Plan for lectures

- L1: Experimental tests of the quantum superposition principle in the macroscopic domain
- L2: Experimental tests of the interplay between quantum mechanics and gravity
- [Dark Matter]
- Levitated Optomechanics

To test Collapse models means to test quantum superposition principle

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

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

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(published 2 April 2013)

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 gravity induced collapse models: Diosi-Penrose

Also non-collapse models: Schrödinger-Newton

It is nice to have at one's disposal such exquisite mathematical tools as the present methods of quantum field theory, but one should not forget that these methods have been elaborated in order to describe definite empirical situations, in which they find their only justification. Any question as to their range of application can only be answered by experience, not by formal argumentation. Even the legendary Chicago machine cannot deliver the sausages if it is not supplied with hogs.

L. Rosenfeld, Nucl. Phys. 40 (1963) 353.

Collapse models: What is this?

They are nonlinear and stochastic (phenomenological) modifications of the Schrödinger equation, which include the collapse of the wave function

$$d|\psi\rangle_t = \Big[\underbrace{-\frac{i}{\hbar}H\,dt}_{\textbf{quantum}} + \underbrace{\sqrt{\lambda}(A-\langle A\rangle_t)dW_t - \frac{\lambda}{2}(A-\langle A\rangle_t)^2 dt}_{\textbf{collapse}}\Big]|\psi\rangle_t$$

$$\langle A\rangle_t = \langle \psi_t|A|\psi_t\rangle \longrightarrow \textbf{nonlinear}$$

The wave function is dynamically and stochastically driven by the noise W_t towards one of the eigenstates of the operator A

G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986)

Mass-proportional collapse models: CSL

$$\frac{d}{dt}|\psi_t\rangle = \Big[-\frac{i}{\hbar}H + \frac{\sqrt{\gamma}}{m_0}\int d^3x\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,dW_t(\mathbf{x})$$
$$-\frac{\gamma}{2m_0^2}\int\int d^3x d^3y\, G(\mathbf{x}-\mathbf{y})\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,(M(\mathbf{y}) - \langle M(\mathbf{y})\rangle_t)\Big]\,|\psi_t\rangle$$

$$M(\mathbf{x}) = ma^\dagger(\mathbf{x})a(\mathbf{x}) \qquad G(\mathbf{x}) = \frac{1}{(4\pi r_C)^{3/2}}\,\exp[-(\mathbf{x})^2/4r_C^2]$$

$$w_t(\mathbf{x}) \equiv \frac{d}{dt}W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[w_t(\mathbf{x})] = 0 \quad \mathbb{E}[w_t(\mathbf{x})w_s(\mathbf{y})] = \delta(t-s)G(\mathbf{x}-\mathbf{y})$$

Two parameters

$\gamma = \text{collapse strength}$ $\qquad r_C = \text{localization resolution}$

$\lambda = \gamma/(4\pi r_C^2)^{3/2} = \text{collapse rate}$

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

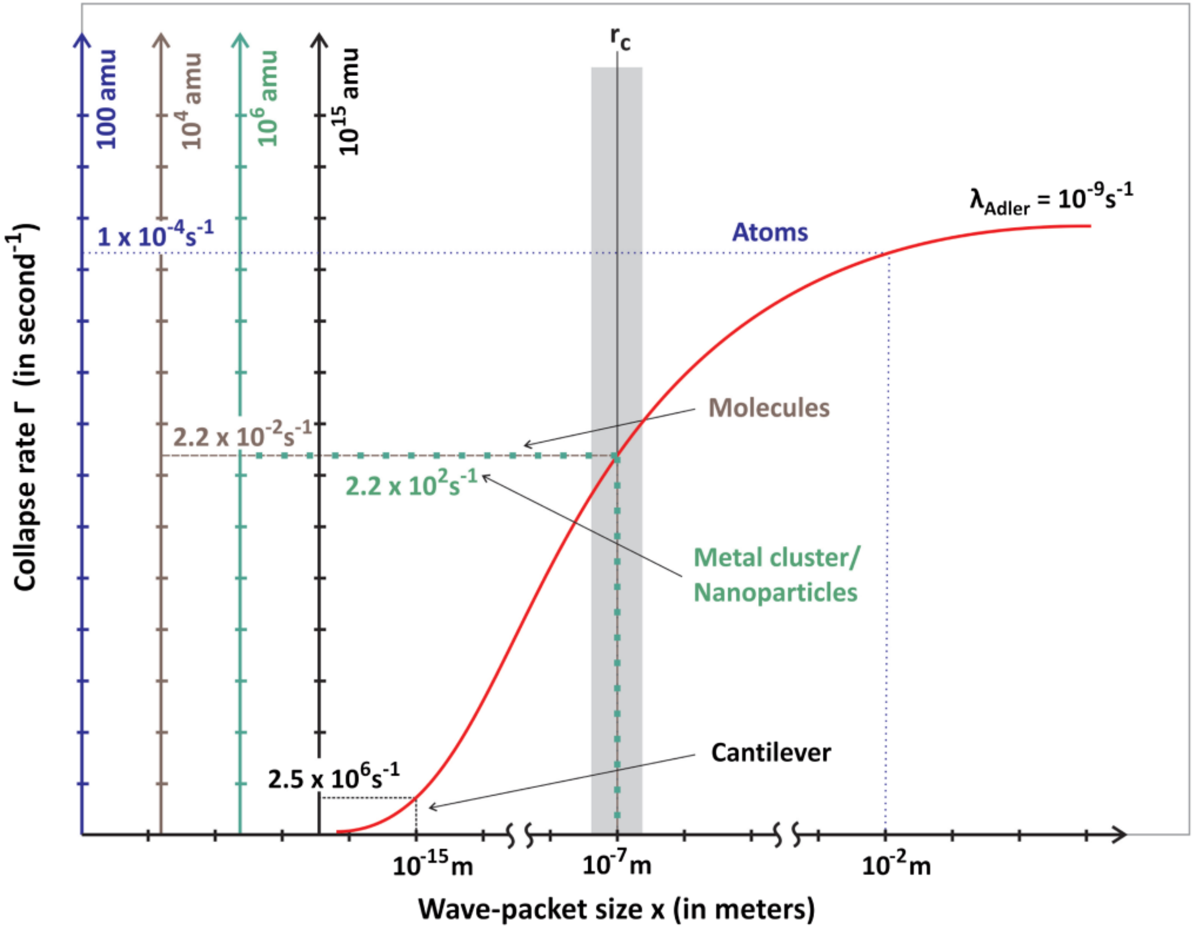
What system parameters do we need to generate macroscopic Quantumness?

Macroscopicity conditions:

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

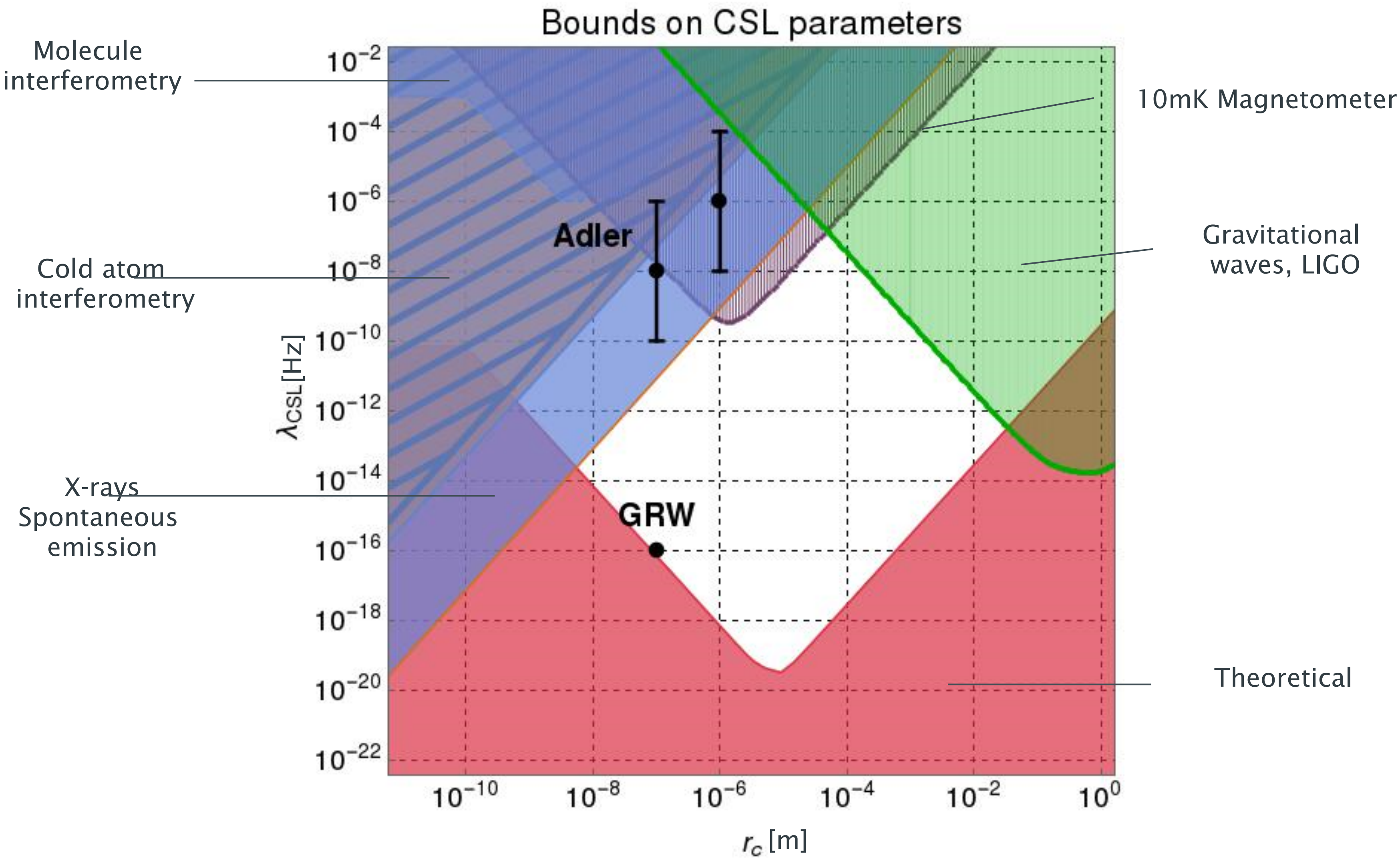
$$\frac{d}{dt}\rho_t(x,y) = -\frac{i}{\hbar}[H,\rho_t(x,y)] - \Gamma_{\rm CSL}(x,y)\rho_t(x,y)$$

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



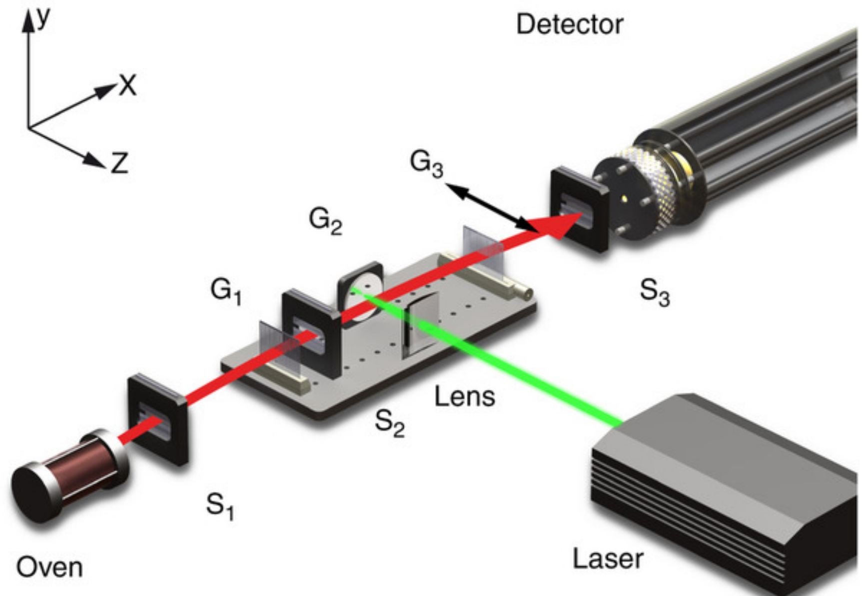
- **All tests are on the level of density matrix.**
- **Appear same as decoherence effects.**
- **You have to know your scalings to distinguish collapse from decoherence effects**

CSL exclusion plot: Angelo's baby

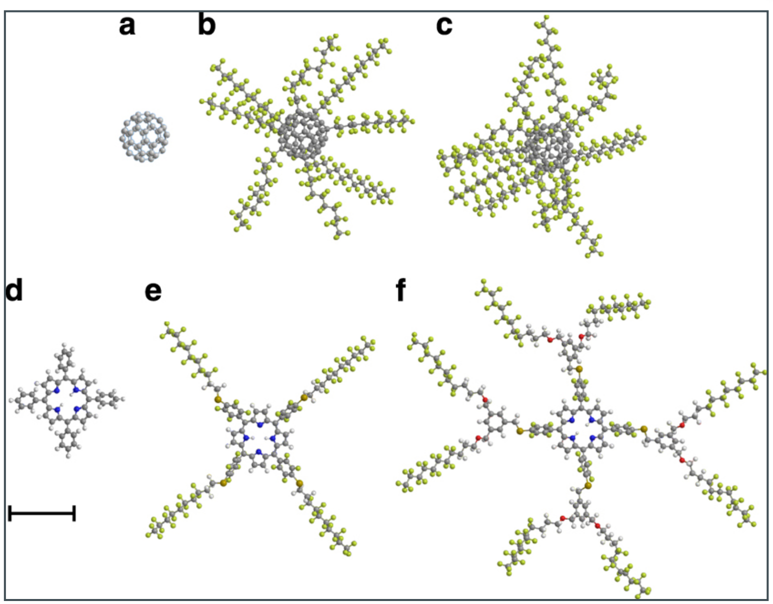


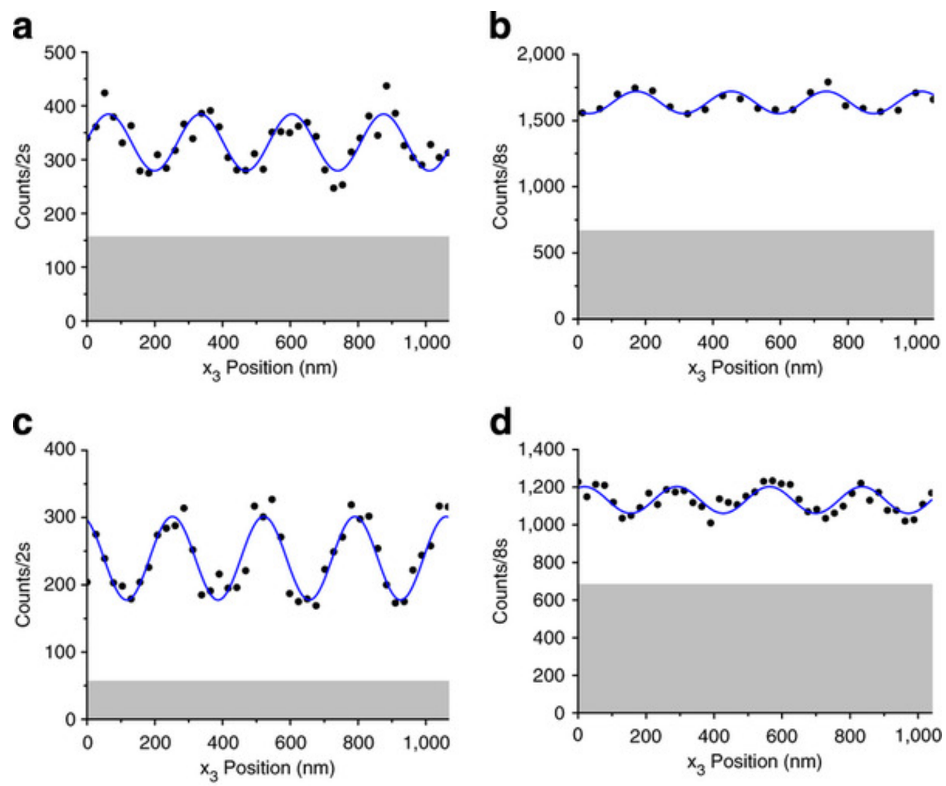
Hope: (Levitated) optomechanics can test down to GRW

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

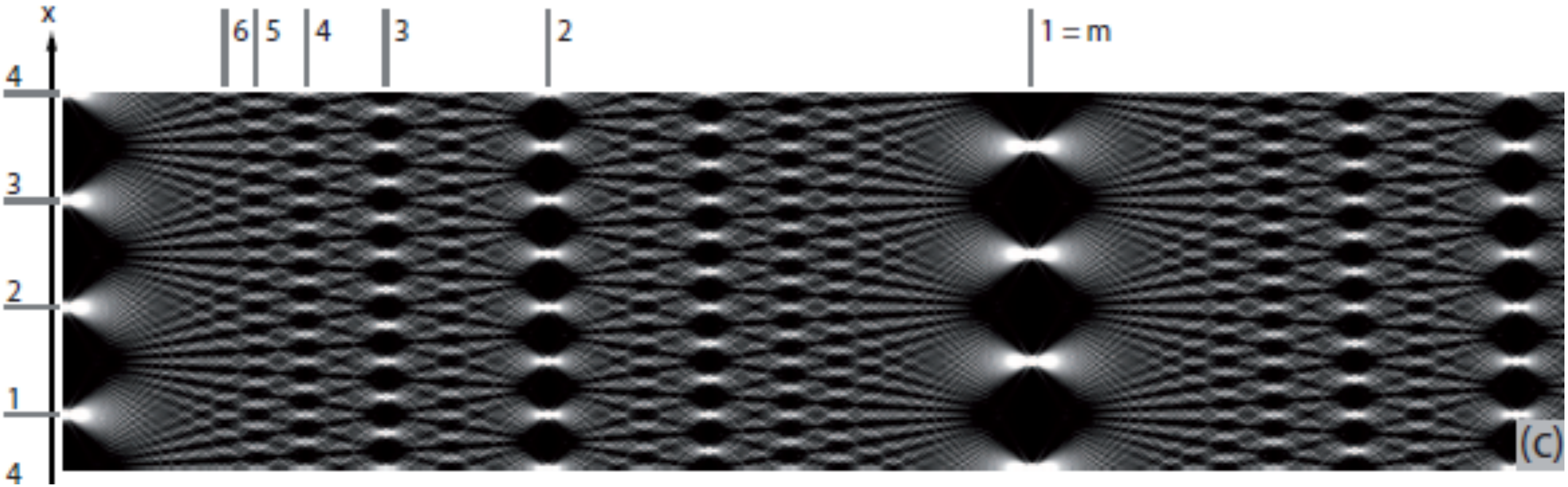


Kapitza-Dirac Talbot-Lau Interferometer

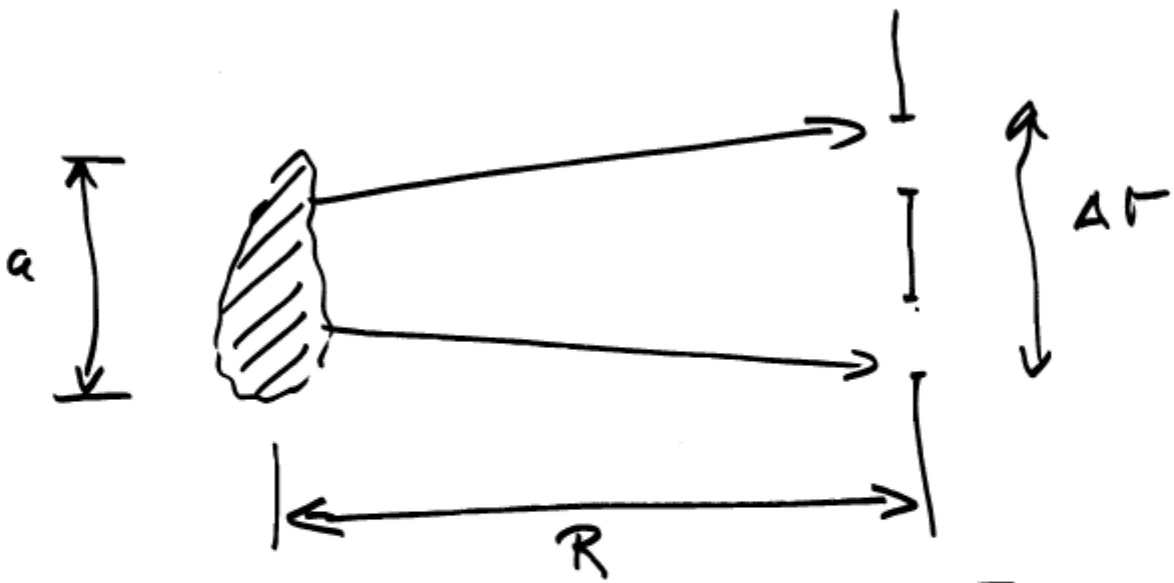




Optical Talbot-Lau effect/ quantum carpet



Transverse coherence: van Zittert - Zernicke

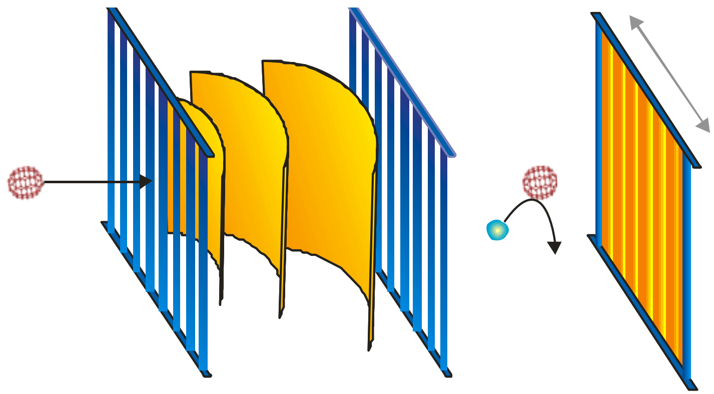


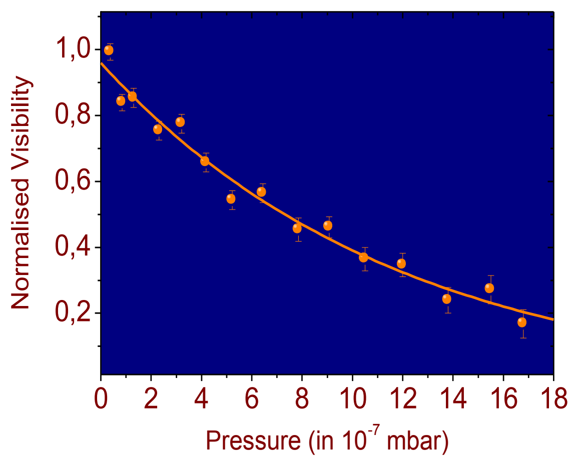
$$\boxed{\Delta r \sim \frac{\lambda}{a} \cdot R}$$

1st grating in TLI: ~ 2000 parallel collimation slits
-> increase in signal by factor 2000

Decoherence: interaction with the environment

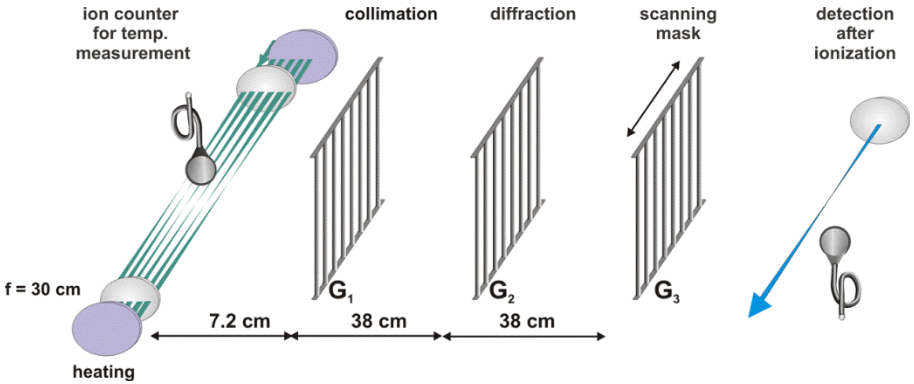
Collisions with residual gas

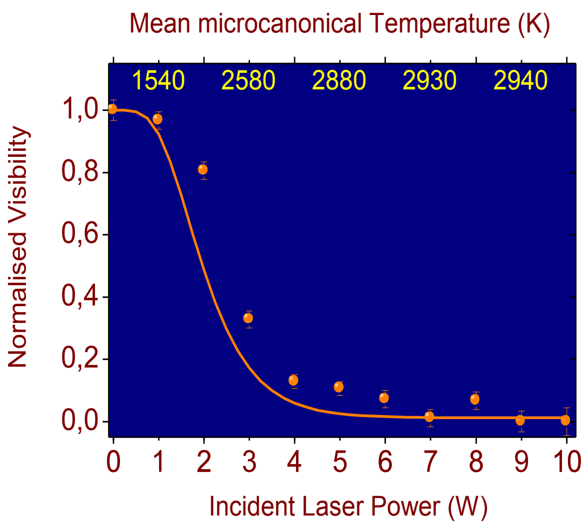




Phys. Rev. Lett. 90, 160401 (2003).
Physics World 18, 35 -40 (2005).

Thermal emission of radiation





NATURE, 427, 711–714 (2004).

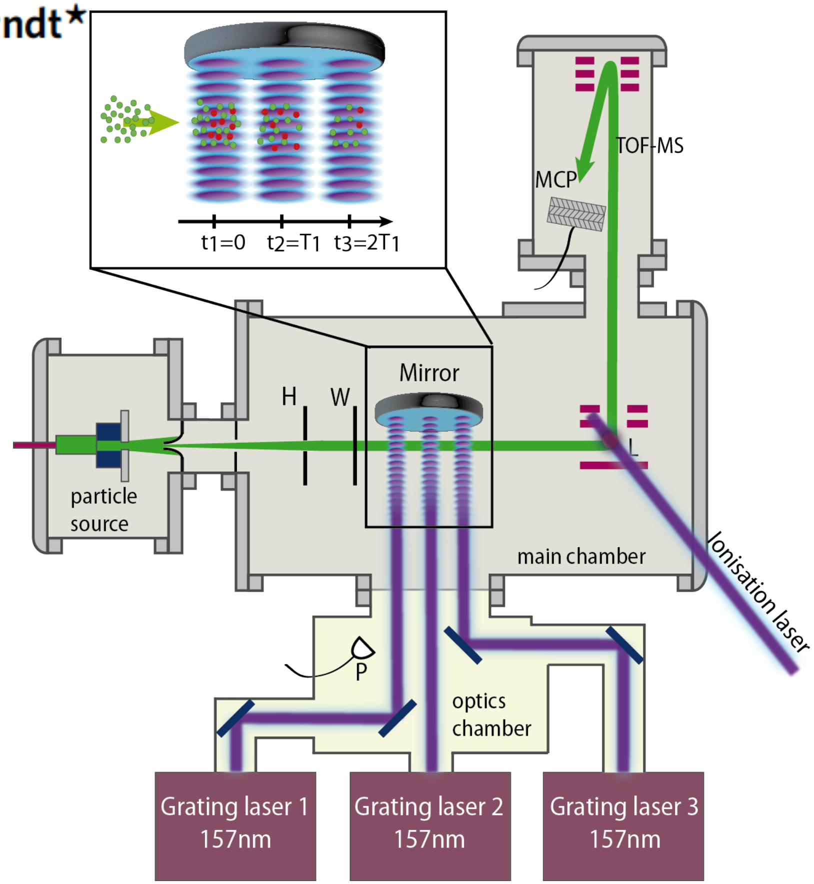
Proposals for ‘macroscopic’ matterwave interferometers

- OTIMA
- Magnetic Microparticle Skatepark
- NATALI
- RAMSEY schemes
- And more ....

LETTERS
PUBLISHED ONLINE: 10 FEBRUARY 2013 | DOI: 10.1038/NPHYS2542
nature physics

A universal matter-wave interferometer with optical ionization gratings in the time domain

Philipp Haslinger, Nadine Dörre, Philipp Geyer, Jonas Rodewald, Stefan Nimmrichter and Markus Arndt*



Can resolve de Broglie waves of 127 fm !!

Quantum Interference of a Microsphere

H. Pino, J. Prat-Camps, K. Sinha, B. P. Venkatesh, and O. Romero-Isart*
Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria. and Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria.

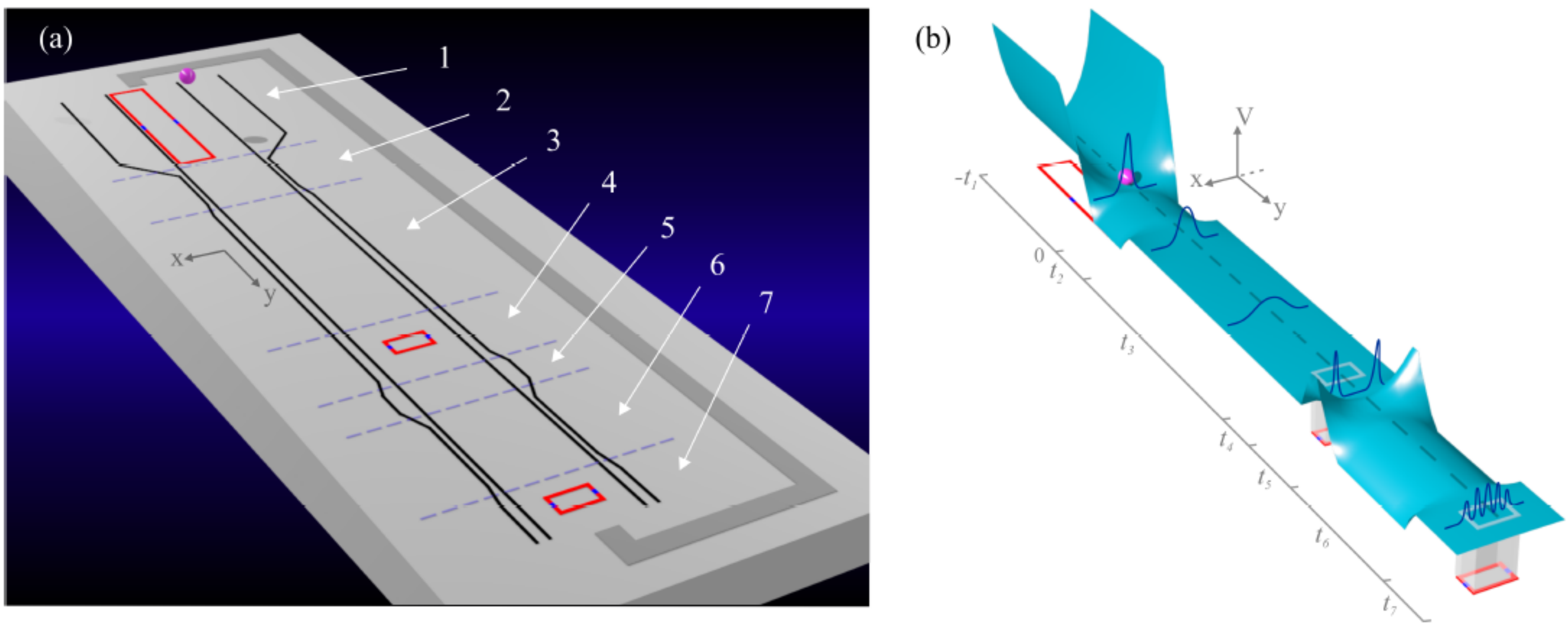


FIG. 3: (a) Sketch of the superconducting chip implementation of the quantum interferometer protocol. Superconducting wires are shown in black and the different stages are separated by dashed lines. The SQUIDs are shown in red. (b) Illustration of the magnetic potential $V(x, y)$ in each of the steps. The position probability distribution in the x-axis is illustrated (dark blue) at the different stages of the protocol. Notice that both figures are not scaled and have only illustrative purposes.

Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions

C. Wan,[1] M. Scala,[1] G. W. Morley,[2] ATM. A. Rahman,[2,3] H. Ulbricht,[4] J. Bateman,[5]
P. F. Barker,[3] S. Bose,[3,*] and M. S. Kim[1]
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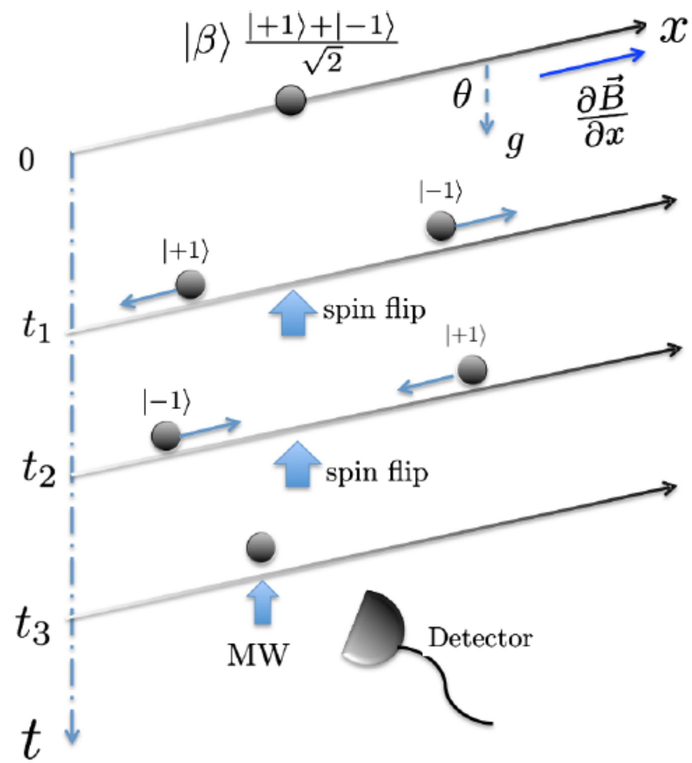
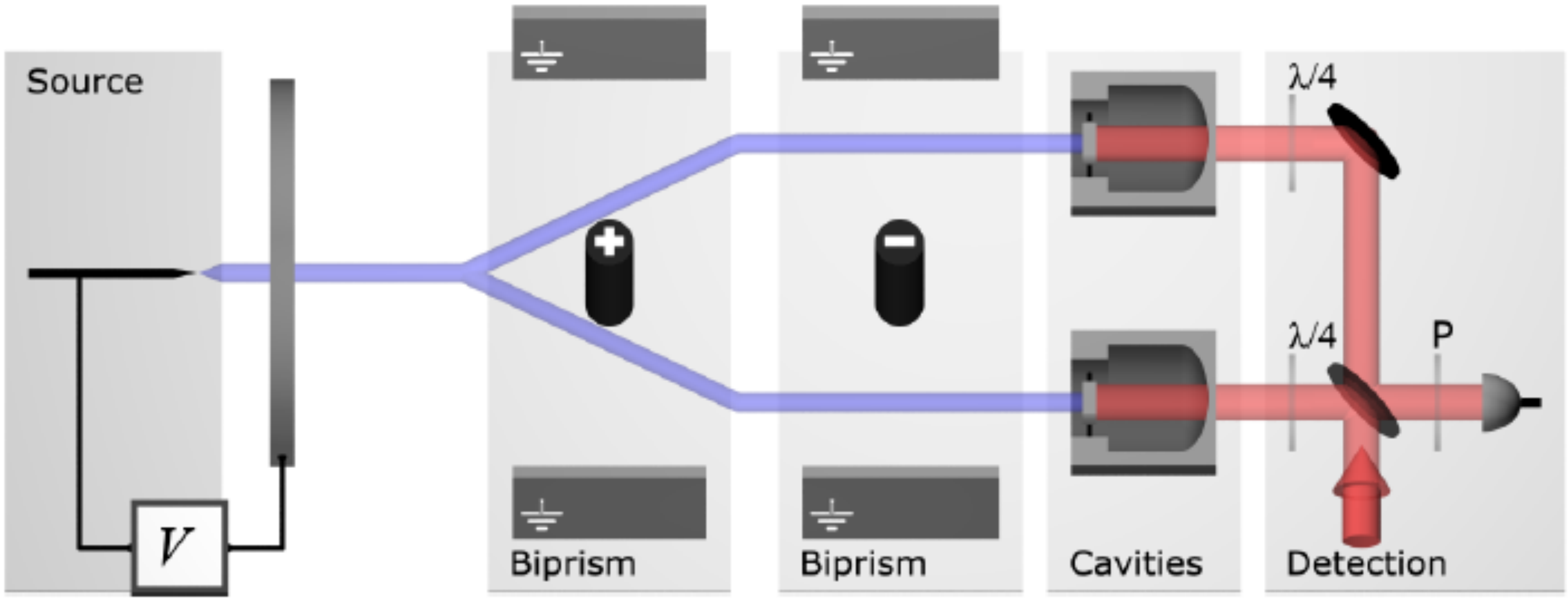
(Received 26 January 2016; published 28 September 2016)



Even larger??



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

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

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	$\sim$57

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

Macroscopicity of Mechanical Quantum Superposition States

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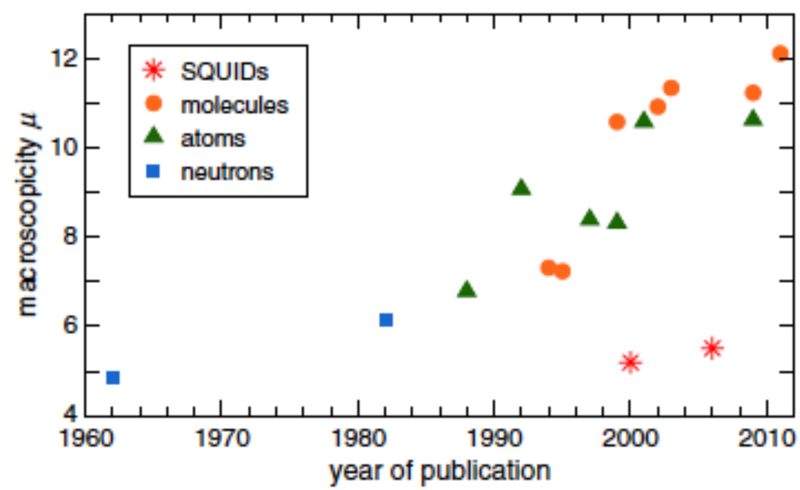
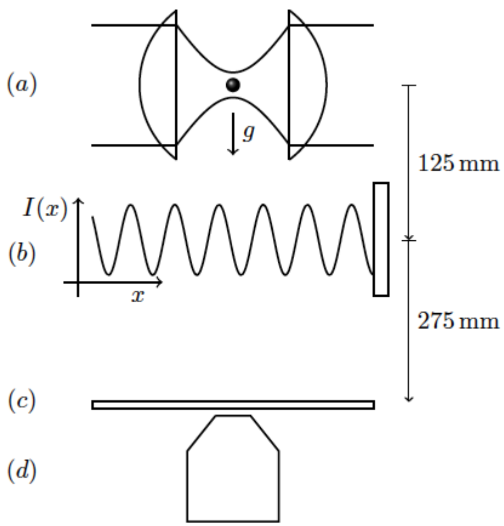
(Received 15 May 2012; revised manuscript received 25 February 2013; published 18 April 2013)

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.

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



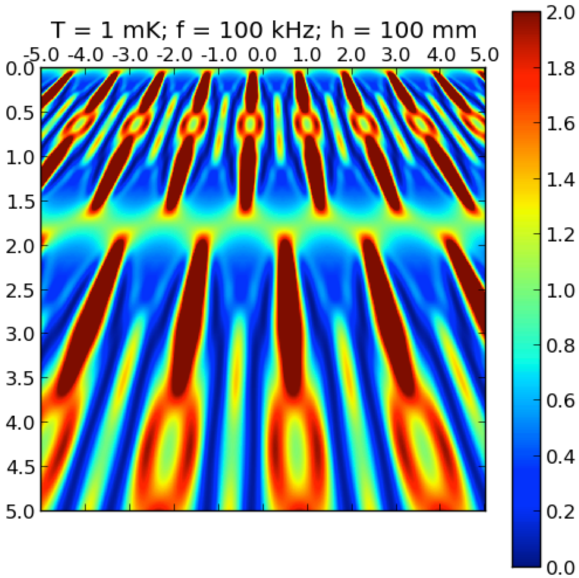
Nanoparticle Talbot Interferometer: NaTalI



Talbot interferometer with particle of mass: 10^6 -10^7 amu (~20nm diameter)

- **Wigner function model of interference pattern**
- **Dominating decoherence effect:** Blackbody emission and absorption.
- **Mass of particle is limited by Earth's gravity … future experiment in space?**

Quantum carpet:

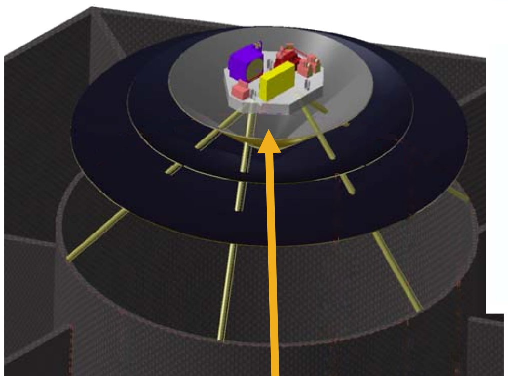


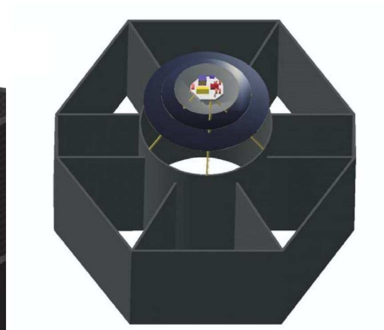
Collimation/Preparation of spatial coherence translates to cooling of the particle in the trap.

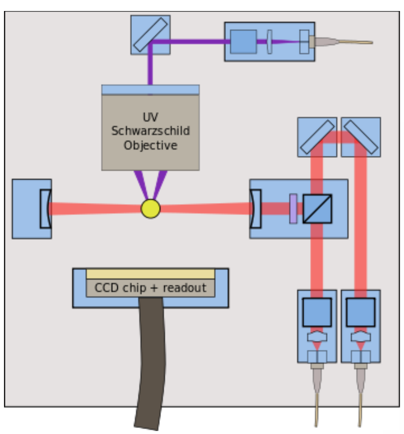
<u>Advantage compared to other schemes:</u>
We don't need ground state of trapped particle before the drop.

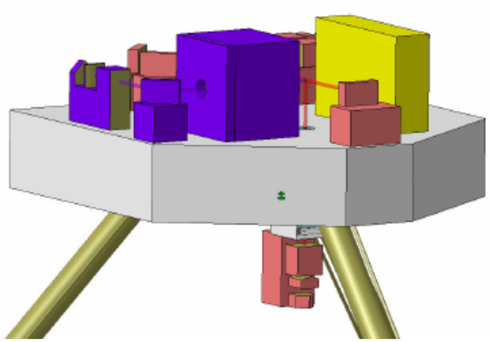
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

MAQRO Nanoparticle interferometer in space to control influence of gravitation, it is impossible on Earth above a certain mass









requirement on	WAX	DECIDE
	environment	
gas pressure	$\leq 6 \times 10^{-14}$ Pa	$\leq 10^{-13}$ Pa
temperature	32 K	16 K
thermal stability	NC	< 0.18 K
	nanosphere	
radius 120 nm	100 nm	
temperature	~ 60 K	20 K
thermal stability	NC	< 0.22 K
influence of cosmic rad.	NC	NC
asymmetry	$< 5\,\%$	$< 5\,\%$
absorption at 1064nm	STA	0.25 ppb/cm
mass density	$\geq 2201\,\frac{\mathrm{kg}}{\mathrm{m}^3}$	$2201\,\frac{\mathrm{kg}}{\mathrm{m}^3}$
	optical setup	
cavity finesse (trap/cool)	~ 30000	~ 30000
position readout accuracy	$\sim 2\,\mu$m	$\sim 2\,\mu$m
ting stability		
rap/Cool Cavity mirrors	$< \frac{180\,\mu\mathrm{rad}}{\sqrt{100\,\mathrm{mHz}}}$	$< \frac{180\,\mu\mathrm{rad}}{\sqrt{100\,\mathrm{mHz}}}$
R beam	$< \frac{180\,\mu\mathrm{rad}}{\sqrt{100\,\mathrm{mHz}}}$	$< \frac{180\mu\mathrm{rad}}{\sqrt{100\,\mathrm{mHz}}}$
V beam	NA	$< 15\mu$rad
mal stability	$\leq 4.6\,\frac{\mathrm{ppm}}{\mathrm{K}}$	$\leq 4.6\,\frac{\mathrm{ppm}}{\mathrm{K}}$
aser stability	critical	critical
laser stability	NA	NC
	spacecraft	
o-thruster acc. noise	$\sqrt{S_A} < 10^{-8}\mathrm{m/s^2\,Hz^{-1/2}}$	$< 1.6 \times 10^{-9}\mathrm{m/s^2\,Hz^{-1/2}}$
tion stability	$\ll 4.5\,\mathrm{mrad\,Hz^{-1/2}}$	$\ll 240\,\mu\mathrm{rad\,Hz^{-1/2}}$
grav.	$\sqrt{S_A} < 10^{-8}\mathrm{m/s^2\,Hz^{-1/2}}$	$< 1.6 \times 10^{-9}\mathrm{m/s^2\,Hz^{-1/2}}$
1 m distance	$\Delta M \leq 39$ kg	$\Delta M \leq 1.6$ kg

- Consortium of 40 groups from all over the world
- Application for an ESA M class mission
- COST action: QTSpace
- It is to bring our Talbot nanoparticle interferometer into space!

LEVITATED OPTOMECHANICS

Subkelvin Parametric Feedback Cooling of a Laser-Trapped Nanoparticle

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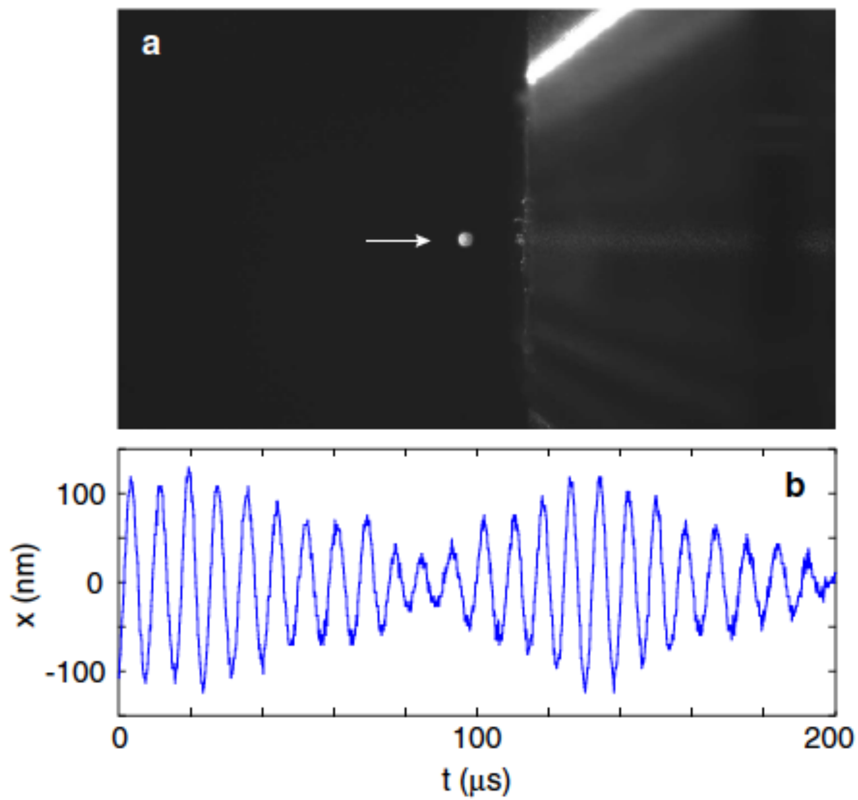
(Received 6 June 2012; published 7 September 2012)



Cavity cooling of an optically levitated submicron particle

Nikolai Kiesel[1,2], Florian Blaser[1], Uroš Delić, David Grass, Rainer Kaltenbaek, and Markus Aspelmeyer[2]

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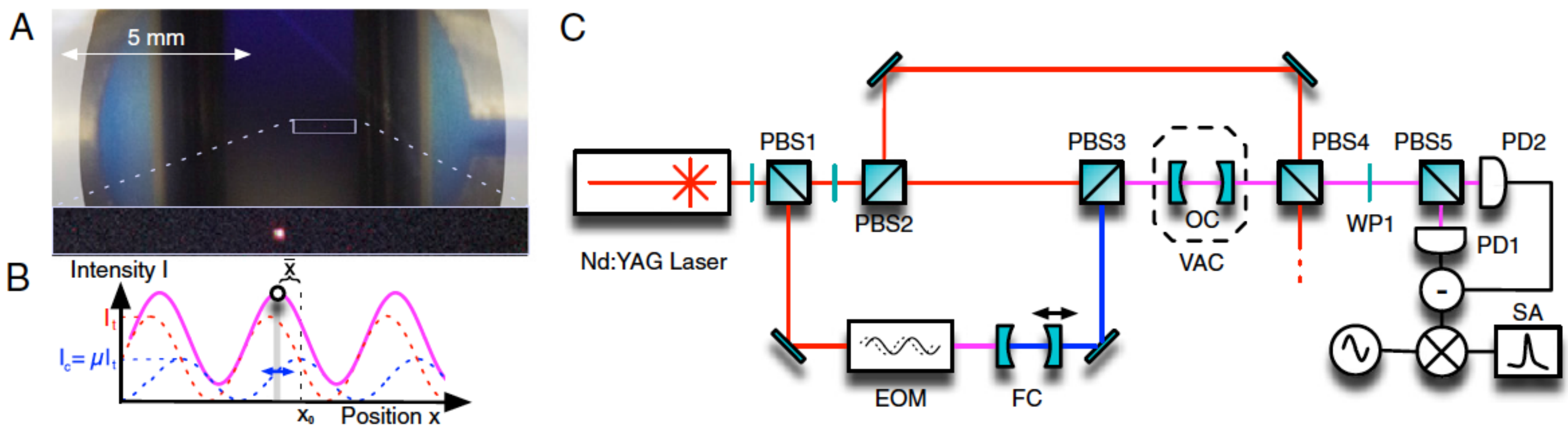
Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved July 16, 2013 (received for review May 14, 2013)



Cavity Cooling a Single Charged Levitated Nanosphere

J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, T. S. Monteiro, and P. F. Barker*
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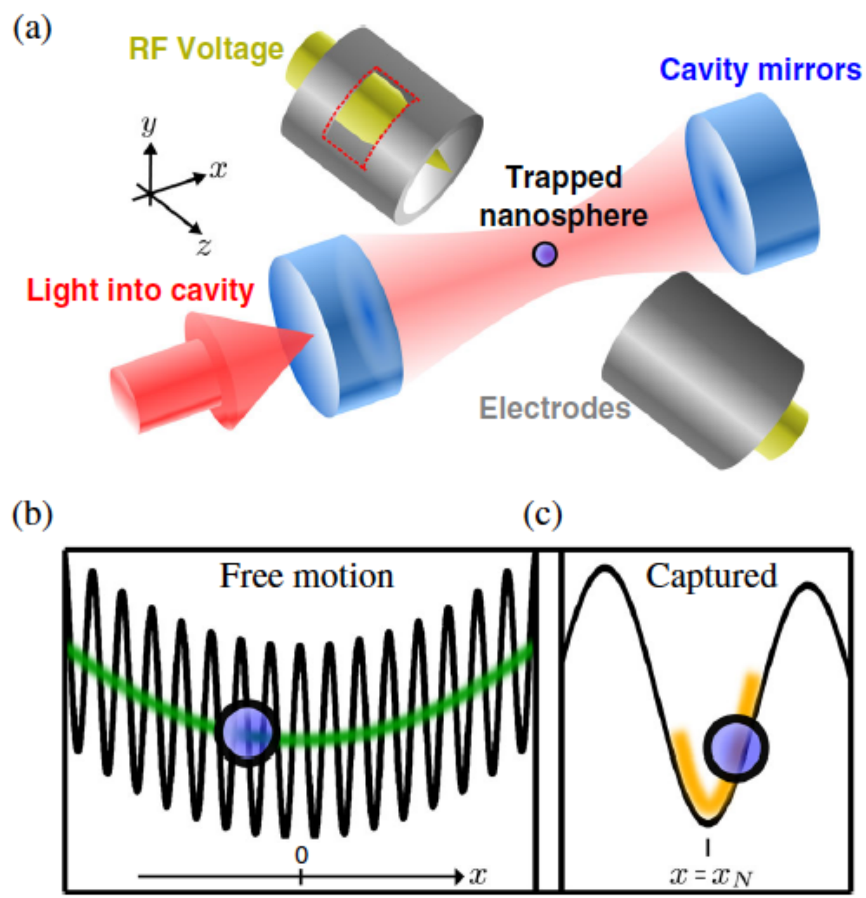
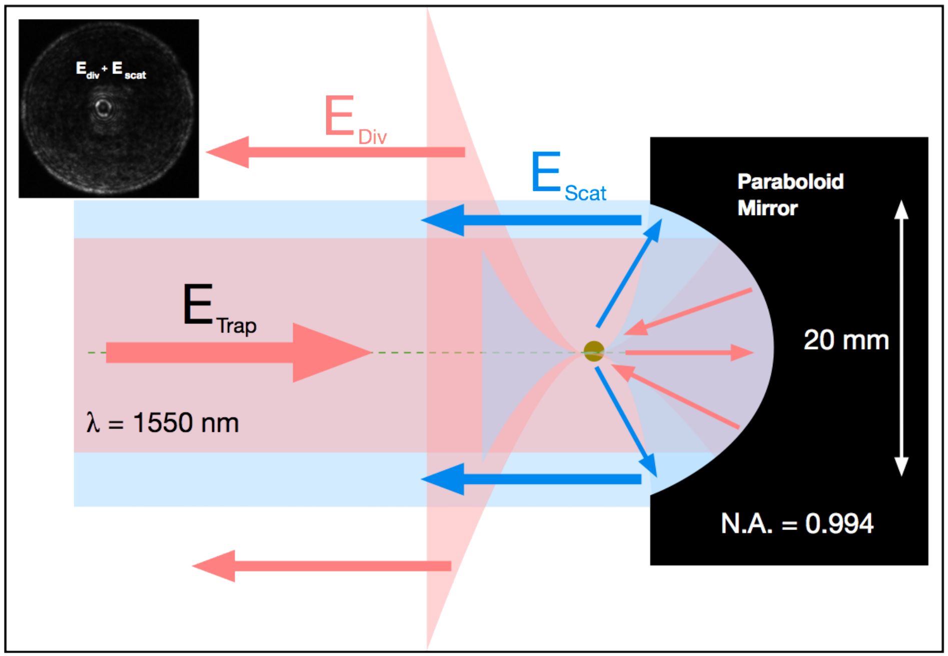
(Received 31 December 2014; published 27 March 2015)



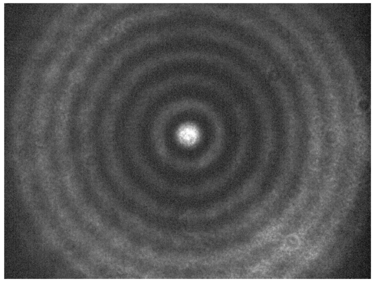
Experiments with nanoparticles: the particle optical trap

- **Trap a single particle in vacuum**
- **Optical parametric feedback to cool the centre of mass motion**

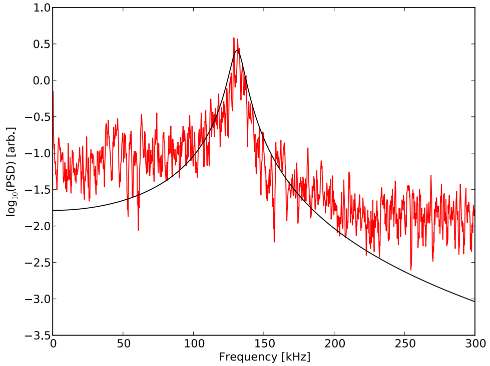
Setup schematics:



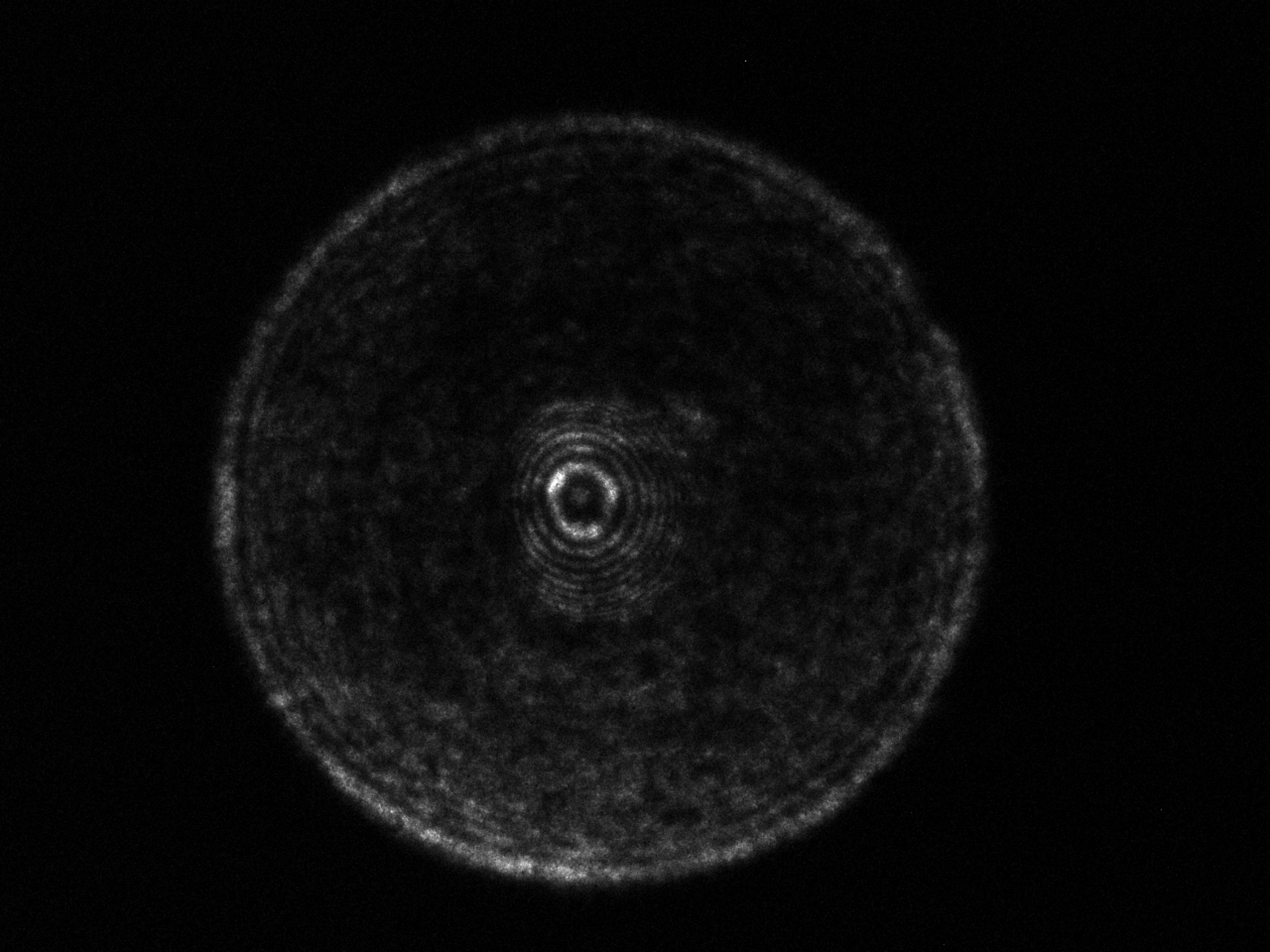
Particle in the trap:
42 nm – 150 nm diameter SiO_2, <100 mW, NA=0.9, down to **1x10^{-6} mbar**



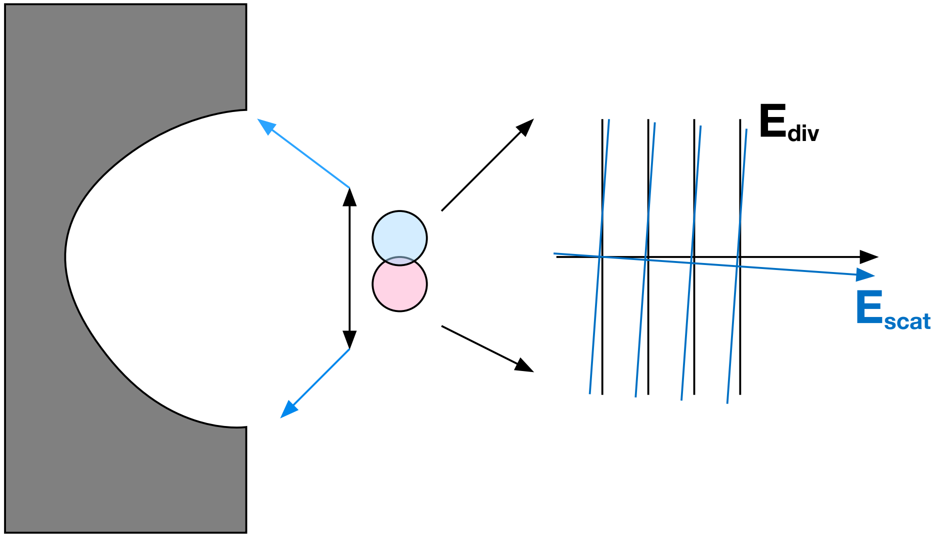
Mechanical frequency measurement:



Trapping, 3d imaging, and 3d cooling done with a single beam of 1550nm light.



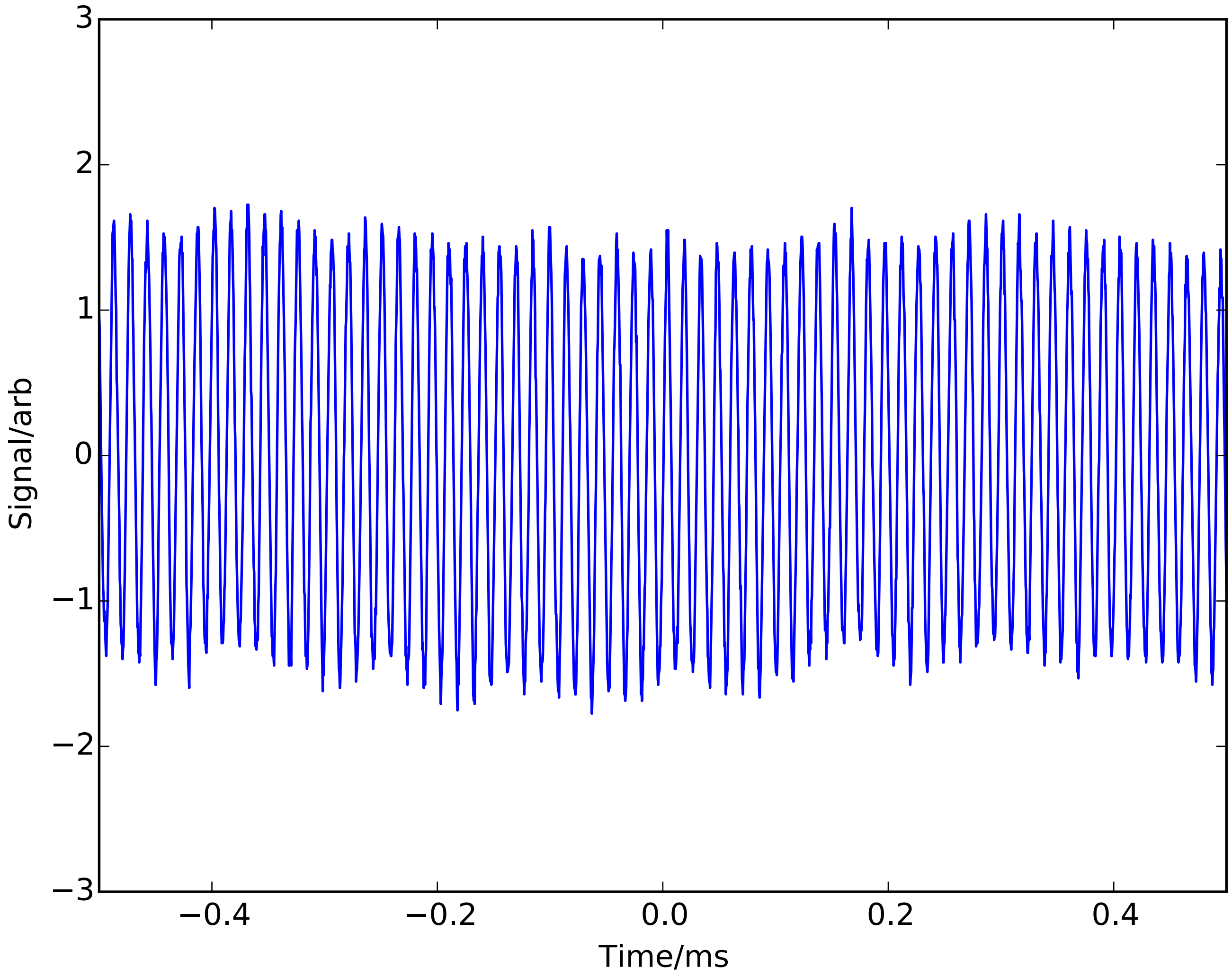
Light Interferometry for Particle Detection of x,y motion:



The total intensity at the detector is:

$$I \propto \left|E_{total}\right|^2 = \left|E_{div} + E_{scat}\right|^2 = E_{div}^2 + 2E_{div}E_{scat}\sin(\phi_{scat}) + E_{scat}^2$$

See the mechanical oscillation ….



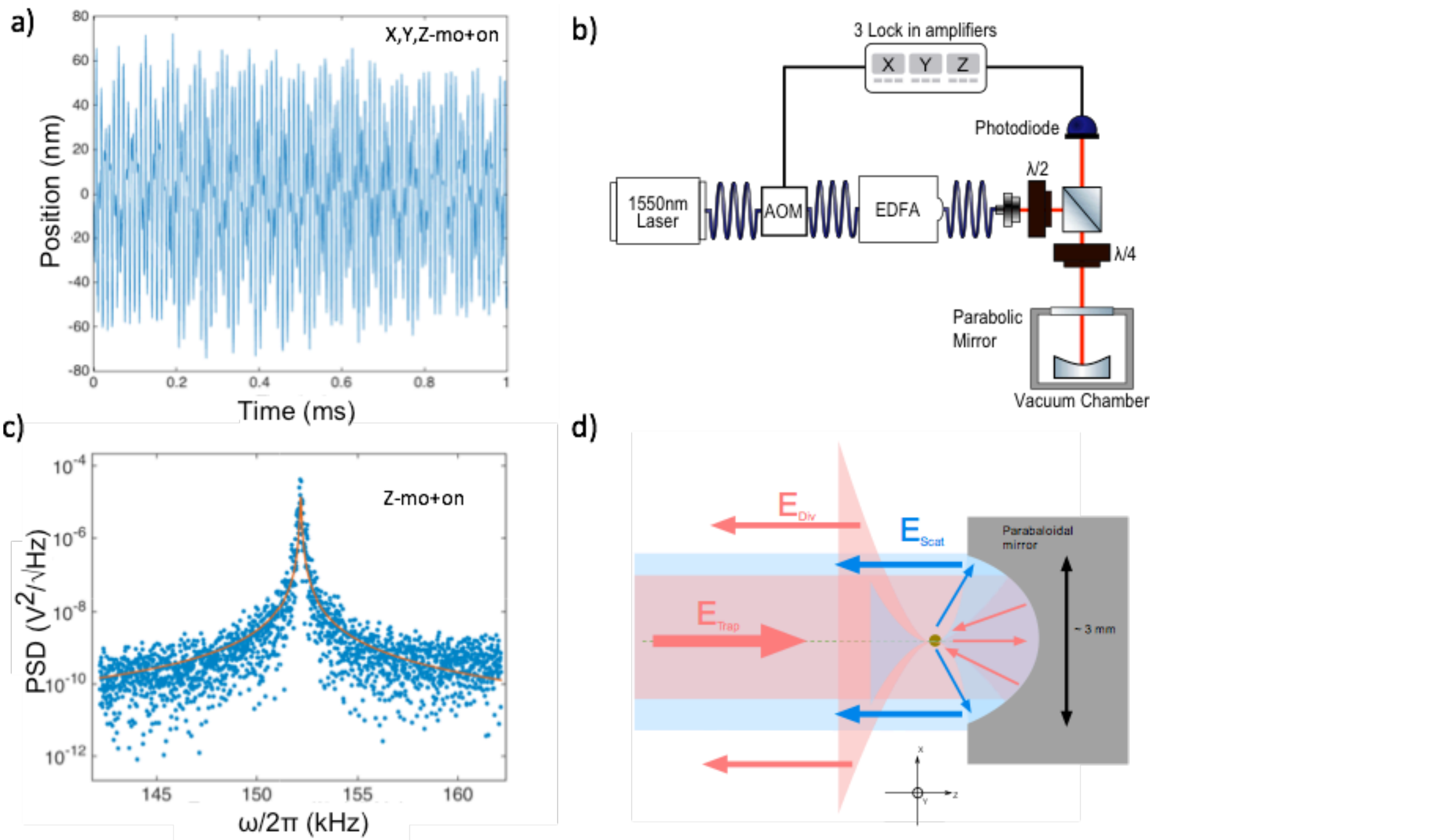
$\omega_0 = \sqrt{k_0/m}$, with $k_0 = 8\alpha P/(c\pi\epsilon_0 \mathrm{w}_\mathrm{f}^4)$

3d of data: 300 K, 1 mbar

Trap and measure position …

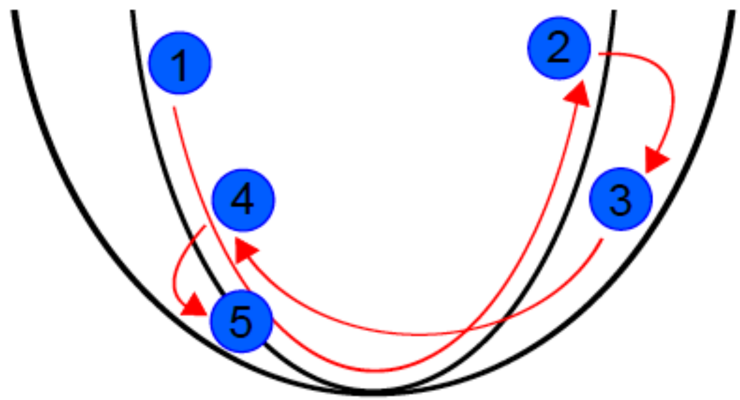
Equation of motion: $$\ddot{x}(t) + \Gamma_0 \dot{x}(t) + \omega_0^2 x(t) = \frac{1}{m}[F_{\text{fluct}}(t) + F_{\text{feed}}(t)]$$

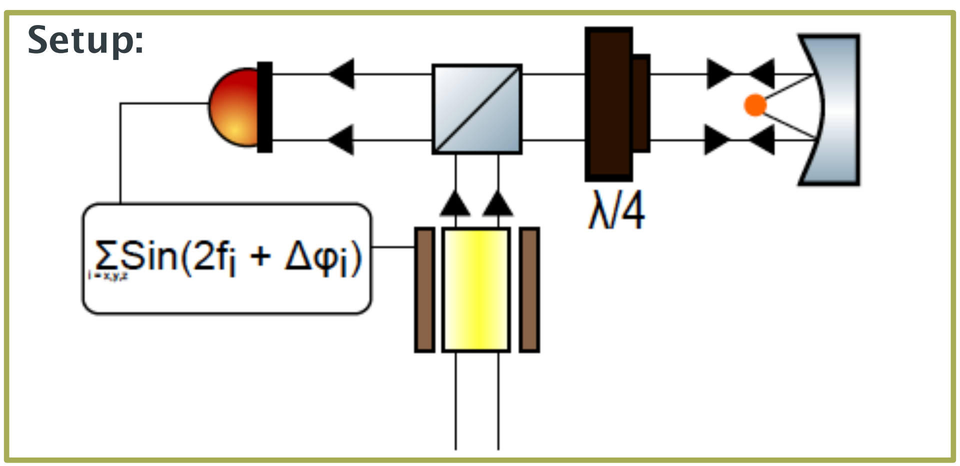
Power spectral density: $$S_x(\omega) = \frac{k_B T_0}{\pi m} \frac{\Gamma_0}{([\omega_0 + \delta\omega]^2 - \omega^2)^2 + \omega^2 [\Gamma_0 + \delta\Gamma]^2}$$



LEVITATED OPTOMECHANICS: COOLING

Parametric Feedback Cooling: use the interference signal to modulate the trapping laser light intensity





- Cooling the COM motion of the particle by modulation of the trap depth => trapping laser power modulation
  - Increase trap depth when particle is moving away from center.
  - Decrease trap depth when particle is moving towards the depth.
- Feedback signal in the form of:

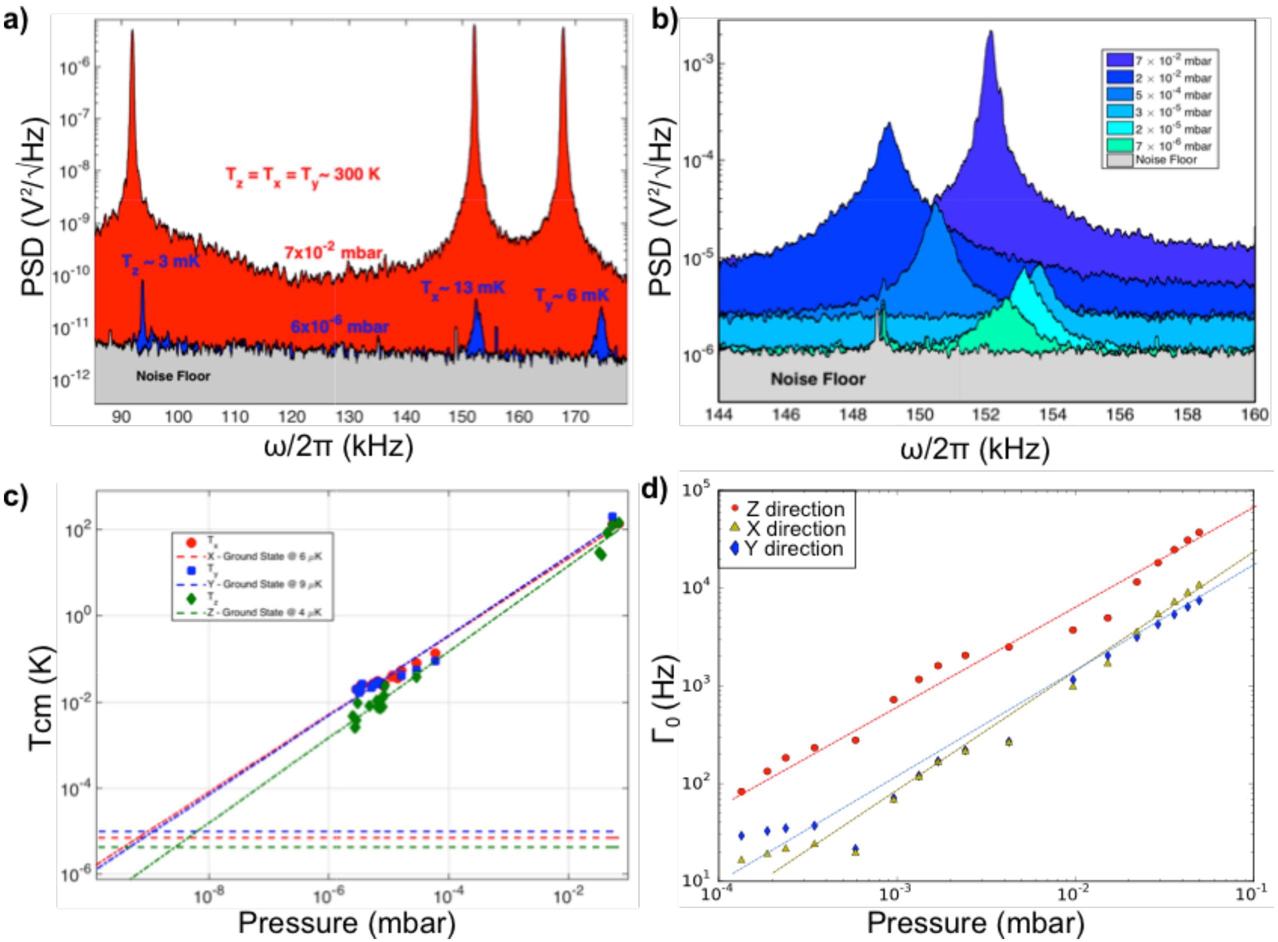
$$\propto \sin(2\omega_0 t + \phi)$$

3d with cooled motion in z-direction: 3K, 1 mbar

and cooling live in the lab

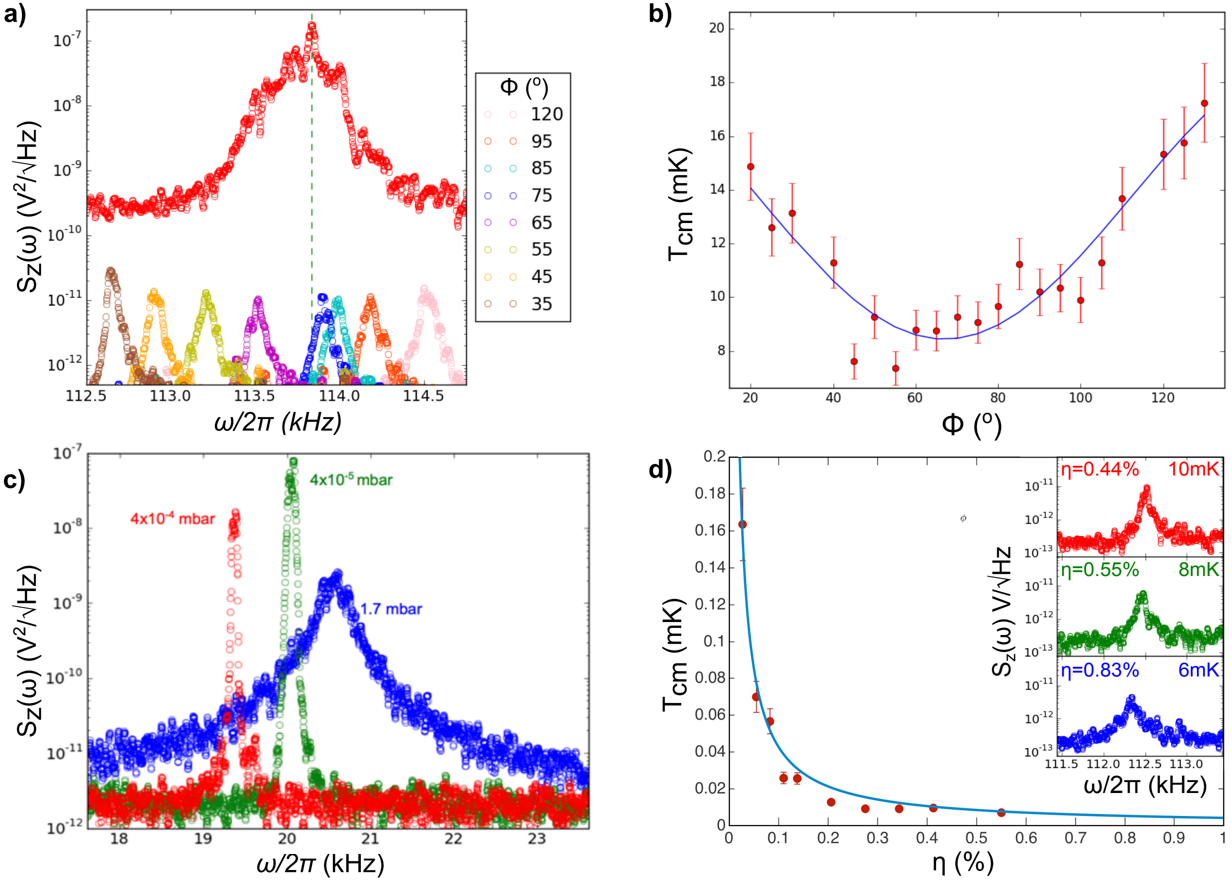
Studying the dynamics of the trapped particle ...

Power spectral density: $$S_x(\omega) = \frac{k_B T_0}{\pi m}\frac{\Gamma_0}{([\omega_0+\delta\omega]^2-\omega^2)^2+\omega^2[\Gamma_0+\delta\Gamma]^2}$$



- 26nm to 150nm particle
- X,y,z cooled to ~1 mK
- Q = 10^7 measured @10^{-5} mbar
- Damping by gas collision
- 200fm/sqrt{Hz} position resolution of detection

The effect of the parametric feedback …

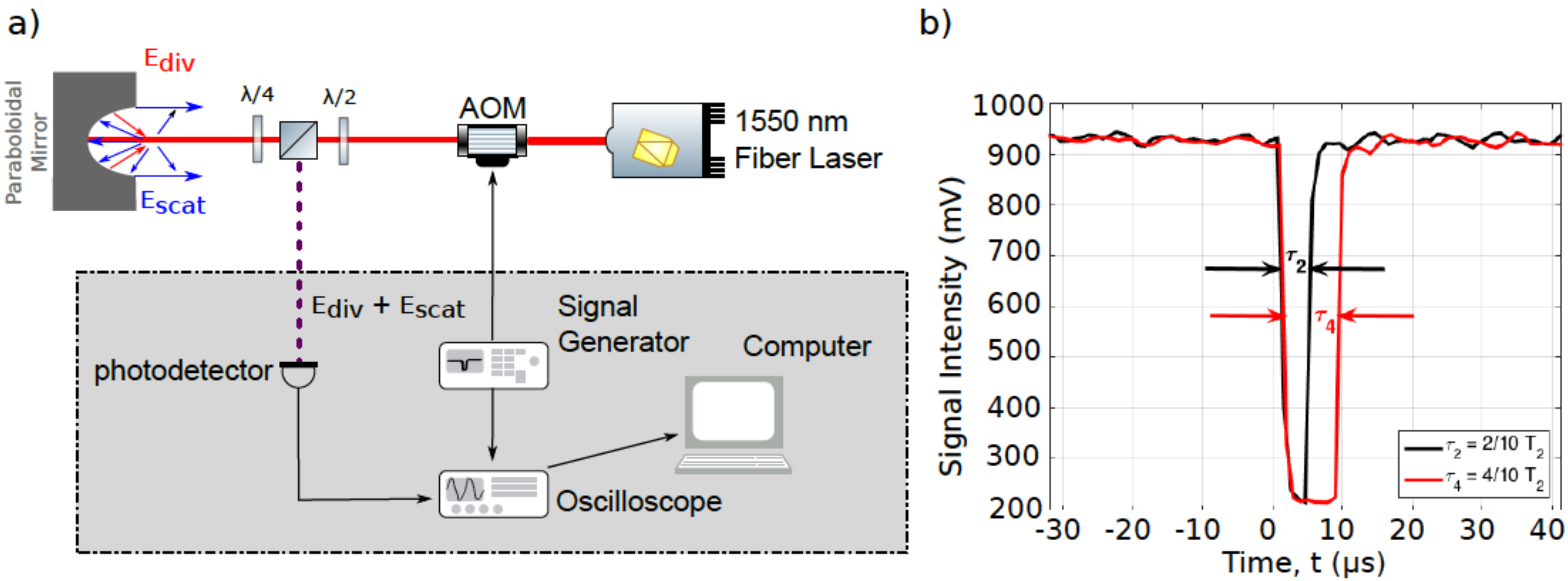


Result: We have a source, now we build the Talbot Interferometer to test the superposition principle in a new mass range!

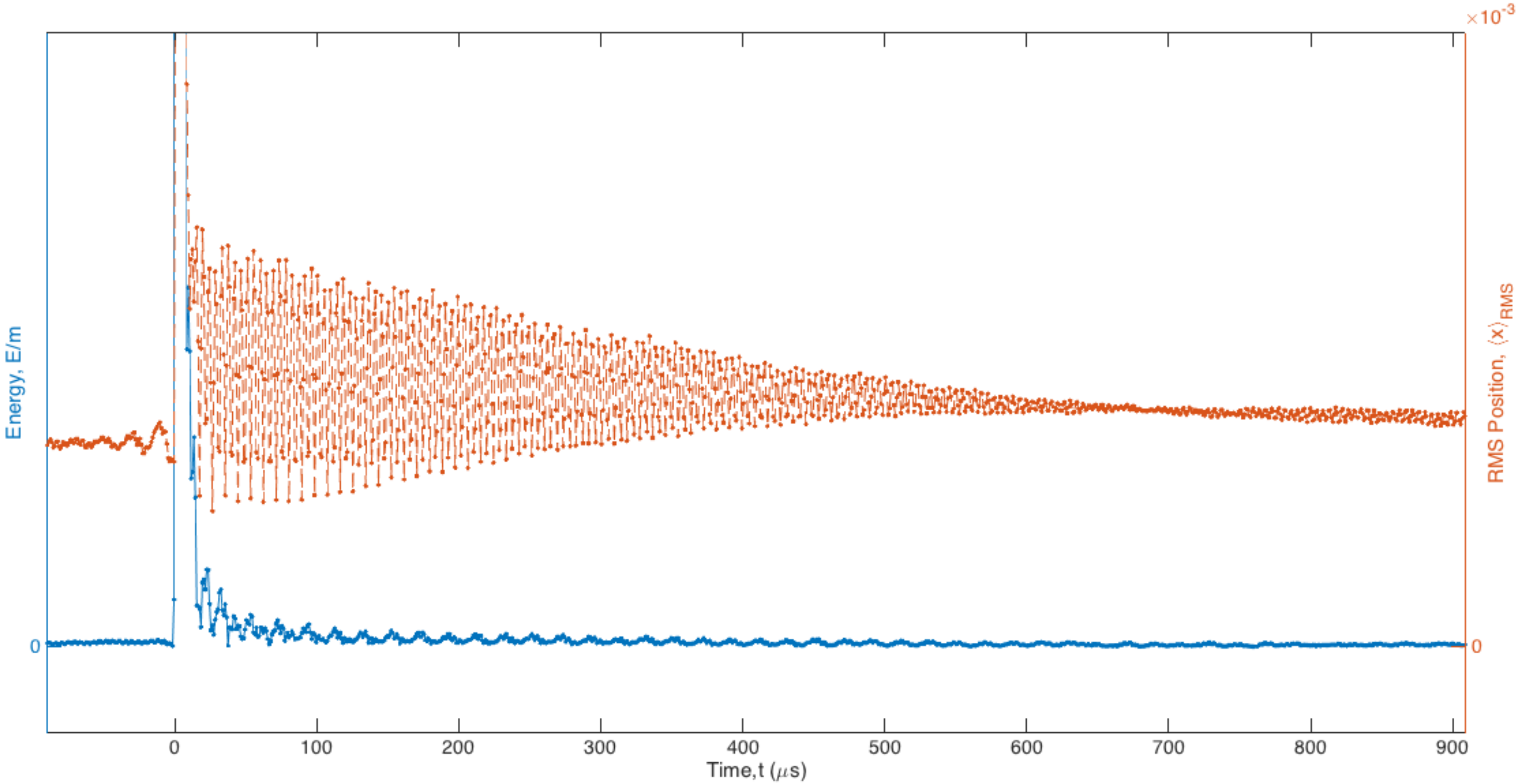
Vovrosh, J., M. Rashid, D. Hempston, J. Bateman, and H. Ulbricht, ***Controlling the Motion of a Nanoparticle Trapped in Vacuum***, arXiv:1603.02917 (2016).

LEVITATED OPTOMECHANICS: SQUEEZING

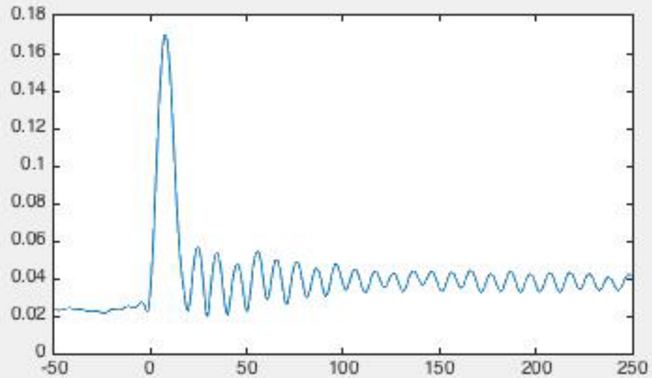
Squeezing: by fast switching the trap frequency

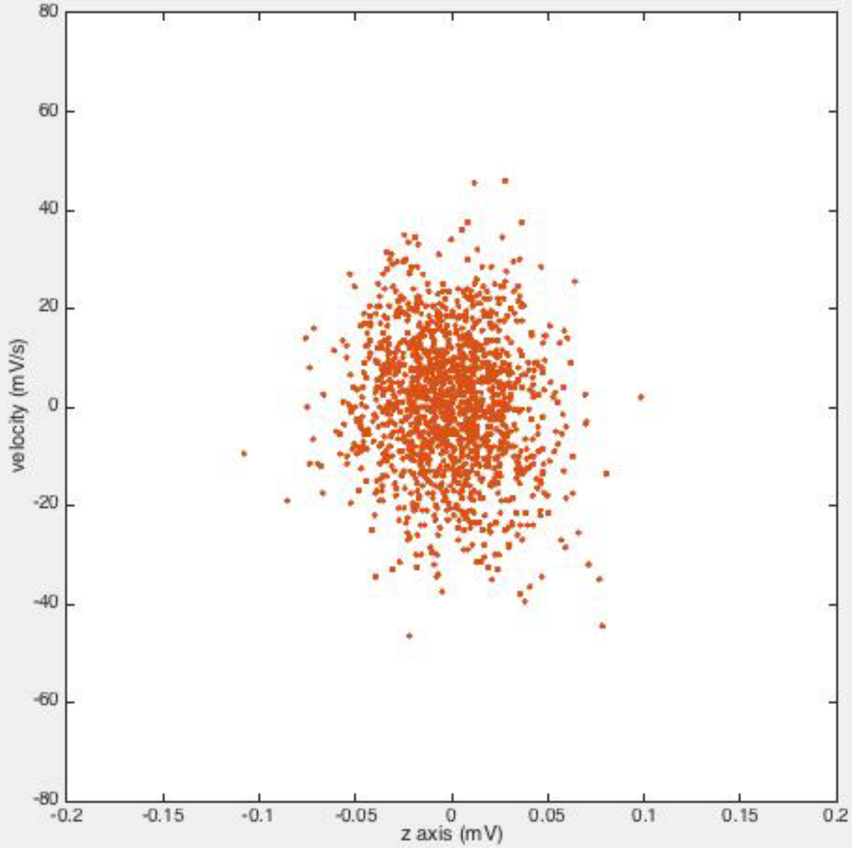


RMS position vs time

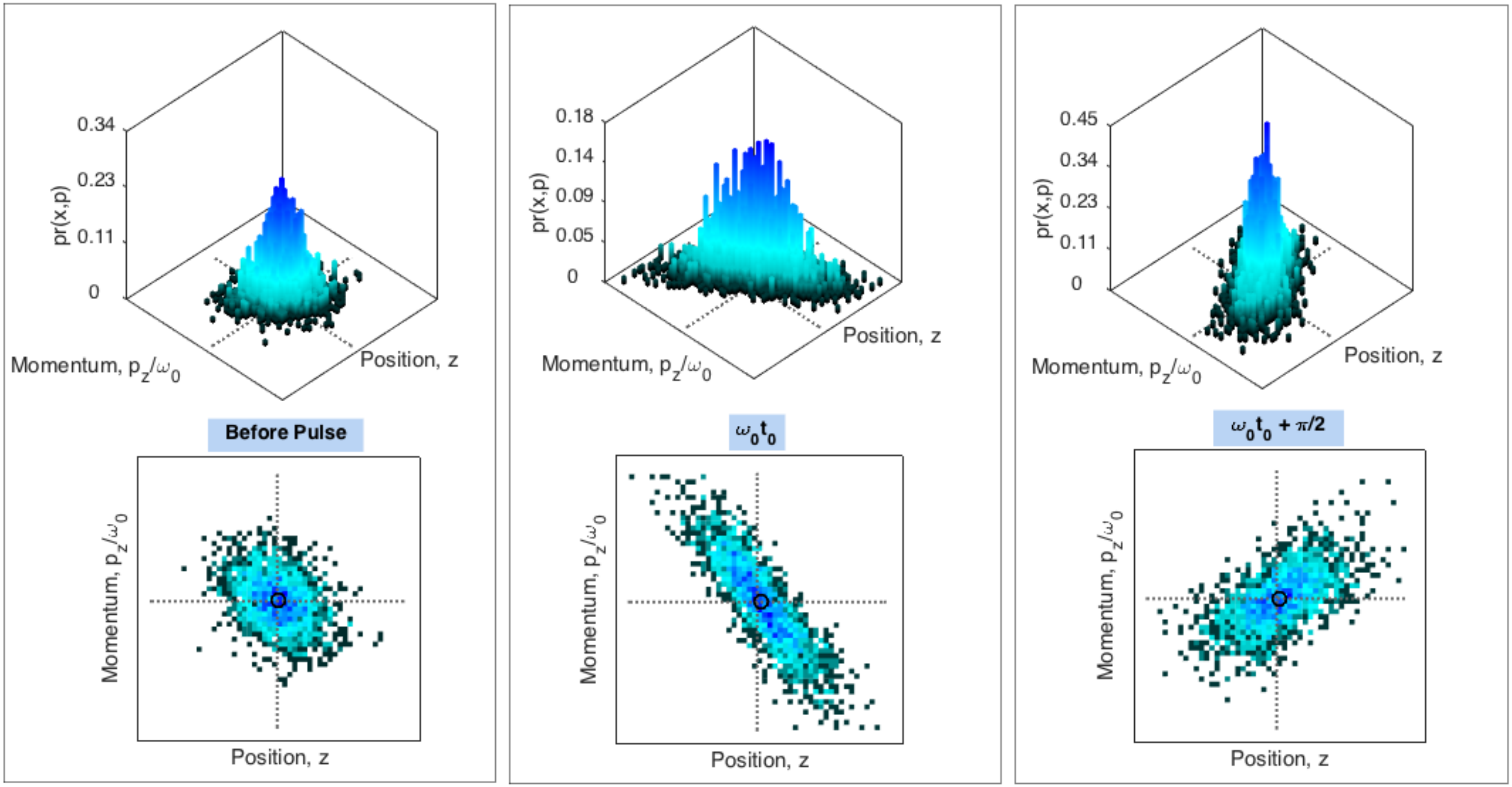


Other quantum optics stuff: squeezing mechanics [of thermal state]



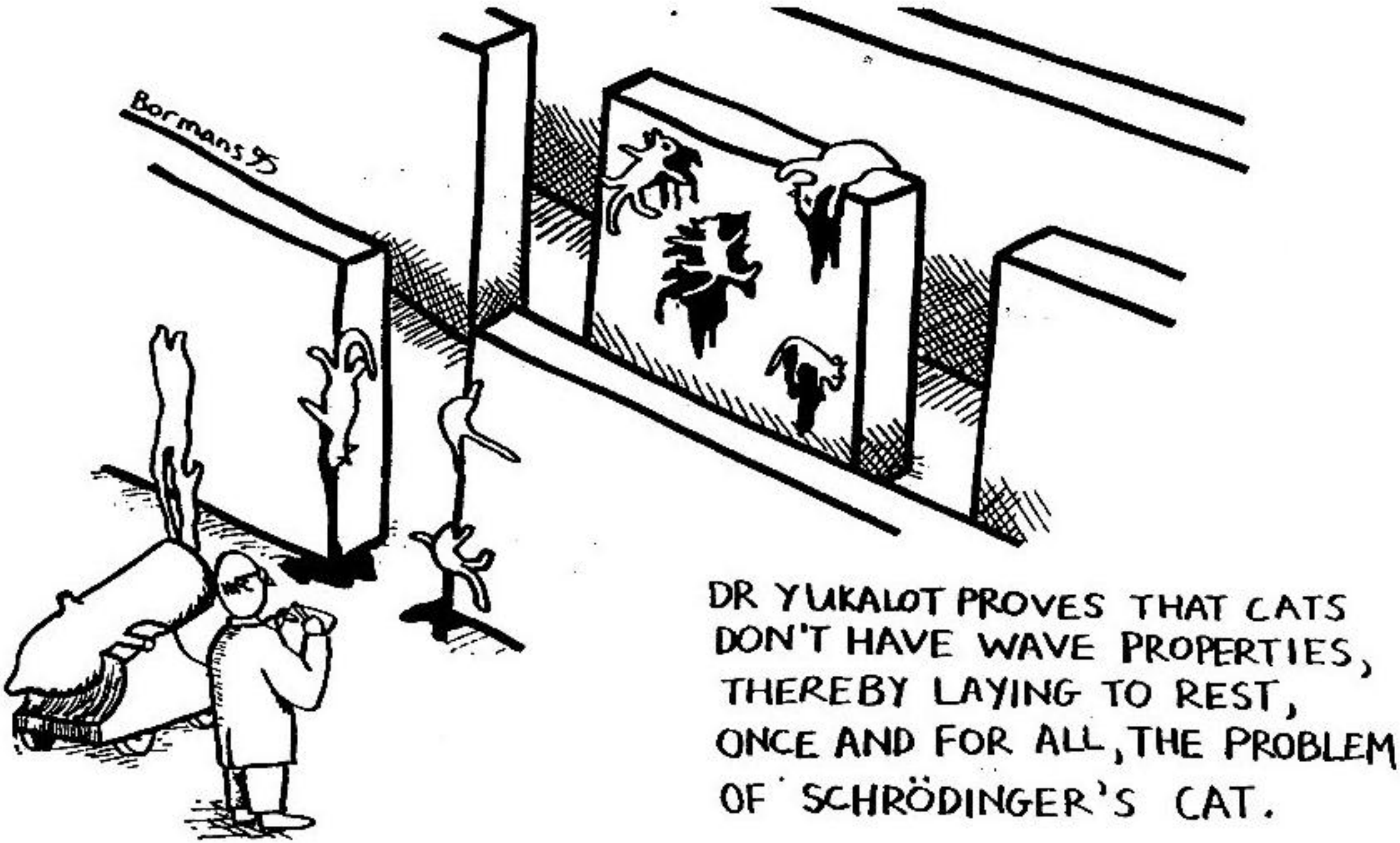


Squeezing the thermal motion



Rashid, M., T. Tufarelli, J. Bateman, J. Vovrosh, D. Hempston, M. S. Kim, and H. Ulbricht, ***Experimental Realisation of a Thermal Squeezed State of Levitated Optomechanics***, arXiv:1607.05509 (2016).

UNIVERSITY OF Southampton



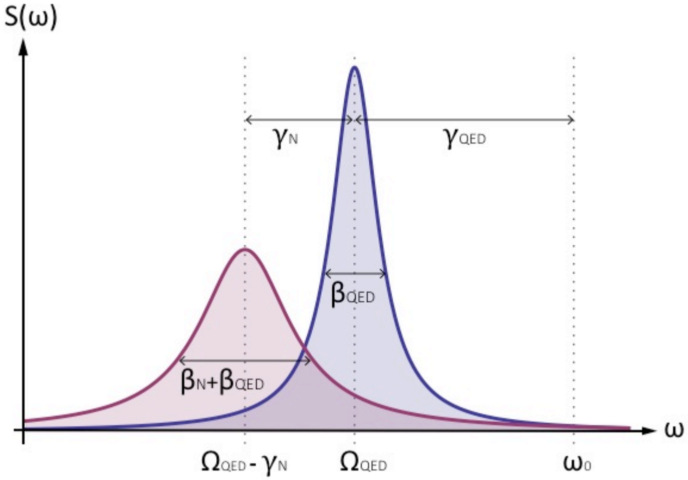
We are not very patient …

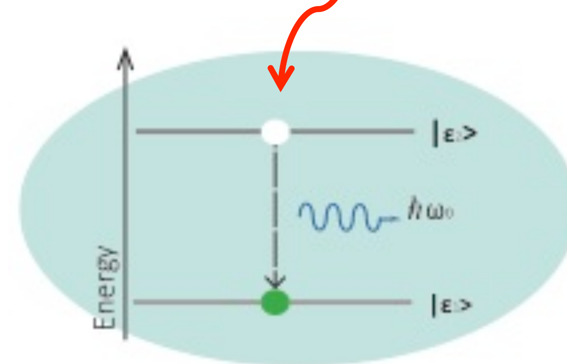
DO WE HAVE TO SHOOT WITH CATS TO TEST CSL?

OR

CAN WE DO NON-INTERFEROMETRIC?

Spectroscopy tests: Generic broadening of spectral line-width from collapse **noise**:

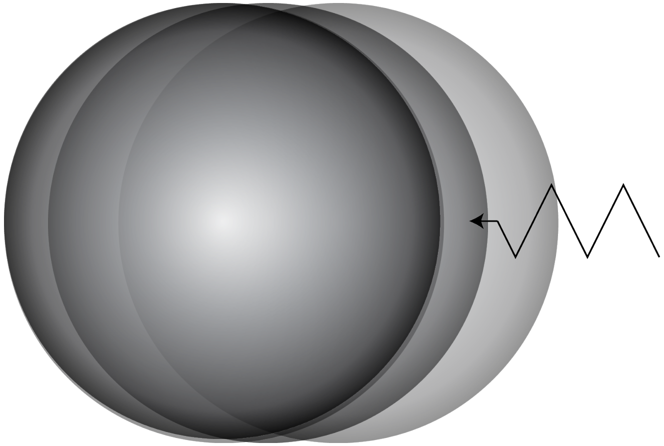




System	$\beta_{\mathrm{N}}\ (\mathrm{s}^{-1})$	$\Omega_{\mathrm{N}}\ (\mathrm{s}^{-1})$
Hydrogen-like Atoms	$10^{-20} - 10^{-18}$	$\sim 10^{-53}$
Harmonic oscillator	$\frac{3\Lambda}{4}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{32\omega_0}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^4$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

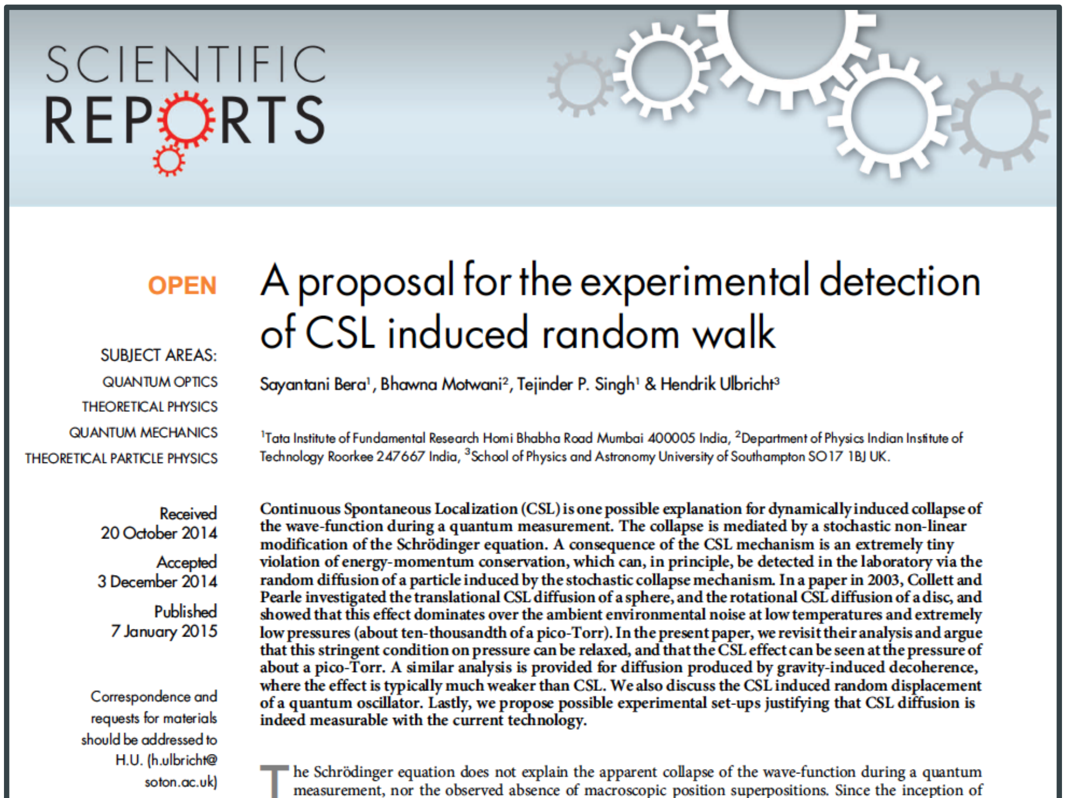
Bahrami, M., A. Bassi, and H. Ulbricht
Testing the quantum superposition principle in the frequency domain
Phys. Rev. **A 89**, 032127 (2014)]

Collapse as Noise or do we have to build a full Matter-wave interferometer to test collapse models?



Collapse induces random walk … in position space

- Corresponding spatial effect to the heating/broadening effect on the opto-mechanical system, which was in the frequency domain.
- A well-enough isolated particle should perform a random walk [like Brownian motion] triggered by collapse ‘kicks’. – first suggested by Collet and Pearle



SCIENTIFIC REPORTS

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A proposal for the experimental detection of CSL induced random walk

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SUBJECT AREAS:
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QUANTUM MECHANICS
THEORETICAL PARTICLE PHYSICS

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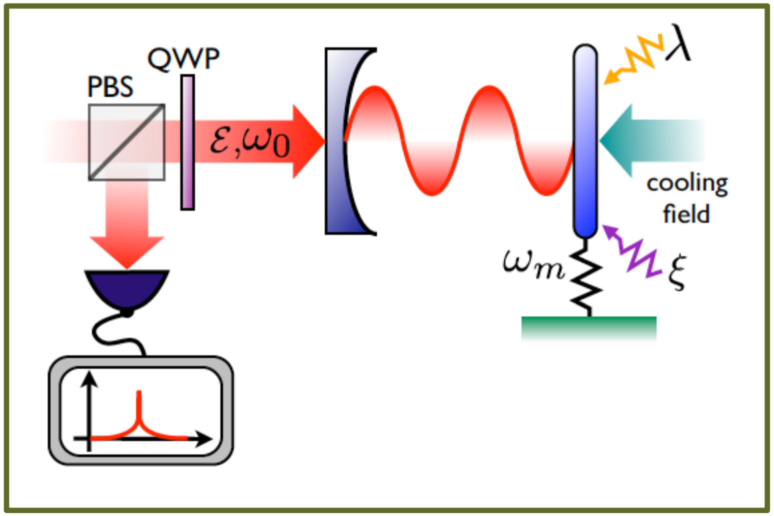
Continuous Spontaneous Localization (CSL) is one possible explanation for dynamically induced collapse of the wave-function during a quantum measurement. The collapse is mediated by a stochastic non-linear modification of the Schrödinger equation. A consequence of the CSL mechanism is an extremely tiny violation of energy-momentum conservation, which can, in principle, be detected in the laboratory via the random diffusion of a particle induced by the stochastic collapse mechanism. In a paper in 2003, Collett and Pearle investigated the translational CSL diffusion of a sphere, and the rotational CSL diffusion of a disc, and showed that this effect dominates over the ambient environmental noise at low temperatures and extremely low pressures (about ten-thousandth of a pico-Torr). In the present paper, we revisit their analysis and argue that this stringent condition on pressure can be relaxed, and that the CSL effect can be seen at the pressure of about a pico-Torr. A similar analysis is provided for diffusion produced by gravity-induced decoherence, where the effect is typically much weaker than CSL. We also discuss the CSL induced random displacement of a quantum oscillator. Lastly, we propose possible experimental set-ups justifying that CSL diffusion is indeed measurable with the current technology.

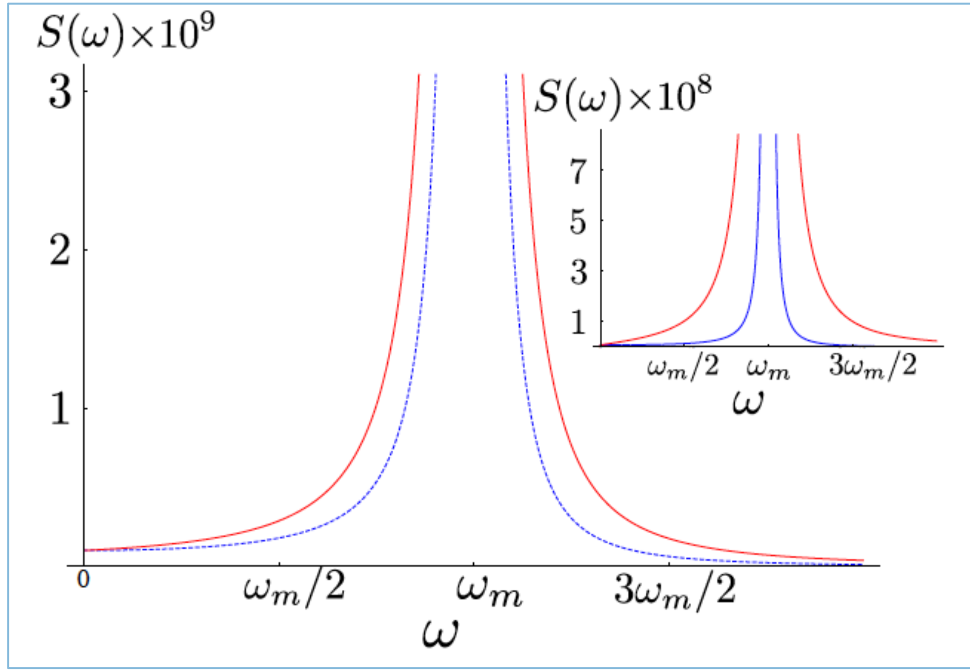
The Schrödinger equation does not explain the apparent collapse of the wave-function during a quantum measurement, nor the observed absence of macroscopic position superpositions. Since the inception of

- **Test is possible with levitated particles at low temperature and pressure.**

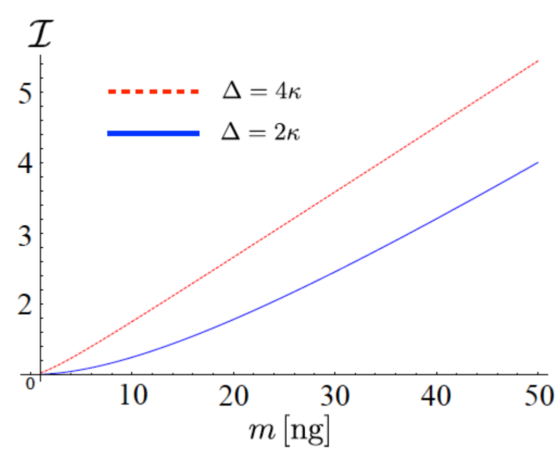
- **Possible with todays technology [optical levitation, magnetic levitation at 100mK and 10^{-10}mbar]**

Non-interferometric: Optomechanics again





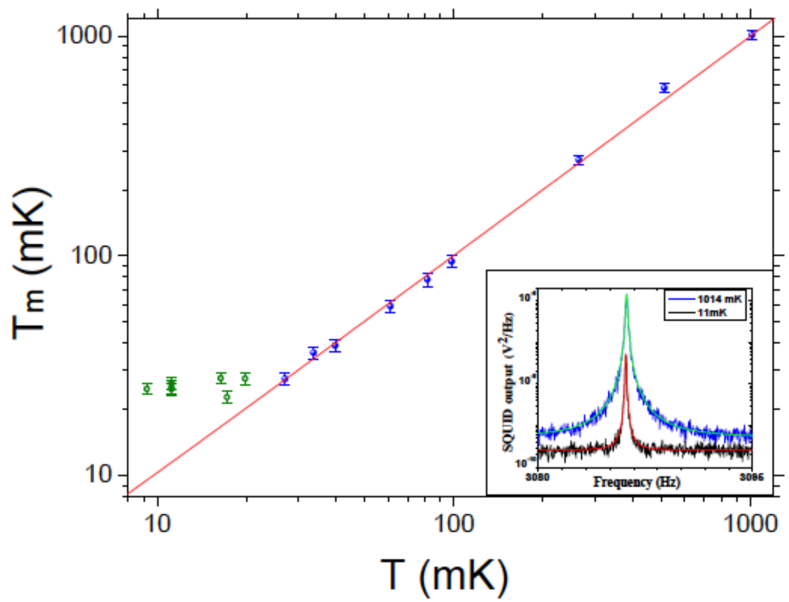
- **Collapse noise affects mechanical motion of opto-mechanical system, read out by optics**
- **Broadening effect modeled by input/output theory of opto-mechanics.**

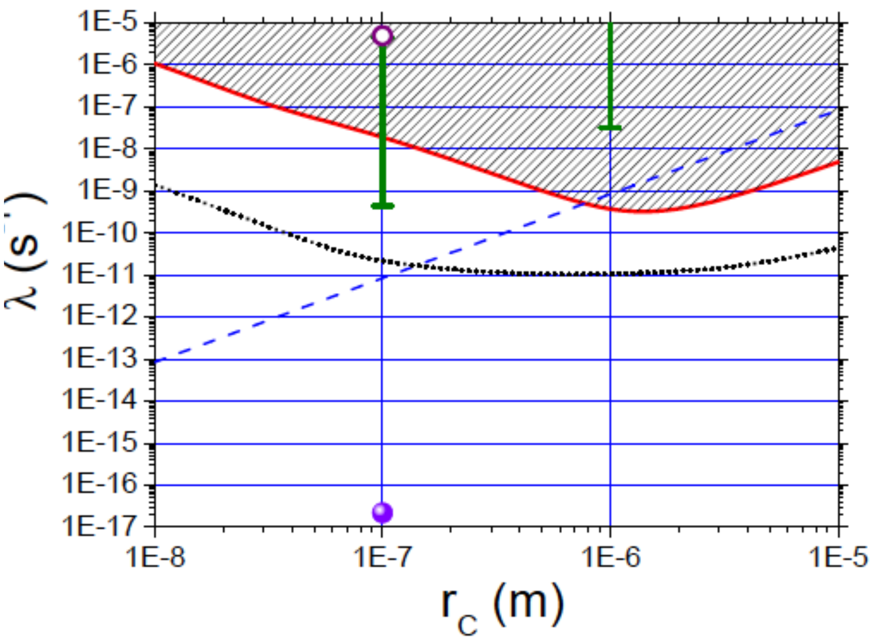


M. Bahrami, M. Paternostro, A. Bassi and H. Ulbricht
Proposal for Non-interferometric Test of Collapse Models in Optomechanical Systems*, PRL* **112***, 210404 (2014).*

Experimental bound to CSL from heated mechanical device:

- Magneto-mechanics in a 10mK fridge, a cantilever [MRFM device]
- No CSL broadening observed: One model excluded? [Adler's CSL model]





A. Vinante, M. Bahrami, A. Bassi, O. Usenko, G. Wijts, T.H. Oosterkamp, **Upper bounds on spontaneous wave-function collapse models using millikelvin-cooled nanocantilevers,** arXiv:1510.05791 (2015).