Macroscopic quantumness and the classical to quantum transition

P. Barker,
University College London,
UK

Quantum optomechanics at UCL

Macroscopic quantum systems

- Cooling and manipulation of nanoparticles in optical, electric and magnetic traps
- Creation of non-classical states, wave function collapse

Laser refrigeration – cooling internal degrees of freedom

- Controlling decoherence

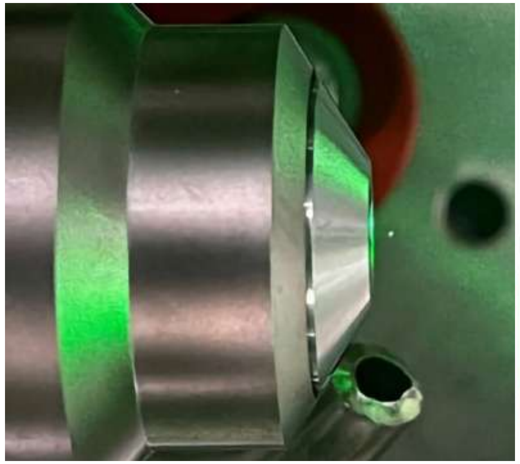
Sensing

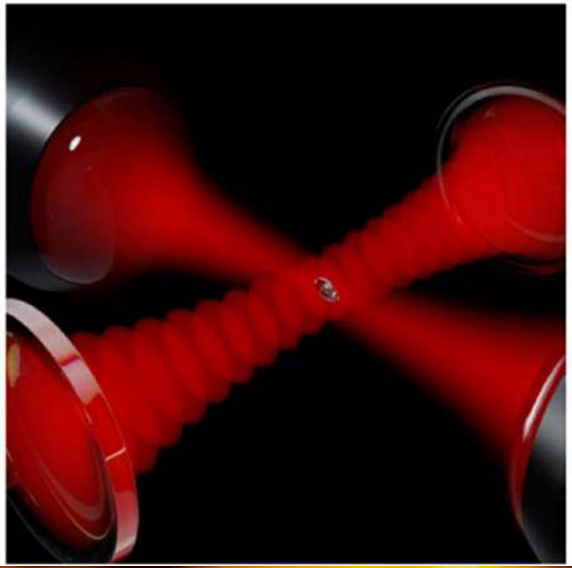
- Dark matter detection
- Electric field sensing

Applications

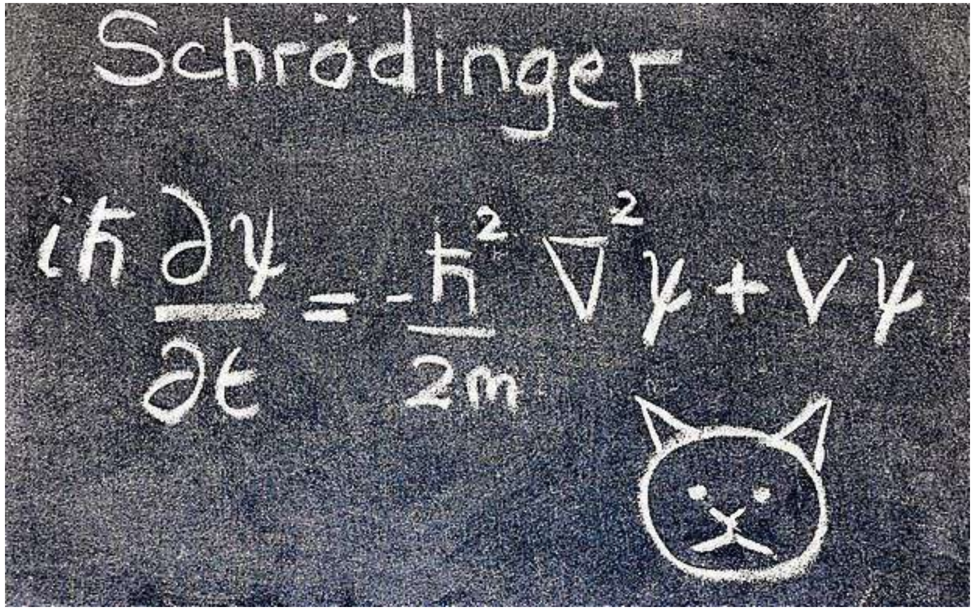
- Accelerometers
- Nanoparticle characterisation

https://www.ucloptomechanics.com





Testing the macroscopic limits of quantum mechanics



- Experimental observation of superposition with increasing size, mass and complexity is of key importance for testing the validity of quantum mechanics.
- Gain understanding of the transition to classicality
- Lab tests of quantumness of gravity
- Important for the development and establishing limits of macroscopic quantum technologies
  - systems could be easier to engineer and control

Testing the macroscopic limits of quantum mechanics

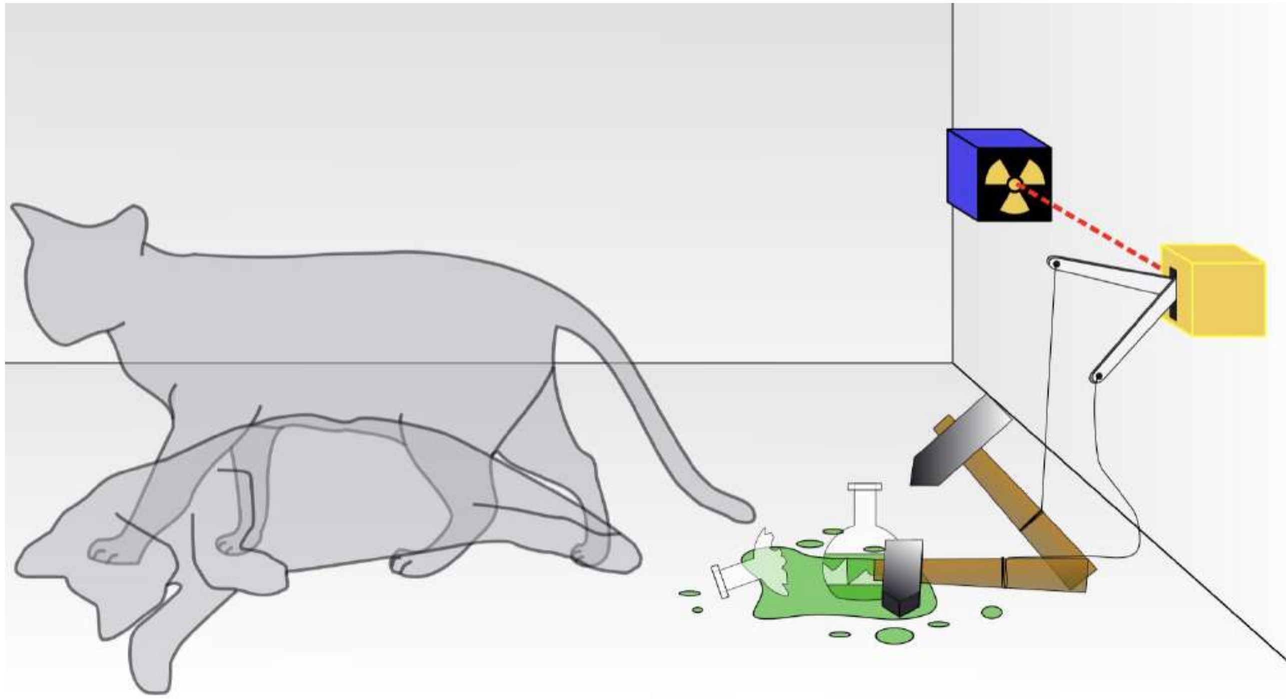
Schrödinger cat : superposition of an atom being "decayed" and "not decayed" mapped onto a superposition of the cat being simultaneously "dead" and "alive."

Classically counterintuitive:
1) a cat is a macroscopic, everyday object
2) "dead" and "alive" are mutually exclusive

Is our inability to make macroscopic ''cats'' or other non-classical states just technical or a fundamental limitation?

No observation:
Too complex with many sources of decoherence to sustain a superposition.
<u>or</u>
Other theories/modifications/effects beyond standard quantum mechanics: wave function collapse from intrinsic stochastic noise, gravitational collapse, …..

Schrödinger, E., 1935, Die Naturwissenschaften **23**, 1.



Testing the macroscopic limits of quantum mechanics

- A range of increasingly complex, macroscopic and massive systems have demonstrated non-classicality

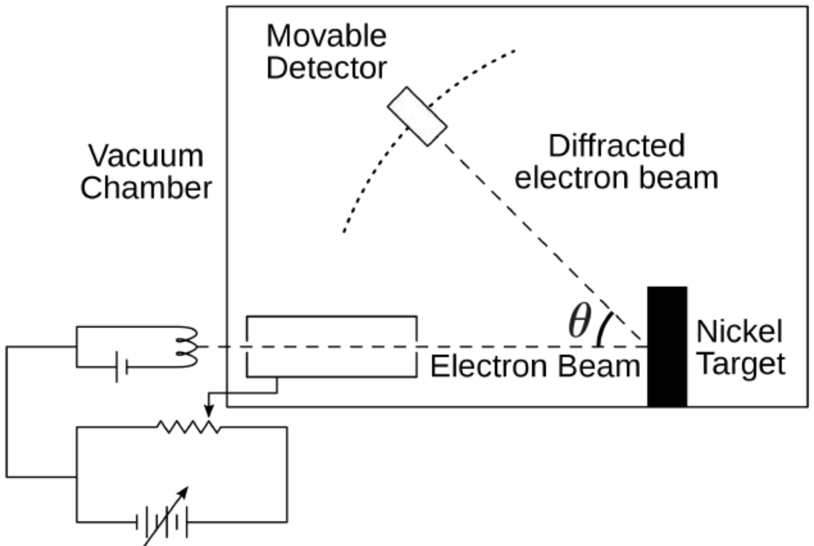
- Includes cold atoms, BECs, SQUIDs, electromechnical systems

LETTER

doi:10.1038/nature16155

Quantum superposition at the half-metre scale

T. Kovachy[1], P. Asenbaum[1], C. Overstreet[1], C. A. Donnelly[1], S. M. Dickerson[1], A. Sugarbaker[1], J. M. Hogan[1] & M. A. Kasevich[1]



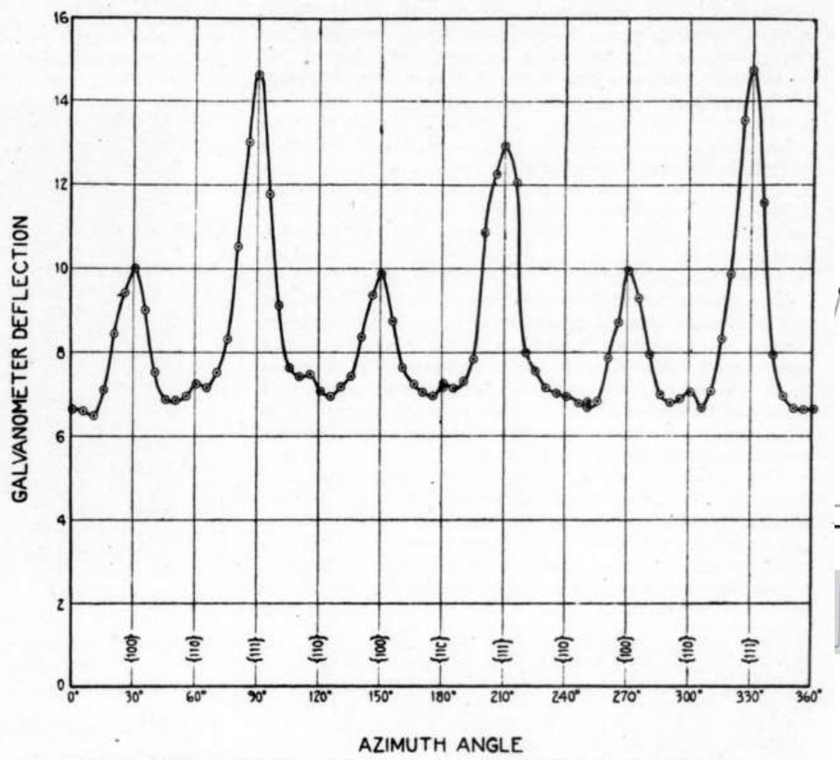
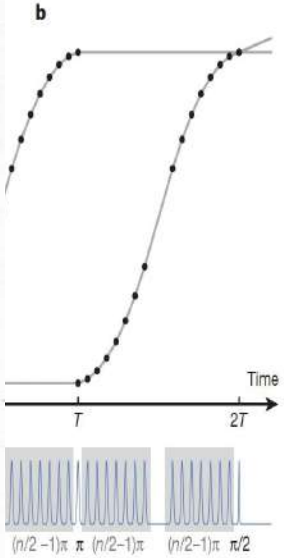
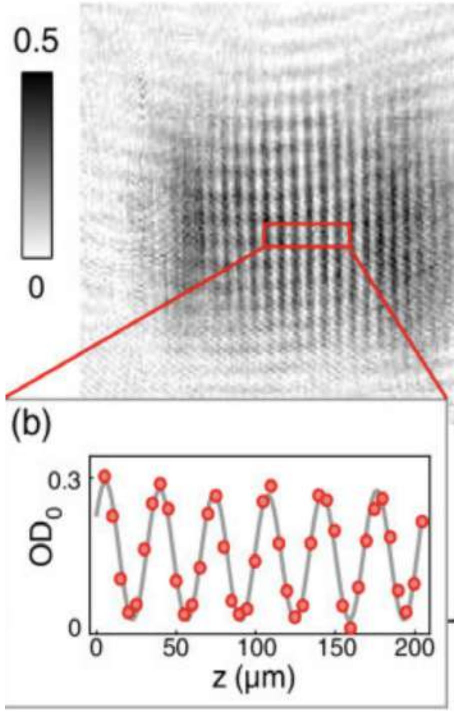
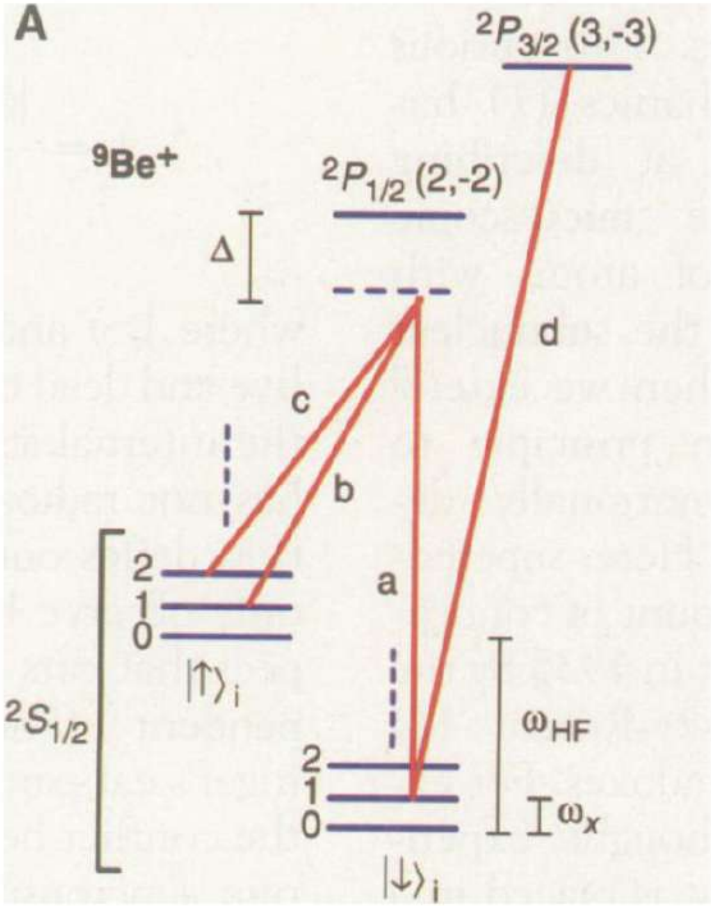


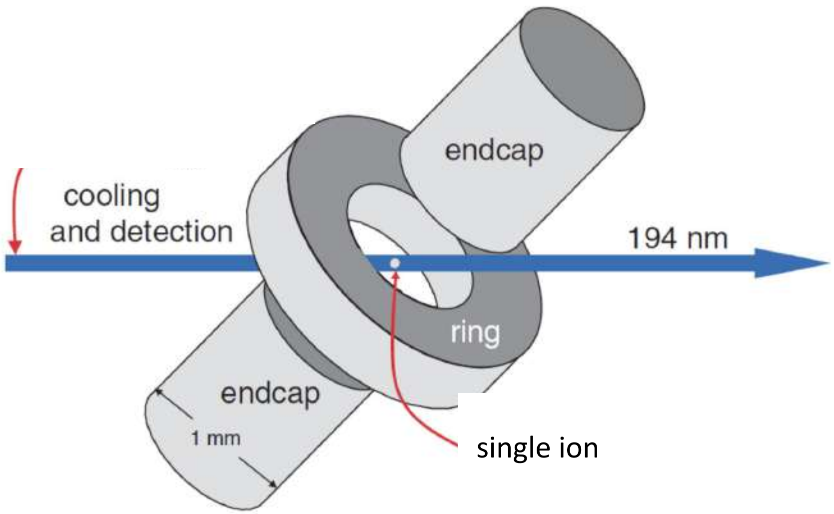
FIG. 2.—Intensity of electron scattering vs. azimuth angle—54 volts, co-latitude 50°.





Superposition in atomic ions





$$\psi = \frac{|x_1\rangle|\uparrow\rangle + |x_2\rangle|\downarrow\rangle}{\sqrt{2}}$$

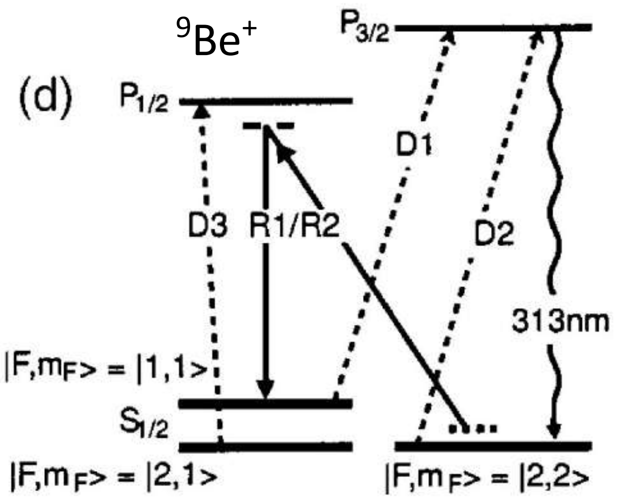
A "Schrödinger Cat" Superposition State of an Atom

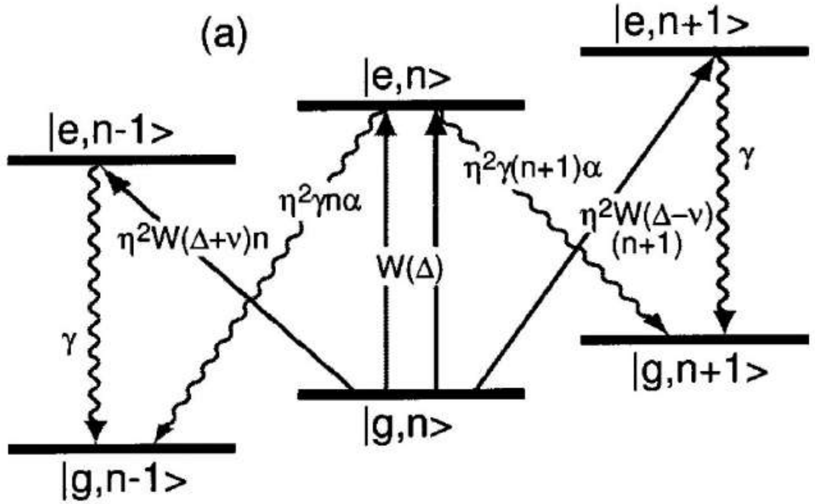
C. Monroe,* D. M. Meekhof, B. E. King, D. J. Wineland

SCIENCE • VOL. 272 • 24 MAY 1996

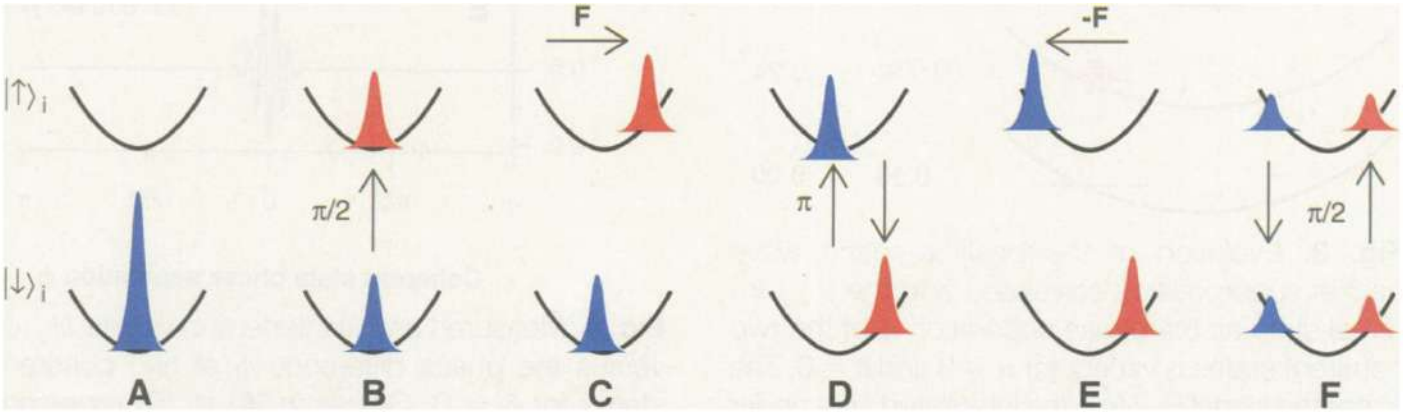
Superposition in atomic ions

State preparation

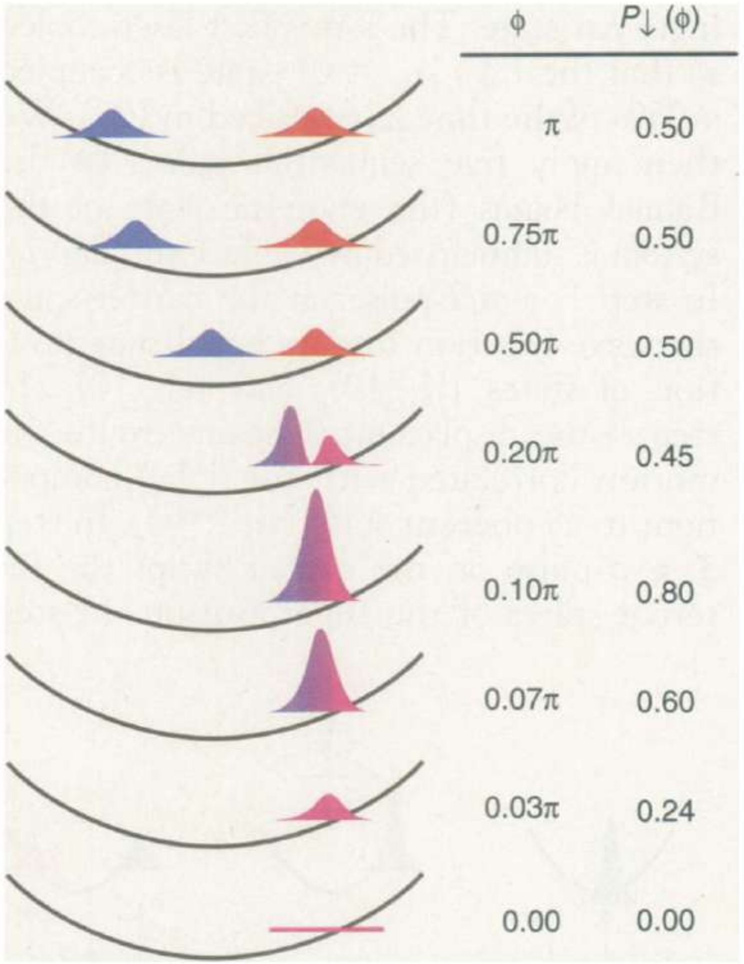


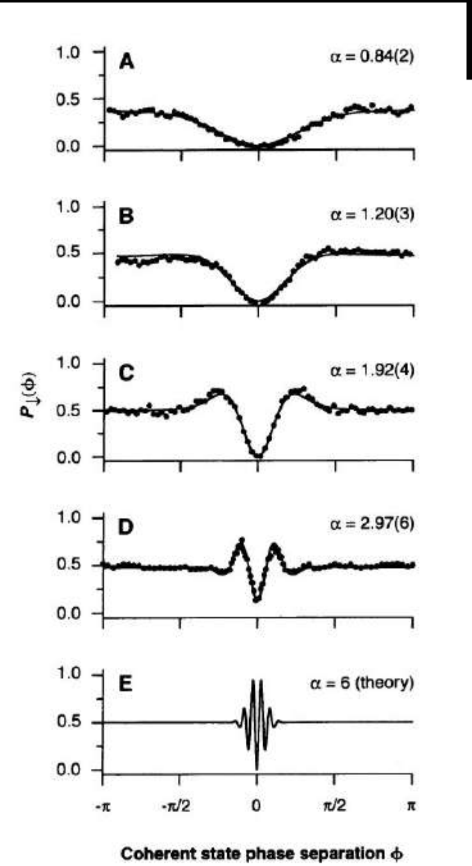


Cat state creation and measurement



Superposition in atomic ions





80 nm superposition

7 nm wavepacket spread

Mass = 1.5×10^{-26} kg

Larger separation – lifetime of the superposition shortens.

Decoherence underlies why quantum superpositions are not generally seen in the macroscopic world

Experimental difficulty in preparing and maintaining even mesoscopic superpositions

Macroscopicity

Nimmrichter, S. & Hornberger, K. Macroscopicity of mechanical quantum superposition states. *Phys. Rev. Lett.* **110**, 160403 (2013).

Measure for any experimental tests of the quantum super- position principle

Extent to which minimal nonlinear modifications to quantum mechanics are ruled out by experiment

$$\partial_t \rho_N = [\mathsf{H}, \rho_N]/i\hbar + \mathcal{L}_N \rho_N$$

Larger macroscopicity - better for ruling out minimal modifications that predict failure of the superposition principle.

Leggett, A. J., 1980, Prog. Theor. Phys. Suppl. **69**, 80.

Modification: decay of off diagonal elements of pos. and mom and diffusion -> classicalising motion

$$\mu = \log_{10}\left(\frac{\mathcal{T}_e}{1\,\mathrm{s}}\right)$$

For interferometry experiments macroscopicity measure is:

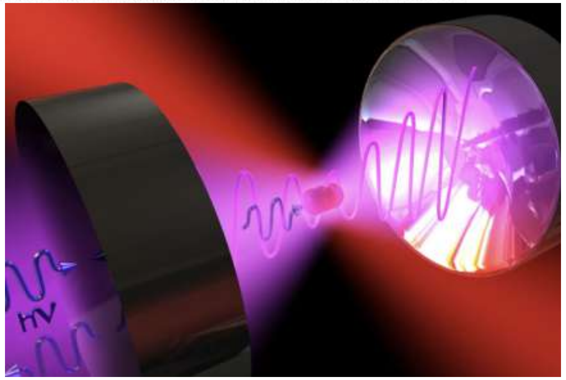
$$\mu = \log_{10}\left(\frac{1}{\ln(\eta)}\left(\frac{m}{m_e}\right)^2 \frac{\tau}{1\,\mathrm{s}}\right)$$

Macroscopicity

Conceivable experiments	μ
Oscillating micromembrane	11.5
Hypothetical large SQUID	14.5
Talbot-Lau interference [29] at 10^5 amu	14.5
Satellite atom (Cs) interferometer [45]	14.5
Oscillating micromirror [30]	19.0
Nanosphere interference [46]	20.5
Talbot-Lau interference [29] at 10^8 amu	23.3
Schrödinger gedanken experiment	~ 57

Toward quantum superposition of living organisms

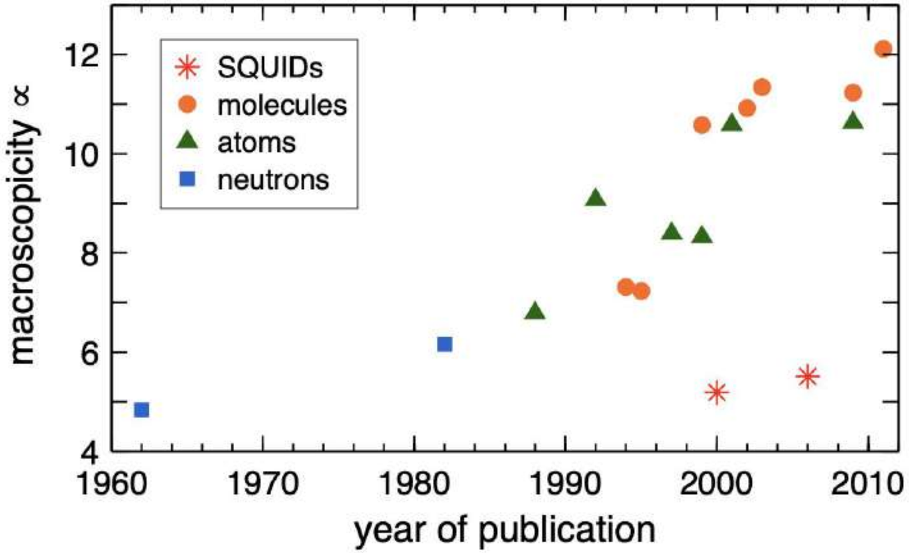
To cite this article: Oriol Romero-Isart *et al* 2010 *New J. Phys.* 12 033015



LETTERS
https://doi.org/10.1038/s41567-019-0663-9
nature physics

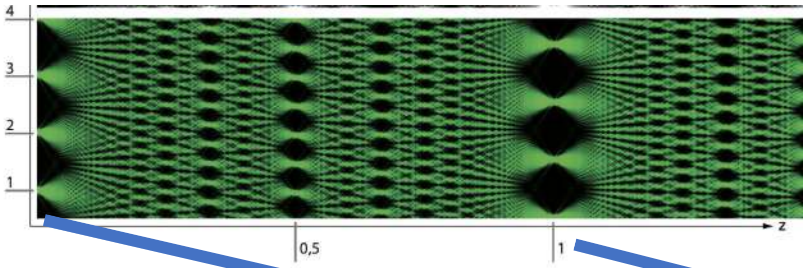
Quantum superposition of molecules beyond 25 kDa

Yaakov Y. Fein[1], Philipp Geyer[1], Patrick Zwick[2], Filip Kiałka[1], Sebastian Pedalino[1], Marcel Mayor[2,3,4], Stefan Gerlich[1] and Markus Arndt[1]*



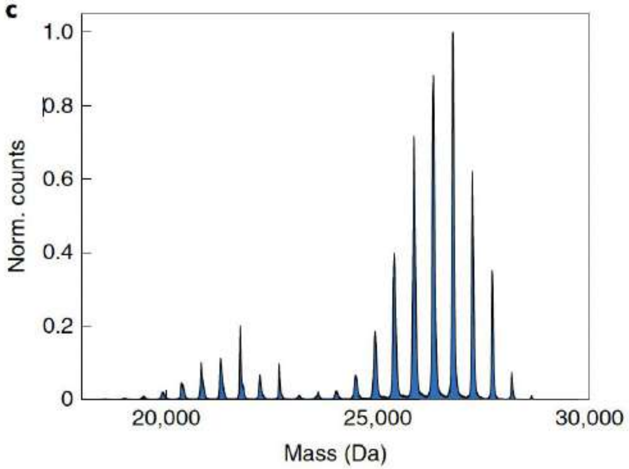
Matter wave interferometry limits

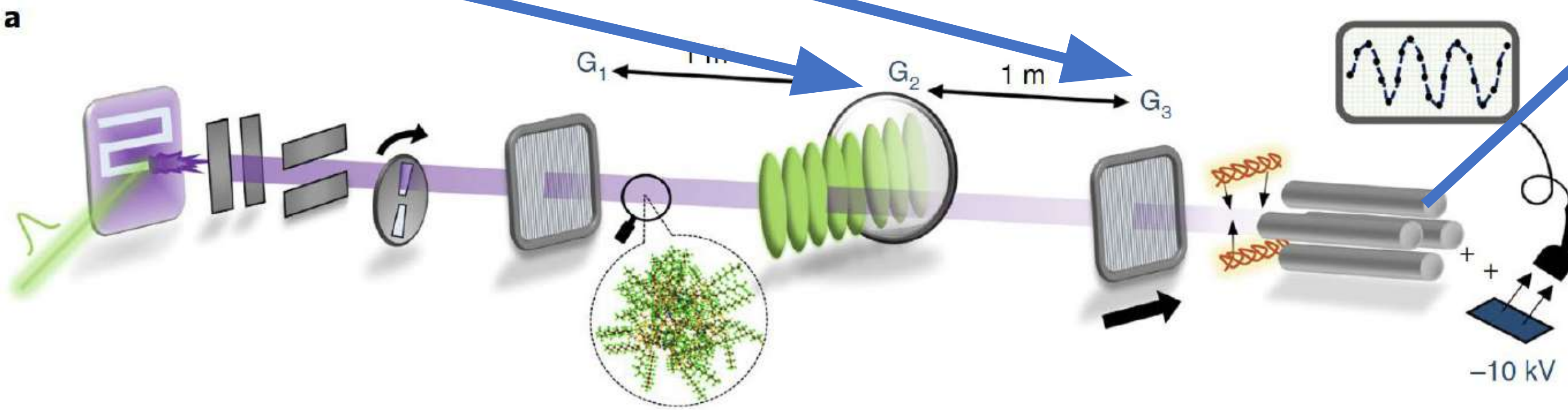
$$L_T = d^2/\lambda_{dB}$$



deBroglie wavelength
$\lambda_{DB} > 5.3\text{x}10^{-14}$ m

Mass
$m = 8.3\text{x}10^{-24}$ kg





nature physics

Quantum superposition of molecules beyond 25 kDa

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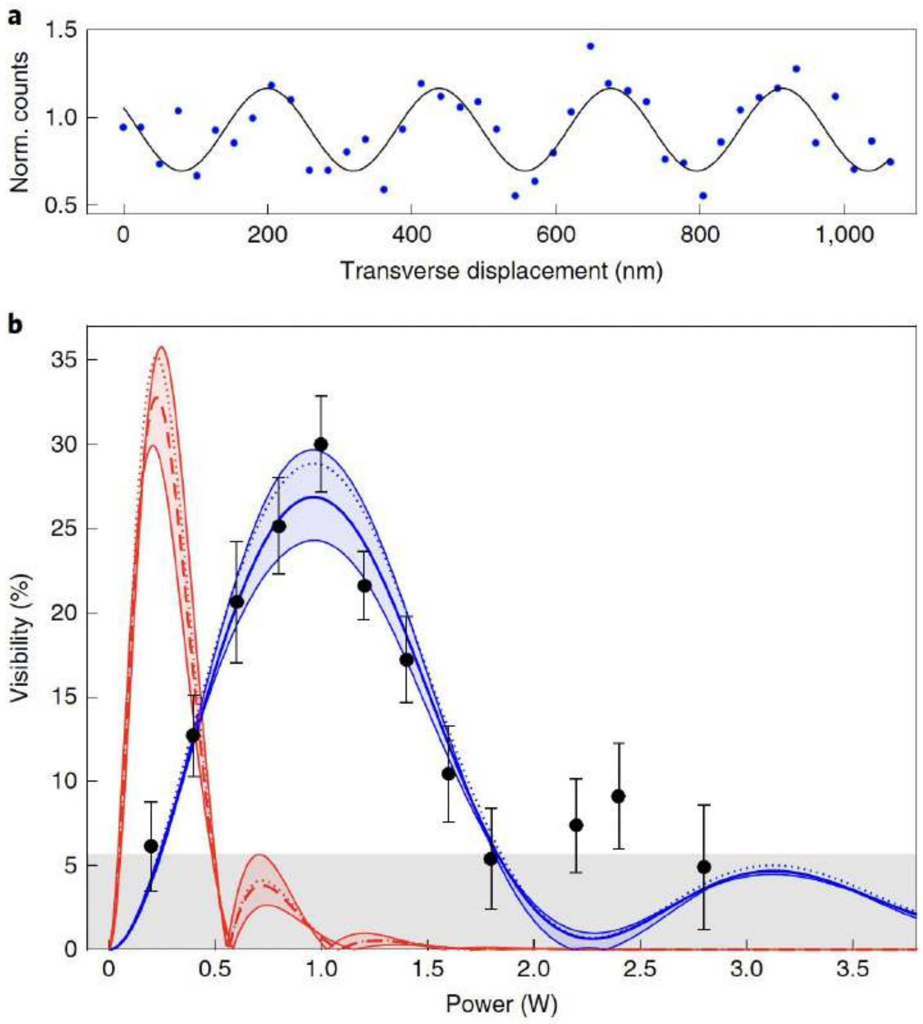
Zinc-coordinated porphyrins around a tetraphenylmethane core

Matter wave interferometry limits



deBroglie wavelength
$\lambda_{DB} > 5.3\text{x}10^{-14}$ m

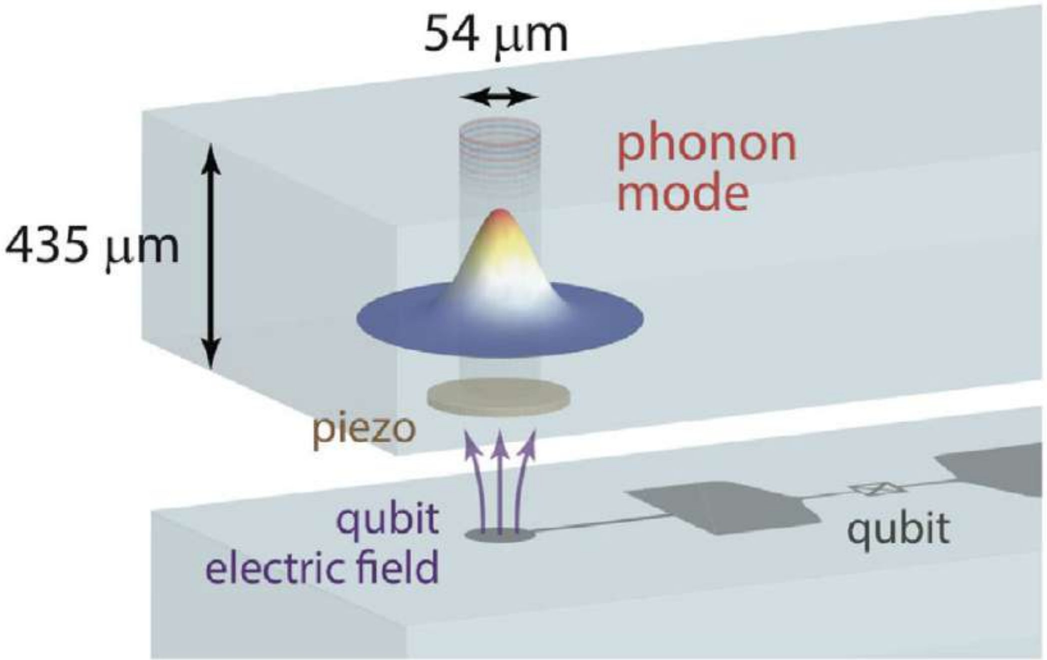
Mass
m = $8.3\text{x}10^{-24}$ kg

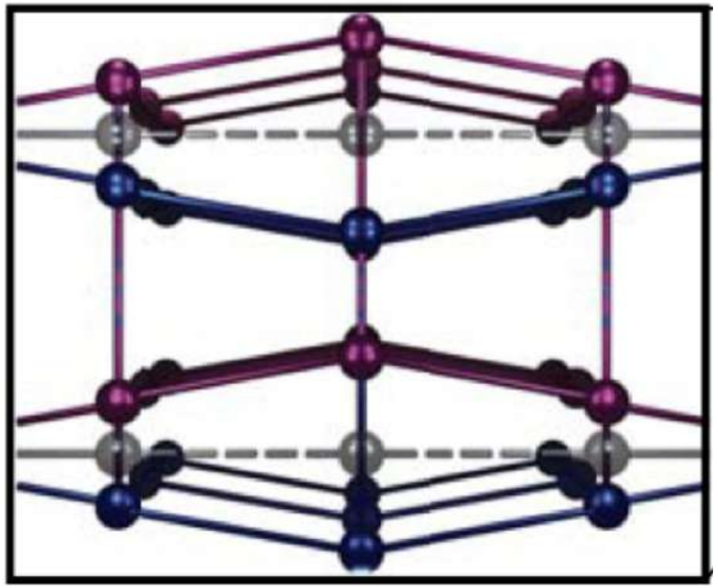
Coherence time
τ =7.5 ms

Macroscopicity

$$\mu = \log_{10}\left(\frac{1}{\ln(\eta)}\left(\frac{m}{m_e}\right)^2 \frac{\tau}{1\,\mathrm{s}}\right) = 14.1$$

Electromechanical systems





High-overtone bulk acoustic-wave resonator (HBAR) coupled to a superconducting transmon qubit.

JC interaction Hamiltonian

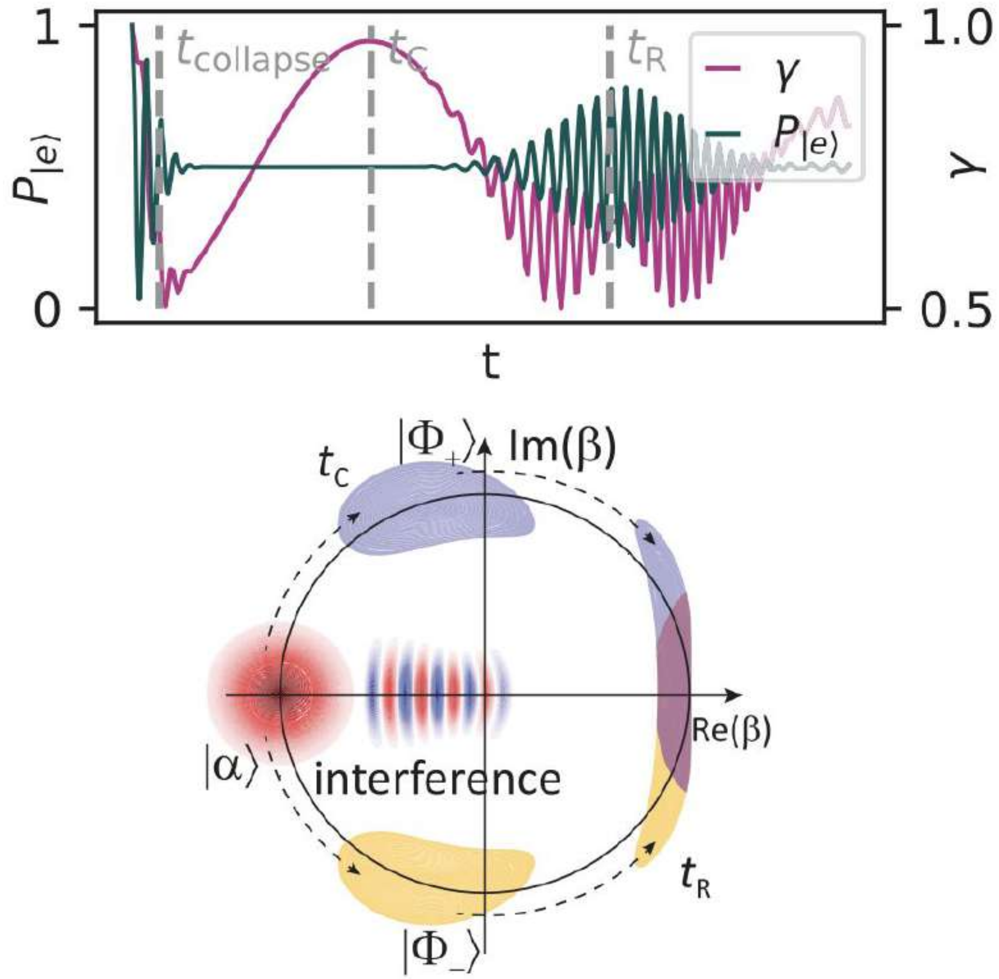
$$H/\hbar = g_0(\sigma^+ a + \sigma^- a^\dagger)$$

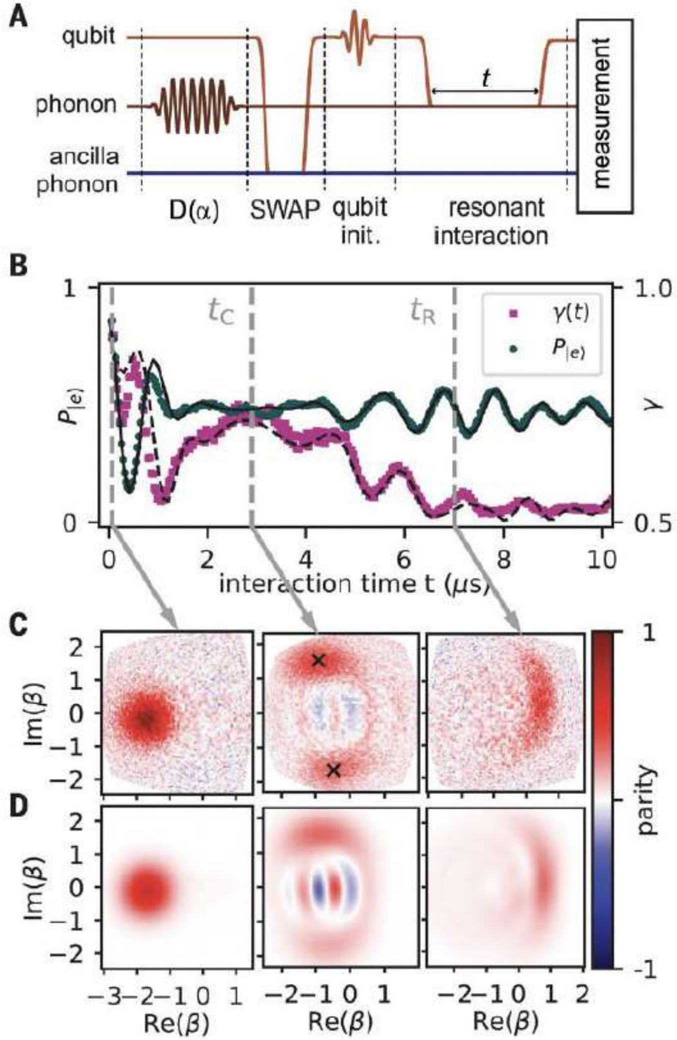
Superposition in phase oscillation of sapphire crystal

m_{eff} = 1.6x10^{-8} kg

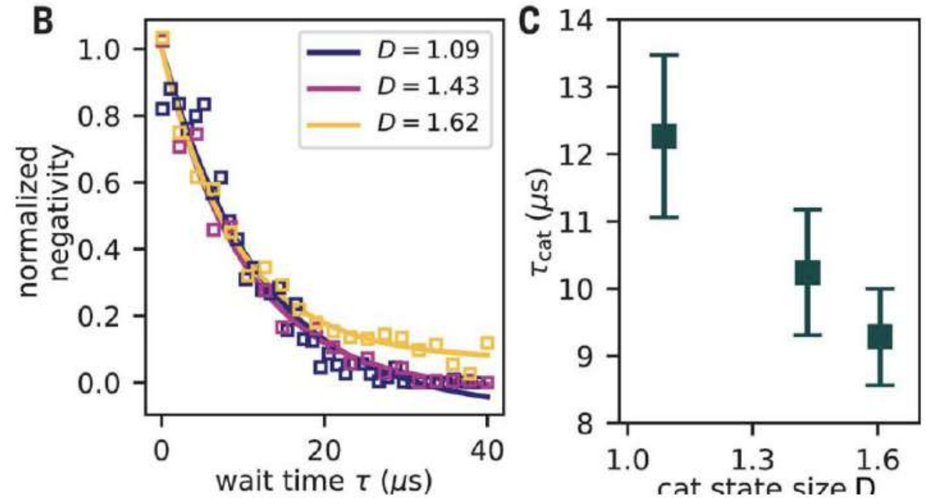
Δz = 10^{-18} m (larger than noise)

Electromechanical systems





Electromechanical systems



Coherence time ~ 10 μs

PHYSICAL REVIEW LETTERS **130,** 133604 (2023)

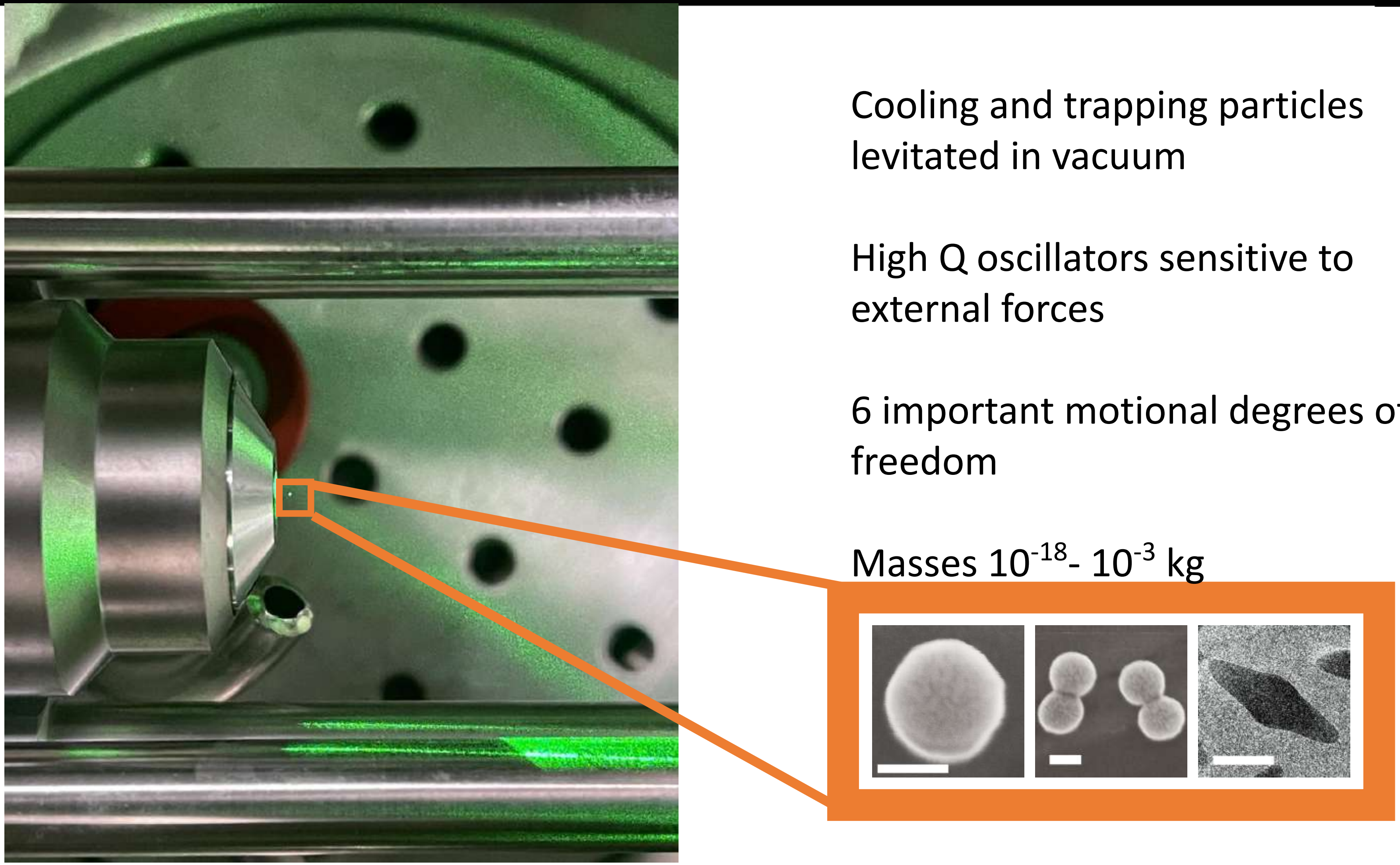
Featured in Physics

Macroscopic Quantum Test with Bulk Acoustic Wave Resonators

Björn Schrinski,[1] Yu Yang,[2] Uwe von Lüpke,[2] Marius Bild,[2] Yiwen Chu,[2] Klaus Hornberger,[3] Stefan Nimmrichter,[4] and Matteo Fadel[2,*]

	Experiment	Year	μ
Mechanical resonators	*Bulk acoustic waves [this Letter]*	*2022*	*11.3*
	Phononic crystal resonator [13]	2022	~9.0*
	Surface acoustic waves [12]	2018	~8.6*
Matter-wave interference	Molecule interferometry [8]	2019	14.0
	Atom interferometry [6]	2019	11.8
	BEC interferometry [5]	2017	12.4

Levitodynamical systems



Cooling and trapping particles levitated in vacuum

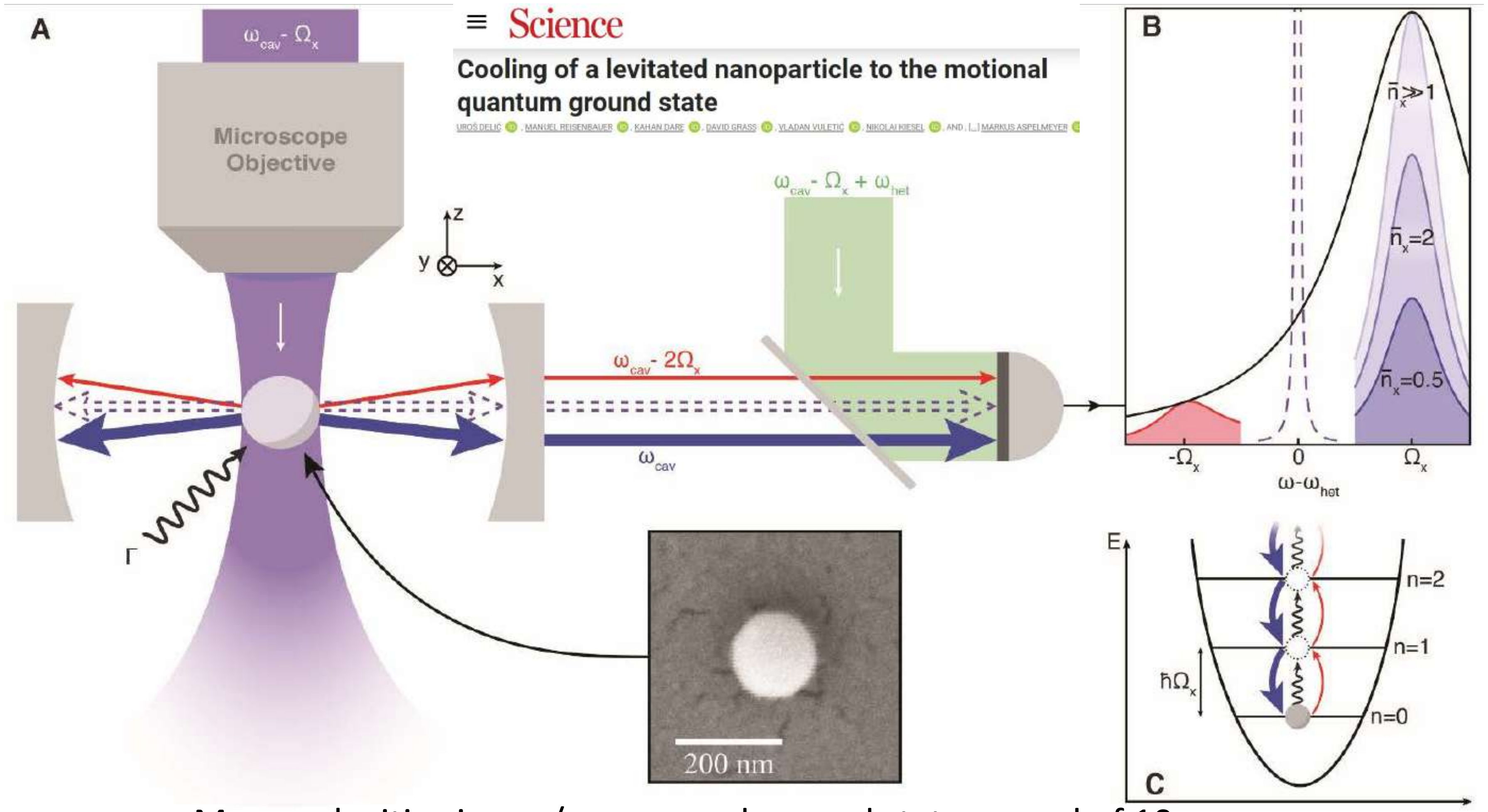
High Q oscillators sensitive to external forces

6 important motional degrees of freedom

Masses 10^{-18}- 10^{-3} kg

With the promise of macroscopicity > 20

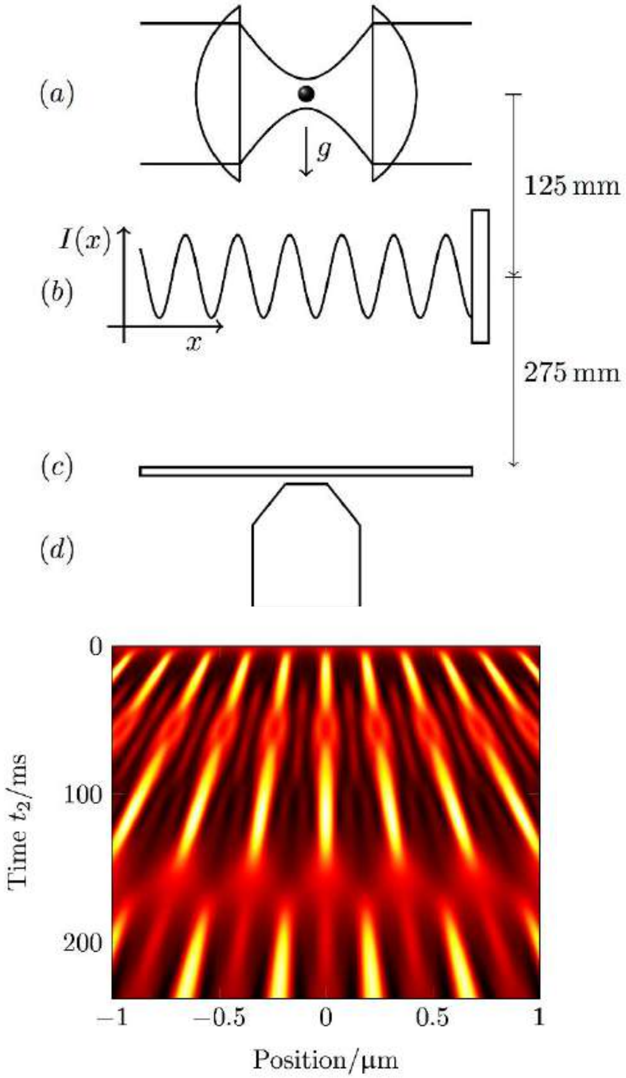
A new quantum system



Mean velocities in μm/s range and ground state spread of 10 pm.

Superposition with nanoparticles

- Trap and cool
- Switch off the levitating field
- Record position



ARTICLE

Received 18 Mar 2014 | Accepted 24 Jul 2014 | Published 2 Sep 2014
DOI: 10.1038/ncomms5788

Near-field interferometry of a free-falling nanoparticle from a point-like source

James Bateman[1], Stefan Nimmrichter[2], Klaus Hornberger[2] & Hendrik Ulbricht[1]

Nanoparticle nonclassical states

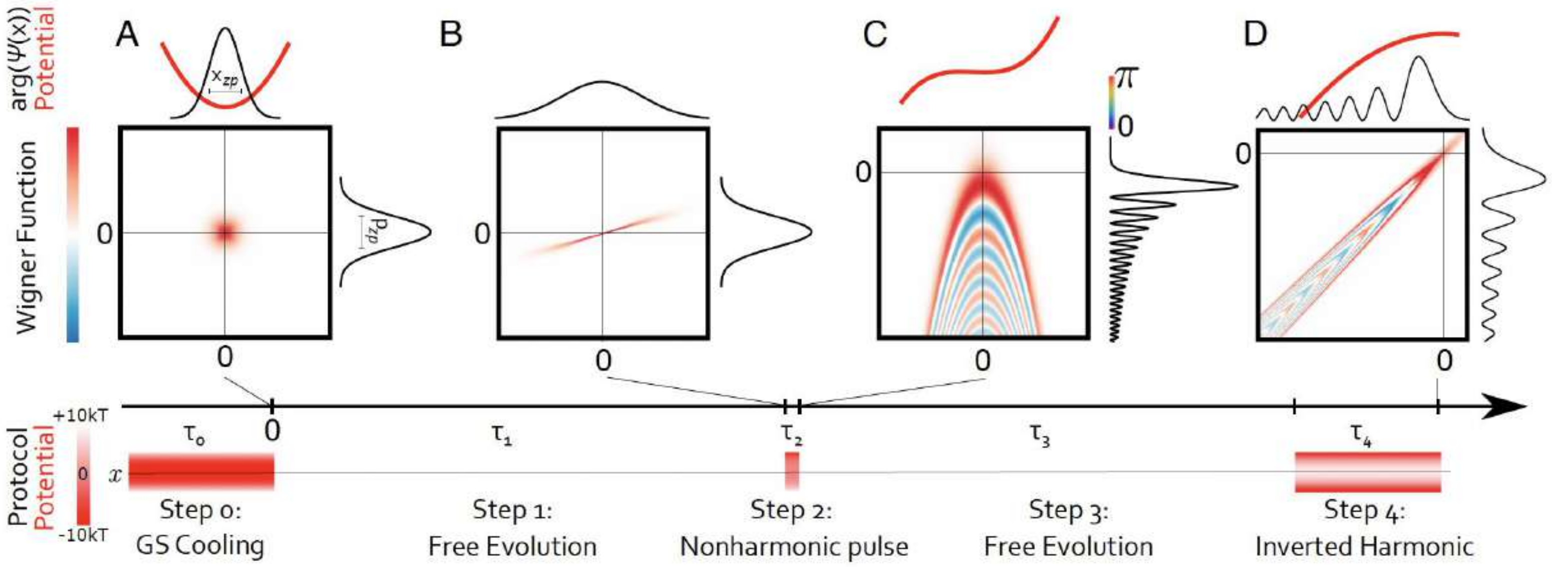
PNAS RESEARCH ARTICLE | PHYSICS OPEN ACCESS

Fast quantum interference of a nanoparticle via optical potential control

Lukas Neumeier[a], Mario A. Ciampini[a,1], Oriol Romero-Isart[b,c], Markus Aspelmeyer[a,d], and Nikolai Kiesel[a]

Protocol limits:

- Single particle
- Limited time due to decoherence from collisions
- No time of flight
- Small ground state spread



Nanoparticles with quantum impurities (Hybrid systems)

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

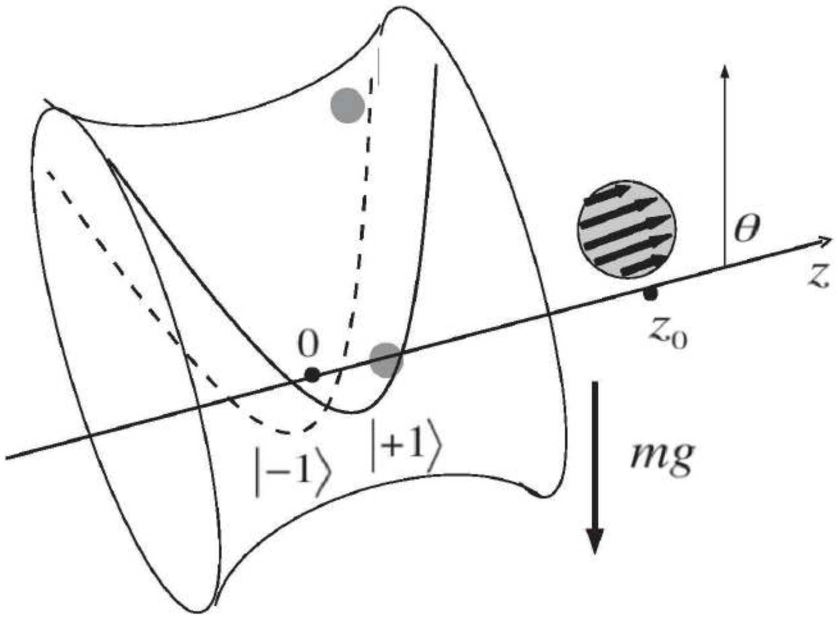
Matter-Wave Interferometry of a Levitated Thermal Nano-Oscillator Induced and Probed by a Spin

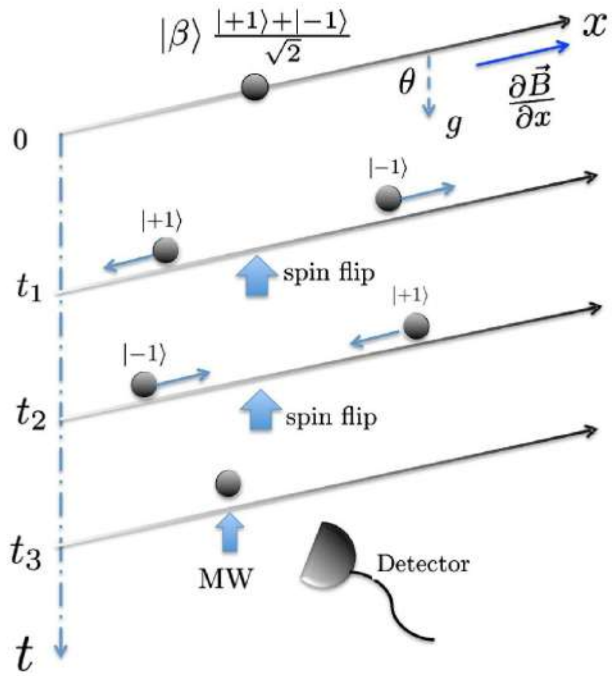
M. Scala,[1] M. S. Kim,[2] G. W. Morley,[3] P. F. Barker,[1] and S. Bose[1]

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

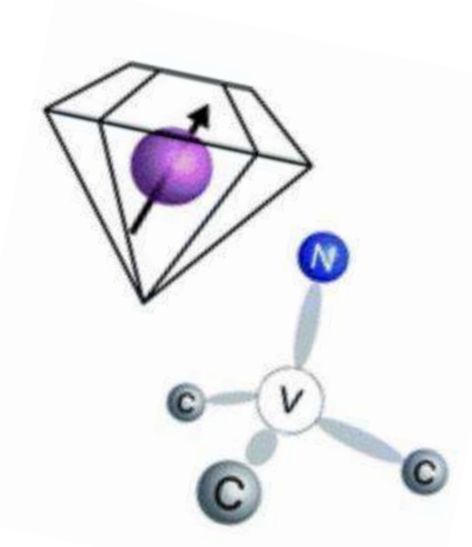
Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions

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]





Atomic like system

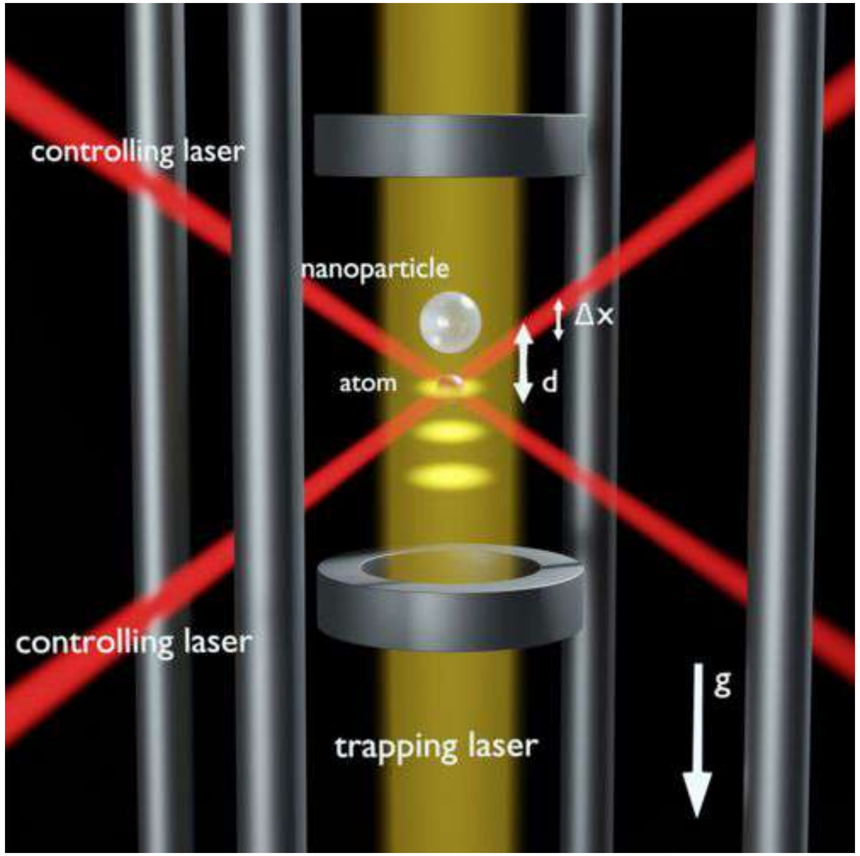


Nanoparticles with quantum impurities (Hybrid systems)

PHYSICAL REVIEW RESEARCH **3**, 033218 (2021)

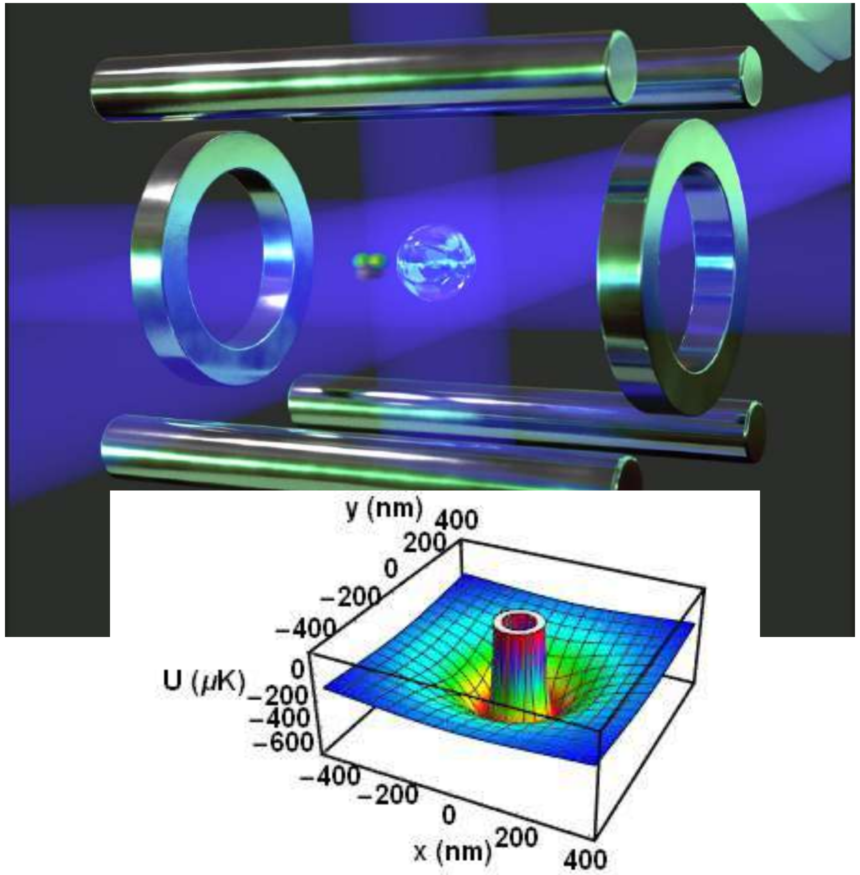
Creating atom-nanoparticle quantum superpositions

M. Toroš,[1,2] S. Bose,[2] and P. F. Barker[2]
[1]*School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[2]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*

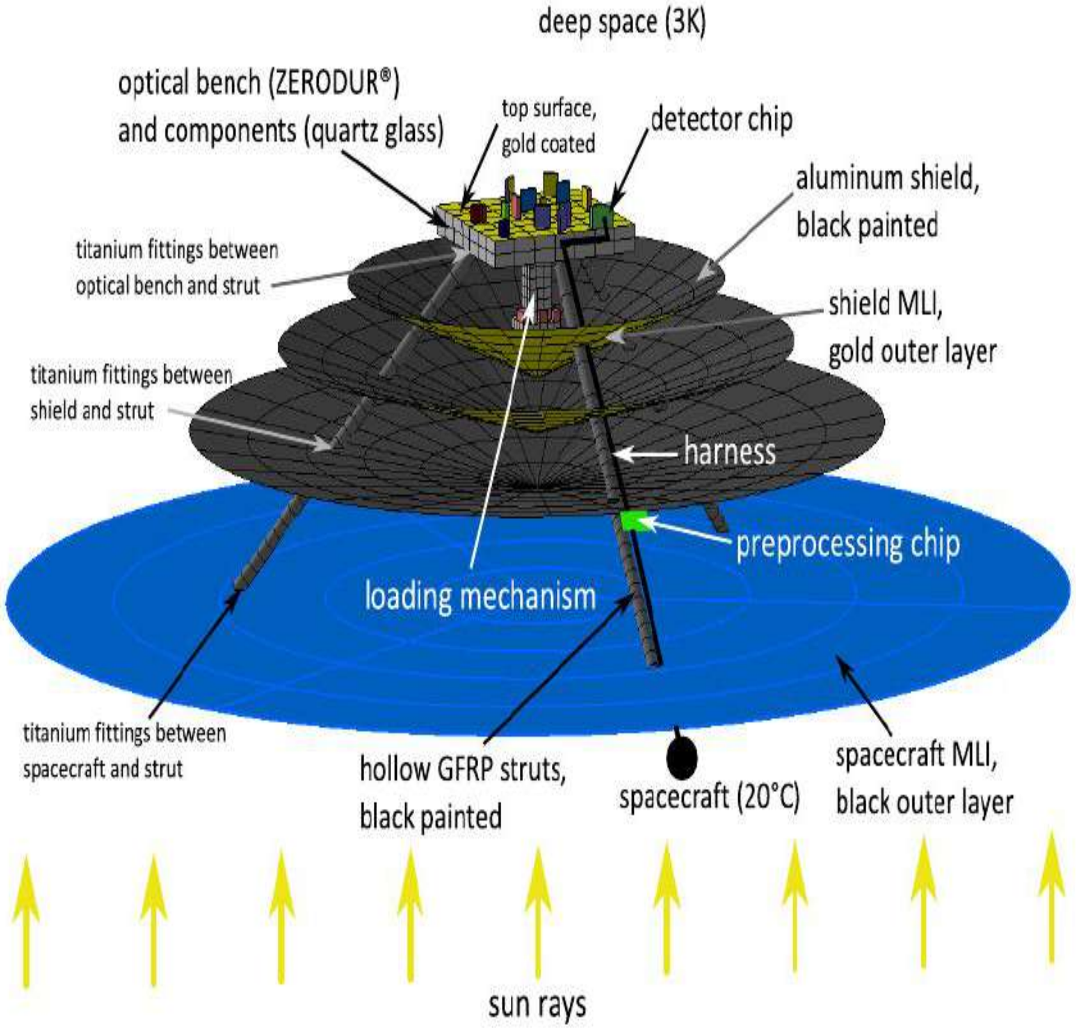


A levitated atom-nanosphere hybrid quantum system

To cite this article: A Hopper and P F Barker 2024 *New J. Phys.* **26** 013015



MAQRO



deep space (3K)
optical bench (ZERODUR®)
and components (quartz glass)
top surface,
gold coated
detector chip
aluminum shield,
black painted
titanium fittings between
optical bench and strut
shield MLI,
gold outer layer
titanium fittings between
shield and strut
harness
preprocessing chip
loading mechanism
titanium fittings between
spacecraft and strut
hollow GFRP struts,
black painted
spacecraft (20°C)
spacecraft MLI,
black outer layer
sun rays

Quantumness of gravity

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn

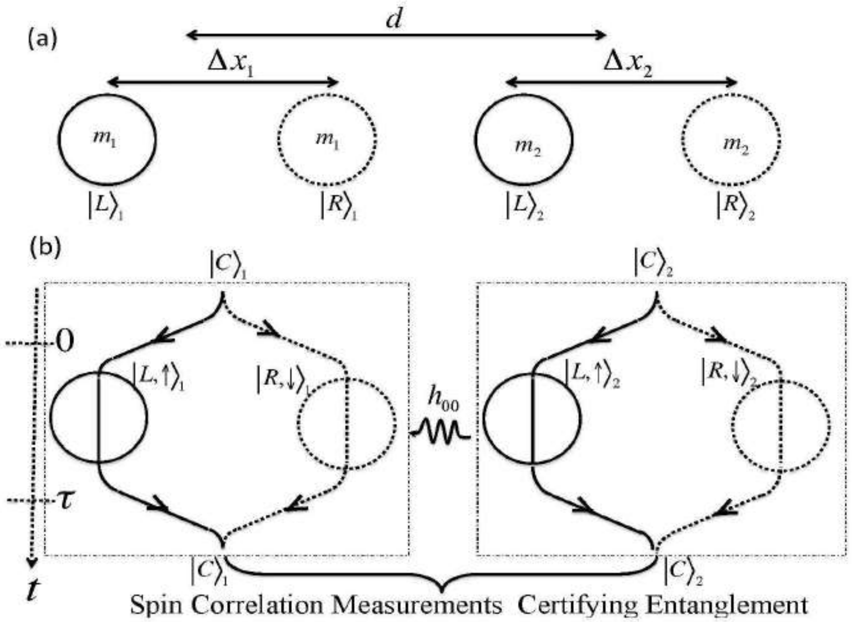
Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017

Physics See Synopsis: A Test of Gravity's Quantum Side

New Scientist

NEWS & TECHNOLOGY 22 November 2017

Free-fall experiment could test if gravity is a quantum force



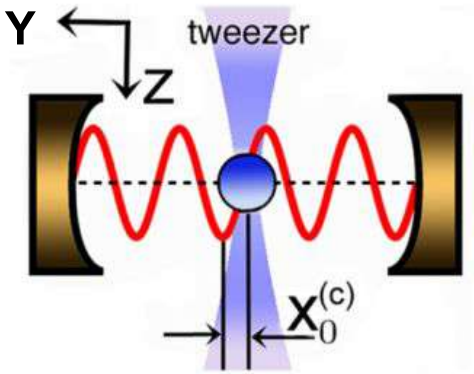
Casimir, Coulomb, diamagnetic interactions must be taken into account

Requirements for experiments

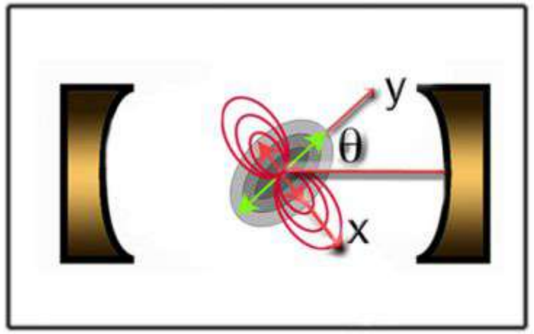
- Isolation - ultra-high vacuum (> 10^{-13} mbar) and low environmental temperatures (10 K)
- Low internal temperatures – 10's K
- Control and cool all motional degrees of freedom
  - Coherent scattering and feedback – 6 DOF cooling
  - Sympathetic cooling – all degrees of freedom
  - Reducing back action from recoil
- Detailed understanding density, charge, temperature, shape and material and fluctuations.

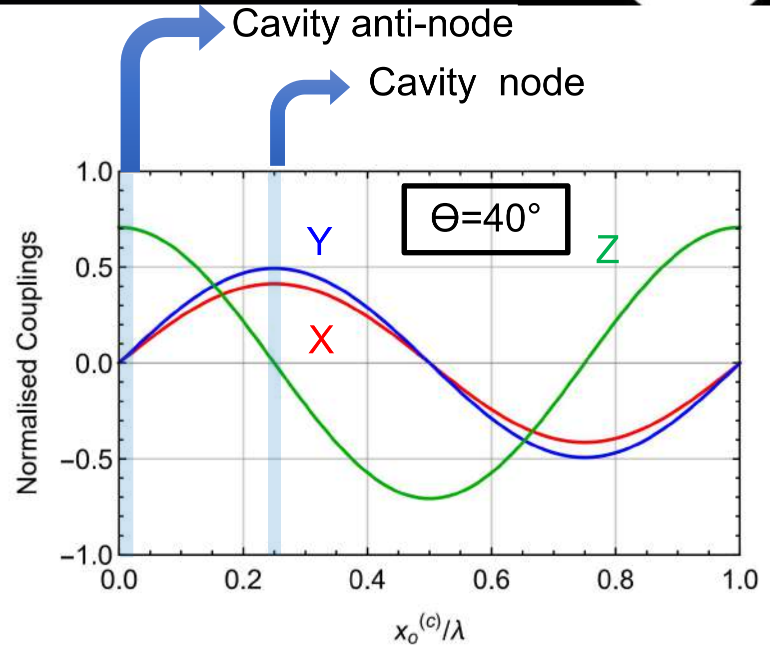
Cooling by coherent scattering

Optical tweezer linearly polarized along Y



Scattered light can populate the cavity field depending on angle Θ



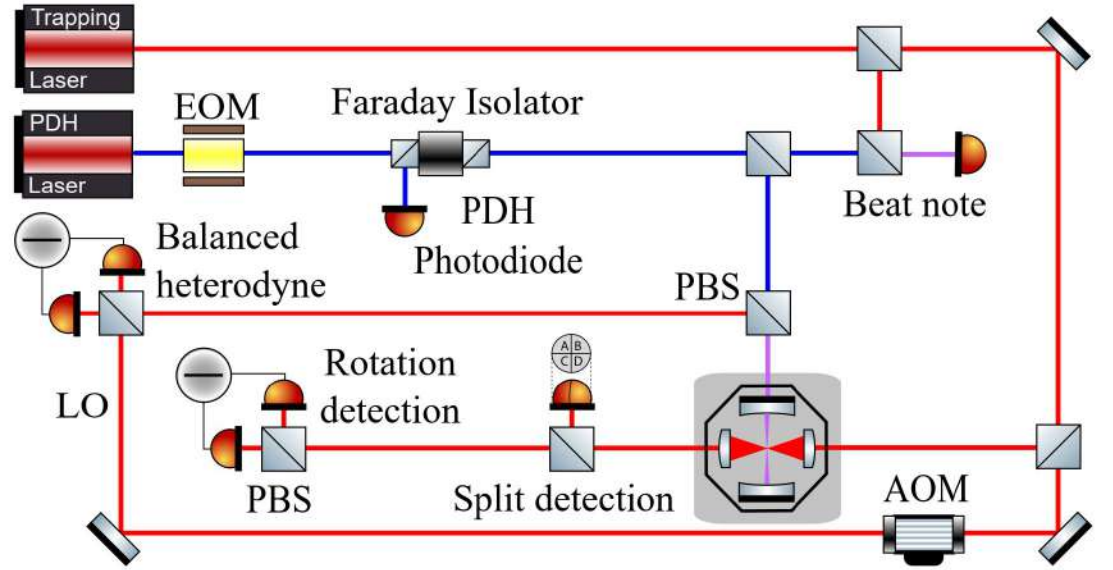


If the tweezer field is resonant with the cavity

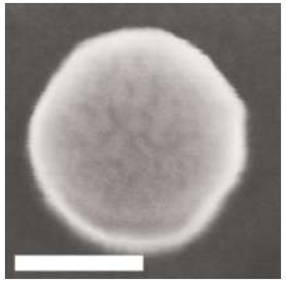
$$\hat{H} = -\frac{\alpha}{2}|\hat{\mathbf{E}}_{\rm tw}|^2 - \frac{\alpha}{2}|\hat{\mathbf{E}}_{\rm cav}|^2 \underbrace{- \frac{\alpha\sin(\theta)}{2}(\hat{\mathbf{E}}^\dagger_{\rm cav}\hat{\mathbf{E}}_{\rm tw} + \hat{\mathbf{E}}_{\rm cav}\hat{\mathbf{E}}^\dagger_{\rm tw})}_{\text{Interference term}}$$

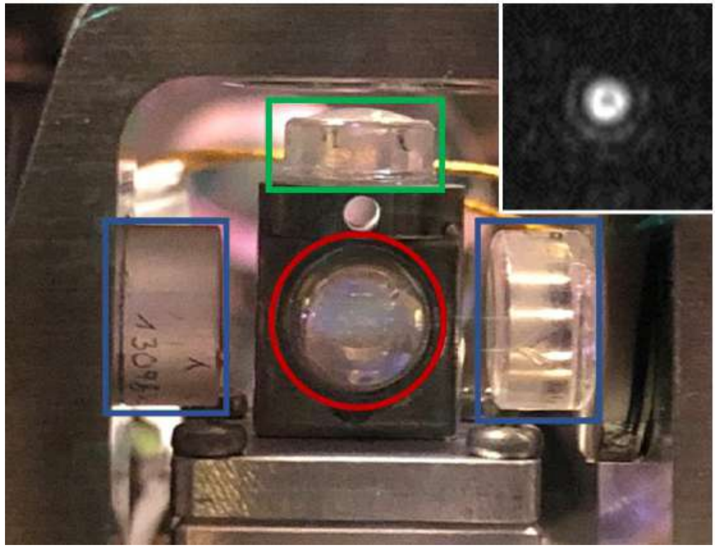


Experimental setup



Monolithic tweezer assembly





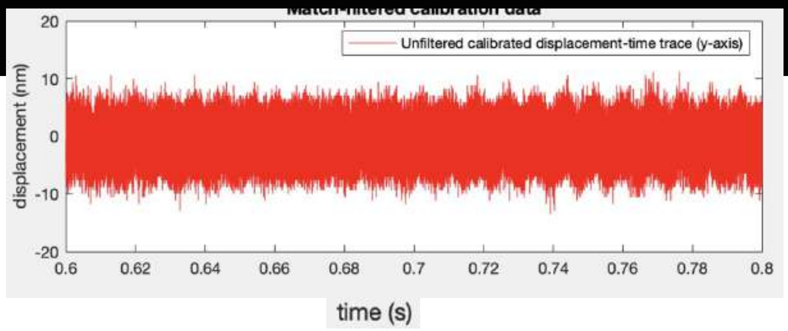
Silica nanoparticle

P_{TW} ~200-500 mW@ 1064nm
Lens NA~0.77 (single lens)

Cavity parameters

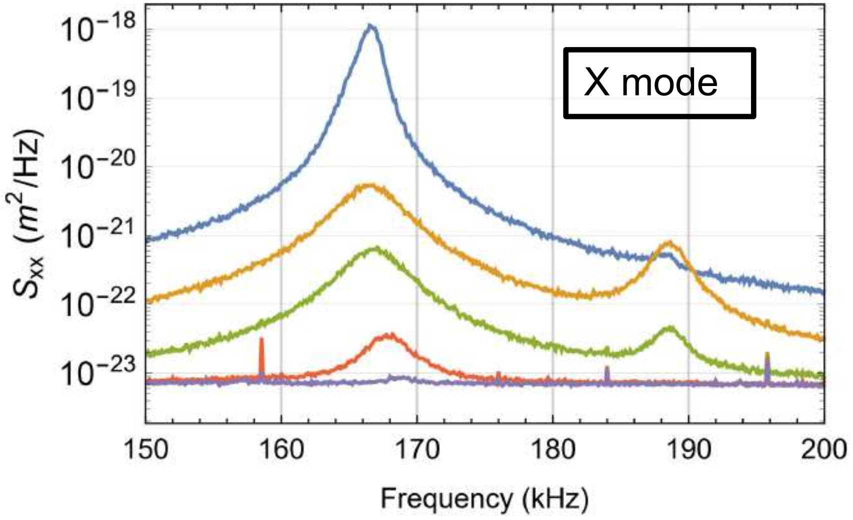
Lcav=12.23 ± 0.02 mm
$\kappa/2\pi$=198 ± 1 kHz
Finesse ~ 31000

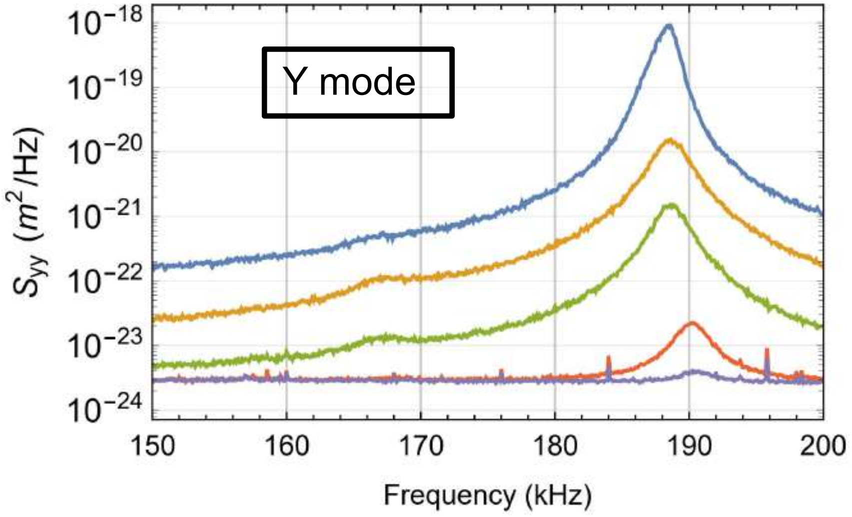
Temperature of r=60 nm SiO_2 nanosphere



$$\langle x^2 \rangle = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_{xx}(\omega)d\omega = \frac{k_B T_{eff}}{m\omega_x^2}$$

As the pressure is reduced





Motion cooled by factor ~10^7

Zero-point motion ~ 7 pm

2D cooling in the tweezer polarization plane

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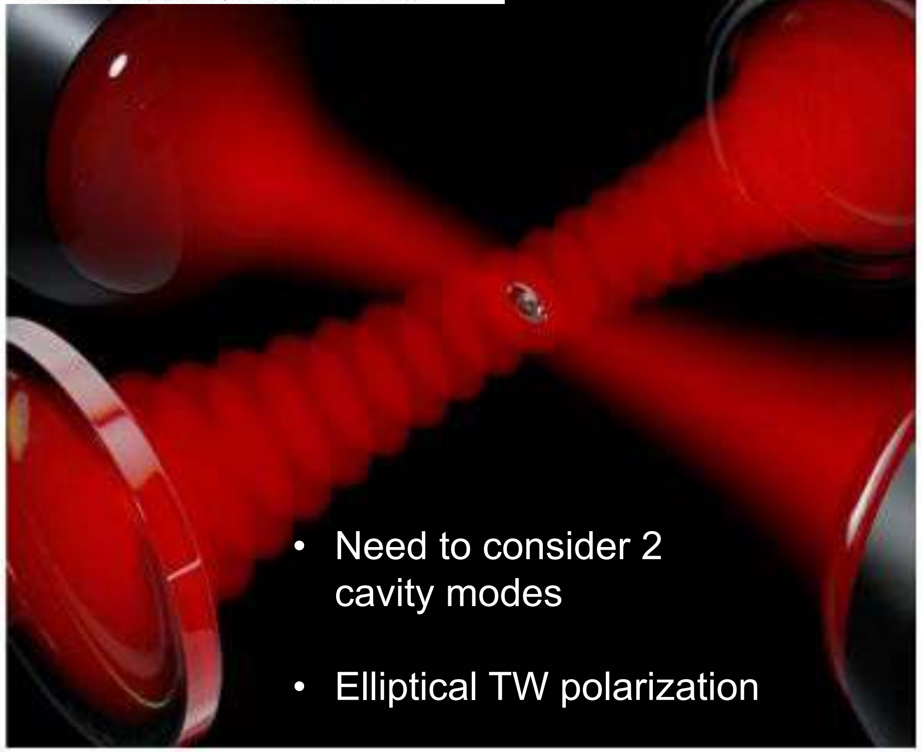
Cooling of ellipsoidal nanoparticles

UCL

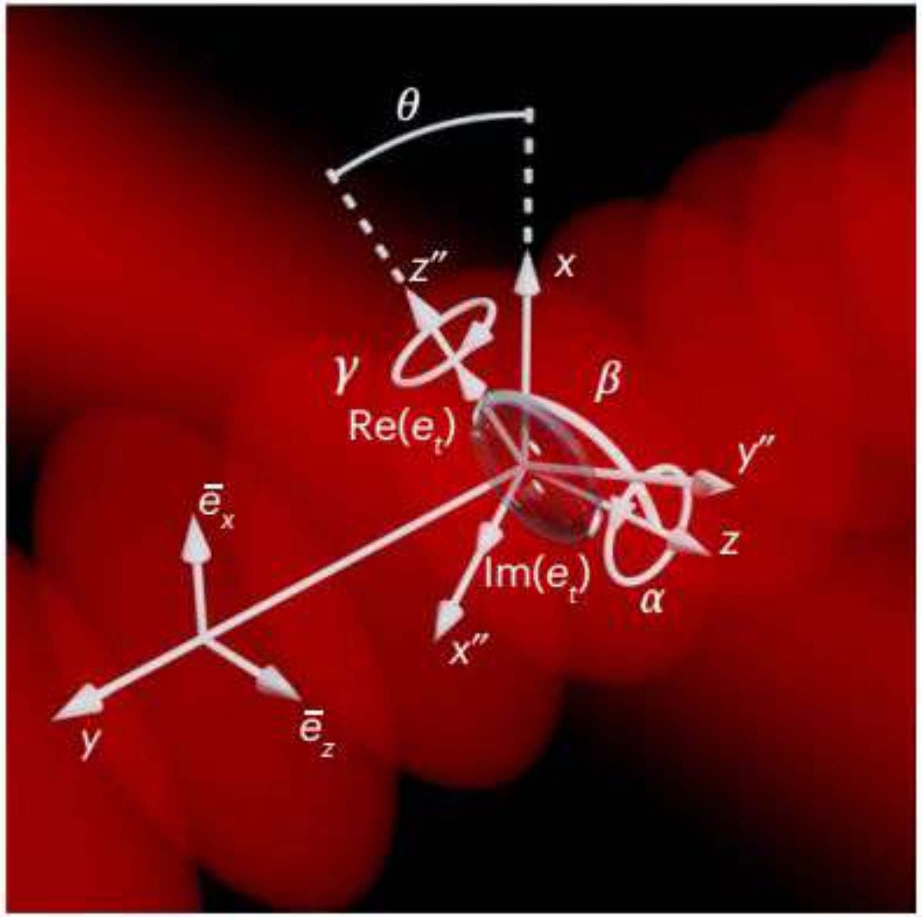
nature physics
Article
https://doi.org/10.1038/s41567-023-02006-6

Simultaneous cavity cooling of all six degrees of freedom of a levitated nanoparticle

A. Pontin[1], H. Fu[1], M. Toroš[2], T. S. Monteiro[1] & P. F. Barker[1]



- Need to consider 2 cavity modes
- Elliptical TW polarization



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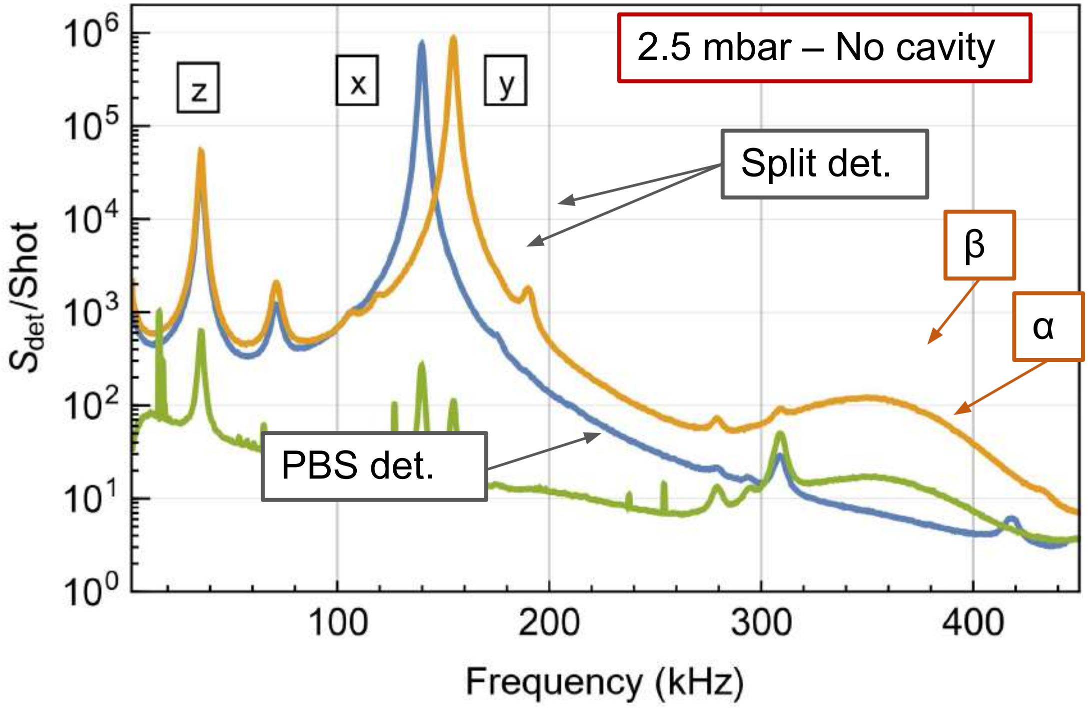
Detection of motion in 5 degrees of freedom



Valid for elliptical polarization

$$V_{split} \propto \delta\beta$$
$$V_{PBS} \propto \delta\alpha$$

Seberson&Robicheaux PRA99,013821(2019)

Spectra exploited to calibrate each DoF assuming thermal equilibrium

γ → free diffusion → Redefine librational normal modes

$$Q = \sqrt{4\omega_\beta^2\omega_c^2 + (\omega_c^2 + \omega_\alpha^2 - \omega_\beta^2)^2}$$
$$\omega_c \simeq (I_3/I_1)(\dot\gamma - \dot\alpha\,\beta)$$
$$\omega_\pm = \sqrt{(\omega_\alpha^2 + \omega_\beta^2 + \omega_c^2 \pm Q)/2}$$

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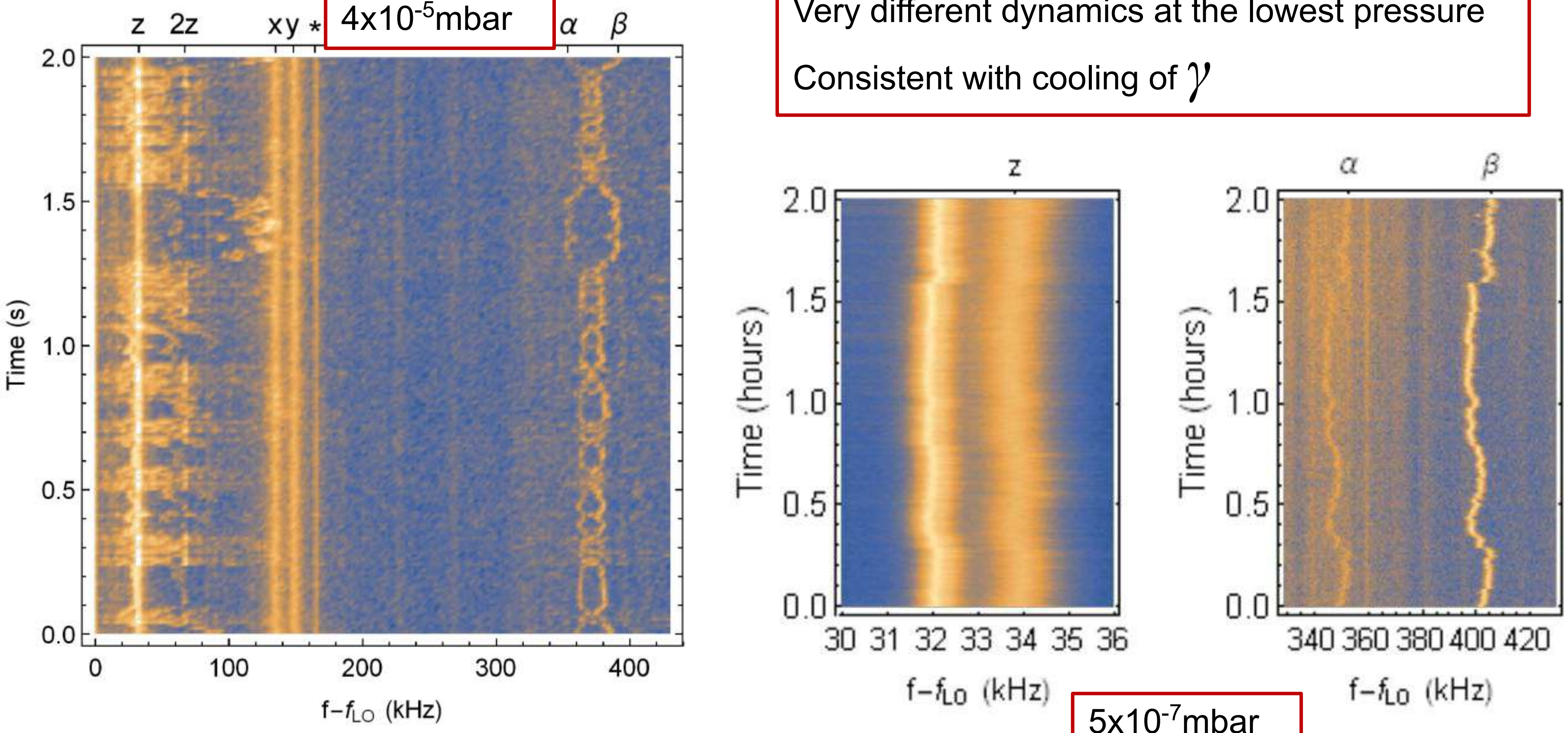
Spectral features with time

Very different dynamics at the lowest pressure

Consistent with cooling of γ

4x10^{-5}mbar



5x10^{-7}mbar

This transition is very well reproduced in numerical simulation

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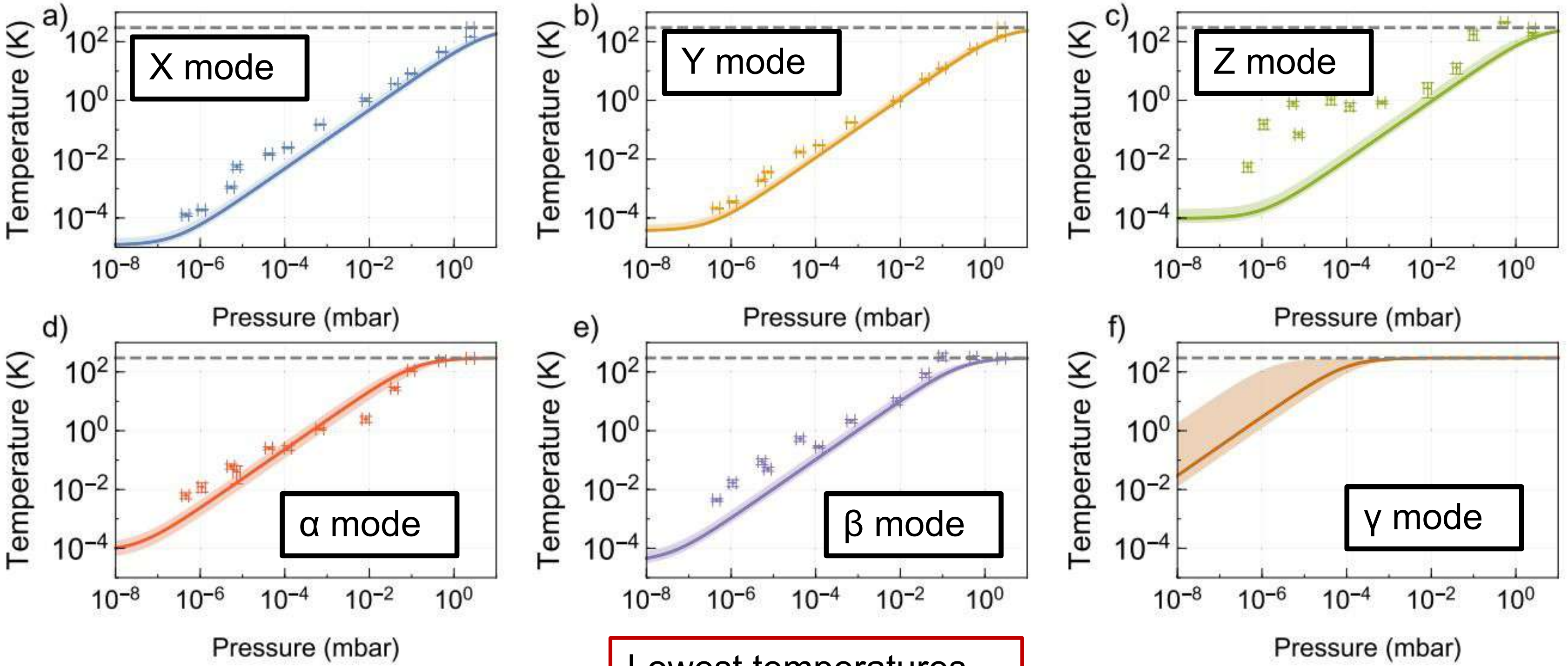
Comparison with analytical estimates



Lowest temperatures @ 4x10^{-7}mbar

Mean occupation

Cooling all 6 degrees of freedom with a single field

Lowest temperatures @ 4x10^{-7}mbar	Mean occupation
$T_x = 130 \pm 20\,\mu\mathrm{K}$	19 ± 3
$T_y = 212 \pm 15\,\mu\mathrm{K}$	29 ± 2
$T_z = 6 \pm 2\,\mathrm{mK}$	
$T_\alpha = 6.6 \pm 4\,\mathrm{mK}$	370 ± 90
$T_\beta = 4.4 \pm 0.5\,\mathrm{mK}$	240 ± 30

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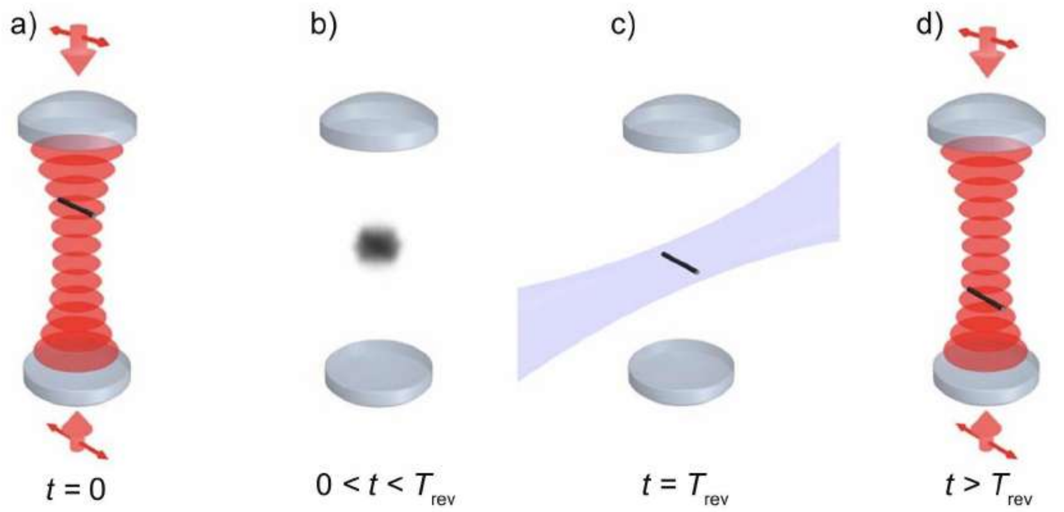
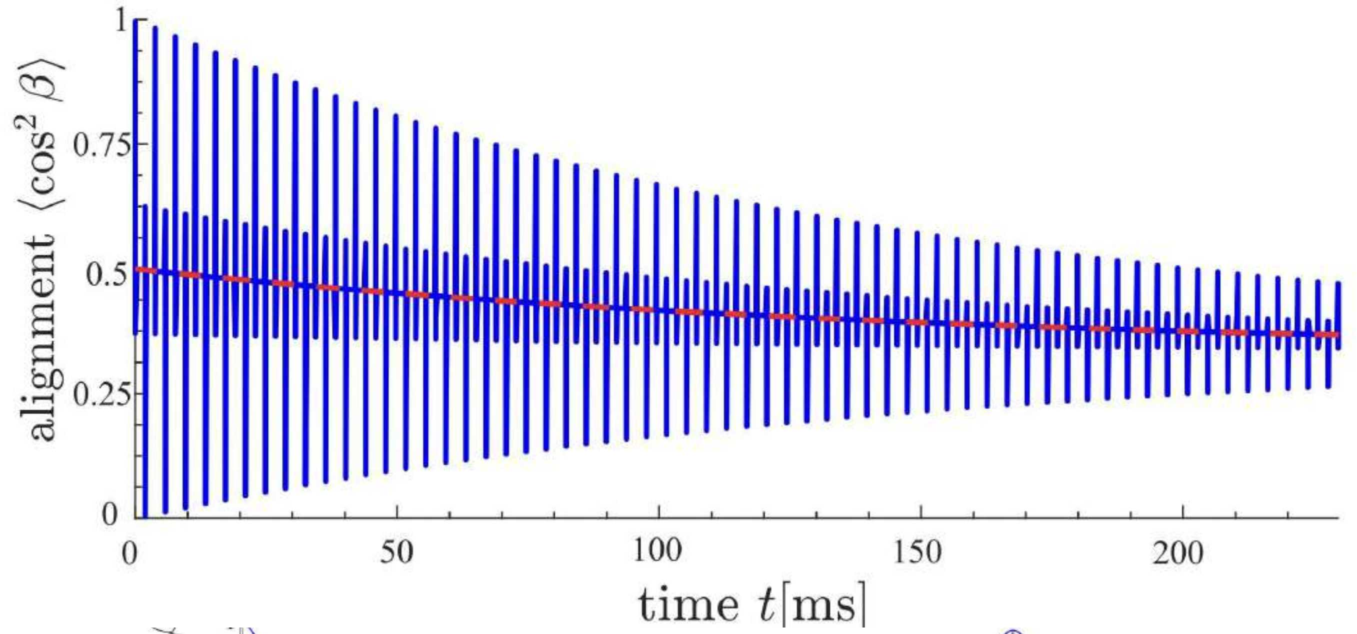
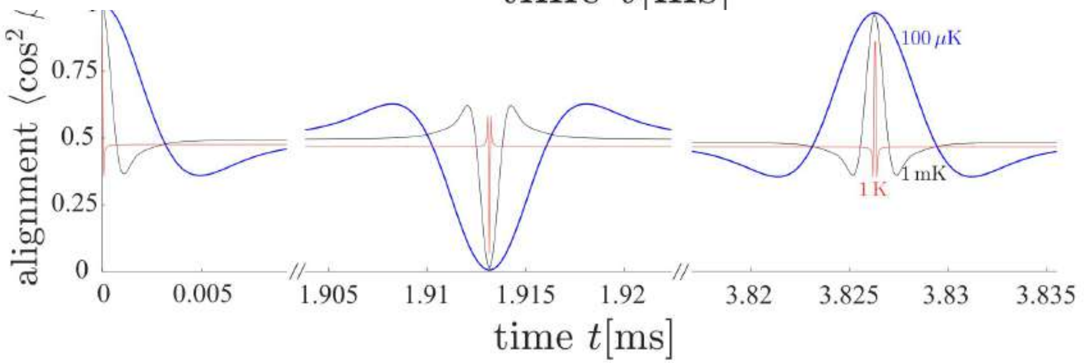
Applications- Interferometry with rotational states

Rotational state interferometry – Rivals of rotational states







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New Journal of Physics

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FAST TRACK COMMUNICATION

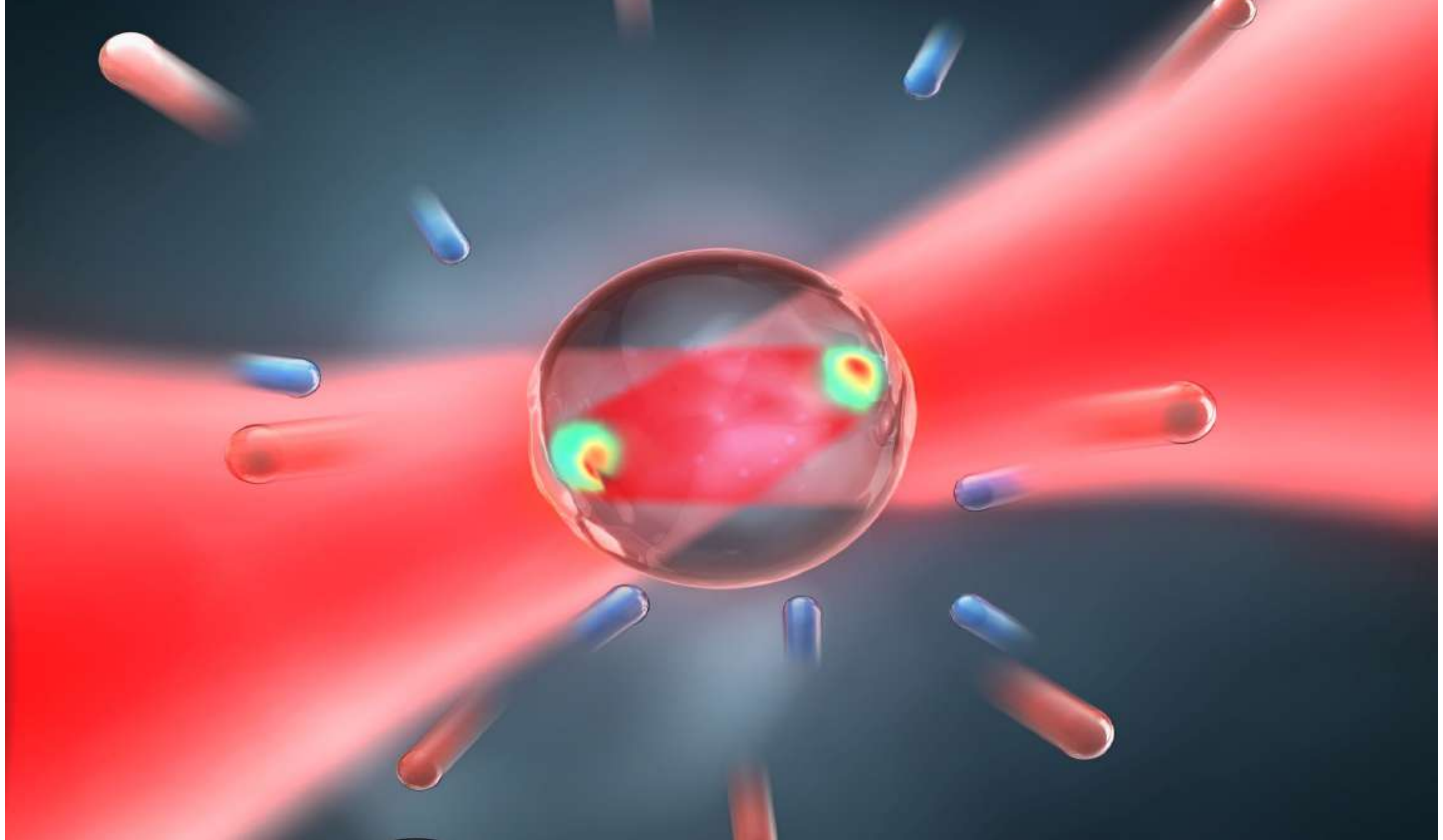
Probing macroscopic quantum superpositions with nanorotors

Benjamin A Stickler[1], Birthe Papendell[1], Stefan Kuhn[2], Björn Schrinski[1], James Millen[2,3], Markus Arndt[2] and Klaus Hornberger[1,4]

Mitigating decoherence from heating

Heating

- leads to spin decoherence in Stern-Gerlach experiments
- Increased temperature for gas collisions
- Black body radiation
- Cryostat not effective



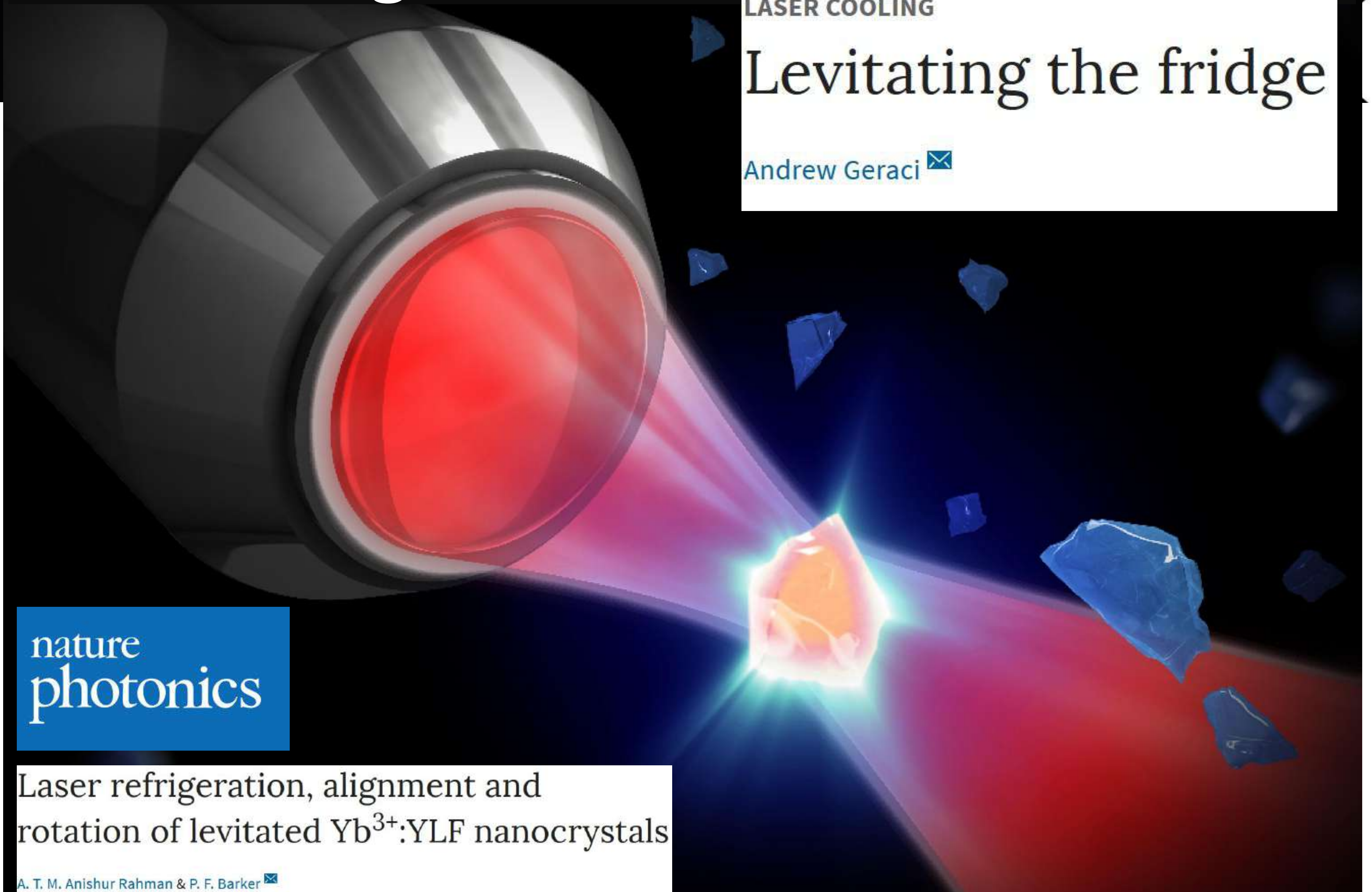
Laser refrigeration

News and Views

LASER COOLING

Levitating the fridge

Andrew Geraci

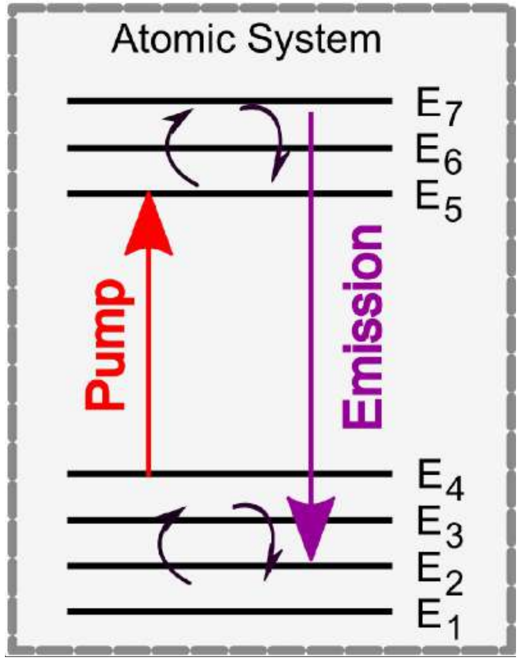


nature photonics

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

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

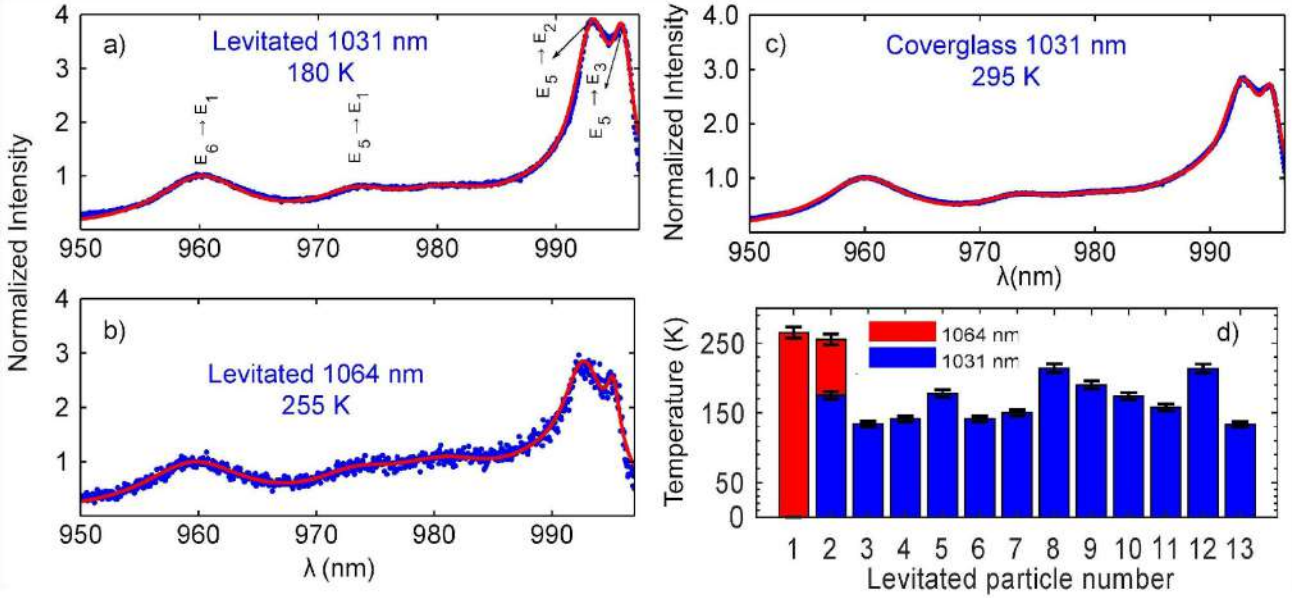
Internal cooling of levitated crystals



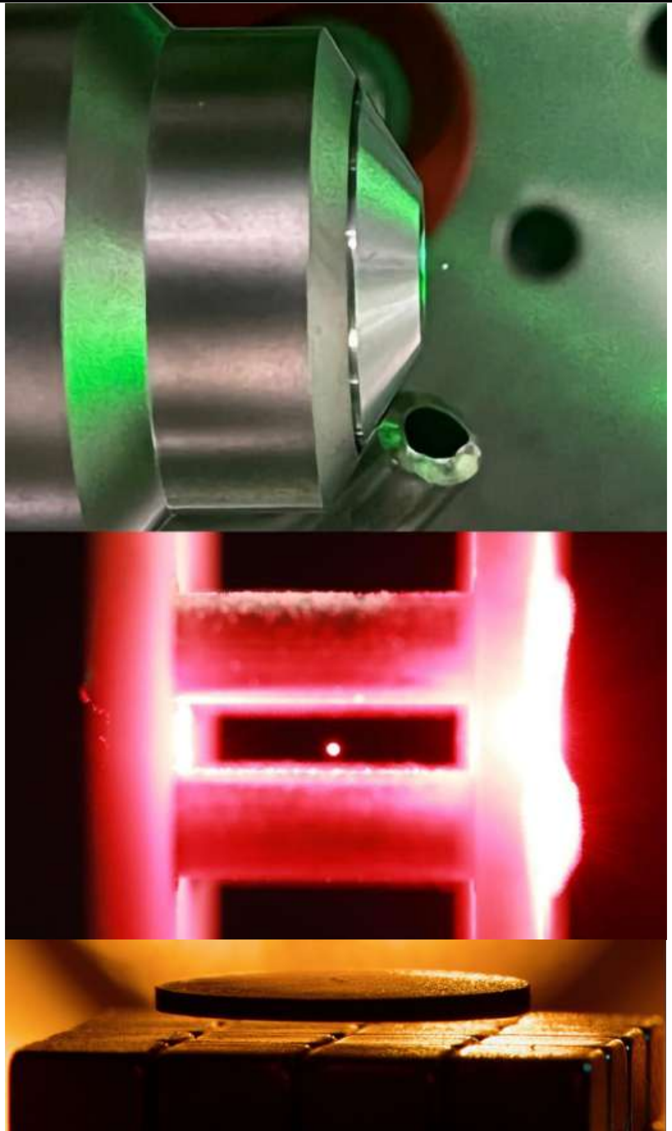
Shielding of 4f by 5s and 5p shells leads to ‘atomic like spectra’

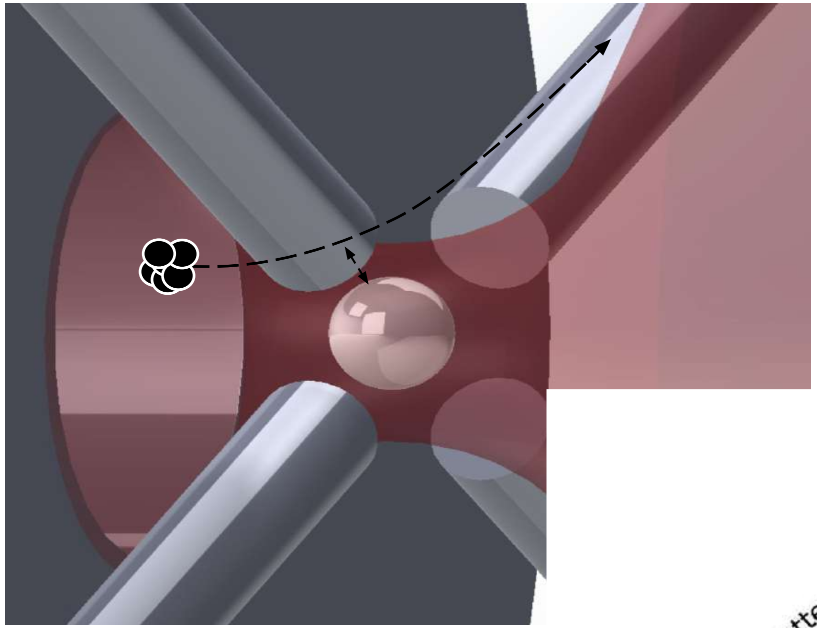
Good coupling to phonons – fast relaxation within electronic levels

Low phonon energy – no non-radiative relaxation



Impulsive force detection

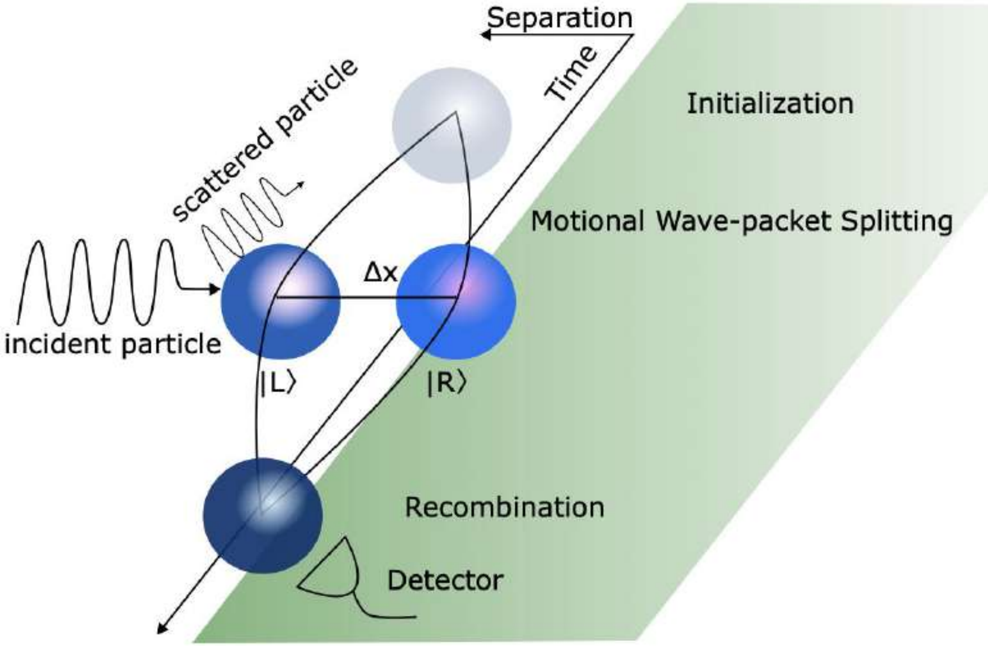




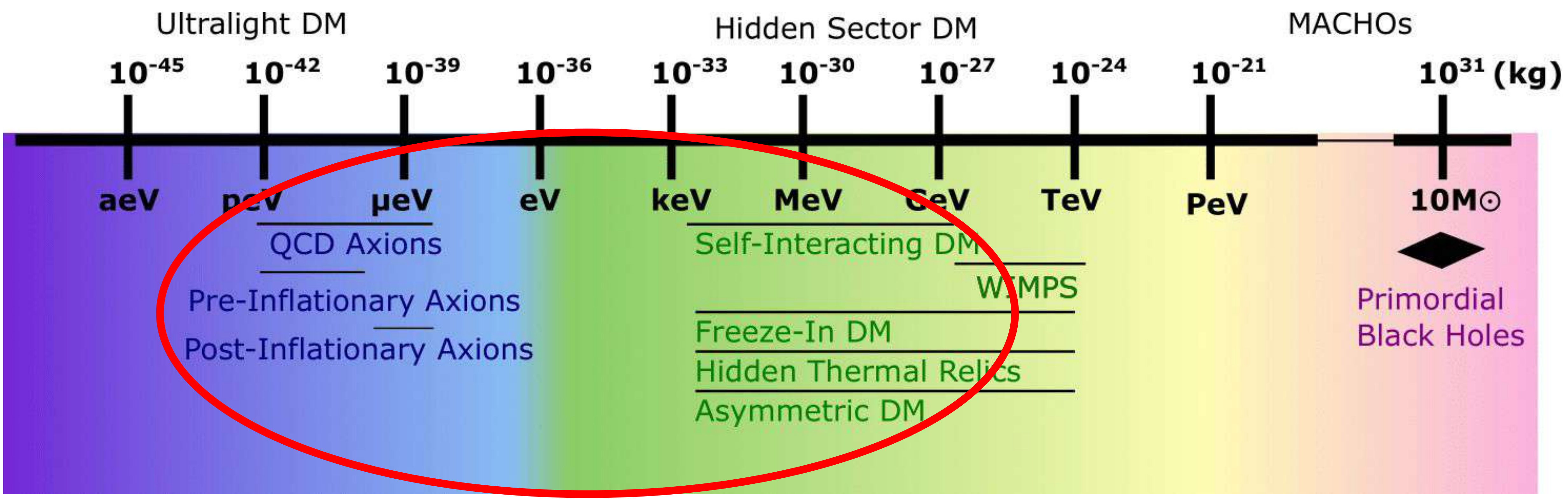
$$\Delta p = \sqrt{\hbar m \omega_0 / 2}$$

Collisions with:

- Molecules
- Photons (x-rays)
- Neutrons
- Dark matter



Dark matter landscape



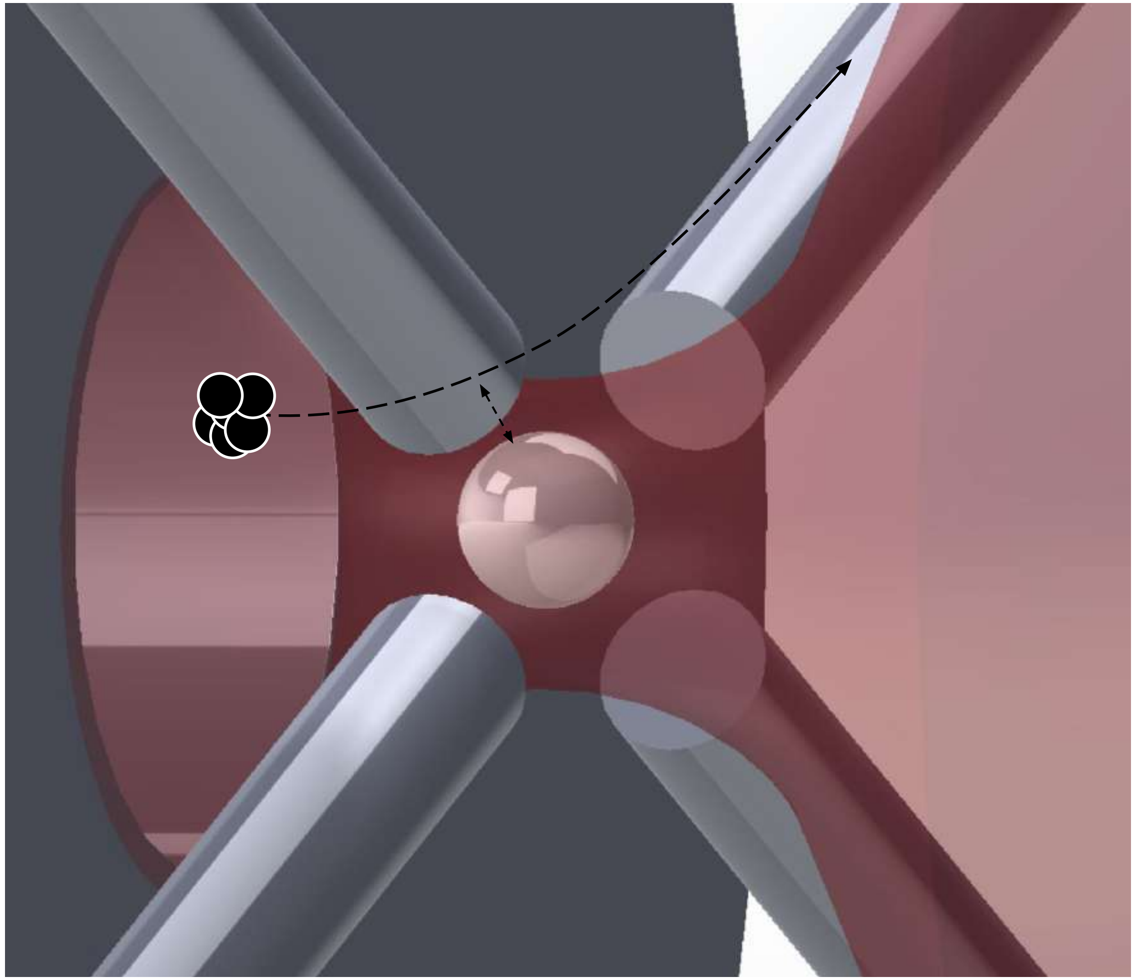
Dark matter nuggets

- Fermionic or bosonic dark matter particle coupling to scalar mediator.
- Coupling can lead to formation of bound dark matter "nuggets".
- Mediator able to couple to nucleons.

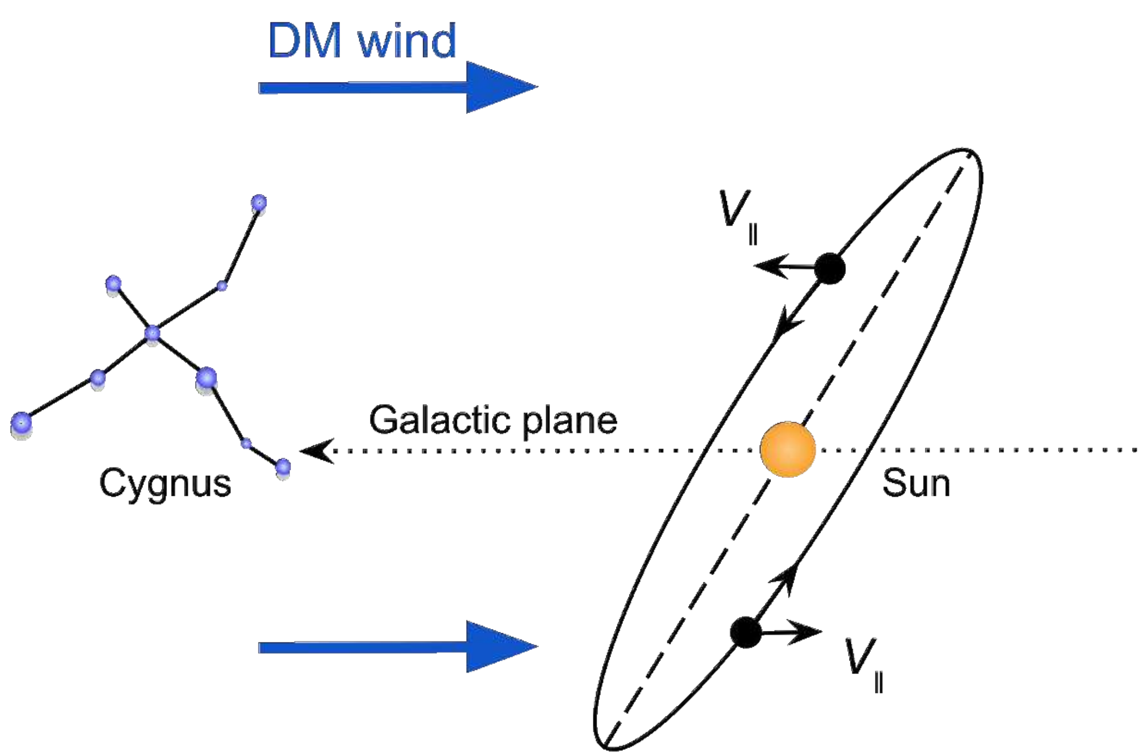
$$V(\vec{r}) = \frac{g_\chi N_\chi g_n N_n}{4\pi} \frac{1}{|\vec{r}|} e^{-m_\phi |\vec{r}|}$$

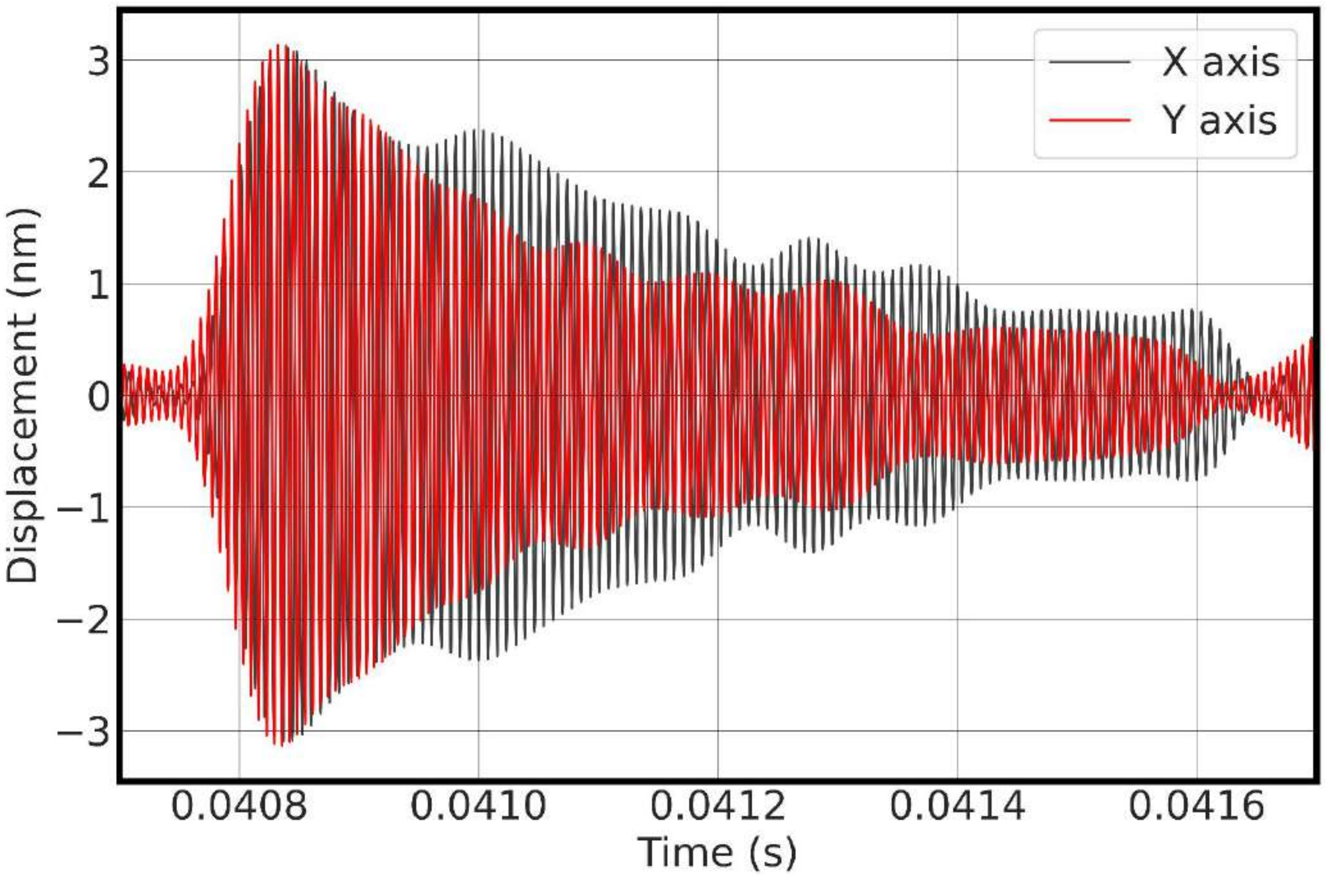
Long-range, small-angle scattering

m_ϕ <eV

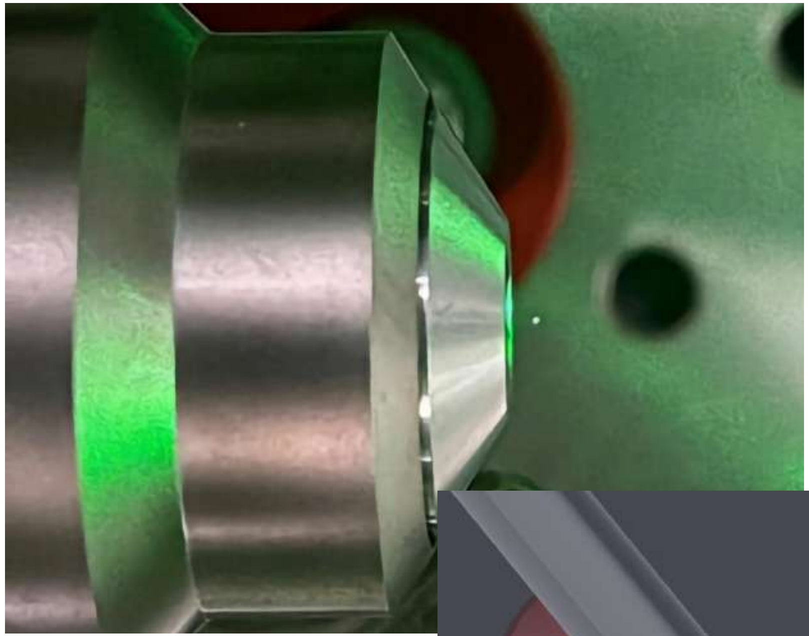


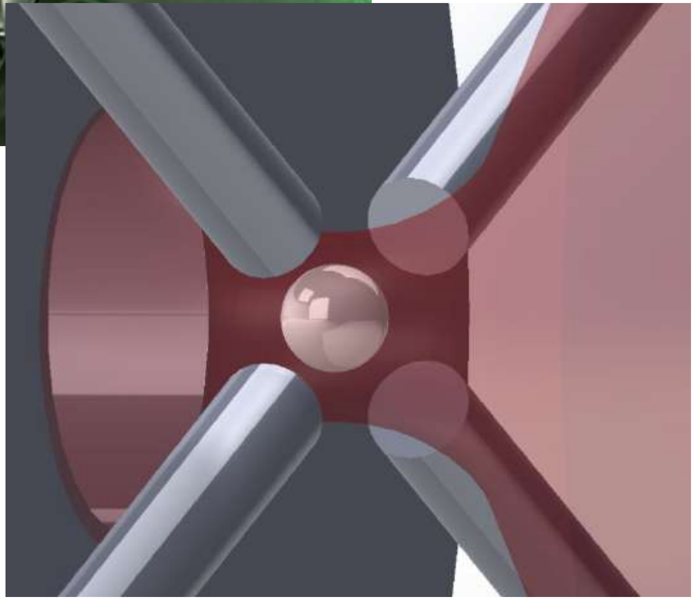
Directionality

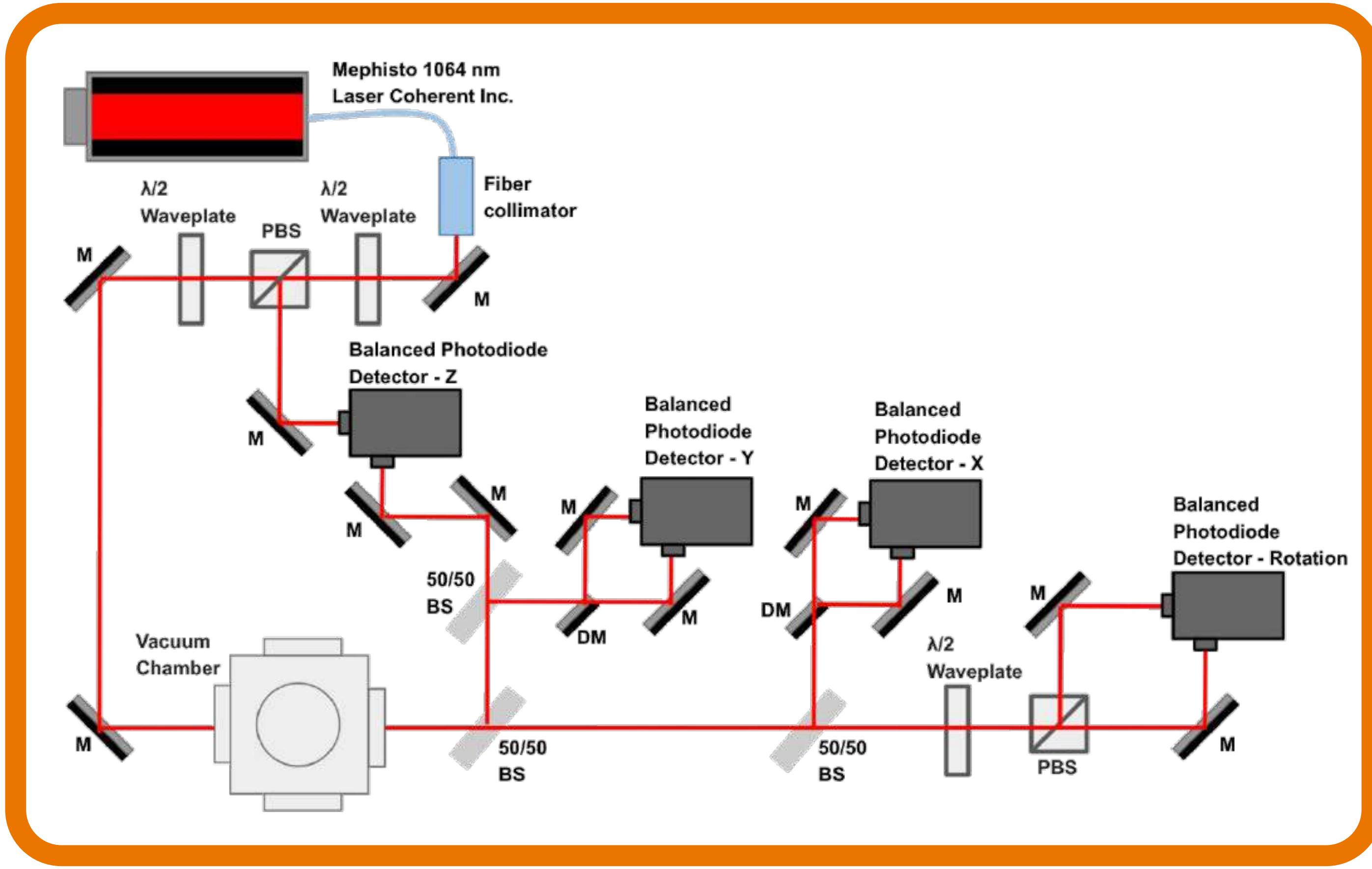




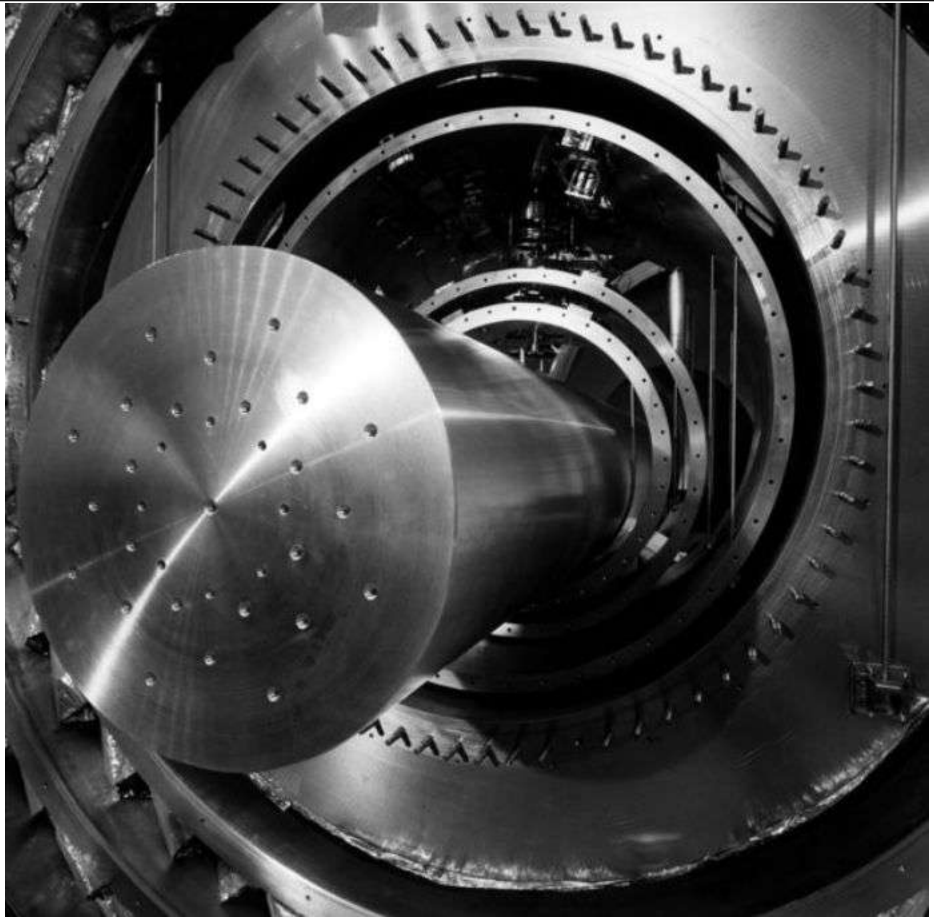
Experimental Setup

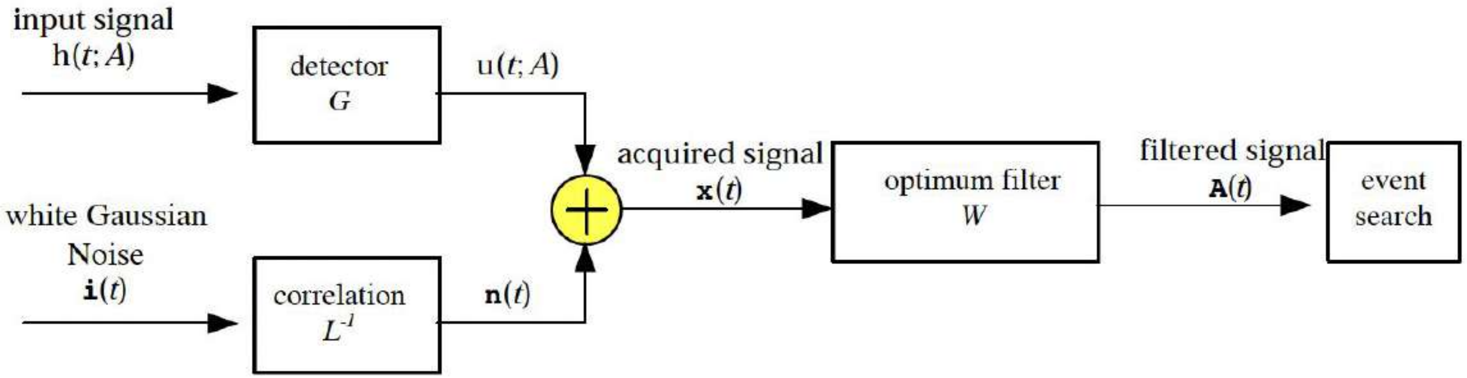






Impulsive event detection





$$M(\omega) = \sigma_A^2 \frac{H^*(\omega) F^*(\omega)}{S(\omega)} e^{-i\omega t_a}$$

Product of 3 filters

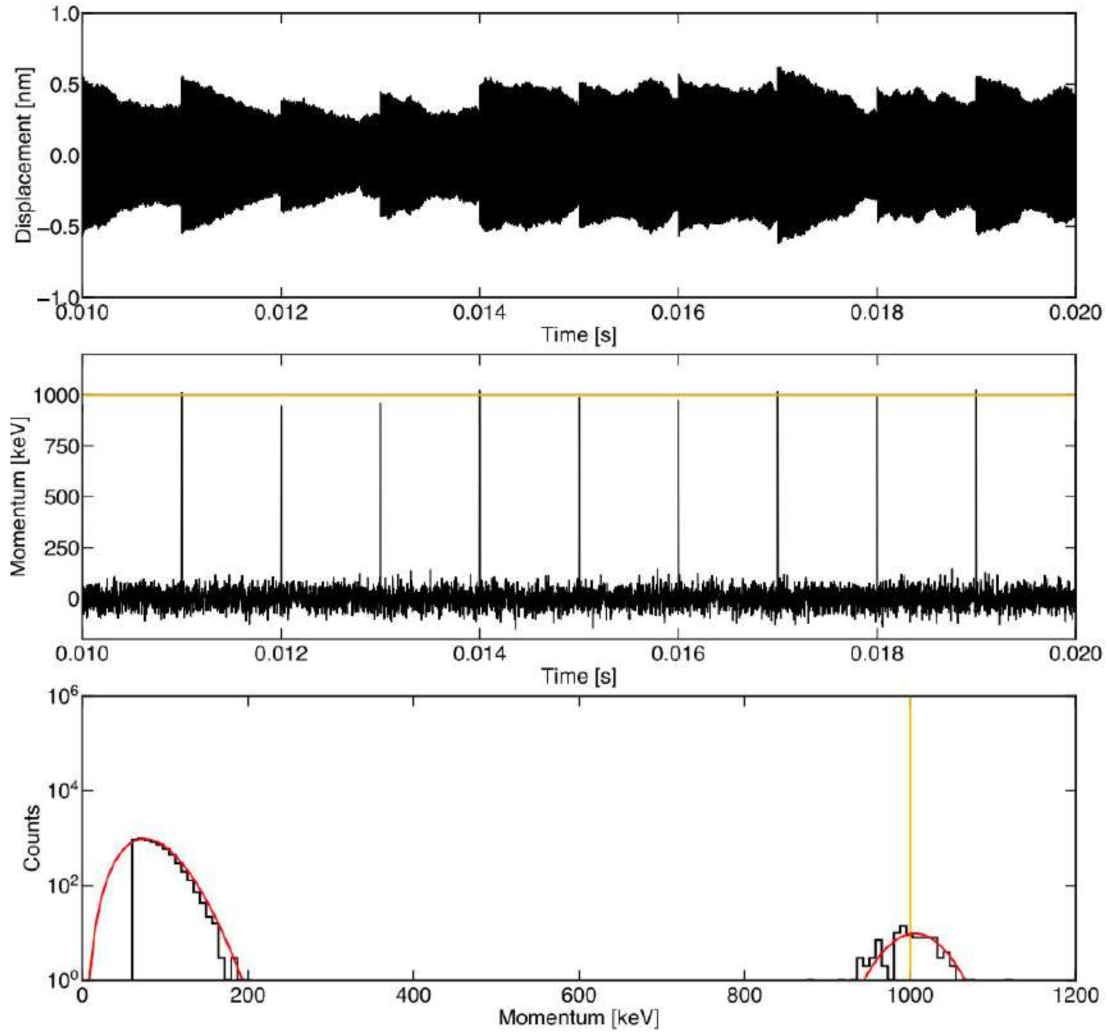
$M^C(\omega) \equiv 1/L(\omega)$ Whitening filter

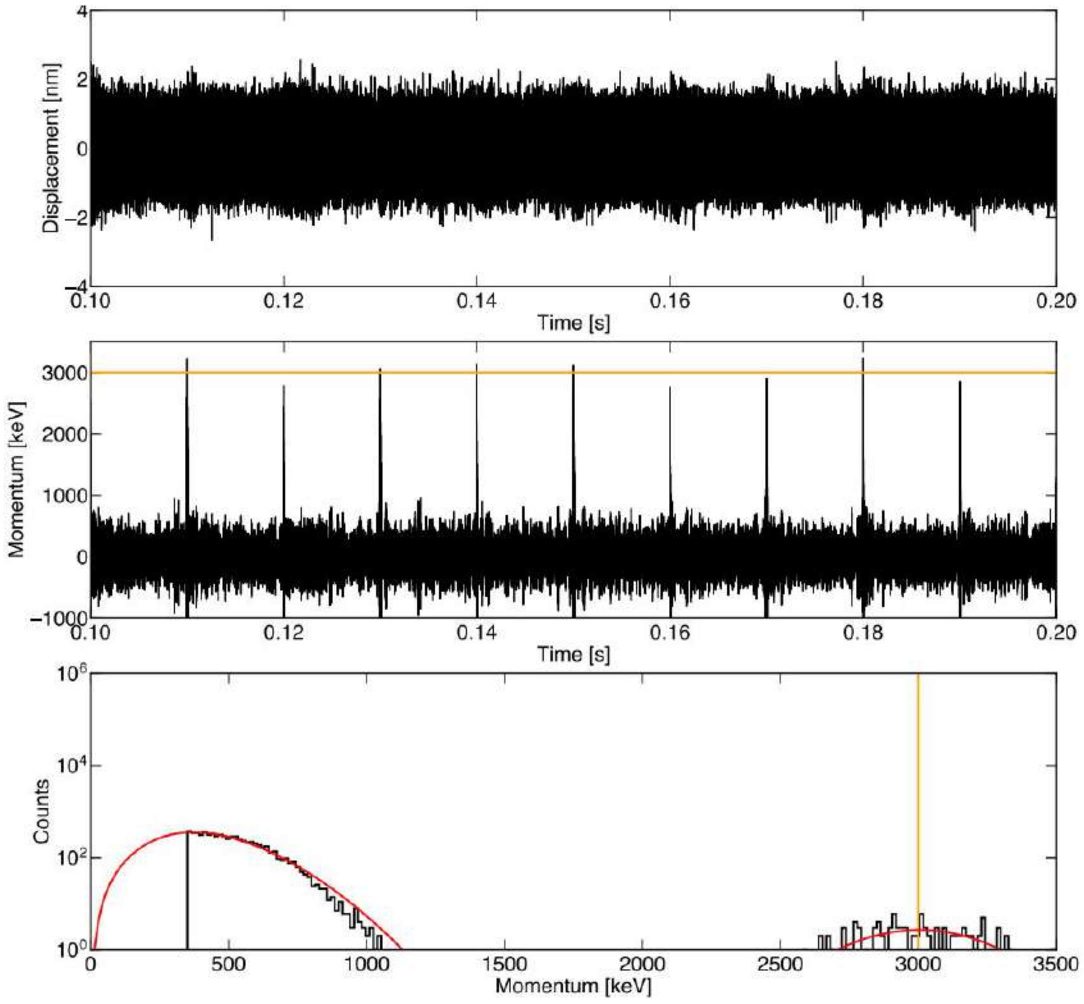
$M^A(\omega) \equiv H^*(\omega)/L^*(\omega)$ δ Pattern matching filter

$F^*(\omega)$

[A. Ortolan et al, Gravitational waves. Proceedings, 2nd Edoardo Amaldi Conference, Geneva, Switzerland, July 1-4, 1997, 204-215]

Experimental Procedure





Concluding remarks

UCL

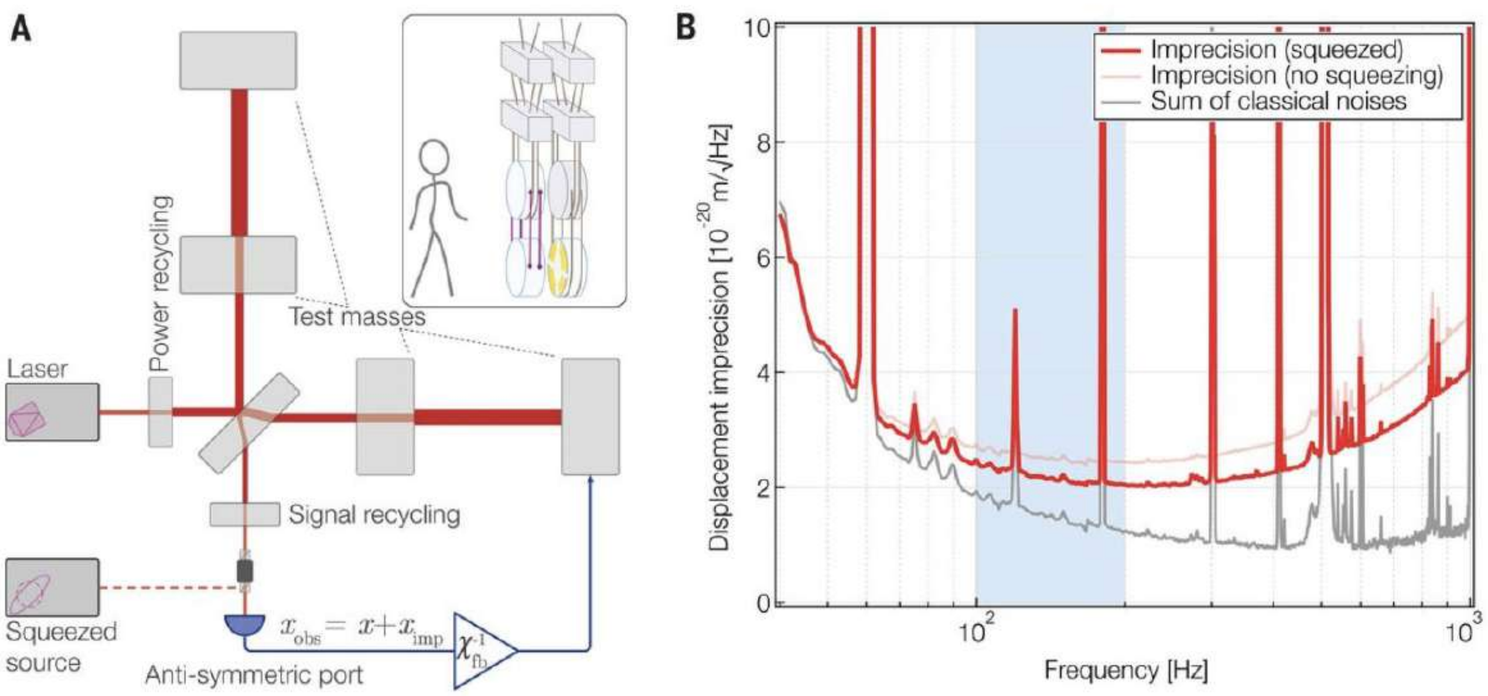
- Provided an overview of the experimental progress towards the creation of macroscopic quantum systems
- Conveyed some of the most promising systems, their limitations and what must be over come
- Personal view focusing on levitated mechanical systems that are set to establish new limits in the next few years

Future directions

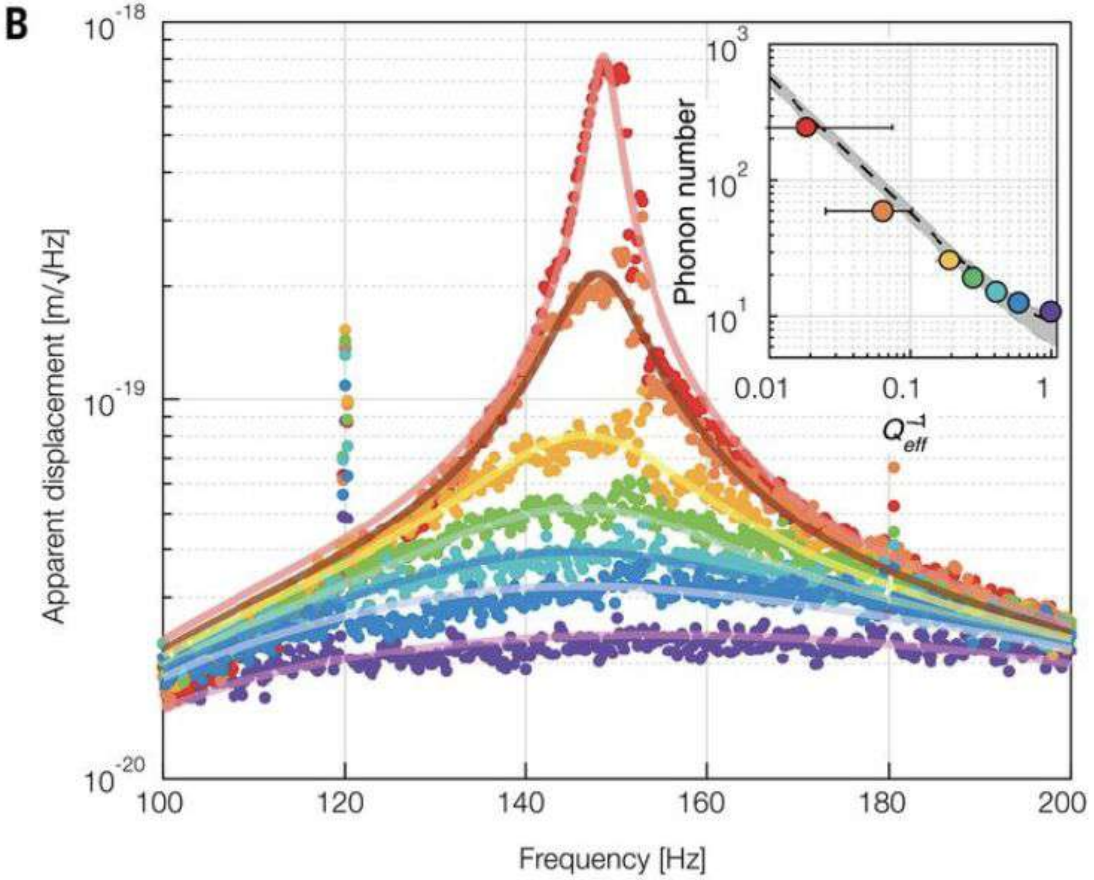
Approaching the motional ground state of a 10-kg object

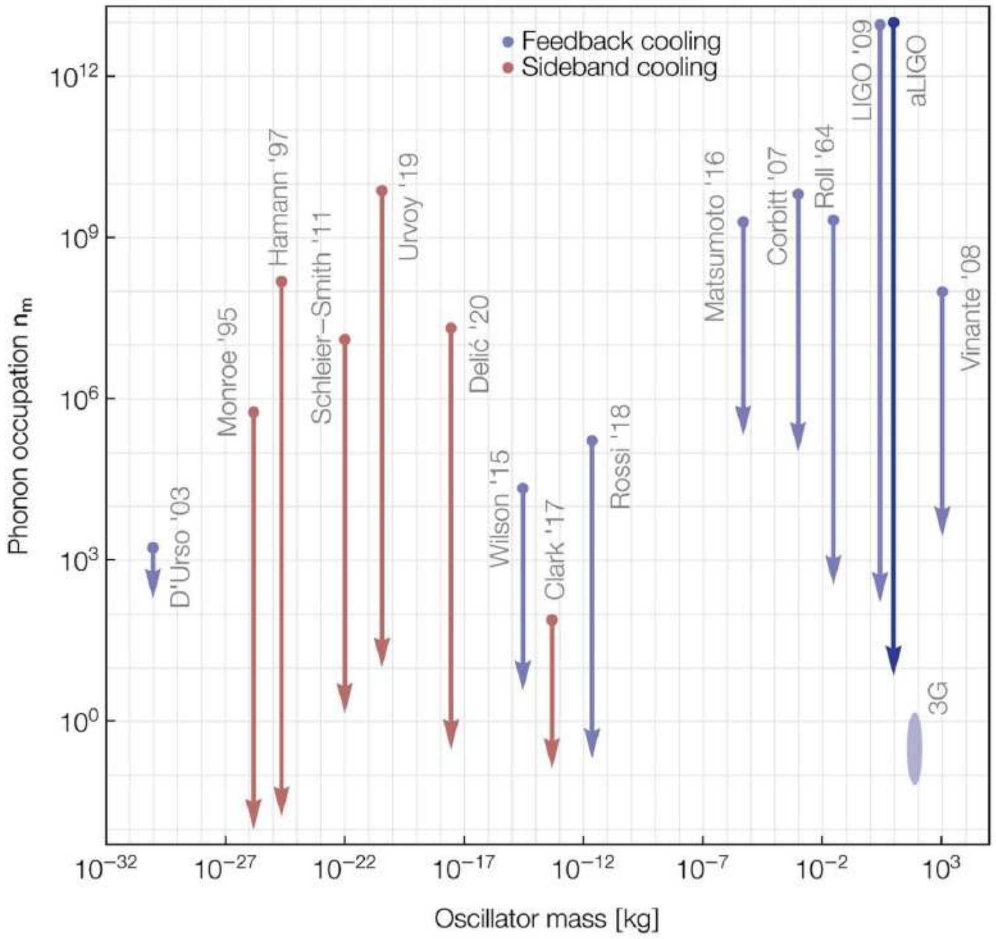
CHRIS WHITTLE, EVAN D. HALL, SHEILA DWYER, NERGIS MAVALVALA, VIVISHEK SUDHIR, R. ABBOTT, A. ANANYEVA, C. AUSTIN, L. BARSOTTI, [...], AND J. ZWEIZIG +190 authors Authors Info & Affiliations

SCIENCE • 18 Jun 2021 • Vol 372, Issue 6548 • pp. 1333-1336 • DOI: 10.1126/science.abh2634



Future directions





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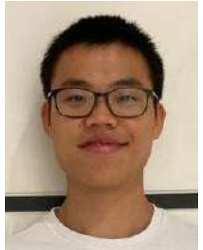
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