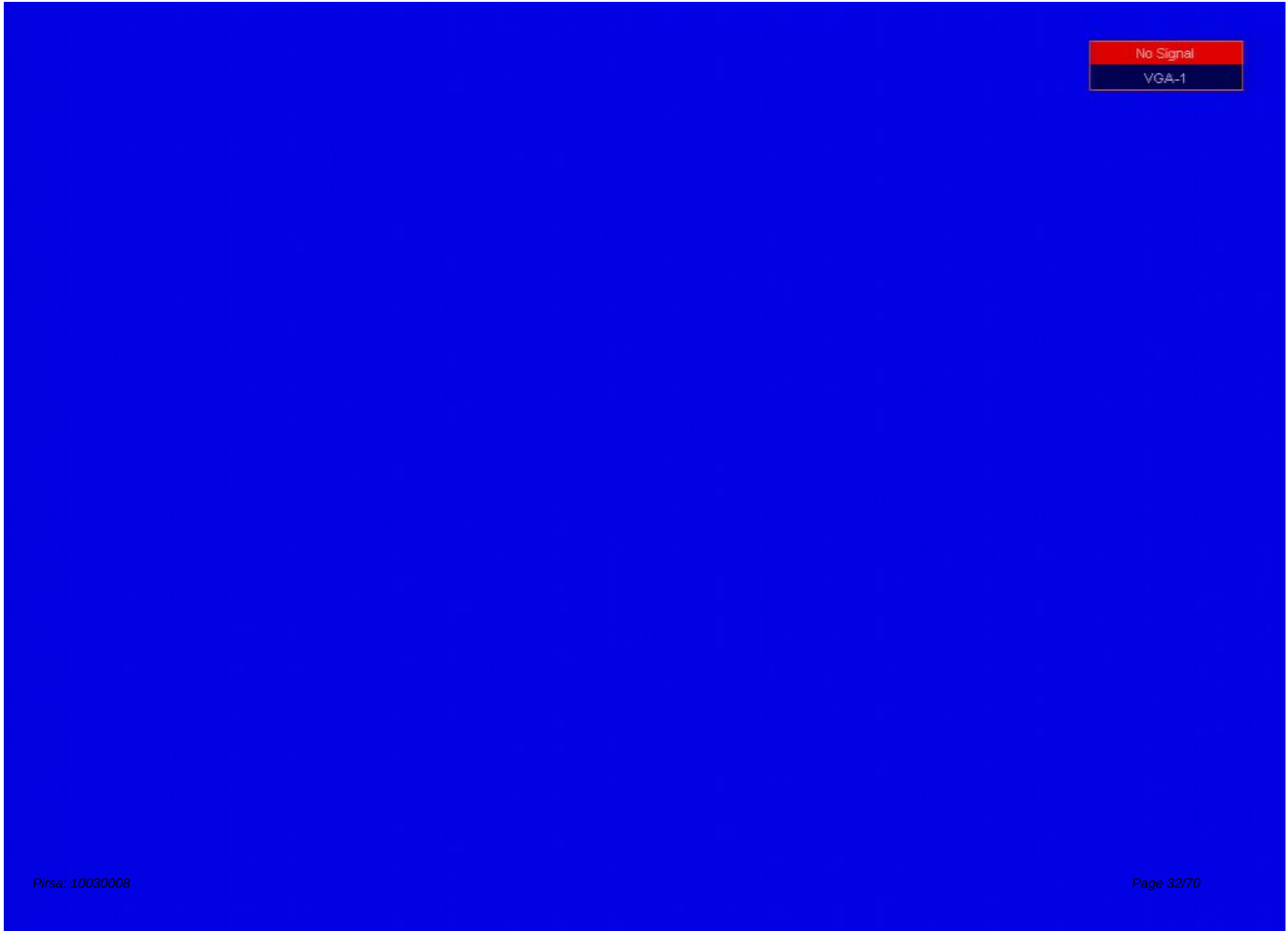


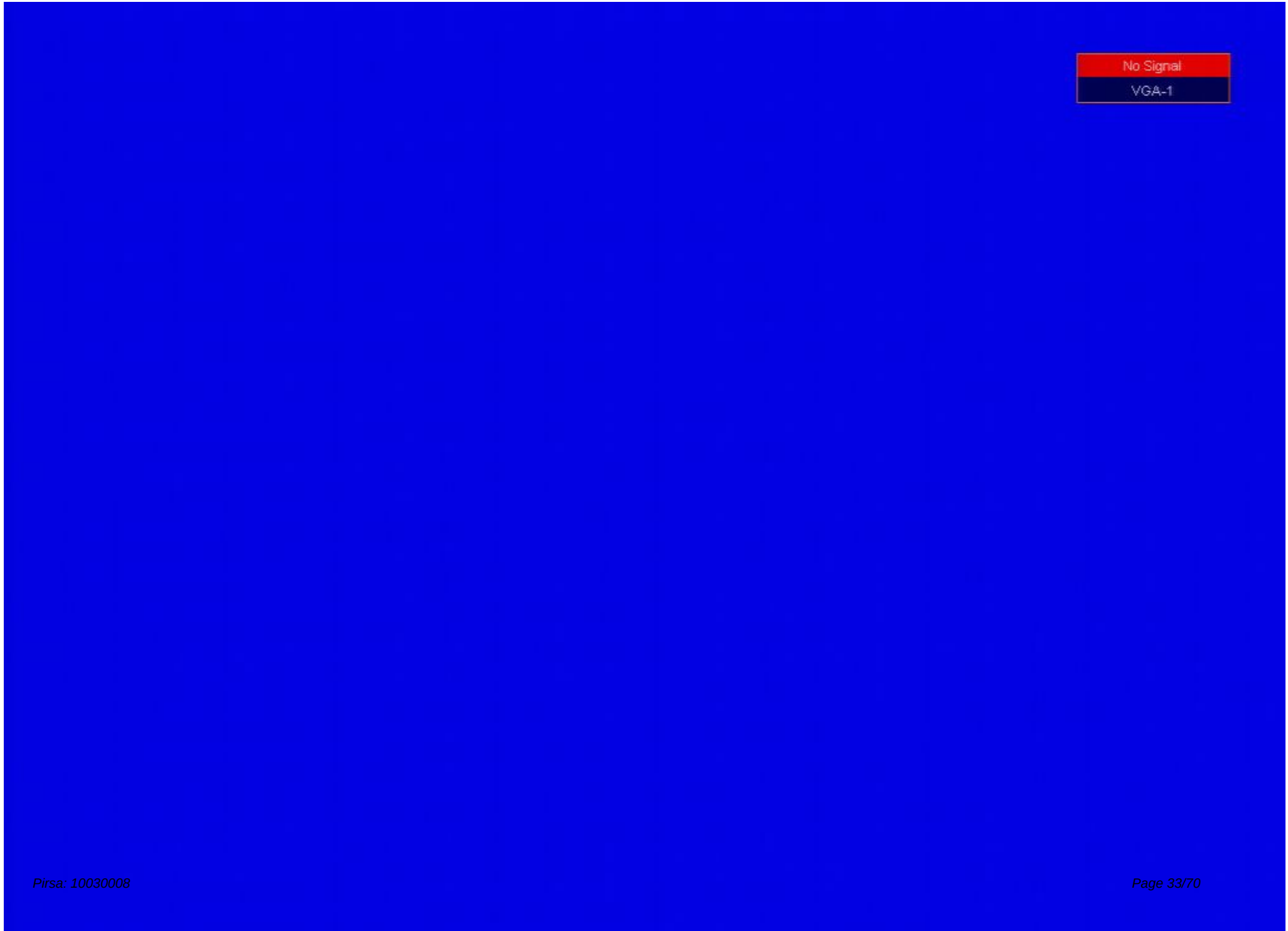
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)


No Signal
VGA-1


No Signal
VGA-1

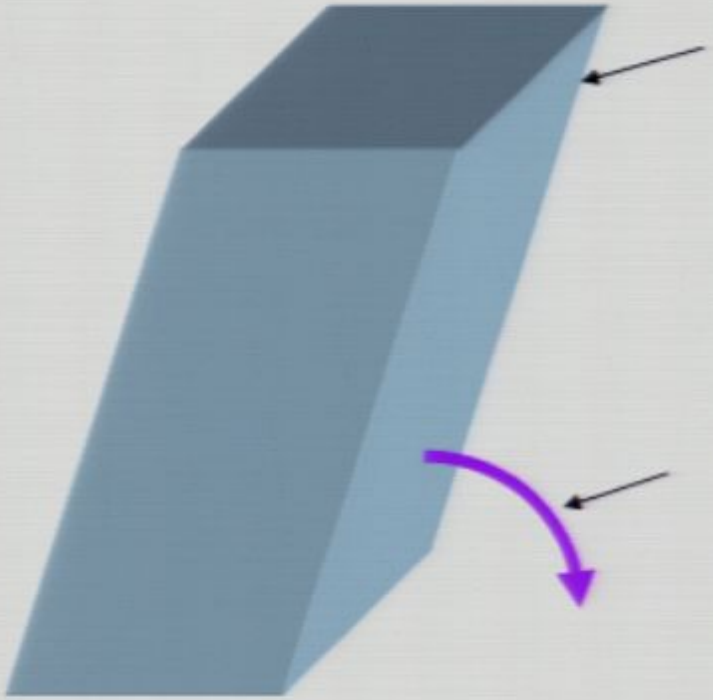

No Signal
VGA-1


No Signal
VGA-1

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



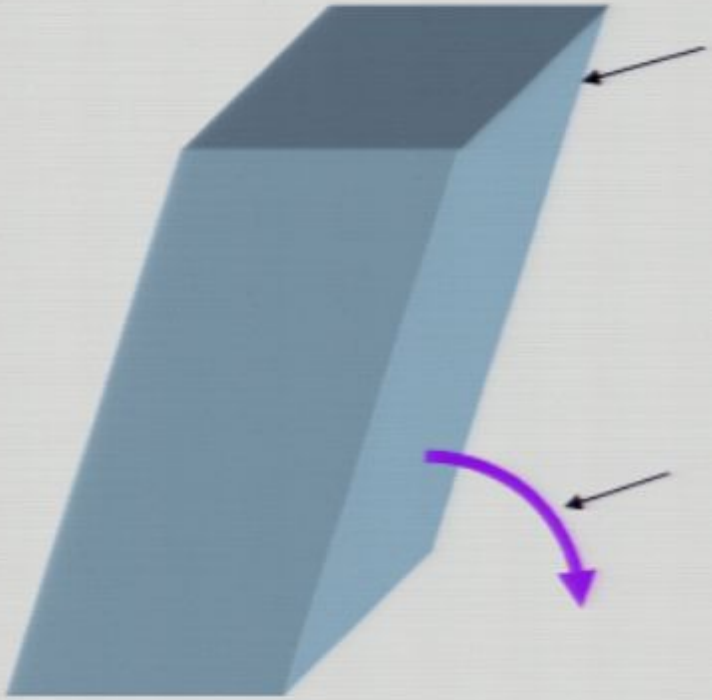
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



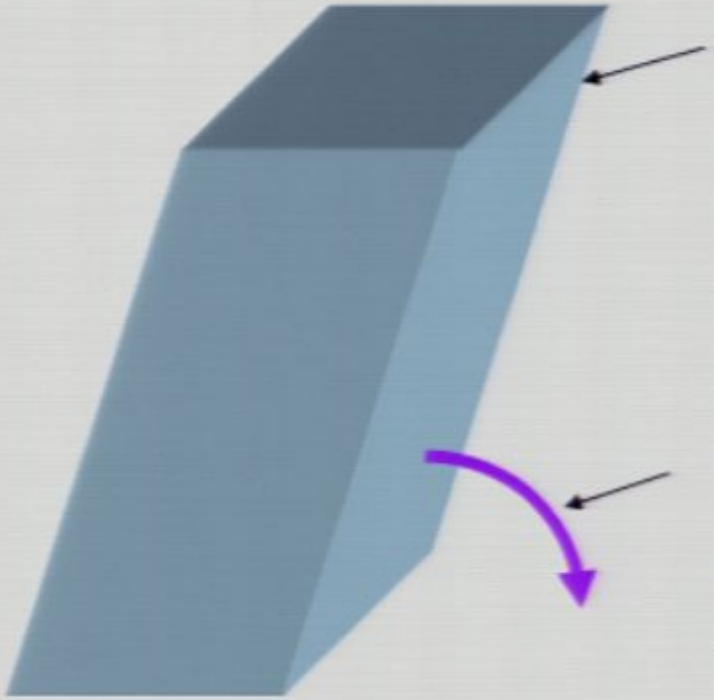
faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

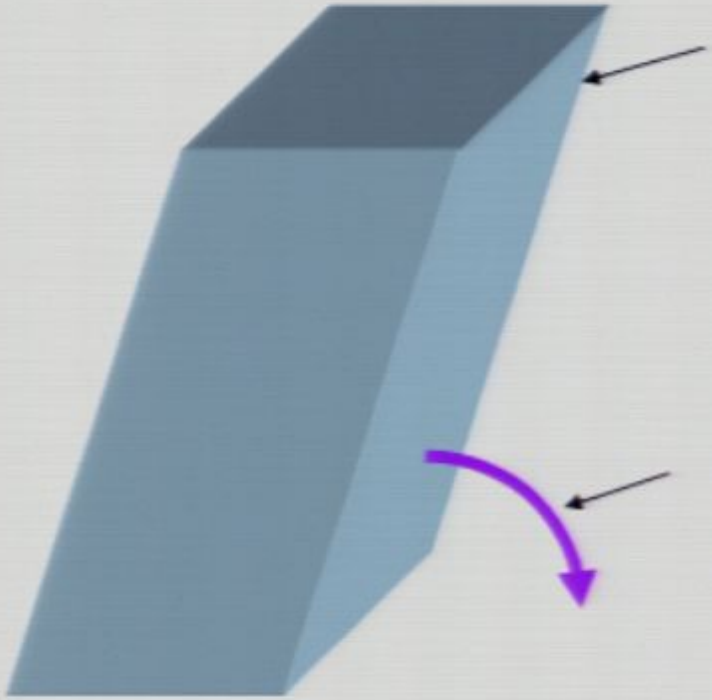
OUR CENTRAL EXPERIMENTAL QUESTION: DO MACROSCOPIC VARIABLES FULLY OBEY QUANTUM MECHANICS?

Must aim at precision measurements: slight discrepancy with quantum theory must be detectable.

TWO CLASSES OF MACROSCOPIC QUANTUM PHENOMENA

I: Macro-scale manifestation of microscopic quantum effects
II: Quantum effect displayed by macroscopic collective variable

Example of single crystal in a metastable position:



faces make
angles determined
by quantum orbitals
(type I phenomenon)

whole crystal will eventually fall,
due to quantum fluctuations of its
center-of-mass position
(type II phenomenon)

OUR CENTRAL EXPERIMENTAL QUESTION: DO MACROSCOPIC VARIABLES FULLY OBEY QUANTUM MECHANICS?

Must aim at precision measurements: slight discrepancy with quantum theory must be detectable.

MACROSCOPIC COLLECTIVE SYSTEMS FOR WHICH QUANTUM MECHANICS IS RELEVANT AT PRESENT

Electrical domain: superconducting circuits

Collective variables: charge, flux, current, voltage

Mechanical domain: microfabricated resonators

Collective variable: position or momentum of beam or membrane

(ground state recently attained at UCSB)

A SUPERCONDUCTING CIRCUIT CAN POSSESS A SINGLE COLLECTIVE DEGREE OF FREEDOM

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

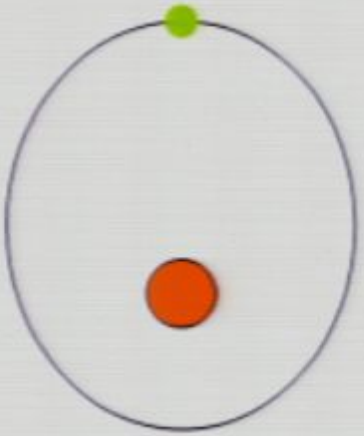
MICROFABRICATION ➡ L ~ 3nH, C ~ 1pF, $\omega_r/2\pi \sim 4\text{GHz}$

$$\omega_r \ll \Delta/\hbar \sim 100\text{GHz}$$

ELECTRONIC FLUID FLOWS BACK AND FORTH BETWEEN PLATES:
ALL ELECTRONS ARE PAIRED AND BEHAVE AS A SINGLE CHARGED ENTITY

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

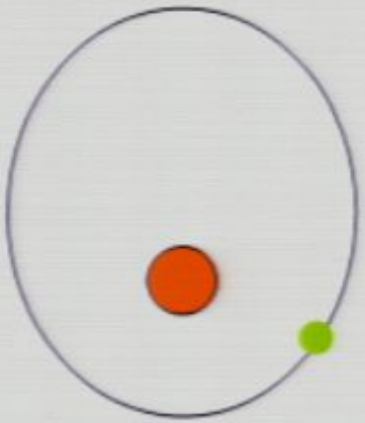
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

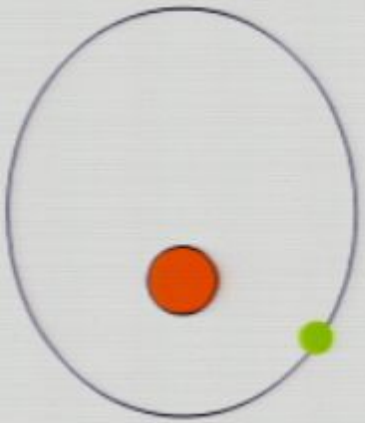
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

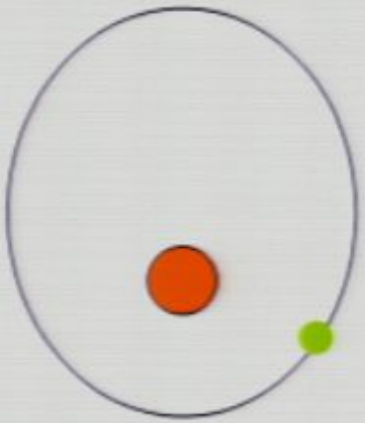
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

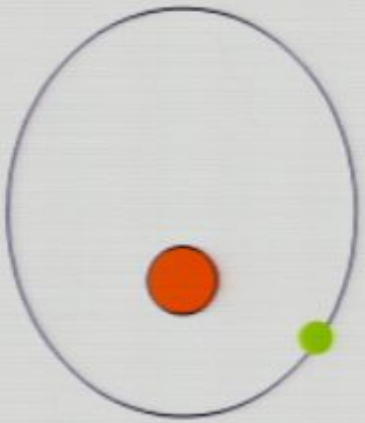
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

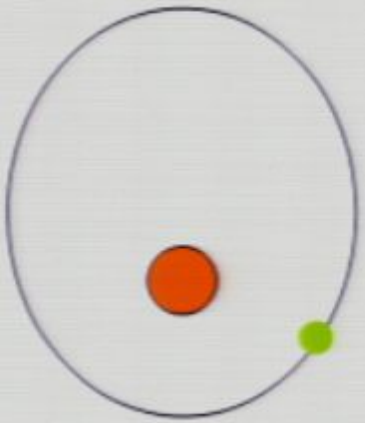
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

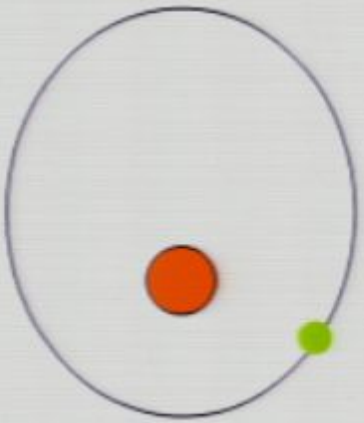
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

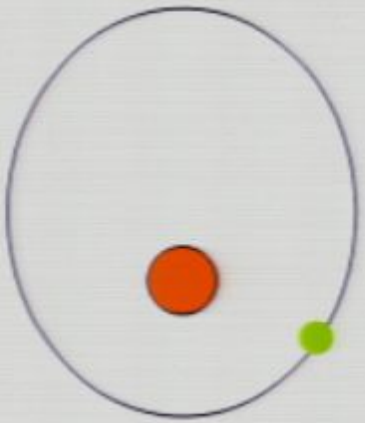
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

Example of Rydberg atom



Superconducting
LC oscillator

A SUPERCONDUCTING CIRCUIT CAN POSSESS A SINGLE COLLECTIVE DEGREE OF FREEDOM

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

MICROFABRICATION ➡ L ~ 3nH, C ~ 1pF, $\omega_r/2\pi$ ~ 4GHz

$$\omega_r \ll \Delta/\hbar \sim 100\text{GHz}$$

ELECTRONIC FLUID FLOWS BACK AND FORTH BETWEEN PLATES:
ALL ELECTRONS ARE PAIRED AND BEHAVE AS A SINGLE CHARGED ENTITY

A SUPERCONDUCTING CIRCUIT CAN POSSESS A SINGLE COLLECTIVE DEGREE OF FREEDOM

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

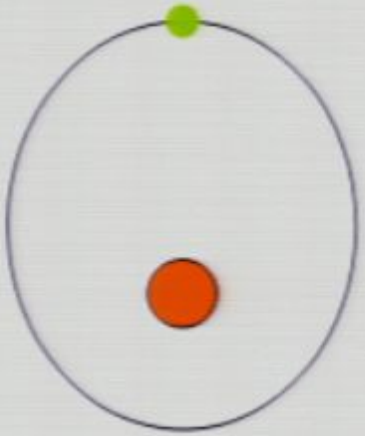
MICROFABRICATION ➡ L ~ 3nH, C ~ 1pF, $\omega_r/2\pi$ ~ 4GHz

$$\omega_r \ll \Delta/\hbar \sim 100\text{GHz}$$

ELECTRONIC FLUID FLOWS BACK AND FORTH BETWEEN PLATES:
ALL ELECTRONS ARE PAIRED AND BEHAVE AS A SINGLE CHARGED ENTITY

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

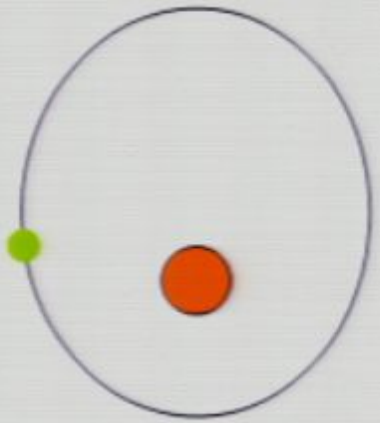
Example of Rydberg atom



Superconducting
LC oscillator

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

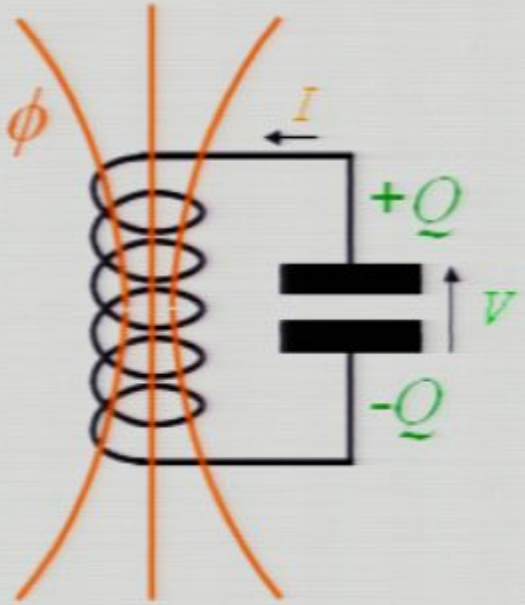
Example of Rydberg atom



Superconducting
LC oscillator

unique electron → whole superconducting condensate
velocity of electron → current through inductor
force on electron → voltage across capacitor

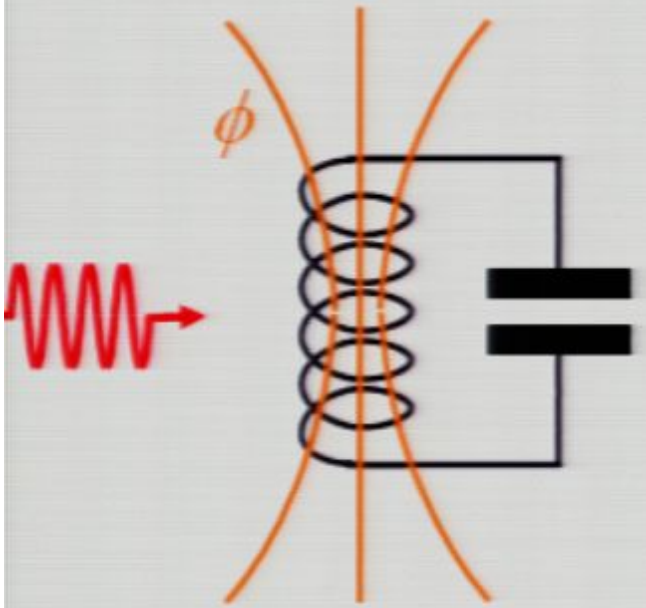
QUANTUM CIRCUITS IN A NUTSHELL: FLUX AND CHARGE DO NOT COMMUTE

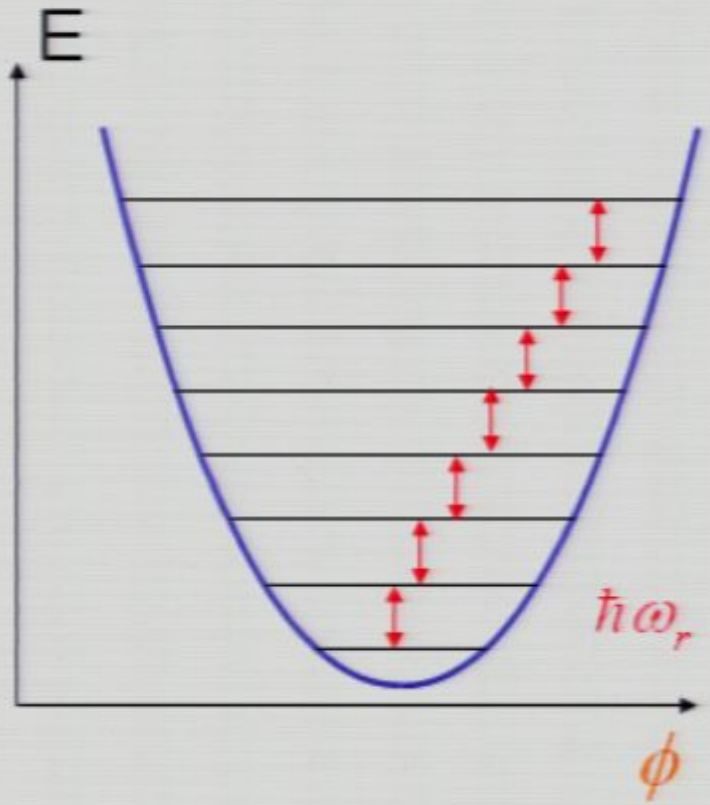


$$\left[\hat{\phi},\hat{Q}\right]=i\hbar$$

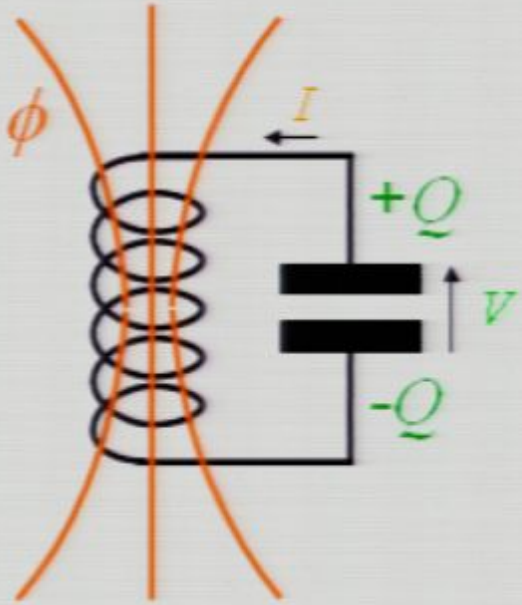
$$\phi = LI \qquad Q = CV$$

PB: IN THE LC CIRCUIT ALL TRANSITIONS ARE DEGENERATE!





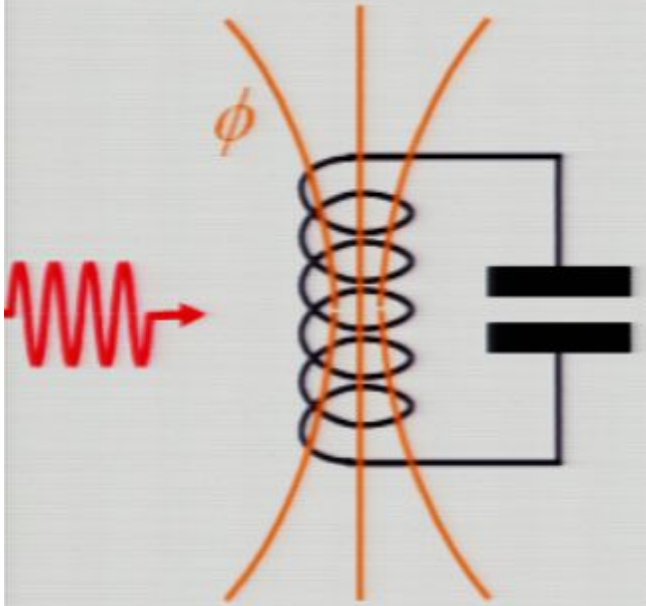
QUANTUM CIRCUITS IN A NUTSHELL: FLUX AND CHARGE DO NOT COMMUTE

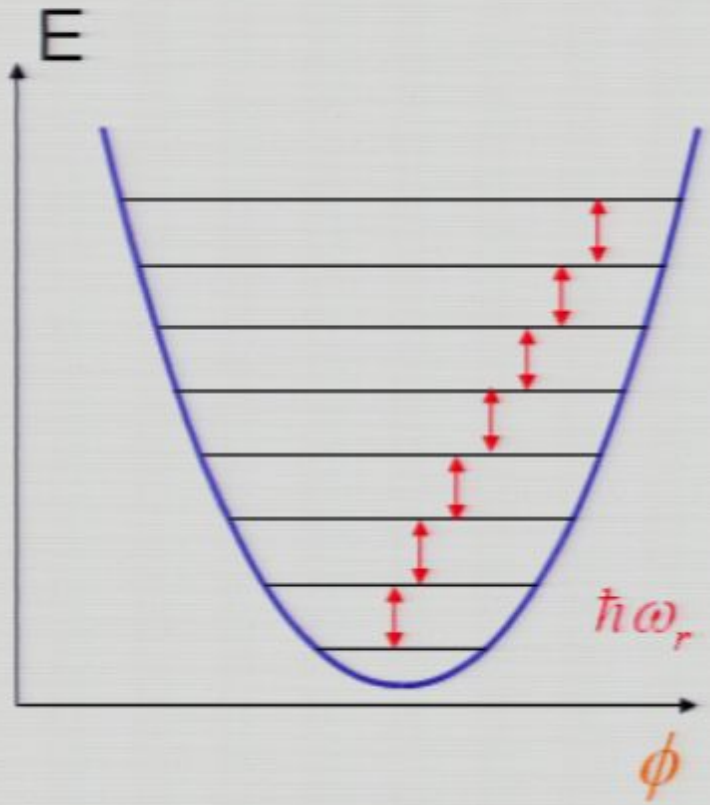


$$\left[\hat{\phi},\hat{Q}\right]=i\hbar$$

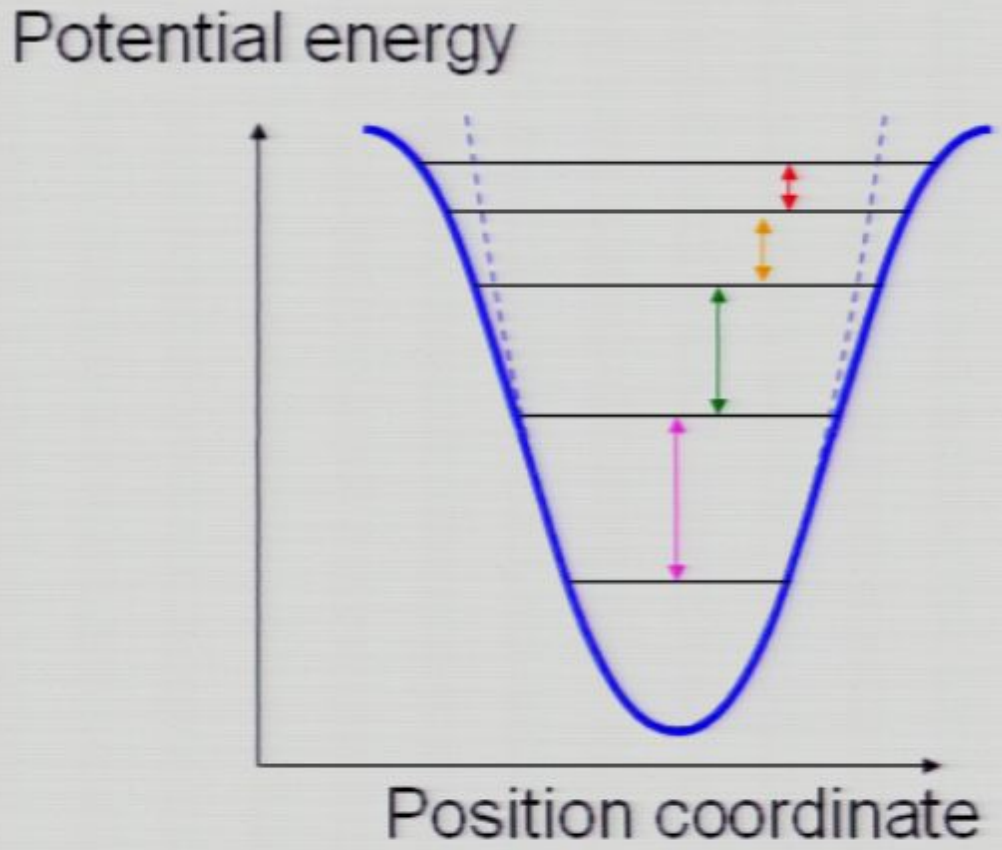
$$\phi = LI \qquad Q = CV$$

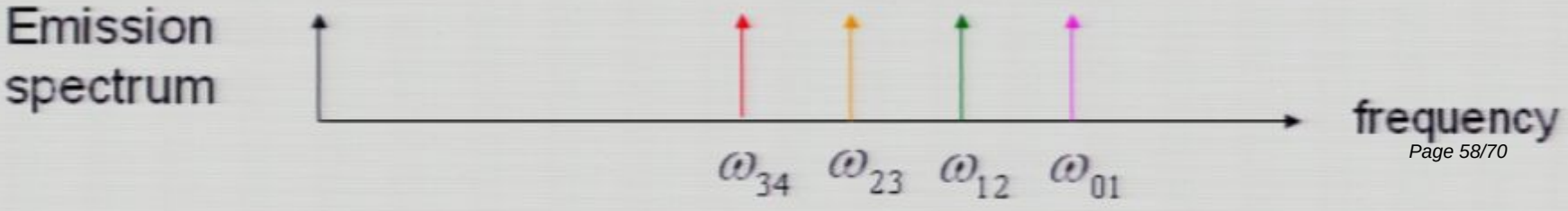
PB: IN THE LC CIRCUIT ALL TRANSITIONS ARE DEGENERATE!





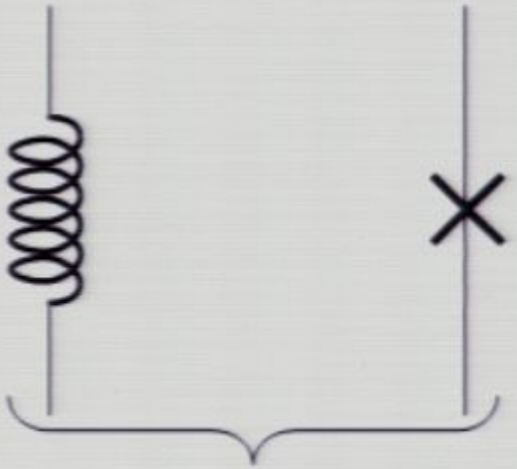
NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS





SUPERCONDUCTING CIRCUIT ELEMENTS

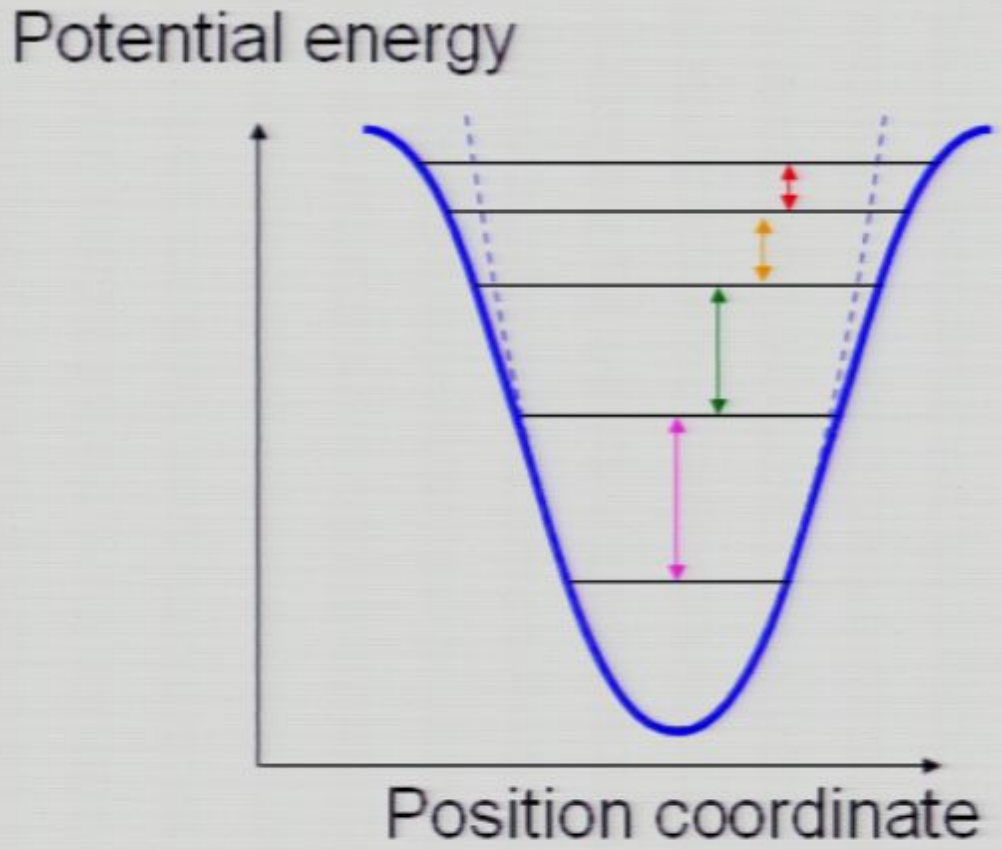
CAPACITANCE

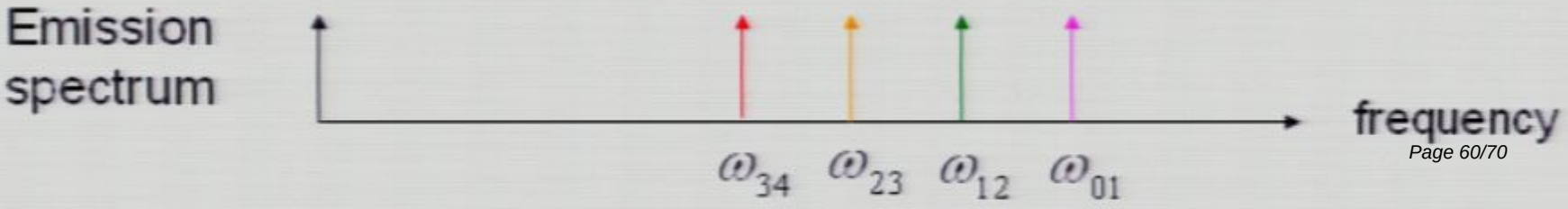


INDUCTANCE

RESISTANCE

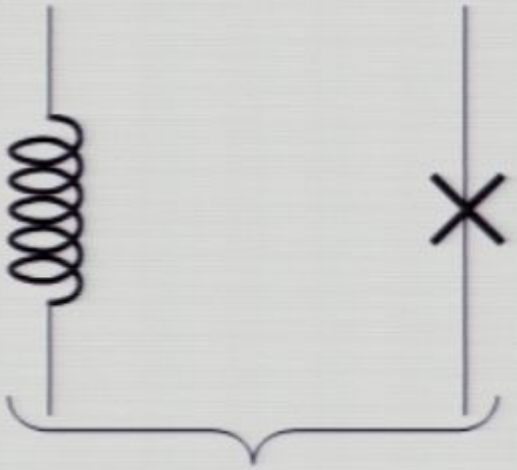
NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS





SUPERCONDUCTING CIRCUIT ELEMENTS

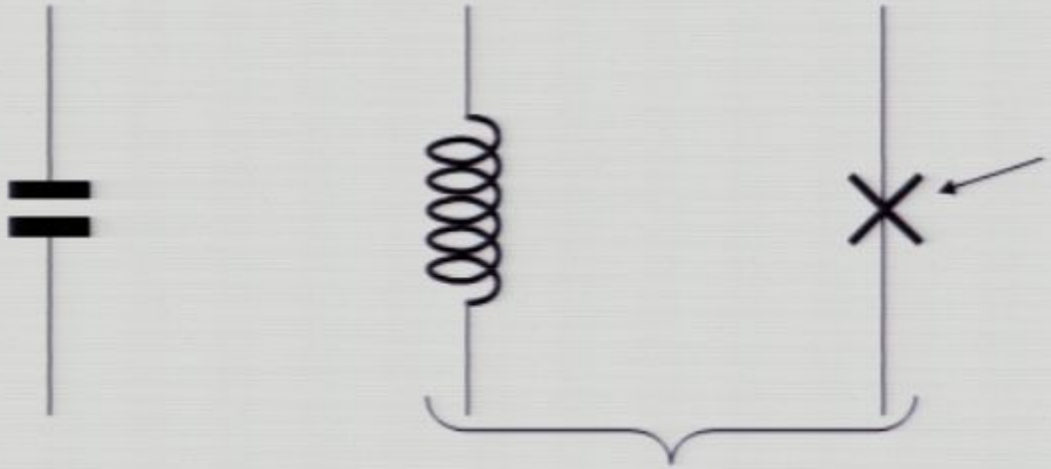
CAPACITANCE



INDUCTANCE

RESISTANCE

SUPERCONDUCTING CIRCUIT ELEMENTS



CAPACITANCE

INDUCTANCE

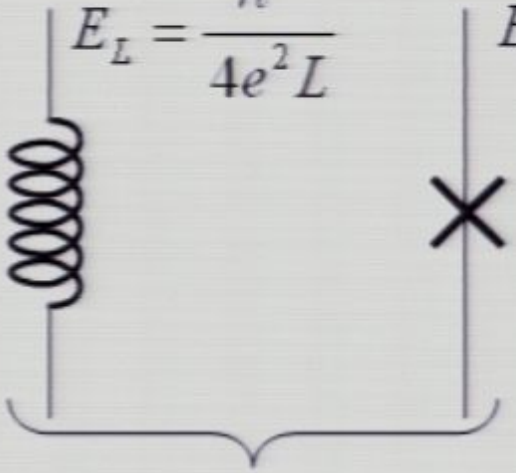
RESISTANCE

SUPERCONDUCTING CIRCUIT ELEMENTS

$$E_C = \frac{e^2}{2C}$$

CAPACITANCE

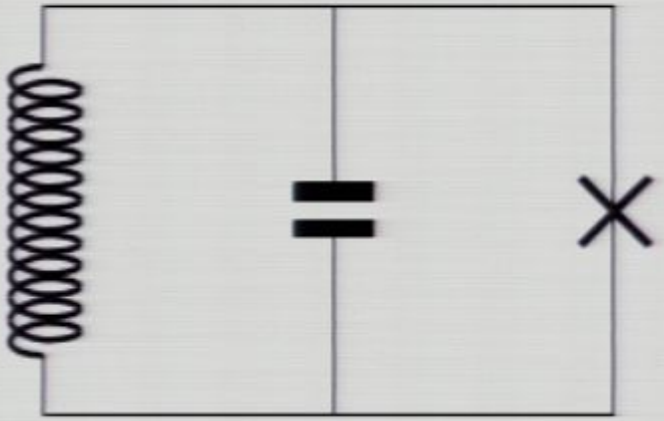
$$E_L = \frac{\hbar^2}{4e^2 L} \qquad E_J = \frac{\hbar^2}{4e^2 L_J}$$



INDUCTANCE

RESISTANCE

THE FLUXONIUM CIRCUIT IS A SIMPLE COMBINATION OF THE 3 BASIC ELEMENTS

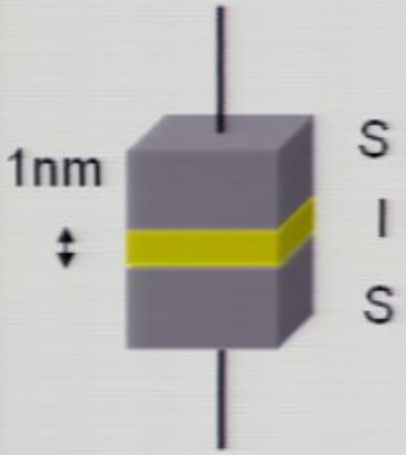


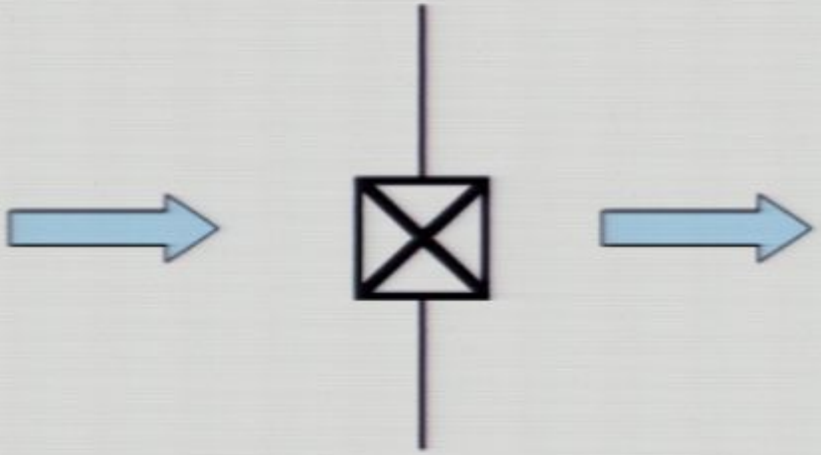
$$E_L \ll E_C \leq E_J$$

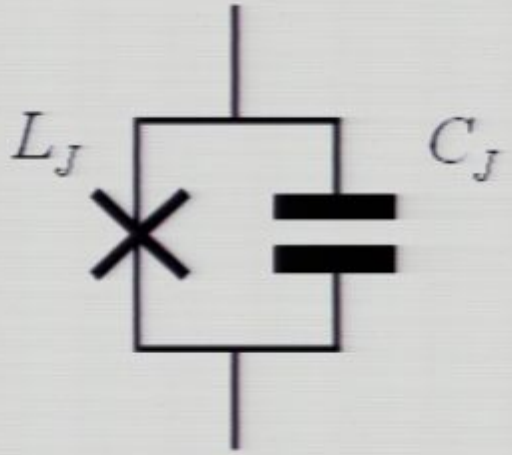
In original proposal of A.J. Leggett, circuit was "RF-SQUID" with:

$$E_C \ll E_L < E_J$$

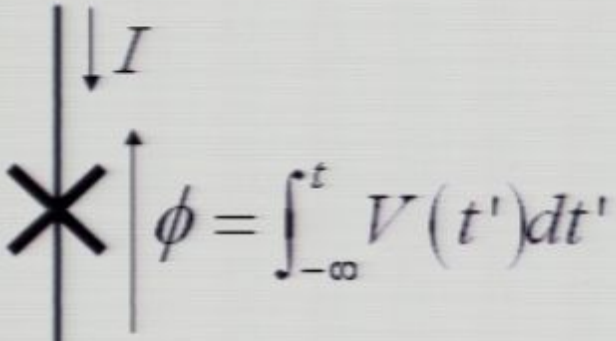
JOSEPHSON TUNNEL JUNCTION PROVIDES A NON-LINEAR INDUCTANCE WITH NO DISSIPATION

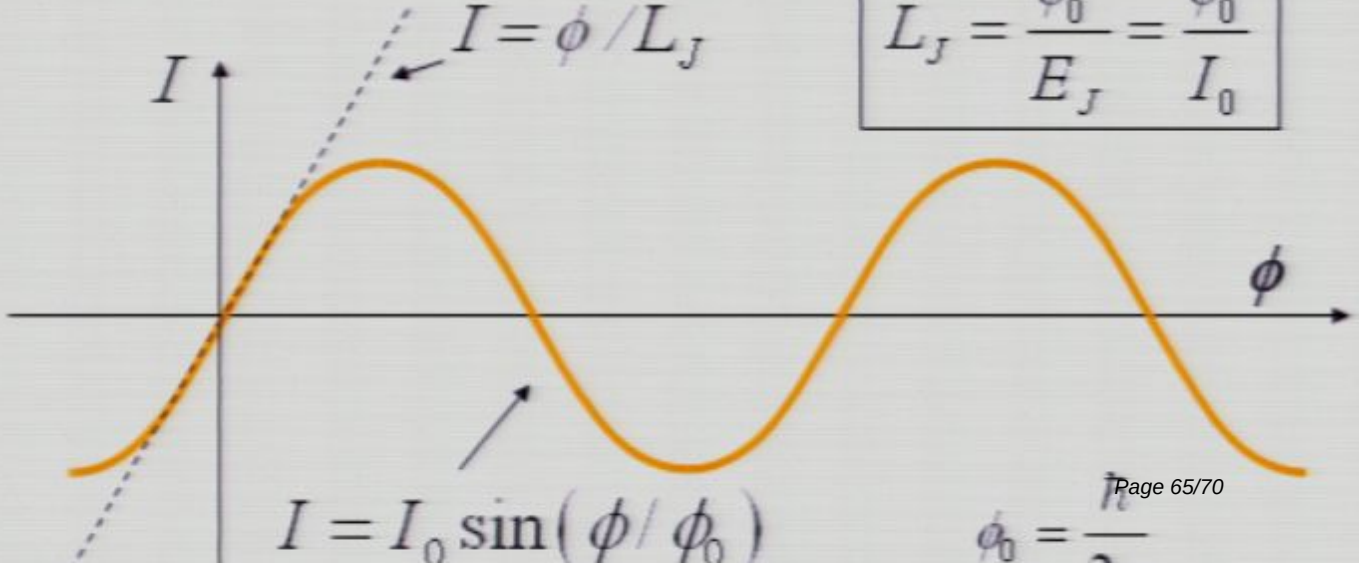




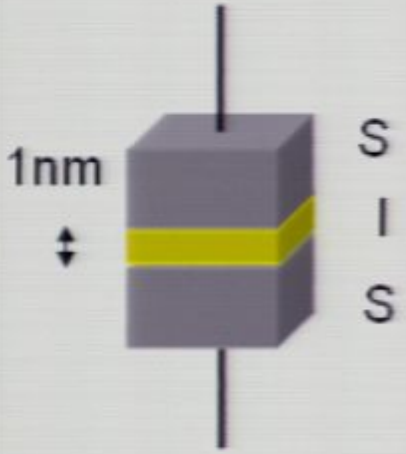


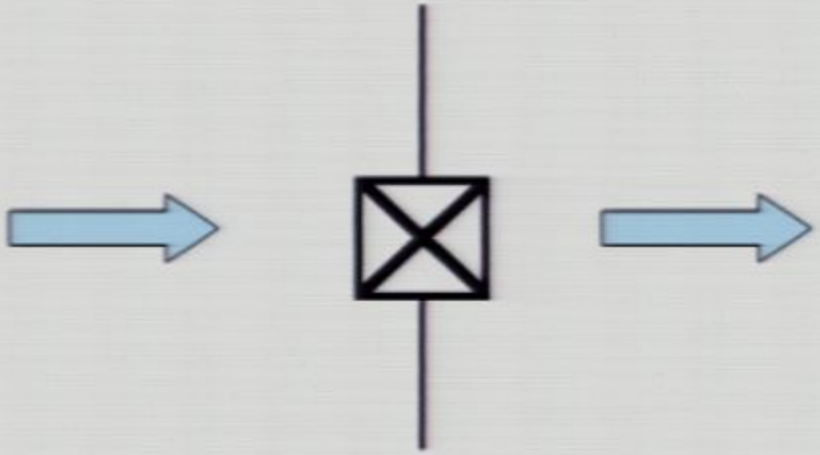
$$L_J = \frac{\phi_0^2}{E_J} = \frac{\phi_0}{I_0}$$

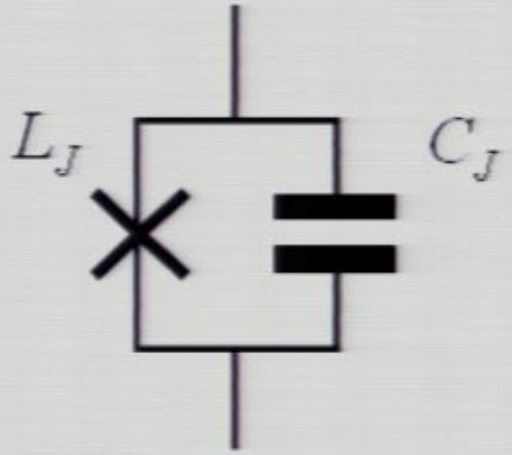




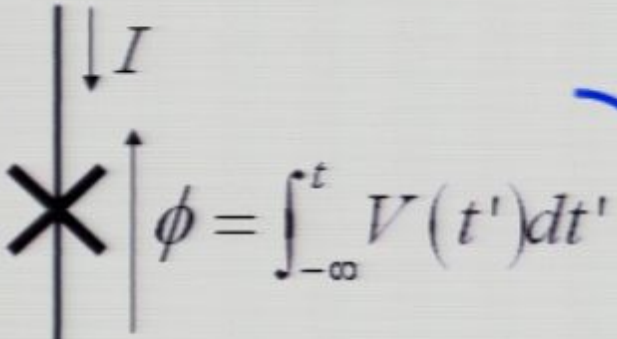
JOSEPHSON TUNNEL JUNCTION PROVIDES A NON-LINEAR INDUCTANCE WITH NO DISSIPATION

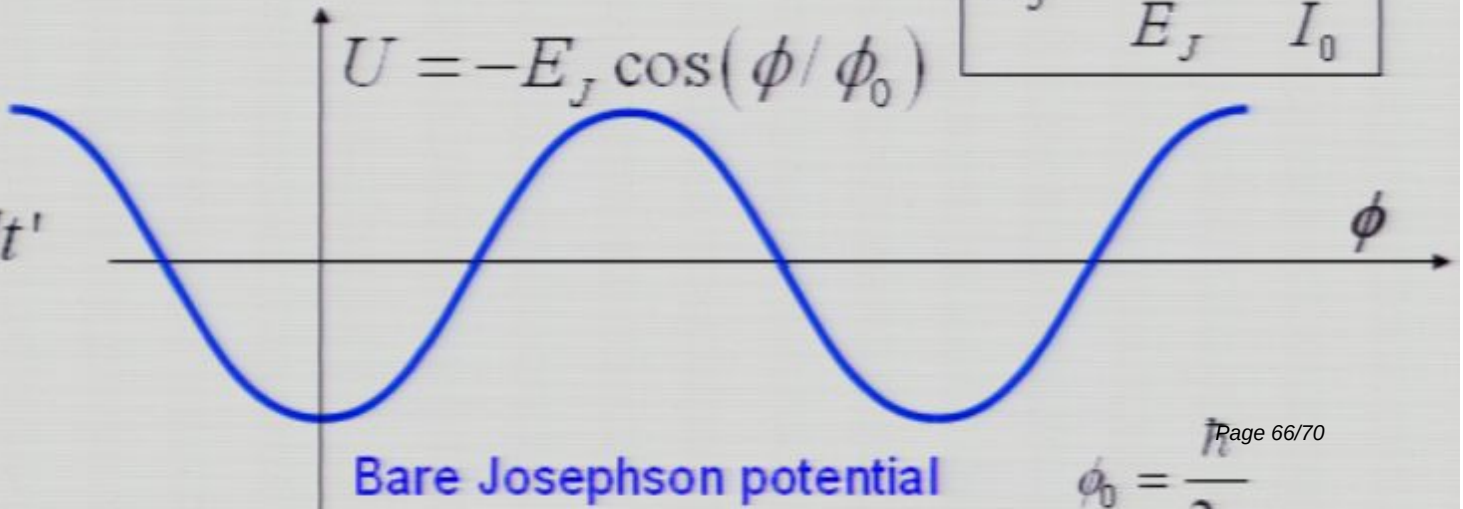






$$L_J = \frac{\phi_0^2}{E_J} = \frac{\phi_0}{I_0}$$

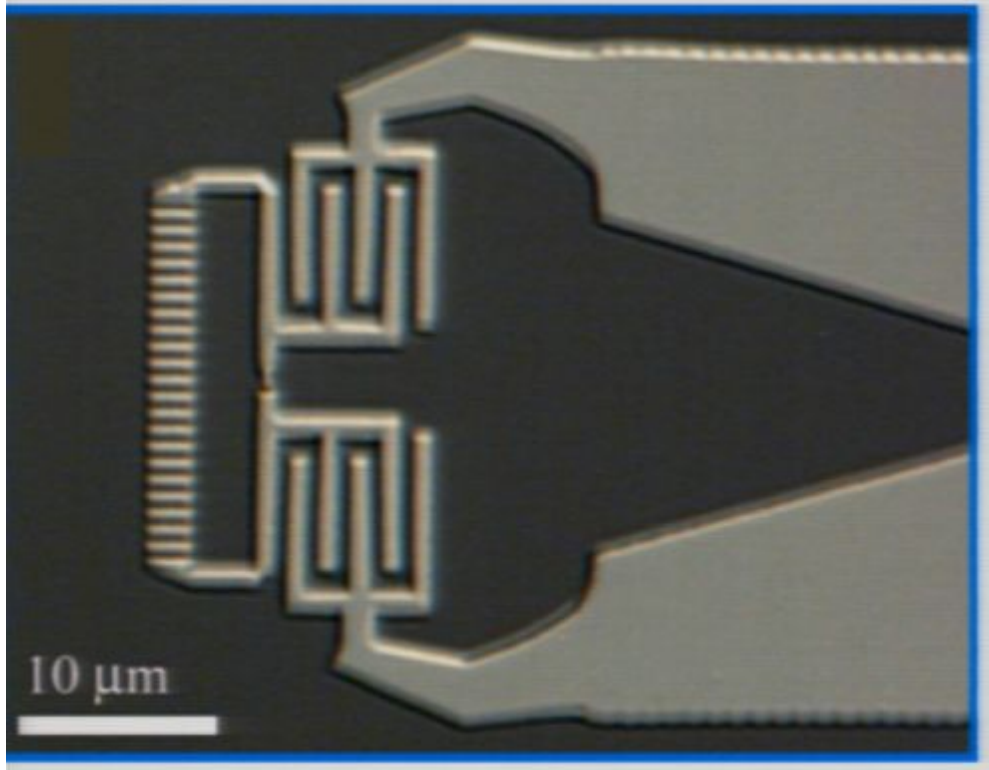


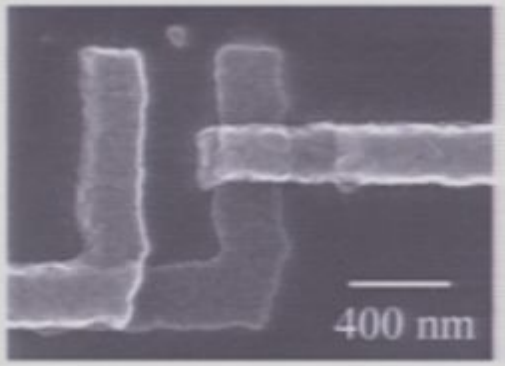


Bare Josephson potential

$\phi_0 = \frac{\hbar}{2}$

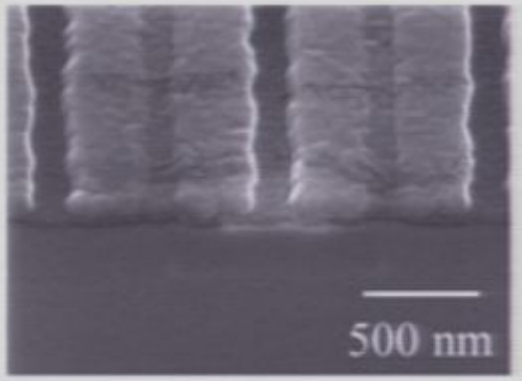
CIRCUIT AT CHIP LEVEL





small junction

Al/AlOx/Al



inductance array junctions

$E_C = \frac{1}{2}\, e^2/(C_J+C_c) = 2.5$ GHz

$E_J = \frac{1}{2}\, (\Phi_0/2\pi)^2/L_J = 8.9$GHz

$E_L = \frac{1}{2}\, (\Phi_0/2\pi)^2/L = 0.52$GHz

T=15mK (~300MHz)

Number of atoms: ~10^{13}

JLC CIRCUIT = PENDULUM + SPRING

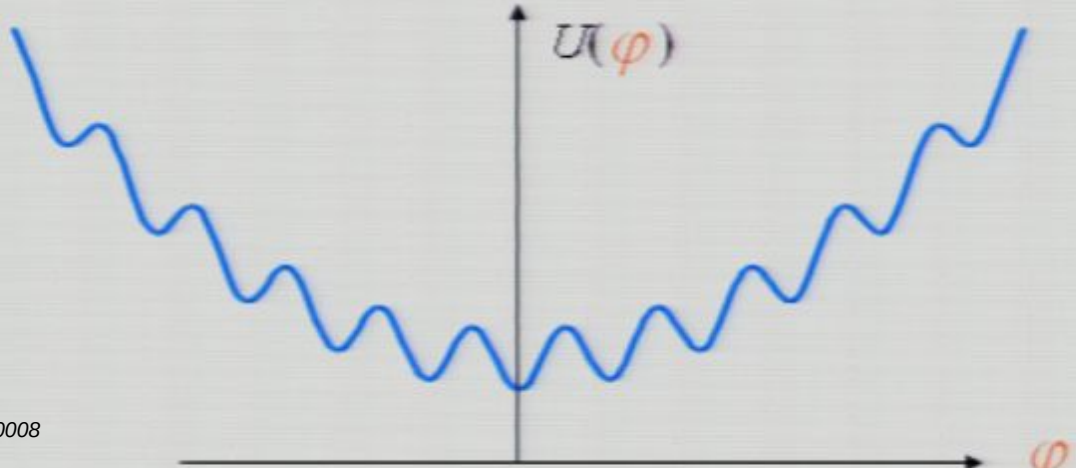
angle of pendulum : gauge invariant phase difference

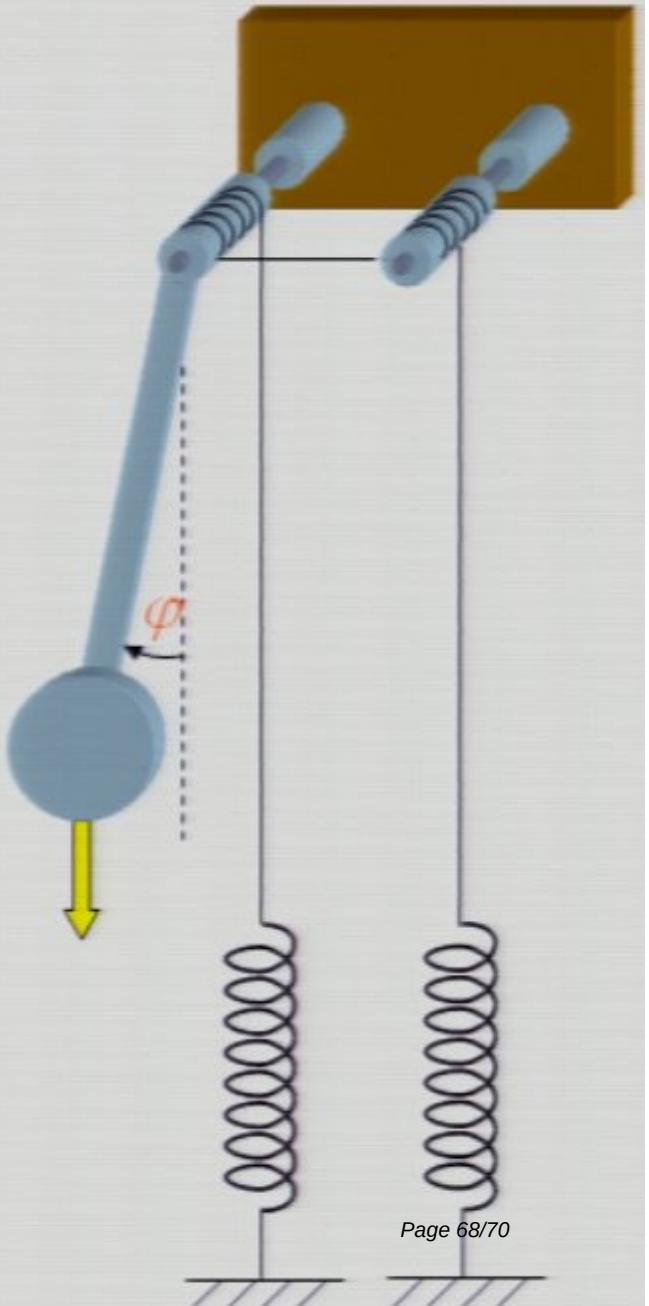
moment of inertia of pendulum : junction capacitance

spring system : loop inductance

torque due to gravity : Josephson current

potential energy of pendulum : Josephson energy





CLASSICAL vs QUANTUM REGIMES IN JOSEPHSON CIRCUITS

Josephson energy

Coulomb energy (1e)

barrier transp^{cy}

$$E_J = \frac{1}{8}\mathcal{N}\mathcal{T}\Delta$$ ← s.c. gap

valid for opaque barrier

cond^{ion} channels

$$E_C = \frac{e^2}{2C_J}$$

proportional to junction area A

Characteristic frequency $$\omega_p = \frac{1}{\hbar}\sqrt{8E_J E_C} = \frac{1}{\sqrt{L_J C_J}} \sim 10\text{GHz}$$

ind^t of A

Number of levels in main well ~ $$\sqrt{\frac{E_J}{8E_C}} \sim A$$ ← can vary by 10^6!

JLC CIRCUIT = PENDULUM + SPRING

angle of pendulum : gauge invariant phase difference

moment of inertia of pendulum : junction capacitance

spring system : loop inductance

torque due to gravity : Josephson current

potential energy of pendulum : Josephson energy