Test of quantum gravity effects with mechanical oscillators

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HUMOR

Heisenberg Uncertainty Measured with Opto-mechanical Resonators

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Planck units

Special Relativity → c

Quantum Mechanics → $\hbar$

Newton Theory → G

It is interesting to note that with the help of the [above constants] it is possible to introduce units [...] which [...] remain meaningful for all times and also for extraterrestial and non-human cultures, and therefore can be understood as 'natural units'.

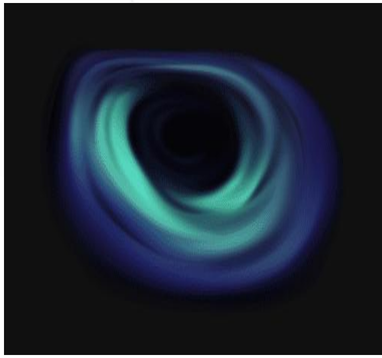
Max Planck, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin (1899), p. 479

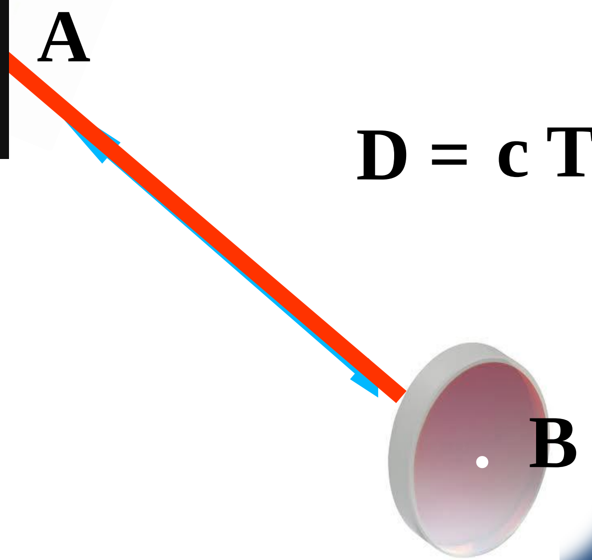
$$m_p = \sqrt{\frac{\hbar c}{G}} \simeq 2.18 \times 10^{-8}\ kg \sim 1.2 \times 10^{19}\ \mathrm{GeV}$$

$$l_p = \sqrt{\frac{\hbar G}{c^3}} \simeq 1.62 \times 10^{-35} m$$

$$t_p = \sqrt{\frac{\hbar G}{c^5}} \simeq 5.39 \times 10^{-44} s$$

Limits to distance measurements





$$\Delta v \sim \frac{\hbar}{2m\Delta x}$$

A mass m compressed in a sphere of radius D must be

$$m < \frac{Dc^2}{G}$$

(Schwarzschild limit)

BLACK HOLE

$$\Delta D \sim \delta x + \frac{\hbar T}{2m\Delta x} \Rightarrow \Delta D_{min} = \sqrt{\frac{\hbar T}{2m}} = \sqrt{\frac{\hbar D}{mc}}$$

$$\Delta D_{min} \geq \sqrt{\frac{\hbar G}{c^3}} = L_p$$

Quantum gravity phenomenology

Quantum Mechanics + Gravity → Minimal measurable length

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta_0 \left(\frac{L_p \Delta p}{\hbar}\right)^2\right) \qquad \Delta x_{min} = \sqrt{\beta_0} L_p$$

Physical interpretation

1. The high energies used to probe Planck-scale distances disturb the spacetime geometry ('Induced' spacetime fuzziness) → High-energy experiments
2. Quantum space-time fluctuations related to the creation and annihilation of particles (Spacetime is 'intrinsically' discrete) → Low energy experiments

GUP can be associated to a modified canonical commutator

$$[x, p] = i\hbar \left(1 + \beta_0 \left(\frac{p}{M_p c}\right)^2\right)$$

MODIFIED SPECTRUM OF A QUANTUM SYSTEM

MODIFIED DYNAMICS → MORE STRINGENT LIMITS

Phenomenological quantum gravity

- General 'remark': one cannot determine a position with an accuracy better than the Planck length **$L_P = \sqrt{hG/c^3} = 1.6\ 10^{-35}$ m**
- Generalized Heisenberg uncertainty relations (GUP)
- Generalized commutators between *p* e *q*
- Modified quantum physics

→ Detecting signatures of Planck scale-physics in highly-sensitive metrological systems

Basic assumptions:

$$\frac{d\hat{O}}{dt} = \frac{1}{i\hbar}[\hat{O}, H]$$

Heisenberg dynamics

$$[x, p] = i\hbar\left(1 + \beta_0\left(\frac{p}{M_p c}\right)^2\right)$$

Deformed commutation relations

from $\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta_0\left(\frac{\Delta p}{M_p c}\right)^2\right)$

$$H = \frac{\hbar\omega_0}{2}\left(X^2 + P^2\right)$$

Solution:

$$\beta = \beta_0 \frac{\hbar m \omega_0}{M_p^2 c^2}$$

$$X = X_0\left[\sin(\tilde{\omega}t) + \frac{\beta}{8}X_0^2 \sin(3\,\tilde{\omega}t)\right]$$

3° harmonic

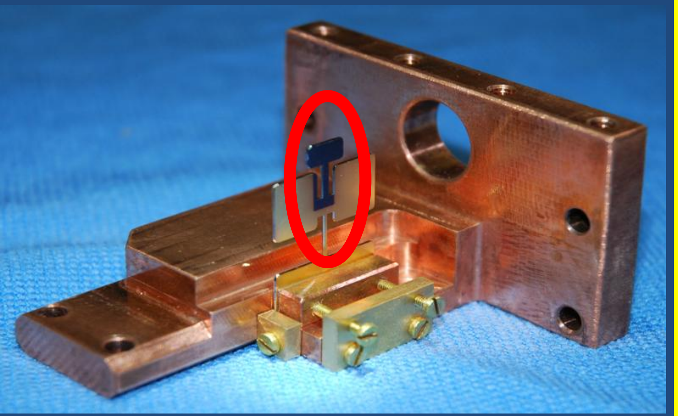
$$\tilde{\omega} = \left(1 + \frac{\beta}{2}X_0^2\right)\omega_0$$

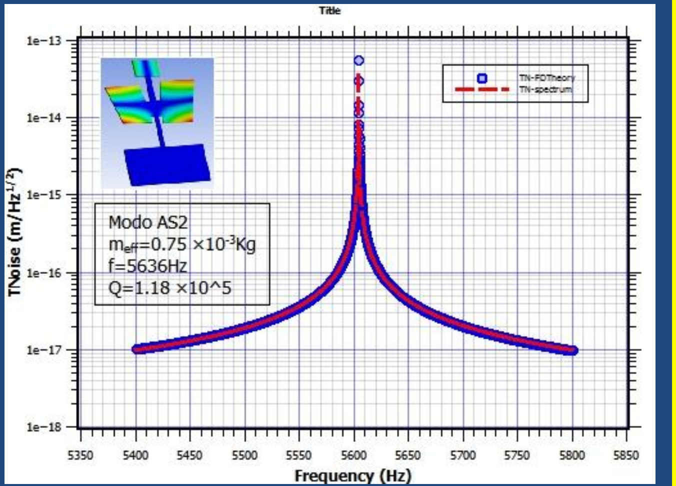
Freq. shift

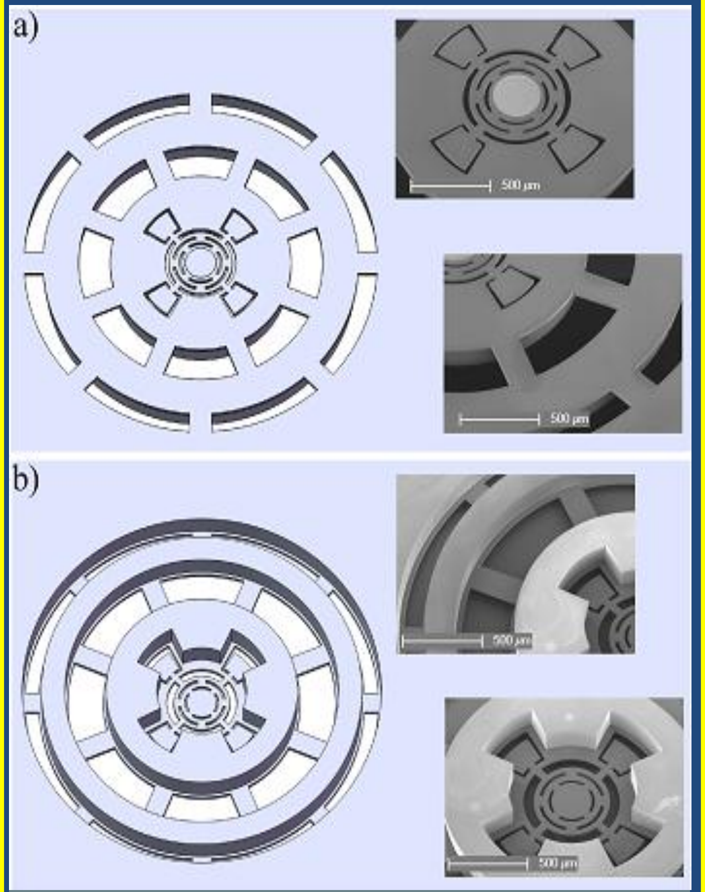
(First order in βX_0^2)

- Test on a wide mass range
- High mechanical quality factor $\rightarrow$ ‘isolated’ oscillators
- Exploit the slow decay to obtain frequency/3° harmonic vs amplitude curves

1° oscillator:	2° oscillator:	3° oscillator:
$m \cong 1$ g	$m \cong 100$ μg	$m \cong 100$ ng





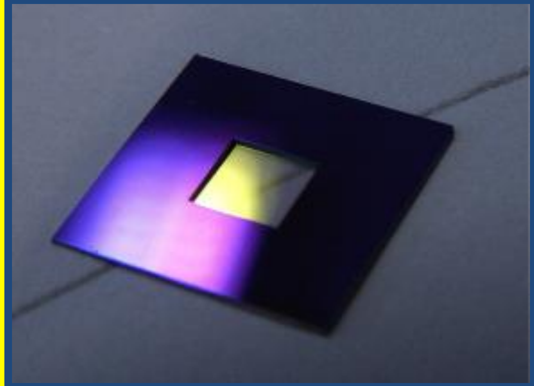


$m = 20$ μg

$f_m = 141$ KHz

$Q = 1.2 \times 10^6$

$T = 4.3$ K

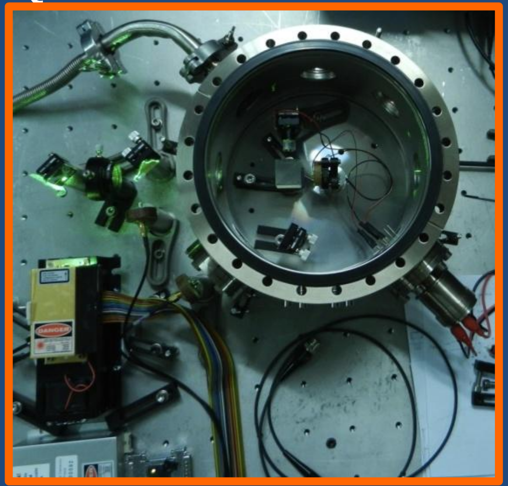


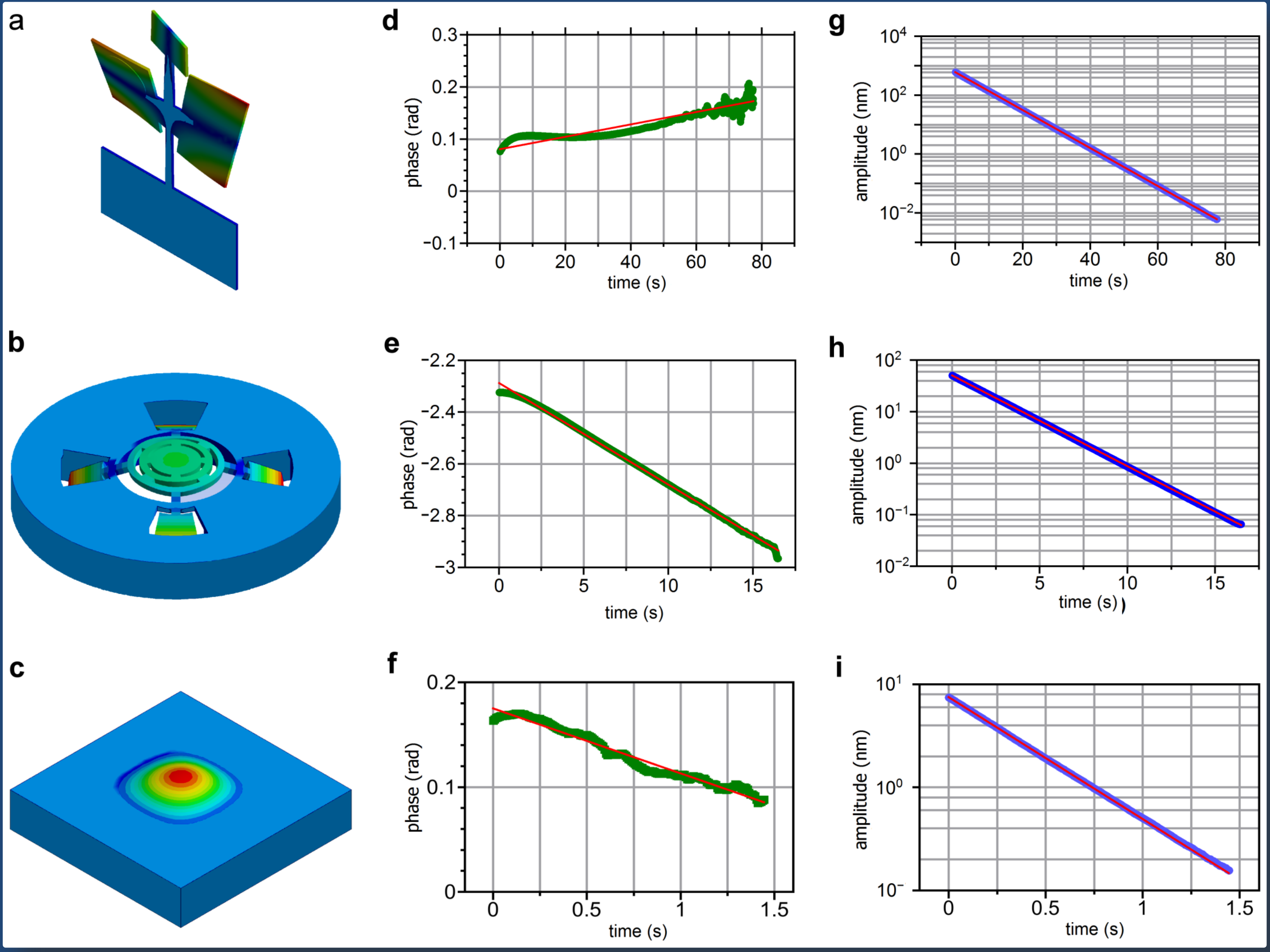
SiN membrane

0.5×0.5 mm^2 x 50nm

mass = 135 ng

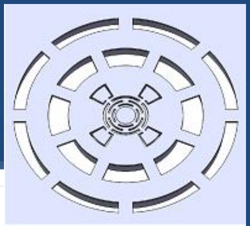
$Q = 8.6 \times 10^5$

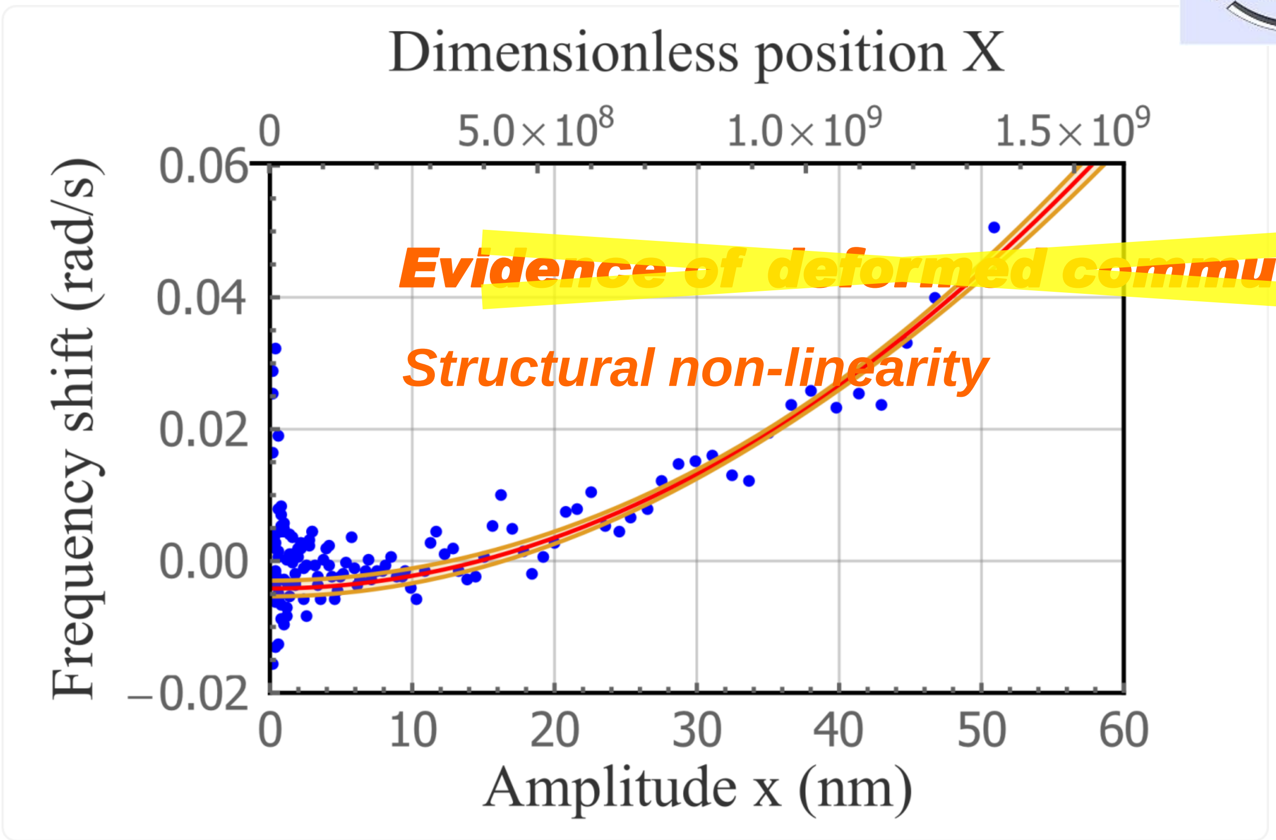




a
b
c
d
e
f
g
h
i
phase (rad)
amplitude (nm)
time (s)

$$\tilde{\omega} = \left(1 + \frac{\beta}{2} X_0^2\right)\omega_0$$

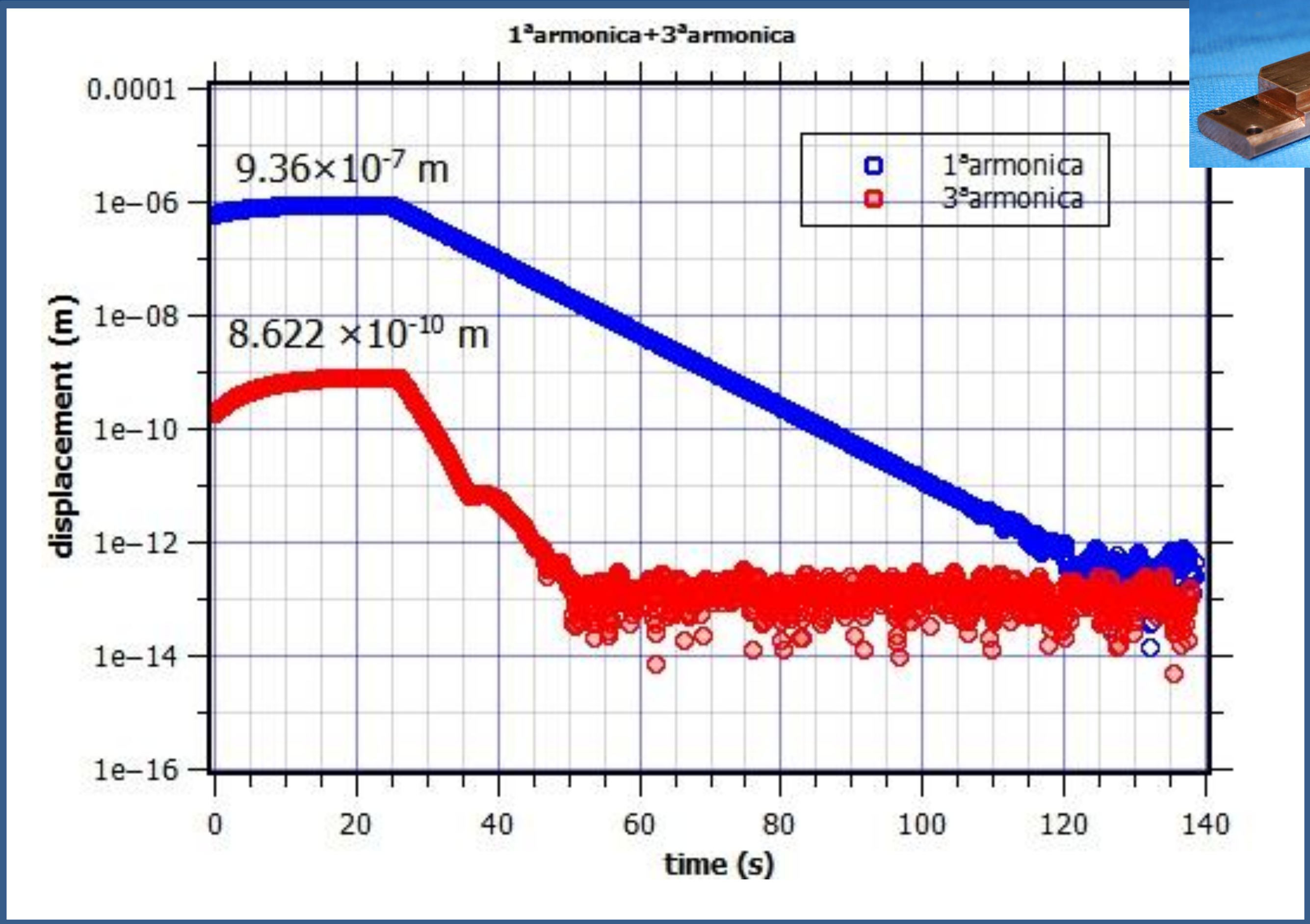


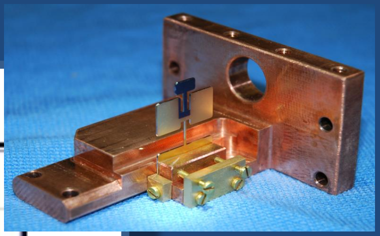


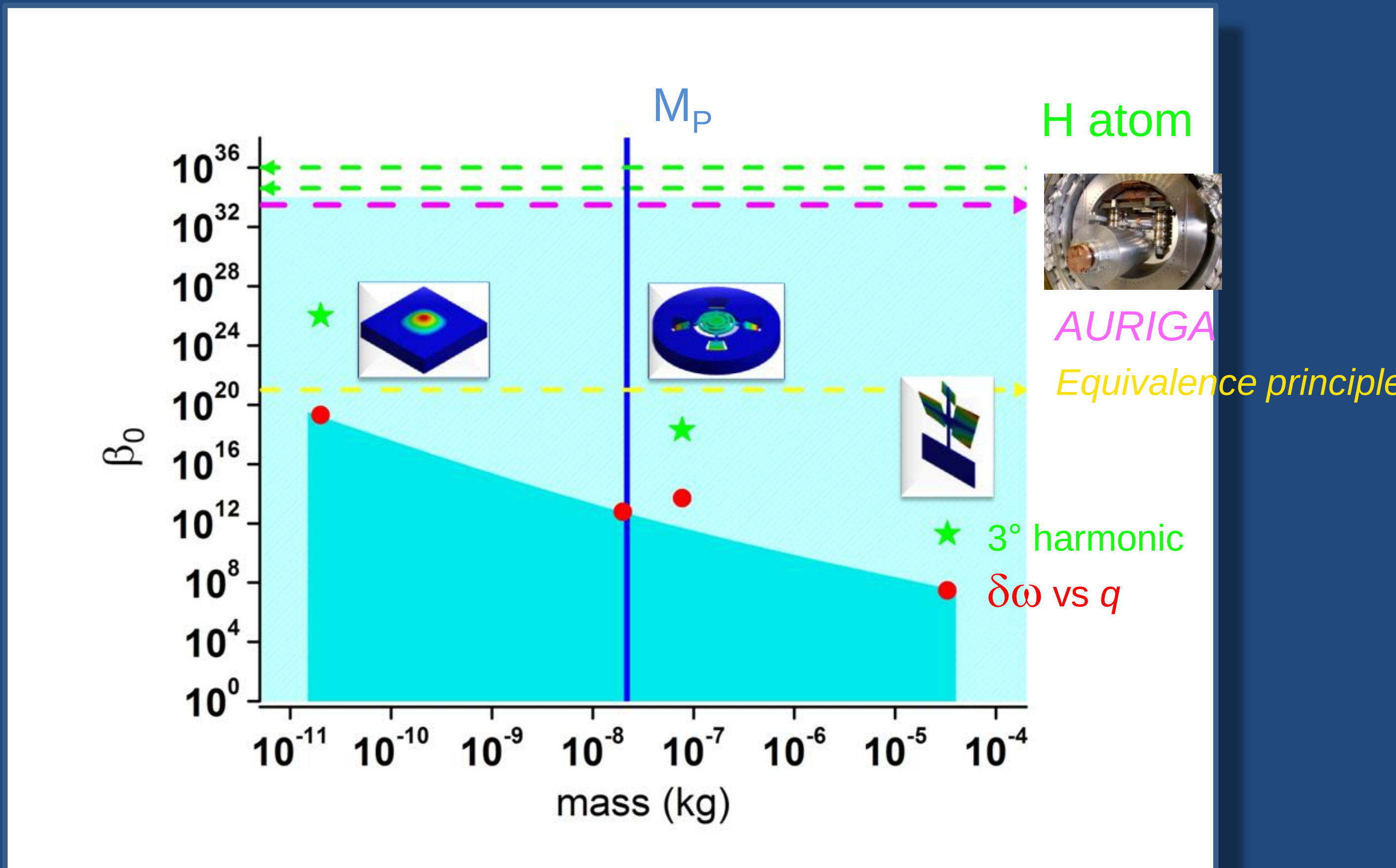
'Model-independent' limits

Mass (kg)	Frequency (Hz)	Max. ampl. (nm)	Max. Q_0	Max. $\Delta\omega/\omega_0$
3.3×10^{-5}	5.64×10^{3}	600	6×10^{10}	4×10^{-7}
2×10^{-8}	1.42×10^{5}	55	7×10^{8}	6×10^{-8}
2×10^{-11}	7.47×10^{5}	7.5	7×10^{6}	4×10^{-8}

$$X = X_0\left[\sin(\tilde{\omega}t) + \frac{\beta}{8}X_0^2\sin(3\,\tilde{\omega}t)\right]$$







M. Bavaj. et al., arXiv: 1411.6410 (to be published on Nature Communications)

If a deformed commutator applies to the coordinates of a *fundamental constituent*, then its effect on a macroscopic object (composed of N such constituents) should decrease as 1/N

- what is a fundamental constituent?
- geometrical properties of space-time $\rightarrow$ property of each particle
- not in the spirit of quantum mechanics: the position and momentum of an oscillator c.m. should be THE meaningful (i.e., measurable) quantities. Uncertainty relation between p and q is tightly related to the general problem of quantum measurements (see Braginsky, Caves, etc.)

LETTER

1038/nature10461

Focus on peculiar quantum properties

Deriving bounds on the deformation parameter in the QUANTUM regime.

Are there alternative, more “quantum” ways that can be applied in the quantum regime ?

Modified commutators and deformed uncertainty relations could be directly seen by looking at **second order moments (covariance matrix).**

Straightforward way: deformation seen as **NONGAUSSIAN modification of the steady state of the system** (possible estimators from higher-order correlations in homodyne measurement data); bounds for β derived from upper bounds of a nonGaussianity parameter

Less straightforward:

i) use more general measure of non-Gaussianity (M. Genoni et al., PRA A **78**, 060303(R) (2008))
ii) Detecting signature of the deformation parameter β from the dynamics of variances (it is already known that deformed commutators yield a small quadrature squeezing)

Testing non-local EFT with macroscopic quantum objects?

$$\epsilon = \frac{m\omega}{\hbar\Lambda^2}$$

Suppose

$$m = 1\mu g = 10^{-9}Kg$$

and

$$\omega \approx 5 \cdot 10^4 Hz.$$

Then our parameter will be

$$\epsilon \approx 5 \cdot 10^{29} l_{nl}^2$$

that means

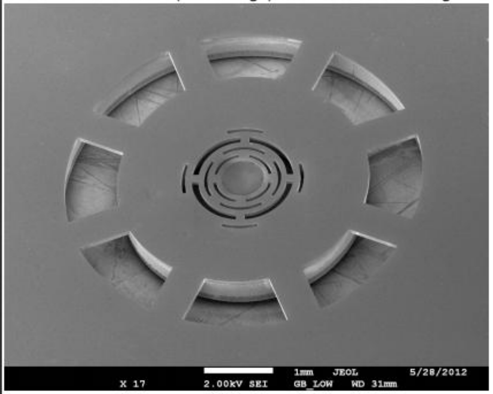
$$\epsilon \ll 1 \Leftrightarrow l_{nl} \ll \sqrt{2} \cdot 10^{-14} m$$

The expansion is justified for small ε but for it to be within experimental reach one wants macroscopic quantum objects.
Best case scenario: macroscopic quantum oscillators? (or alternative lighter but better developed BEC?)

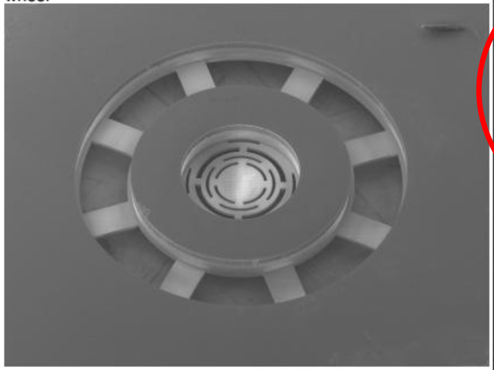
HUMOR
Heisenberg Uncertainty Measured with Opto-mechanical Resonators

Collaboration SISSA gravity group with with F. Marin, F. Marino, A. Ortolan.

1 - Front view of DWO (SEM image) with the central coating



2 - Back view DWO (SEM image) with the insulation wheel



Determine evolution of

$$\langle x \rangle = \langle \psi | \, x \, | \psi \rangle$$

$$\langle x^2 \rangle$$ and correlators...

See
F. Marin talk...

Others on gravity + macro quantum oscillator

PRL 112, 210404 (2014) PHYSICAL REVIEW LETTERS

Proposal for a Noninterferometric Test of Collapse Models in Optomechanical Systems

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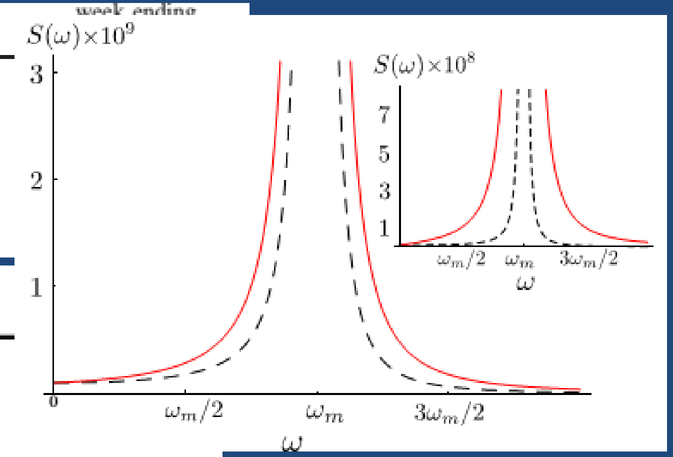

PRL 110, 170401 (2013) PHYSICAL REVIEW LETTERS

Macroscopic Quantum Mechanics in a Classical Spacetime

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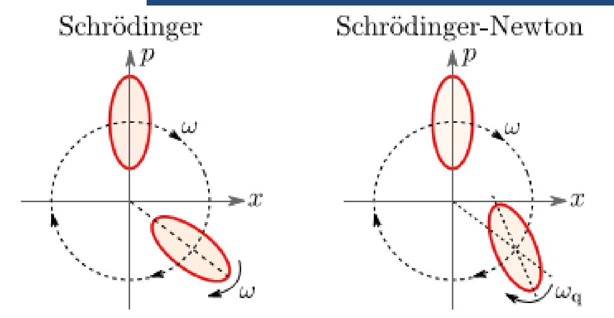
We apply the many-particle Schrödinger-Newton equation, which describes the coevolution of a many-particle quantum wave function and a classical space-time geometry, to macroscopic mechanical objects.



Gravity-related spontaneous wave function collapse in bulk matter

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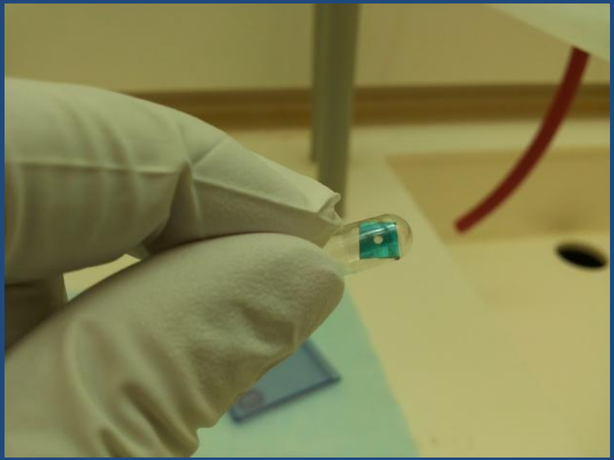
Abstract
In the DP-model, gravity-related spontaneous wave function collapses suppress Schrödinger cat states which are conceptually problematic especially for gravity and space-time. We derive the equations of the model for the hydrodynamic-elastic (acoustic) modes in a bulk. Two particular features are discussed: the universal dominance of spontaneous collapses at large wavelengths, and the reduction of spontaneous heating by a slight refinement of the DP-model.

… toward a quantum mechanical oscillator

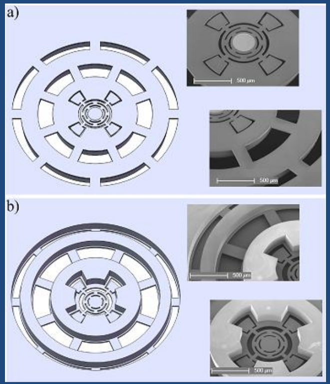
(quantum fluctuations prevails over thermal fluctuations)

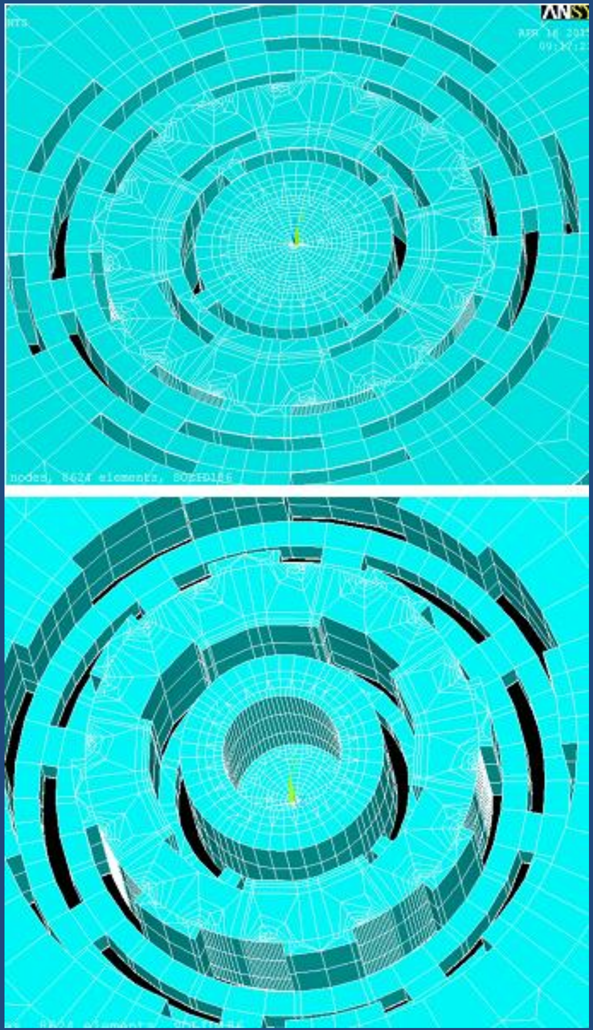
- nanoparticle trapped in optical potential
- SiN nano-membranes



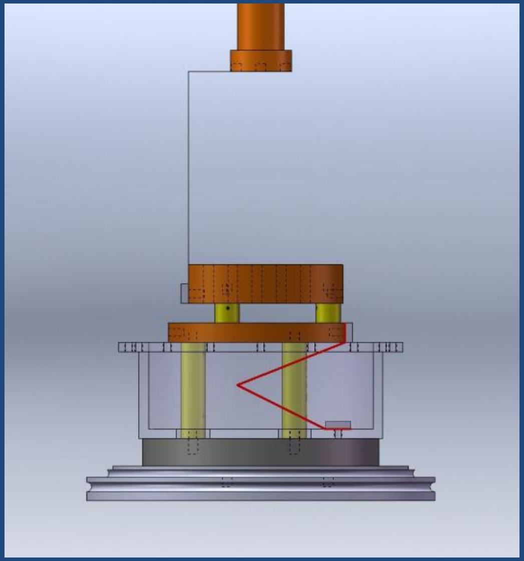
Fabricated SiN membranes by deep-DRIE

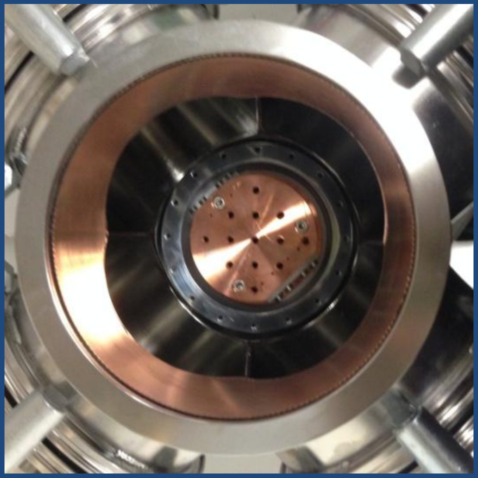
The membranes will be integrated on isolation systems realized from SOI

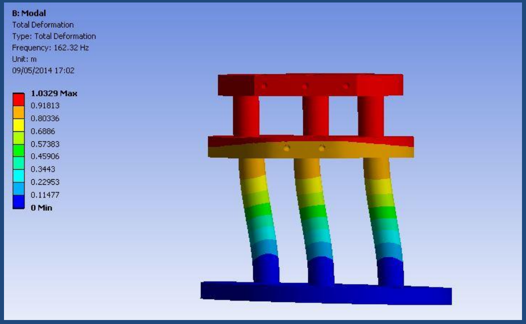




Designed and realized a low-noise cryostat







… tests on quantum oscillators coming soon