How to be in two places at the same time

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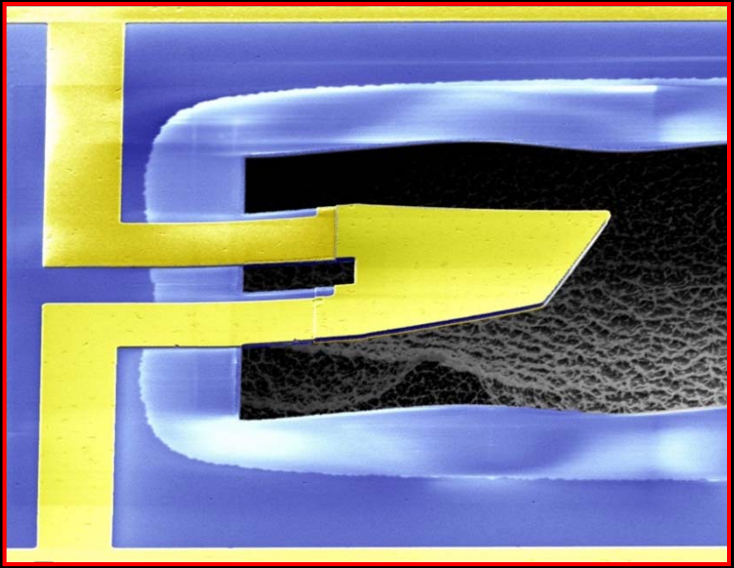

collaborators:
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Michael Geller (U Georgia - Athens)

COLLÈGE DE FRANCE 1530

21 Juin 2011
15:00

quantum mechanics

Quantum mechanics imposes disagreeable limits on physicists:

1. You can only calculate probabilities

2. Simultaneous measurements are often limited in precision:

$$\underline{m\Delta v \cdot \Delta \mathrm{x}} \geq \hbar$$

Heisenberg uncertainty principle

you cannot *precisely* measure velocity and position at the same time

quantum mechanics

Quantum mechanics is the most precise physical theory :

atomic hydrogen 1S-2S transition frequency:

experiment: 2 466 061 413 187 103 Hz

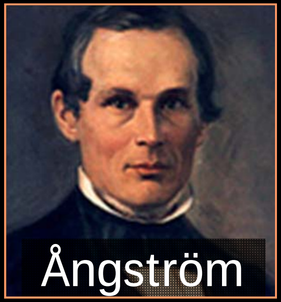
theory: 2 466 061 413 2XX XXX Hz

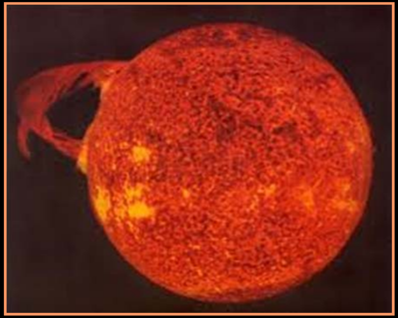
limited by precision of
physical constants

“Measurement of the H 1*S*-2*S* transition”
M. Niering et al. *Phys. Rev. Lett*. (2000)
MPI Garching & Observatoire de Paris & LKB, Paris

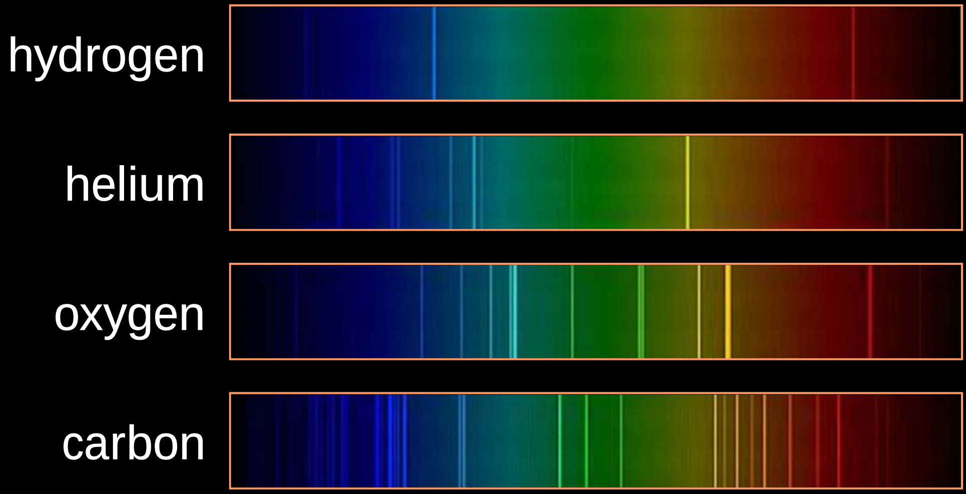
historical perspective


Fraunhofer


Ångström



Each atom has specific wavelengths




de Broglie

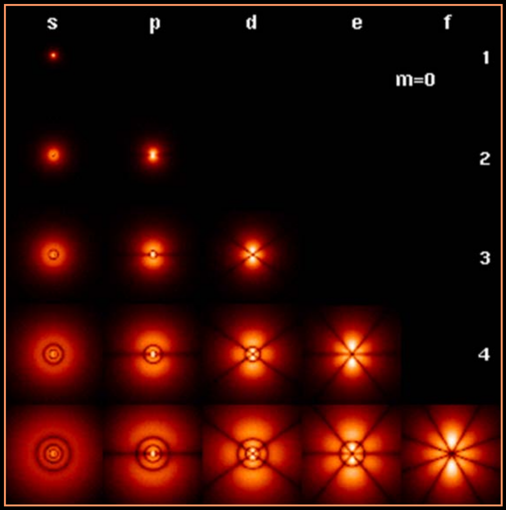

Bohr


Schrödinger

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

$$\hat{H}|\Psi\rangle = i\hbar \frac{\partial}{\partial t}|\Psi\rangle$$

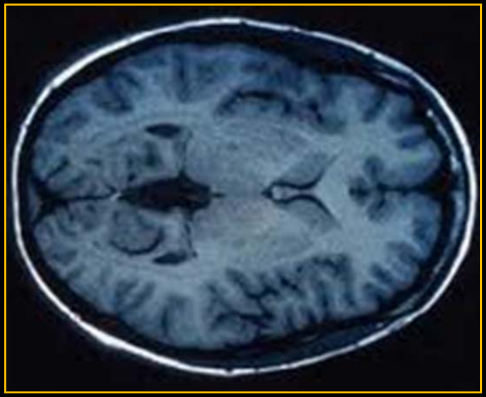
wave
nature of
electrons
in atoms



quantum mechanics

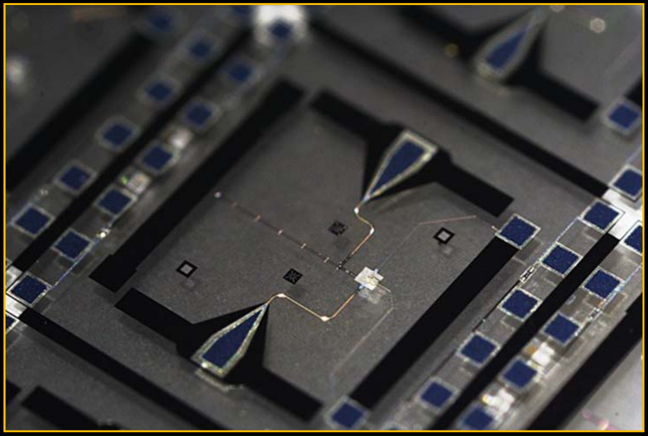
laser

atomic clock / GPS



MRI

photosynthesis



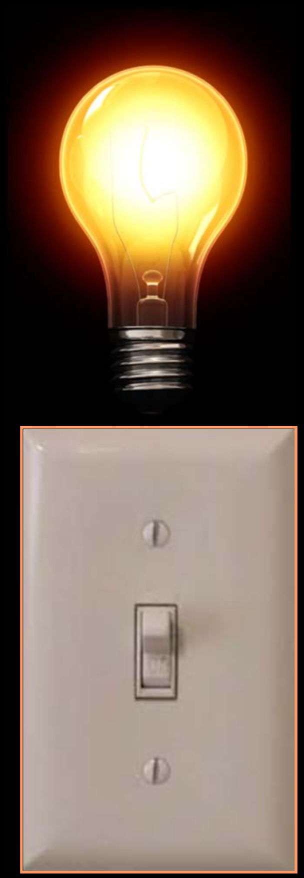
quantum computer

classical perceptions

Our macroscopic world is classical:

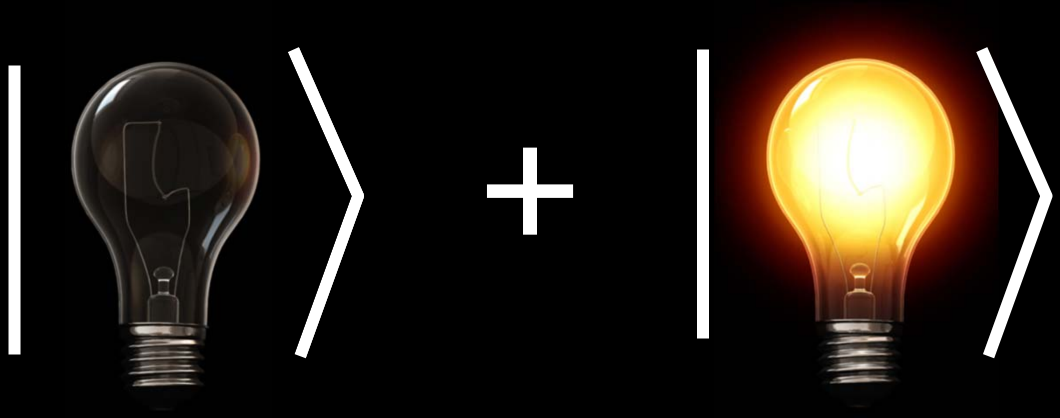
off

on



quantum superposition

Quantum mechanics allows *superpositions* of states:

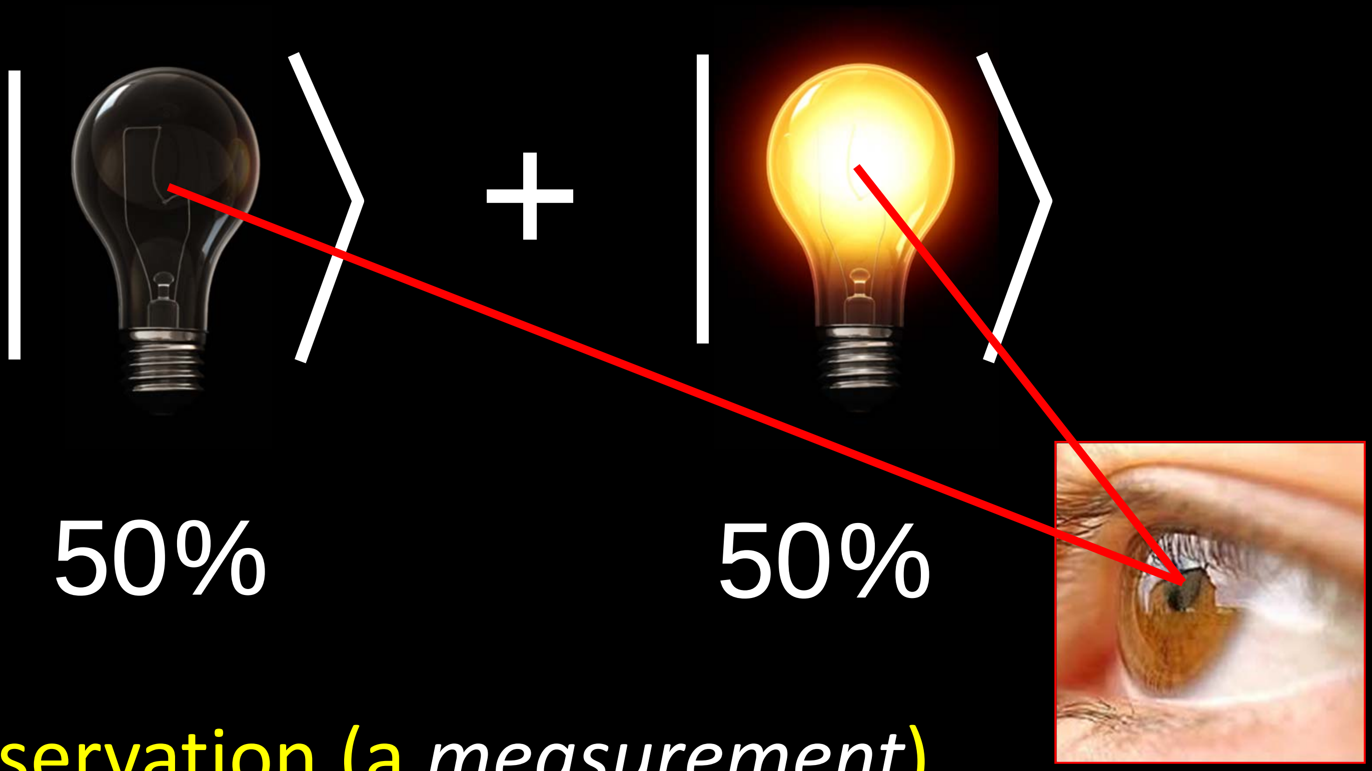


A light bulb can be both on and off

.... at the same time

quantum superposition

A *measurement* forces the system to “choose”:

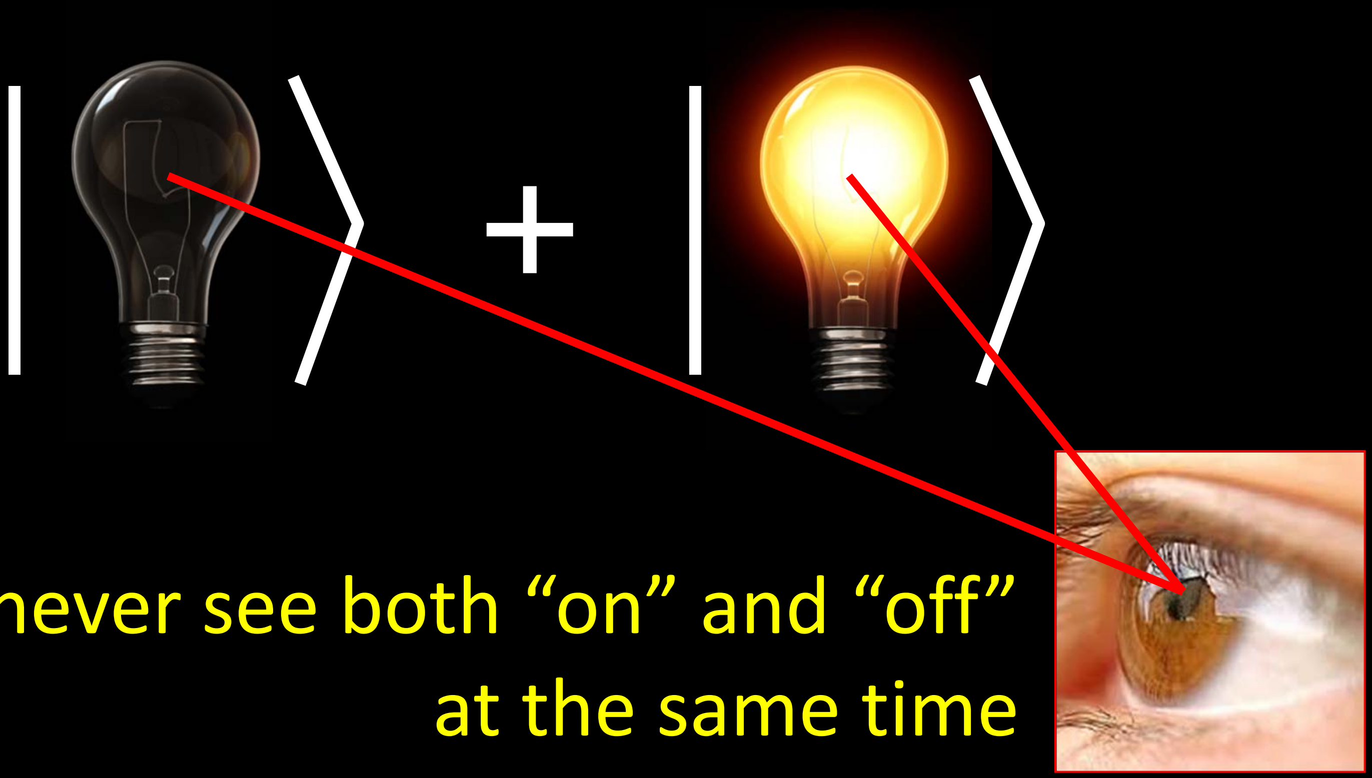


50% 50%

An observation (a <u>*measurement*</u>) “collapses” the quantum state

quantum superposition

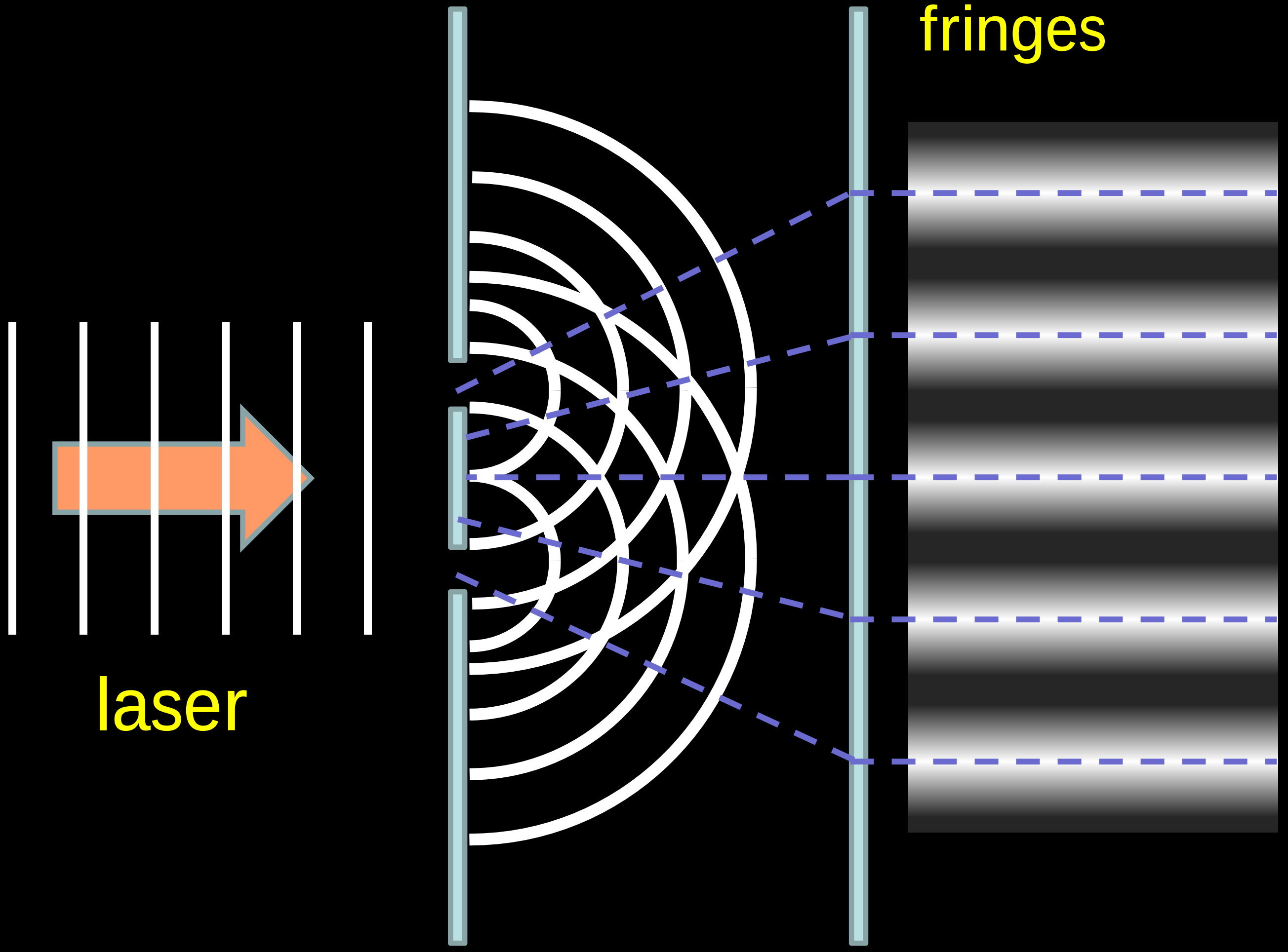
Measurement forces the system to “choose”:



You never see both “on” and “off”
at the same time

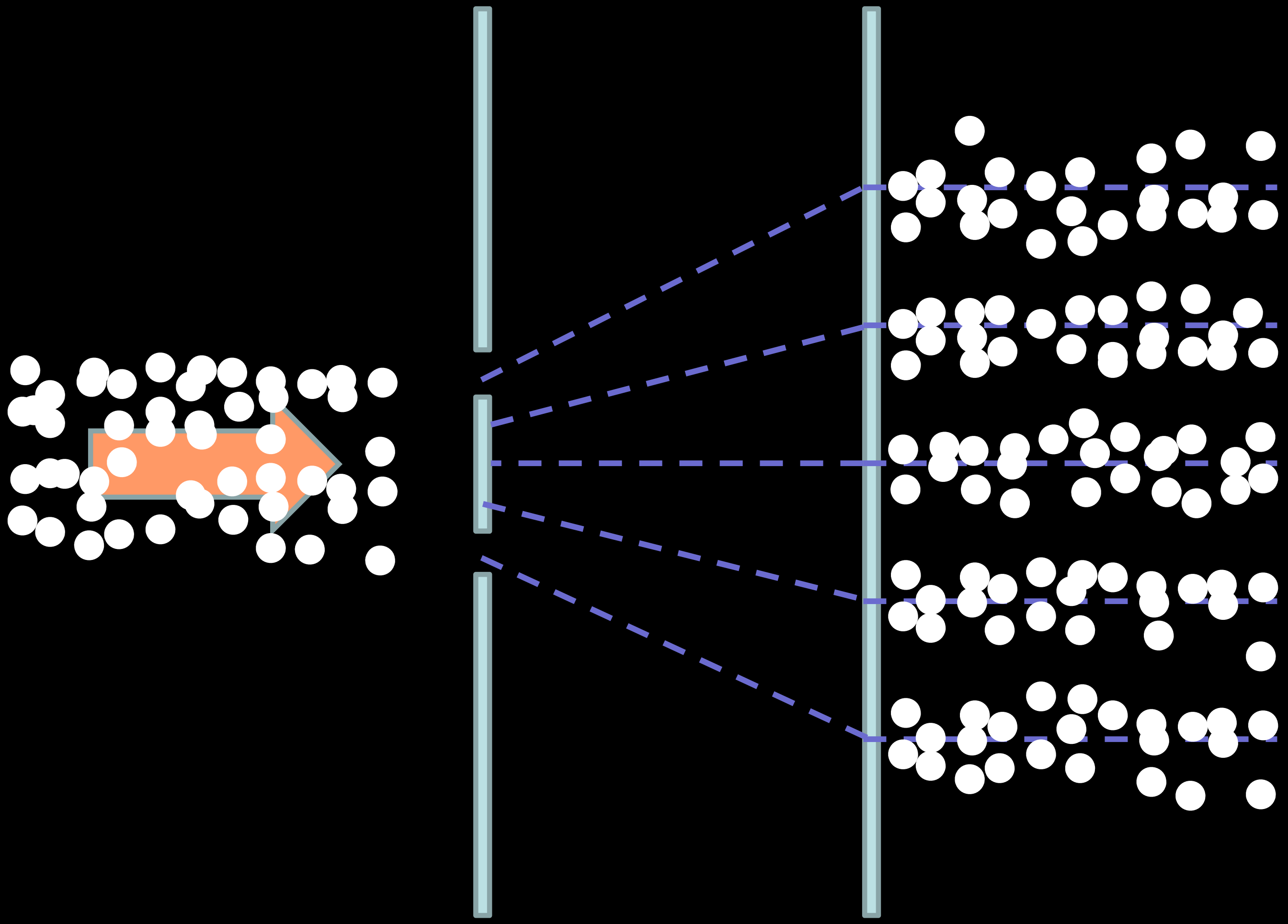
a simple experiment with light

Two-slit experiment with light



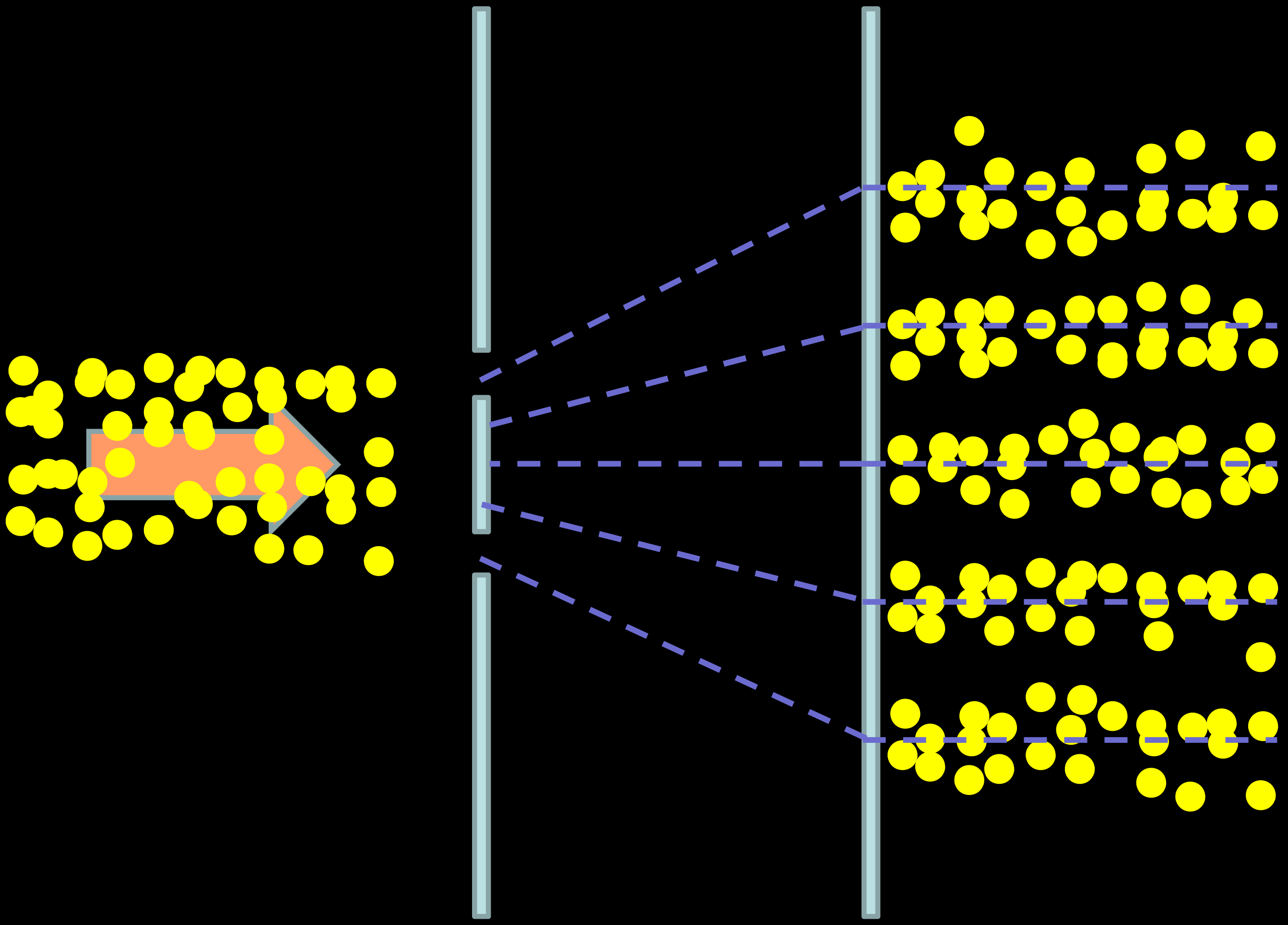
a simple experiment with light

Two-slit experiment with ~~light~~ photons



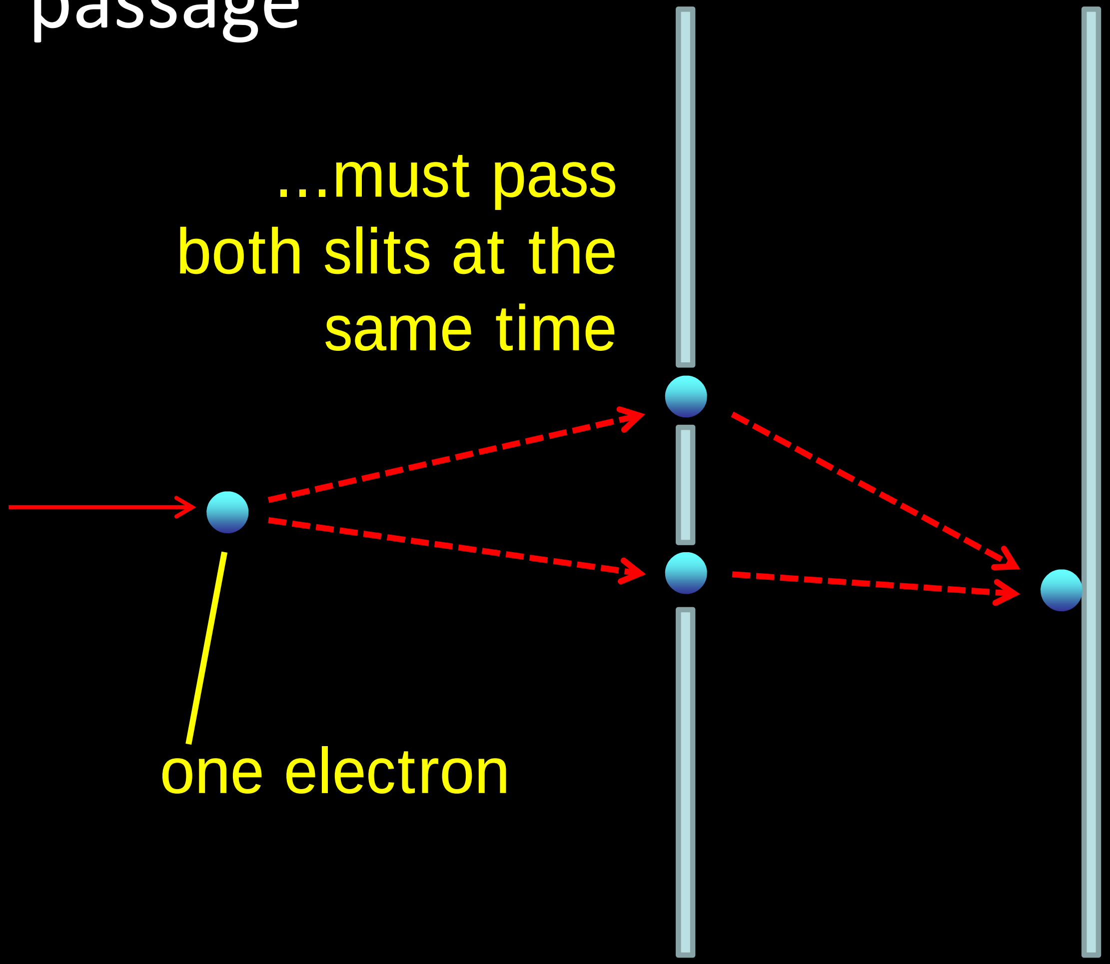
matter's wave properties

Two-slit experiment with ~~light~~ ~~photons~~ electrons



matter’s wave properties

Interference one-at-a-time requires simultaneous passage



…must pass both slits at the same time

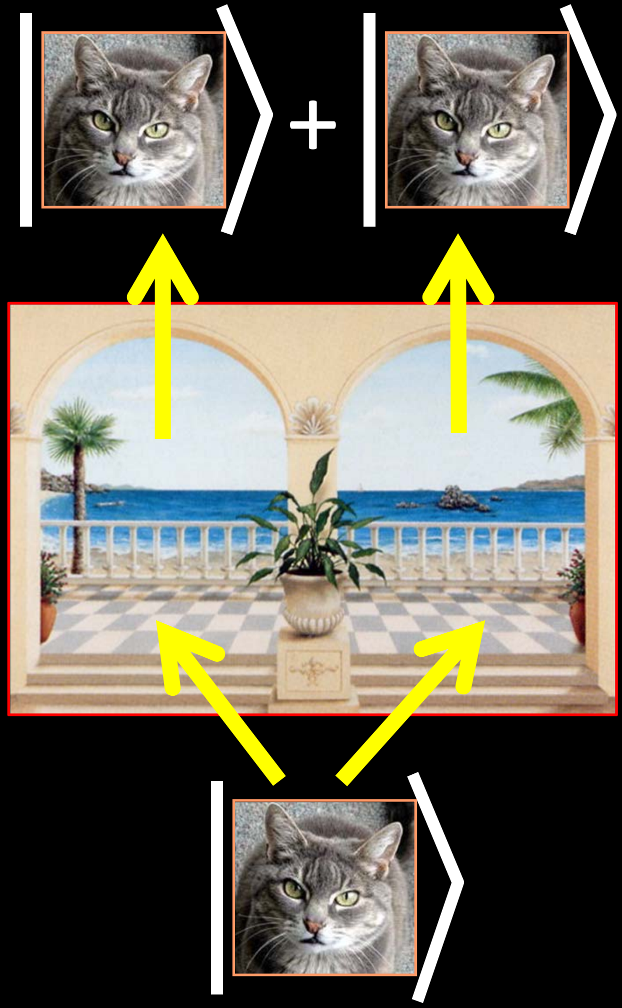
one electron

and then interfere with itself

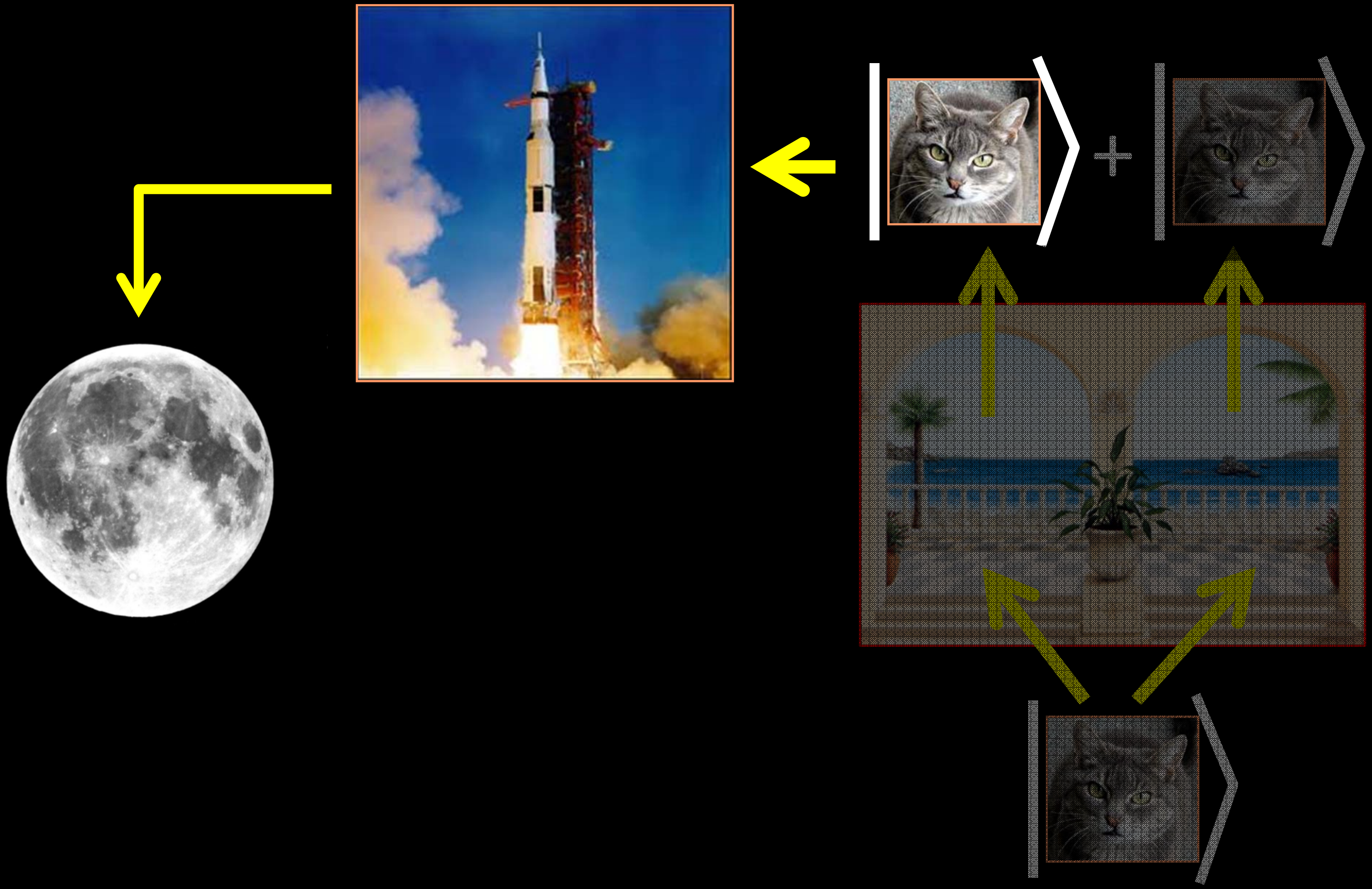
…The electron is “in two places at the same time”

splitting a cat

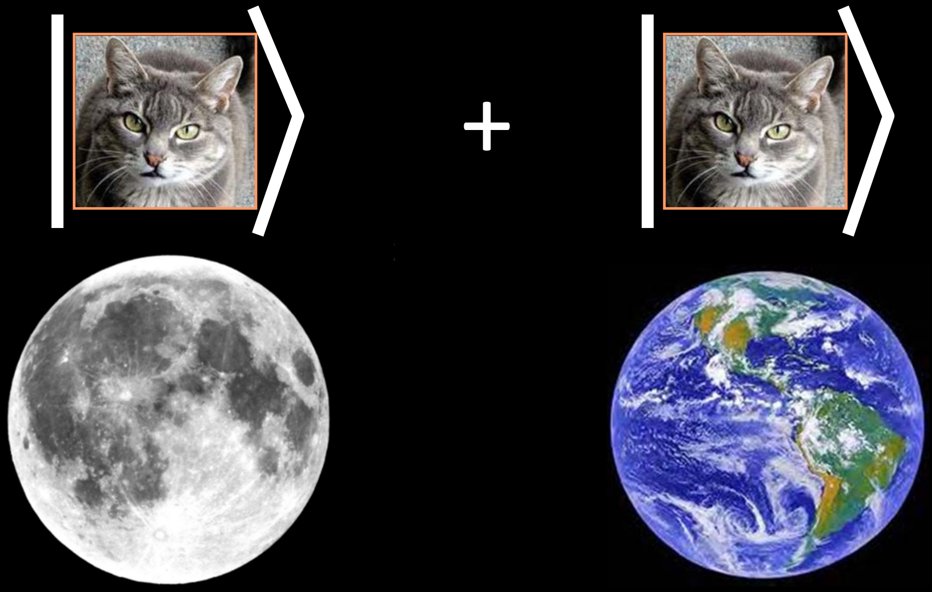
“Schrödinger’s cat”



splitting a cat



superposition state



What are the physical requirements?

~~Are there philosophical implications?~~

~~Does the cat's thinking affect this process~~?

coherence requirements

What is required to observe quantum effects?

1. Weak environment (no “looking”)
2. Preparing a “split” quantum state
3. Measuring the quantum state

Does quantum mechanics only work for small things (atoms, electrons)?

Environment

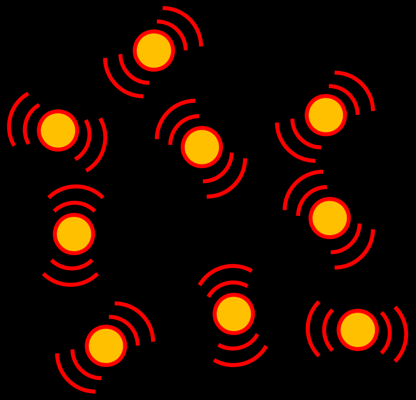
The outside world is always "measuring":

- gas molecules
- mechanical forces
- electric forces

These cause quantum collapse ("measurement")

➢ Must minimize!

The outside world has non-zero temperature:

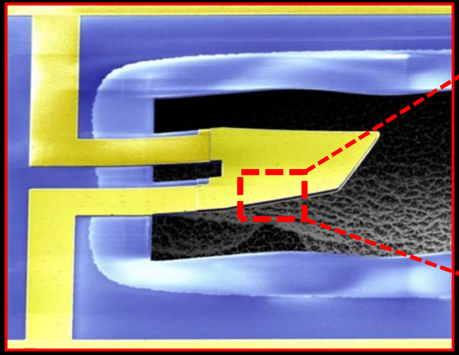


Thermal vibrations destroy quantum states:

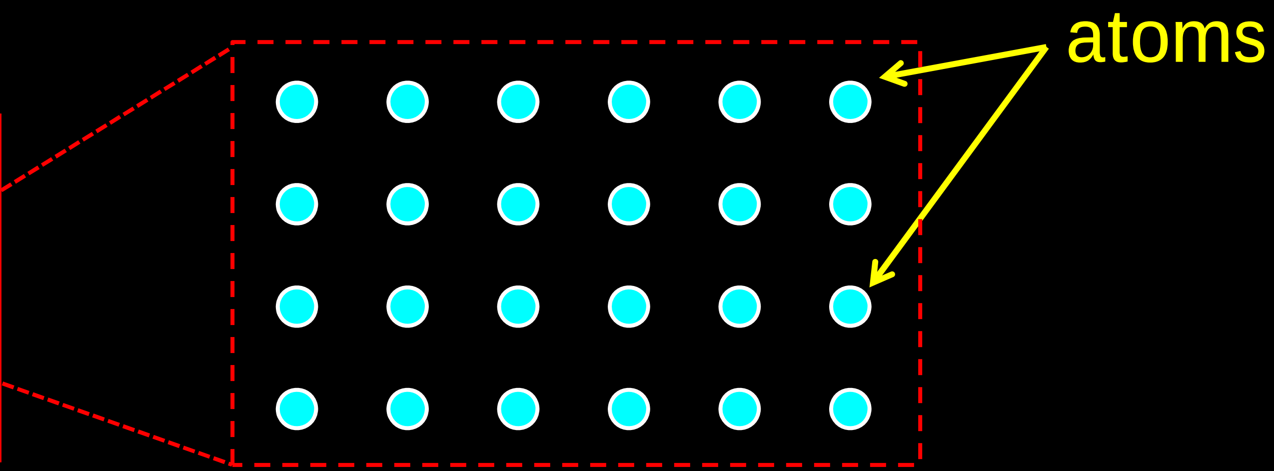
➢ Must minimize!

experimental system

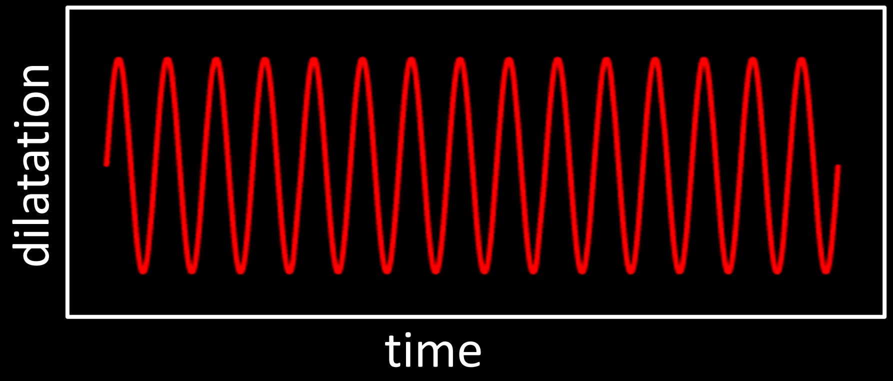
dilatational resonator



Mechanics of dilatation:

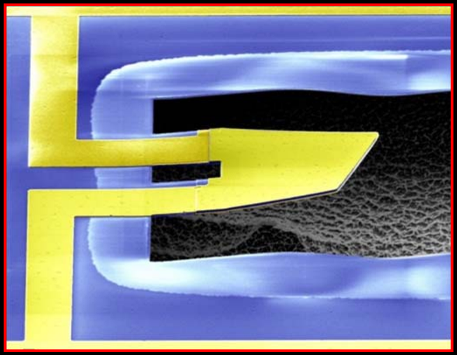


6 billion oscillations per second



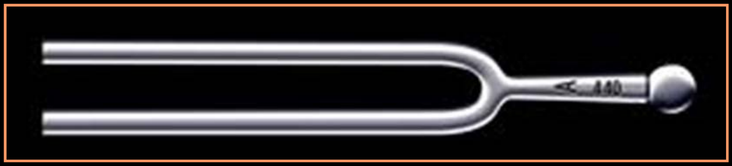
experimental system

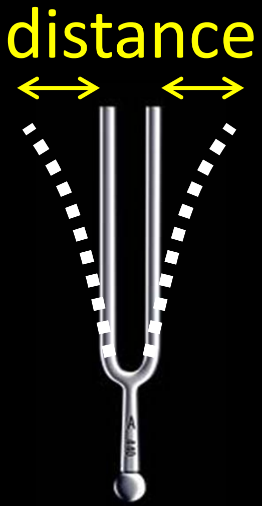
dilatational resonator

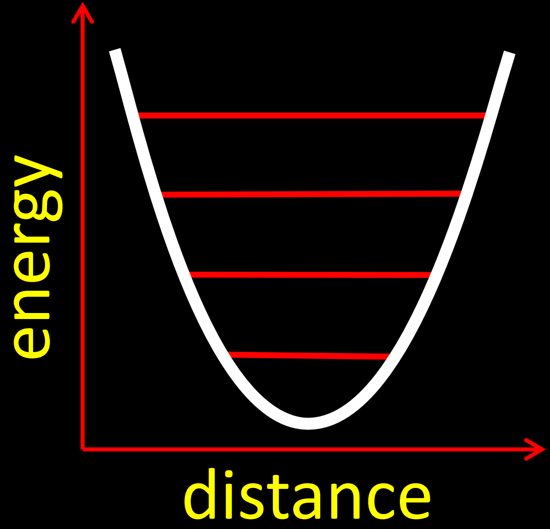


⇔

A microwave frequency tuning fork







Classically:

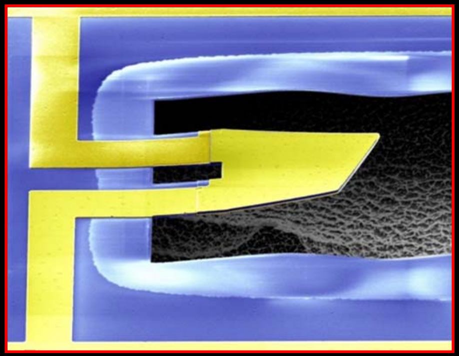
- energy is continuous
- all values possible

Quantum:

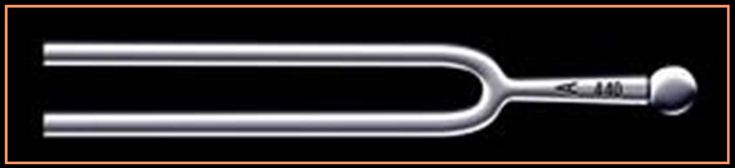
- energy is discrete
- only certain values

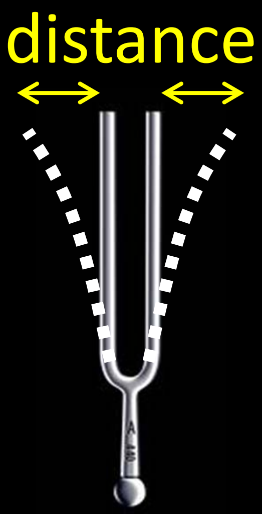
experimental system

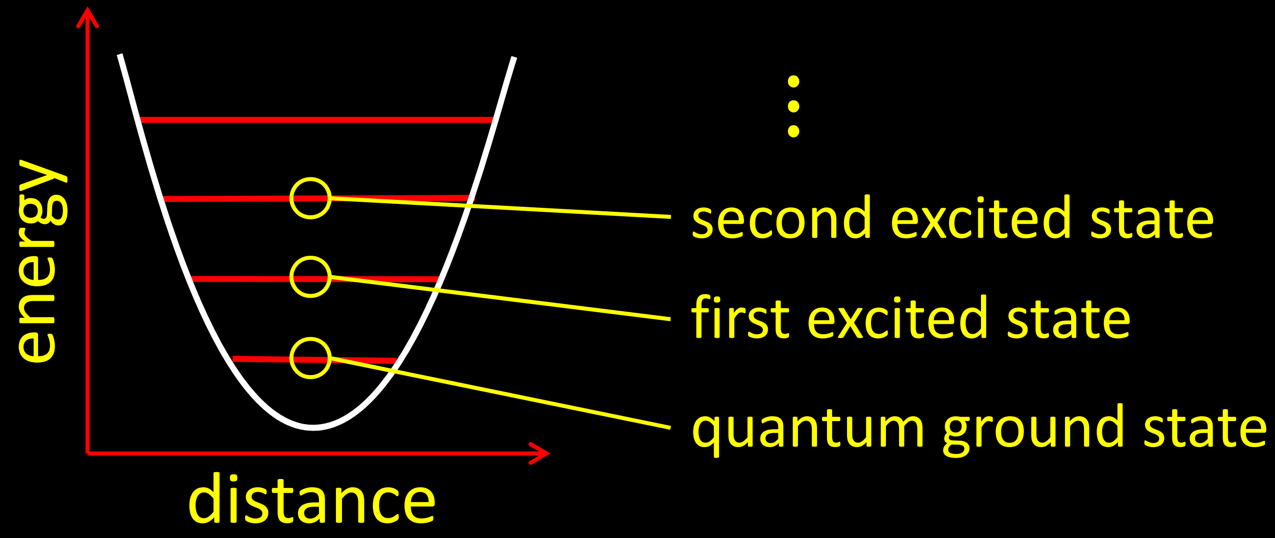
dilatational resonator



A microwave frequency tuning fork







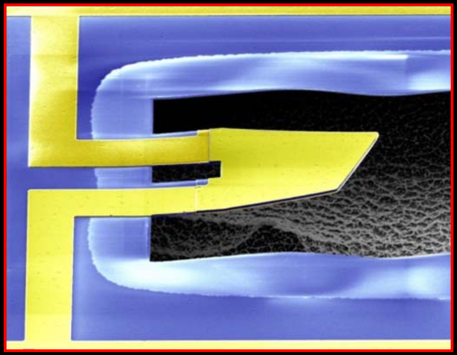
second excited state

first excited state

quantum ground state

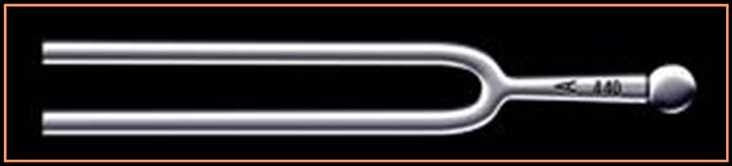
experimental system

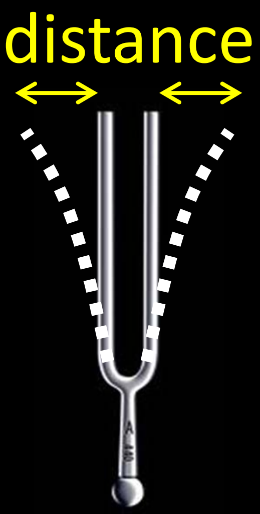
dilatational resonator

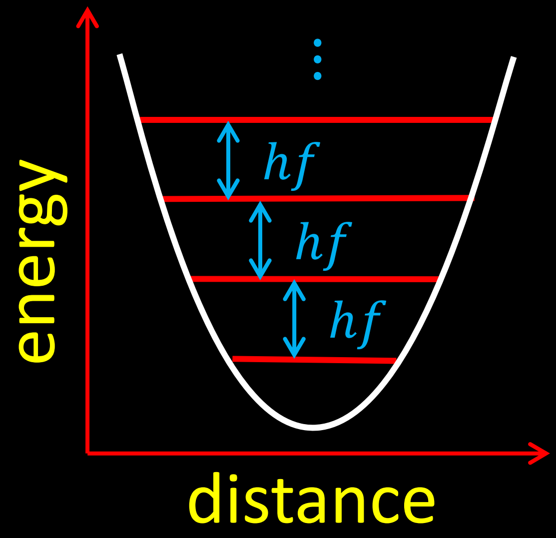


⇔

A microwave frequency tuning fork



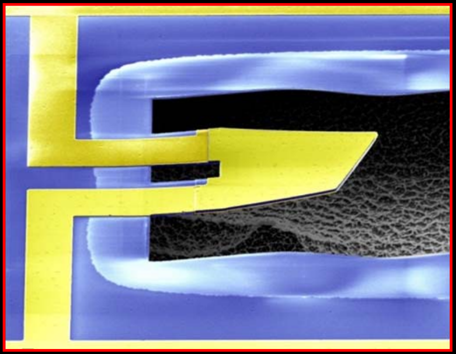




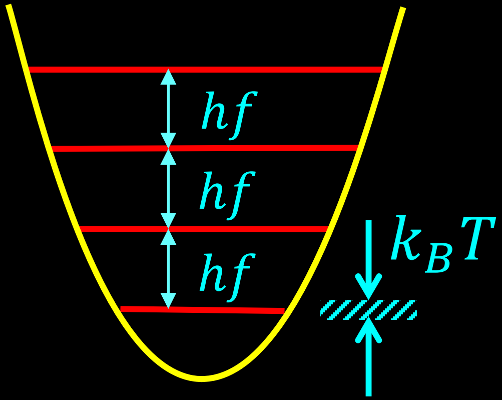
- Higher frequency “tuning forks” have larger energy level spacing

experimental system

dilatational resonator



Cool to quantum ground state:

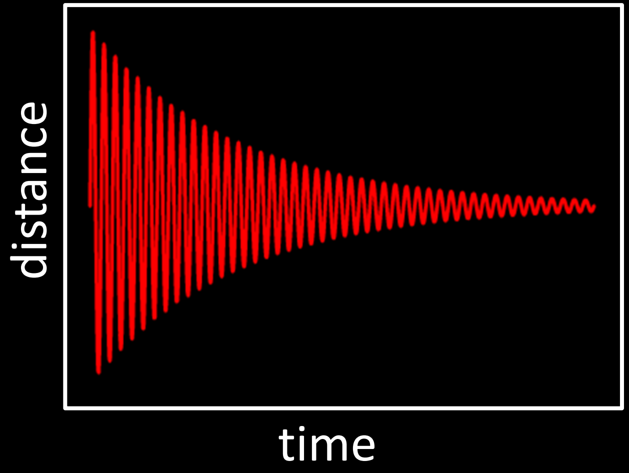


- need $T \ll h\,f/k_B$

  frequency f = 6 GHz

  $\Longrightarrow T \ll 300$ mK

dilution refrigerator
20 mK ✓



Reduce environment effects:

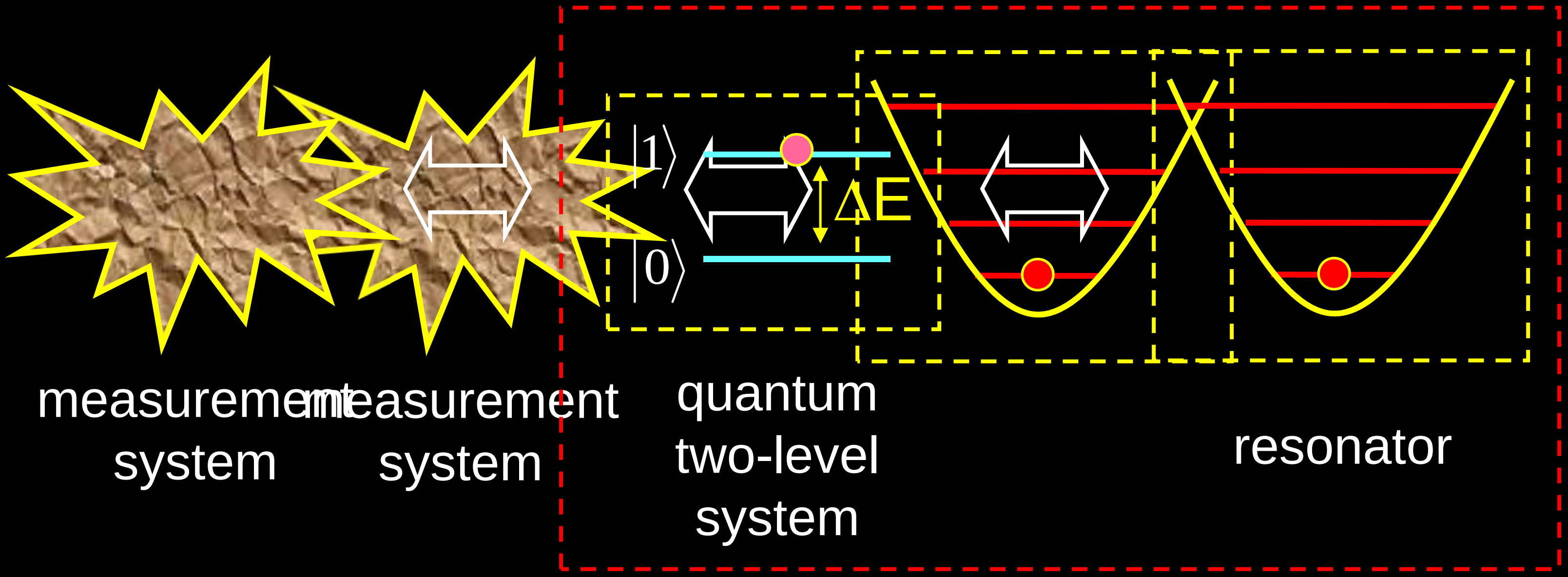
- decay due to environment
- lifetime ~40 oscillations

sufficient for
quantum operation ✓

resonator quantum control

Measure a mechanical resonator in the quantum limit?

1. Interpose a quantum two-level system ("quantum violin")
2. Two-level system and resonator form coherent system
3. Complete quantum control & measurement possible



measurement system

measurement system

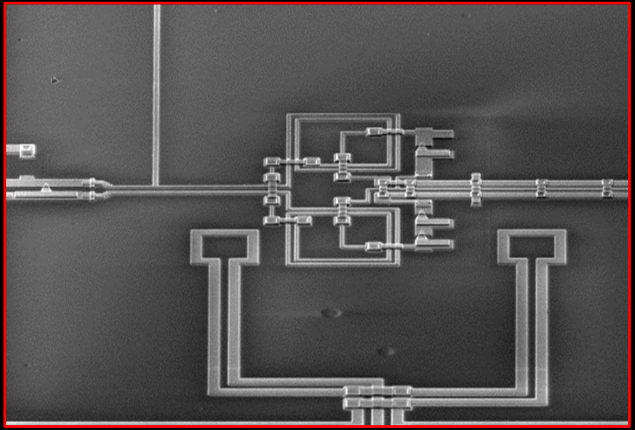
quantum two-level system

resonator

coupled system quantum coherent
allows complete quantum measurement & control

experimental system

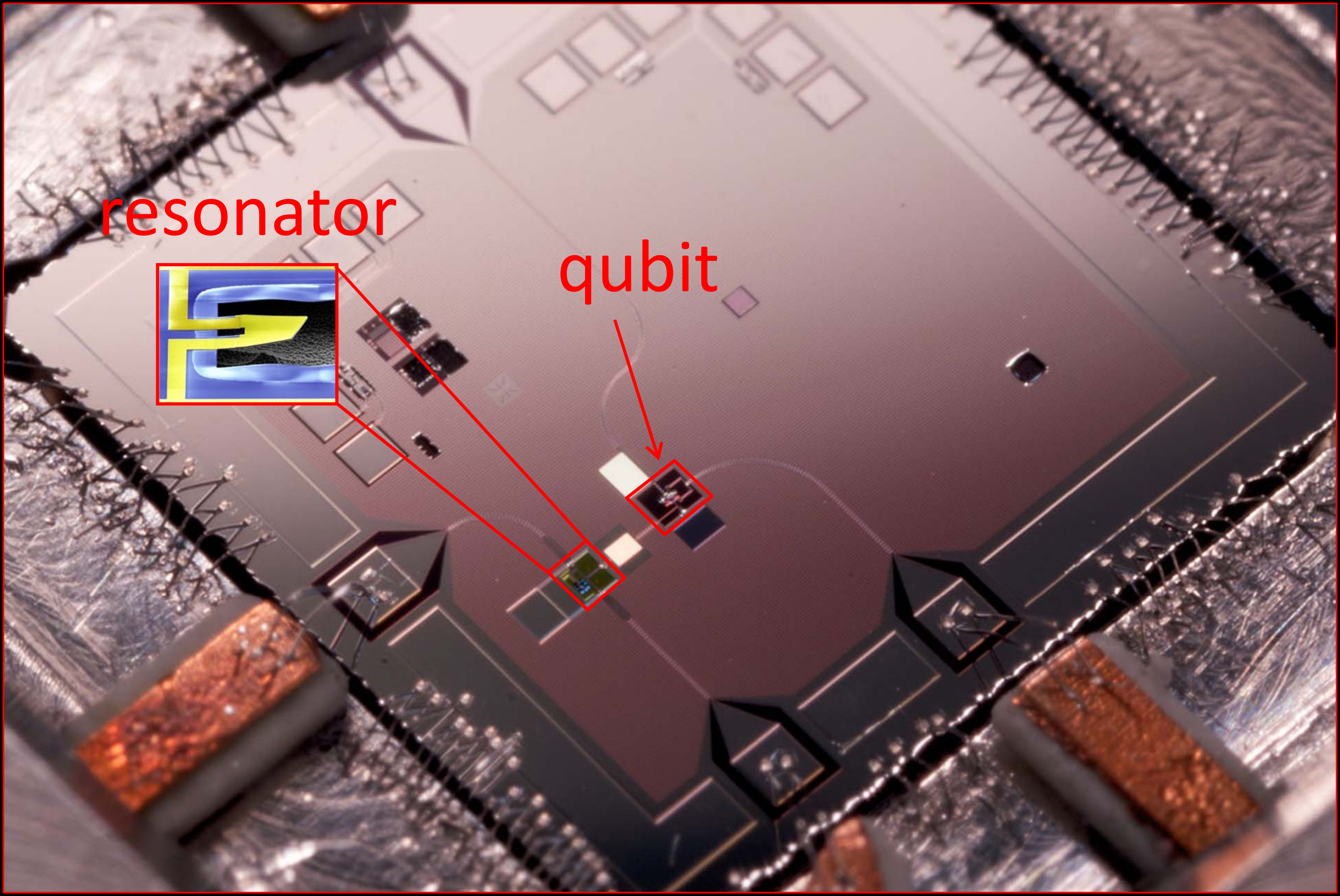
The superconducting phase qubit:
A type of “quantum violin”



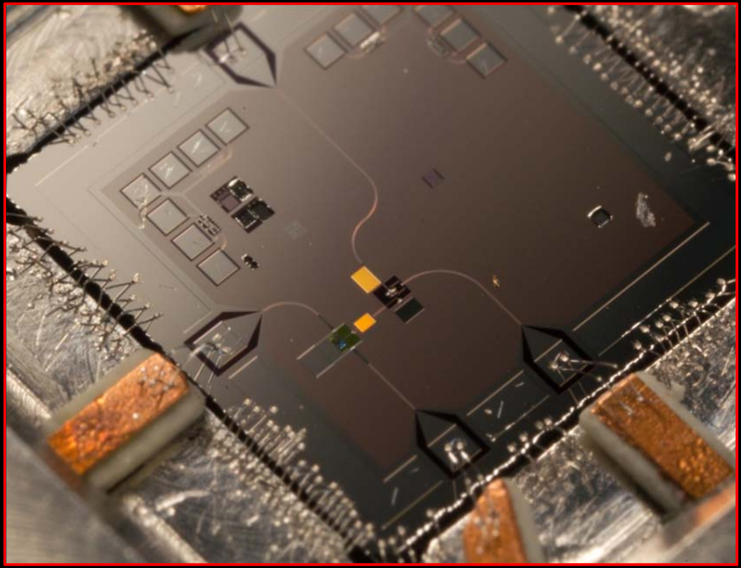
- electronic device
- can change frequency
- quantum control
- quantum measurement

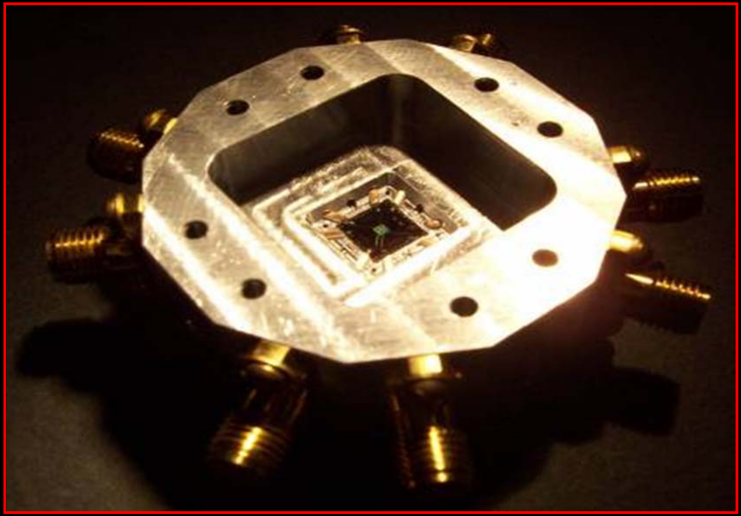
$\Rightarrow$ Quantum control of mechanical resonator

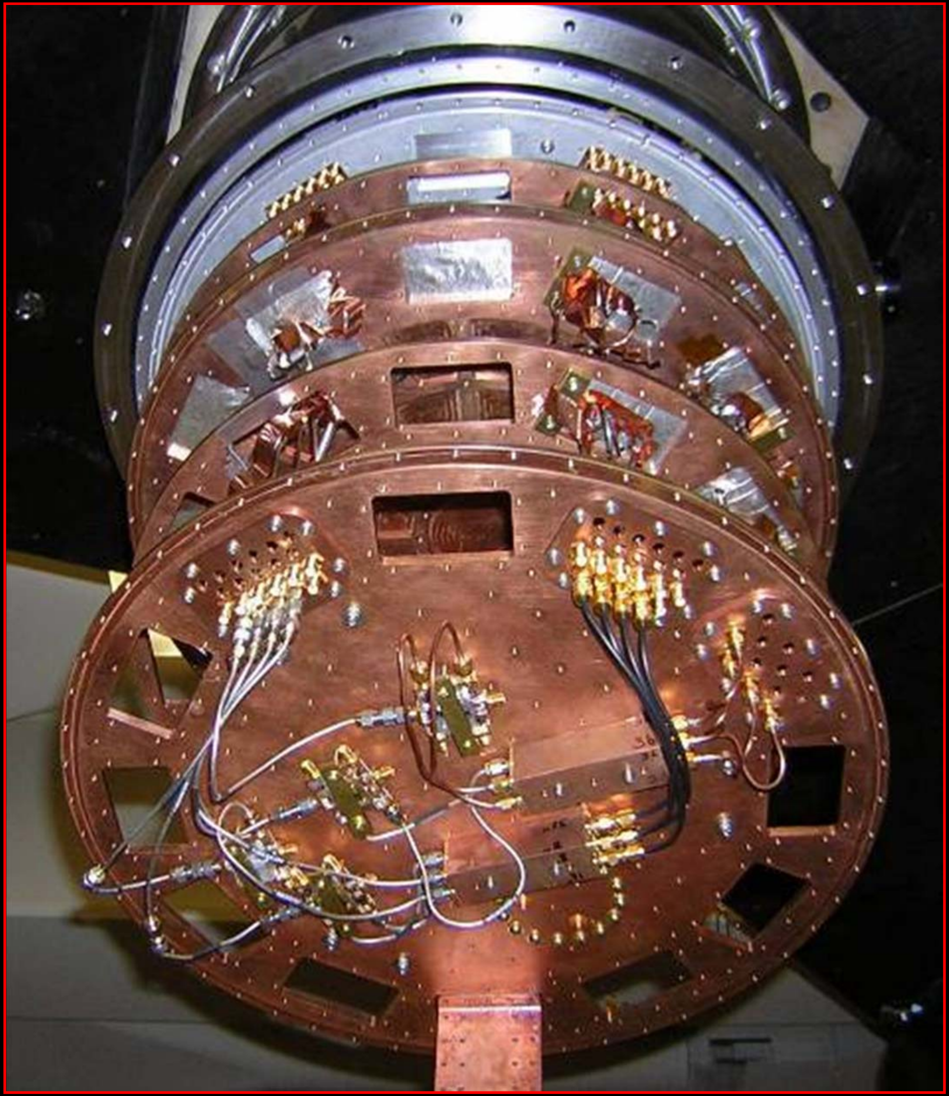
experimental system



experimental system

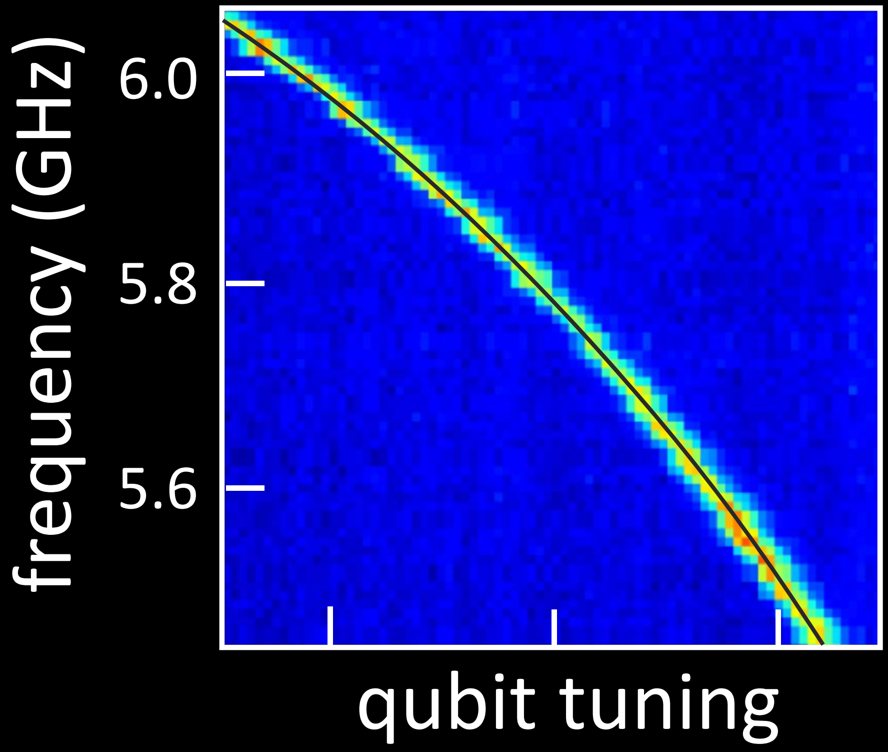




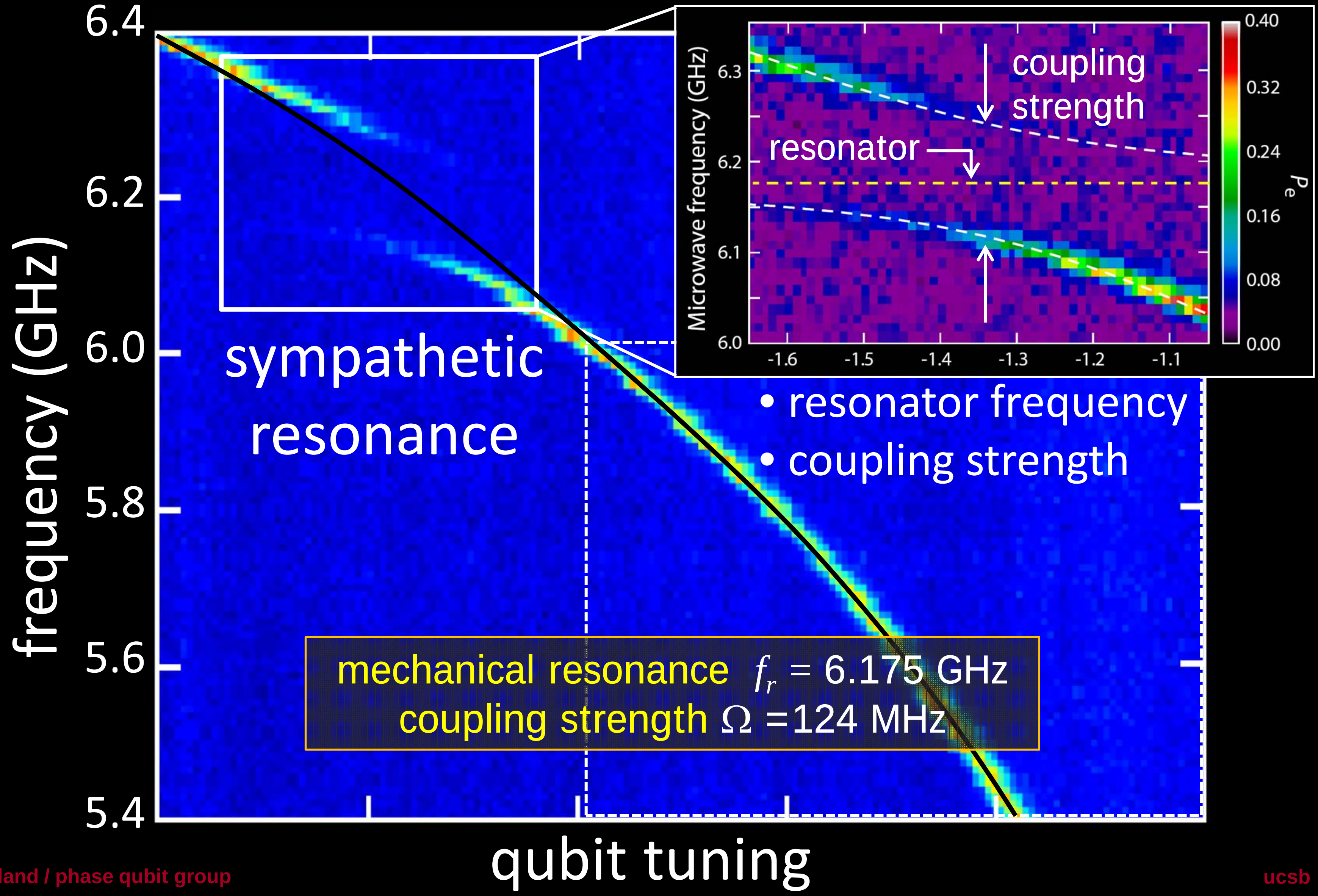


experimental system

- Tune qubit frequency
- Measure resonance ("pluck & listen")
- Qubit tunes as expected



experimental system



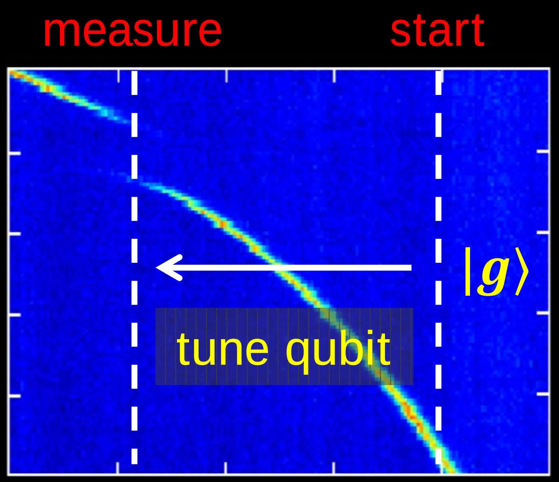
sympathetic resonance

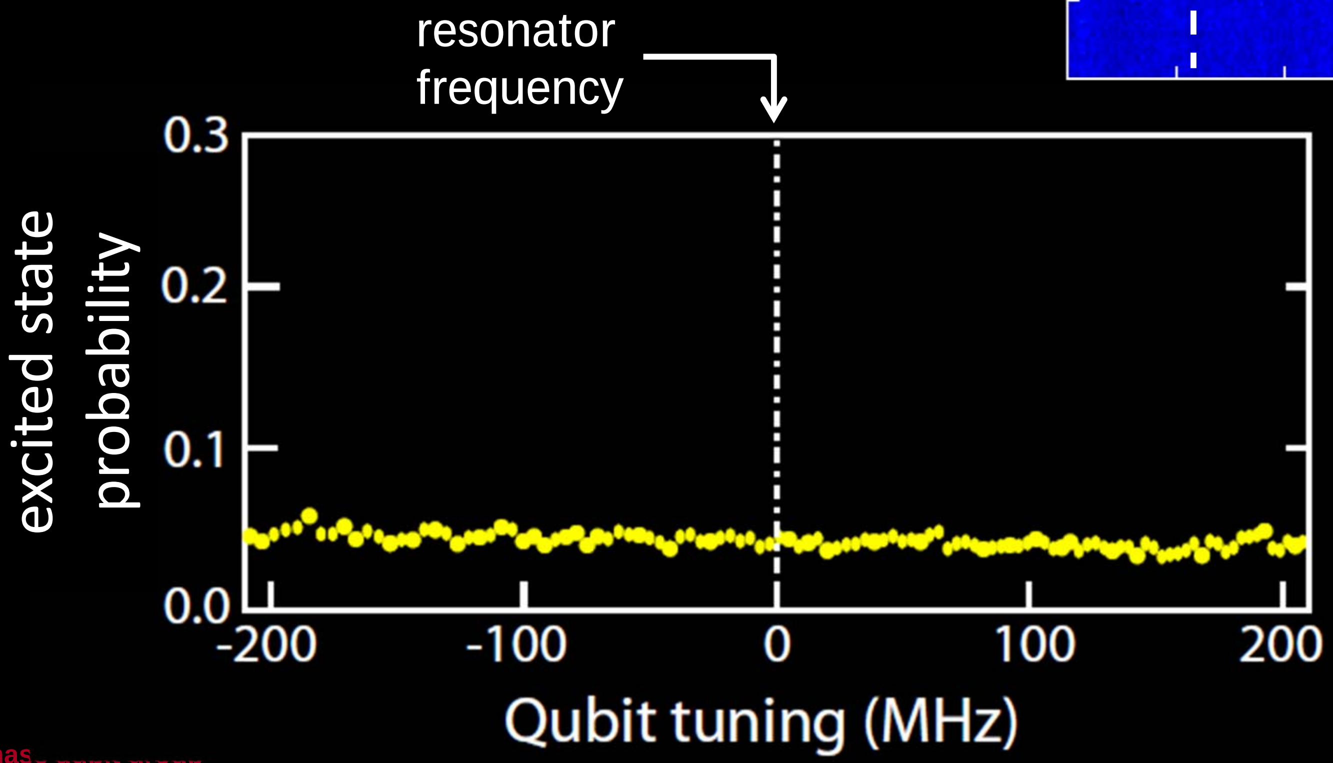
- resonator frequency
- coupling strength

mechanical resonance f_r = 6.175 GHz
coupling strength Ω =124 MHz

quantum ground state

- Qubit as thermometer
- Measure resonator temperature
- Sensitive to a single quantum





quantum ground state

- Qubit as thermometer
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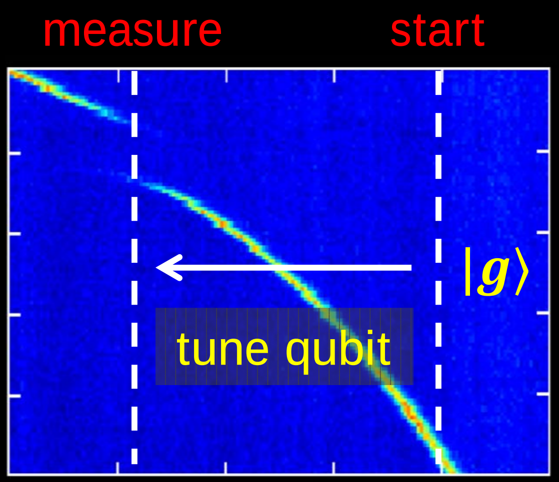
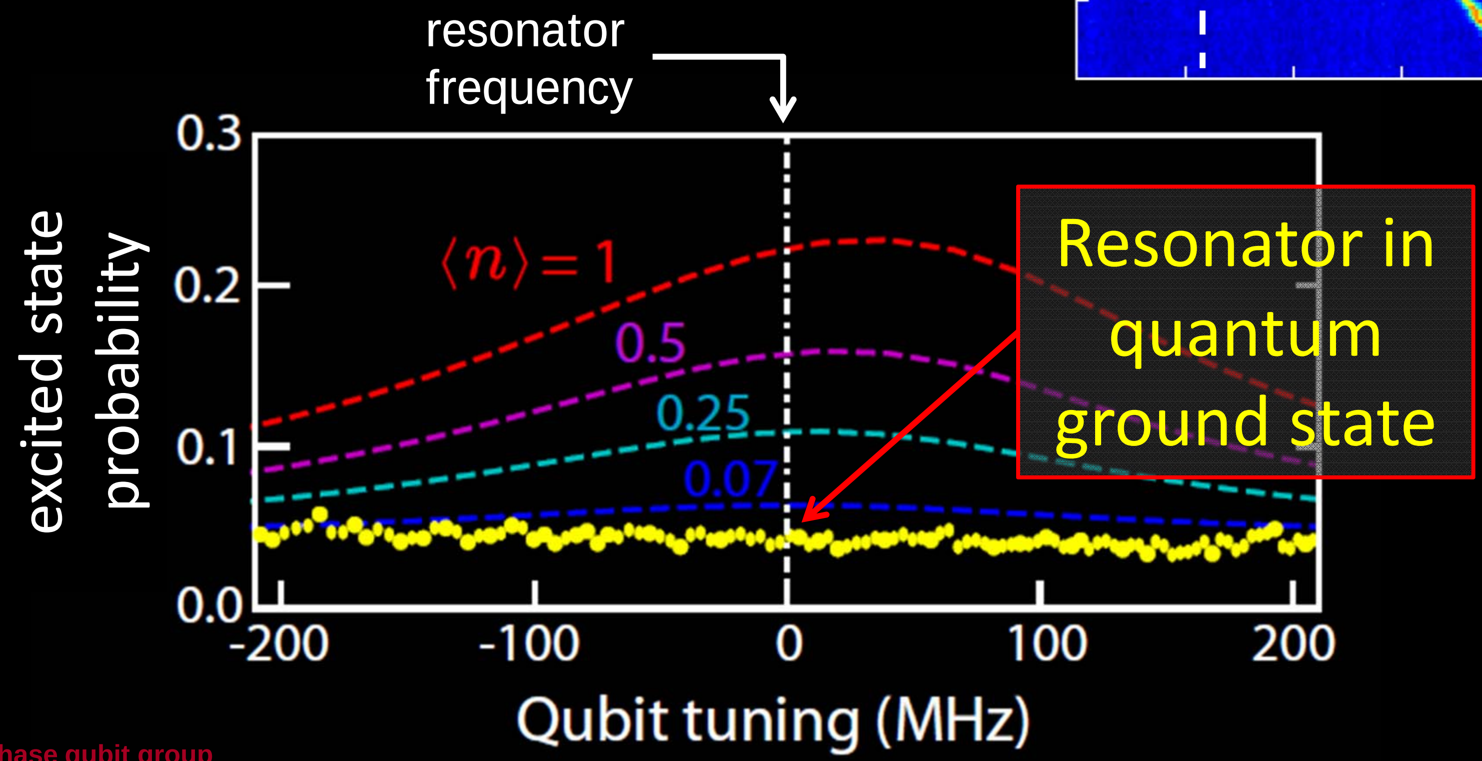
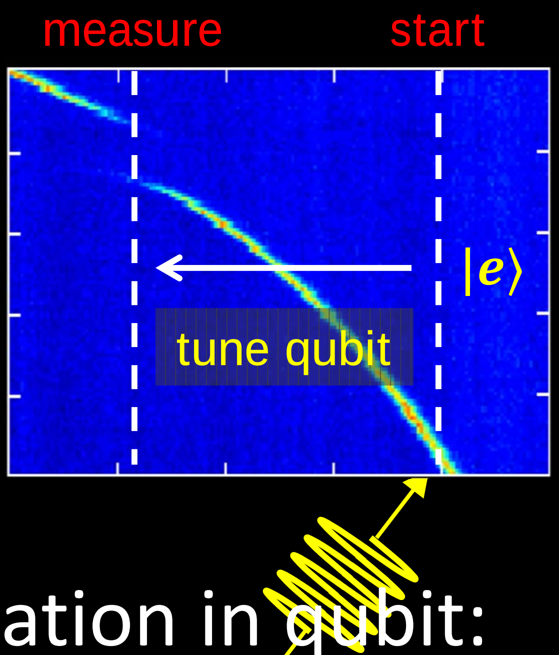




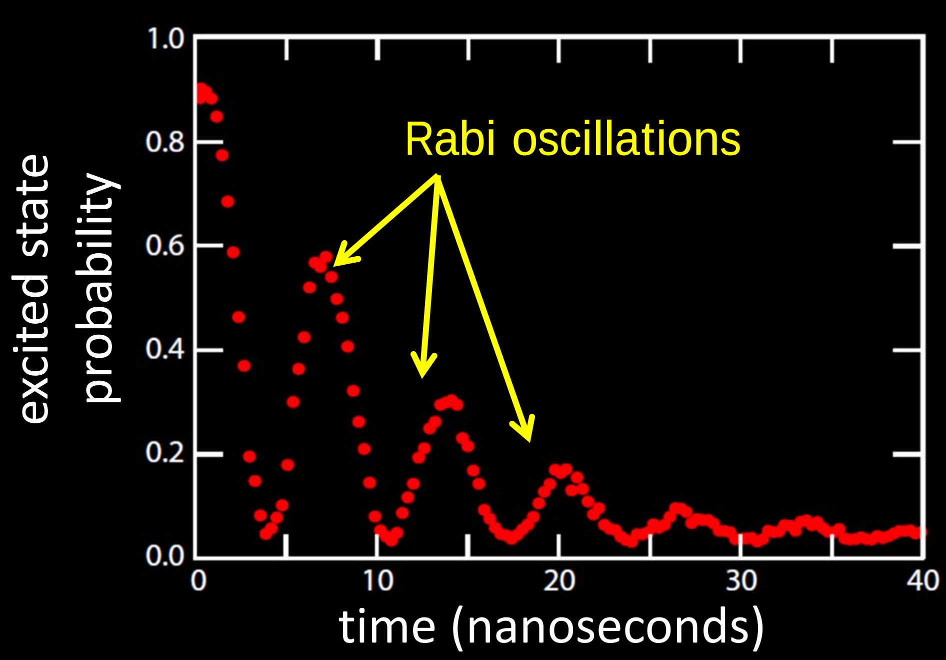
Resonator in quantum ground state

first excited state

- Excite qubit
- Tune to resonance
- Create sympathetic resonance:
  - ➢ Transfer one quantum to resonator



excite with one quantum

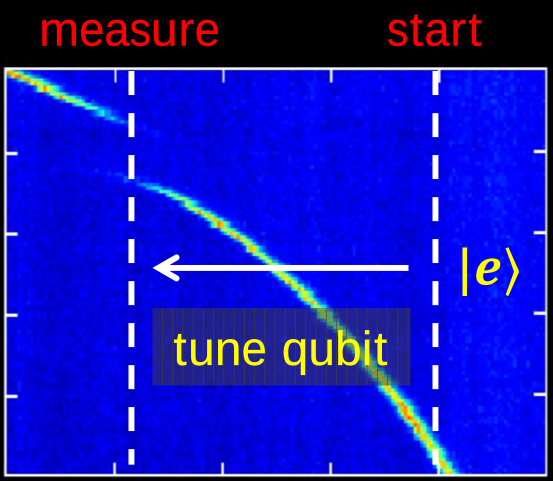


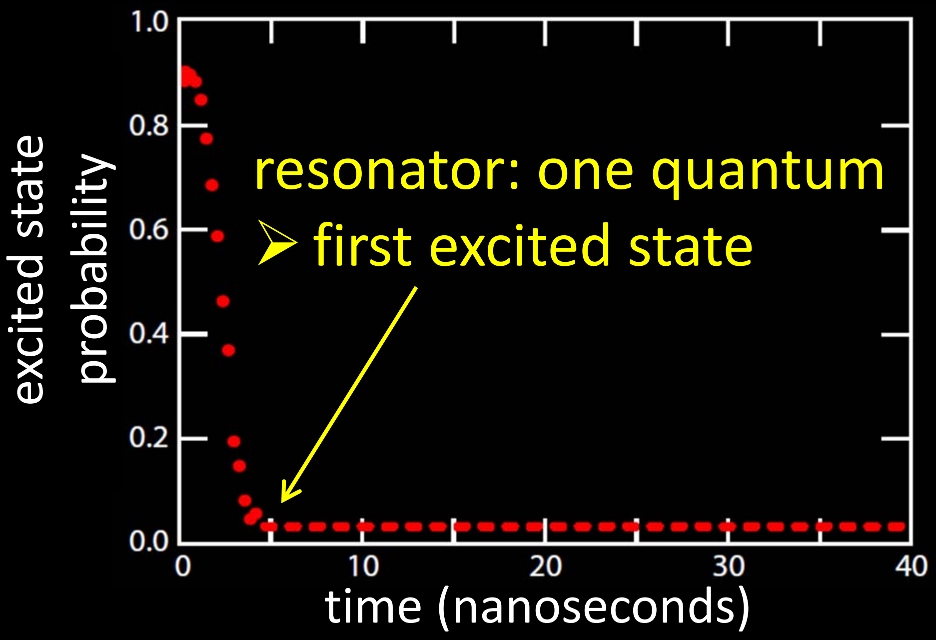
oscillation in qubit:

- sympathetic resonance
- single quantum exchange
- quantum resonator

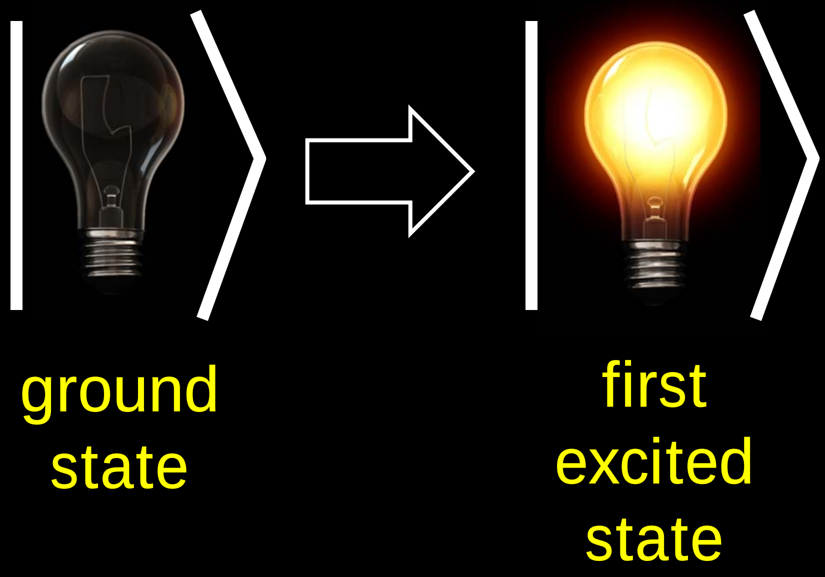
first excited state

- Excite qubit
- Tune to resonance
- Create sympathetic resonance:
  - ➢ Transfer one quantum to resonator

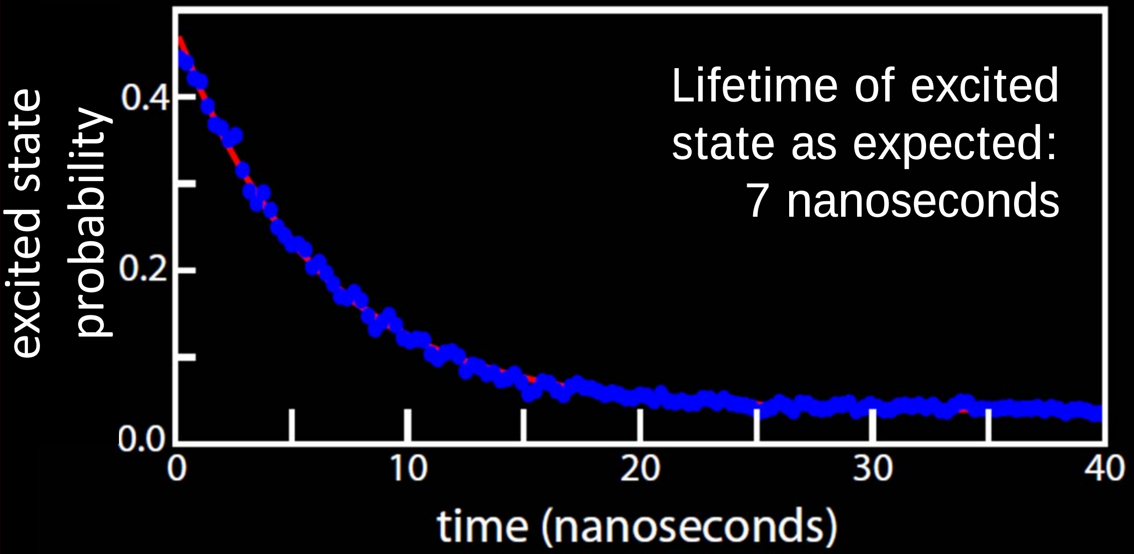




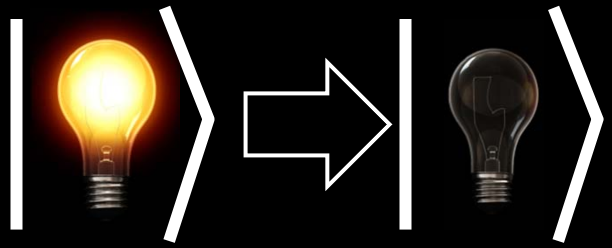
resonator: one quantum
➢ first excited state

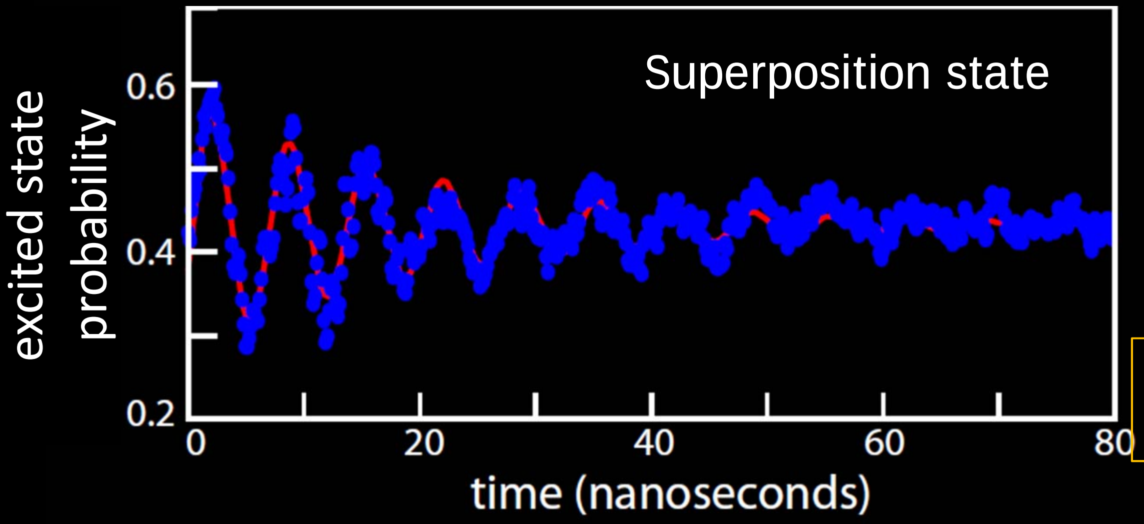


superposition states

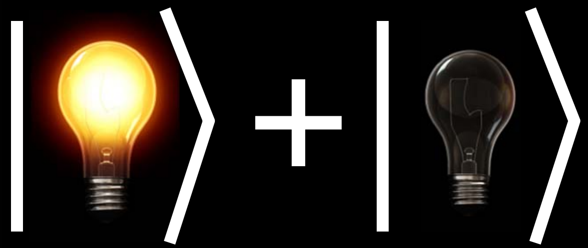

Lifetime of excited state as expected: 7 nanoseconds

Decay from excited state to ground state



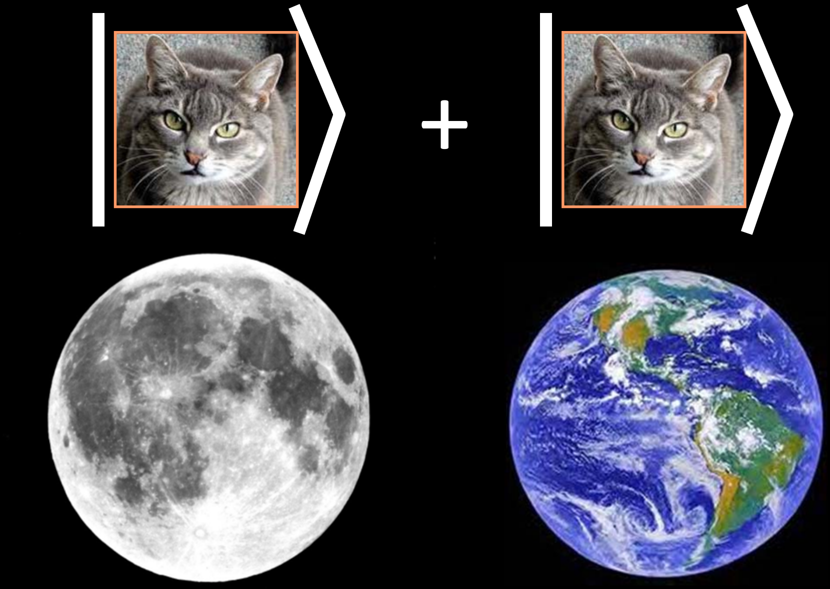

Superposition state

Superposition state



10 trillion atoms

Schrödinger’s cat

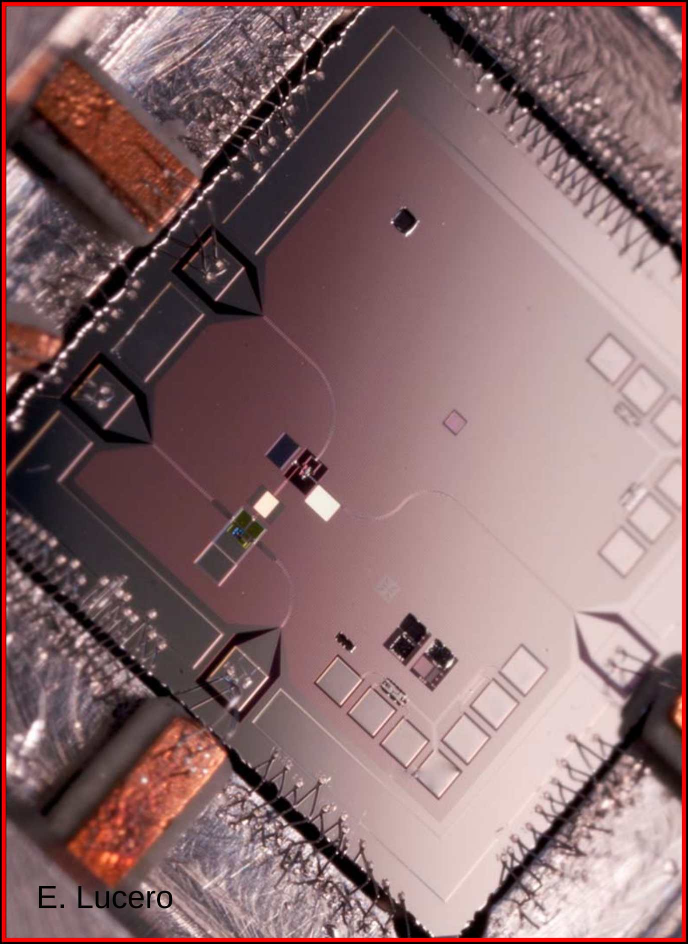


We are still very far from a “cat superposition”

Requirements:

- Minimal thermal noise
- Very weak coupling to environment
- Quantum coherence over long enough times

How to be in two places at the same time



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John M Martinis

Rami Barends
Jörg Bochmann
Yu Chen
(Max Hofheinz)
Matteo Mariantoni
(Haohua Wang)
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Julian Kelly
Erik Lucero
Peter O'Malley
Daniel Sank
James Wenner
Ted White

Anthony Megrant
Charles Neill
(Aaron O'Connell)
Amit Vainsencher

graduate students

support:
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