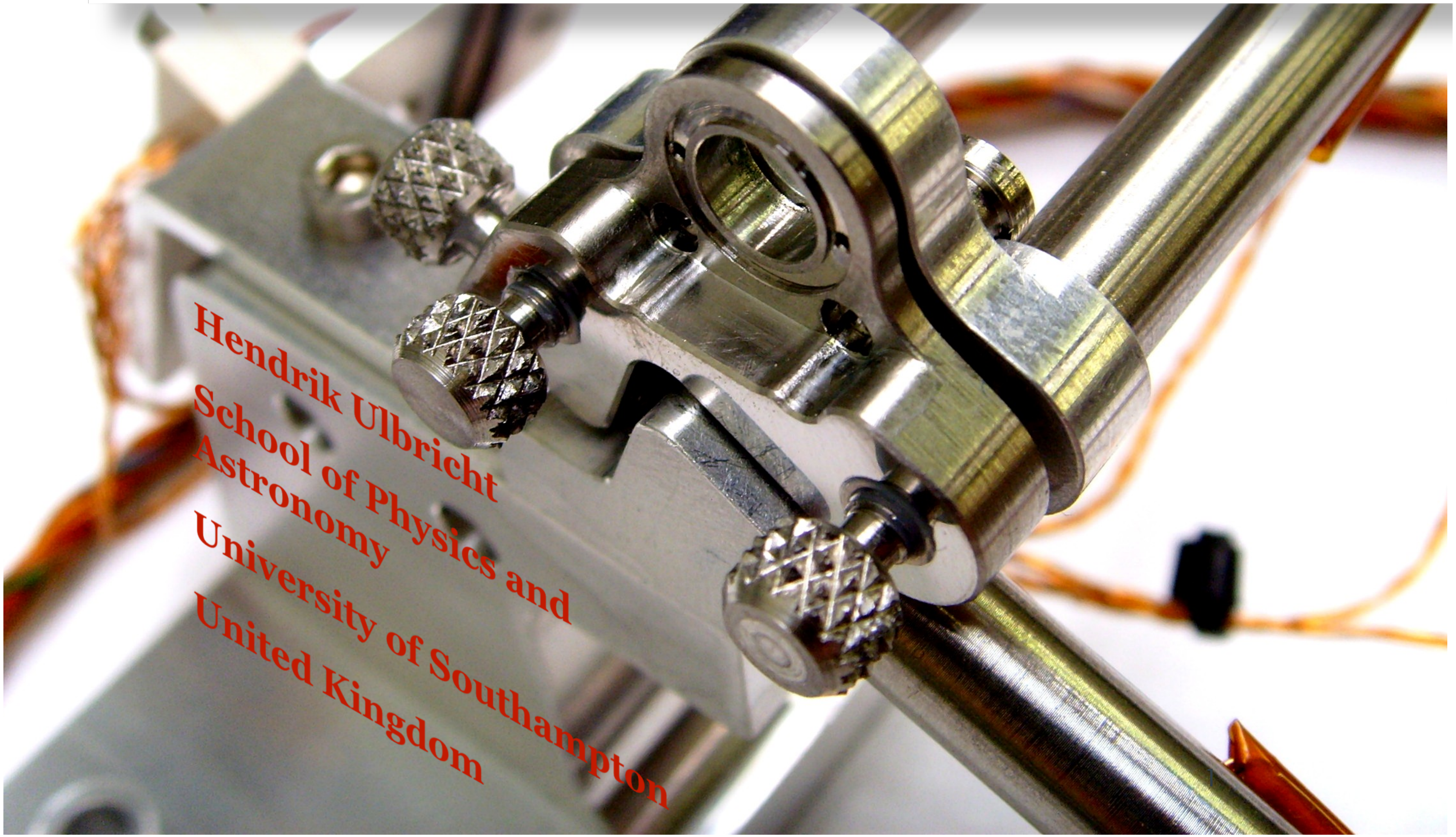
The experimental test of GRW: Interferometry and beyond



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One motivation: Test Collapse models

REVIEWS OF MODERN PHYSICS, VOLUME 85, APRIL–JUNE 2013

Models of wave-function collapse, underlying theories, and experimental tests

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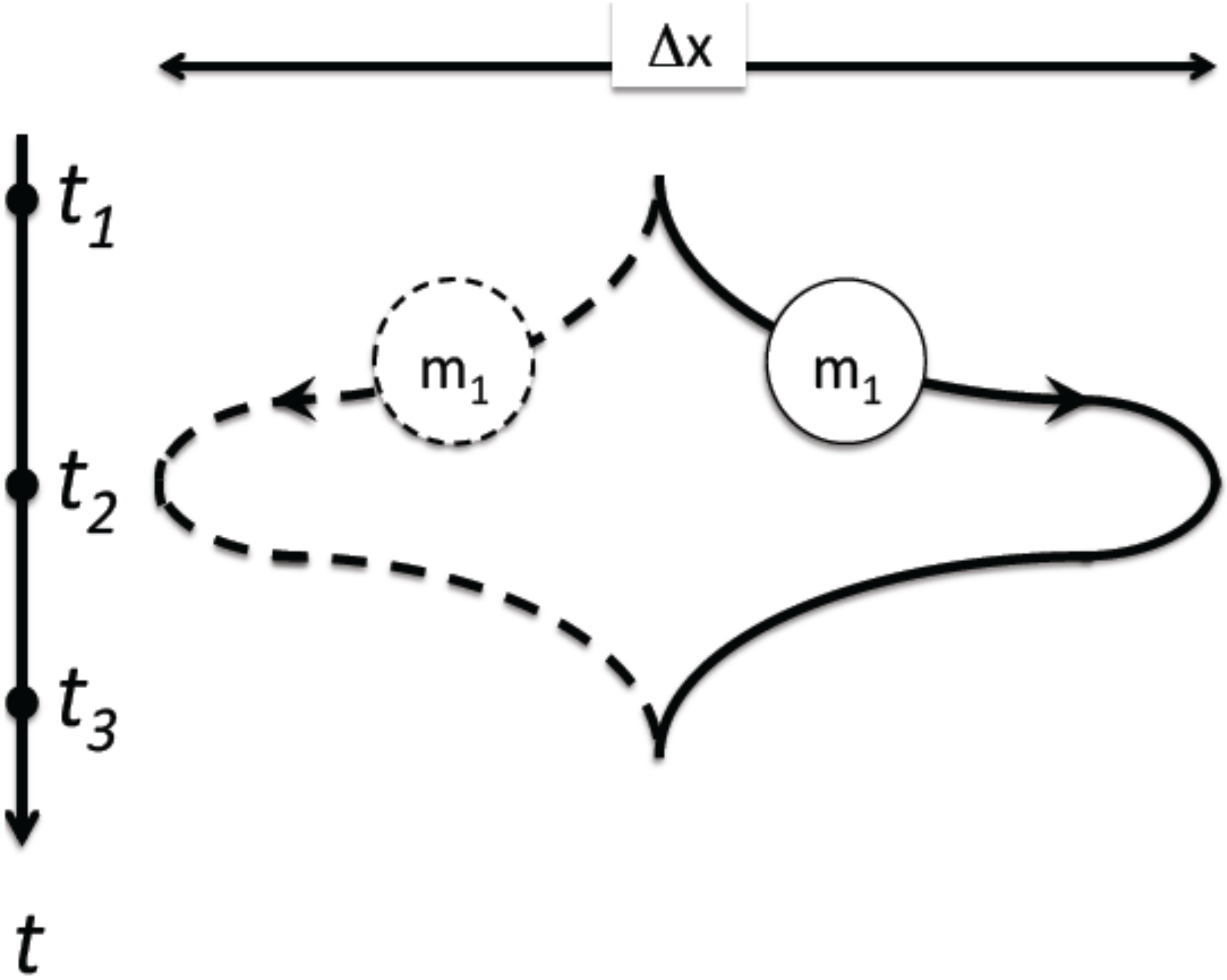
Quantum mechanics is an extremely successful theory that agrees with every experimental test. However, the principle of linear superposition, a central tenet of the theory, apparently contradicts a commonplace observation: macroscopic objects are never found in a linear superposition of position states. Moreover, the theory does not explain why during a quantum measurement, deterministic evolution is replaced by probabilistic evolution, whose random outcomes obey the Born probability rule. In this article a review is given of an experimentally falsifiable phenomenological proposal, known as continuous spontaneous collapse: a stochastic nonlinear modification of the Schrödinger equation, which resolves these problems, while giving the same experimental results as quantum theory in the microscopic regime. Two underlying theories for this phenomenology are reviewed: trace dynamics and gravity-induced collapse. As the macroscopic scale is approached, predictions of this proposal begin to differ appreciably from those of quantum theory and are being confronted by ongoing laboratory experiments that include molecular interferometry and optomechanics. These experiments, which test the validity of linear superposition for large systems, are reviewed here, and their technical challenges, current results, and future prospects summarized. It is likely that over the next two decades or so, these experiments can verify or rule out the proposed stochastic modification of quantum theory.

DOI: 10.1103/RevModPhys.85.471 PACS numbers: 03.65.Ta, 03.65.Ud, 03.65.Yz, 42.50.Xa

Collapse models:
CSL, GRW, …

Also non-collapse Models:
Schroedinger-Newton
Diosi-Penrose,

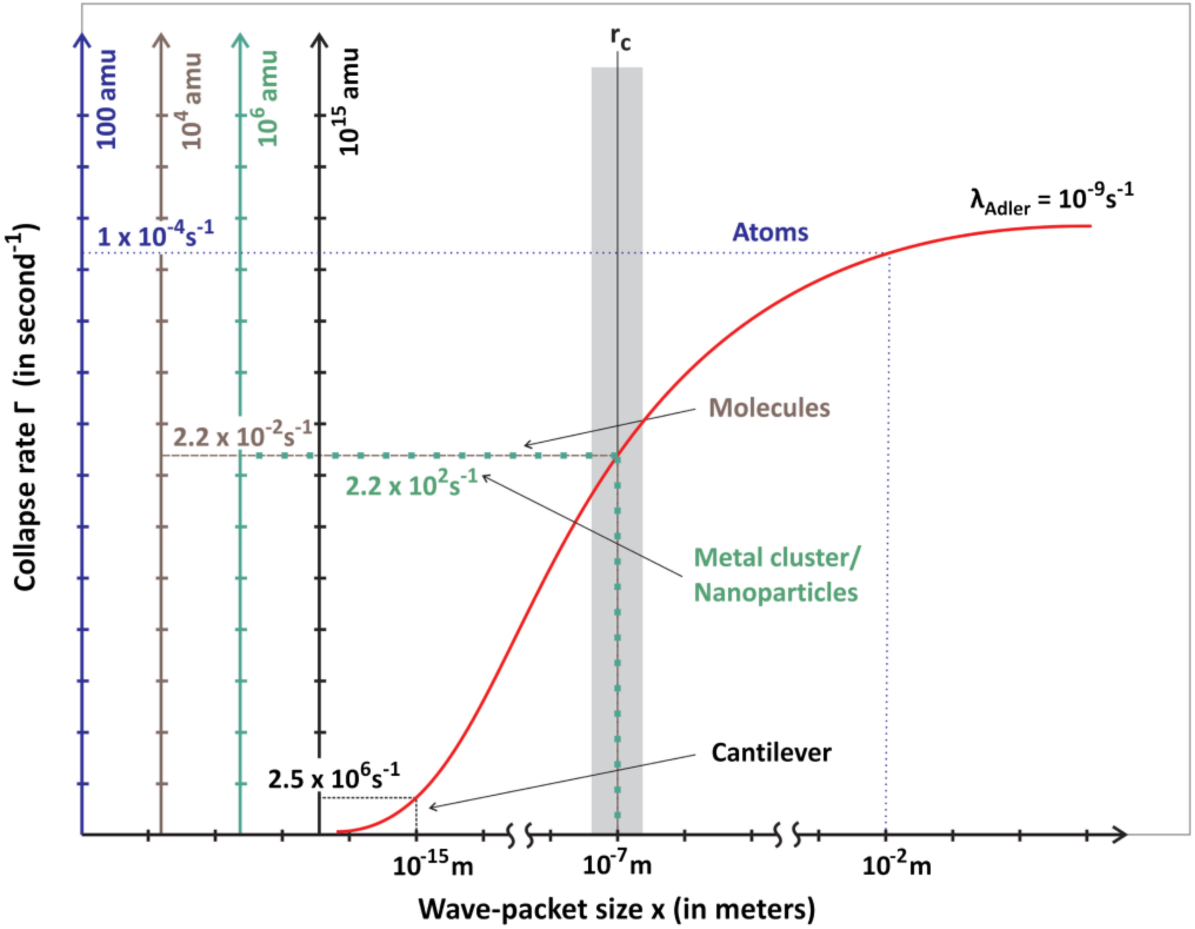


Δx
t_1
t_2
t_3
t
m_1
m_1

What system parameters do we need to generate macroscopic Quantumness?

- Large mass
- Larger spatial separation/ size of superposition state
- Large time for the superposition state to exist

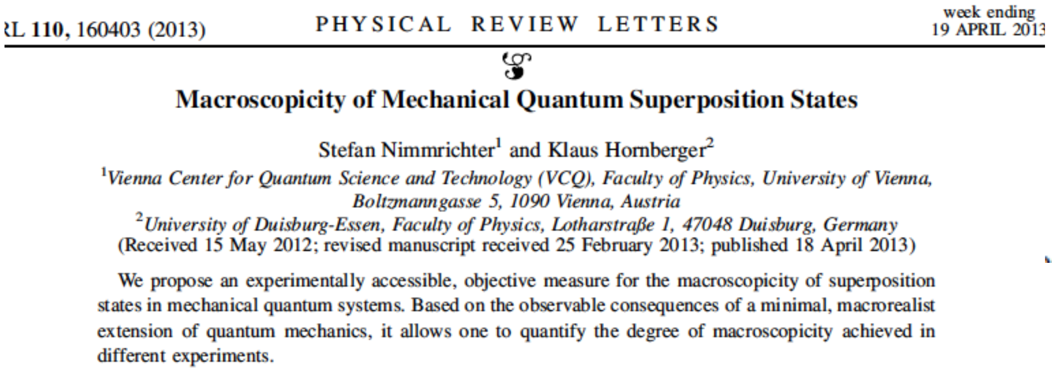
$$\frac{d}{dt}\rho_t(x,y) = -\frac{i}{\hbar}[H,\rho_t(x,y)] - \Gamma_{\mathrm{CSL}}(x,y)\rho_t(x,y)$$



$$\Gamma_{\mathrm{CSL}}(x) = \lambda[1 - e^{-x^2/4r_c^2}],$$

All tests is only on the level of density matrix …

Macroscopicity measure: to compare different experiments and to check if they test the superposition principle and CSL models



RL **110**, 160403 (2013) PHYSICAL REVIEW LETTERS week ending 19 APRIL 2013

Macroscopicity of Mechanical Quantum Superposition States

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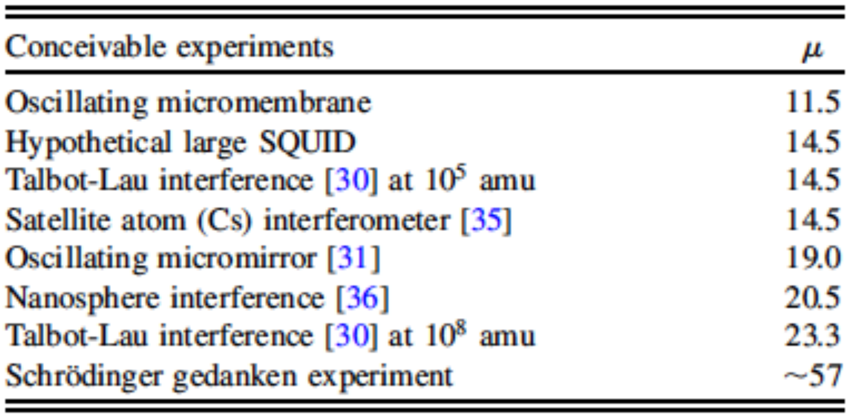
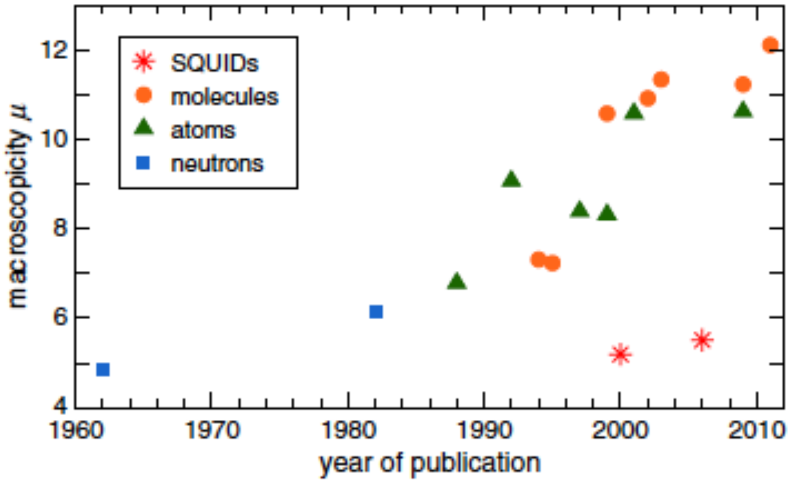
We propose an experimentally accessible, objective measure for the macroscopicity of superposition states in mechanical quantum systems. Based on the observable consequences of a minimal, macrorealist extension of quantum mechanics, it allows one to quantify the degree of macroscopicity achieved in different experiments.



Conceivable experiments	μ
Oscillating micromembrane	11.5
Hypothetical large SQUID	14.5
Talbot-Lau interference [30] at 10^5 amu	14.5
Satellite atom (Cs) interferometer [35]	14.5
Oscillating micromirror [31]	19.0
Nanosphere interference [36]	20.5
Talbot-Lau interference [30] at 10^8 amu	23.3
Schrödinger gedanken experiment	~57

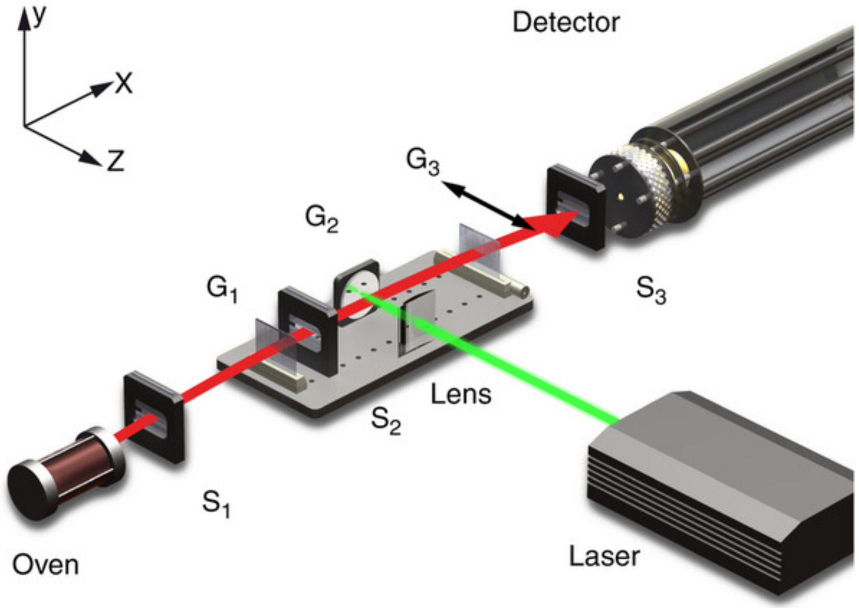
$$\mu = \log_{10}\left[\left|\frac{1}{\ln f}\right|\left(\frac{M}{m_e}\right)^2 \frac{t}{1\,\mathrm{s}}\right].$$



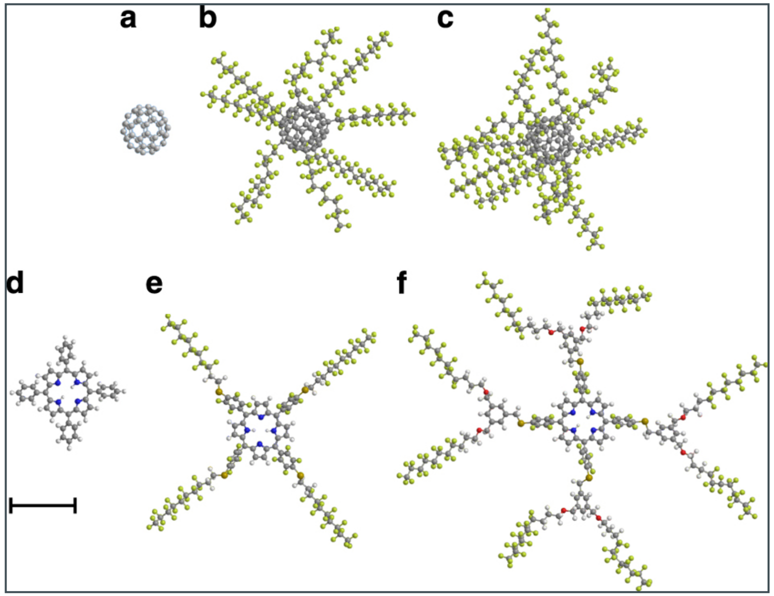
Scaling mass in matter-wave interferometry …

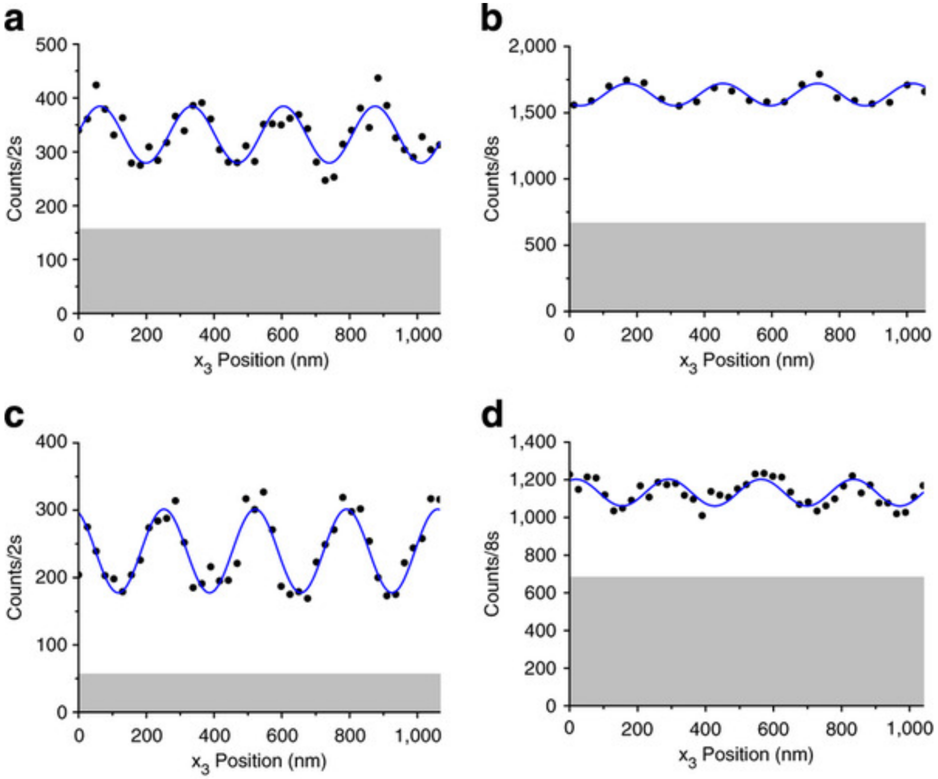
MOLECULE INTERFROMETRY

Mass record in matter-wave interferometry, 2013, Vienna: 10,000 amu



Kapitza-Dirac Talbot-Lau Interferometer





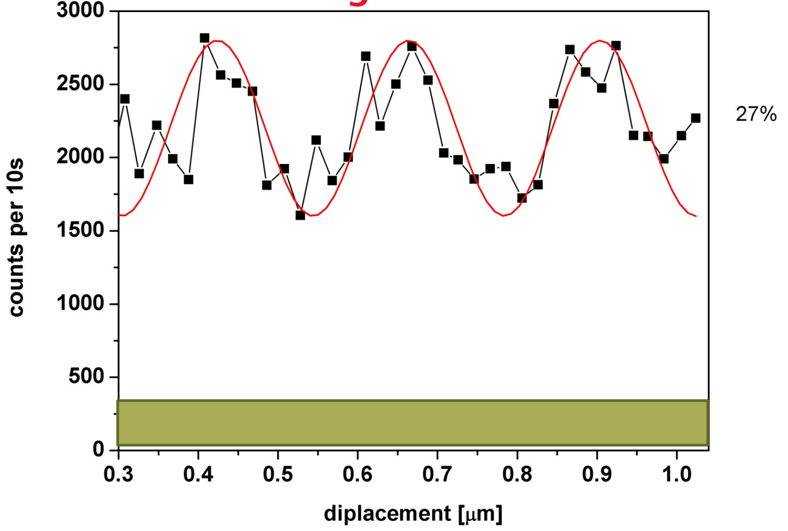
Talbot-Lau Interferometer

Set up of vertical interferometer
in Southampton:

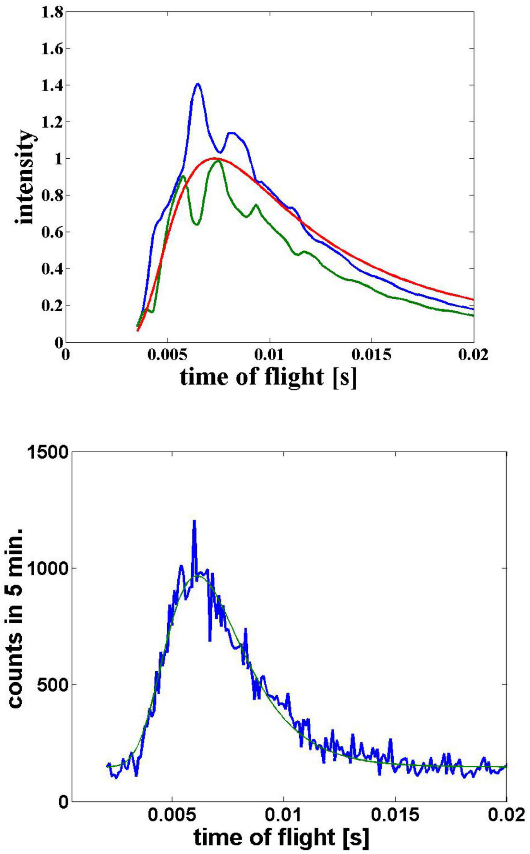
- Van der Waals/Casimir Polder interactions
- Wigner function reconstruction
- Spin effects
- **WORK IN PROGRESS**

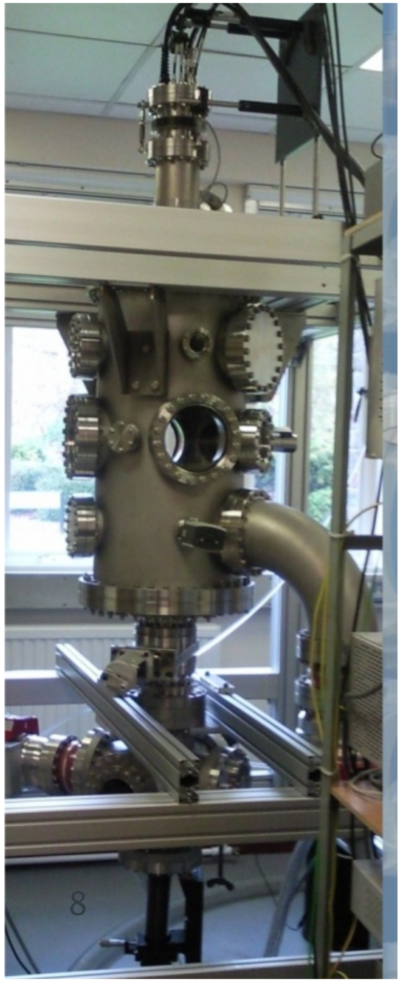
Settings:
- 10^{-8} mbar base pressure
- Water cooled Knudsen source
- In-situ grating alignment & positioning
- TOF scheme

Some signs of life!



Time-of Flight modification



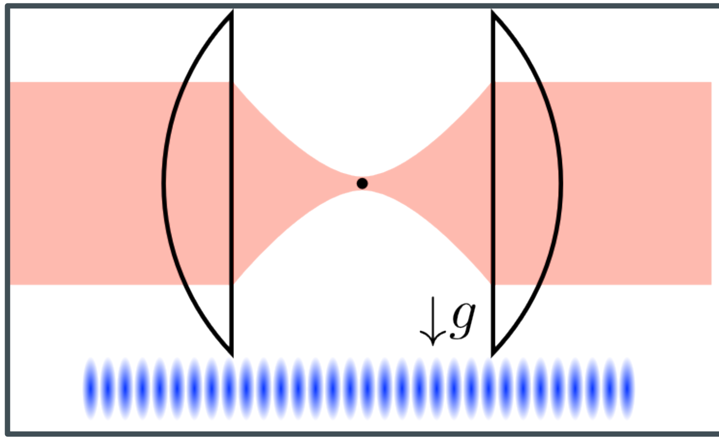


Scaling mass even further … good for gravity sensing (decoherence and dephasing) … technologies much simpler than for molecules

NANOPARTICLE INTERFEROMETRY

Our Scheme: Matter-wave interferometry of 10 nm sphere

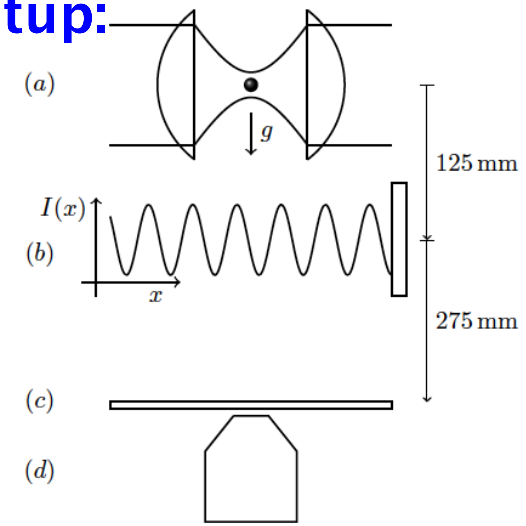
Talbot interference of mass: 10^6 amu



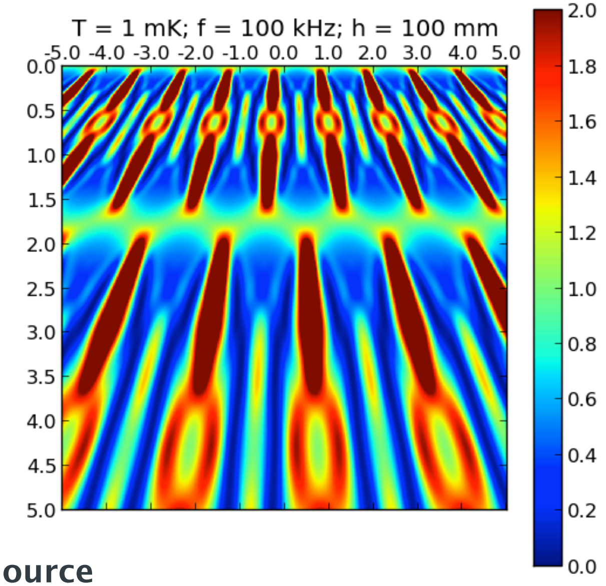
A single nanoparticle in a standing-wave optical dipole trap

Standing-wave phase-grating

Setup:



Quantum carpet:



- **Wigner function model of interference pattern** with all known dephasing and decoherence effects.
- **Dominating decoherence effect:** Thermal photo-emission.
- **Mass of particle is limited by Earth's gravity … future experiment in space?**
- **Based on existing techniques!**

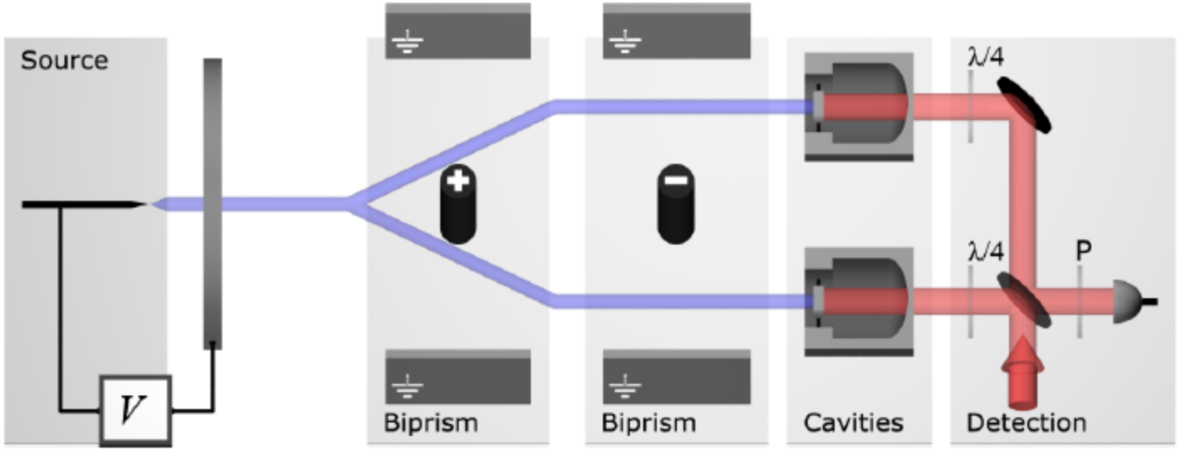
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

To scale mass even further .... (10^{13} amu)

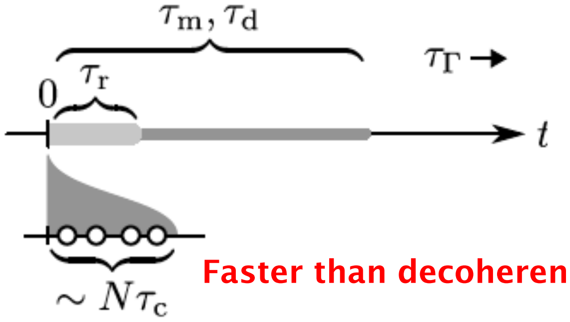
THE MATTER-WAVE TO OPTO-MECHANICS INTERFACE

How to go bigger?: Transfer superposition state!

Scheme for experiment (matter-wave->mechanics->optics**):**
- Spatial superposition state of atomic He$^+$ is incident to a pair of mirrors
- Mirrors are coupled to light in cavity
- Read-out of light field by state tomography by pulsed opto-mechanics scheme



Time- scales involved:



Faster than decoherence!

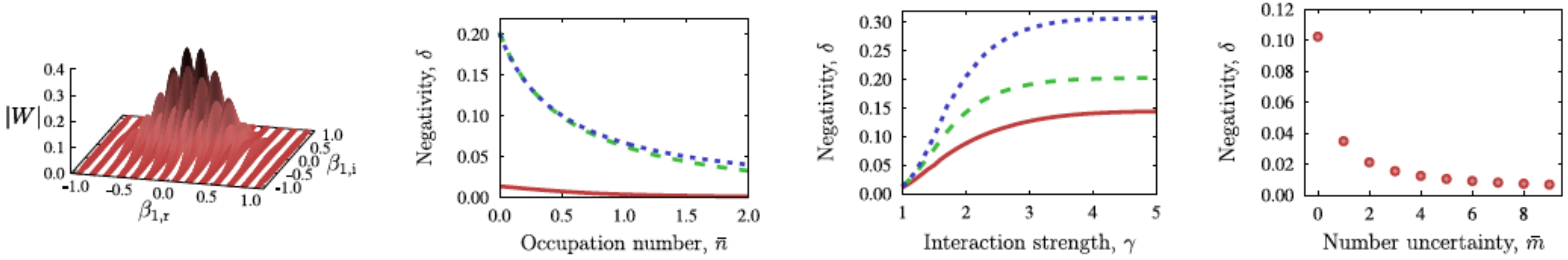
- All parts of this proposal are based on existing, demonstrated technology
- Macroscopicity of 30 (Nimmrichter macroscopicity)

Xuereb, A., H. Ulbricht, and M. Paternostro, **Optomechanical interface for matter-wave interferometry**, Scientific Reports 3, 3378 (2013).

Theoretical analysis:

- **Number state for incoming particle in superposition**
- **Thermal state for both opto-mechanical systems (no ground state needed!, state can be different for both)**
- **Definition of joint motional state of opto-mechanics**
- **Negativity of Wigner function of the joint mechanical state by state tomography (as by pulsed optomechanics)**

$$\delta = \iint \mathrm{d}^2\beta_1 \mathrm{d}^2\beta_2 |W(\beta_1,\beta_2)| - 1$$



(a) (b) (c) (d)

Result: Superposition state survives transfer!

Xuereb, A., H. Ulbricht, and M. Paternostro, **Optomechanical interface for matter-wave interferometry**, Scientific Reports 3, 3378 (2013).

Study the system: Look into a definition of macroscopicity of this specific system, treatment of decoherence …

Macroscopicity of our system

C.-W. Lee, H. Jeong, Quantification of Macroscopic Quantum Superpositions within Phase Space, Phys. Rev. Lett. 106 (22) (2011) 220401. doi:10.1103/PhysRevLett.106.220401.

$$\mathcal{I}(W) = \max\left\{0, \frac{\sum_{r,r',R,R'=0}^{N} \mathcal{N}(r,r',R,R')}{8(2\bar{n}+1)^2\left[\sum_{r,r'=0}^{N} \mathcal{D}(r,r')\right]^2}\right\}$$

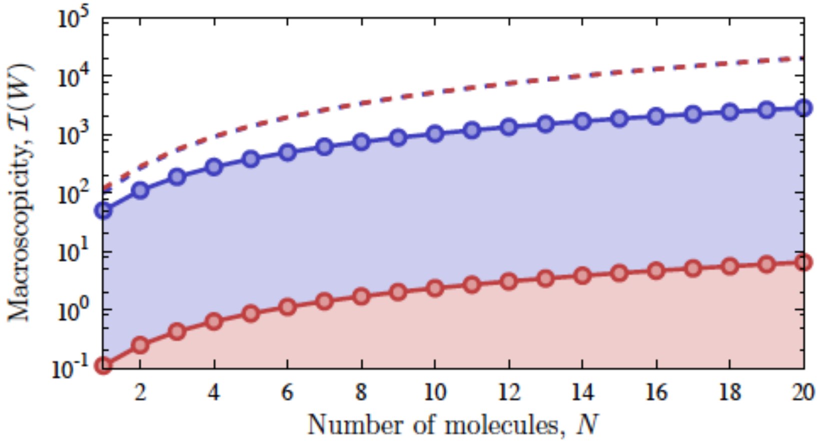


Figure 2: Effect of increasing the number of particles impinging on the mirrors for a constant value of $\bar{n}$; the macroscopicity of the superposition state increases monotonically with increasing N. We show two values for $\bar{n}$: 0 (blue data points), and 10 (red). For this figure we took $\gamma = 10$. The dashed blue curve represents the mean number of phonons in the system, n_{ph}; note that $\mathcal{I}(W) > n_{\text{ph}}$ throughout.

Macroscopicity depending on generic decoherence

$$\phi(r) = \exp\left[-(d\,r)^2\right]$$

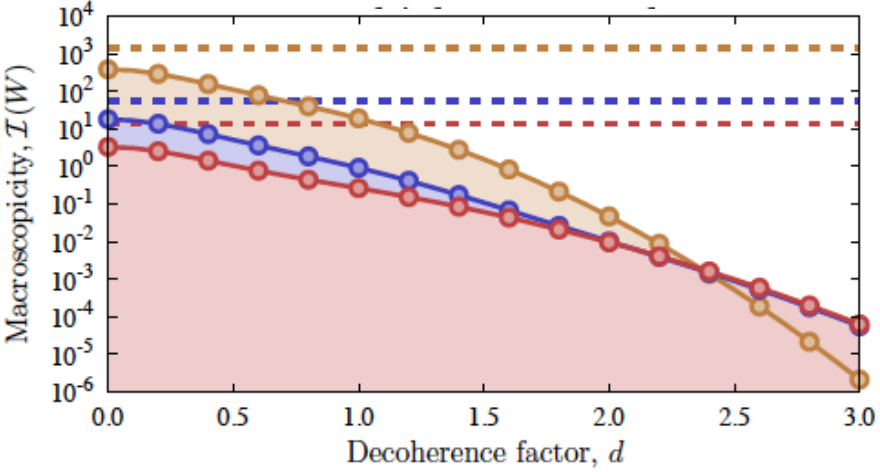
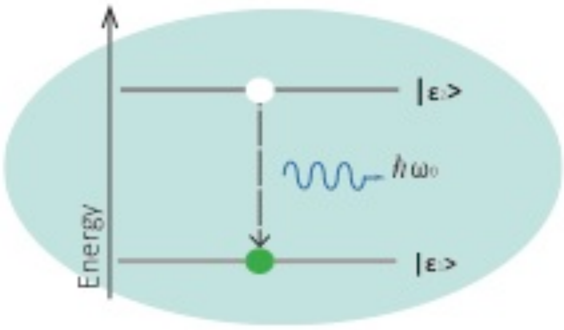


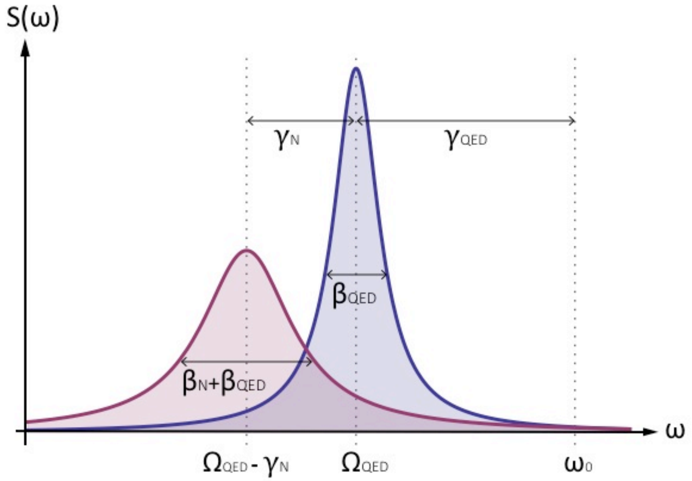
Figure 5: The effects of decoherence. We set $N = 5$ and $\bar{n} = 0$, and plot data for three values of γ: 1 (red data points), 2 (blue), and 10 (brown). Note the cross-over point beyond which increasing γ worsens the situation. The dashed curves represent the mean number of phonons at $d = 0$.

A. Xuereb, H. U., M. Paternostro, Macroscopicity in an optomechanical matter-wave interfrometer, Octics Comm. (2014).

DIFFERENT APPROACH: FREQUENCY DOMAIN TESTS

Generic broadening of spectral linewidth from collapse (noise):

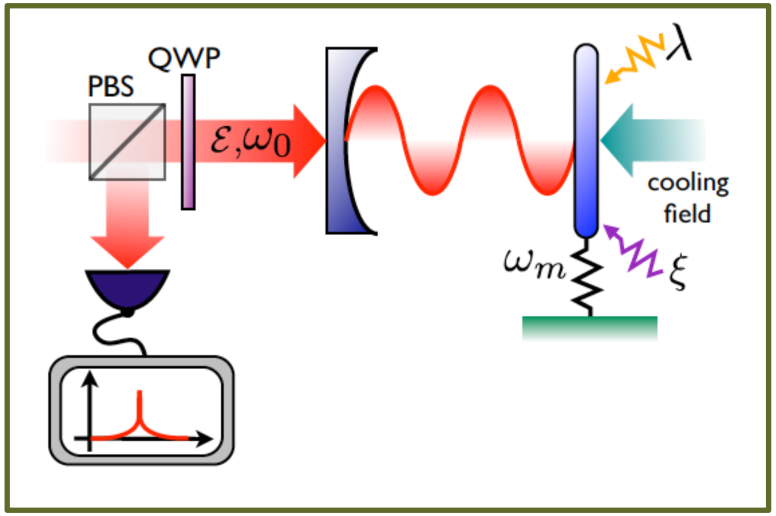


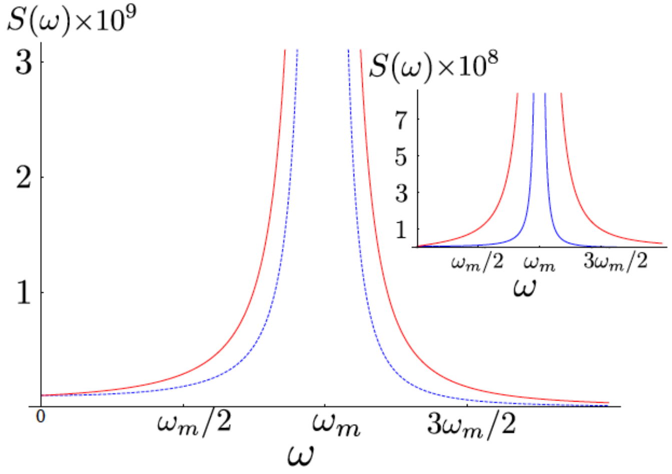


System	β_N (s^{-1})	Ω_N (s^{-1})
Hydrogen-like Atoms	$10^{-20}-10^{-18}$	$\sim 10^{-53}$
Harmonic oscillator	$\frac{3\Lambda}{4}\left(\frac{\mu\,x_0}{m_0\,r_C}\right)^2$	$\frac{\Lambda^2}{32\omega_0}\left(\frac{\mu\,x_0}{m_0\,r_C}\right)^4$
$\mu = 1\,\text{amu and}\ \omega_0 = 10^{10}\text{s}^{-1}$	5.3×10^{-13}	6.2×10^{-36}
$\mu = 10^7\,\text{amu and}\ \omega_0 = 1.7\times10^{8}\text{s}^{-1}$	3.1×10^{-4}	1.3×10^{-16}
Double-well	$\frac{\Lambda}{8}\left(\frac{\mu\,q_0}{m_0\,r_C}\right)^2$	$\frac{\Lambda^2}{128\,\omega_0}\left(\frac{\mu\,q_0}{m_0\,r_C}\right)^4$
$\mu = m_e = 5.5\times10^{-4}\,\text{amu and}\ q_0 = 1\text{Å}$	4.2×10^{-23}	$10^{-57}-10^{-55}$
$\mu = 1\,\text{amu and}\ q_0 = 1\text{Å}$	1.4×10^{-16}	$10^{-44}-10^{-42}$
$\mu = 10^7\,\text{amu and}\ q_0 = 1\text{Å}$	0.014	$10^{-16}-10^{-18}$

Bahrami, M., A. Bassi, and H. Ulbricht
Testing the quantum superposition principle in the frequency domain
Phys. Rev. **A 89**, 032127 (2014)]

Applied to opto-mechanical system



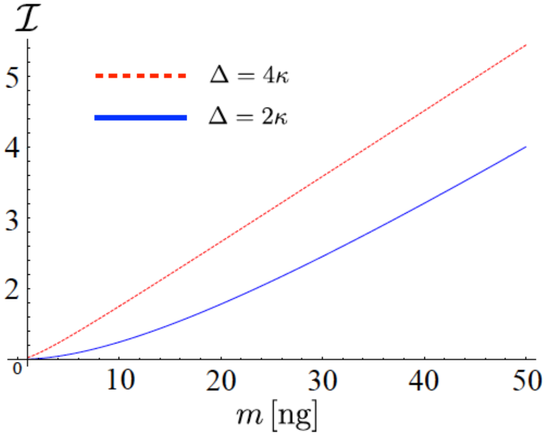


- **Collapse noise affects mechanical motion of opto-mechanical system, read out by optics**

- **Broadening effect modeled by input/output theory of opto-mechanics.**

- **Factor of 5 effect for cooled mechanics predicted for realistic experimental conditions to test Adler CSL.**

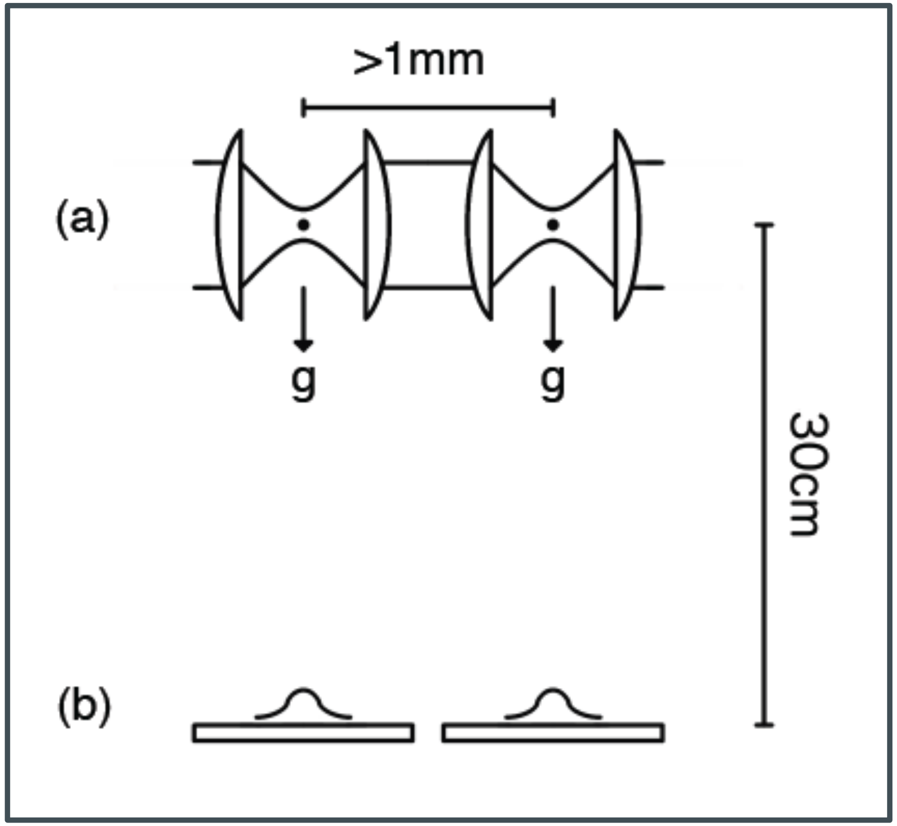
- **Can also be applied to levitated opto-mechanics**

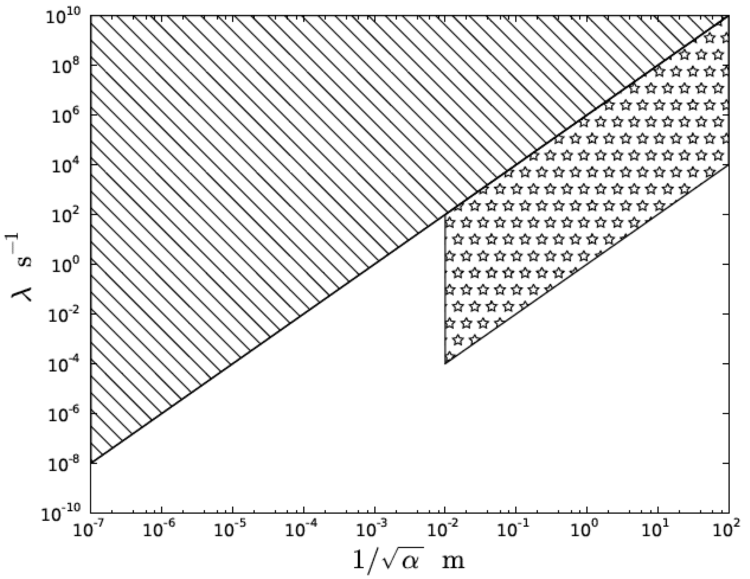


M. Bahrami, M. Paternostro, A. Bassi and H. Ulbricht
Proposal for Non-interferometric Test of Collapse Models in Optomechanical Systems, *PRL* **112**, 210404 *(2014).*

ANOTHER APPROACH: CORRELATION TESTS

Correlated random walk – correlation generated by collapse field





Possibility to observe correlation depends on CSL length parameter, Therefore the length parameter can be tested directly.

Bedingham and Ulbricht, arXive:1411.6921 (2014).

Thanks to … collaborators

- **Group at Southampton:** James Bateman, Nathan Cooper, Muddassar Rashid, David Hempston, Jamie Vovrosh.

- **Quantum Optics Theory:** Mauro Paternostro, Andre Xuereb.

- **Matter-wave Interferometry and Experiments:** Markus Arndt, Klaus Hornberger, Stefan Nimmrichter,

- **Foundations of Physics:** Angelo Bassi, Mohammad Bahrami, Tejinder P Singh, Daniel Bedingham