Levitated optomechanics for fundamental physics

Peter Barker
University College London

Strong community in the UK

Experiment

Hendrik Ulbricht – Southampton
Gavin Morley – Warwick
James Millen – King's College
James Bateman - Swansea

Theory

Sougato Bose - UCL
Tania Monteiro - UCL
Mauro Paternostro – Queens
Myunshik Kim – Imperial
Andrew Steane – Oxford

EPSRC
Engineering and Physical Sciences Research Council

European Commission

Cavity optomechanics

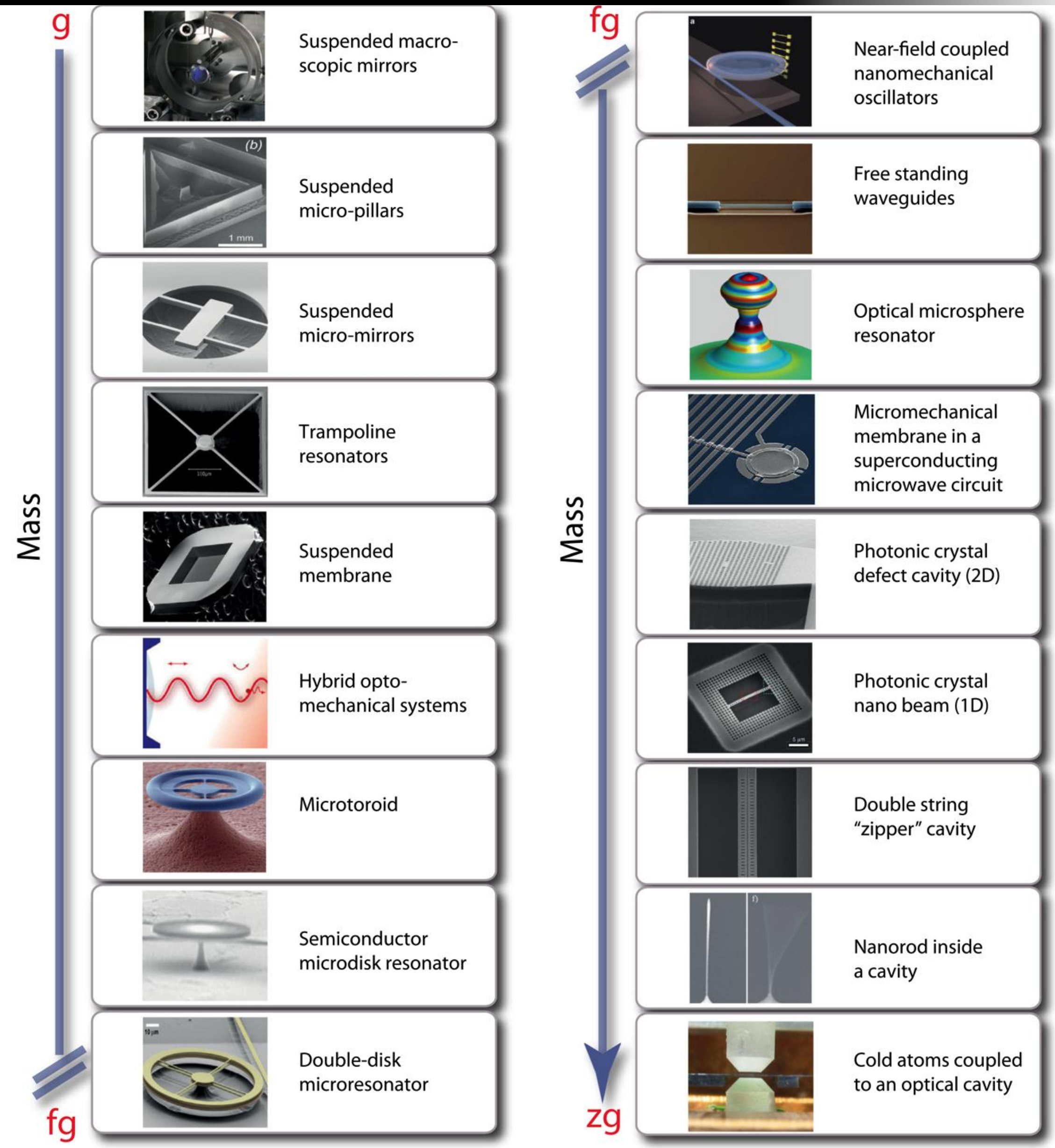
Control and cooling of oscillators with light

Enhanced by optical cavity

Engineered systems

Can be cooled to ground state

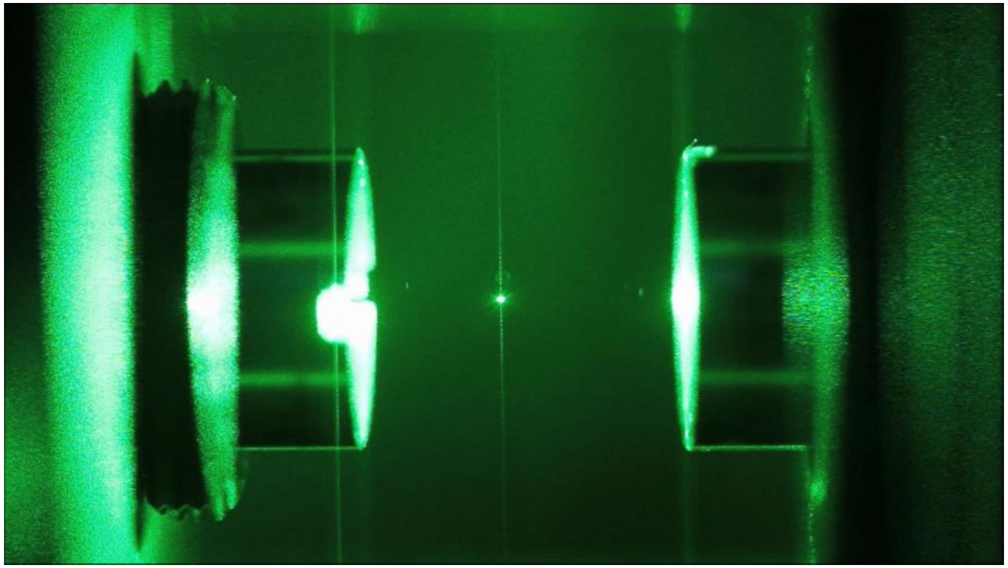
Quantum limited sensing



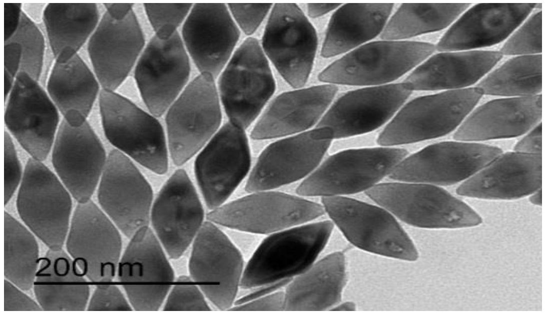
T. J. Kippenberg, K. J. Vahala, *Science* 321, 1172 (2008)

Levitated optomechanics

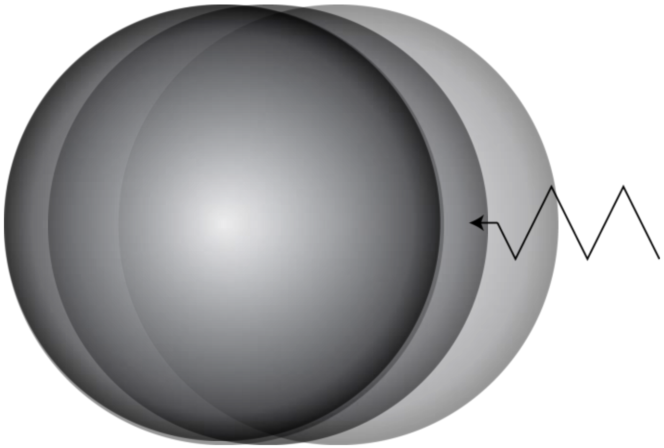
- Uses tools developed for atomic physics and optical trapping community
- Mass of 10^{6} – 10^{15} amu, Q ~ 10^{11}
- Field insulates the particle from environment
- Tunable spring constant/ trapping freq.
- Can be released



- Three translation modes (10 Hz – 1 MHz)
- Rotation (GHz)
- Torsional motion (MHz)
- Vibration (1 – 200 GHz)



Testing superposition



Matter-wave interferometry

PRL **111,** 180403 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

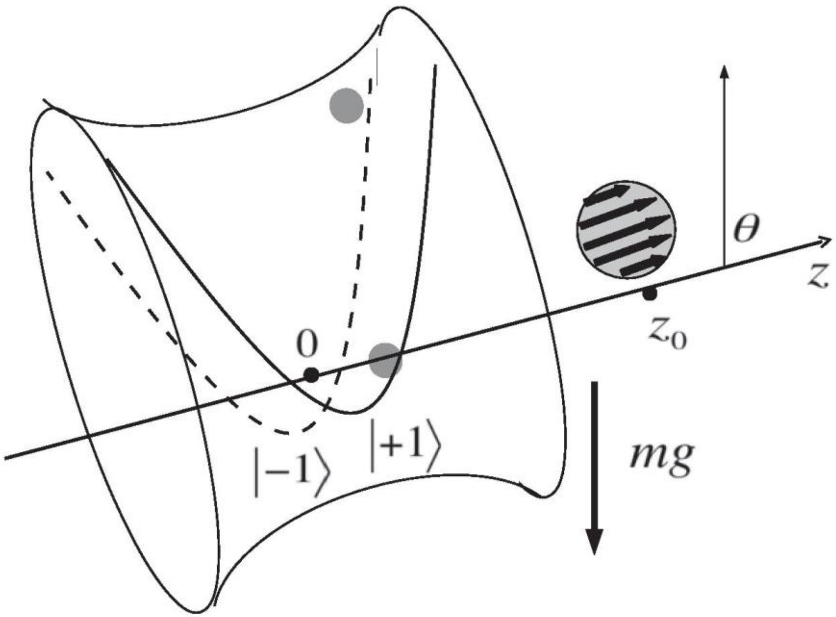
Matter-Wave Interferometry of a Levitated Thermal Nano-Oscillator Induced and Probed by a Spin

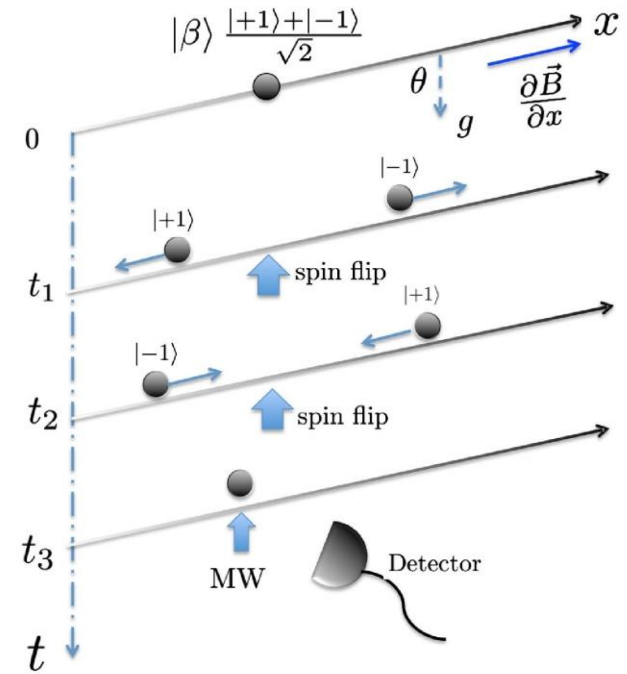
M. Scala,[1] M. S. Kim,[2] G. W. Morley,[3] P. F. Barker,[1] and S. Bose[1]

PRL **117,** 143003 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

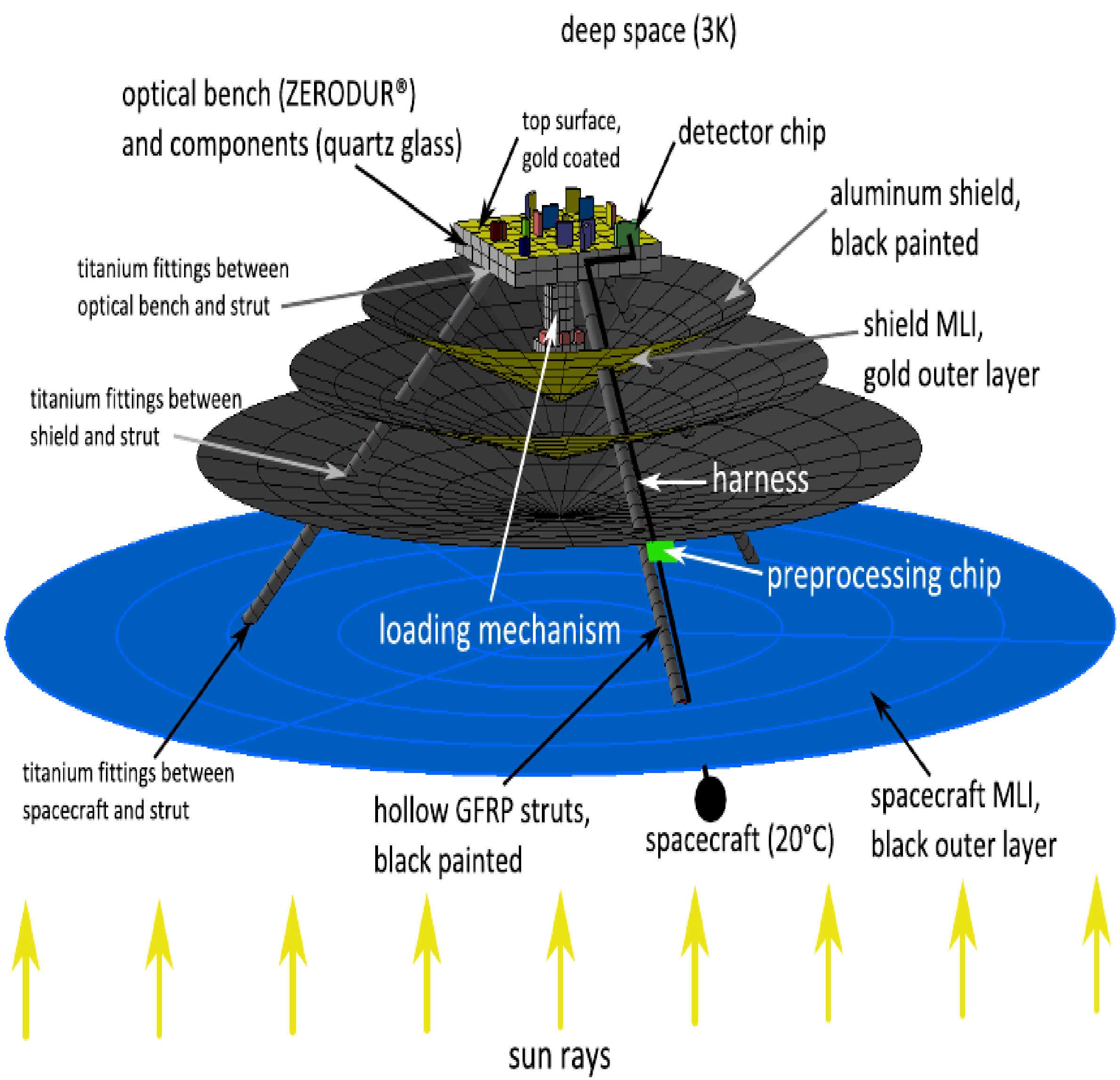
Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions

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]





MAQRO – Macroscopic quantum resonators

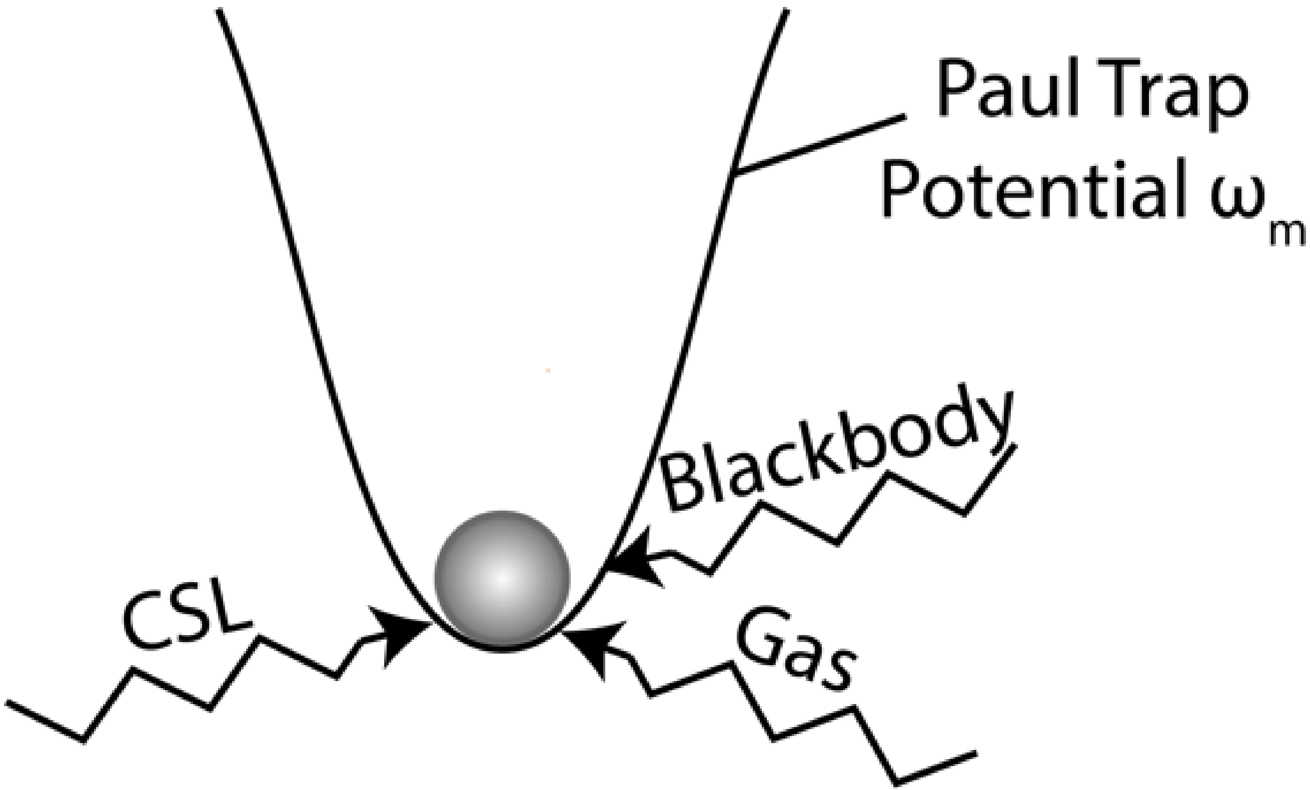


Collapse as excess noise

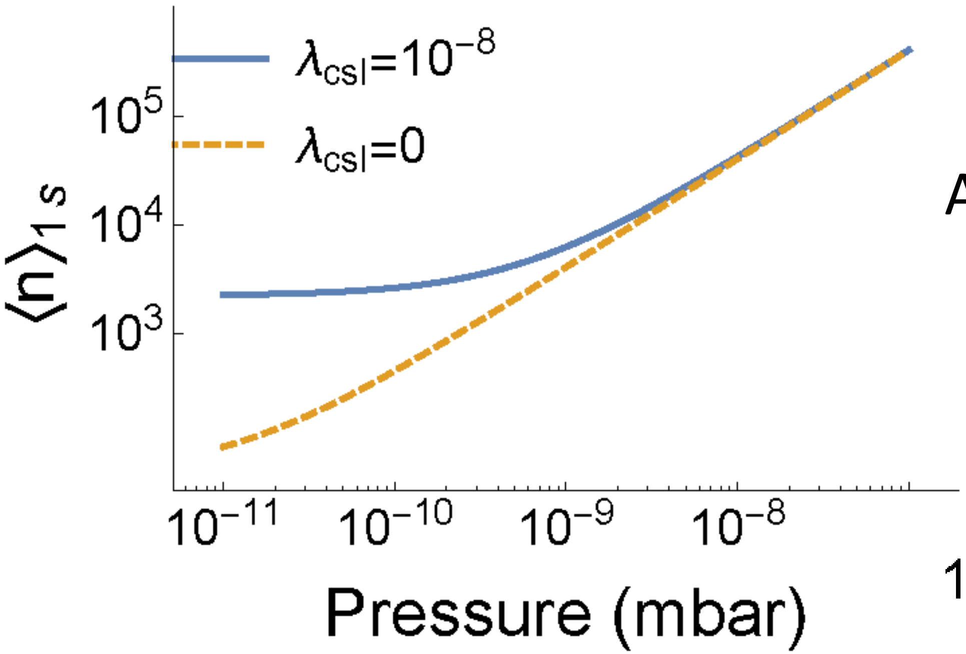
Testing wave-function-collapse models using parametric heating of a trapped nanosphere, Daniel Goldwater, Mauro Paternostro, and P. F. Barker

Phys. Rev. A **94**, 010104(R) 2016

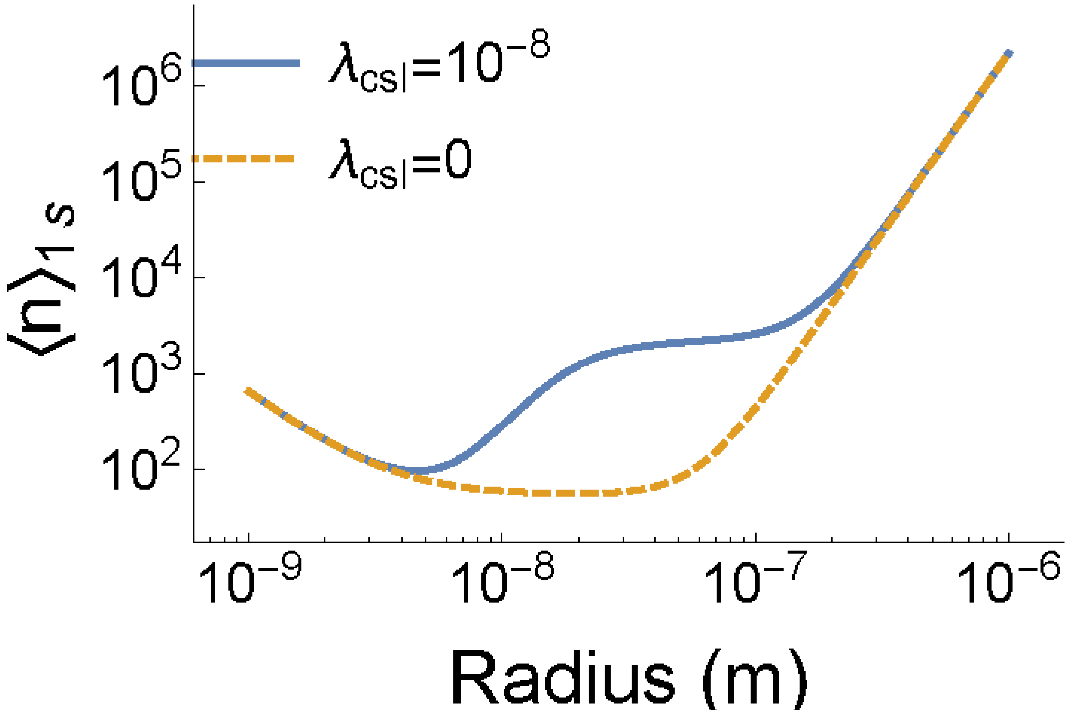
- Turn off optical field, trap in Paul trap alone



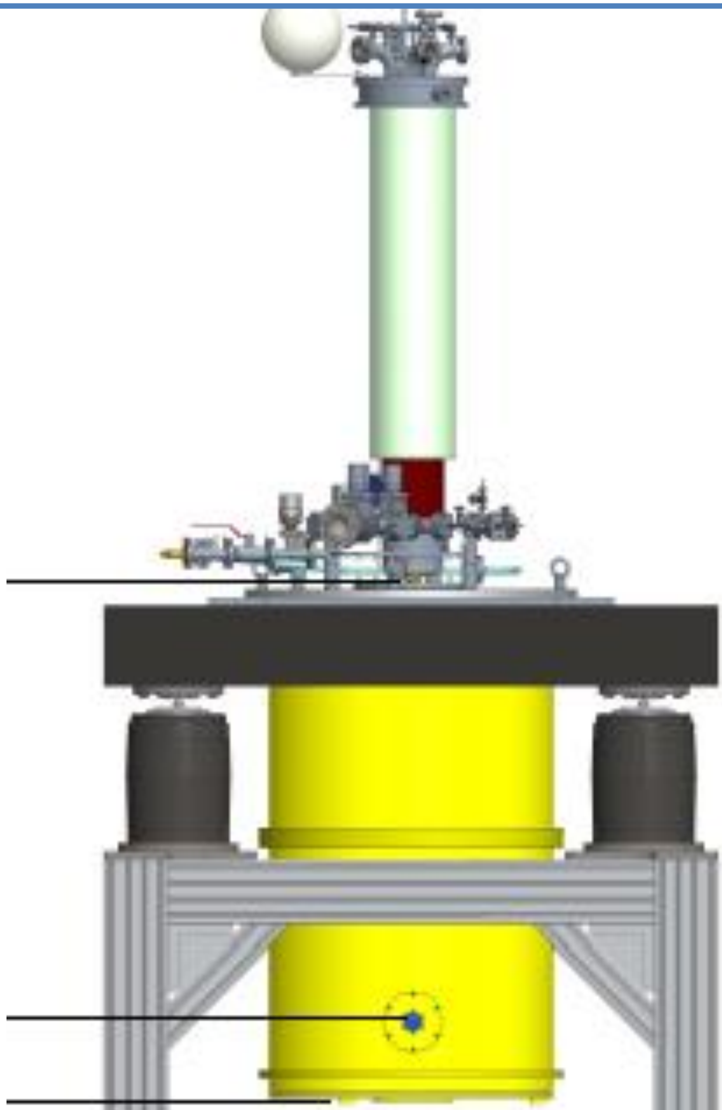
Predictions

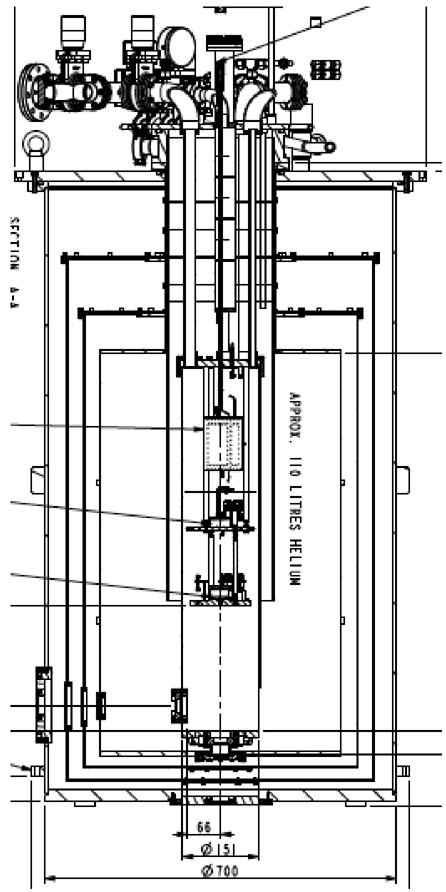


Average phonon number after 1 s



Competition between collapse rate and environmental decoherence

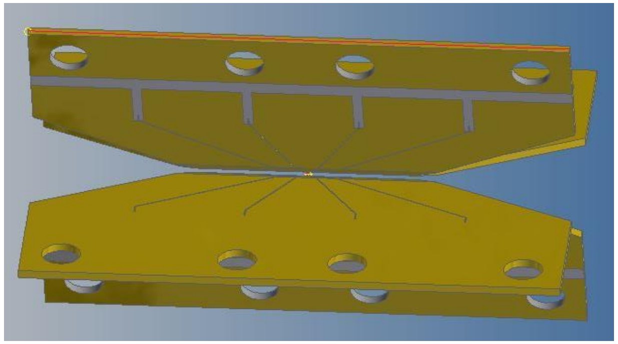




Nanoparticle
ion Paul-trap with optical detection inside a 300 mK cryostat to test CSL.

TEQ :

- EU FET-OPEN project
- Started in 2018 (€4.4M)
- Main experiment at Southampton
- Has 9 EU partners



Force sensing

PRL 105, 101101 (2010) PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 20

Short-Range Force Detection Using Optically Cooled Levitated Microspheres

Andrew A. Geraci,* Scott B. Papp, and John Kitching
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 2 June 2010; published 30 August 2010)

PRL 110, 071105 (2013) PHYSICAL REVIEW LETTERS week en 15 FEBRUA

Detecting High-Frequency Gravitational Waves with Optically Levitated Sensors

Asimina Arvanitaki
Department of Physics, Stanford University, Stanford, California 94305, USA

Andrew A. Geraci
Department of Physics, University of Nevada, Reno, Nevada 89557, USA
(Received 18 July 2012; published 14 February 2013)

We propose a tunable resonant sensor to detect gravitational waves in the frequency range of 50–300 kHz using optically trapped and cooled dielectric microspheres or microdisks. The technique we describe can exceed the sensitivity of laser-based gravitational wave observatories in this frequency range, using an instrument of only a few percent of their size. Such a device extends the search volume for gravitational wave sources above 100 kHz by 1 to 3 orders of magnitude, and could detect monochromatic gravitational radiation from the annihilation of QCD axions in the cloud they form around stellar mass black holes within our galaxy due to the superradiance effect.

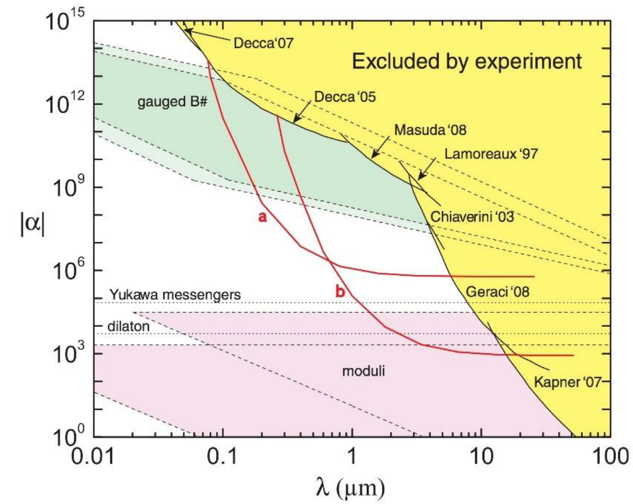
Levitated optomechanics with a fiber Fabry-Perot interferometer

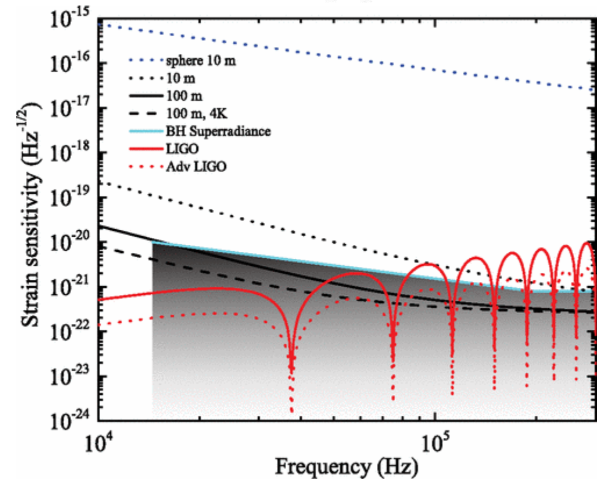
A. Pontin*,[1] L.S. Mourounas,[1] A.A. Geraci,[2] and P.F. Barker[1]

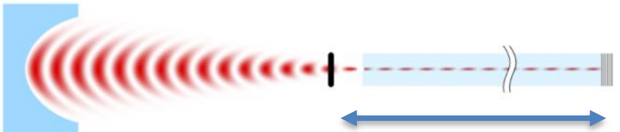
[1] *Physics Department, University College London, London, UK*

⋆ *e-mail: a.pontin@ucl.ac.uk*

[2] *Physics Department, University of Nevada, Reno, NV, USA*

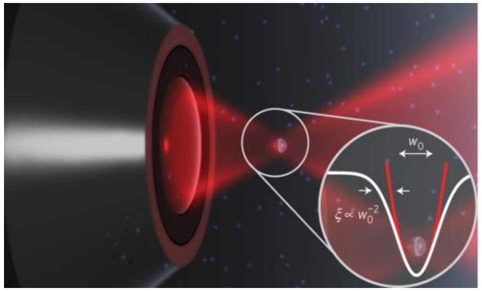






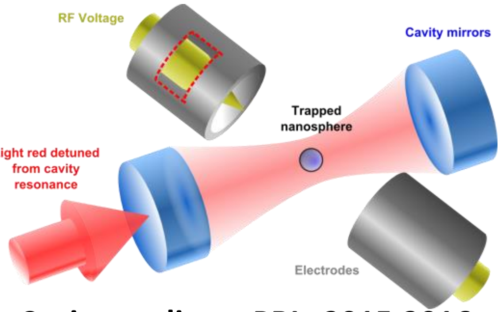
What have we and others done?

- Trapping, cooling and manipulation in vacuum



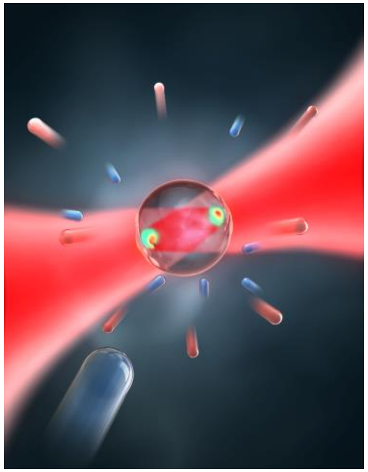
<u>Feed back cooling</u>, Gieseler *et al. Nature Phys.* **9** 806 (2012)

T = 100 μK range



<u>Cavity cooling – PRL, 2015,2016</u>

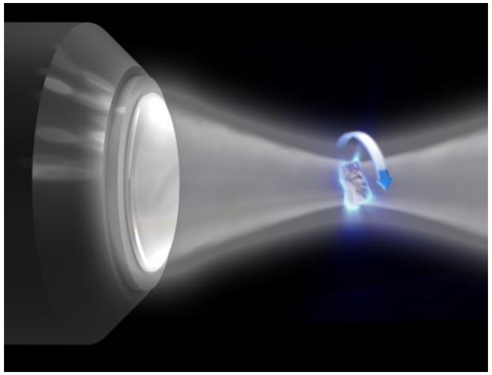
- Heating and decoherence (C.M. and internal)



$$\Gamma_{gas} \approx 15.8 \frac{R^2 p_{gas}}{m v_{gas}}$$

$$\Gamma_{recoil} = \frac{1}{5} \frac{P_{scatt}\omega}{mc^2\omega_t}$$

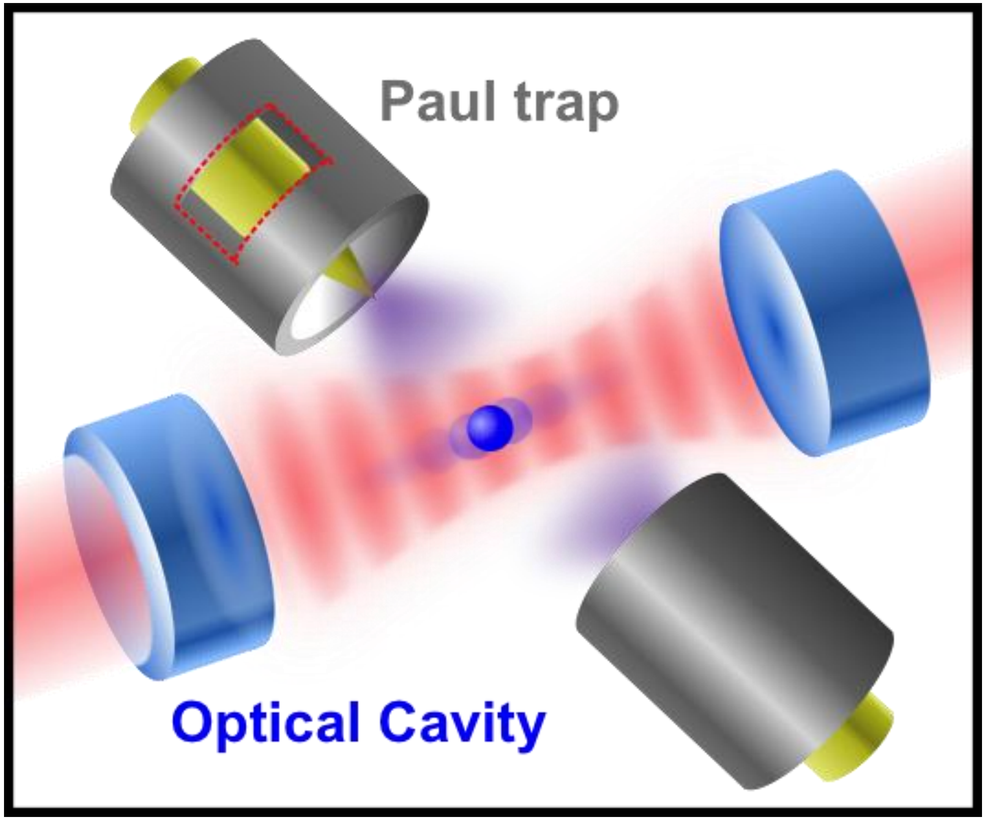
$$\Gamma_{bb} = \frac{72\zeta(5)V}{\pi^2 c^3 \hbar^4} Im \frac{\epsilon - 1}{\epsilon + 2} (k_b T)^5$$



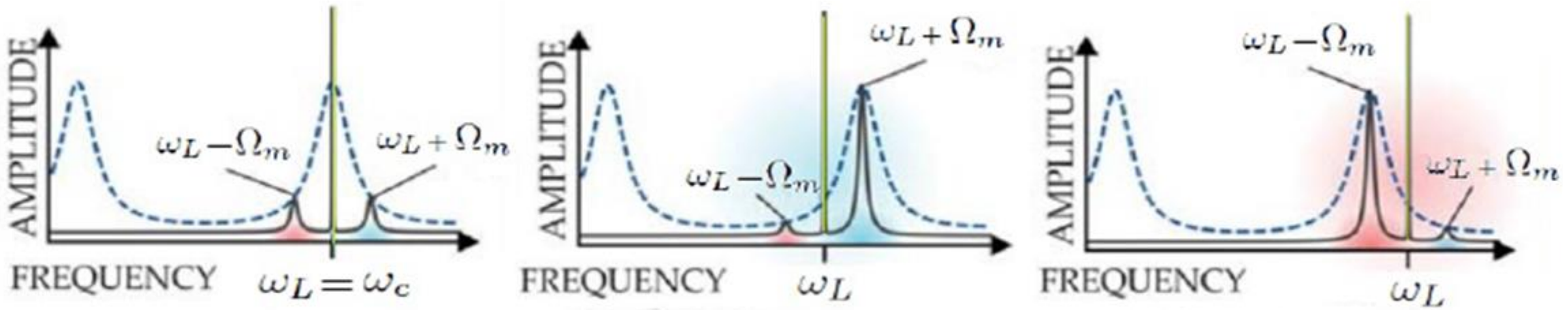
<u>Refrigeration– Nat. Phot.</u>

<u>Gas Heating,</u> Millen et al, Nature Nano. 9 425 (2014)

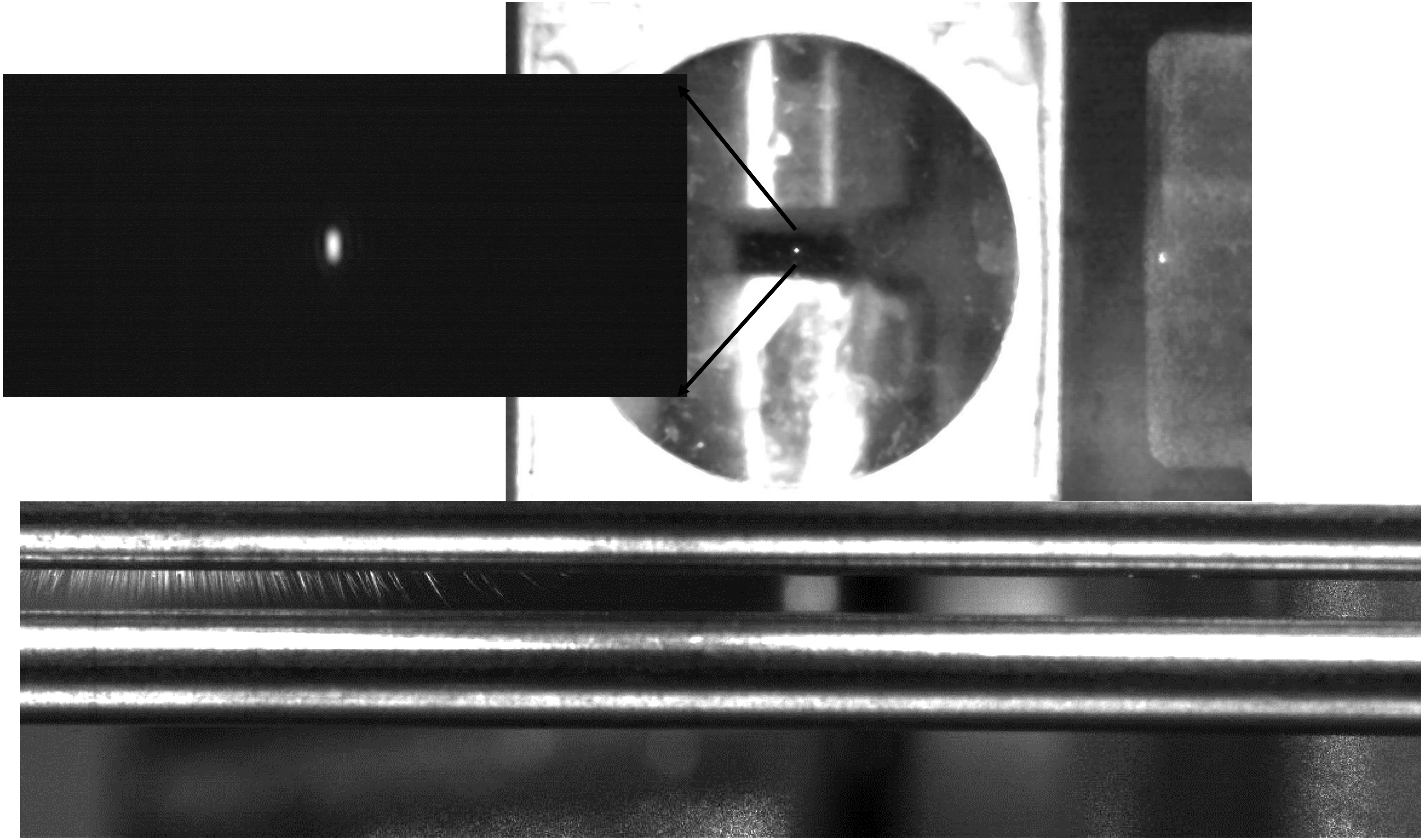
Cavity cooling trapped nanospheres



P. Z. G. Fonseca, E. B. Aranas, J. Millen, T. S. Monteiro, and P. F. Barker, Phys. Rev. Lett. 117, 173602 (2016)

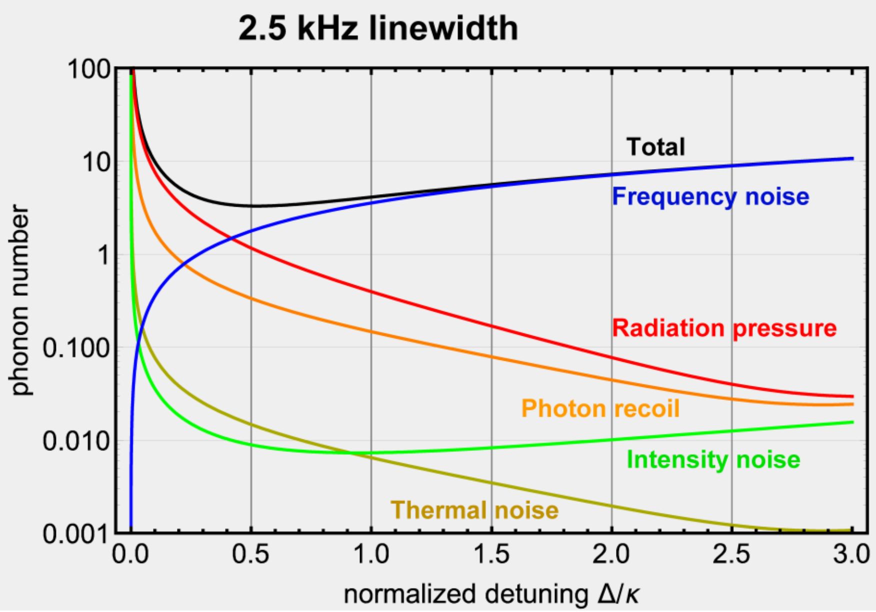


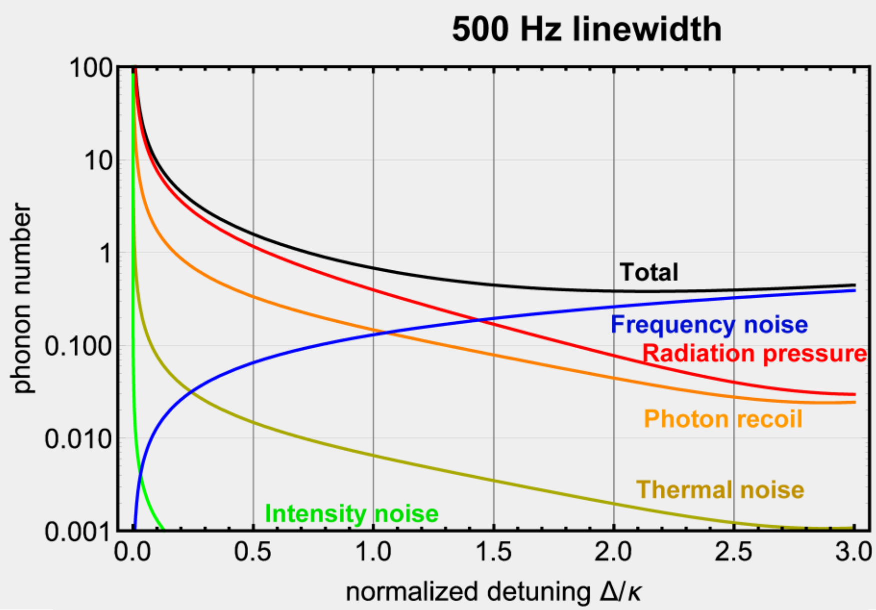
Hybrid trap



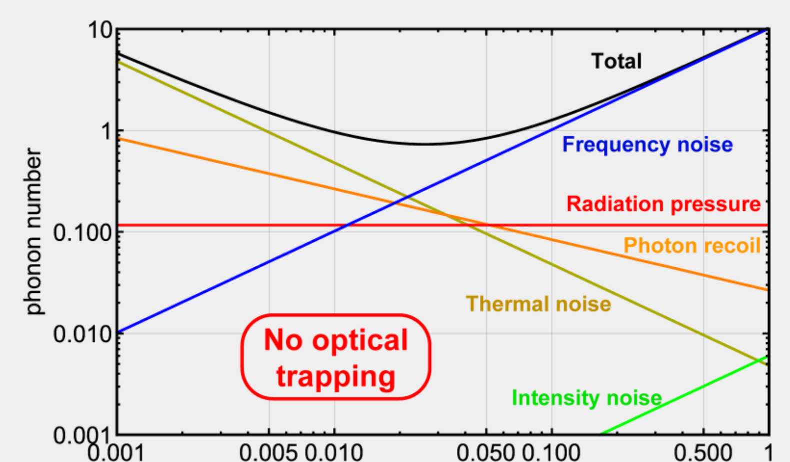
Noise control

Cooling of a mechanical frequency of 100 kHz, 10e-8 mbar for different linewidths of the filtering cavity (Science cavity 26 kHz, 200 nm,)

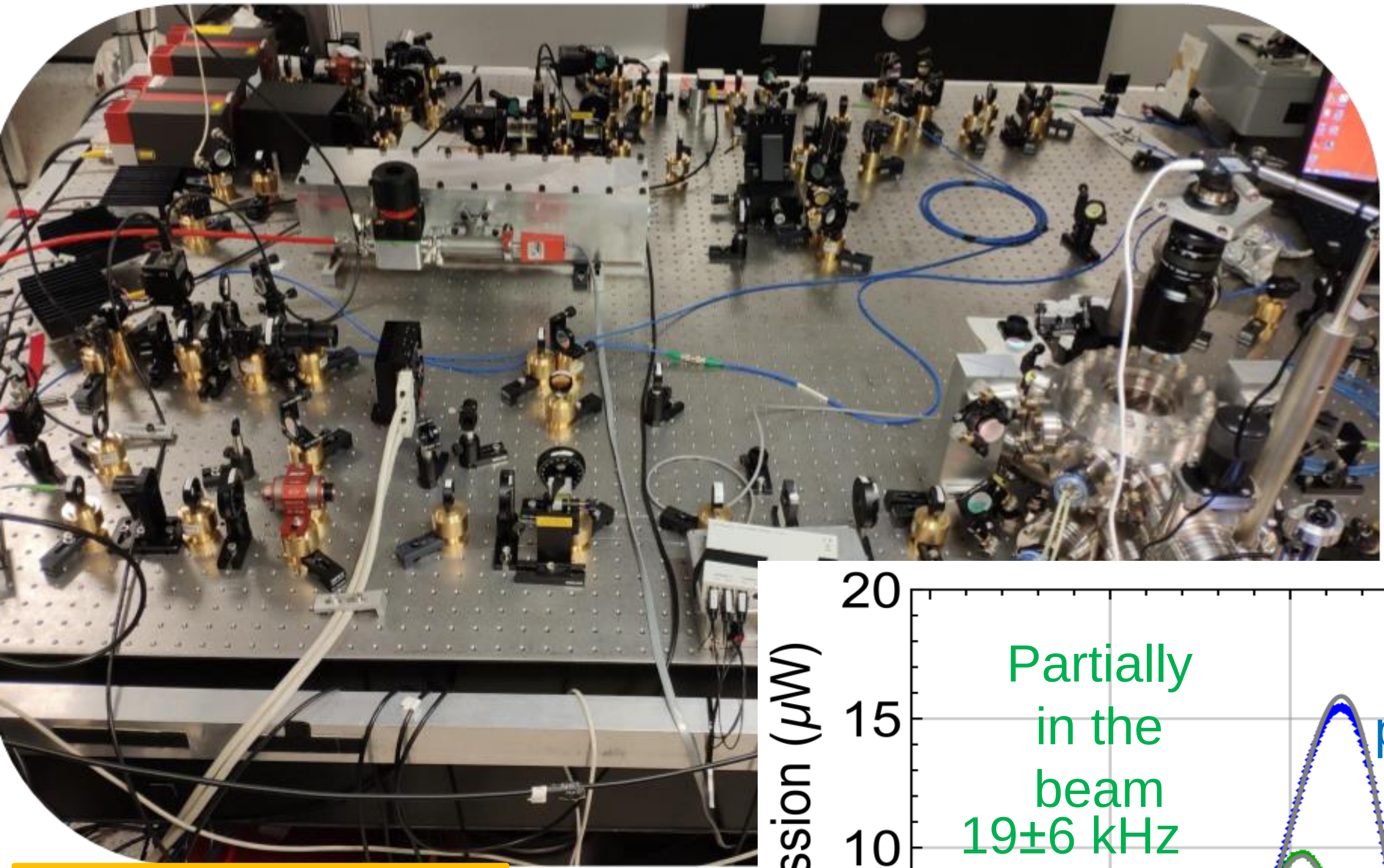


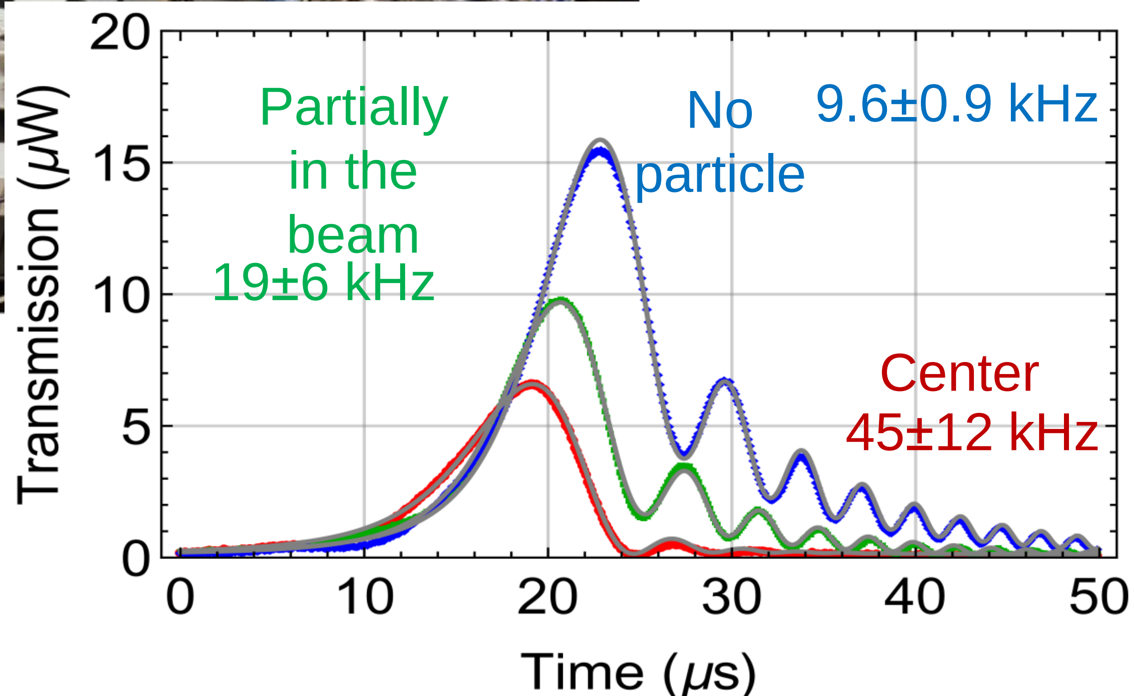


Cooling of a secular frequency of 50 kHz and a filtering cavity of 2.5 kHz linewidth



New system

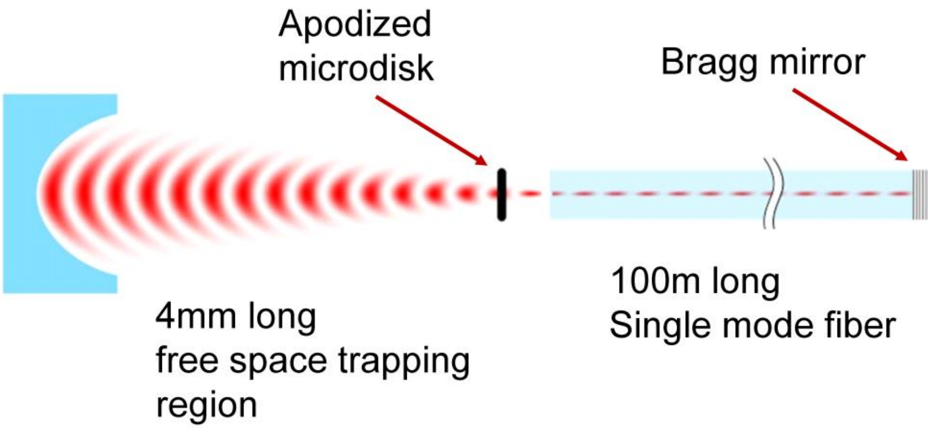




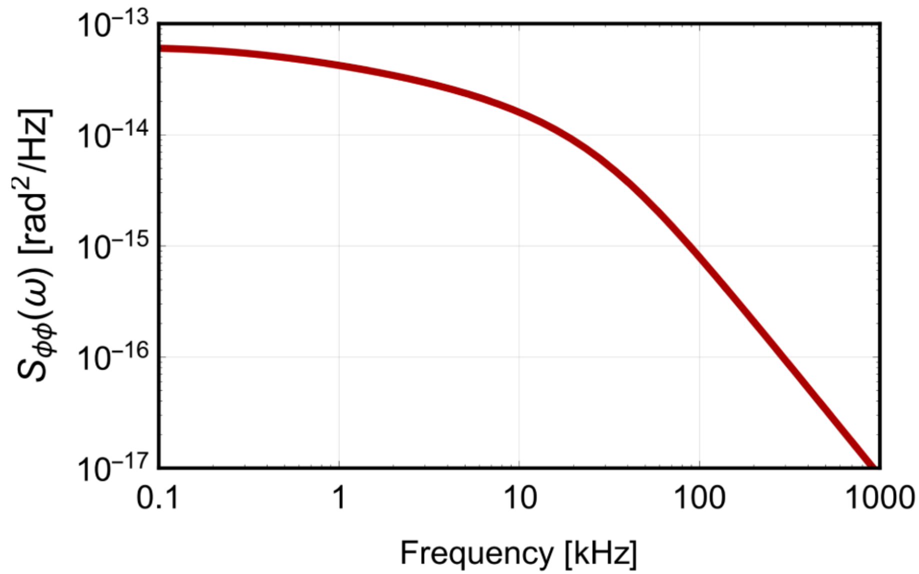
Cavity parameters

λ = 1064 nm
L = 14.6 mm (± 1%)
$\kappa/2\pi$ = 7.5 kHz
$\mathcal{F}$ ≈ 700000
w_o= 62 μm

Fiber cavity optomechanics



A. Pontin *et al.*, New J. Phys. 20 023017(2018)



Cavity parameters

l= 1550nm
L = 100 mm
$\mathcal{F}$ = 10
FSR = 1.0 MHz
k/2p = 51 kHz

Driving fields

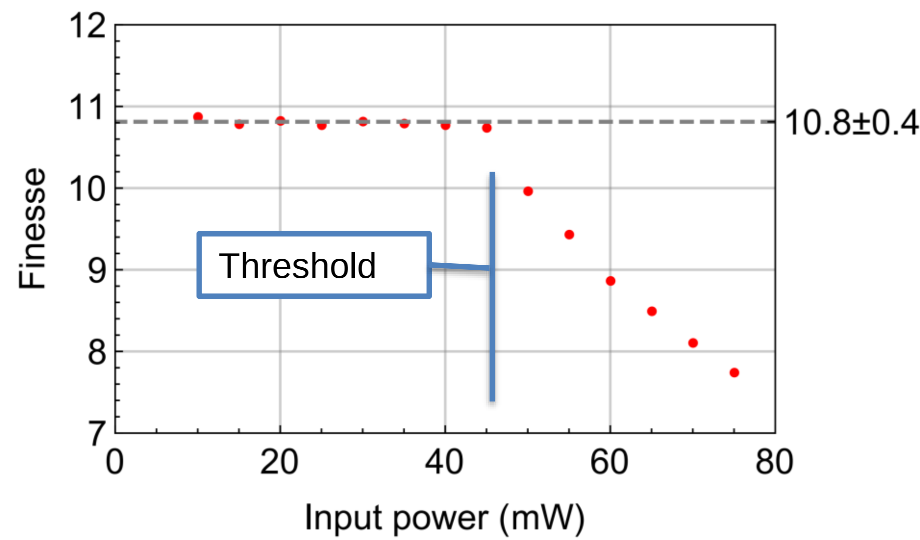
Trapping	P_t = 60mW
Cooling	P_c = 12μW
Meter	P_m = 4μW

Environment

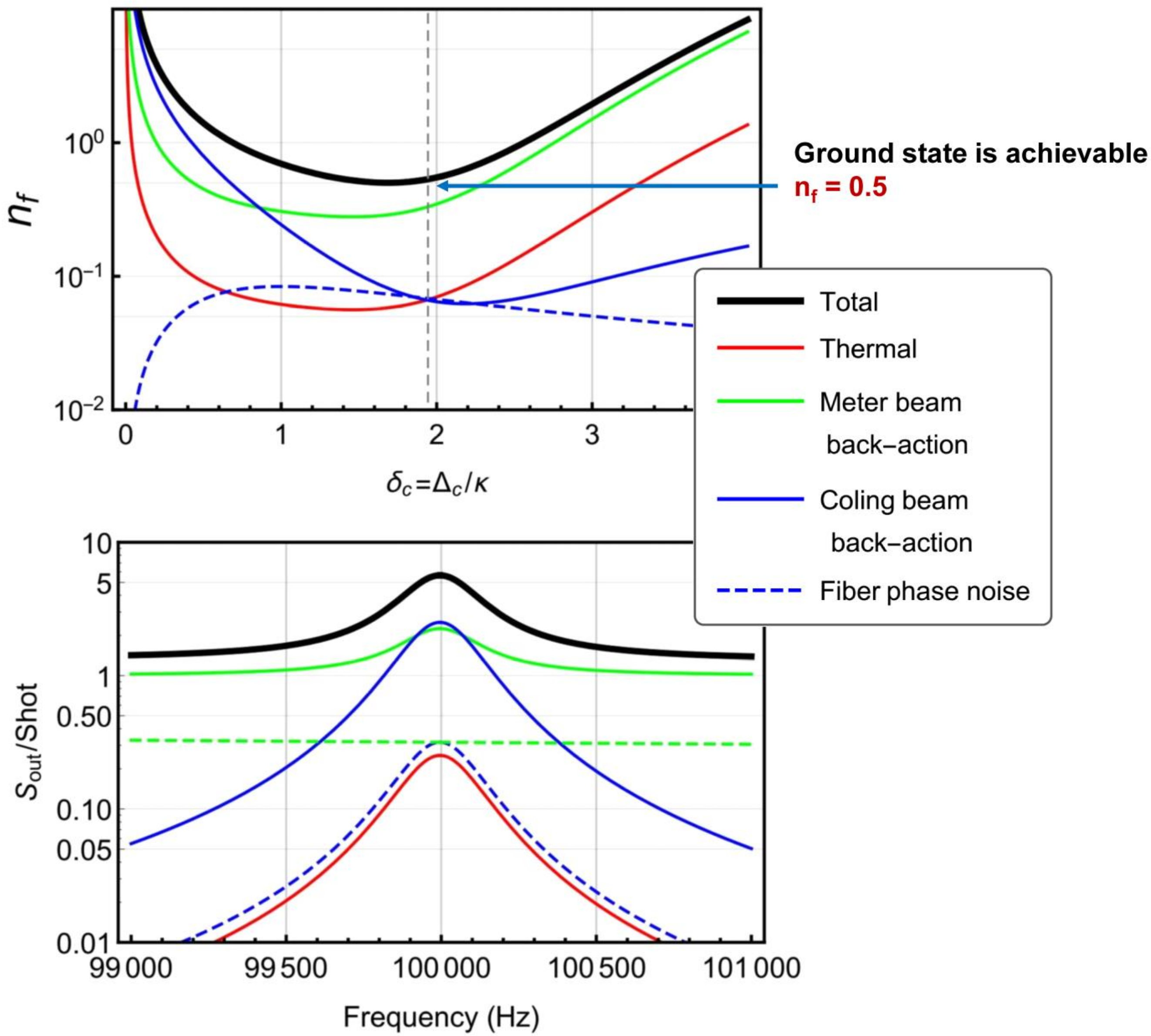
T = 300k
P = 10^{-9} mbar

Microdisk

Radius 8μm
Thickness 0.5μm
r = 2300 kg/m^3
e = 2



Fiber cavity optomechanics



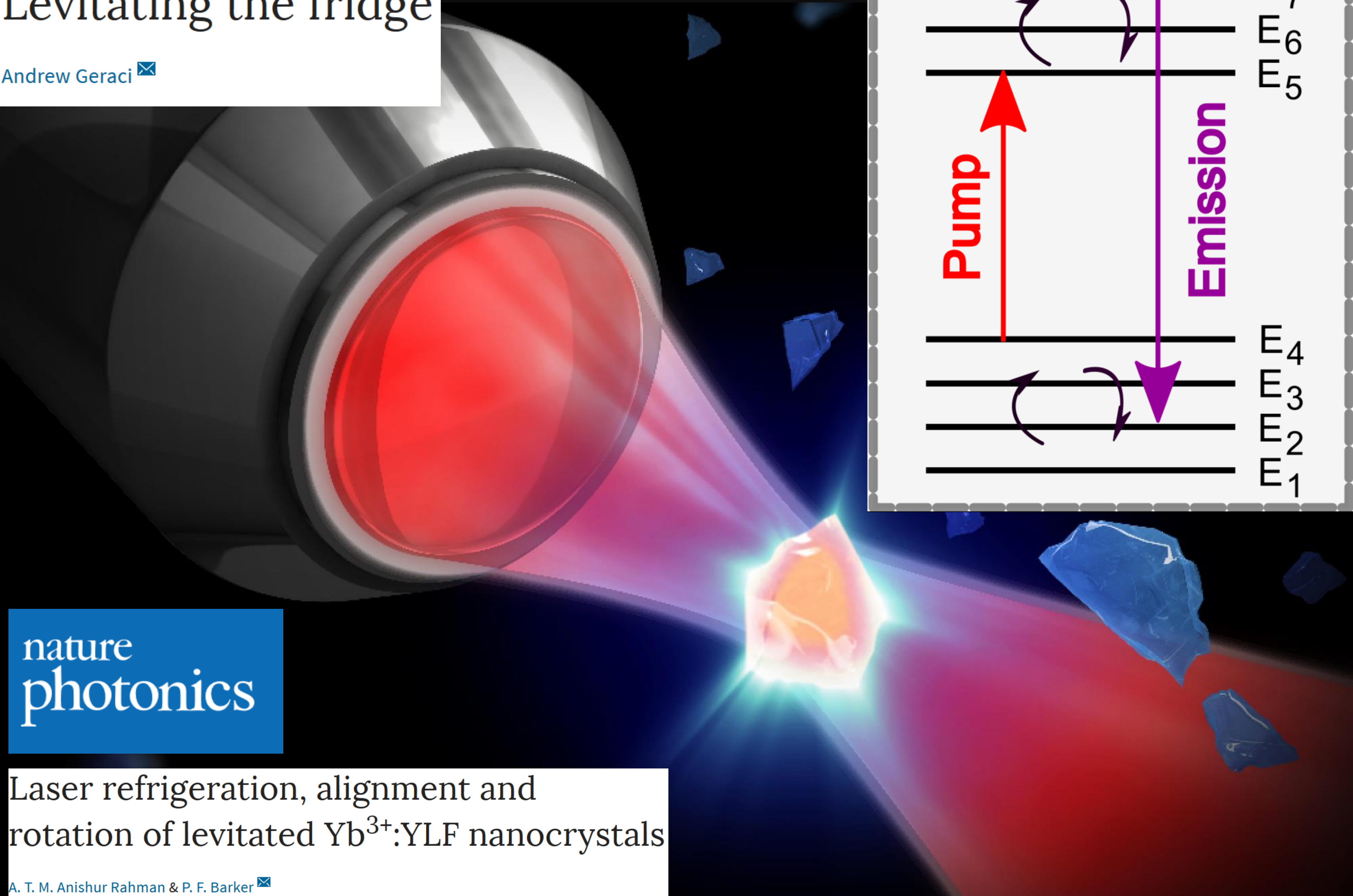
…ration

News and Views

LASER COOLING

Levitating the fridge

Andrew Geraci

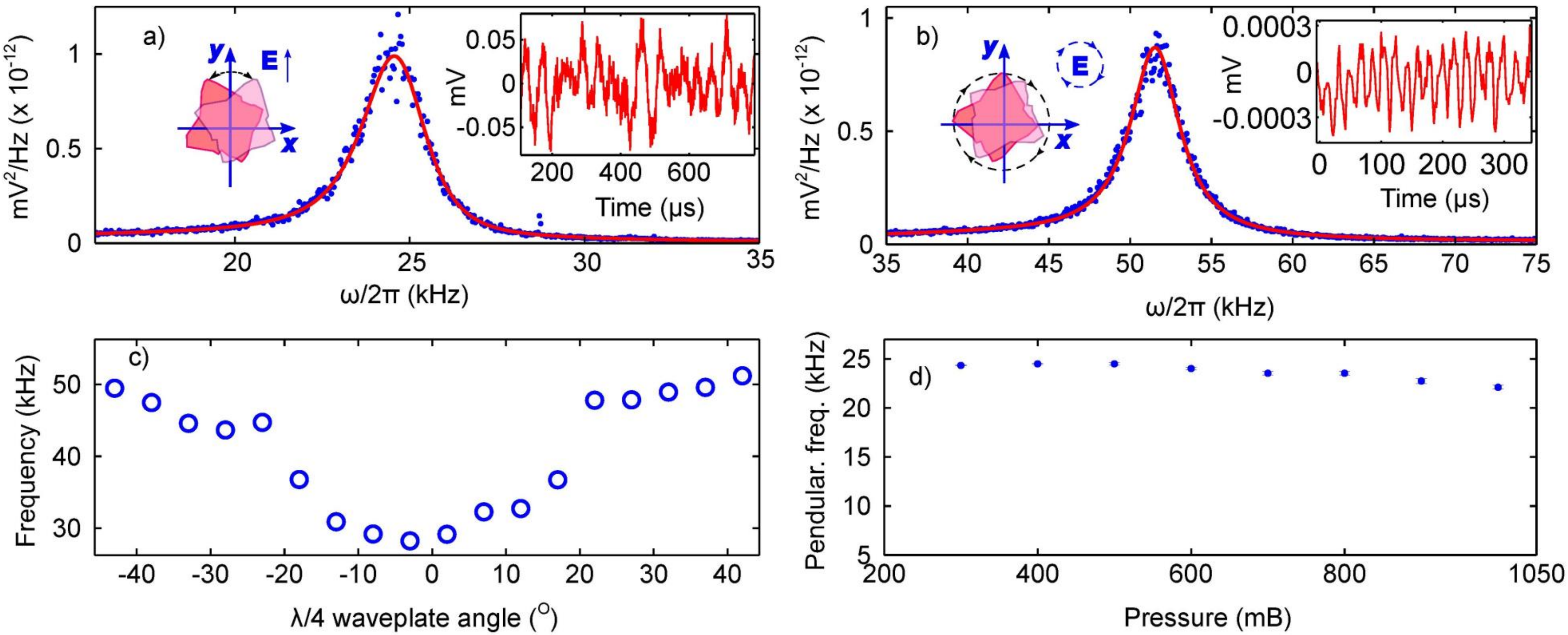


nature photonics

Laser refrigeration, alignment and rotation of levitated Yb^{3+}:YLF nanocrystals

A. T. M. Anishur Rahman & P. F. Barker

Transfer of angular momentum



PRL **113,** 201301 (2014) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2014

Axion Dark Matter Detection Using Atomic Transitions

P. Sikivie
Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 9 September 2014; published 14 November 2014)

Dark matter axions may cause transitions between atomic states that differ in energy by an amount equal to the axion mass. Such energy differences are conveniently tuned using the Zeeman effect. It is proposed to search for dark matter axions by cooling a kilogram-sized sample to millikelvin temperatures and count axion induced transitions using laser techniques. This appears to be an appropriate approach to axion dark matter detection in the 10^{-4} eV mass range.

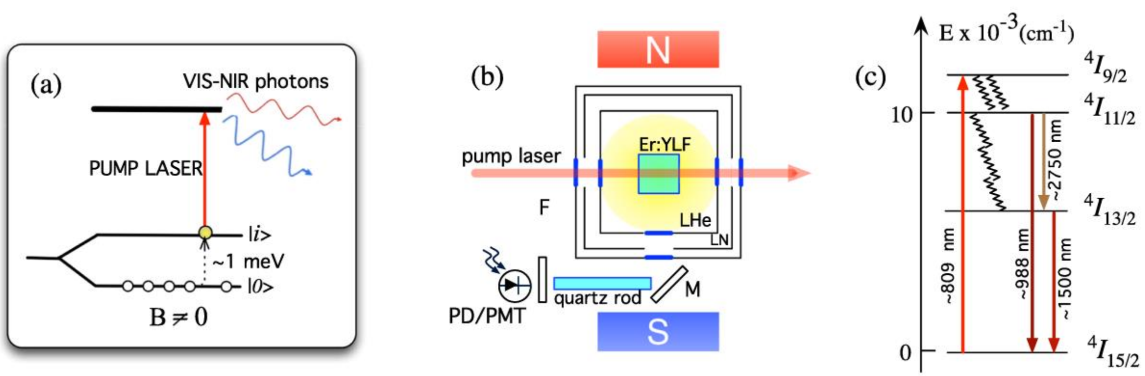
OPEN

Axion dark matter detection by laser induced fluorescence in rare-earth doped materials

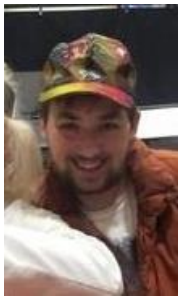
Received: 1 September 2017
Accepted: 25 October 2017
Published online: 09 November 2017

Caterina Braggio[1], Giovanni Carugno[1], Federico Chiossi[1], Alberto Di Lieto[2], Marco Guarise[1], Pasquale Maddaloni[3,4], Antonello Ortolan[5], Giuseppe Ruoso[5], Luigi Santamaria[6], Jordanka Tasseva[4] & Mauro Tonelli[2]

- High doping
- kg size mass
- Searches in 20 – 150 GHz
- Already funded to develop and evaluate materials with laser refrigeration



UCL optomechanics group


Jon Gosling


Peter Barker


Tania Monteiro


Tom Penney

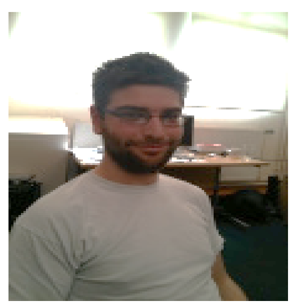

Anishur Rahman


Antonio Pontin


Ying Lia Li


M. Rademacher


Anas Almuqhim


Dan Goldwater


Erika Aranas


Nathanael Bullier