Title: Foundations and Interpretation of Quantum Theory - Lecture 21

Date: Apr 01, 2010 02:30 PM

URL: http://pirsa.org/10040017

Abstract: Macroscopic quantum coherence

MACROSCOPIC QUANTUM PHENOMENA IN SUPERCONDUCTING CIRCUITS

OUTLINE

TUESDAY: BASIC QUESTIONS ADDRESSED BY SUPER-CONDUCTING CIRCUITS

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

MACROSCOPIC QUANTUM PHENOMENA IN SUPERCONDUCTING CIRCUITS

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TUESDAY: BASIC QUESTIONS ADDRESSED BY SUPER-CONDUCTING CIRCUITS

TODAY: **INTRODUCTION TO** MACROSCOPIC QUANTUM EXP^{TS} ON THE FLUXONIUM ARTIFICIAL ATOM

OPENING REMARKS

In the absence of a specific alternative to quantum mechanics theory for macro-objects, we can only guess which type of superconducting circuit is most sensitive to reveal the discrepancy. Which parameter is important: total mass, # free electrons, #quarks, classical action in units of h, geometric dimensions, magnitude of currents/voltages etc...?

The higher the SNR in a quantum circuit experiment and the less noise due to microscopic defects/measurement apparatus is present in the system [flux noise, charge noise, critical current noise, energy exchange, etc..], the higher the chance that we resolve a discrepancy with a standard theory. It is thus our goal to maximize the control over Josephson circuits in their manipulation and measurement.

DETAILED OUTLINE

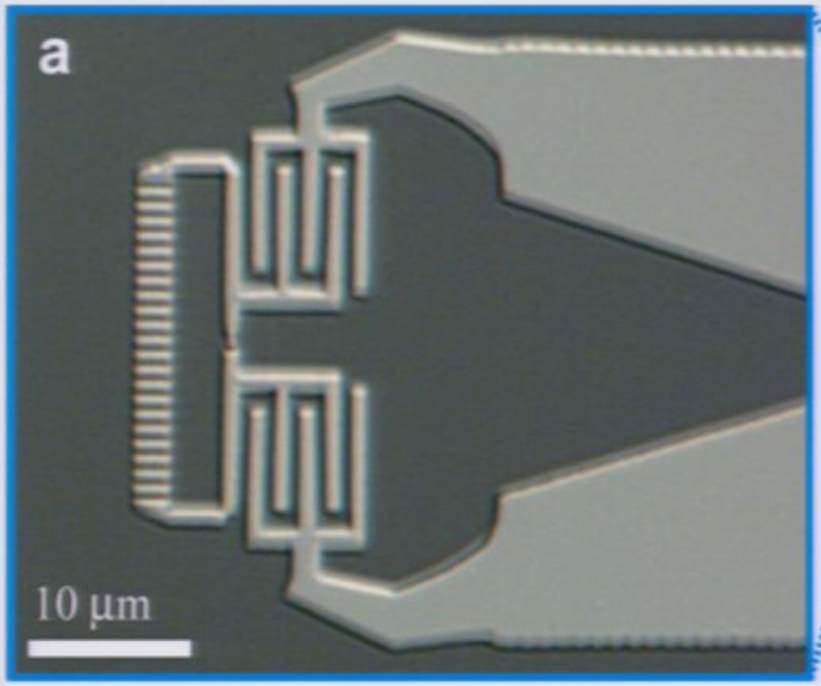
BASIC QUANTUM EXPERIMENTS WITH FLUXONIUM

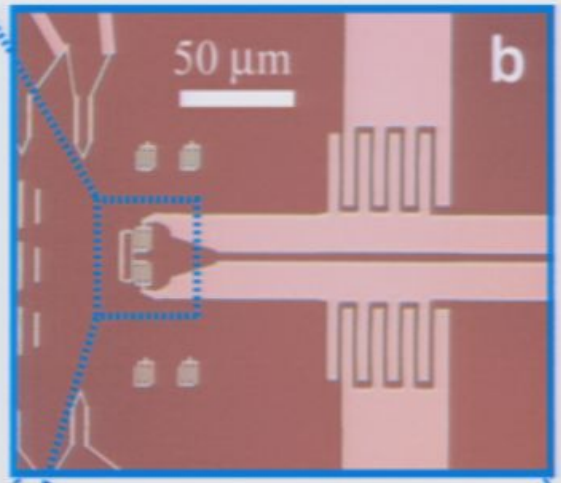
0.5 2.5
Fx
9.0

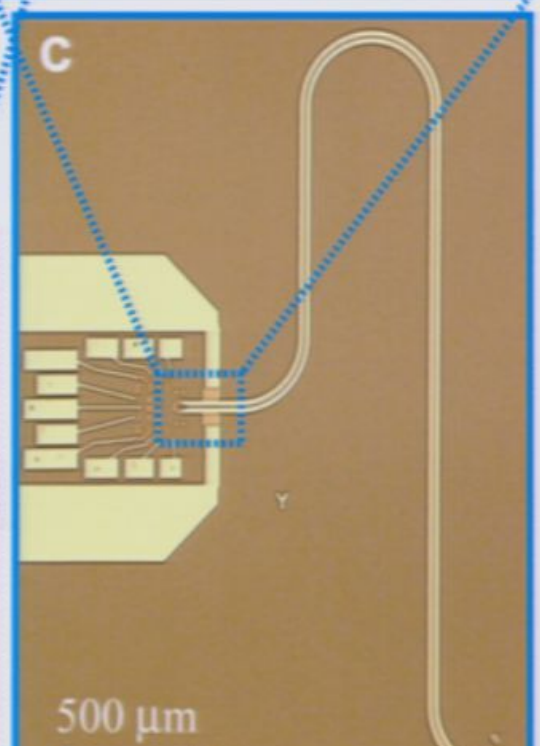
CONTRIBUTION OF THE NEW FLUXONIUM CIRCUIT TO THE "MACROSCOPIC QUANTUM COHERENCE" RESEARCH PROGRAM

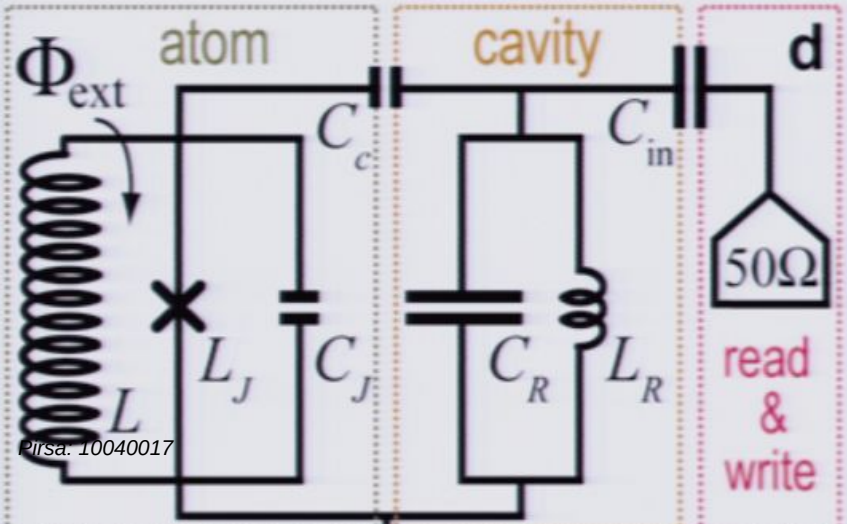
CONTROL AND NON-DESTRUCTIVE MEASUREMENT OF SUPERCONDUCTING CIRCUITS WITH MICROWAVE SIGNALS
(time permitting)

DEVICE IMAGES, MODEL AND PARAMETERS









"Atom"

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

"Cavity"

$\omega_R = (L_R C_R)^{-1/2}/2\pi = 8.2$GHz

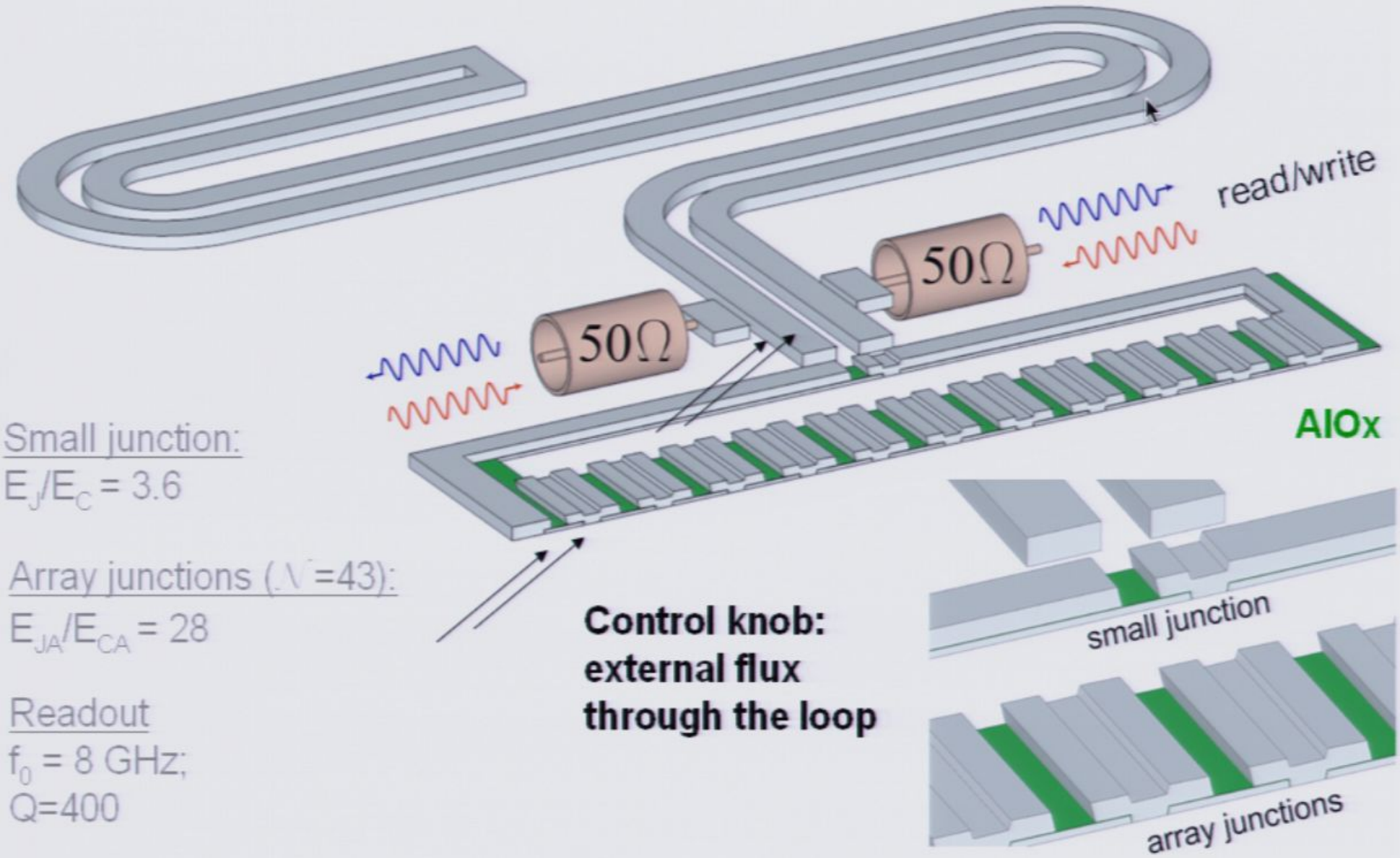
$Z_R = (L_R/C_R)^{1/2} = 82\Omega$

Coupling constant

$g = \omega_R (Z_R/2R_Q)^{1/2}/(1+C_J/C_c)$

$= 135$MHz $(R_Q = 1\ k\Omega)$

DEVICE DETAILED SKETCH



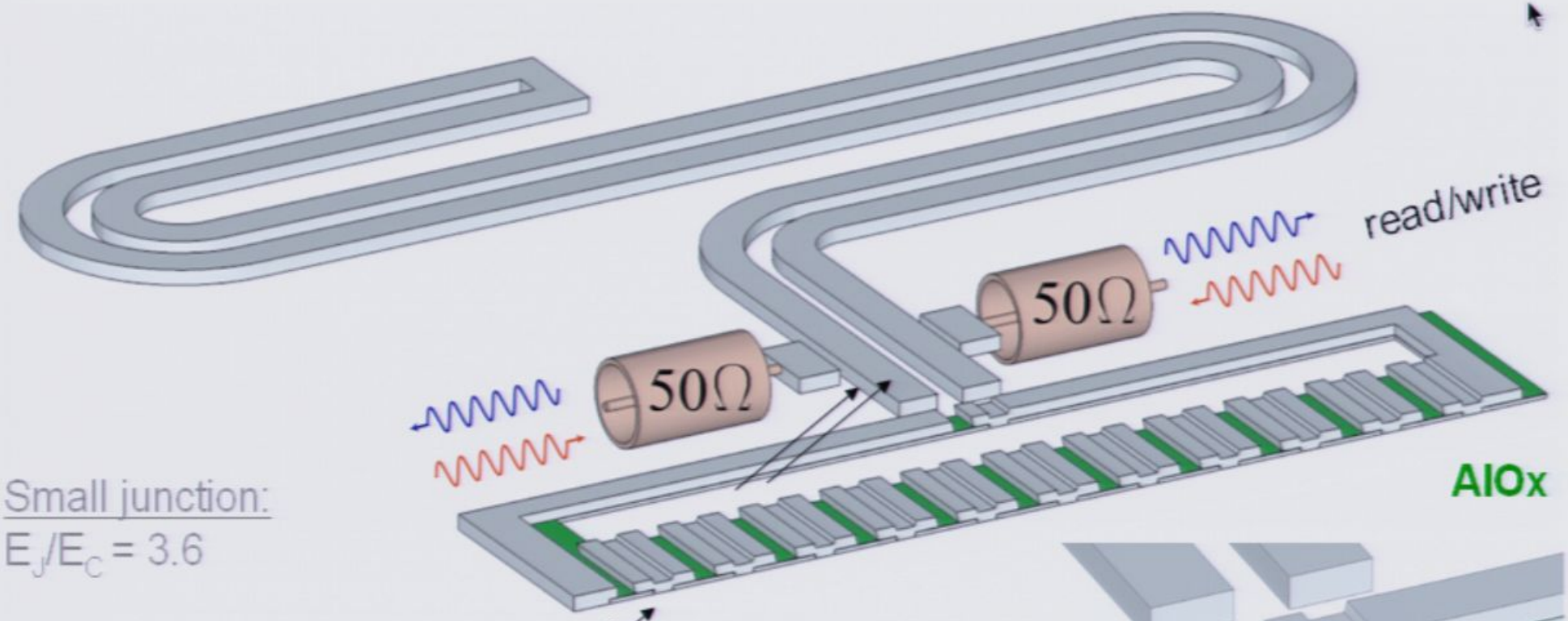
Small junction:
$E_J/E_C = 3.6$

Array junctions (N=43):
$E_{JA}/E_{CA} = 28$

Readout
f_0 = 8 GHz;
Q=400

Control knob: external flux through the loop

1: ATOM IS A LOOP WITH ~50 JJ



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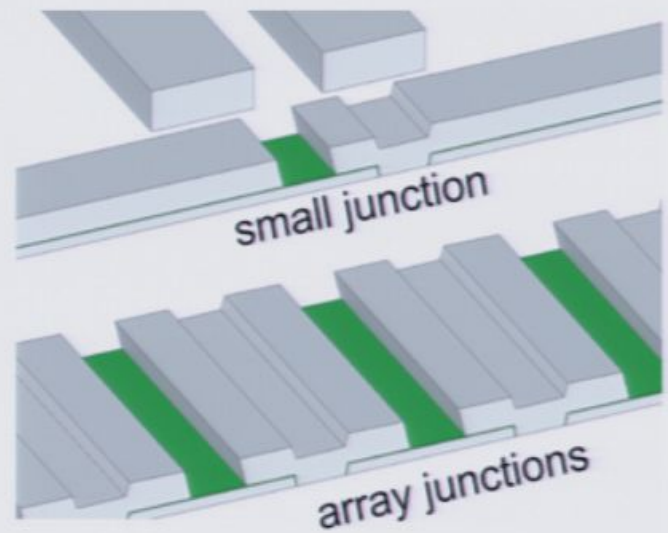
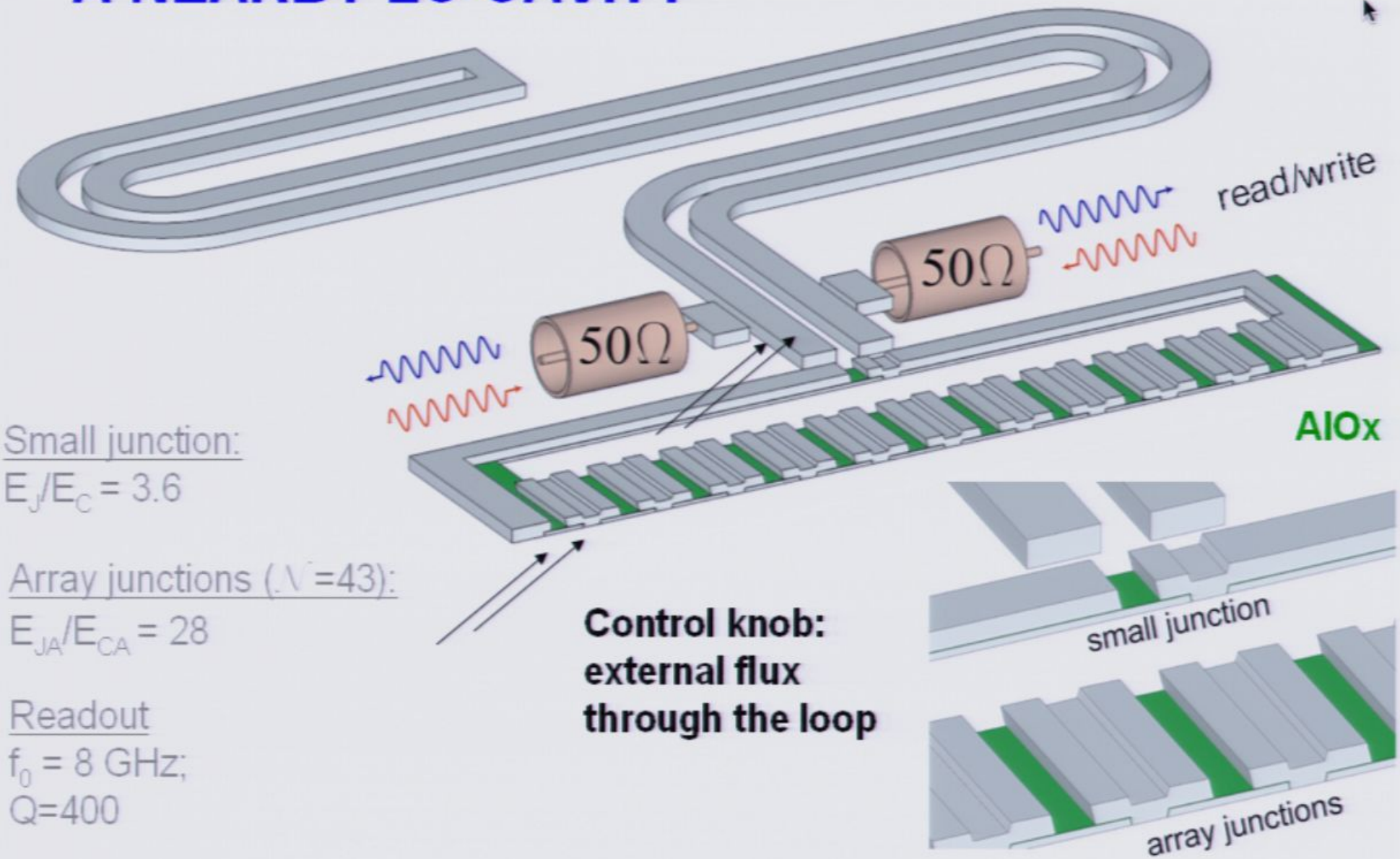


Every island is shunted by a large junction; array performs as a giant inductor

2: READ ATOMIC STATE VIA FREQUENCY OF A NEARBY LC-CAVITY



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Fluxonium modifies resonator's electrical length depending on it's quantum state

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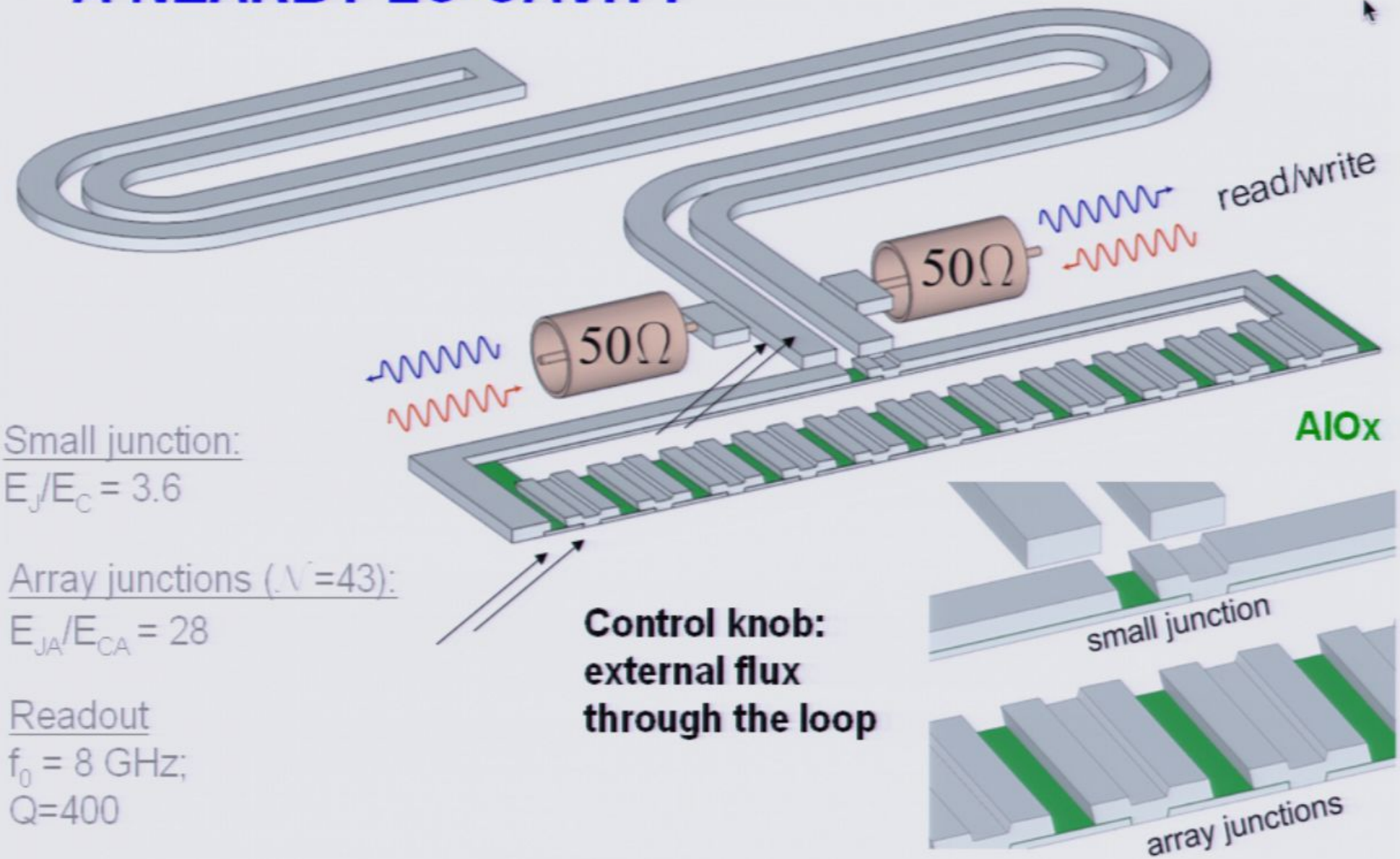

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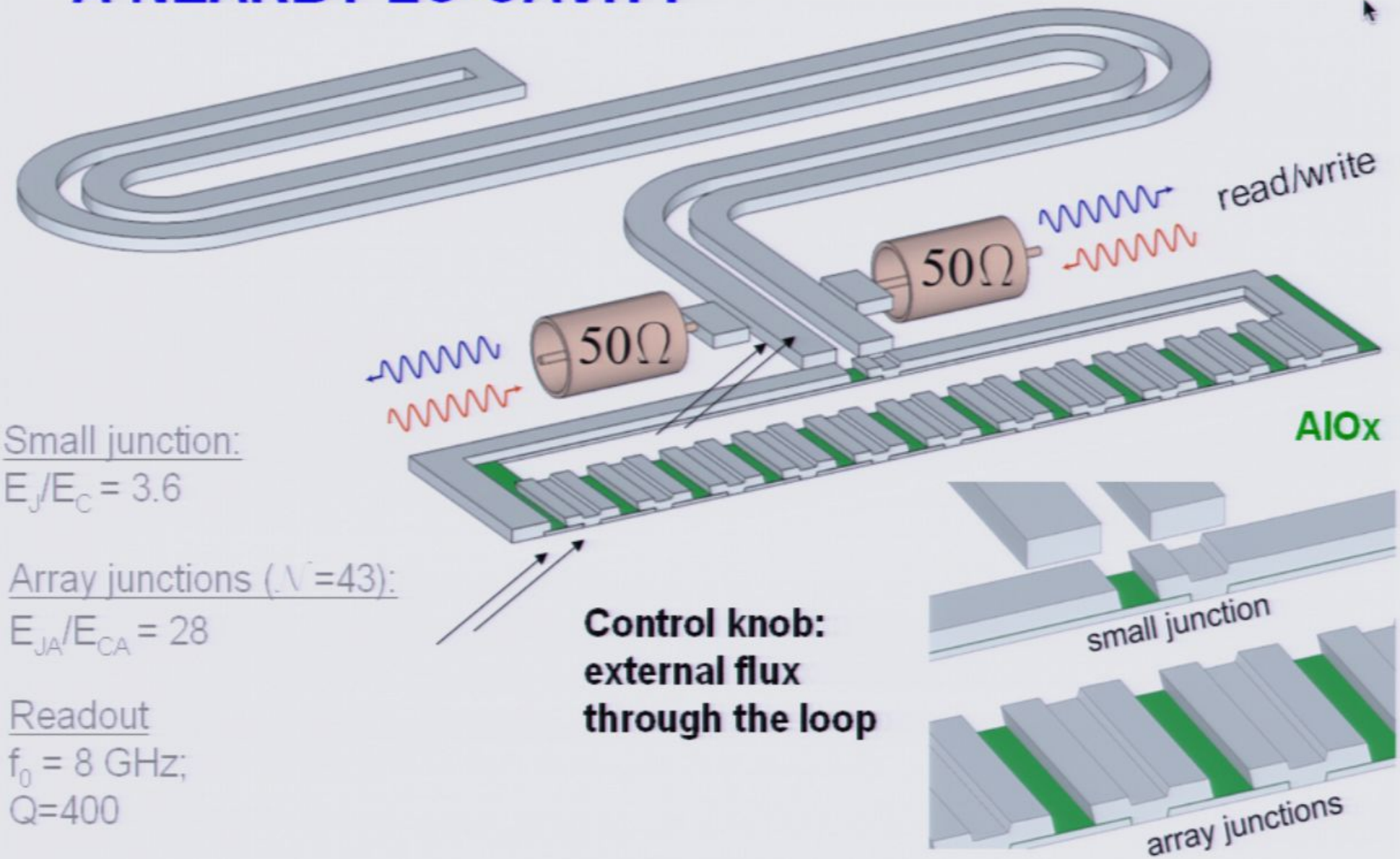

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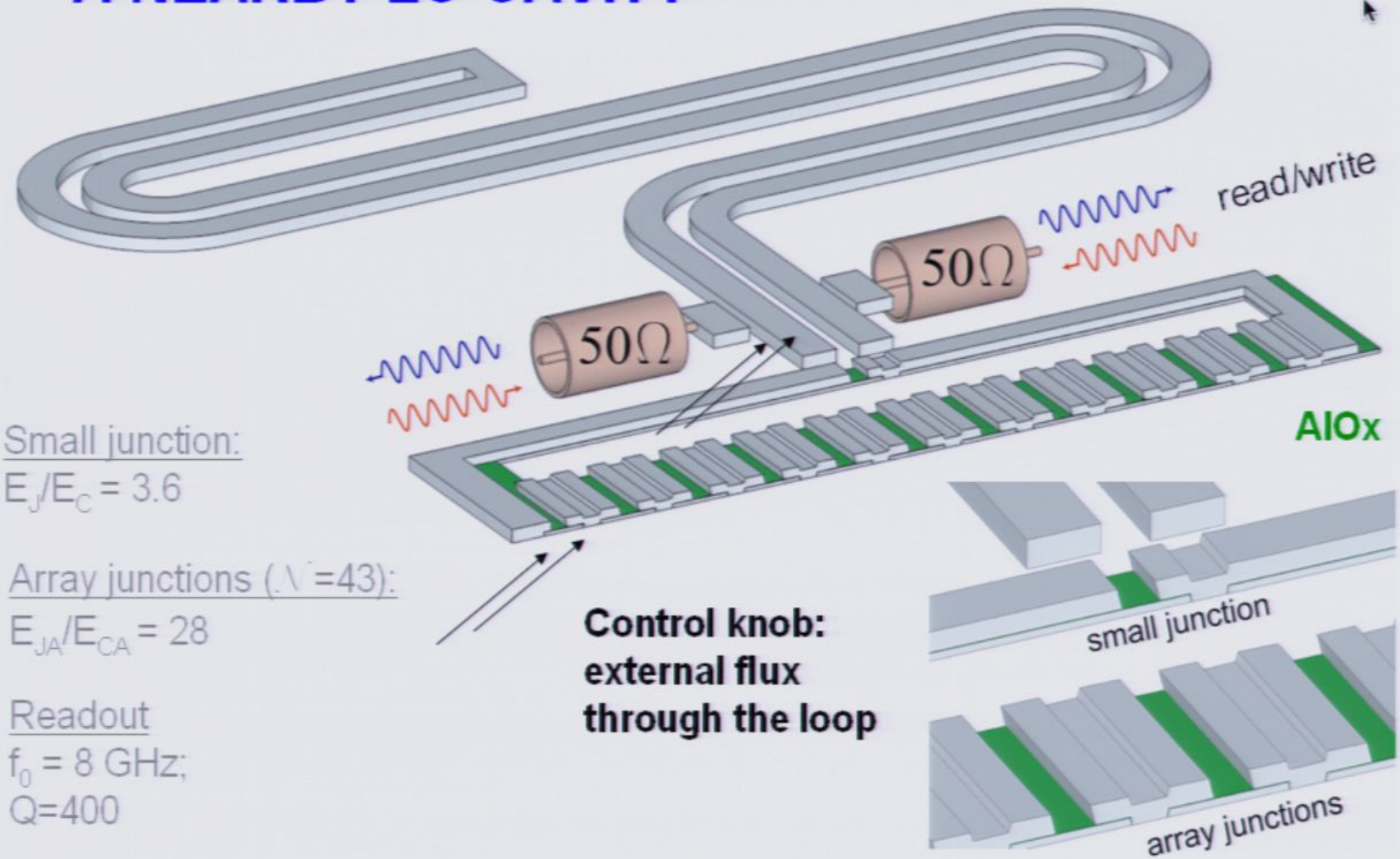

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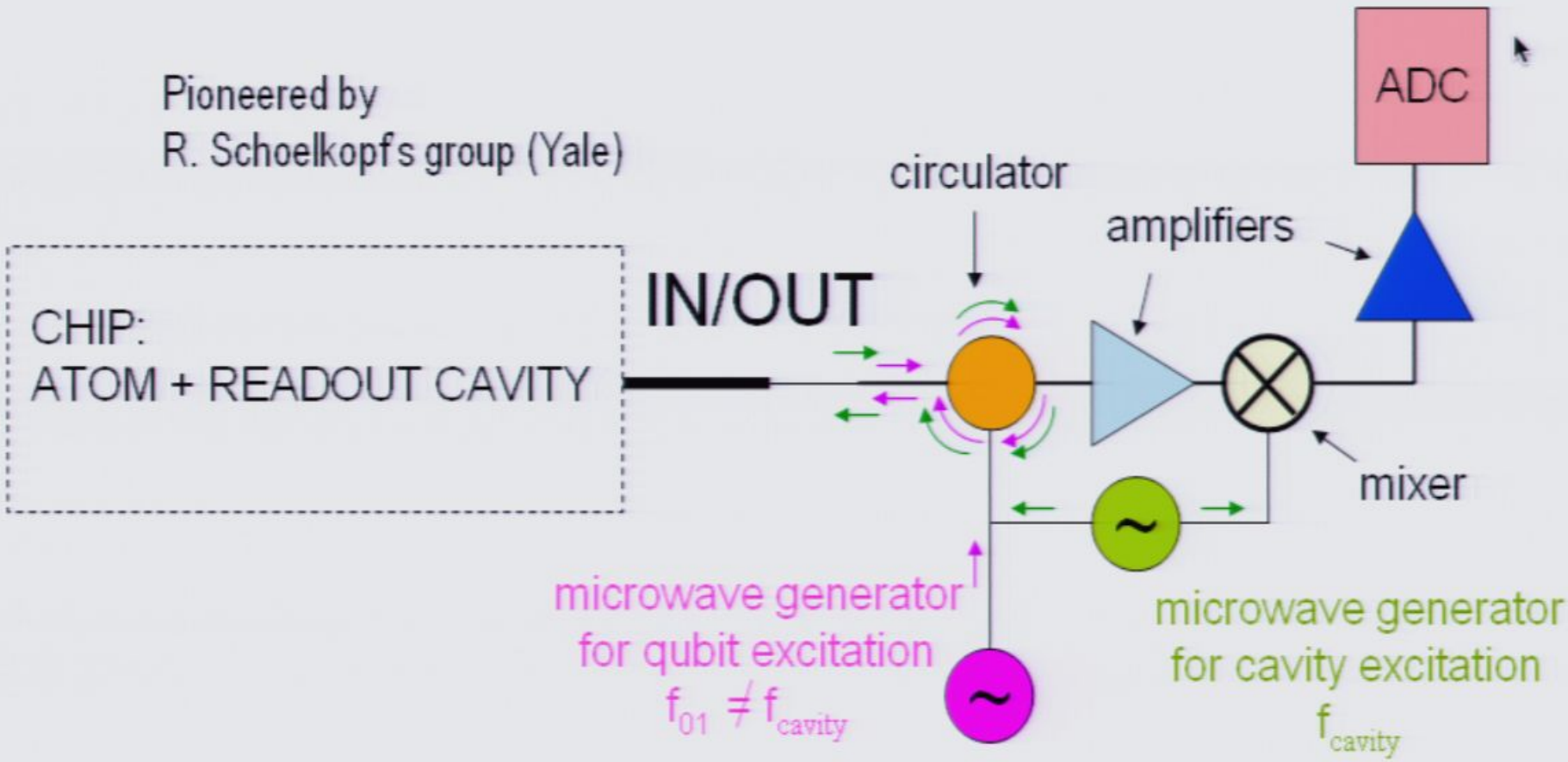
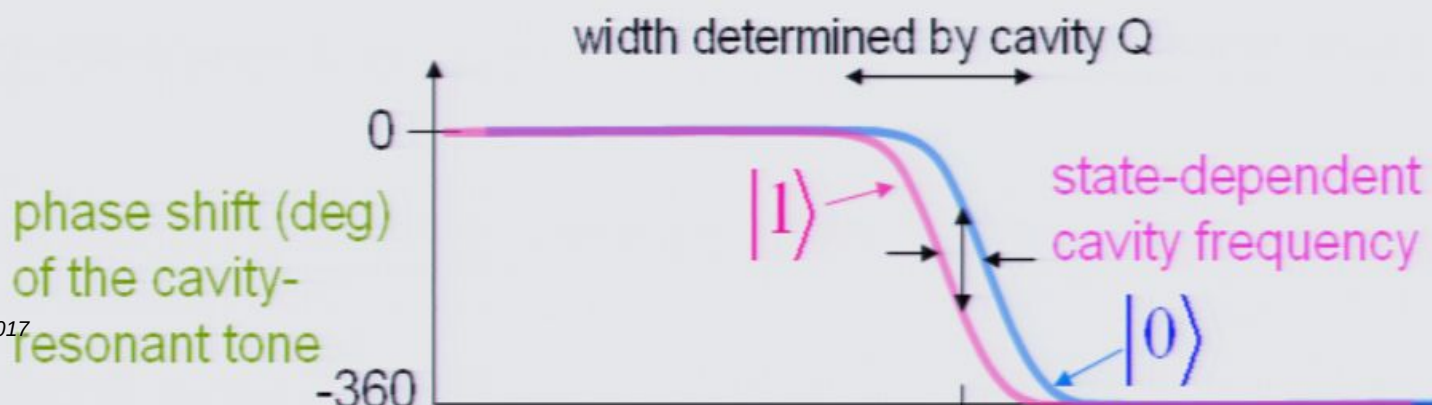
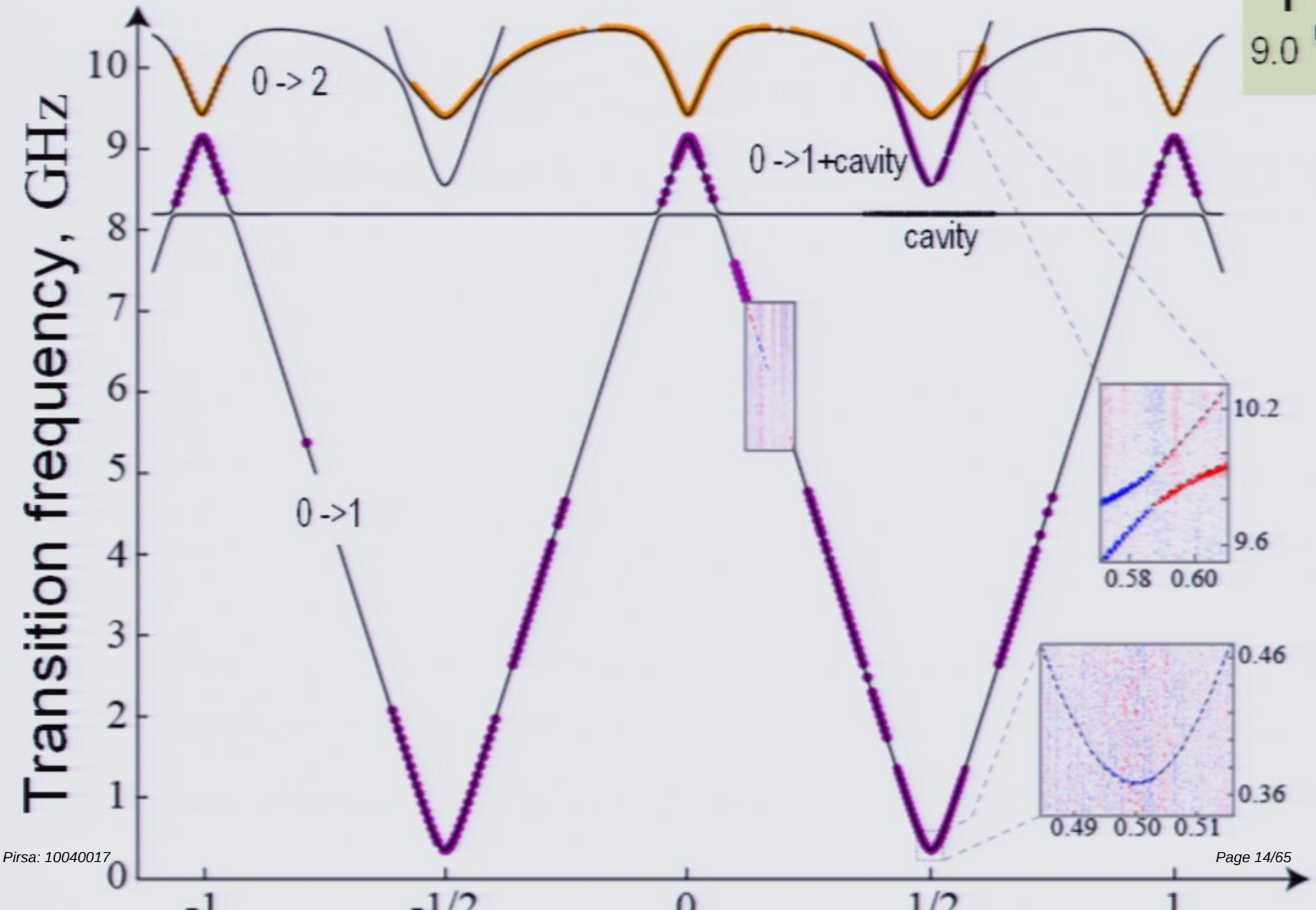
READOUT PROTOCOL

Pioneered by
R. Schoelkopf's group (Yale)





3-LEVEL TUNABLE MICROWAVE SPECTRUM



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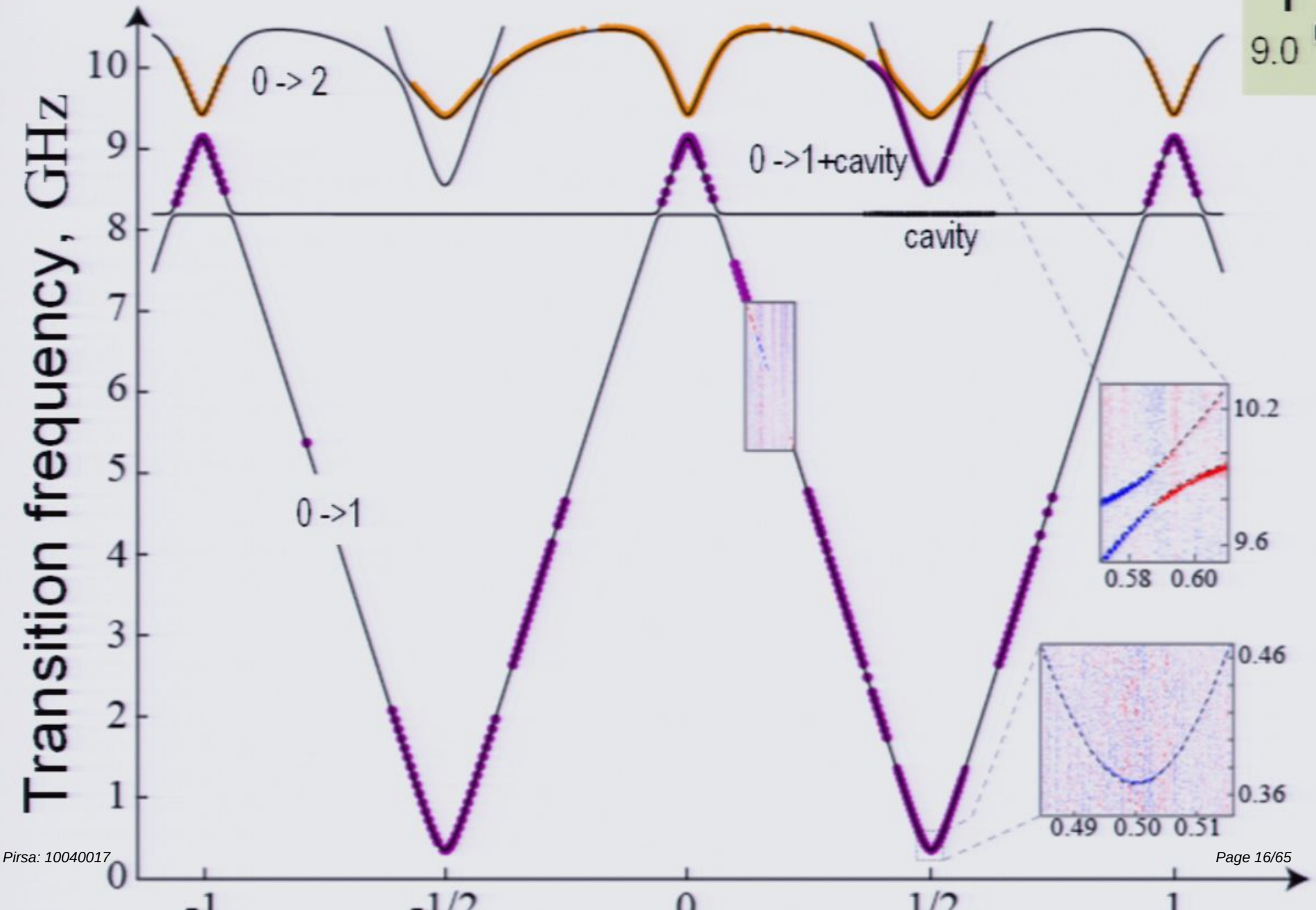
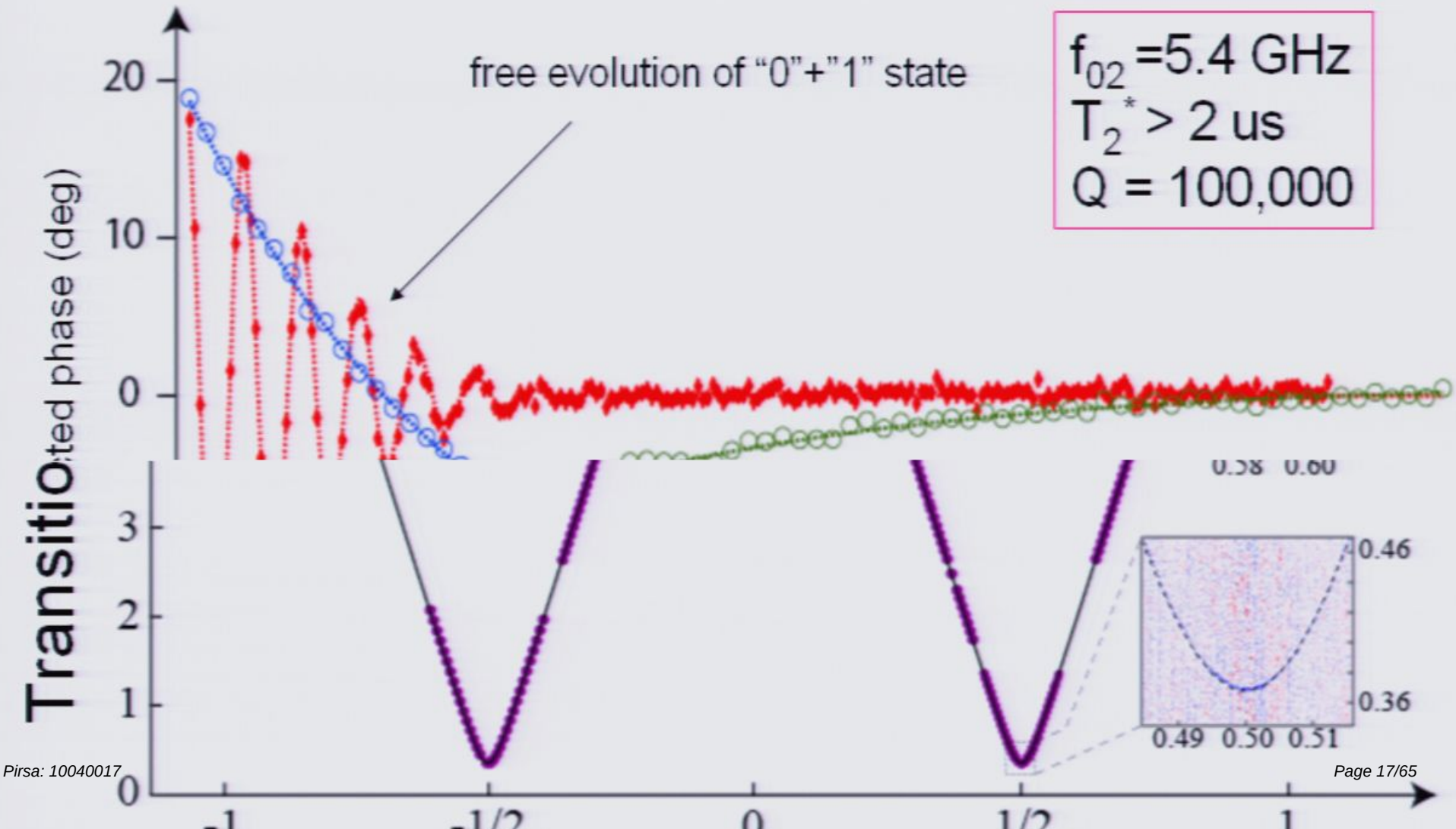


TIME DOMAIN COHERENCE BETWEEN STATES “0” AND “1”



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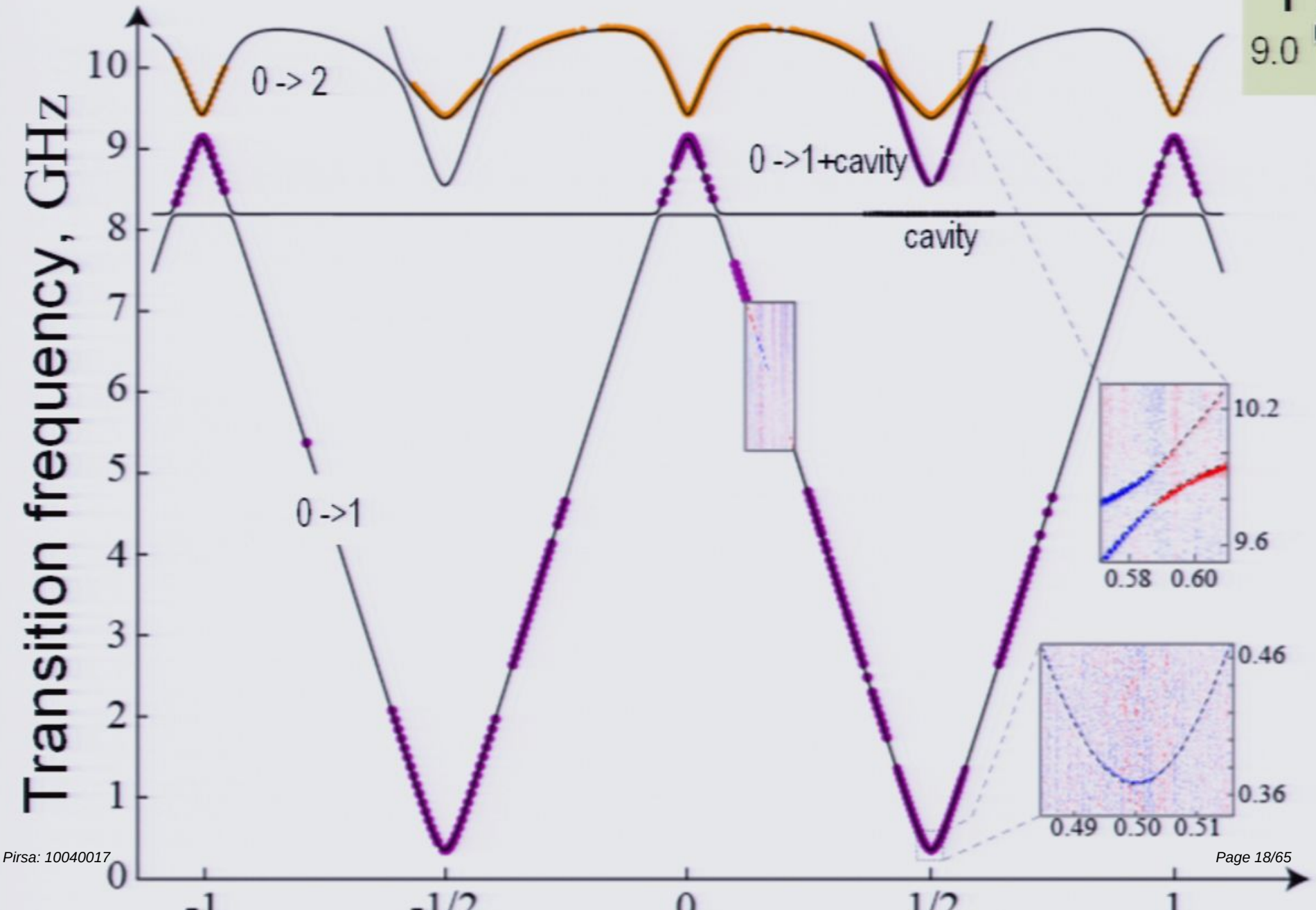

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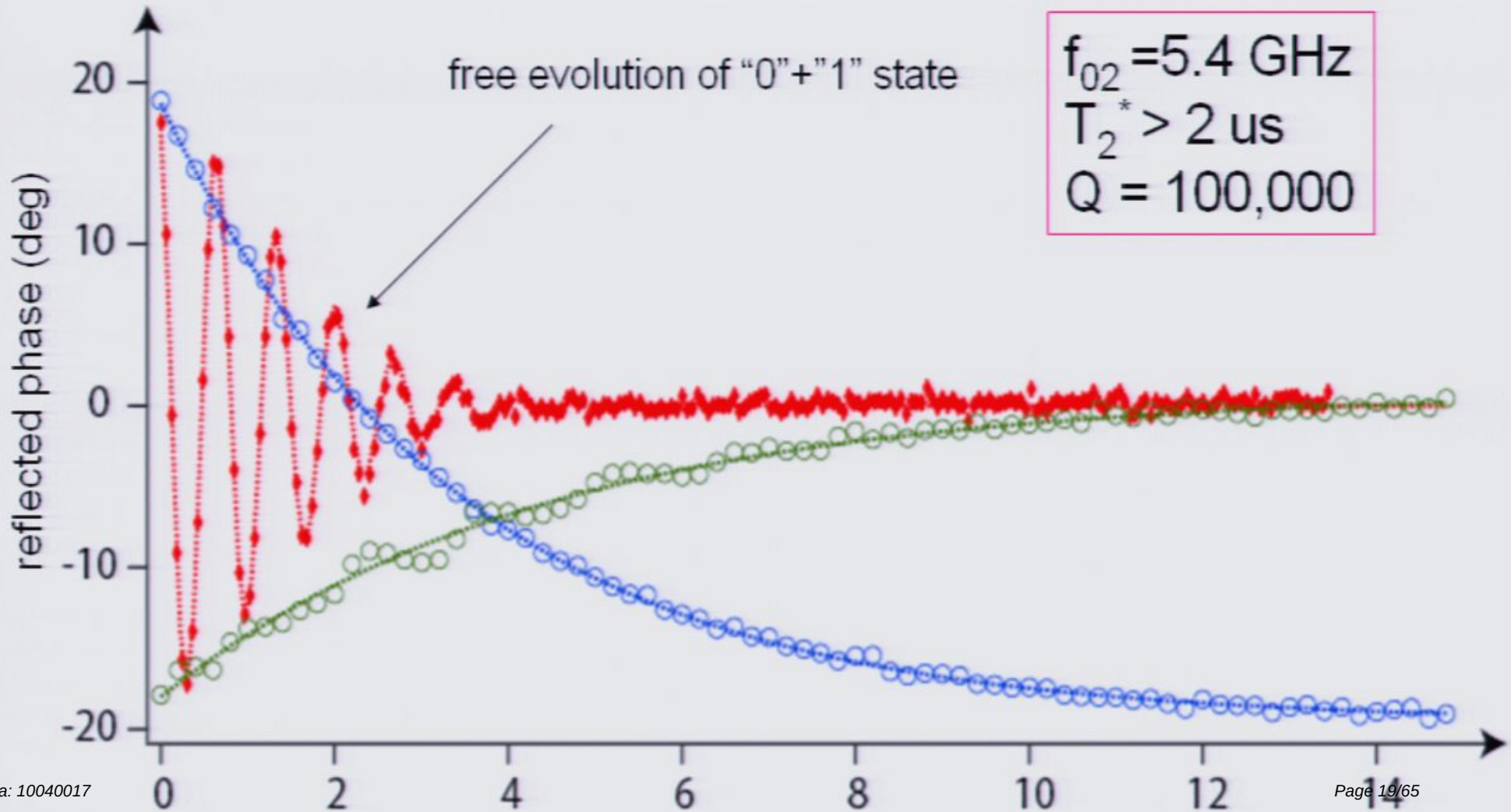
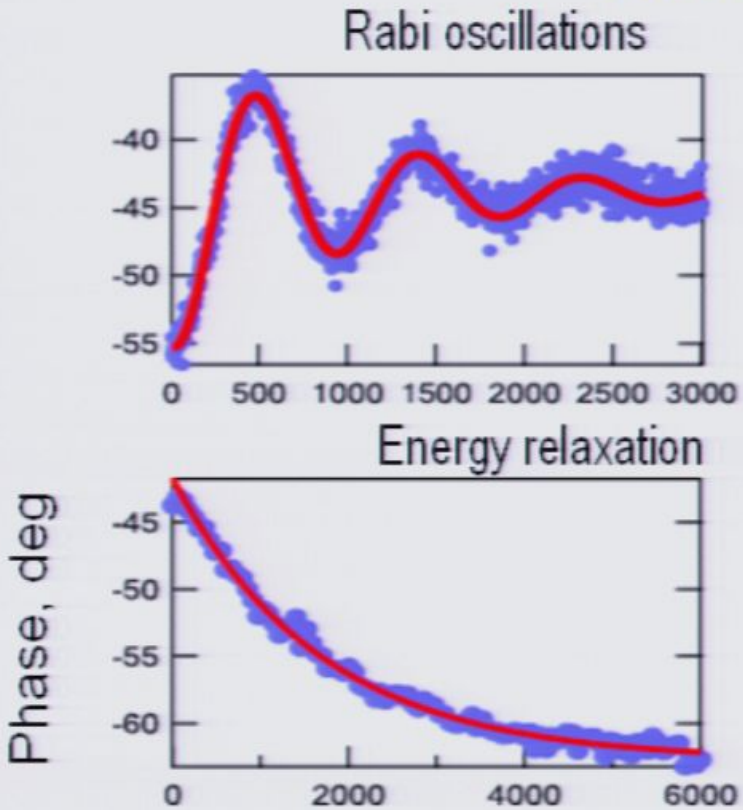
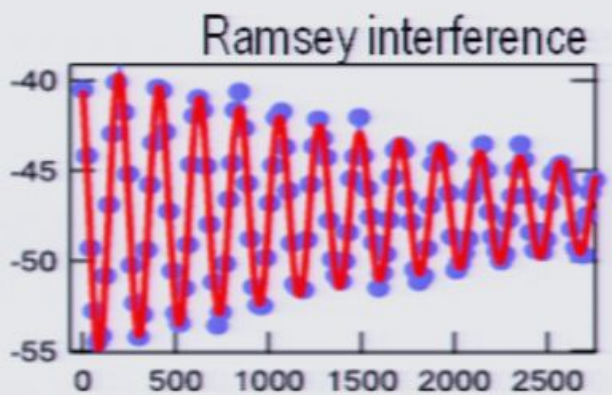


TIME DOMAIN COHERENCE BETWEEN STATES "0" AND "2"



f_{02} =9.4 GHz
T_2^* > 3 us
Q = 200,000

Nearly best superconducting circuit coherence



free evolution of "0"+"1" state

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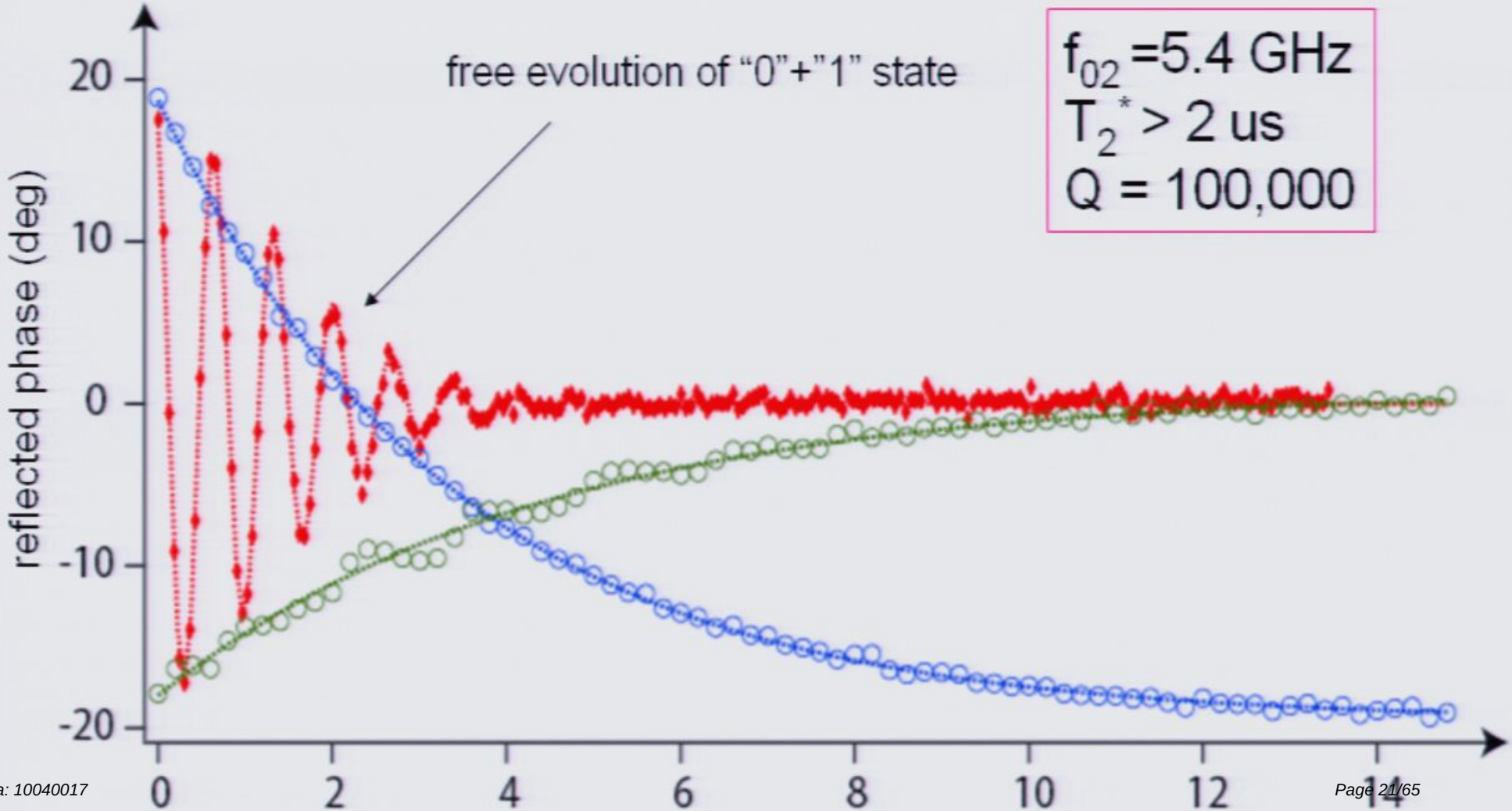
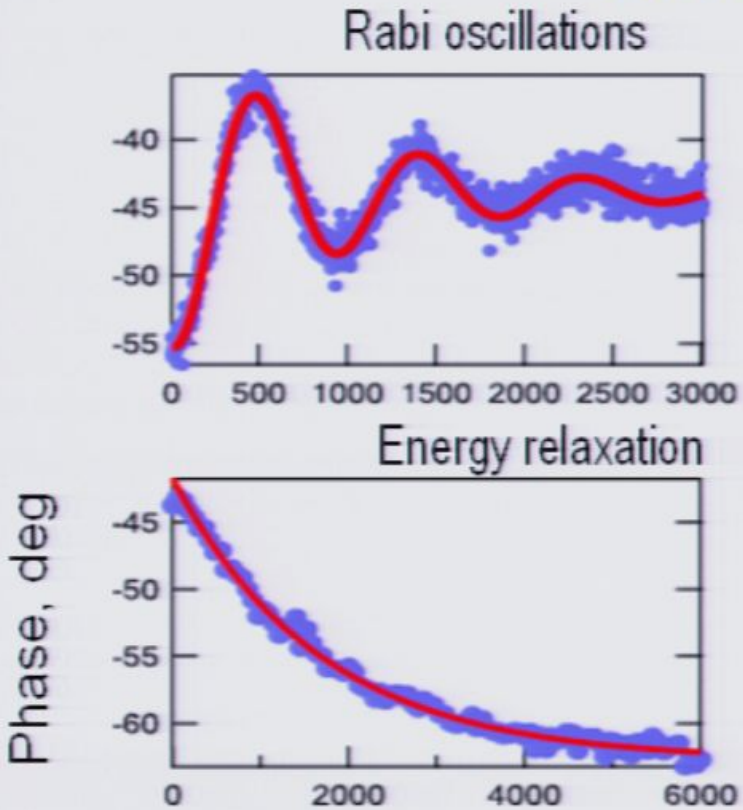


TIME DOMAIN COHERENCE BETWEEN STATES "0" AND "2"



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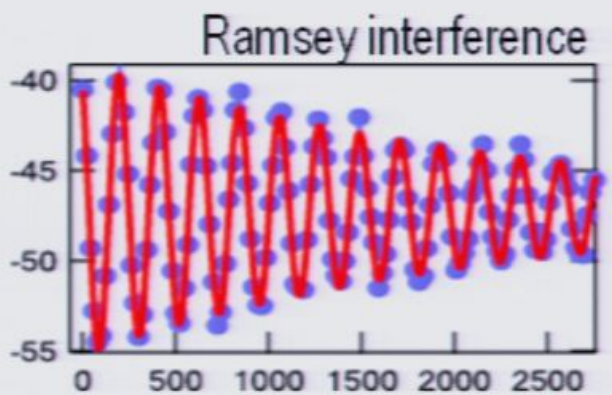

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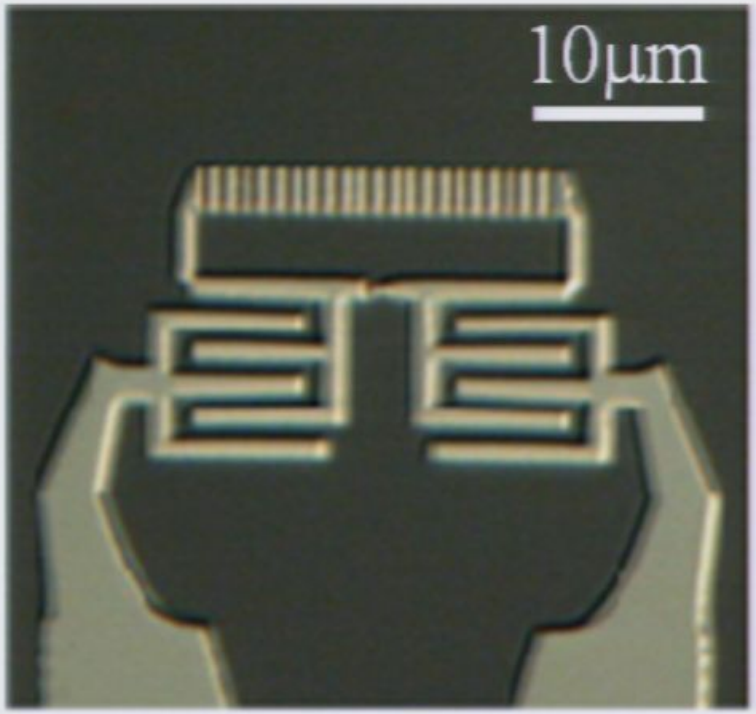
AMONG MOST COHERENT S.C.!



Easy to fabricate:
i) only one step of
e-beam patterning and Al deposition!
ii) spectrum is tolerant to the fab variations

Easy to measure:
atom talks strongly to the cavity without relaxing into it. Will achieve single-shot with better amplifiers

Easy to tune:
0.3 – 12 GHz transition frequencies, flux noise is not a limitation yet, T_φ >35μs

Long lifetimes [2010]:
T1 >10μs, Q > 100,000 but what limits it?

Future is in multi-qubit circuits for error correction, both "software" and "hardware" (A. Kitaev, L. Ioffe et al.)

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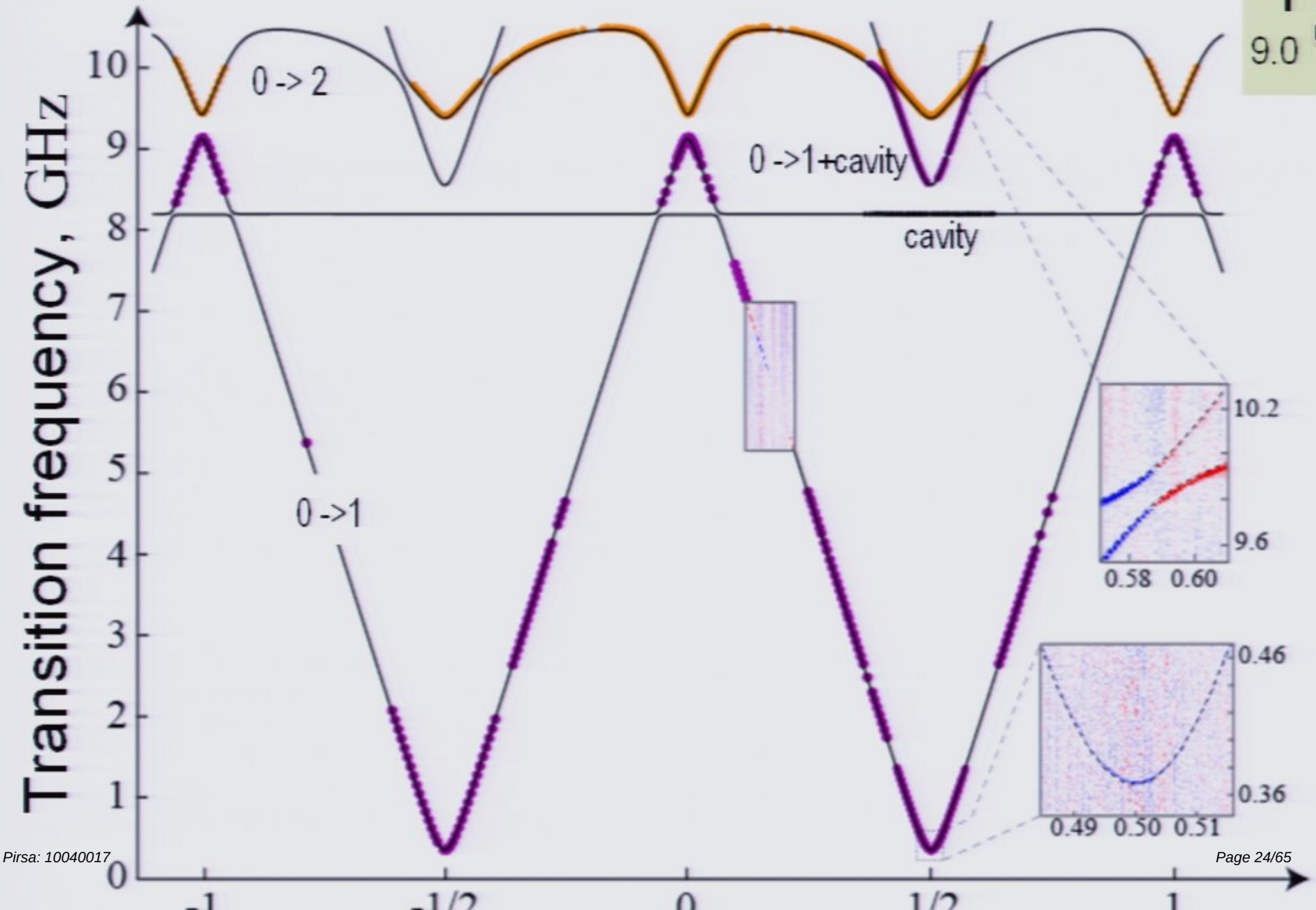

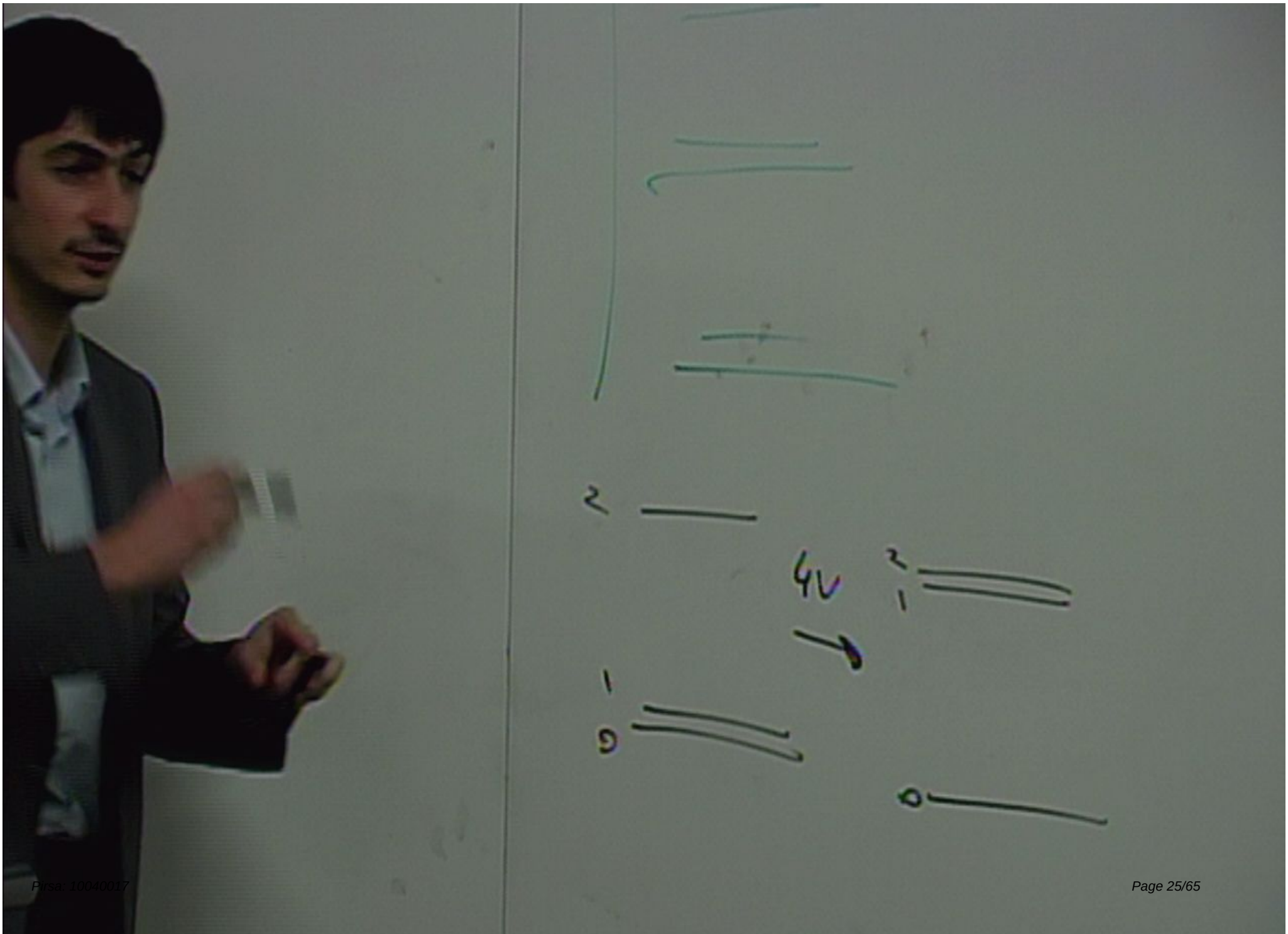
2
4V
2
1
1
0
0

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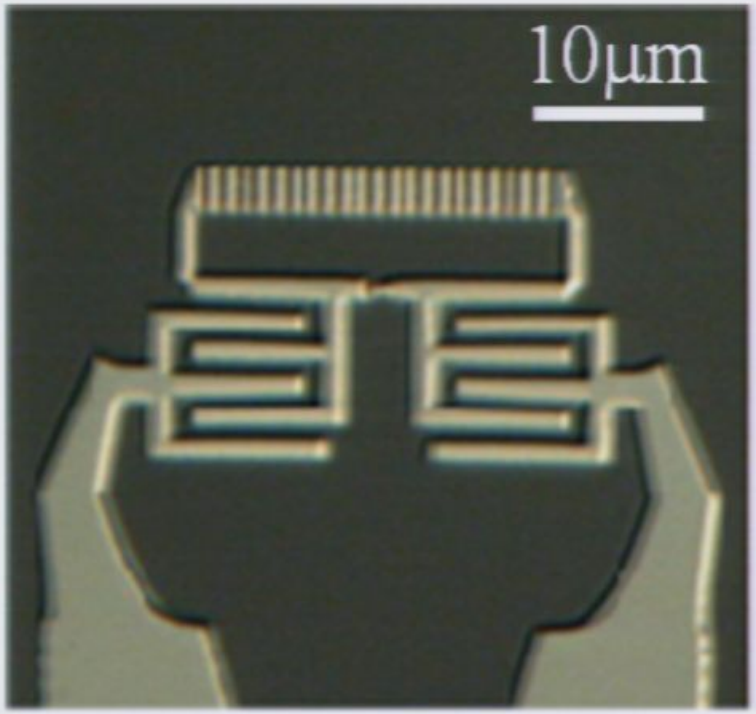

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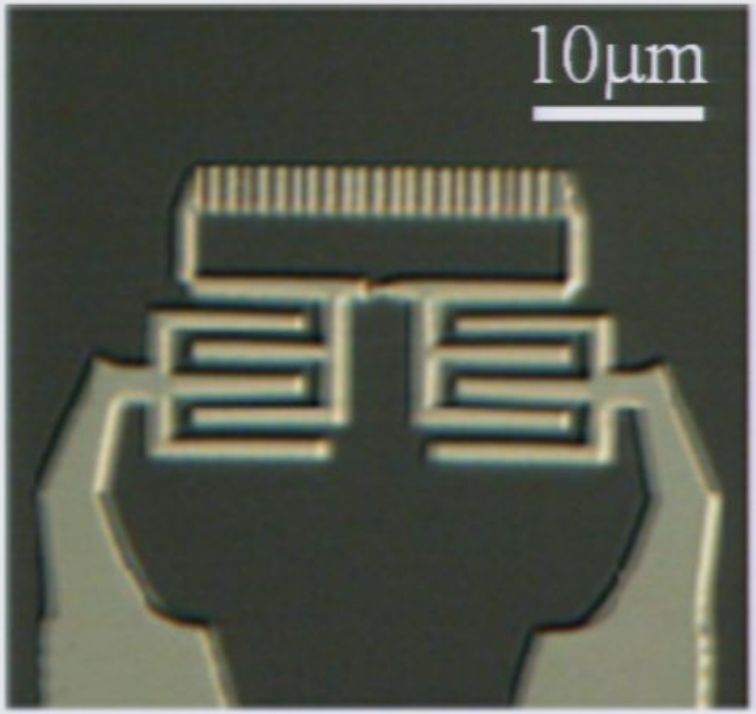

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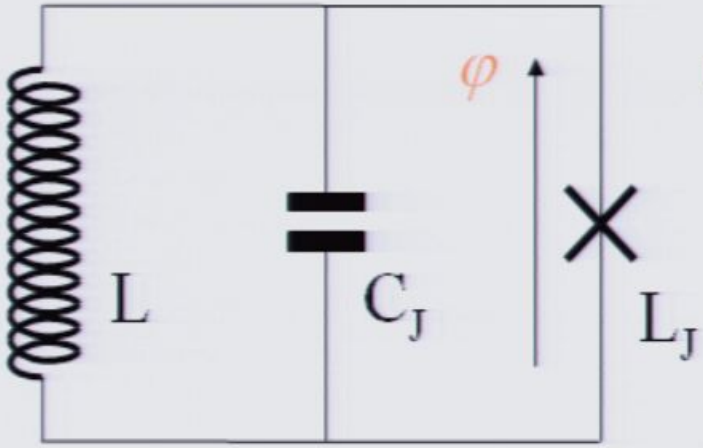
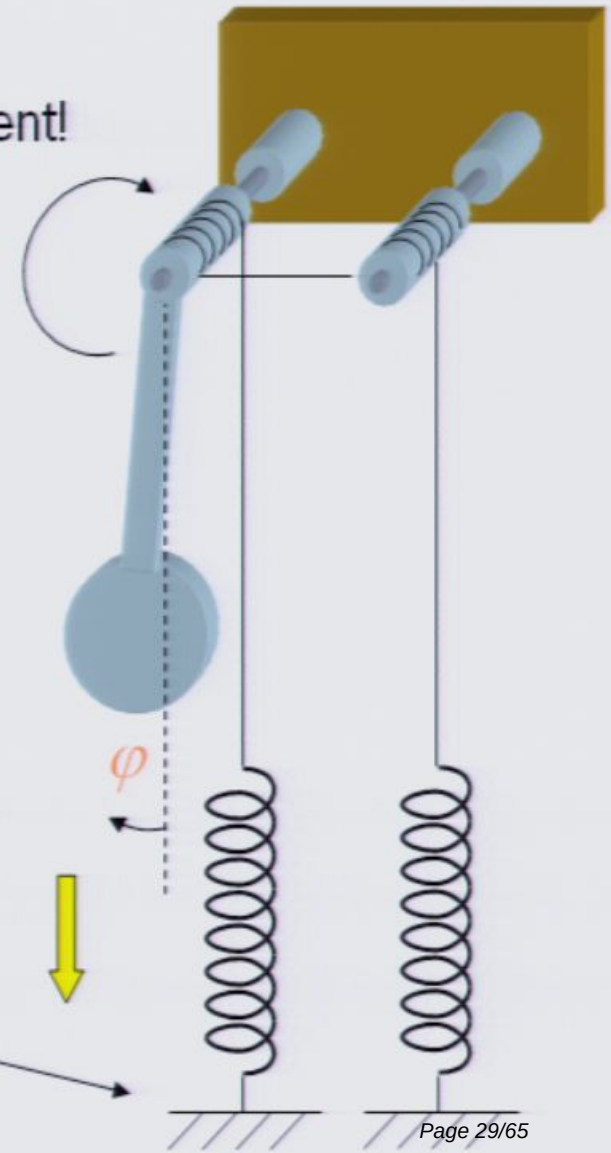
WHAT IS SPECIAL ABOUT FLUXONIUM STATES?

IS IT MORE “MACROSCOPIC” THAN OTHERS?

$L_J||C||L$ = PENDULUM + SPRING



mathematically equivalent!



$L \gg L_J$ ⇔ very soft spring

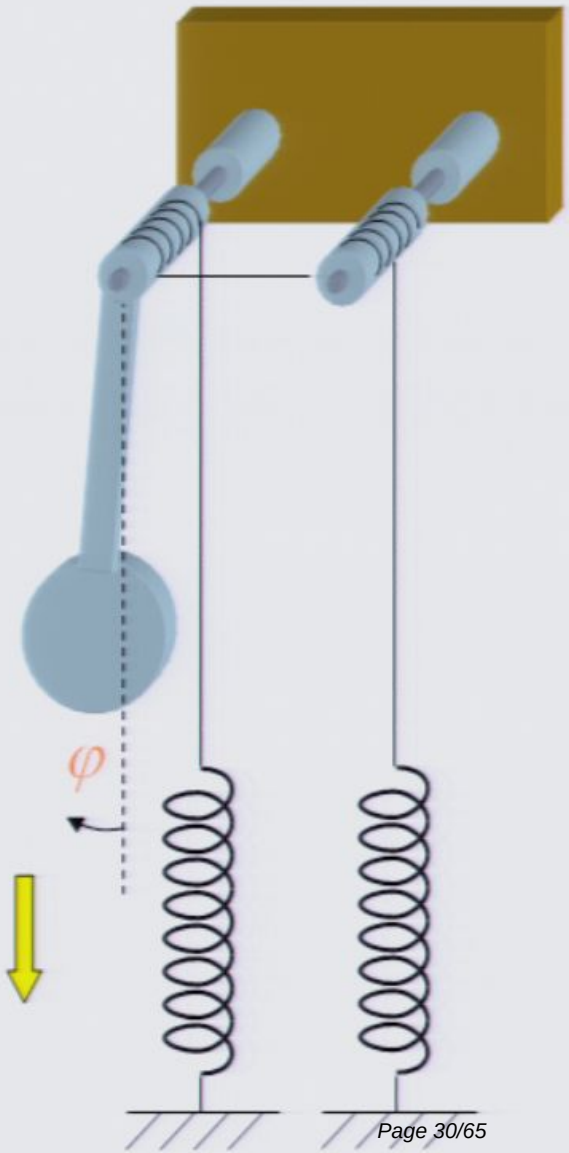
C_J ⇔ pendulum mass

Φ_{ext} ⇔ support position

0 TURNS GROUND STATE

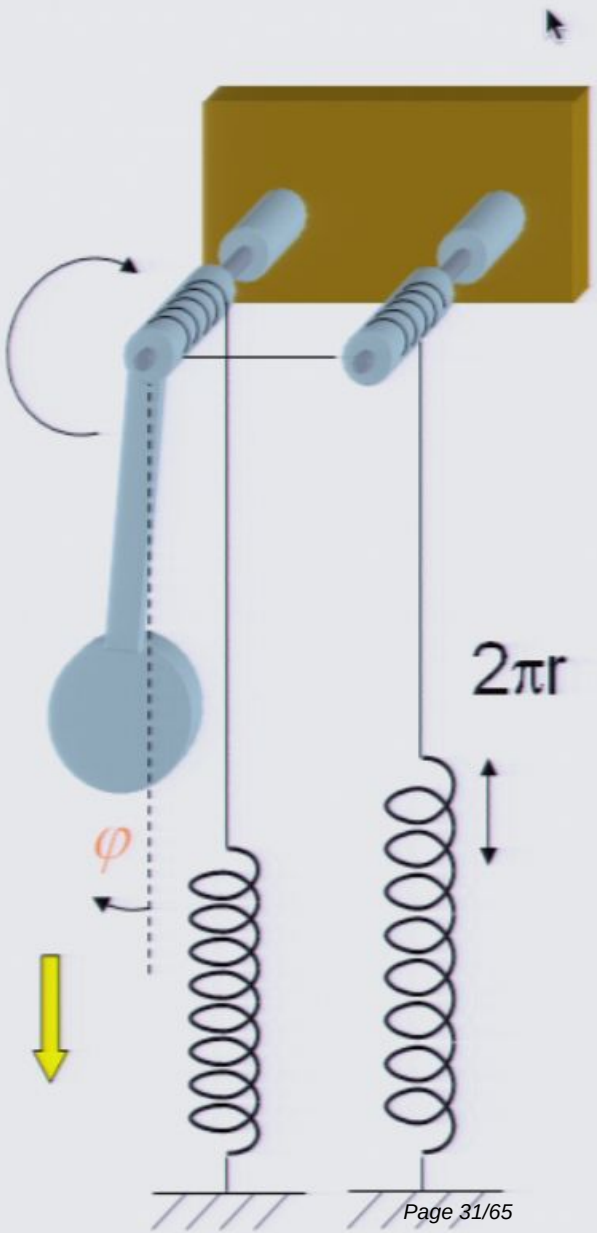
Ground state:
no tension in the springs,
pendulum pointing down

$$E_0=0$$



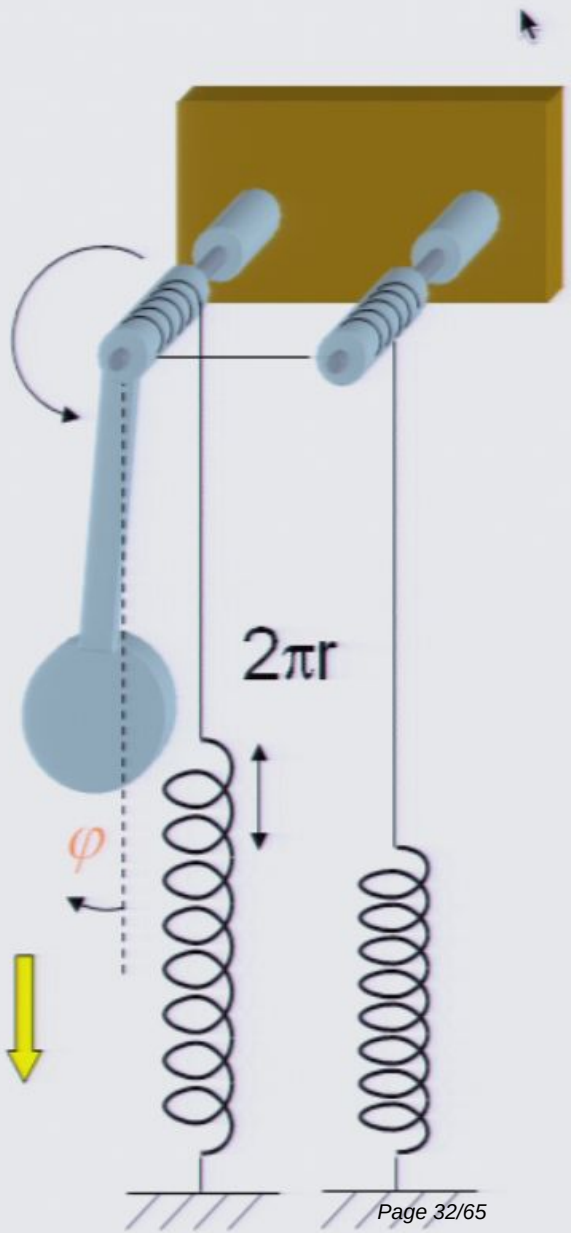
+1 TURN STATE

$$E_{+1} = (2\pi)^2 \, kr^2/2$$

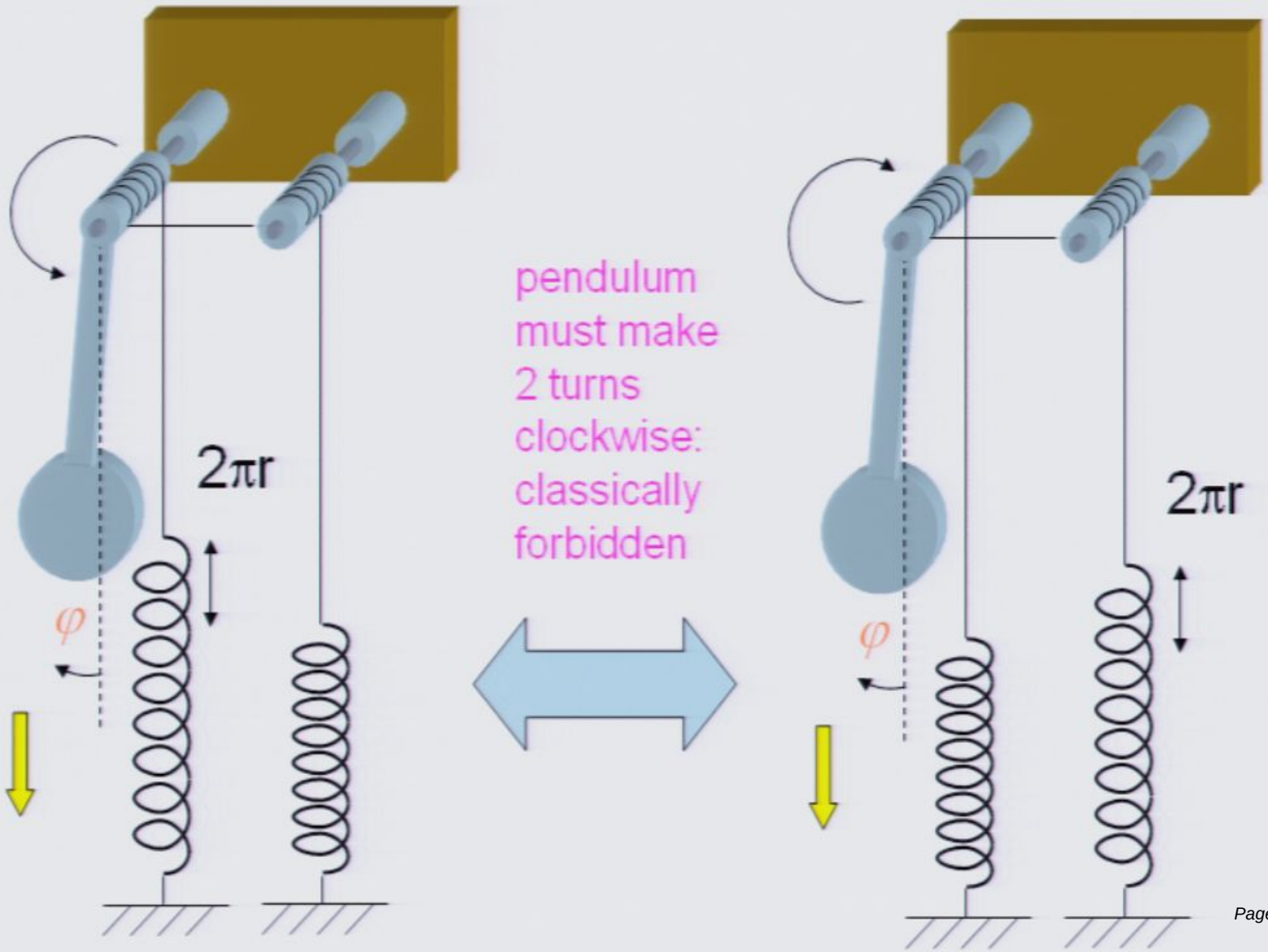


-1 TURN STATE

$$E_{-1} = (-2\pi)^2\, kr^2/2 = E_{+1}$$



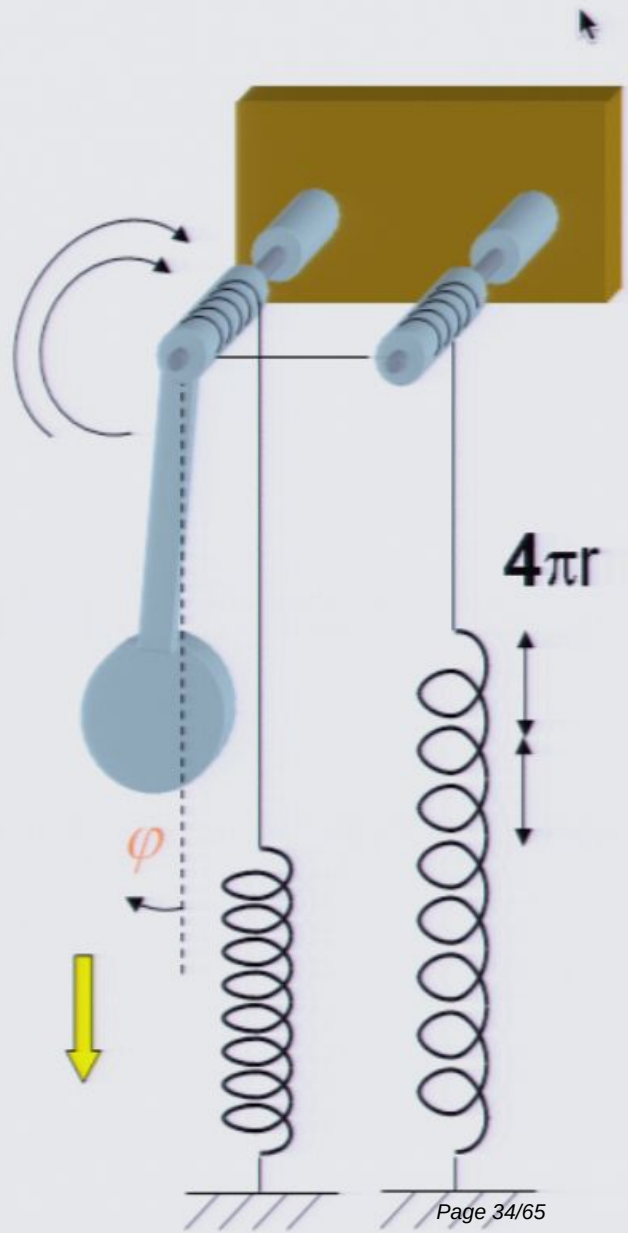
QUANTUM MECHANICAL TUNNELING BETWEEN +1 AND -1 TURN STATES?

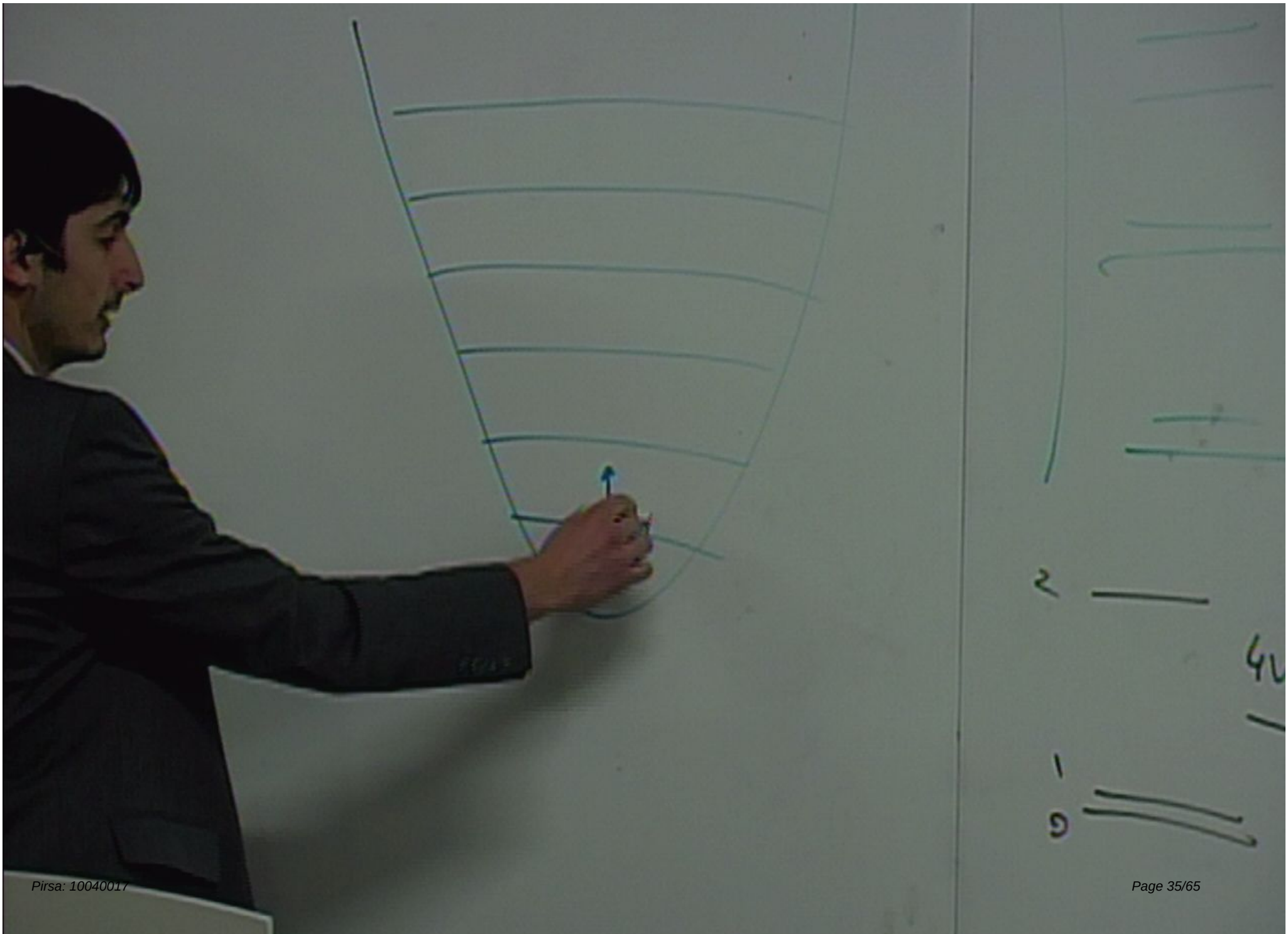


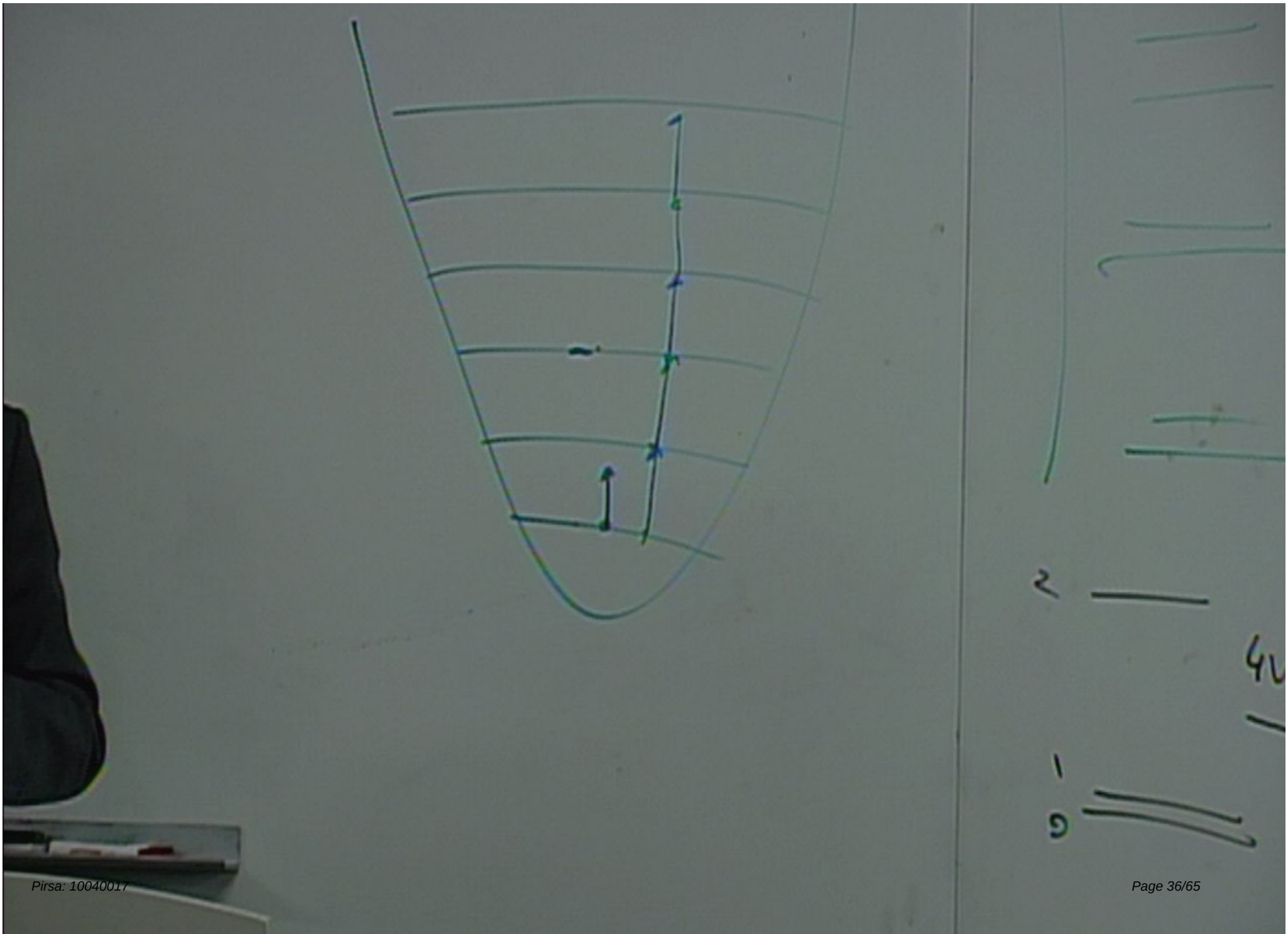
+2 TURN STATE

$$E_{+/-2} = (4\pi)^2\ kr^2/2 = 4E_{+/-1}$$

$$E_{+/-n} = n^2 E_{+/-1}$$ anharmonic!






2
1
0

+2 TURN STATE

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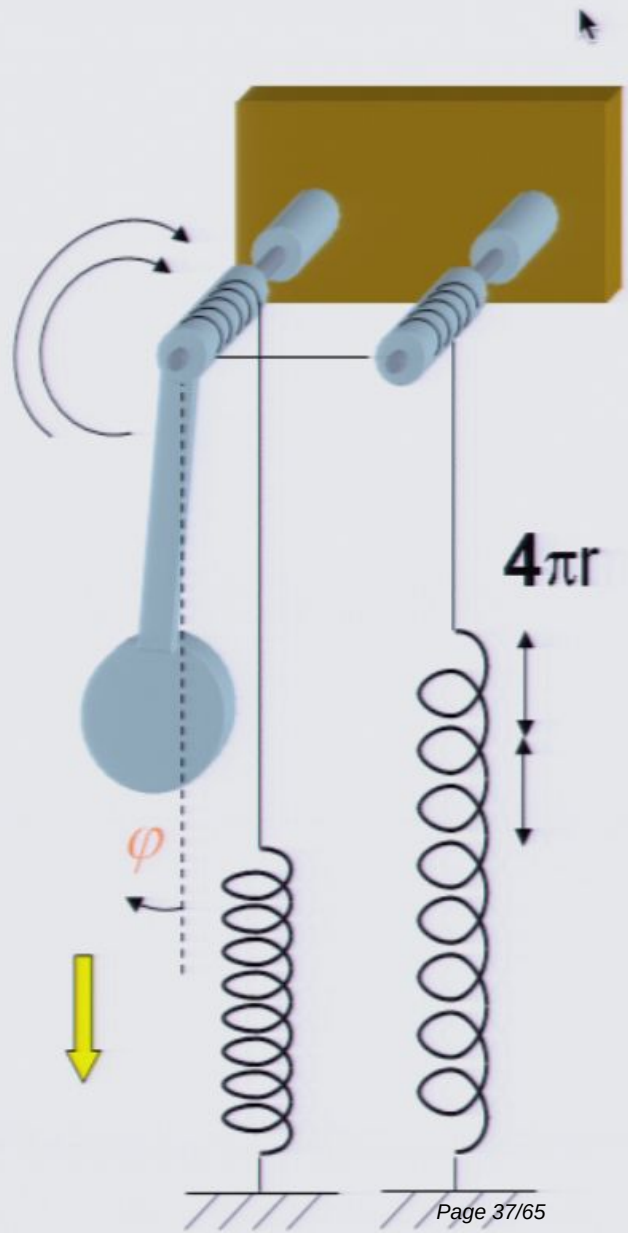
$$E_n = n^2 E_1$$ anharmonic!



N.B. when $n > n_{max} \sim E_J/E_L$ the spring is so stretched that it does not allow more turns.

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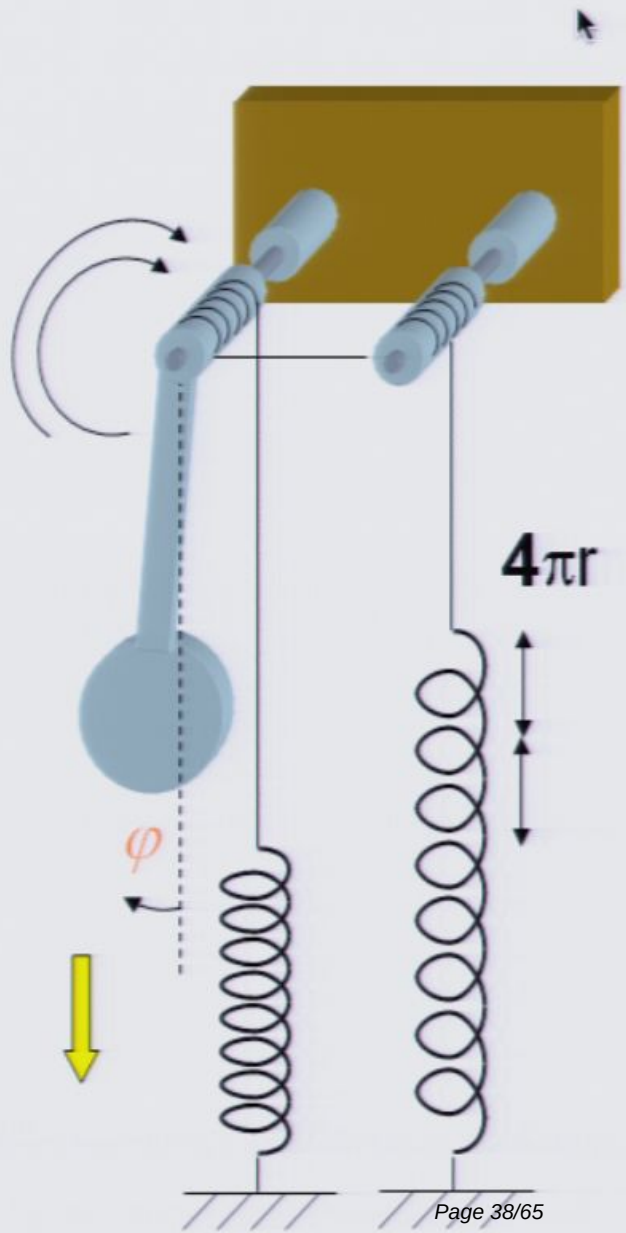
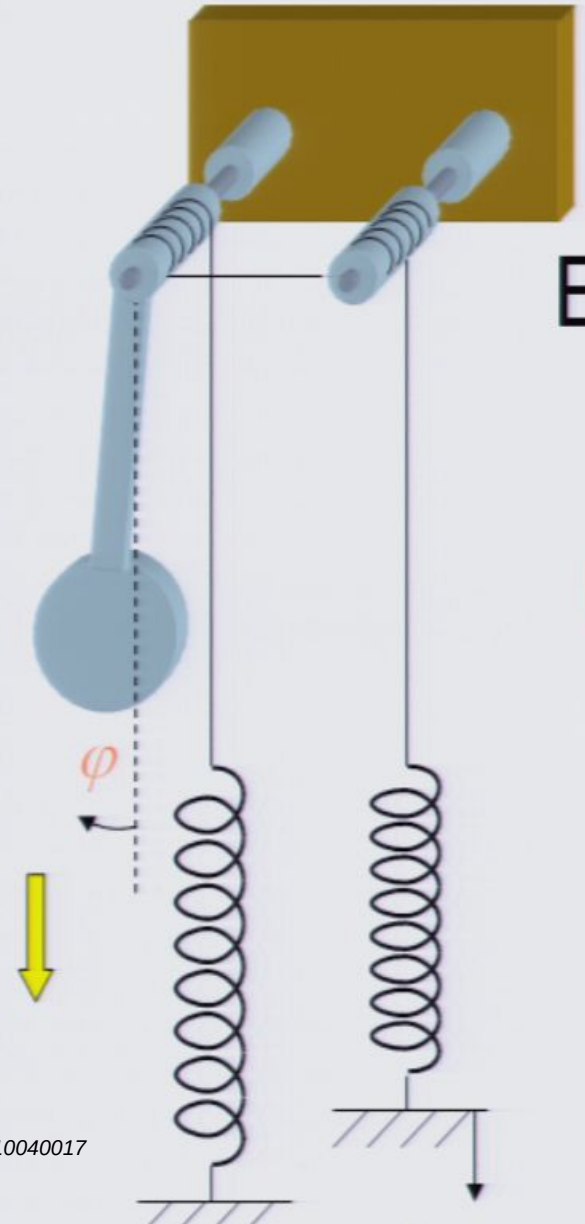
$$E_{+/-2} = (4\pi)^2\ kr^2/2 = 4E_{+/-1}$$

$$E_n = n^2 E_1 \quad \text{anharmonic!}$$



N.B. when $n > n_{max} \sim E_J/E_L$ the spring is so stretched that it does not allow more turns.

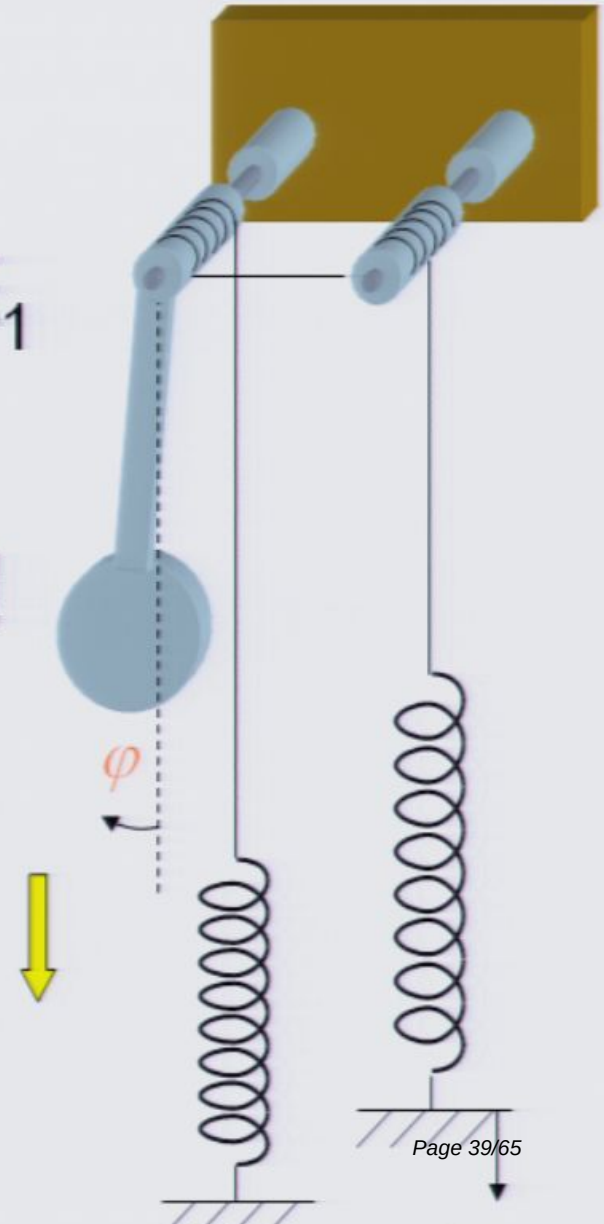
QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?



$$E_n = (n - \delta x/2\pi r)^2 E_1$$

$$\delta x = pr \Leftrightarrow$$

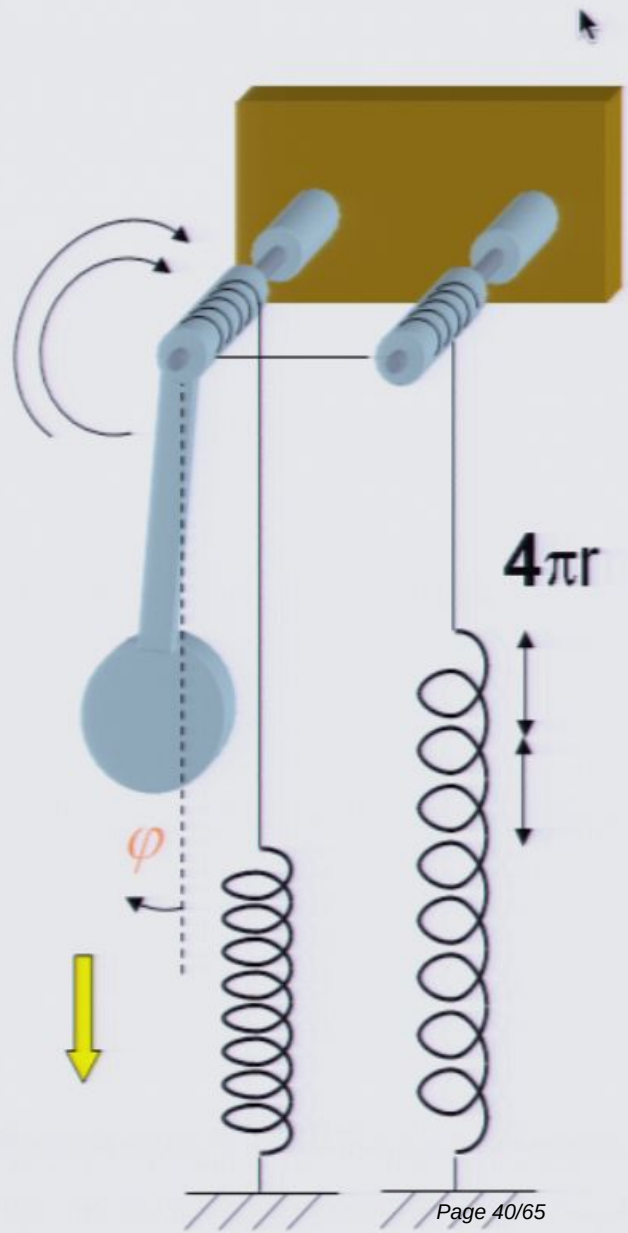
$$E_n(\delta x) = E_{n+1}(\delta x)!$$



+2 TURN STATE

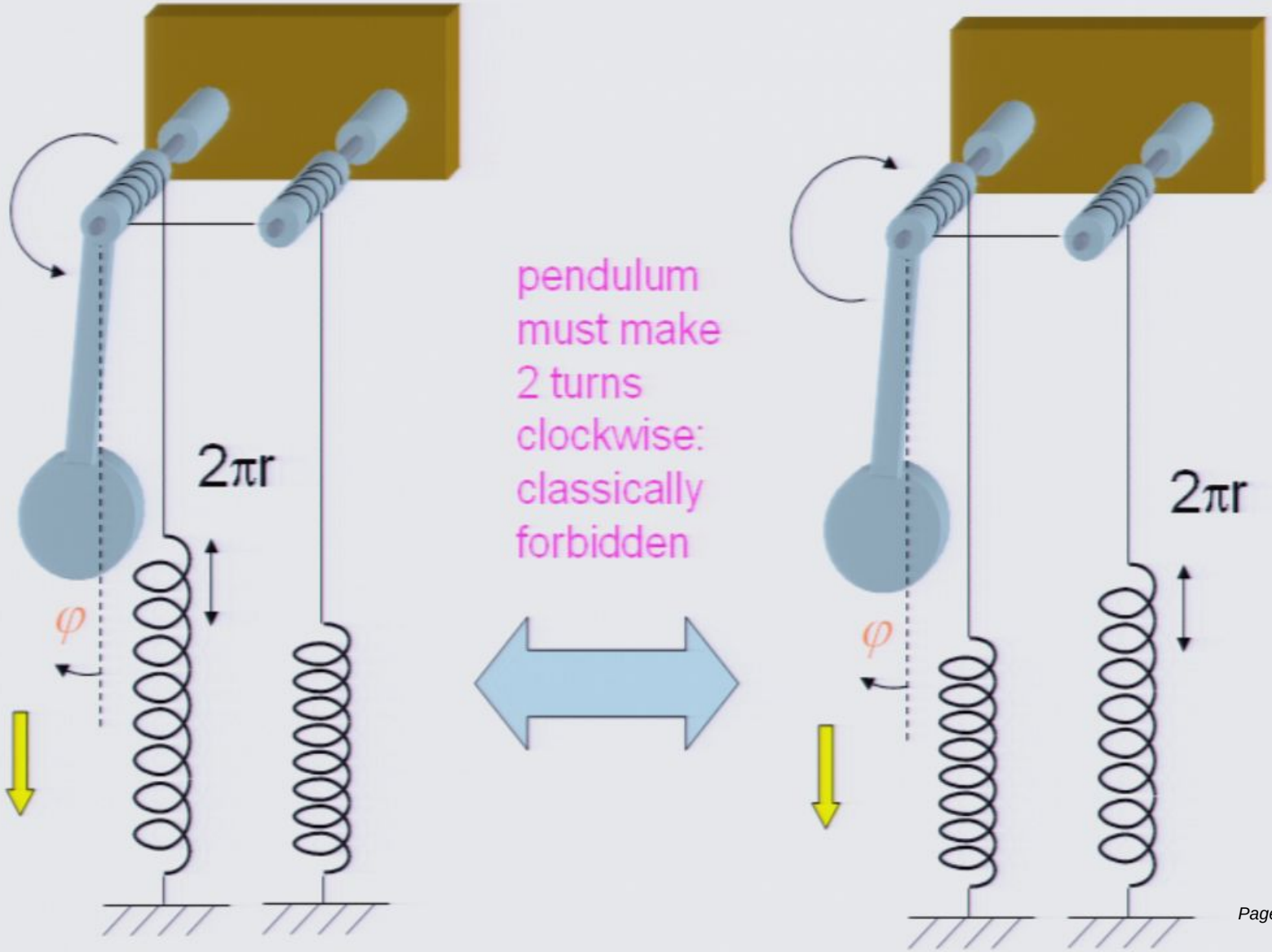
$$E_{+/-2} = (4\pi)^2\ kr^2/2 = 4E_{+/-1}$$

$$E_n = n^2 E_1 \quad \text{anharmonic!}$$

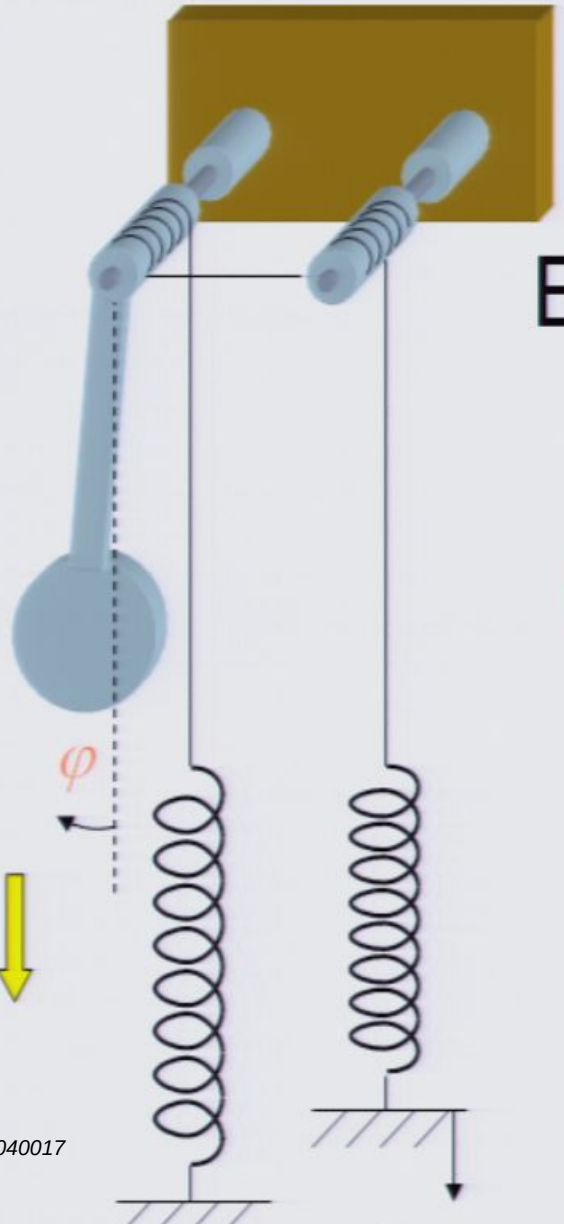


N.B. when $n > n_{max} \sim E_J/E_L$ the spring is so stretched that it does not allow more turns.

QUANTUM MECHANICAL TUNNELING BETWEEN +1 AND -1 TURN STATES?



QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?



$$E_n = (n - \delta x/2\pi r)^2 E_1$$

$$\delta x = pr \Leftrightarrow$$

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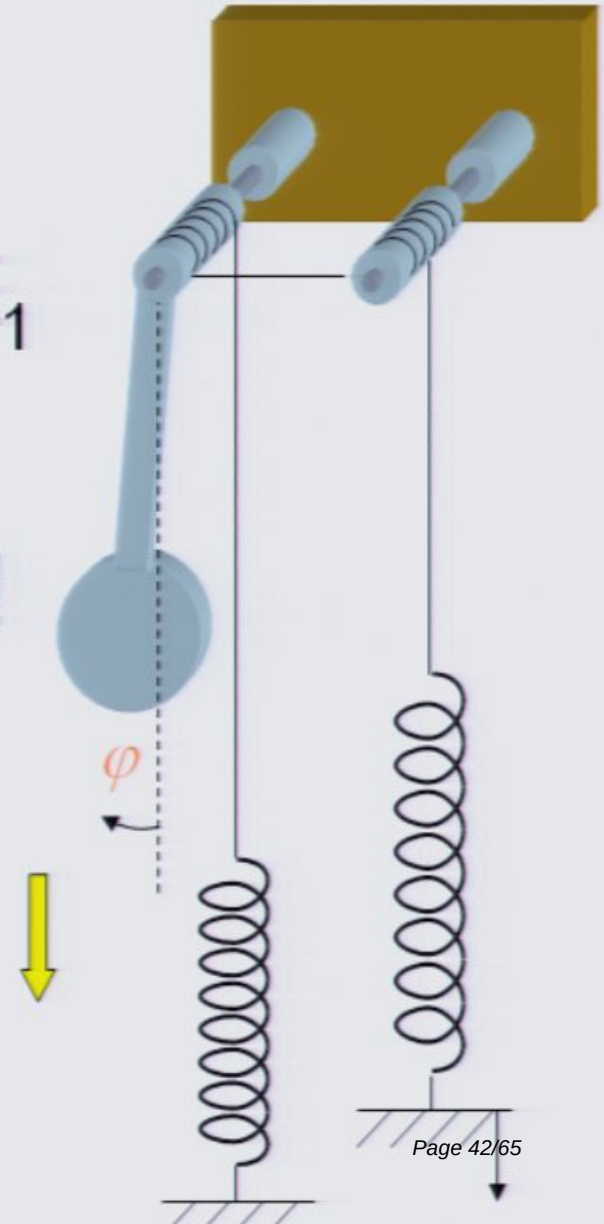
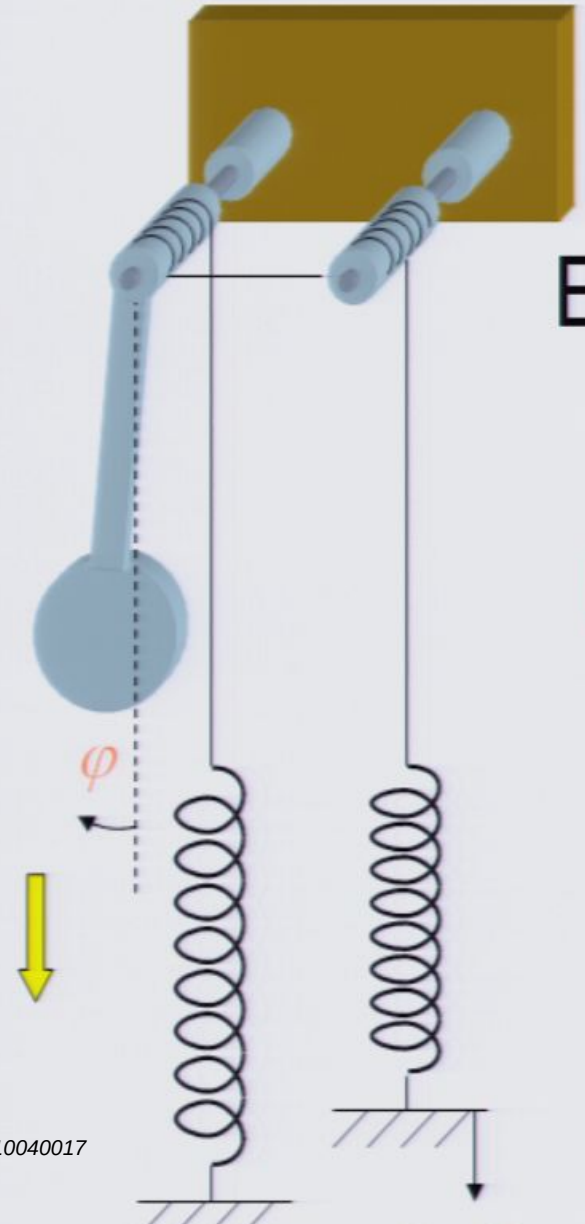


QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?

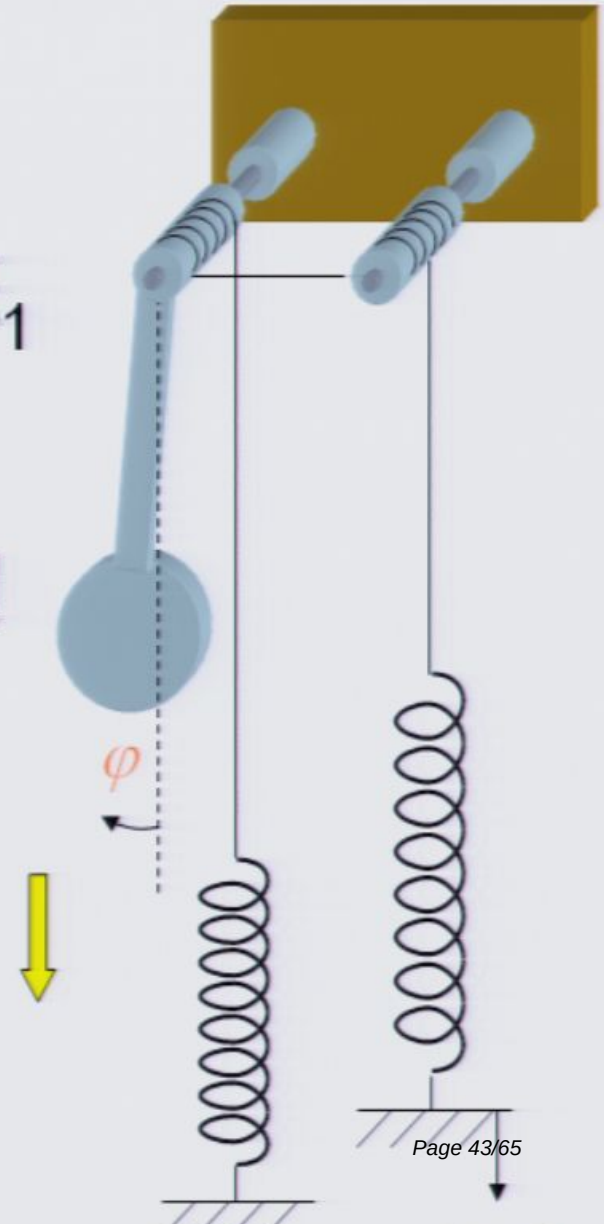


$$E_n = (n - \delta x/2\pi r)^2 E_1$$

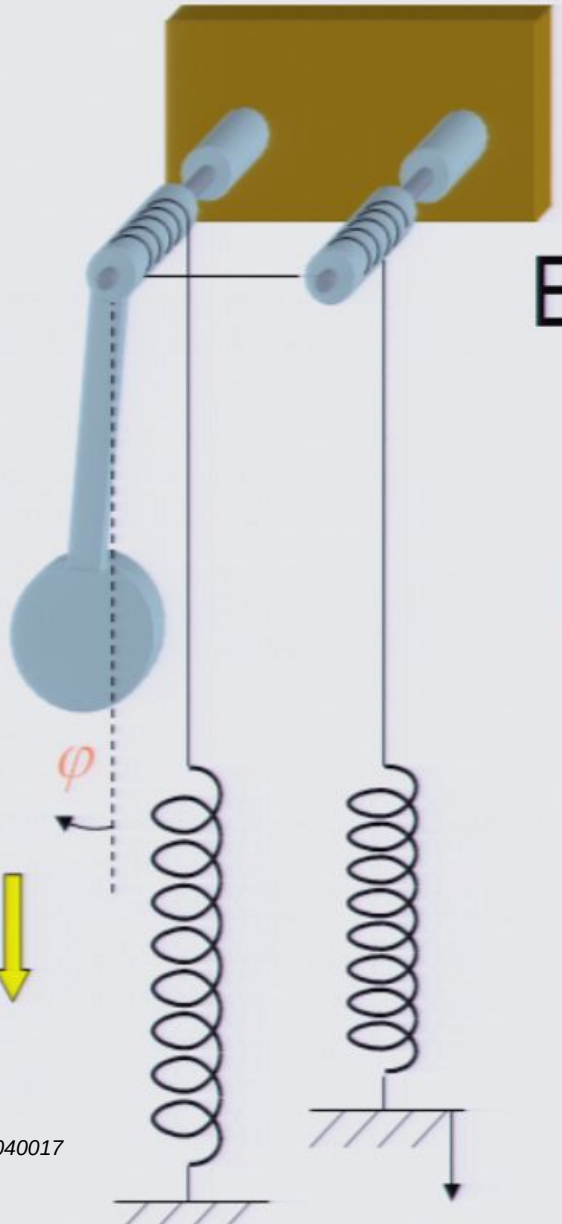
$$\delta x = pr \Leftrightarrow$$

$$E_n(\delta x) = E_{n+1}(\delta x)!$$

now pendulum must make only 1 classically forbidden turn



FLUXON^{IUM} STATES: SIGNATURE ZIG-ZAG BETWEEN 0 AND 1 TURN STATES?



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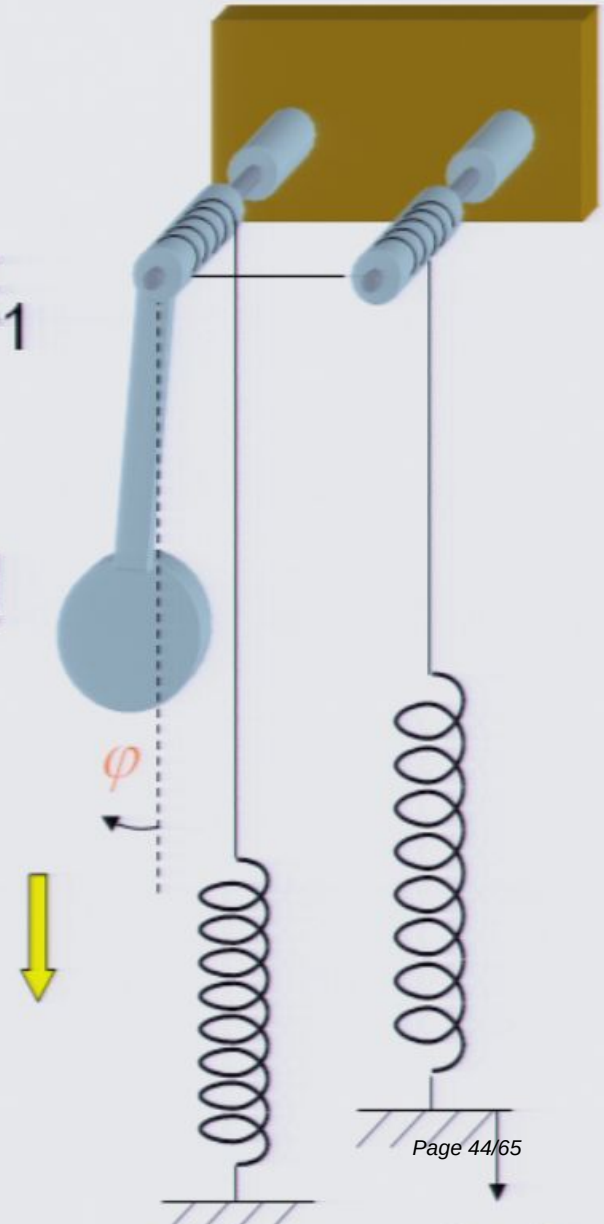
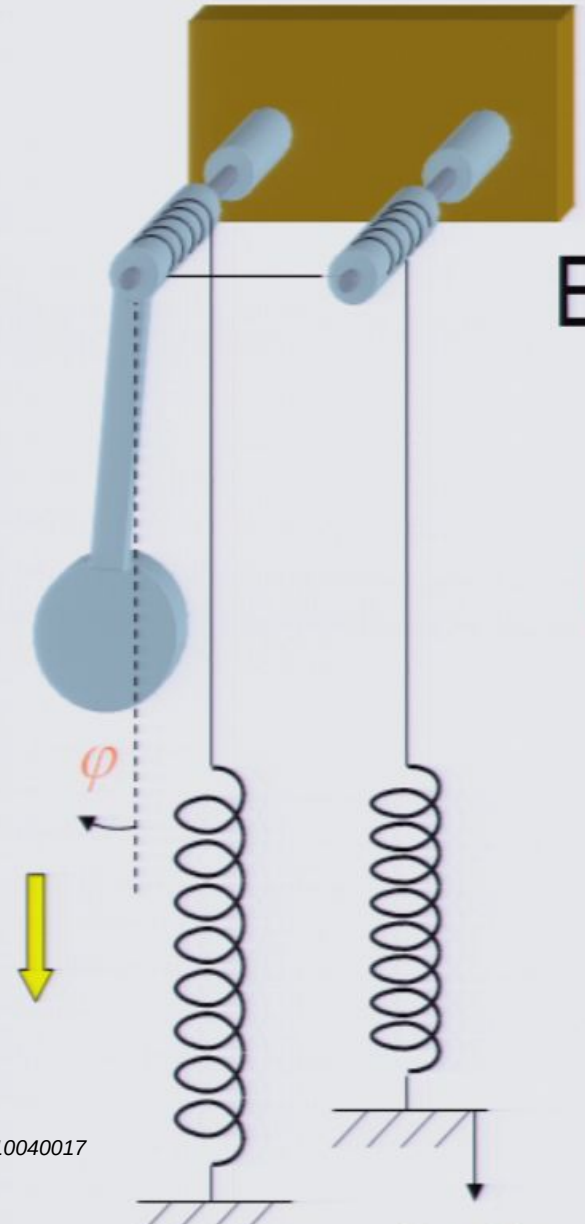


QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?



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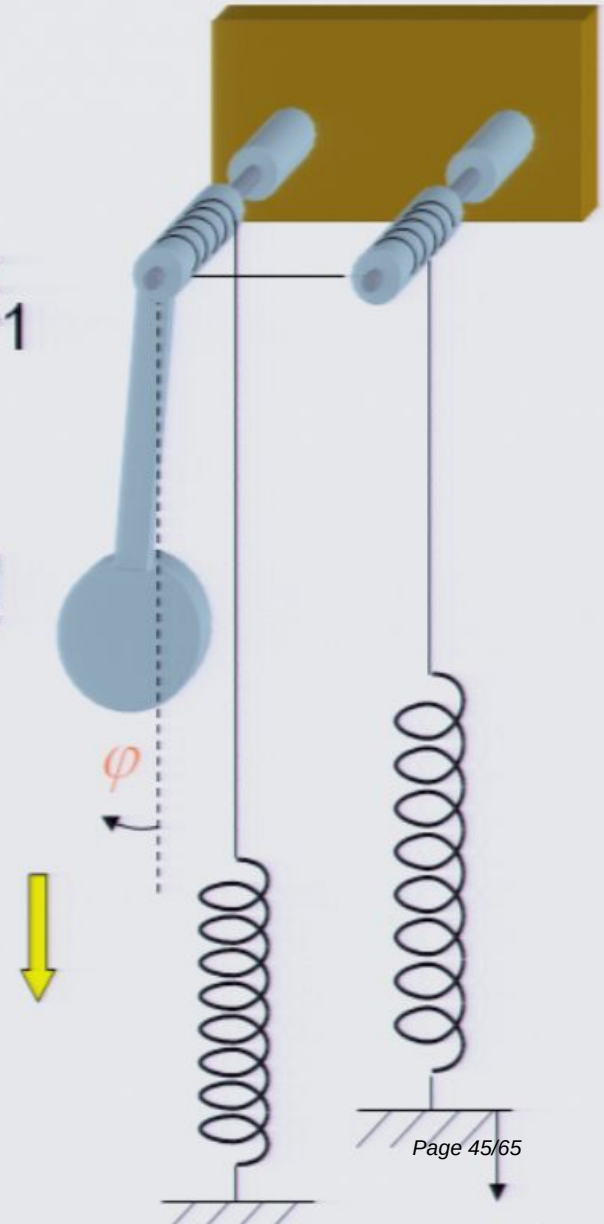
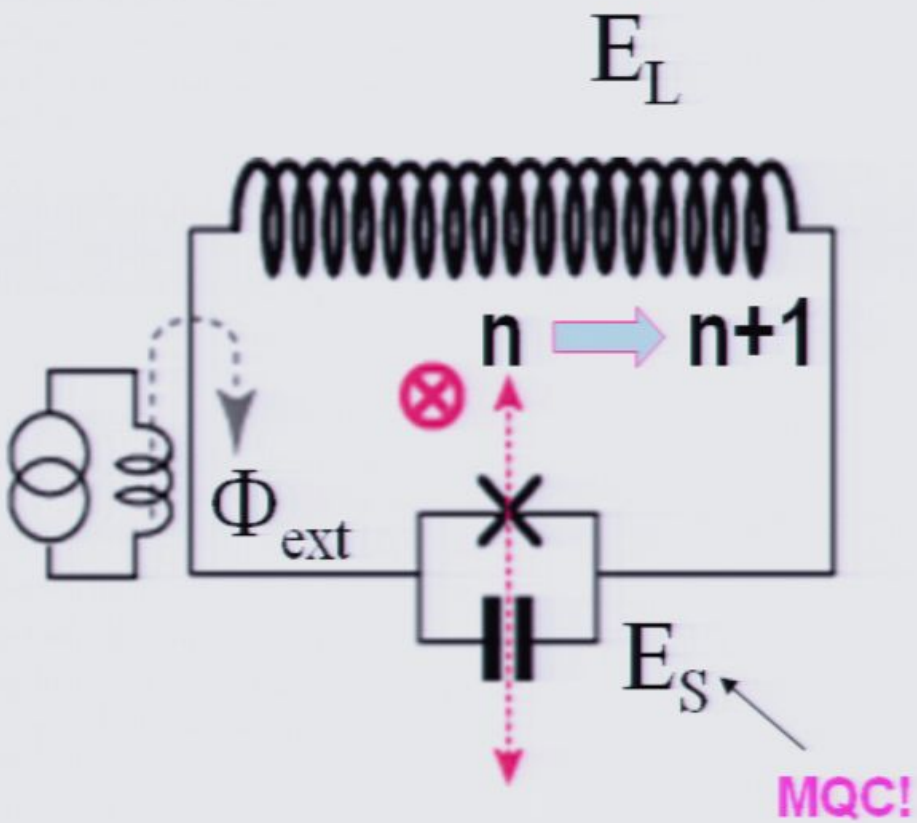
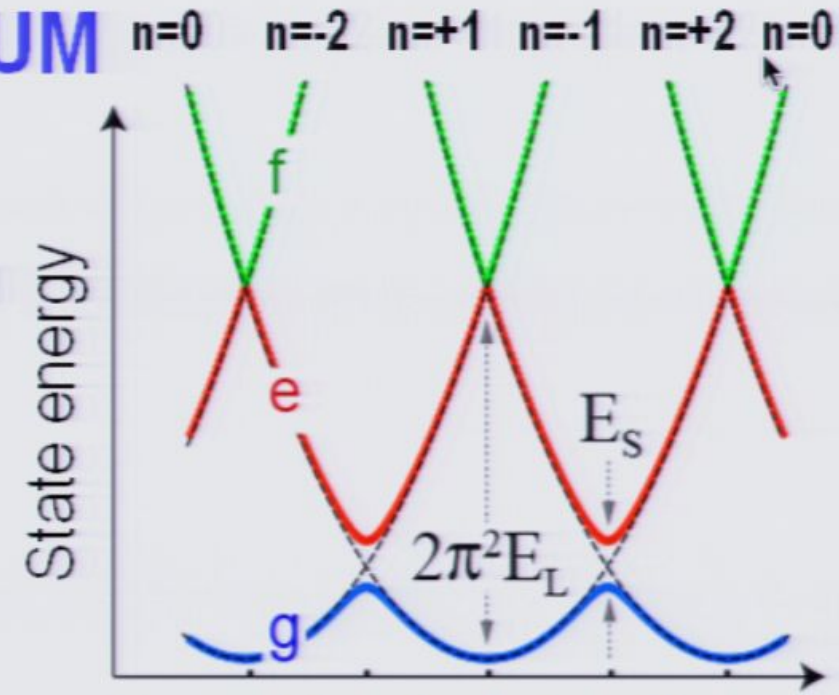
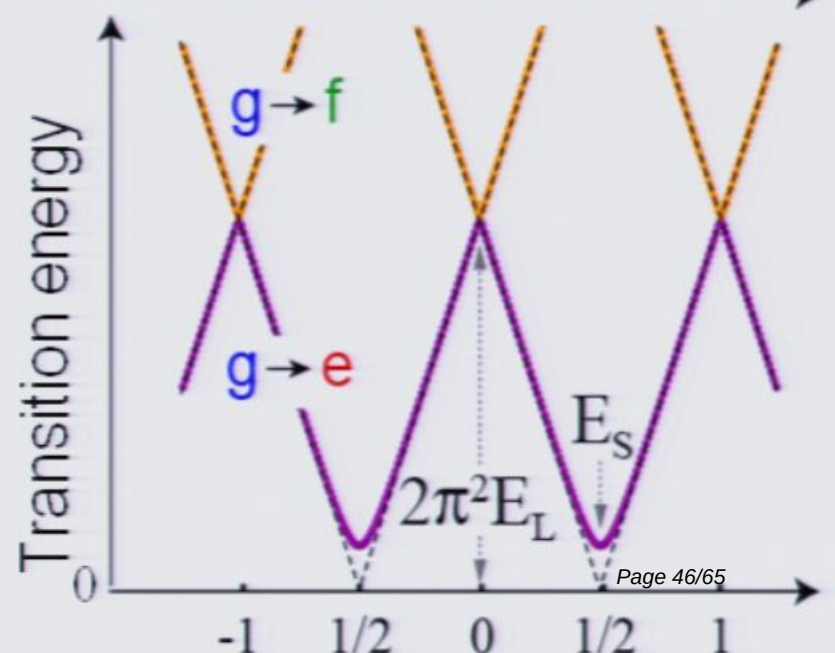


FLUXON[IUM] STATES: SIGNATURE ZIG-ZAG SPECTRUM

n: # of flux quanta in the *loop*
equivalent to # turns of a pendulum

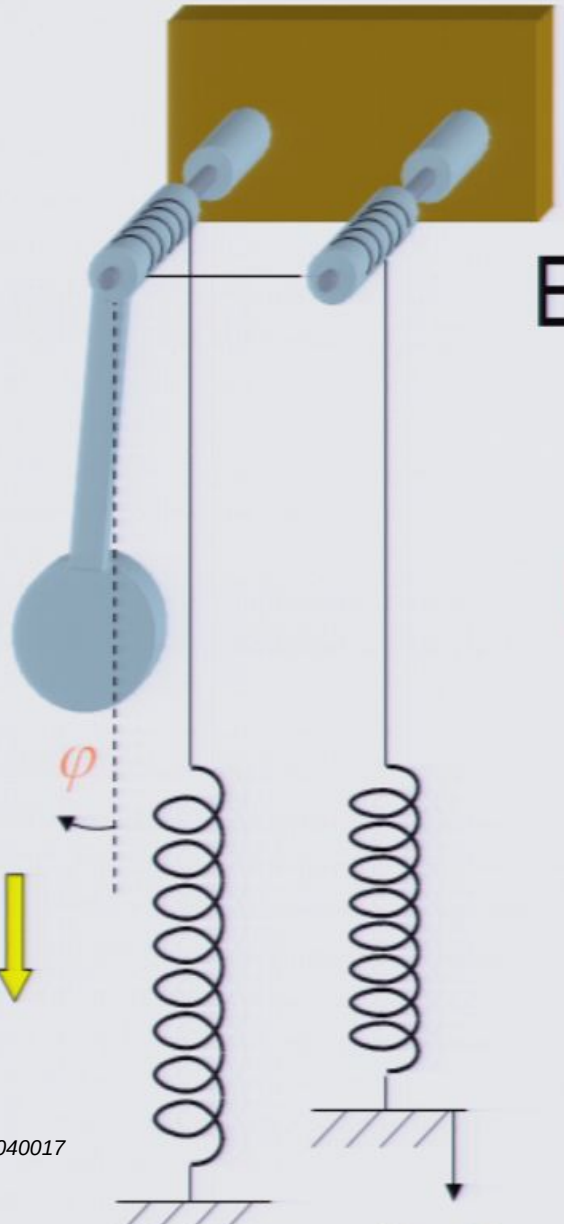






$E_n = (n - \delta x/2\pi r)^2$

QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?



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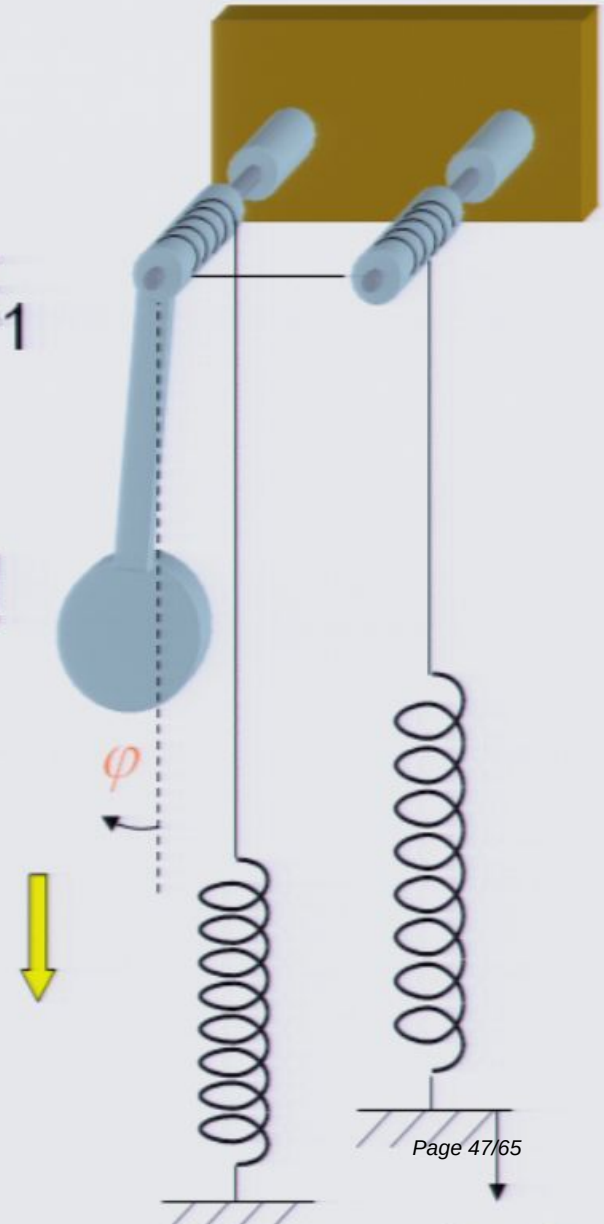
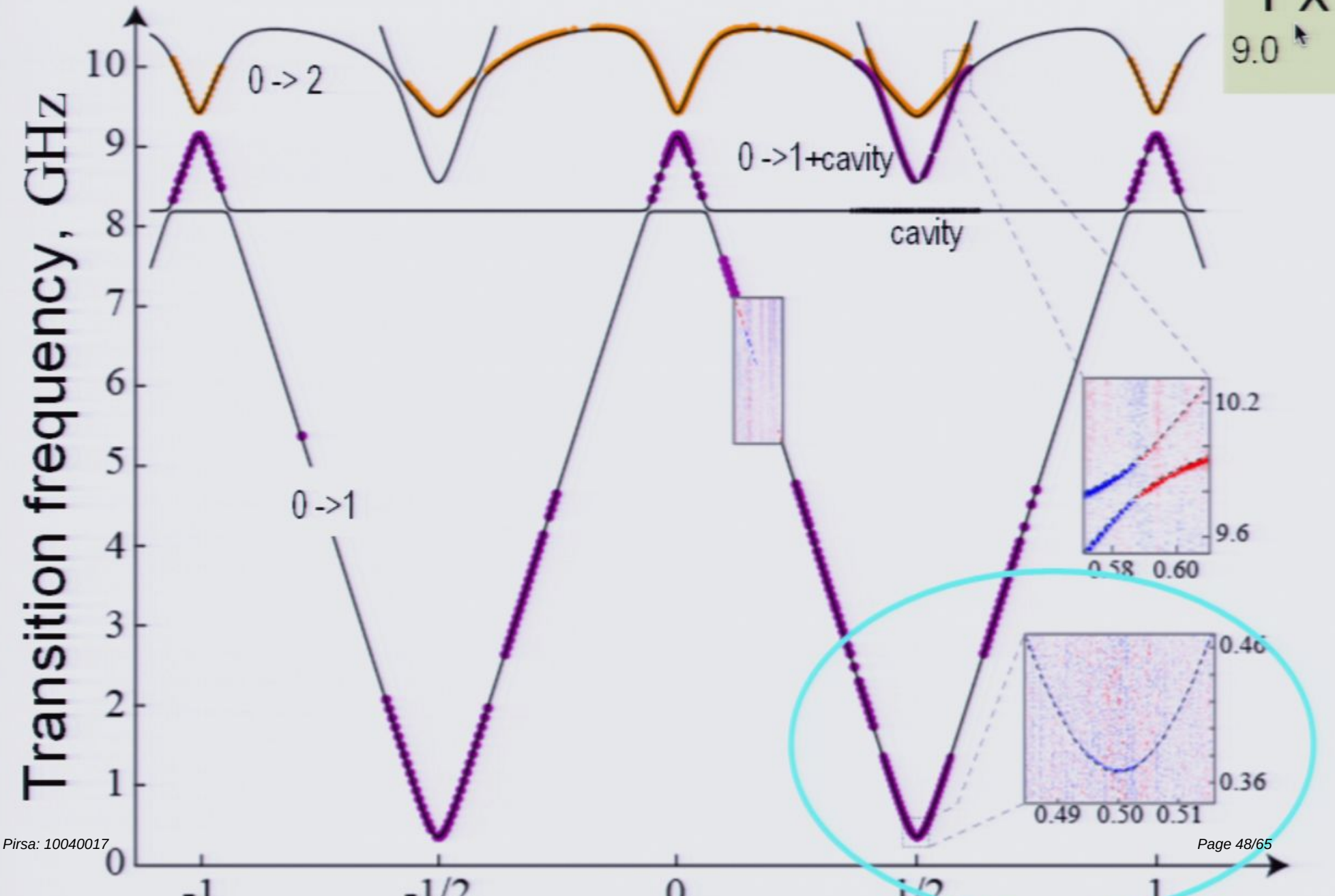
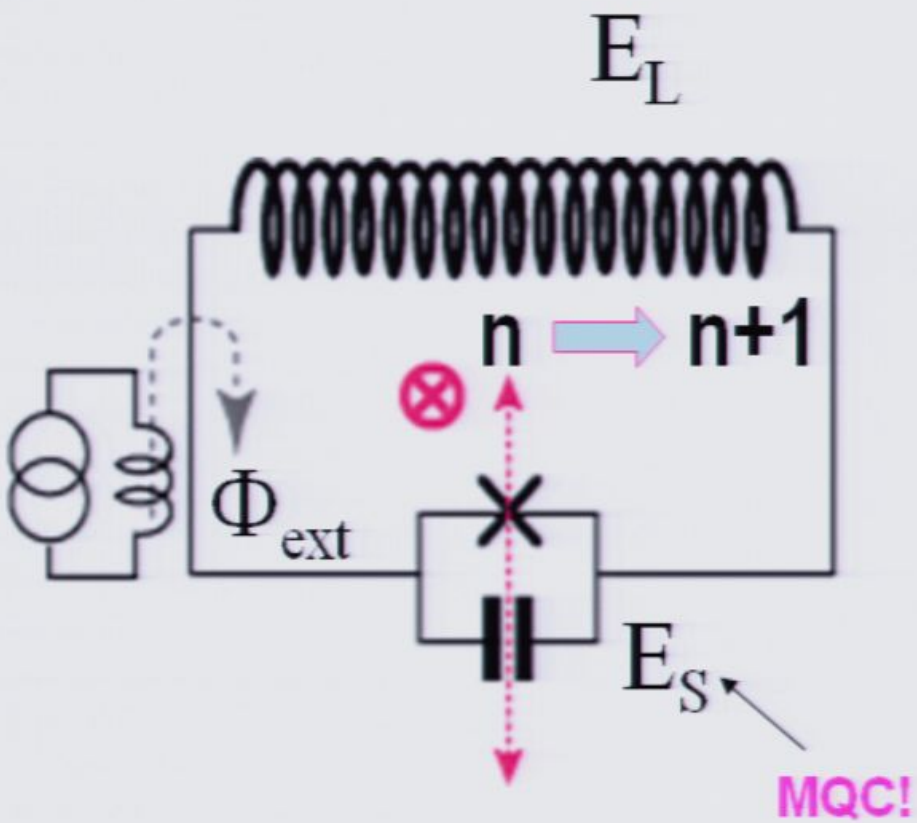


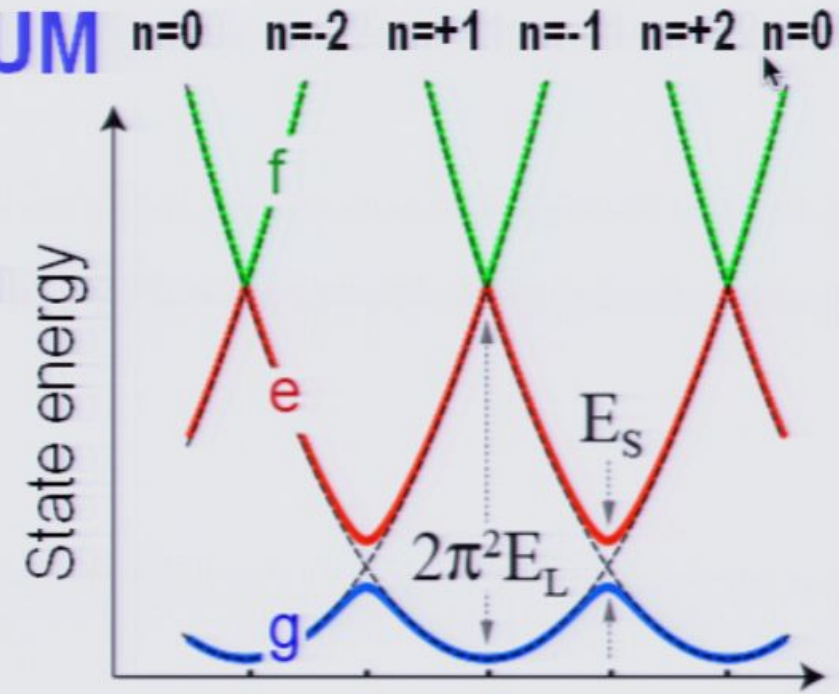
DEJA VU

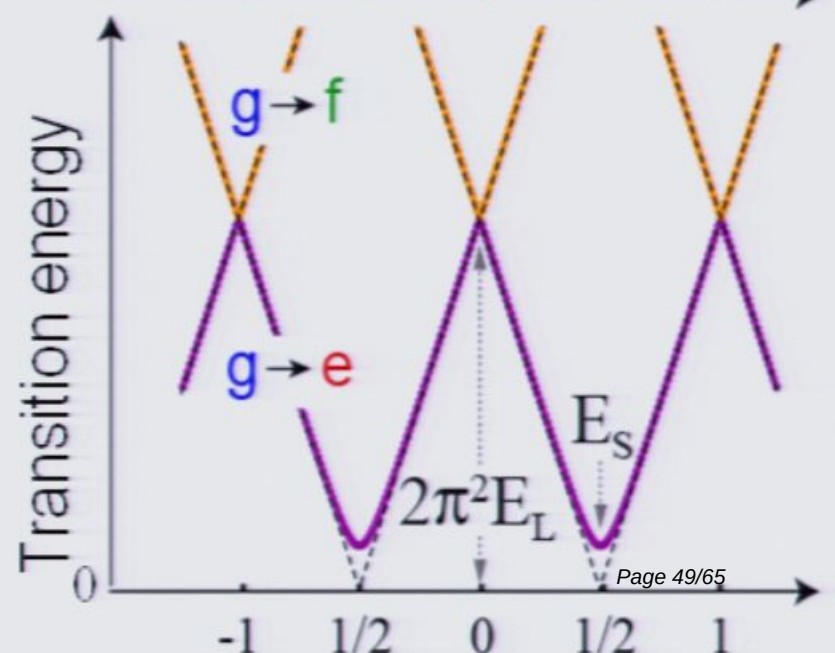

0.5 2.5
Fx
9.0
Transition frequency, GHz
0 -> 2
0 ->1+cavity
cavity
0 ->1
10.2
9.6
0.58 0.60
0.46
0.36
0.49 0.50 0.51
0
1
2
3
4
5
6
7
8
9
10
-1
-1/2
0
1/2
1

FLUXON[IUM] STATES: SIGNATURE ZIG-ZAG SPECTRUM

n: # of flux quanta in the *loop*
equivalent to # turns of a pendulum







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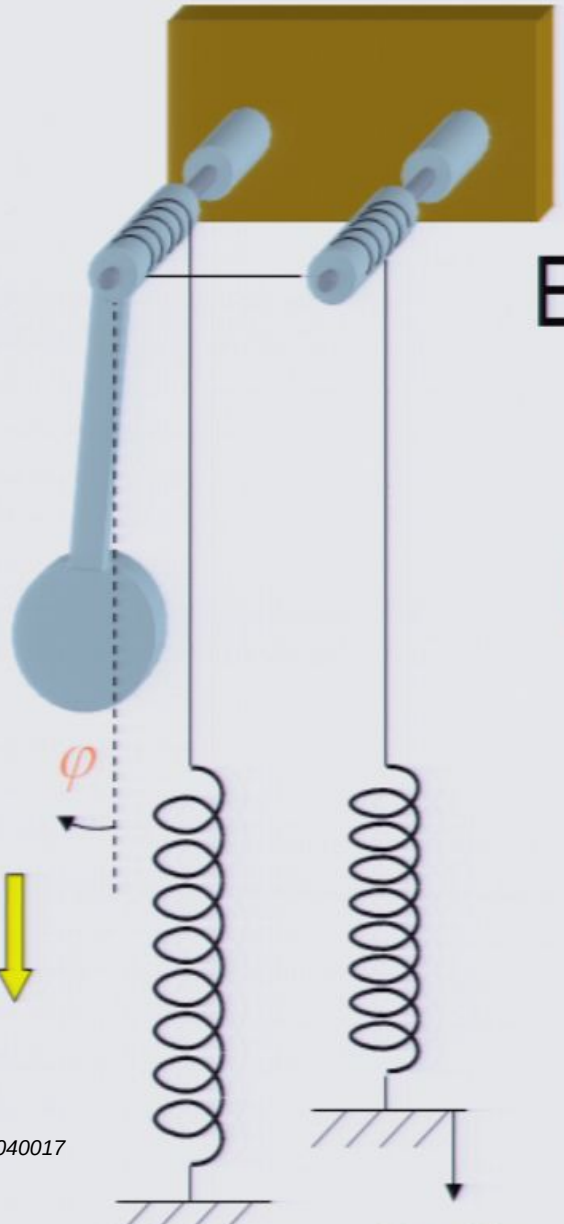
QUANTUM MECHANICAL TUNNELING BETWEEN 0 AND 1 TURN STATES?



$$E_n = (n - \delta x/2\pi r)^2 E_1$$

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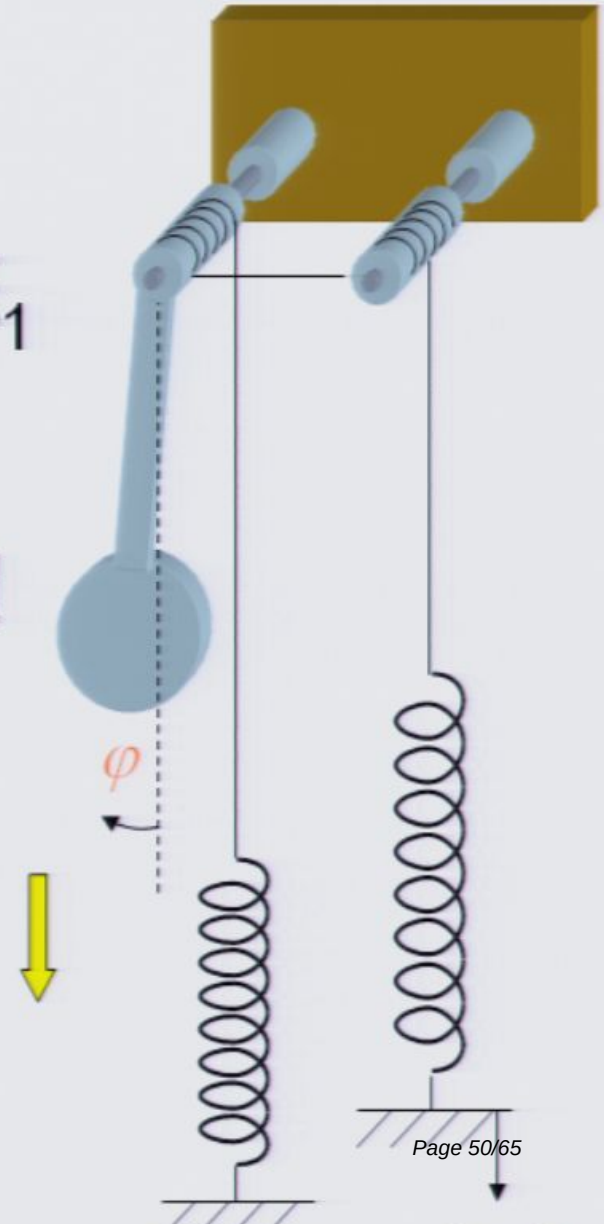
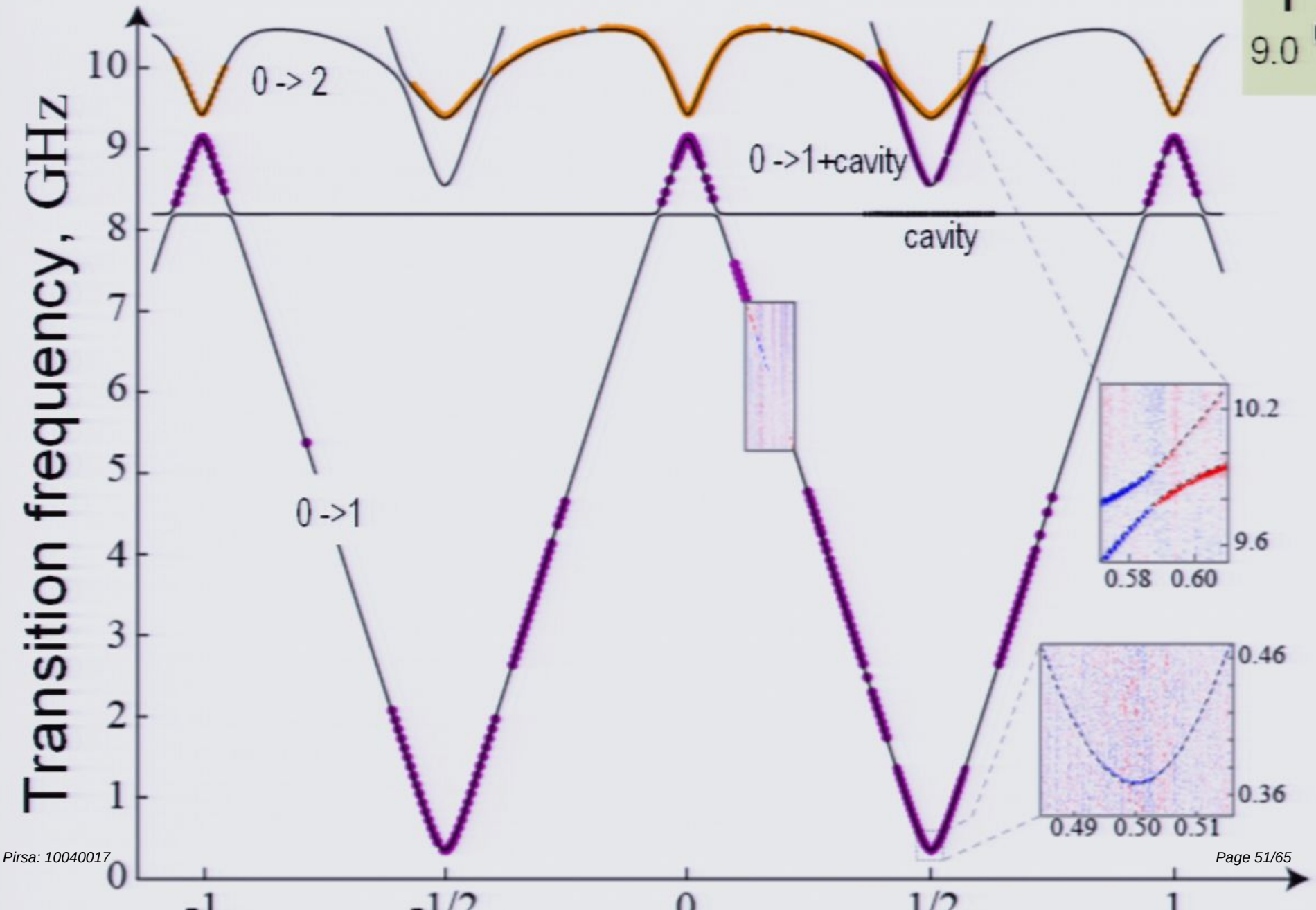


DEJA VU


0.5 2.5
Fx
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Transition frequency, GHz
0 -> 2
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cavity
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0.49 0.50 0.51
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FLUXON[IUM] STATES: SIGNATURE ZIG-ZAG SPECTRUM

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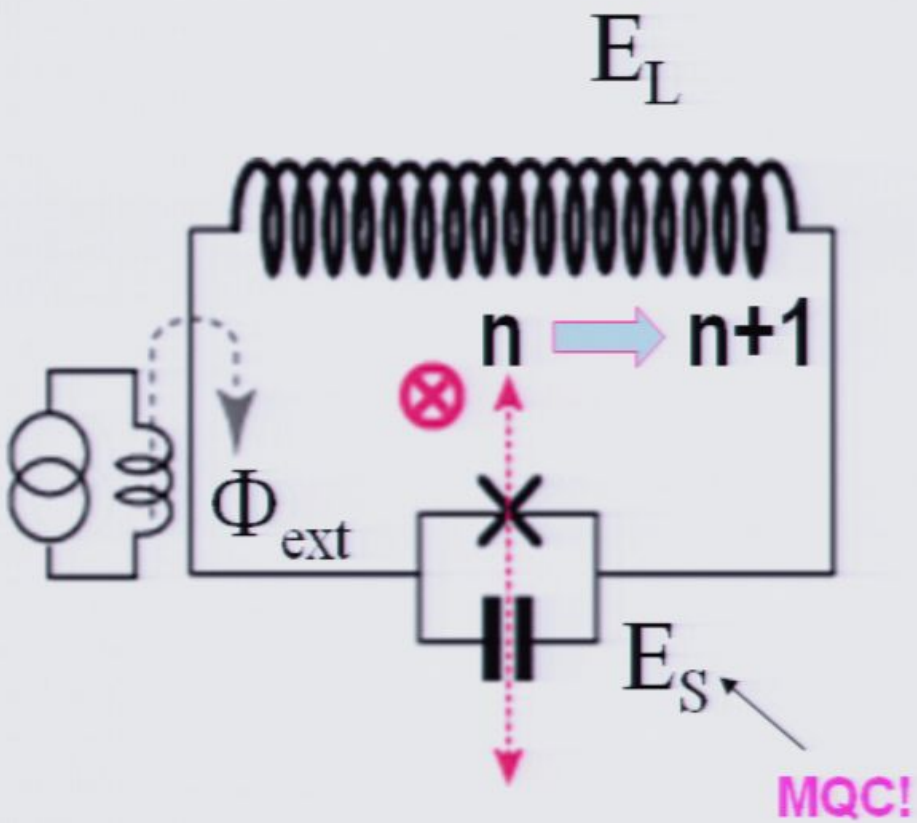
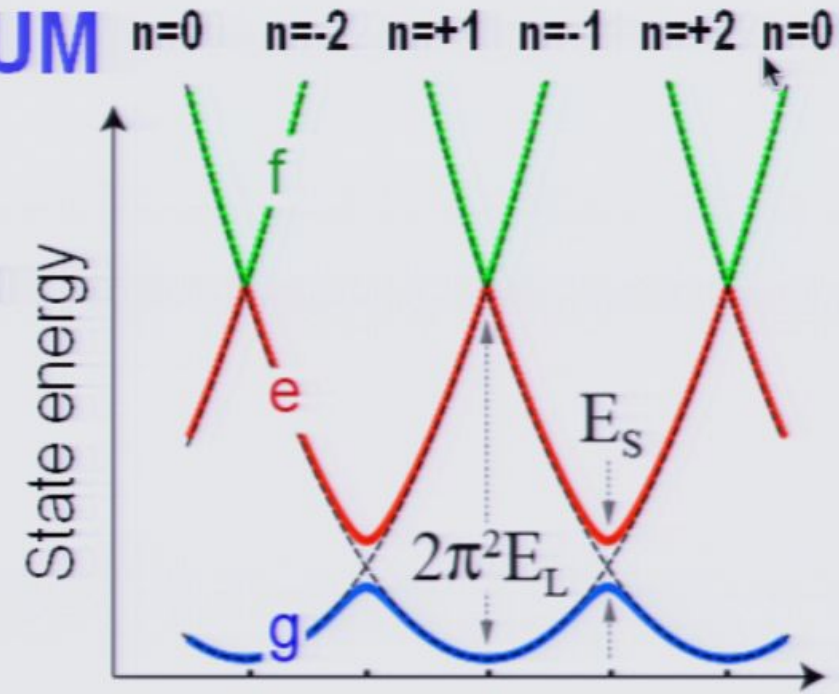
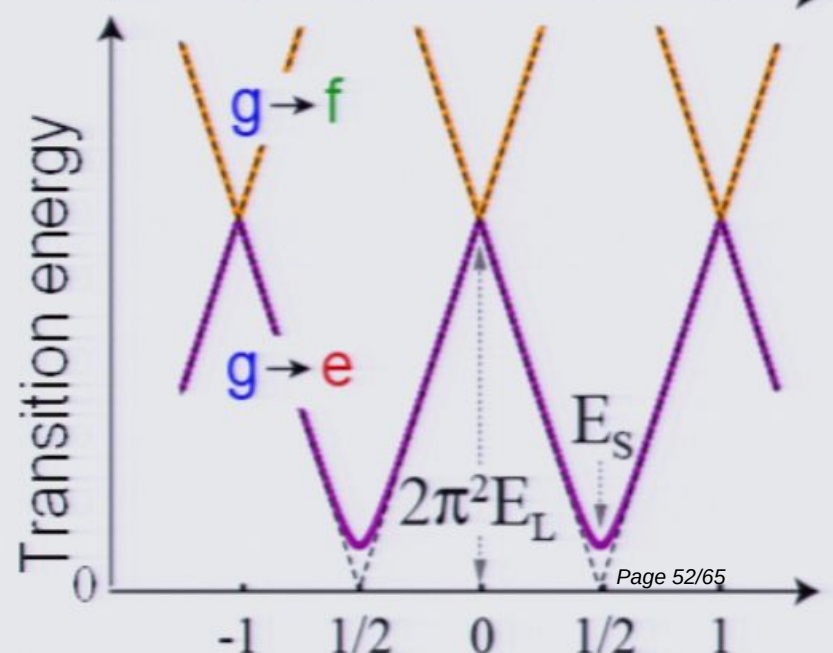
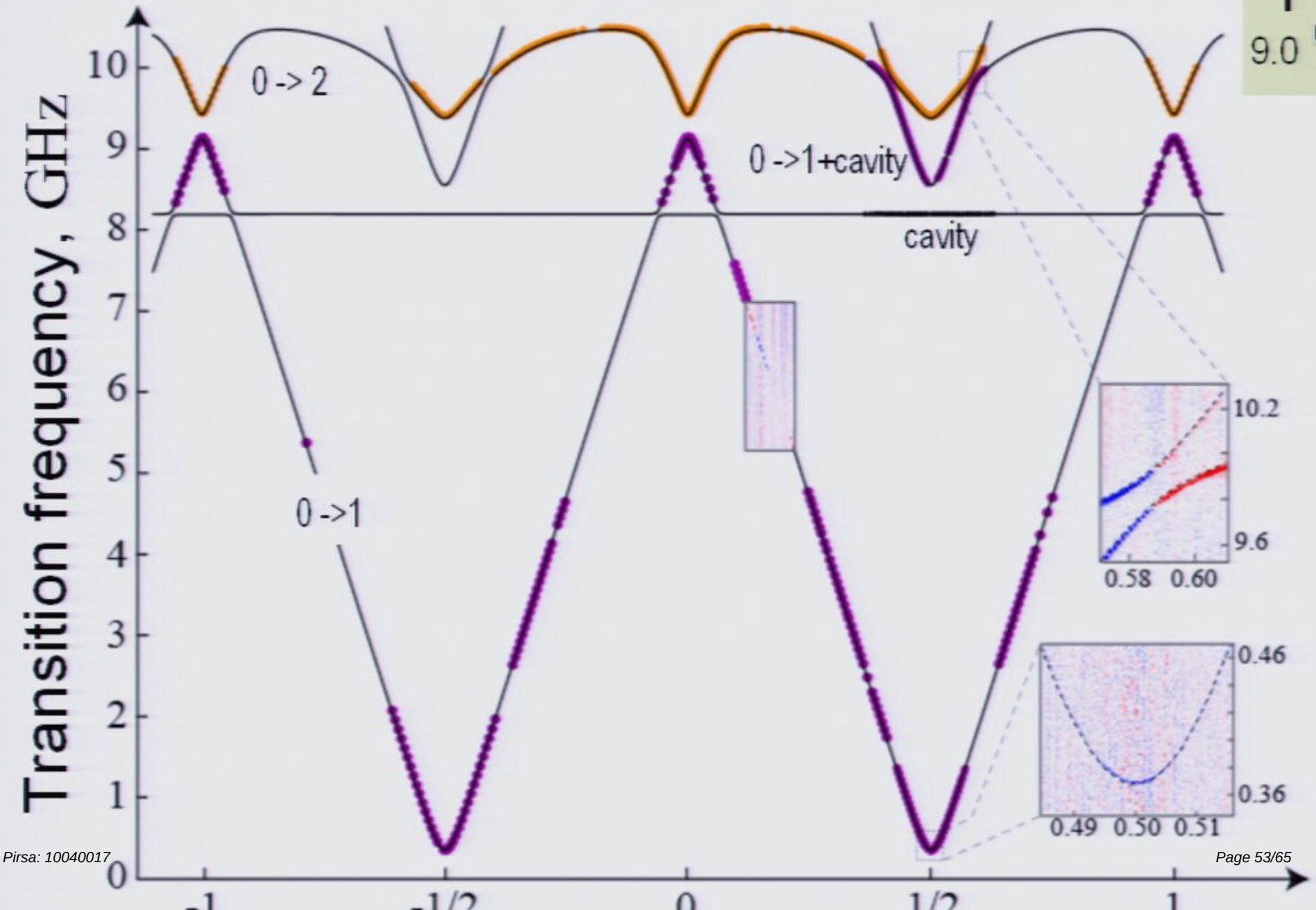






$E_n = (n - \delta x/2\pi r)^2$

DEJA VU


0.5 2.5
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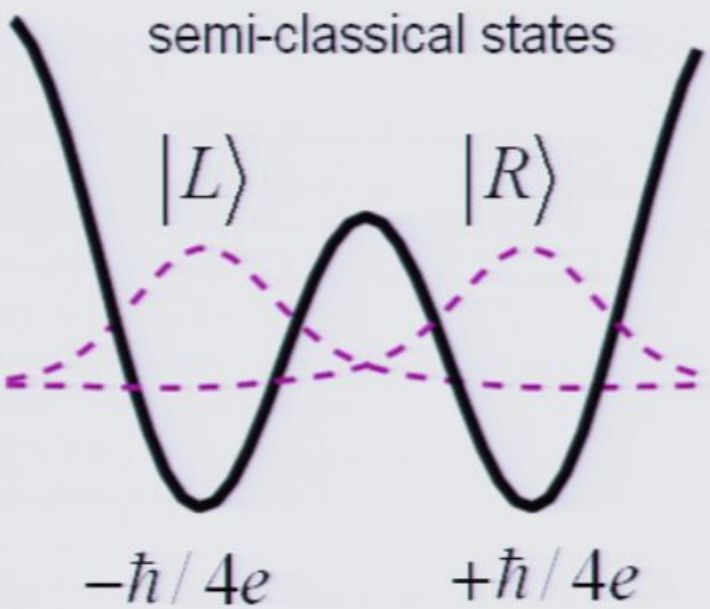
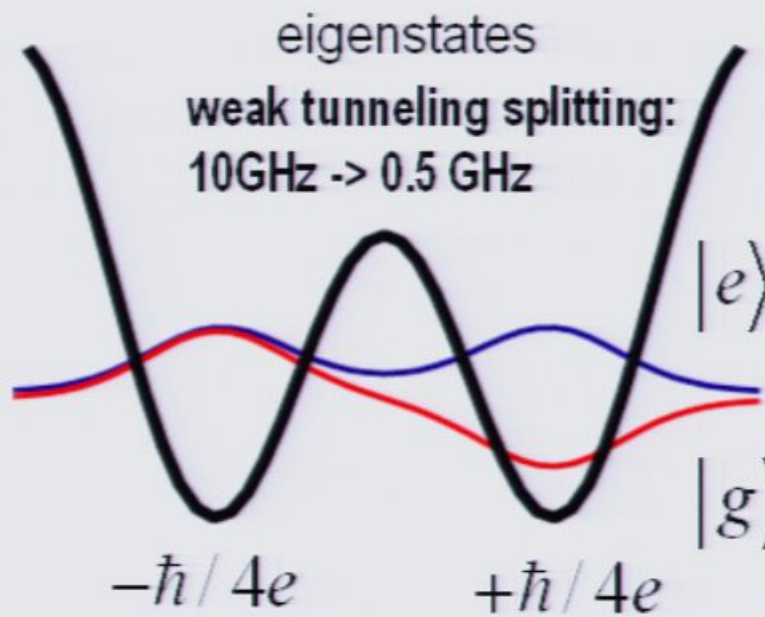
0.36
0.49 0.50 0.51
-1
-1/2
0
1/2
1

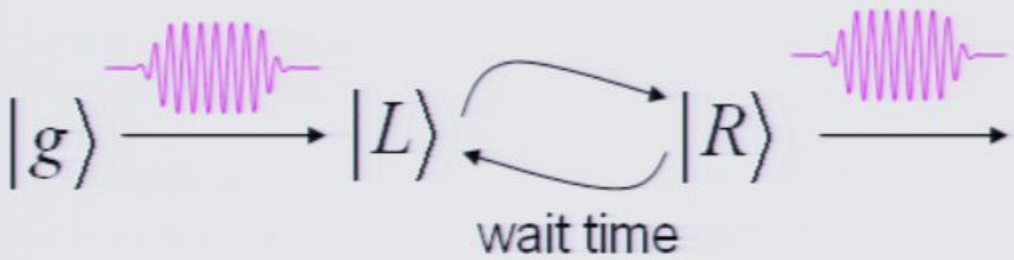
REVERSIBLE TUNNELING OF A SINGLE FLUXON



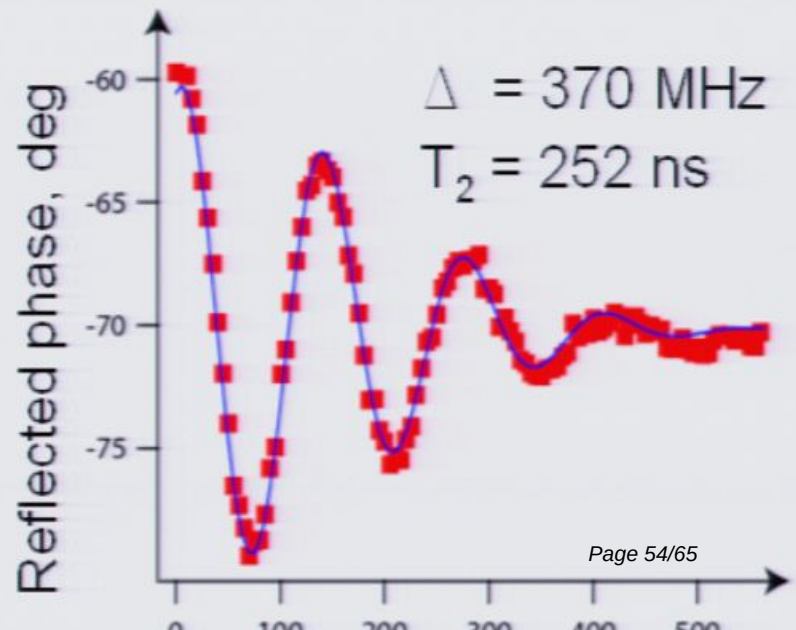


$$|e\rangle = \frac{|L\rangle - |R\rangle}{\sqrt{2}}$$

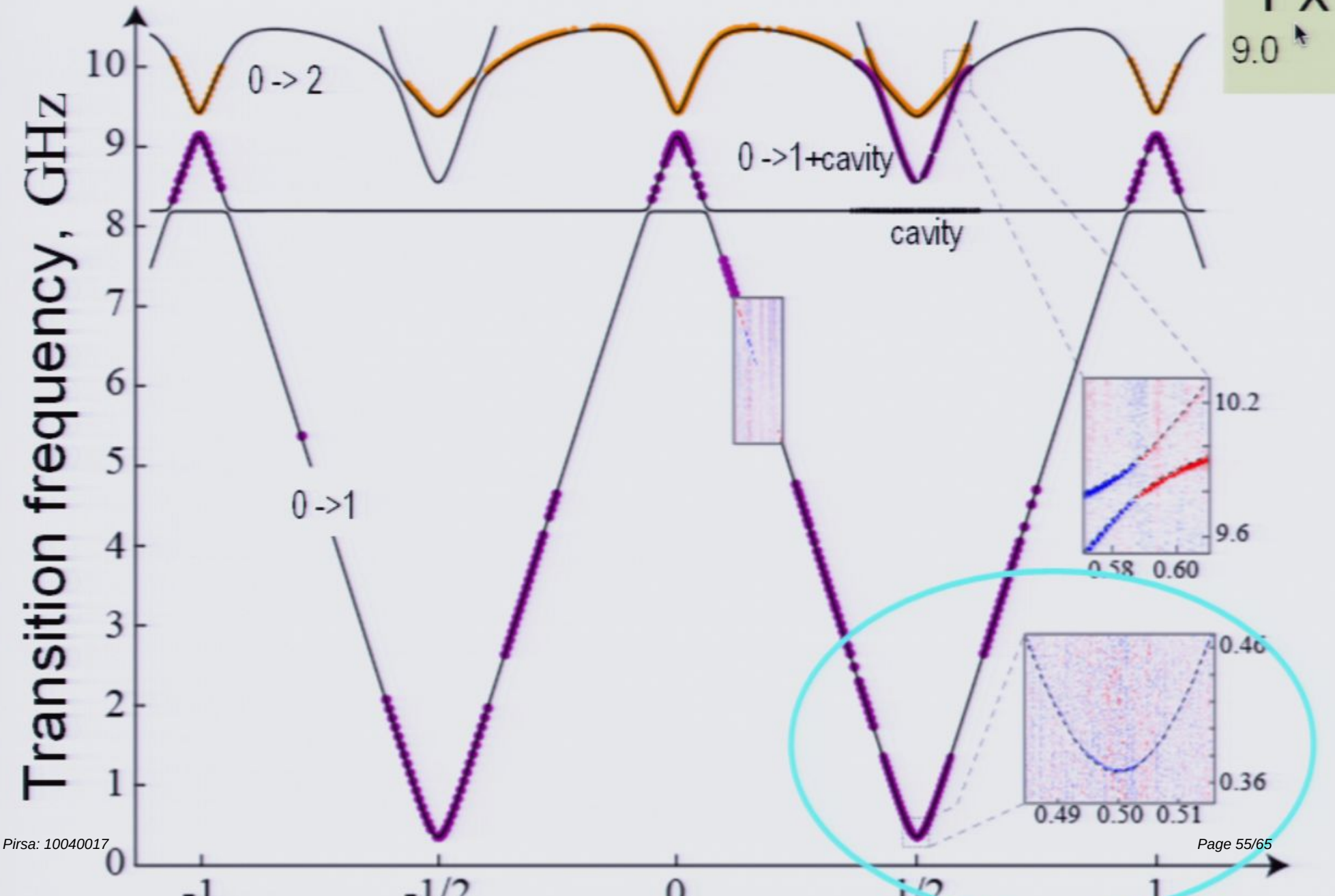
$$|g\rangle = \frac{|L\rangle + |R\rangle}{\sqrt{2}}$$



apply readout pulse, measure $|g\rangle$ or $|e\rangle$



DEJA VU


0.5 2.5
Fx
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Transition frequency, GHz
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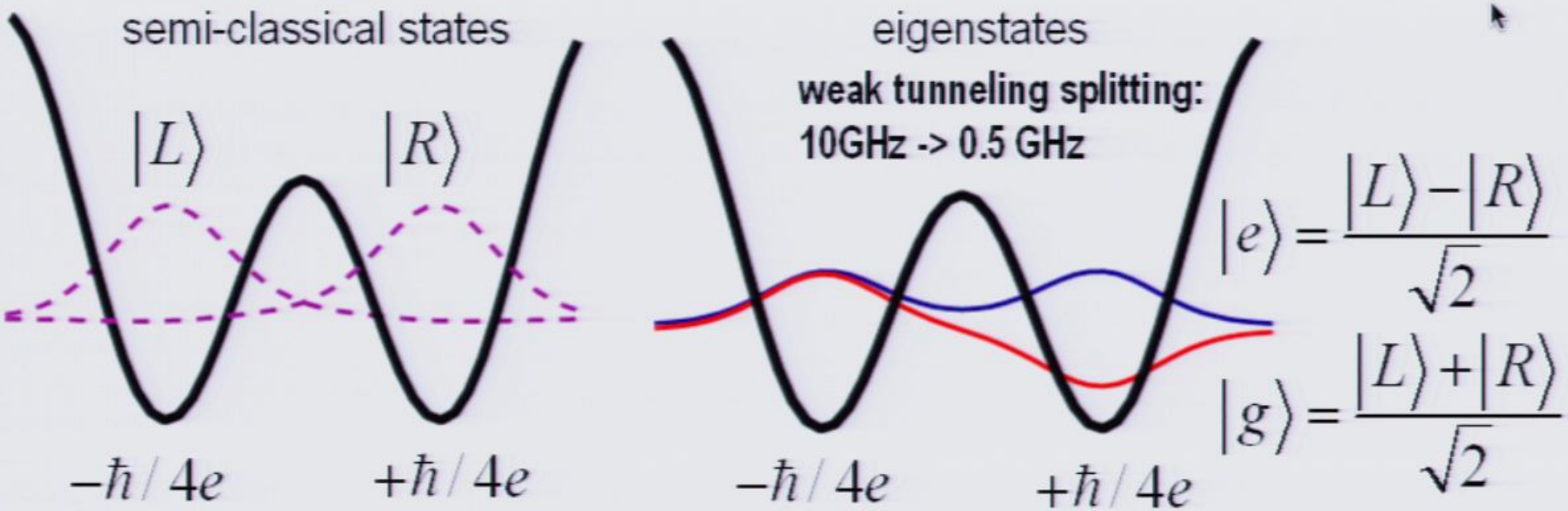
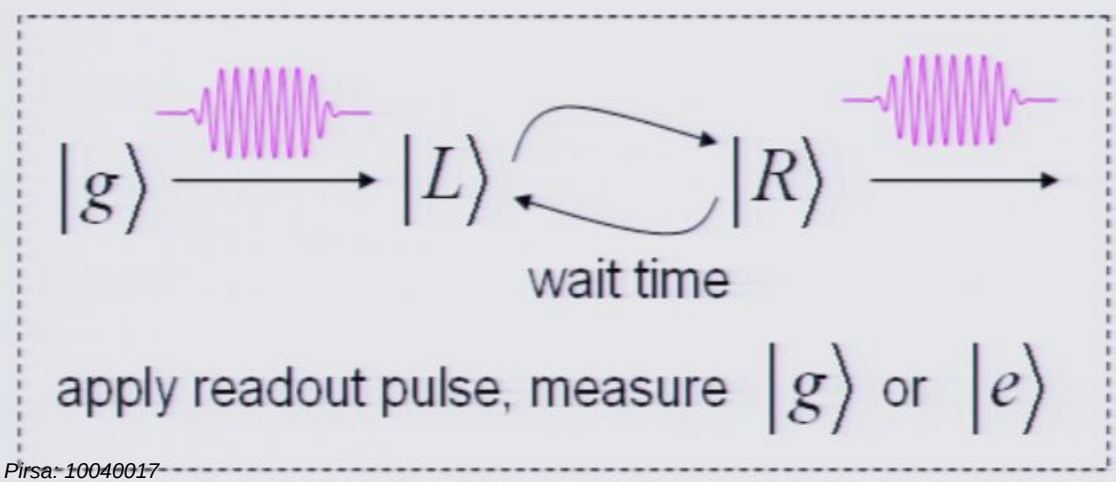
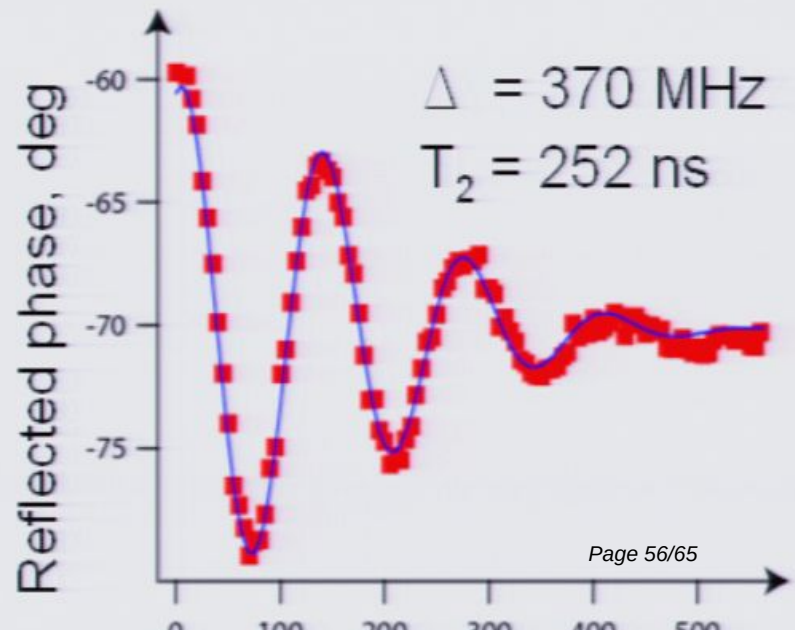
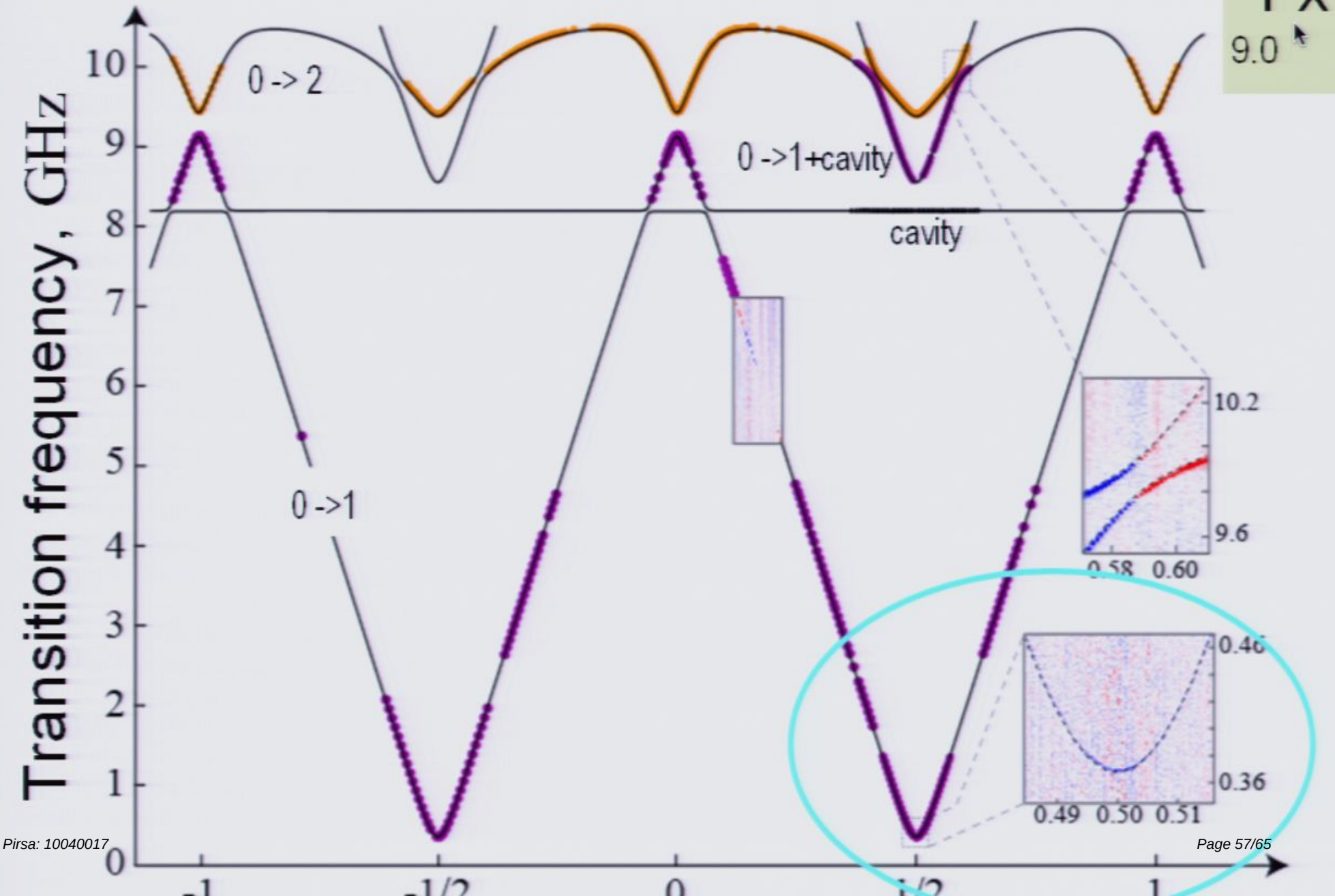
REVERSIBLE TUNNELING OF A SINGLE FLUXON







DEJA VU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FLUXON[IUM] STATES: SIGNATURE ZIG-ZAG SPECTRUM

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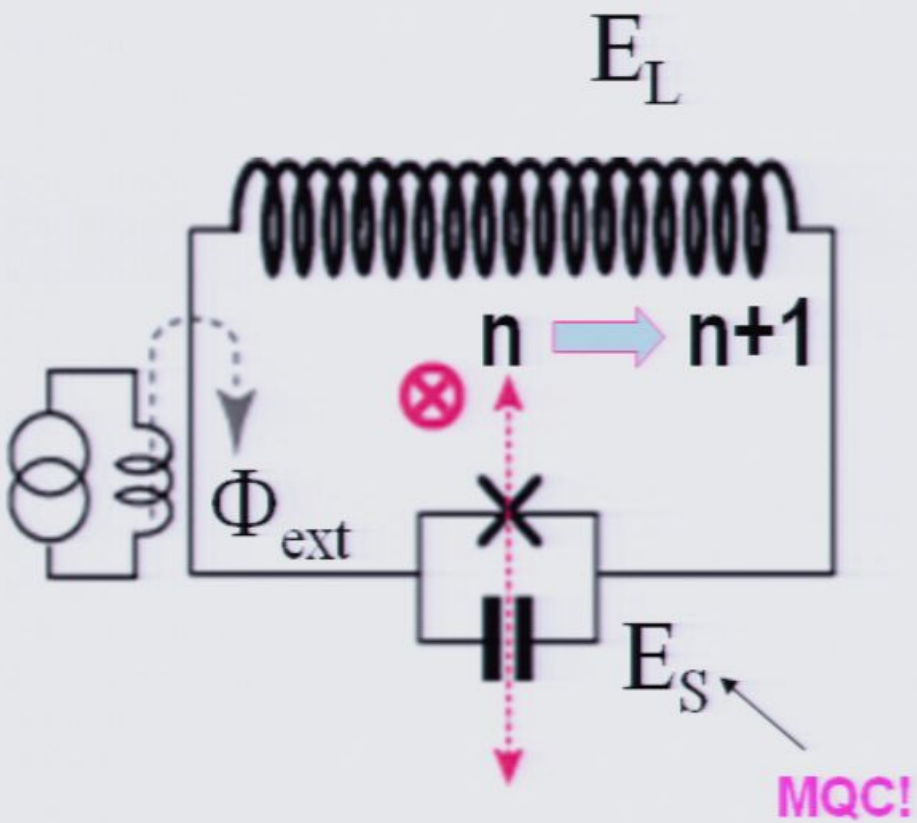
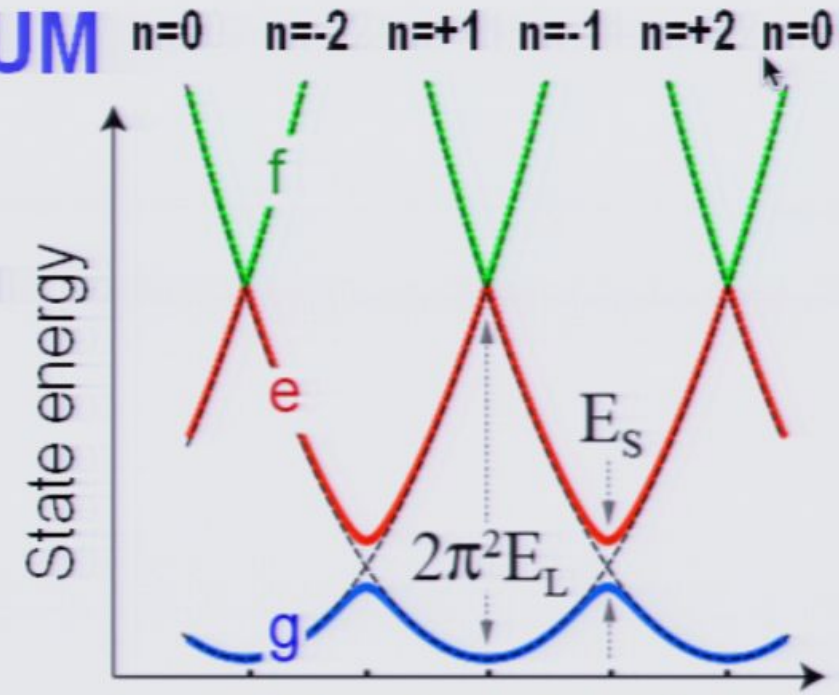
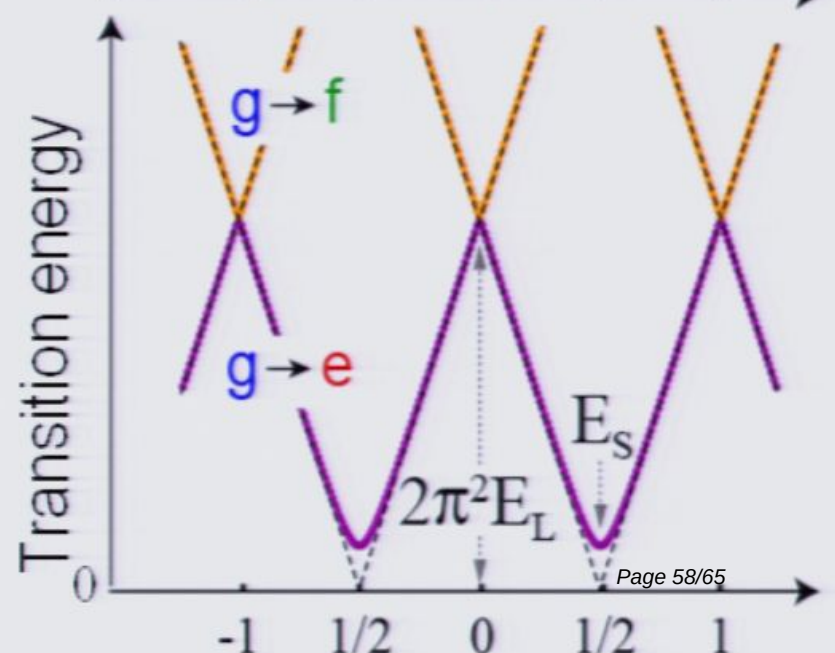
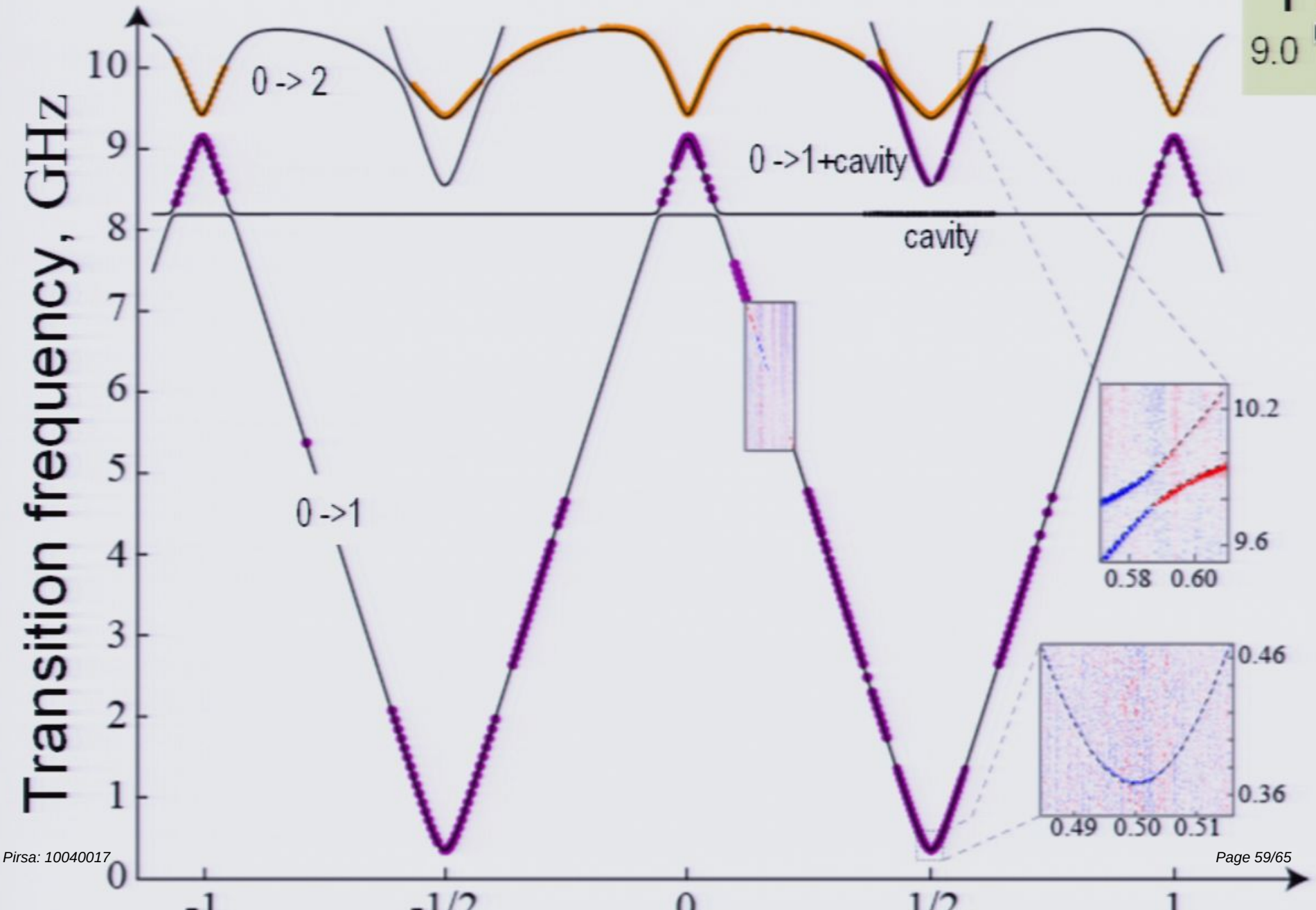






$E_n = (n - \delta x/2\pi r)^2$

DEJA VU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Fx
9.0
Transition frequency, GHz
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0 ->1+cavity
cavity
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0.58 0.60
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0.49 0.50 0.51
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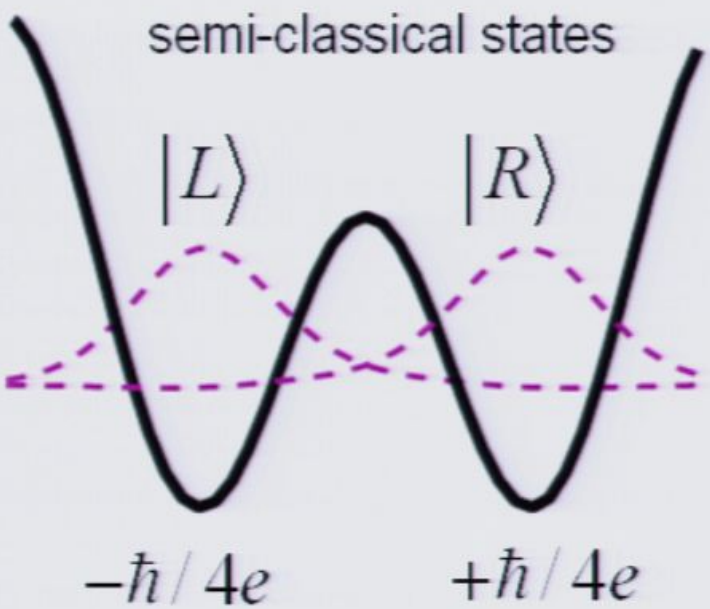
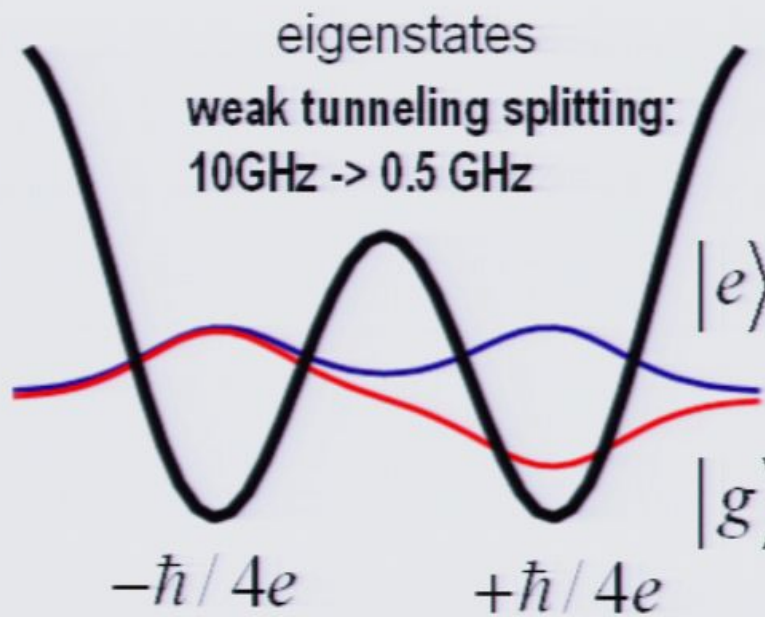
1

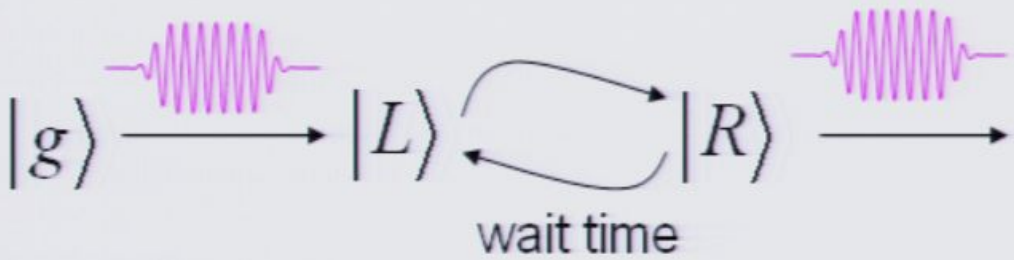
REVERSIBLE TUNNELING OF A SINGLE FLUXON



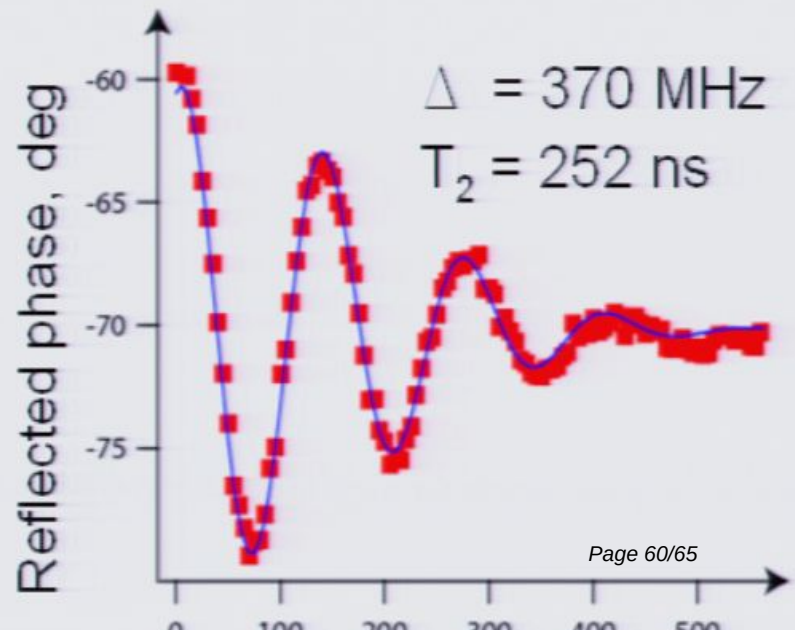


$$|e\rangle = \frac{|L\rangle - |R\rangle}{\sqrt{2}}$$

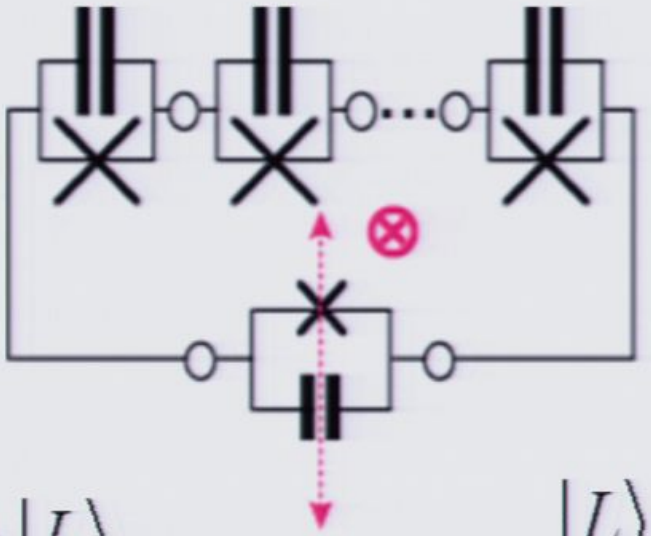
$$|g\rangle = \frac{|L\rangle + |R\rangle}{\sqrt{2}}$$

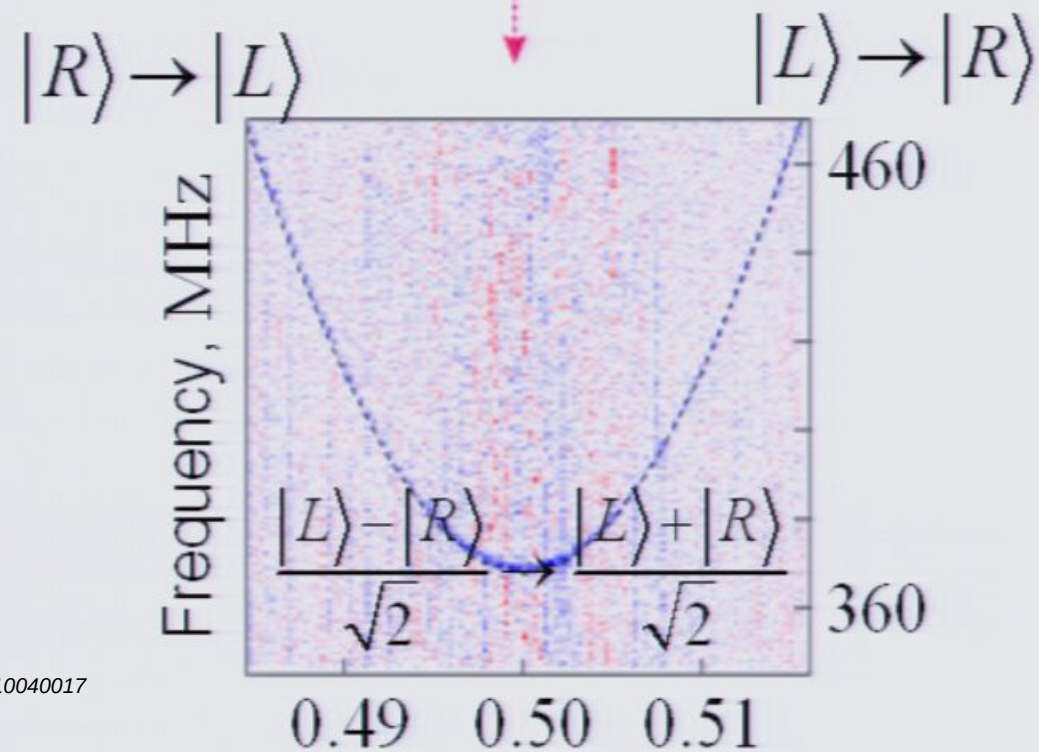


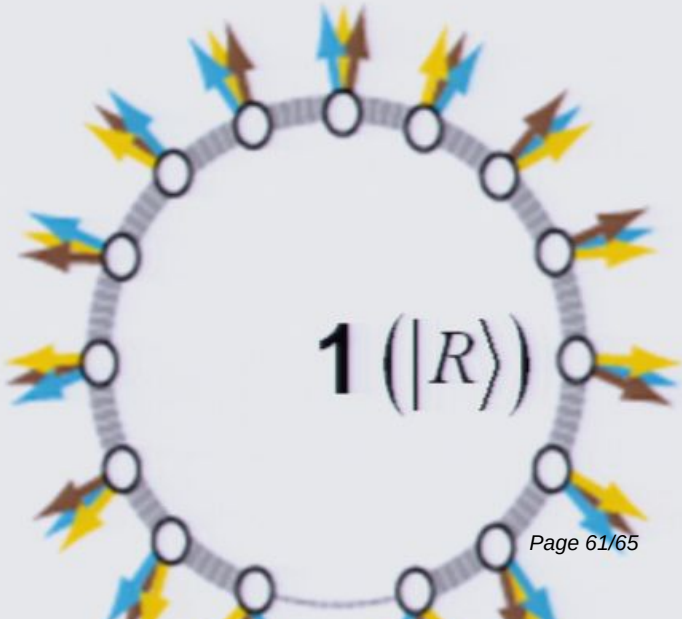
apply readout pulse, measure $|g\rangle$ or $|e\rangle$



FINALLY, HOW DO FLUXONS LOOK LIKE?







CLOSING REMARKS

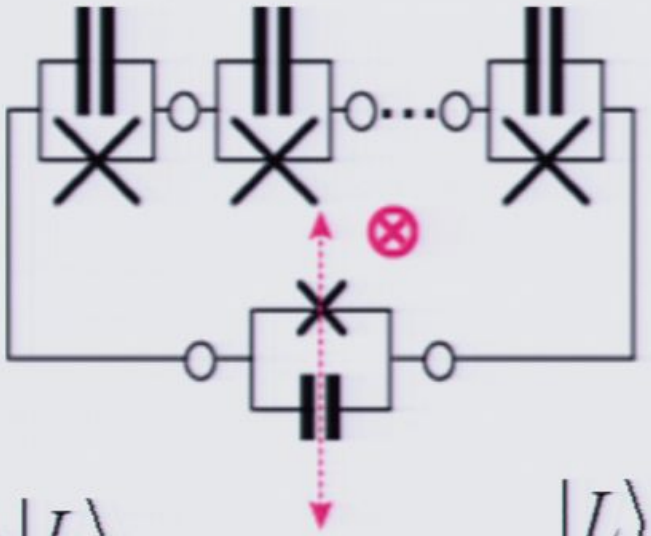
Which parameter is important: total mass, # free electrons, #quarks, classical action in units of h, geometric dimensions, magnitude of currents/voltages etc…?

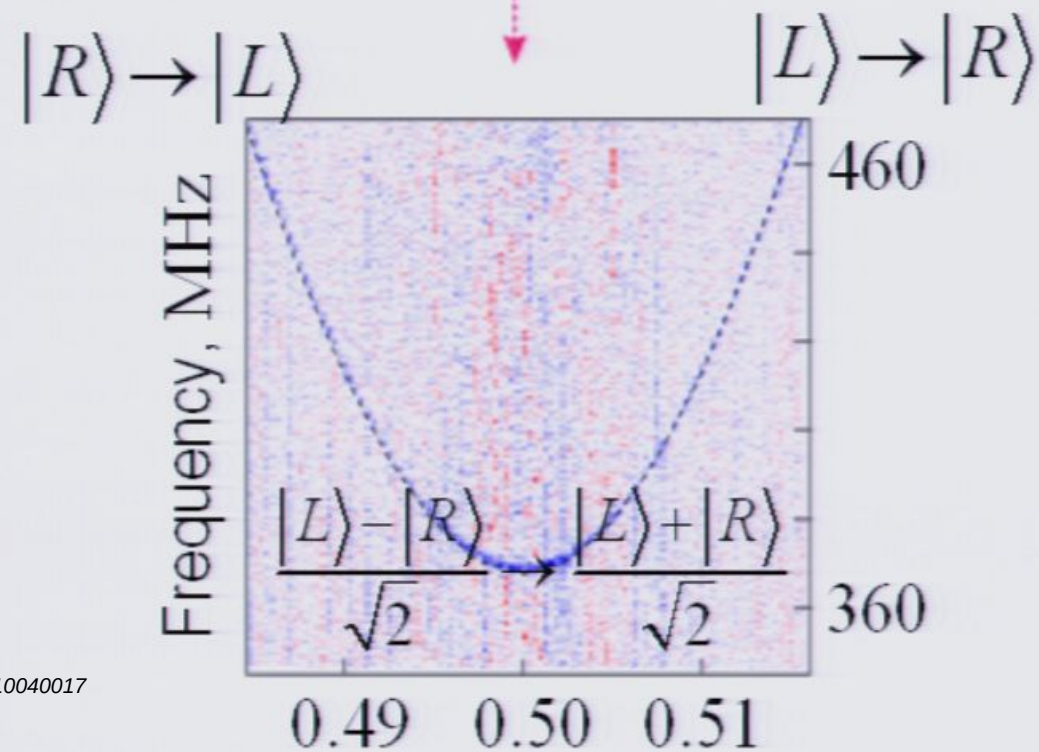
The higher the SNR in a quantum circuit experiment and the less noise due to microscopic defects/measurement apparatus is present in the system [flux noise, charge noise, critical current noise, energy exchange, etc..], the higher the chance that we resolve a discrepancy with a standard theory.

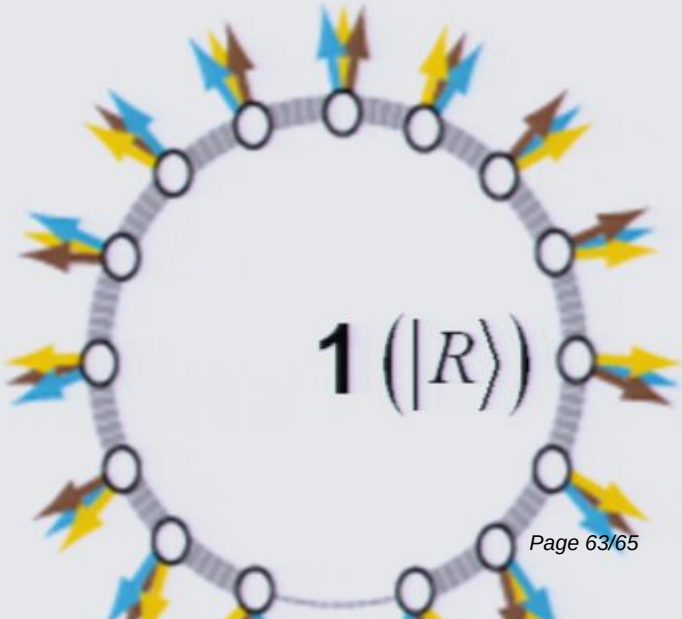
A NEW FLUXONIUM CIRCUIT IMPLEMENTED IN A VASTLY DIFFERENT PARAMETER RANGE

IT ALLOWED FOR THE FIRST TIME TO OBSERVE DEEP REVERSIBLE QUANTUM TUNNELING OF PERSISTING FOR LONG TIME BETWEEN 2 CONFIGURATIONS OF A SUPERCONDUCTING LOOP DIFFERING BY A FLUXON, ONE FULL TURN OF THE COLLECTIVE PHASE DEGREE OF FREEDOM

FINALLY, HOW DO FLUXONS LOOK LIKE?







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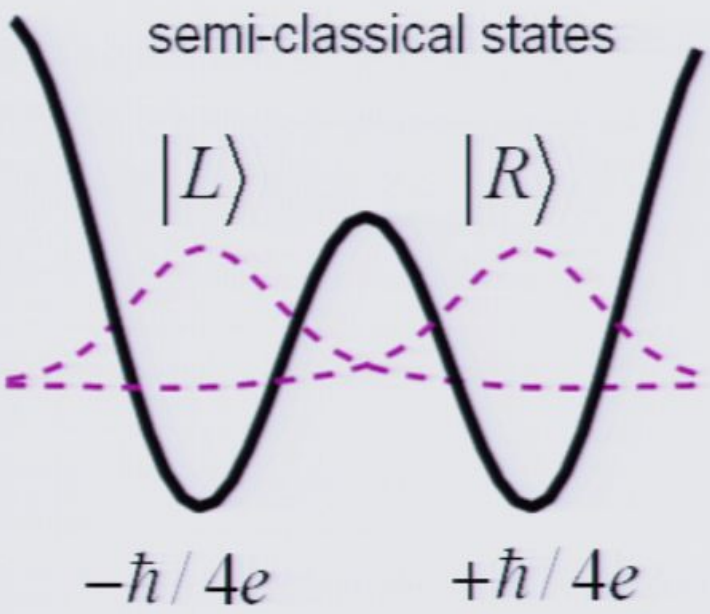

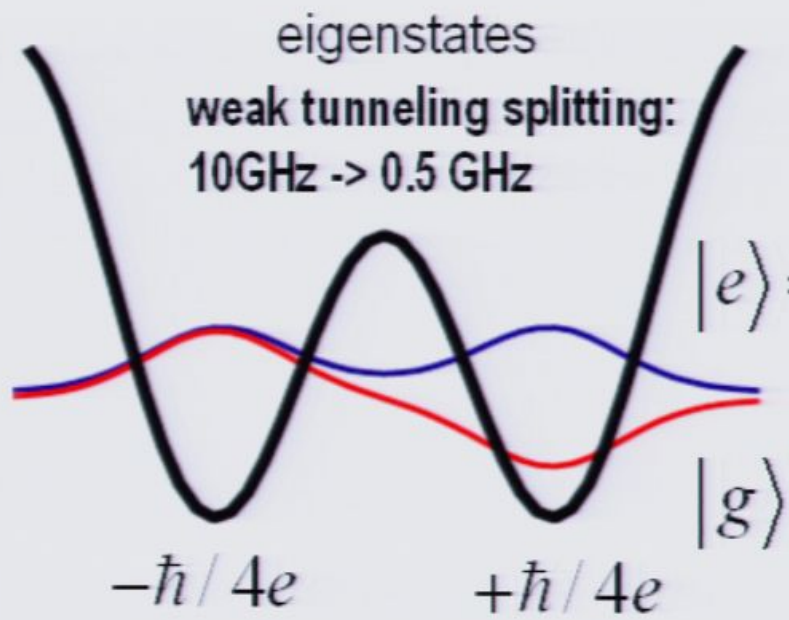

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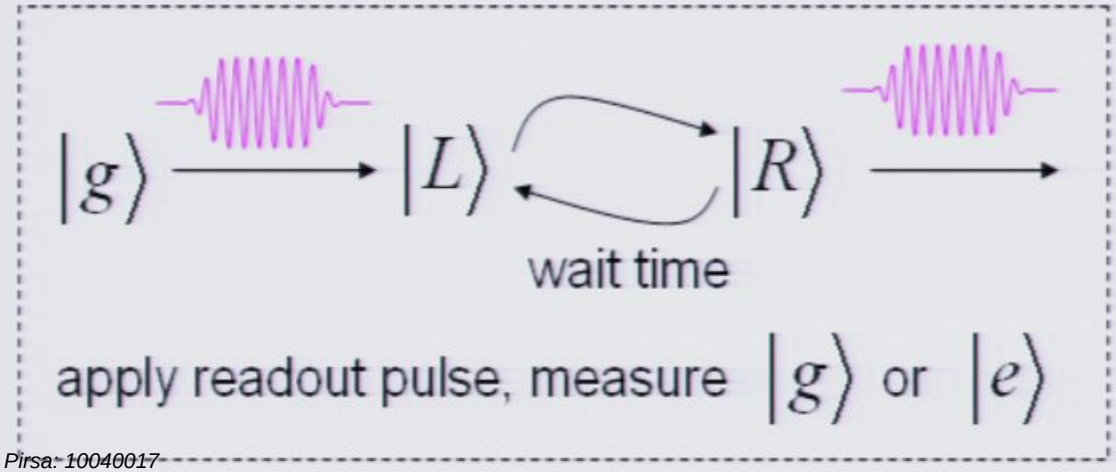

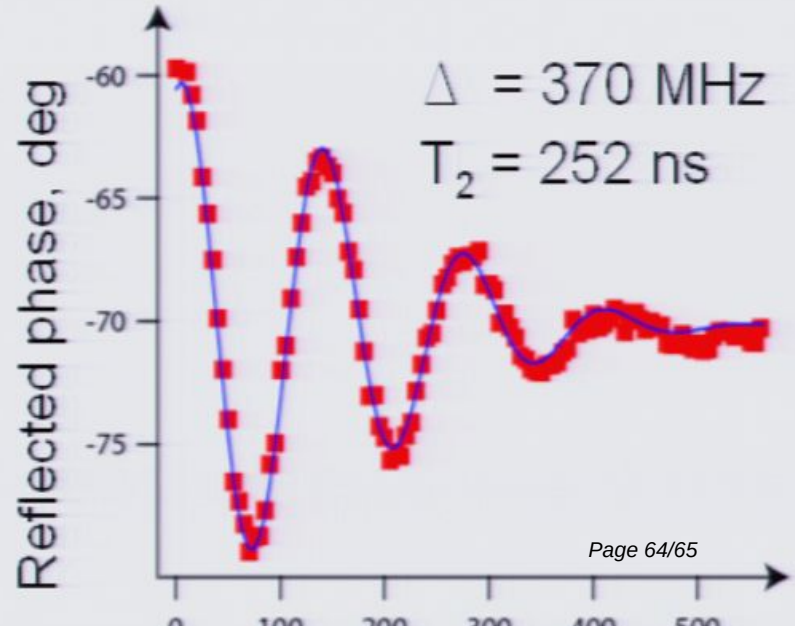

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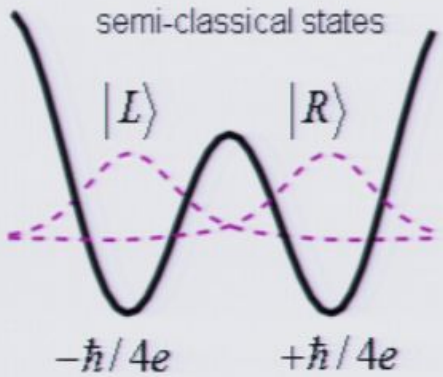

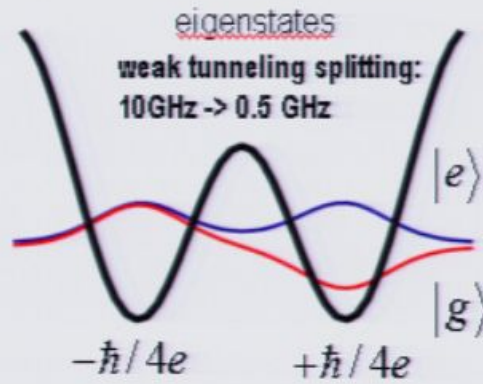

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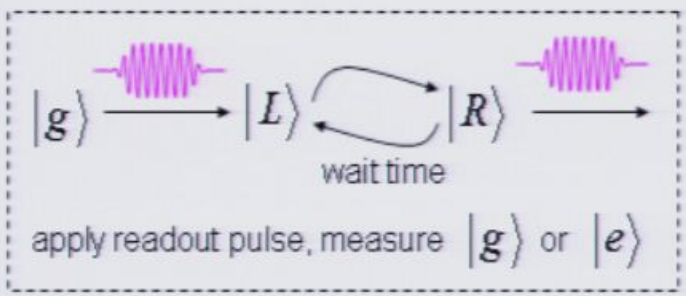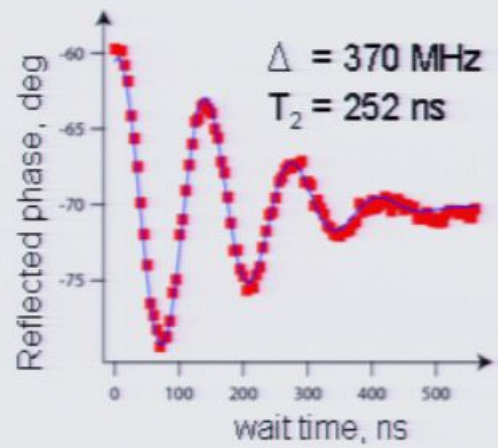
$$|g\rangle = \frac{|L\rangle + |R\rangle}{\sqrt{2}}$$