# Photons and Schrödinger Cats: Quantum Optomechanics

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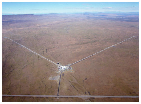
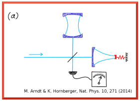
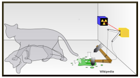
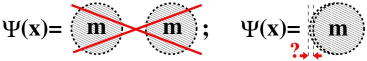




M. Arndt & K. Hornberger, Nat. Phys. 10, 271 (2014)



Wikipedia



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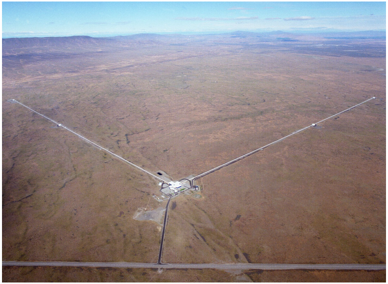
# Abstract

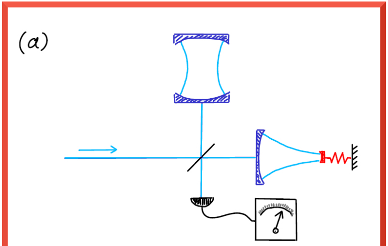
Quantum mechanics of massive mechanical motion produces paradoxical results. Schrödinger drafted in 1935 how the quantum state of a live cat would in principle evolve into the superposition of the live and the dead. For half a century, preparation of massive objects in macroscopically different superpositions was practically impossible. Some speculated that such superpositions should be precluded by modified quantum mechanics. Meanwhile a tremendous development happened in a different field: quantum optics. Photons became the most trustable and flexible probes of quantum systems coupled to them. They became the probes of massive mechanical objects. In quantum optomechanics, a quantized oscillator weighting nanograms or even grams, is coupled to photons for double purpose: preparation and detection of controlled quantum state of the massive oscillator. In the forthcoming decade, optomechanical experiments running already in labs or planned in space may confirm the validity of quantum mechanics for massive objects. Or, alternatively, optomechanics may confirm if standard quantum mechanics gets violated in massive objects.

# Fotonic facilities: largest, smallest



LIGO (Laser Interferometer Gravitational Wave Observatory) at Hanford, Washington State. Michelson interferometer with two 4km arms, pumped by high power laser.

Sketch of table top Michelson interferometer, size about few cm's, "pumped" by a single foton at a time, to test mechanical Schrödinger Cats.



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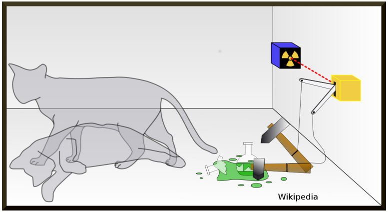
# Expanding domain of quantum theory

- black body radiation
- atom, molecule
- electron
- condensed matter
- elektrodynamics
- nucleus
- elementary particles
- **massive bodies/gravitation ?**
- cosmology?
- information
- living material ?
- human consciousness ?

# Quantum theory of massive bodies?

QM at large can be paradoxical: Schrödinger's Cat (1935)



Lock a live cat and a poisoning mechanism triggered when radioactive decay detected, all inside a black box. Switch off the mechanism at meantime, the cat is remains in superposition forever:

$$\Psi = |alive\rangle + |dead\rangle.$$

Unless you open the box and look at the cat, to cause wave function collapse at random:

$$|alive\rangle + |dead\rangle \Longrightarrow \begin{cases} |alive\rangle \\ |dead\rangle \end{cases}$$

That's standard QM extended for large objects!
Make tractable physics! Change cat for a massive sphere, *alive-or-dead* for *here-or-there*:

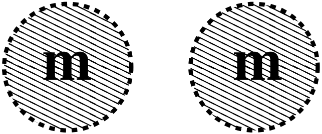
$$|alive\rangle + |dead\rangle \longrightarrow |here\rangle + |there\rangle$$

# Quantum theory of massive bodies?

Mechanical “Schrödinger Cat”:

large “catness”

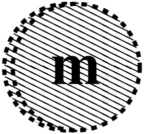
$\Psi(x)=$



;

small “catness”

$\Psi(x)=$



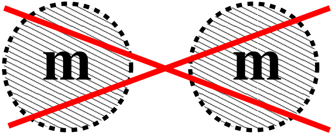
No evidences yet:

- Experiments: max. 10000 amu (2013)
- Theory: ambiguity of Cat’s Newton field (1981)

Why don’t we see any “Cats” in Nature:

- Cats are masked by environmental noise (1970)
- Cats decay spontaneously by gravity-related noise (1986)

$\Psi(x)=$



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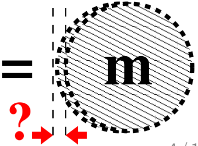
$\Psi(x)=$



# Mechanical Schrödinger Cat in lab

Preperation: extremely demanding for

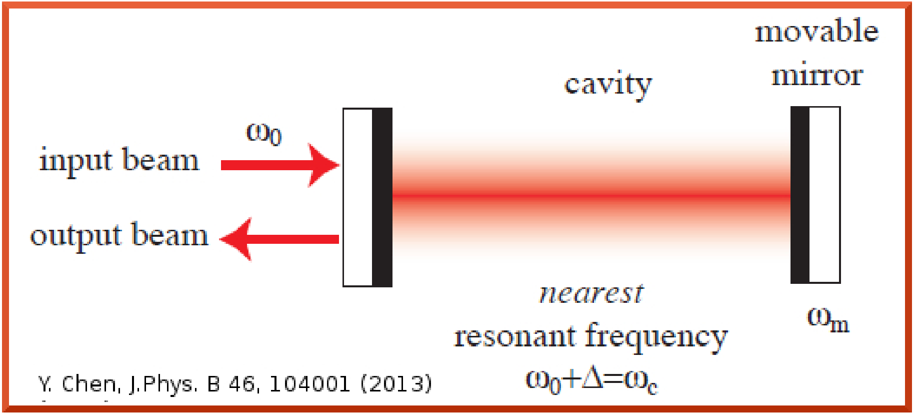
- isolation from environmental noise
  cooling to $\mu$K
  smart suspending, supporting, binding, trapping
- creation of distant *here* and *there*
  by interaction with an other Cat :)
  by many (controlled) interactions with microscopic systems

Verification: extremely demanding for

- the point is interference between *here* and *there*
- can't fly through double-slit, grating

Light quanta helps!
**Optomechanics**: thermal isolation, laser cooling, optical binding, trapping, controlled fotonic interactions, fotons map interference between *here* and *there* into detector counts, ...

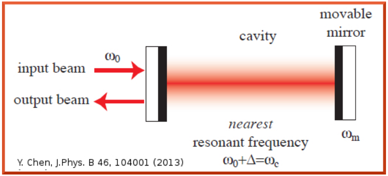
# Quantum optomechanics



Y. Chen, J.Phys. B 46, 104001 (2013)

Two end-mirrors form optical cavity, pumped by input laser beam $\omega_0$, excites nearest e.m. mode $\omega_c = \omega_0 - \Delta$. Mirror on rhs is movable, vibrates like mechanical oscillator $\omega_m$, it is our massive object. Output laser beam encodes position of the rhs mirror.

# Quantum optomechanics — theory



Y. Chen, J.Phys. B 46, 104001 (2013)

i) simple part (Open Q-systems)

- cavity e.m. mode = damped oscillator
- movable mirror = damped oscillator
- coupling = light pressure

ii) less simple part (Input-output formalism)

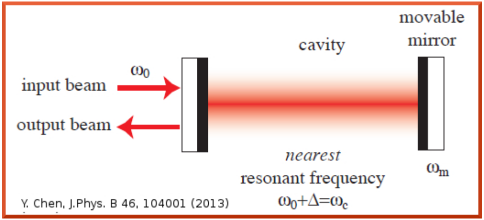
- laser input beam = periodic driving + vacuum fluctuations
- output beam = periodic field + vacuum fluctuations

iii) difficult part (Q-monitoring theory)

- time-continuous measurement of the output beam
- extraction of information on position of movable mirror

# Quantum optomechanics — laser cooling

- Laser cooling was invented for atoms (1978)
- It works for our vibrating mirror as well
- In optomechanics: many cooling methods
- Ground state cooling: mK if $\omega_m$~MHz (2011); $\mu$K if $\omega_m$~kHz (????)



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**Resolved side-band cooling**:

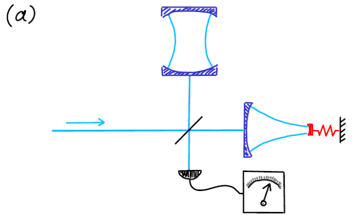
Laser $\omega_0$ tuned below cavity $\omega_c$ just by the mechanical $\omega_m$:

$$\omega_0 + \omega_m = \omega_c$$

Input beam foton can become resonant with the cavity by stealing one energy quantum of the vibrating mirror. The opposite process is off-resonant and suppressed. So, energy flows from mechanical motion to cavity mode. Then cavity dissipates it to the environment.

# Quantum optomechanics — mechanical Cat

Pg mirror on cantilever, $\omega_m \sim$kHz.
Single foton splits into one of the arms.
In “horizontal arm”: light pressure.
In “vertical” arm: no light pressure.
Foton reunites toward bottom or left.
Detector clicks can verify Cat state:
$\Psi = |shifted\ osc.\rangle + |fiducial\ osc.\rangle$



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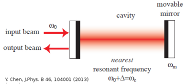
Competing demands:

- soft (kHz) oscillator for light pressure is small
- hard (MHz) oscillator for ground-state cooling

Will be a long march from proposal (2003) to Cat.

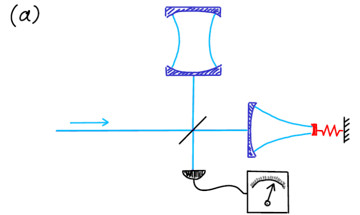


Y. Chen, J.Phys. B 46, 104001 (2013)

# Back to largest, smallest

Advanced LIGO:

- smartly suspended $40$kg mirror
- oscillating at $\omega_m \sim 1$Hz
- control down to quantum limits



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Quantum Optomechanics on table top:

- Foundations: big mass is quantum
- Dozens of running exp.'s
- Proposal: table top on satellite (2012)

Y. Chen: *Macroscopic quantum mechanics: theory and experimental concepts of optomechanics* JPB: At.Mol.Opt.Phys. **46**, 104001 (2013).

M. Arndt, K. Hornberger: *Testing the limits of quantum mechanical superpositions* Nat. Phys. **10**, 271 (2014).