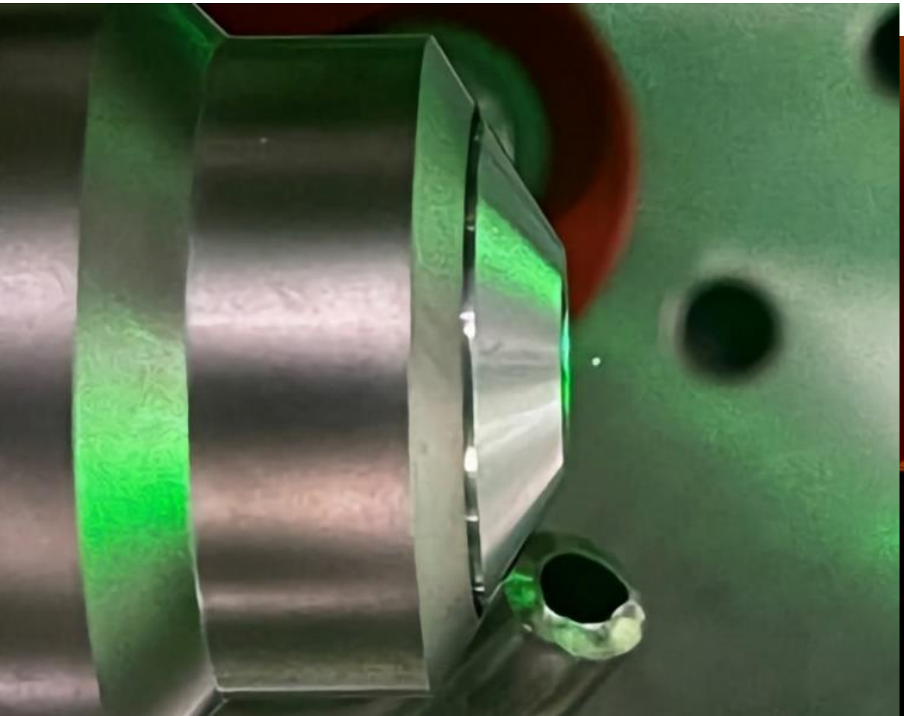
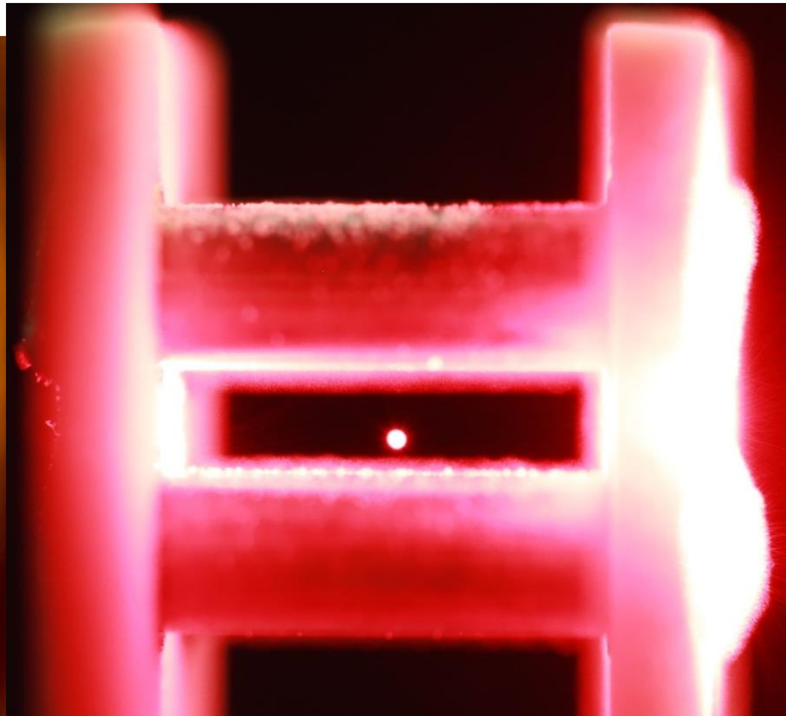
Characterising and calibrating levitated nano-mechanical systems for sensing

P. Barker and the Optomechanics group at UCL





Levitated optomechanics at UCL

Macroscopic quantum systems

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

Laser refrigeration – cooling internal degrees of freedom

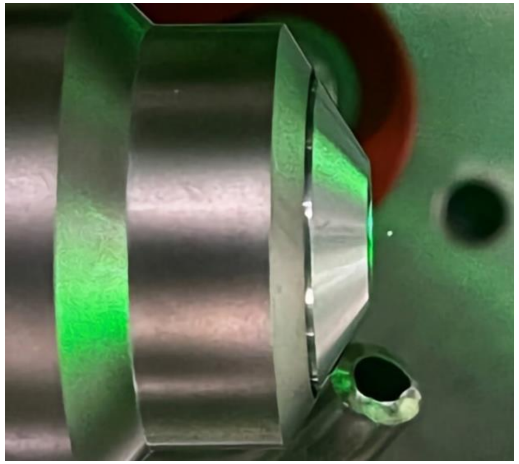
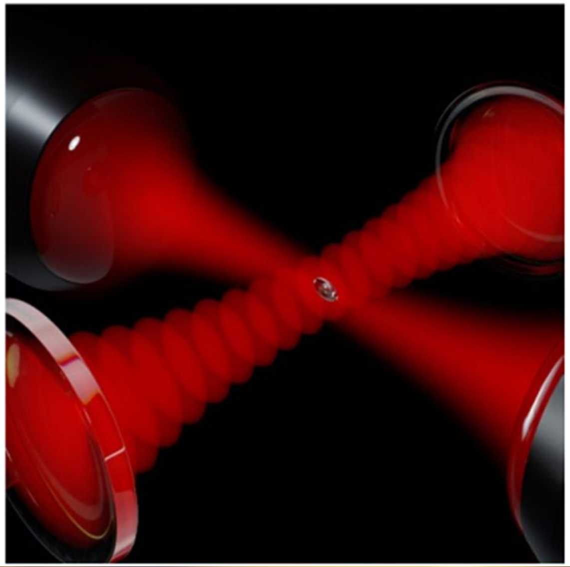
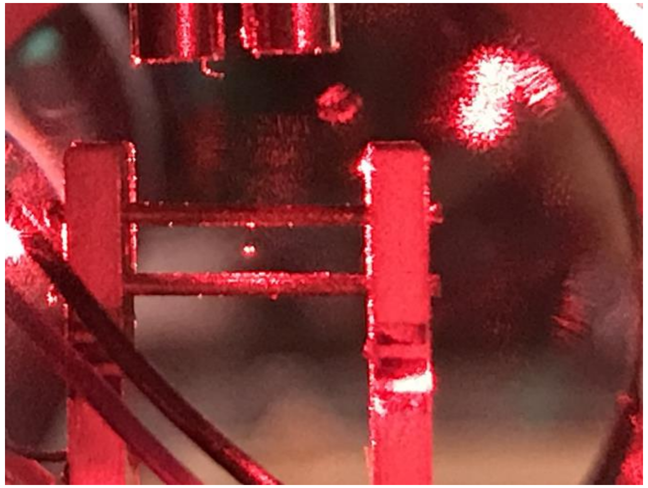
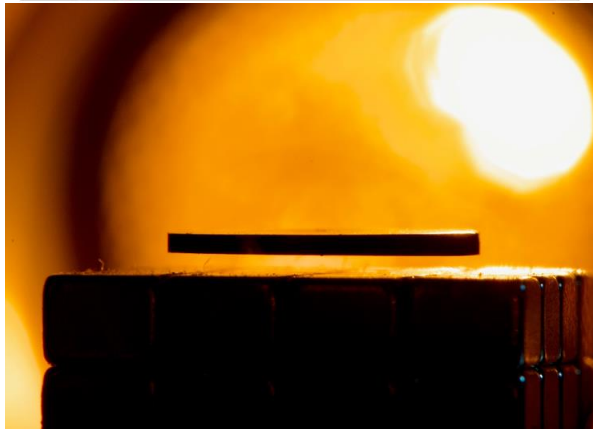
- Controlling motional heating

Force detection

- Dark matter detector
- Interactions with single microscopic particles

Applications

- Accelerometers
- Single nanoparticle characterisation

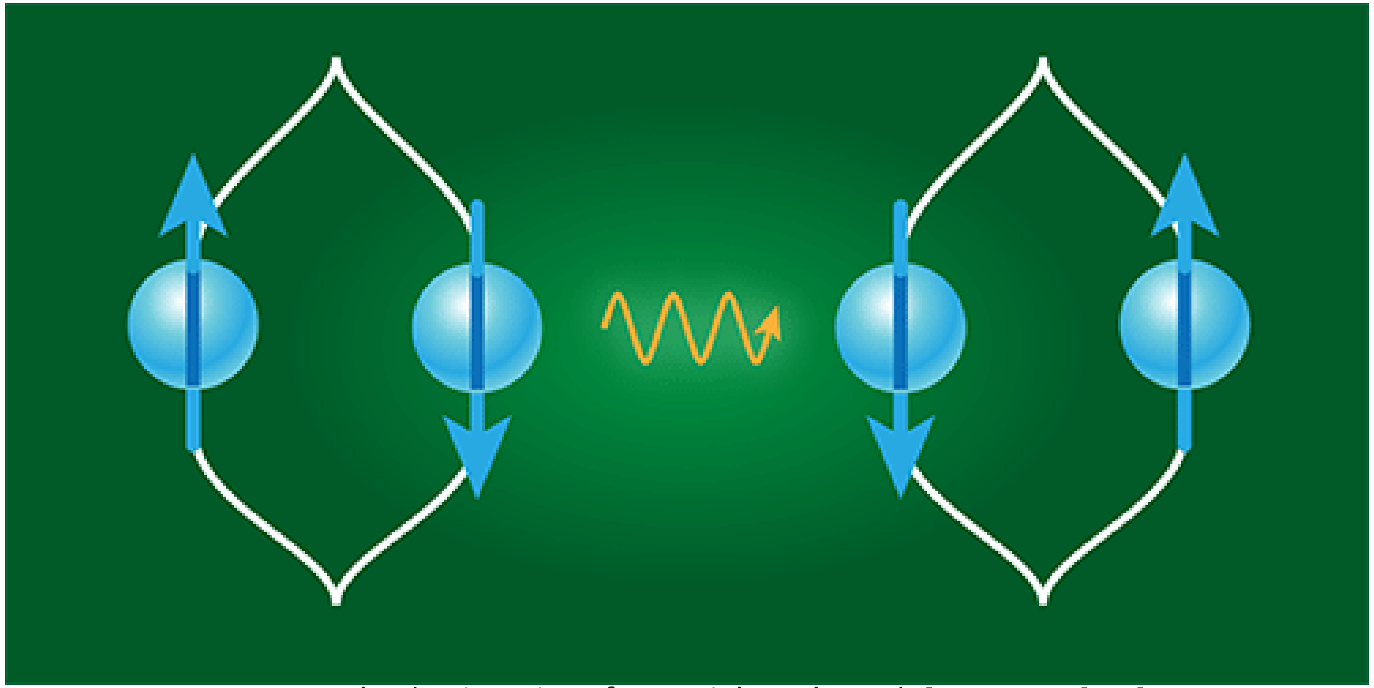
How might our techniques be useful?

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

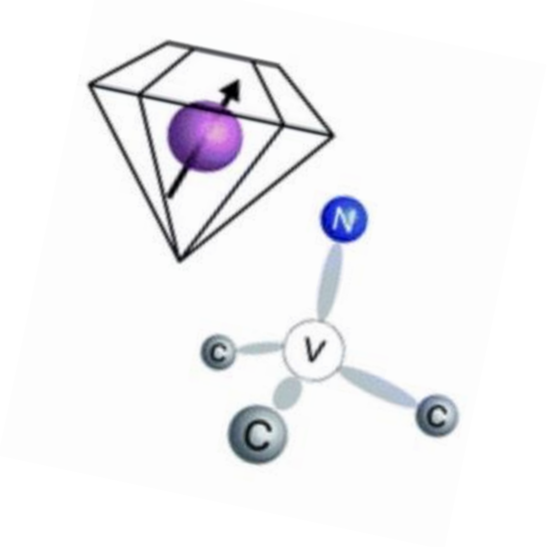
Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017

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



G. W. Morley/University of Warwick and APS/**Alan Stonebraker**

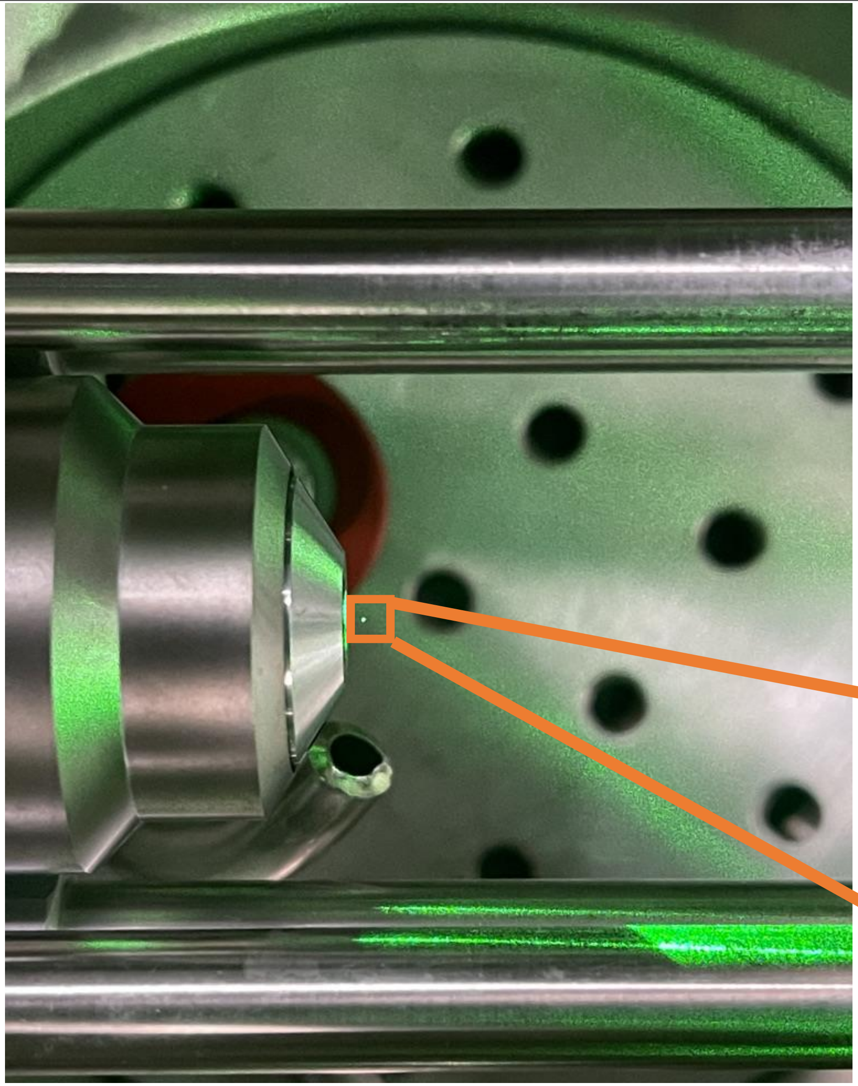
B field



Probable requirements

- Ultra-high vacuum and low environmental temperatures
- Low internal temperatures
  - Refrigeration and **direct cooling**
- Cooling all motional degrees of freedom
  - **Coherent scattering** and feedback – 6 DOF cooling
  - **Sympathetic cooling** – all degrees of freedom
- Detailed understanding mass, charge, temperature, shape and material
  - **Characterisation**
  - **Calibration of fields, forces and charge**

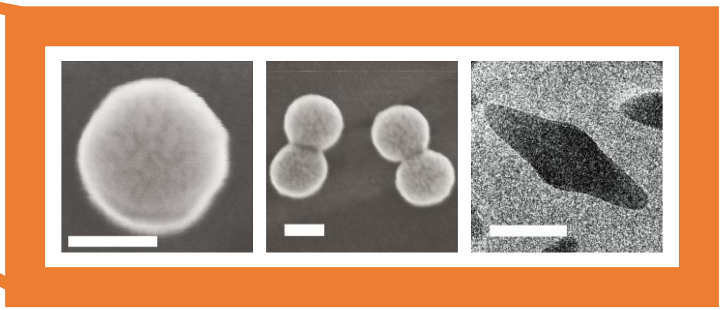
Levitated optomechanics



Cooling and trapping particles levitated in vacuum

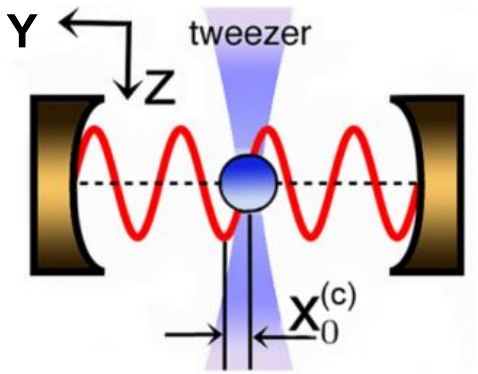
High Q oscillators sensitive to external forces

6 important motional degrees of freedom

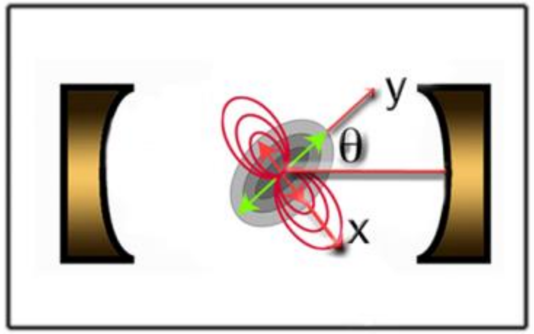


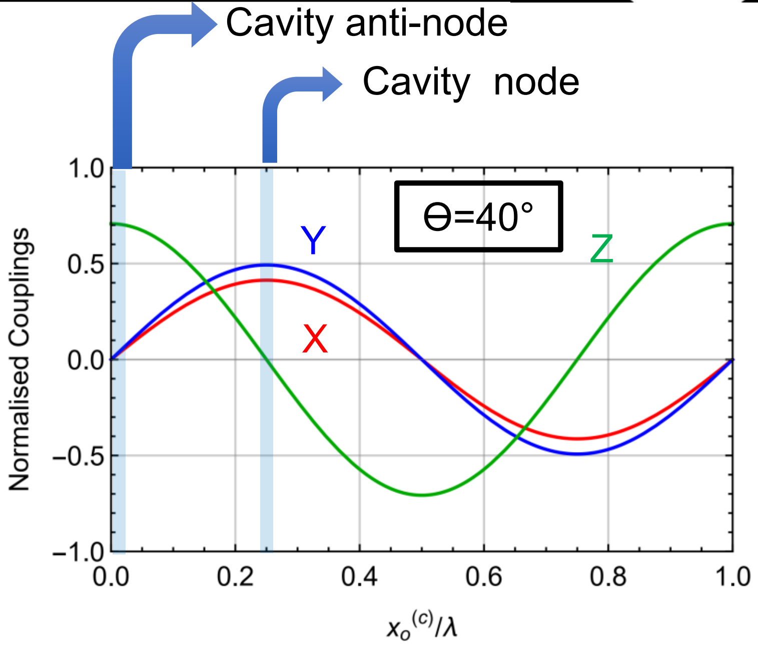
Cooling by coherent scattering

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

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

Interference term

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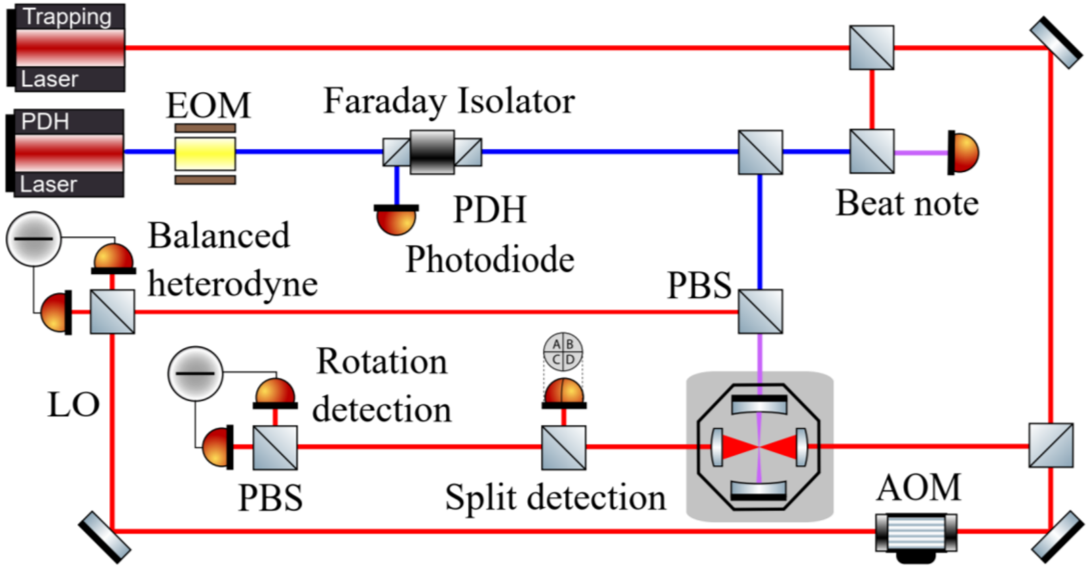
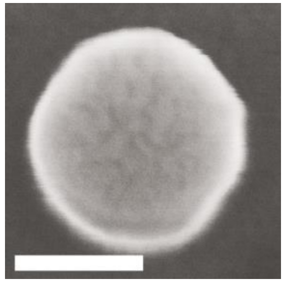
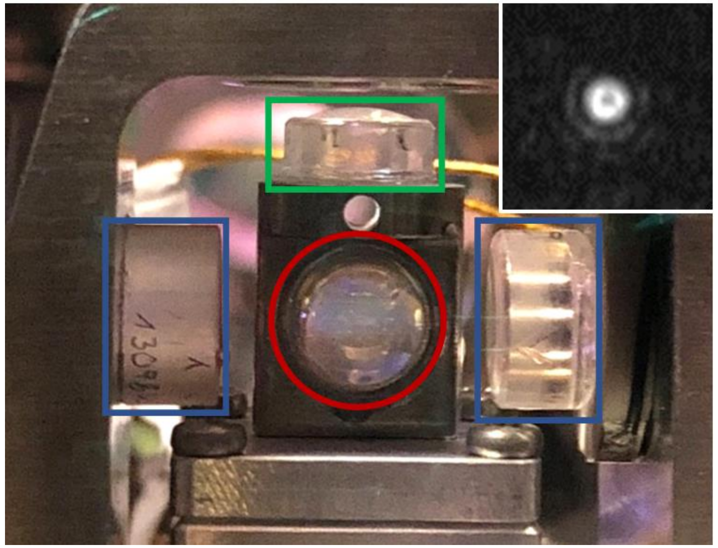
Engineering and Physical Sciences Research Council

Experimental setup



Monolithic tweezer assembly





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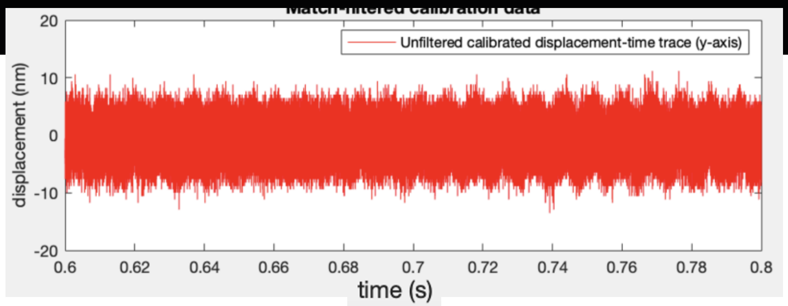
<u>Silica nanoparticle</u>

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

<u>Cavity parameters</u>

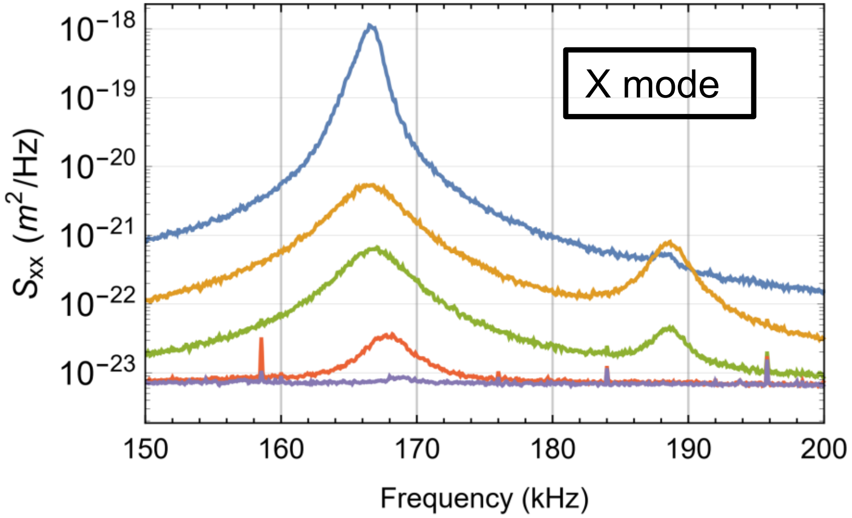
Lcav=12.23 ± 0.02 mm
κ/2π=198 ± 1 kHz
Finesse ~ 31000

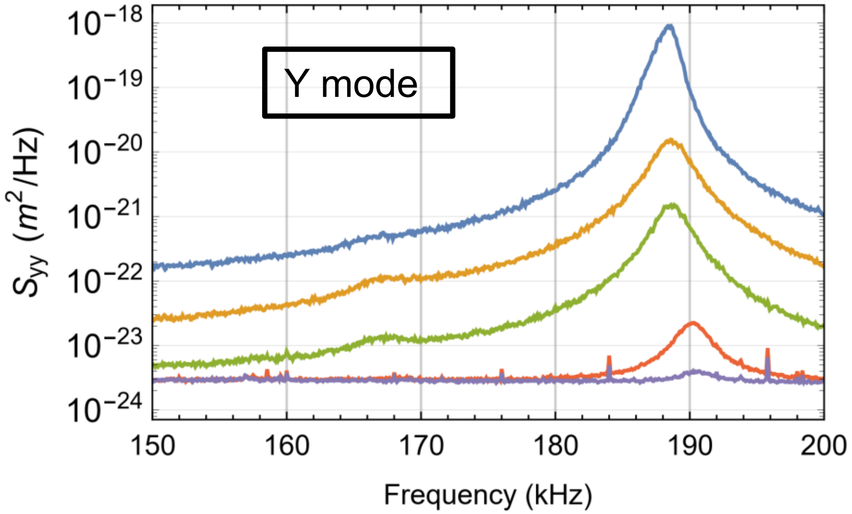
Temperature of r=60 nm SiO_2 nanosphere



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

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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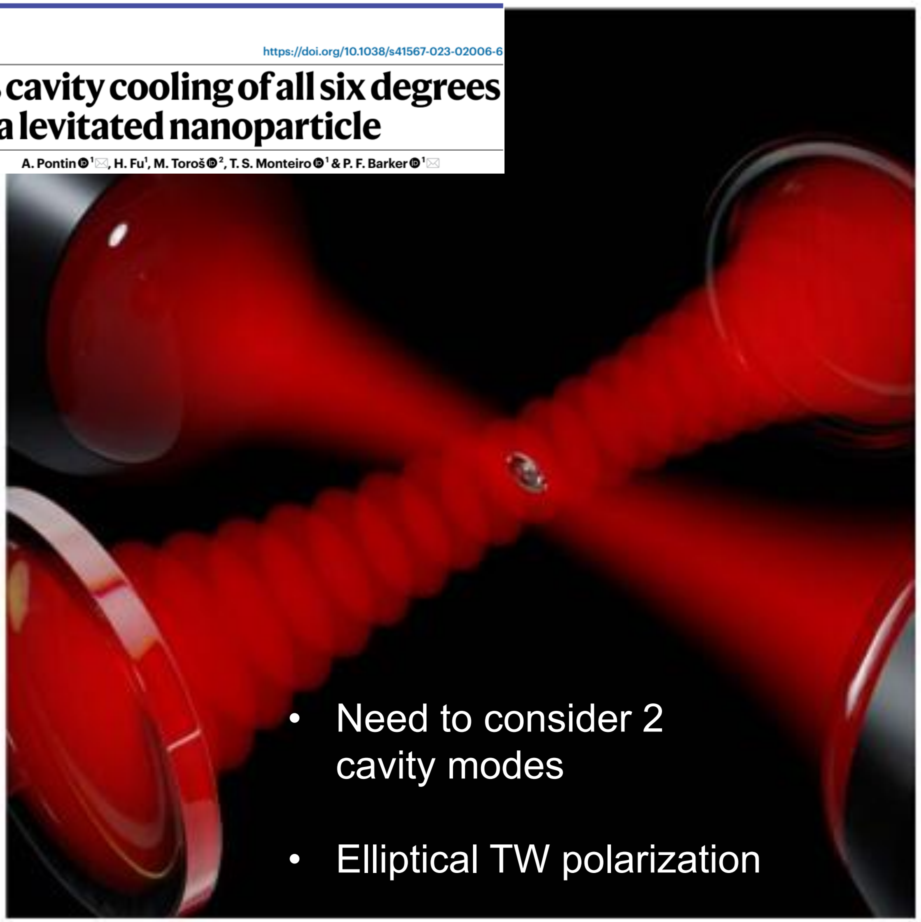
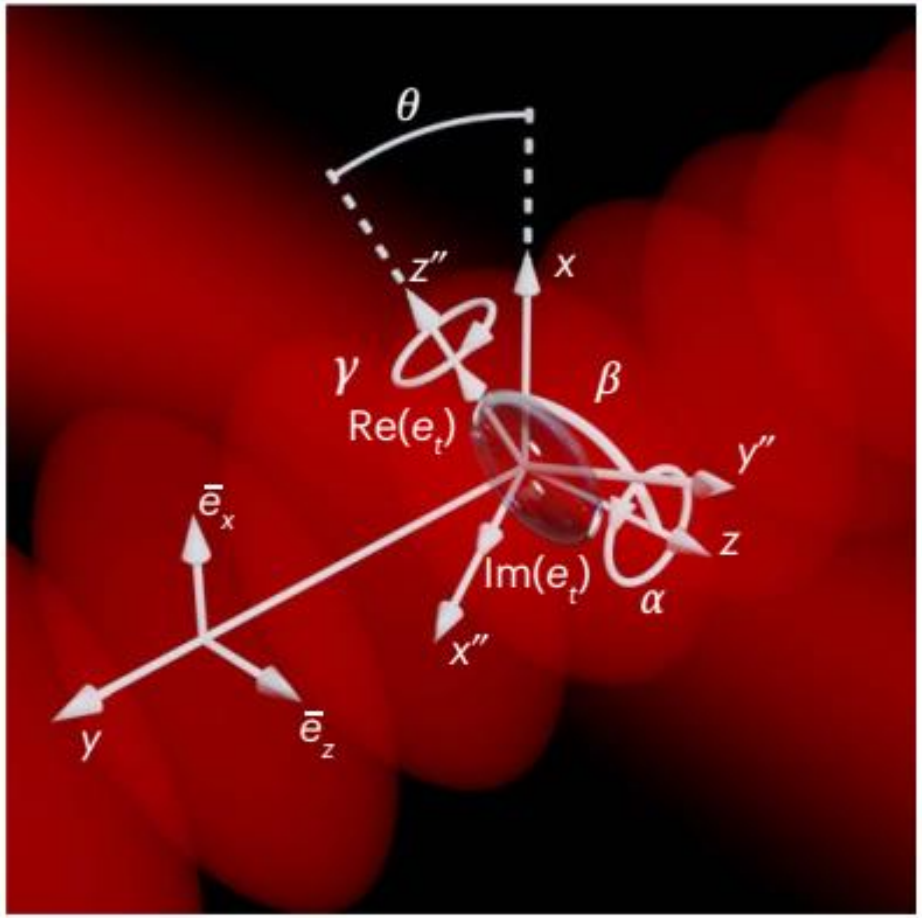
UCL

Cooling of non-spherical nanoparticles

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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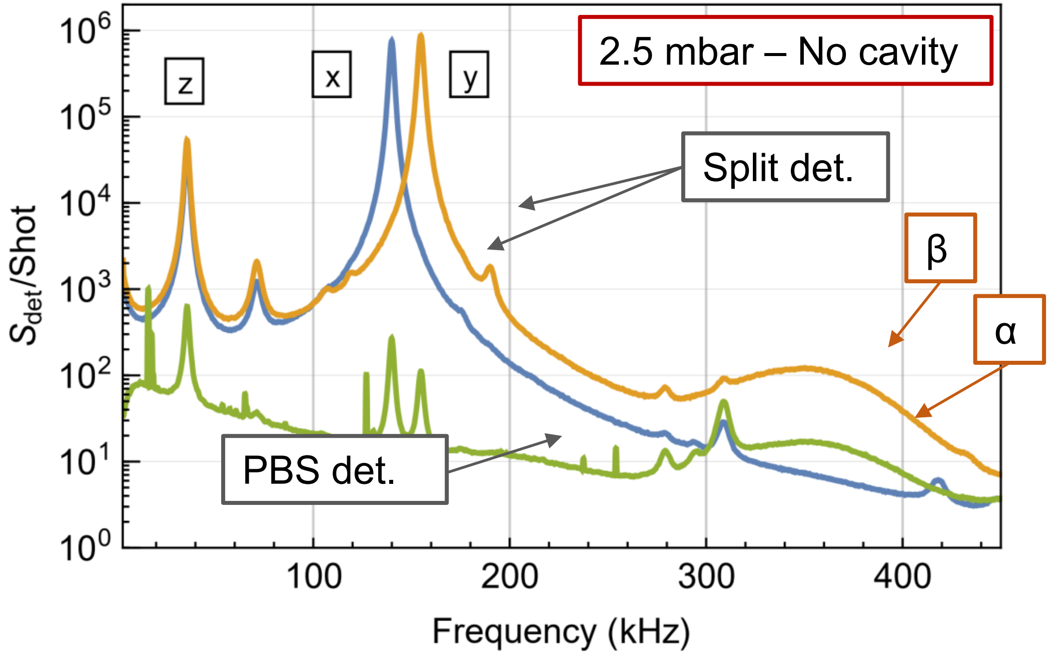
Power spectra



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

$$\omega_{\pm} = \sqrt{(\omega_\alpha^2 + \omega_\beta^2 + \omega_c^2 \pm Q)/2}$$

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

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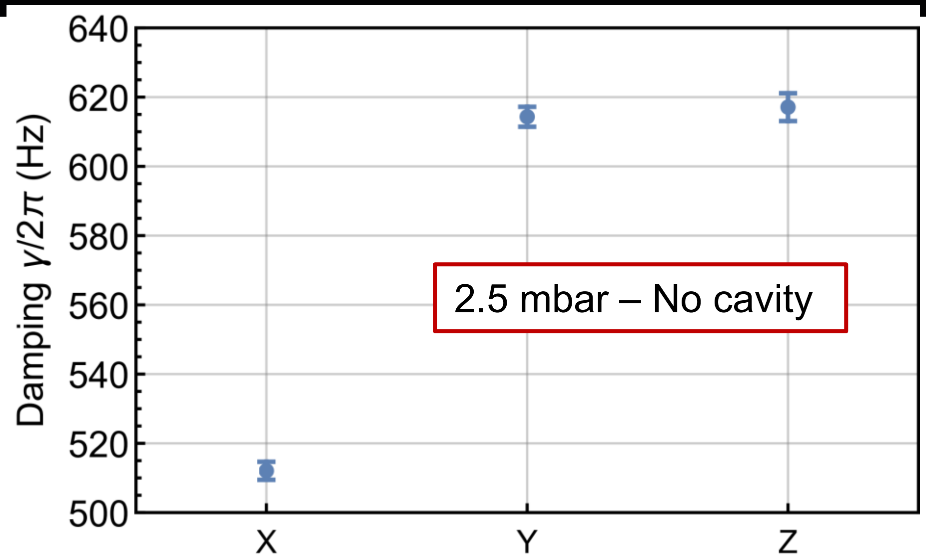
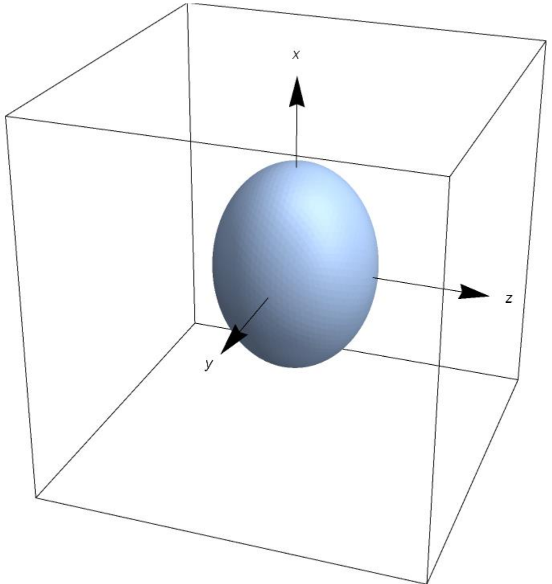
Particle geometry



$$\frac{\gamma_y}{\gamma_x} = 1.200 \pm 0.008$$
$$\frac{\gamma_z}{\gamma_x} = 1.205 \pm 0.01$$

Aspect ratio
~ 1.30 Ellipsoid



Most likely geometry: Ellipsoid

$$R_1 = 83.7 \pm 0.5\,\mathrm{nm}$$
$$R_2 = 84.2 \pm 0.9\,\mathrm{nm}$$
$$R_3 = 109 \pm 2\,\mathrm{nm}$$

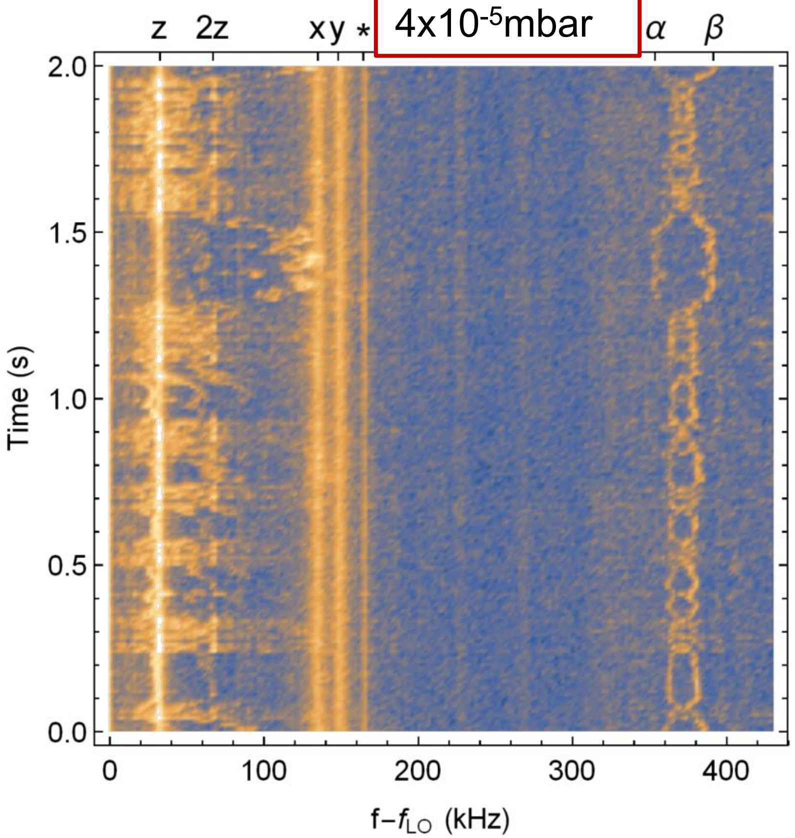
Susceptibility tensor

$$\chi = \mathrm{Diag}(0.72, 0.72, 0.78)$$

$$m = (5.95 \pm 0.13) \times 10^{-18}\,\mathrm{Kg}$$

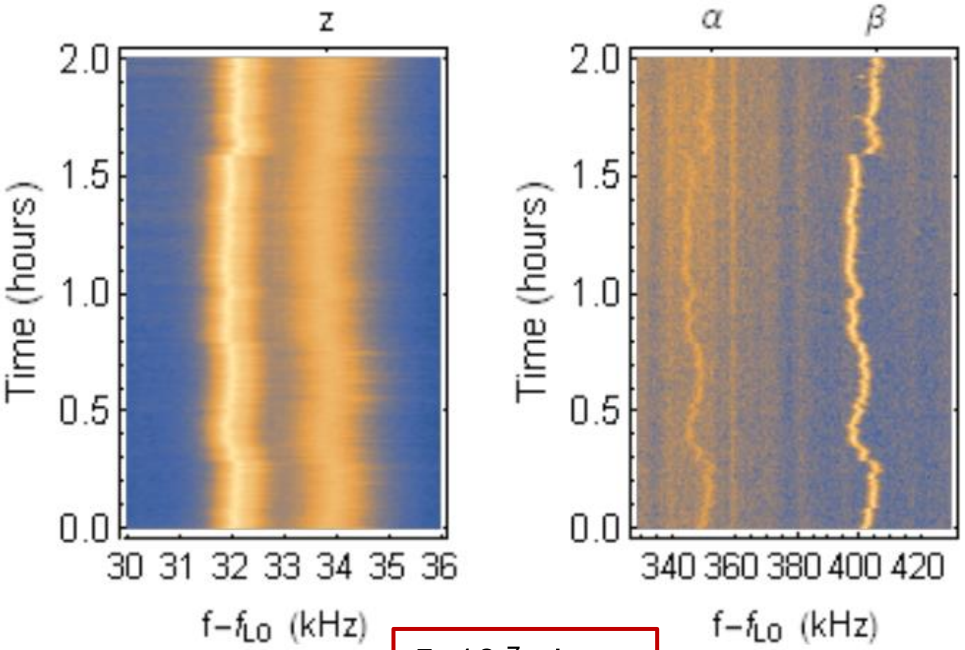
Trento LISA group: A.Cavalleri et.al., Phys.Lett.A **374** 3365 (2010)

Spectral features with time



Very different dynamics at the lowest pressure

Consistent with cooling of γ



5x10^{-7}mbar

This transition is very well reproduced in numerical simulation

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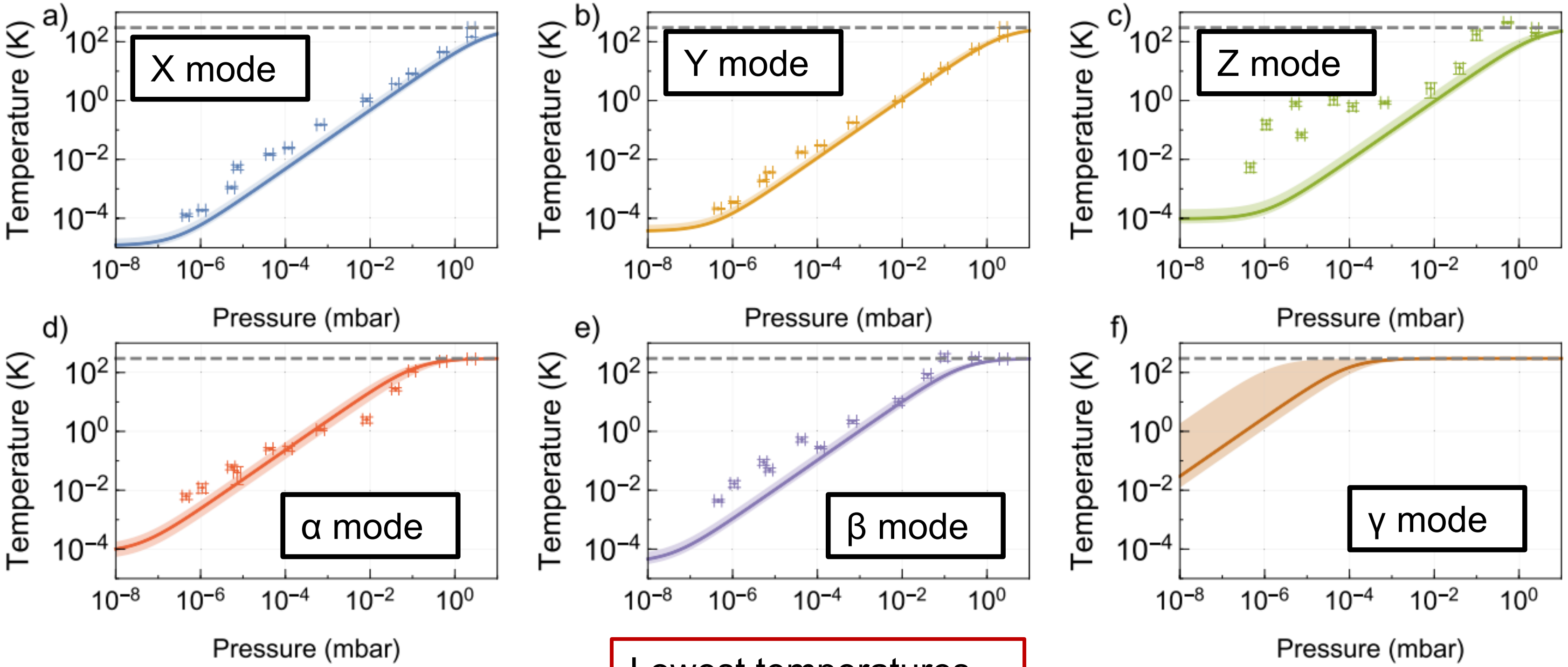
Research Council

Comparison with analytical estimates



Lowest temperatures @ 4x10^{-7}mbar

Mean occupation

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

Cooling all 6 degrees of freedom with a single field

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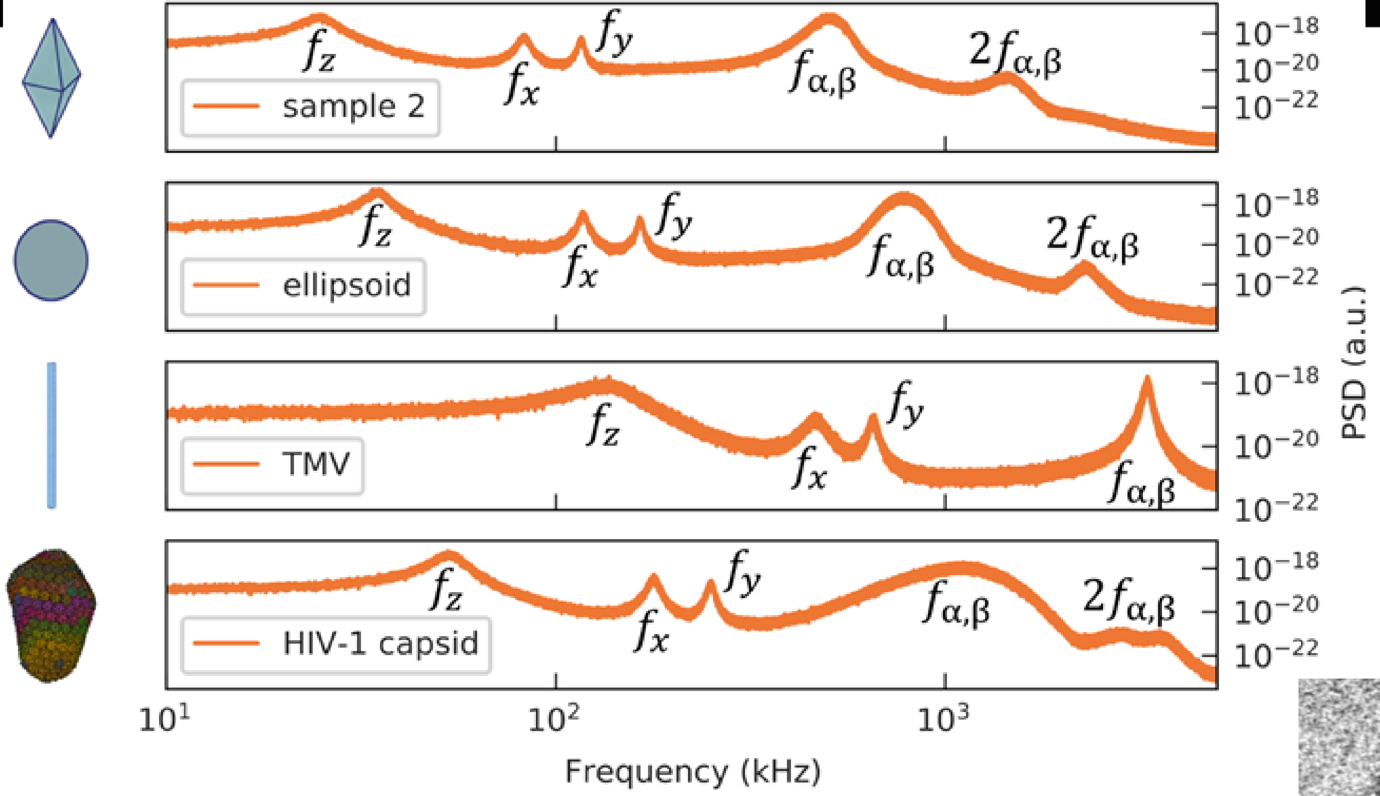
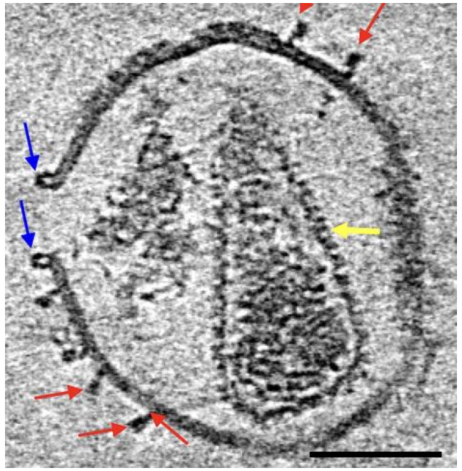
Characterisation

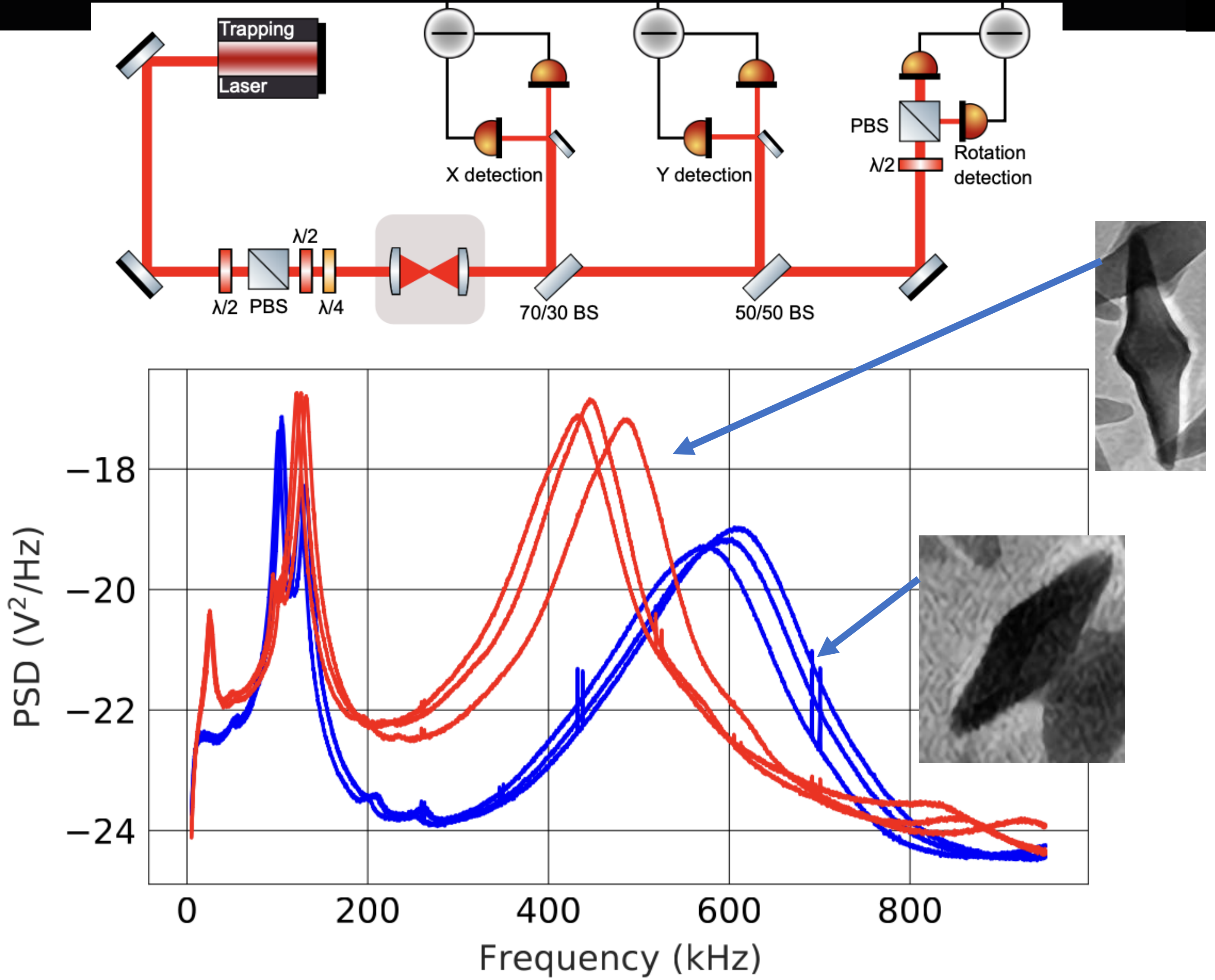




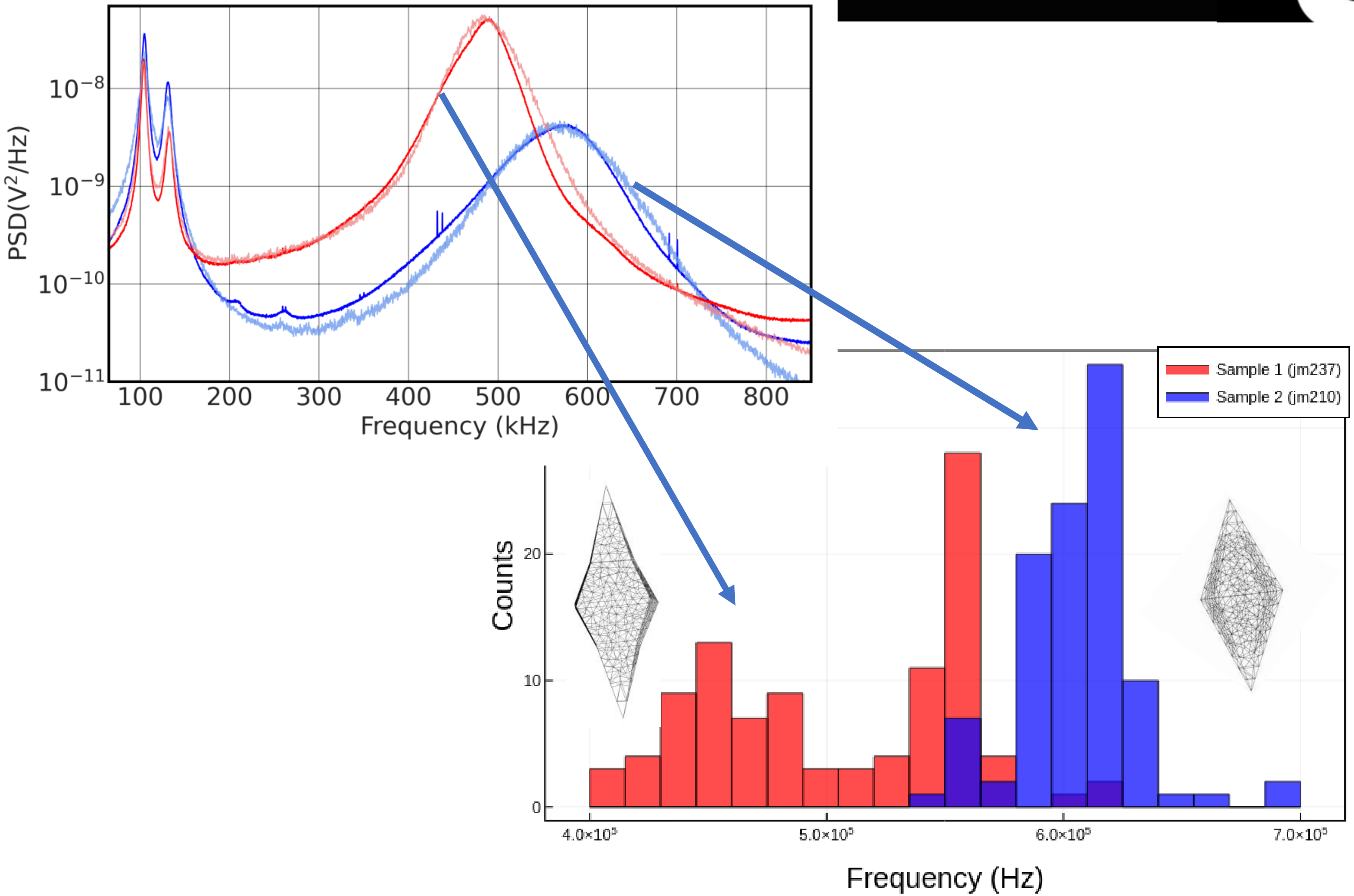
Can we can differentiate between particles with different shapes?

Can we use to identify any shape?

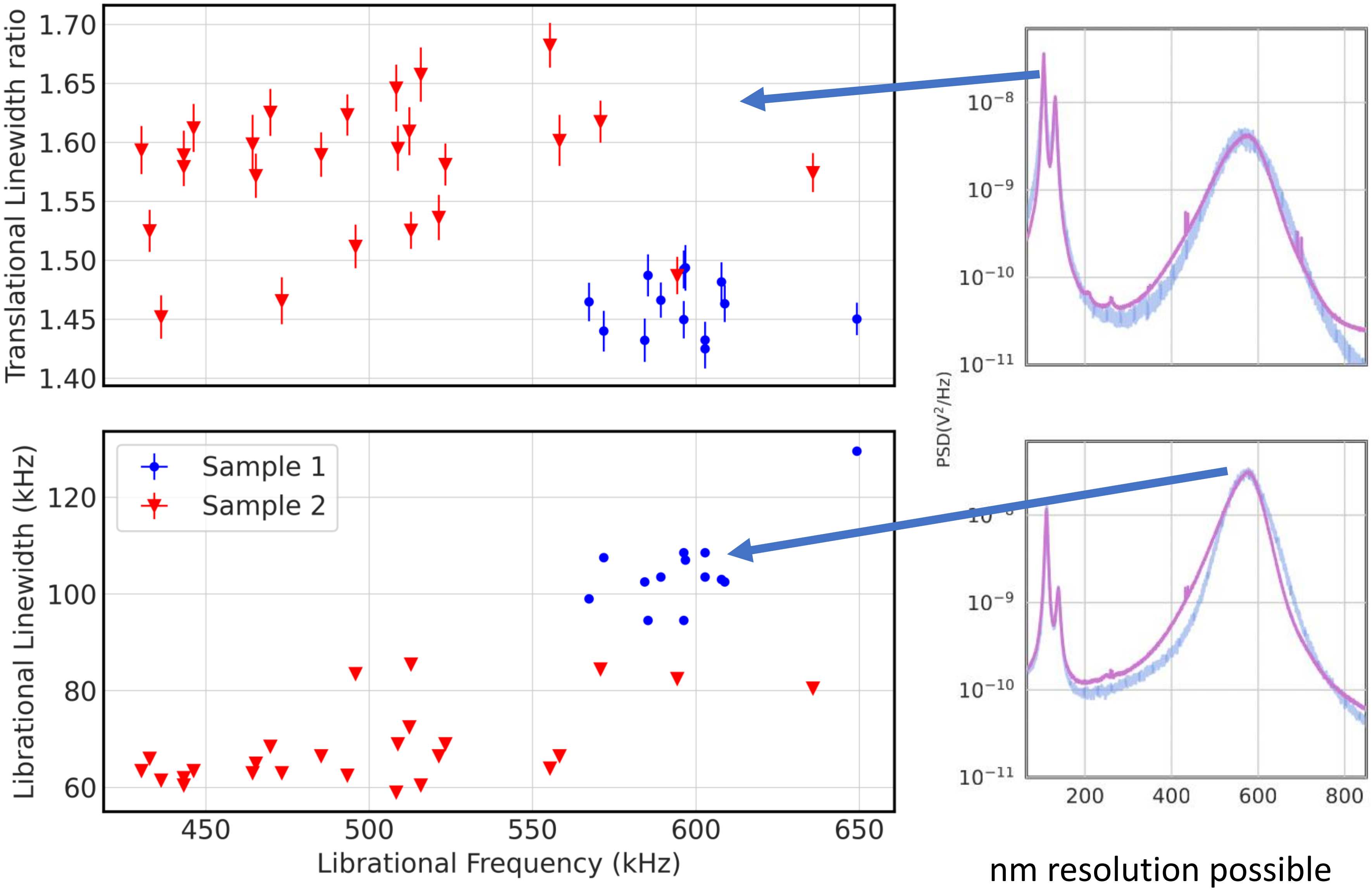
Characterisation



Levitodynamic spectroscopy

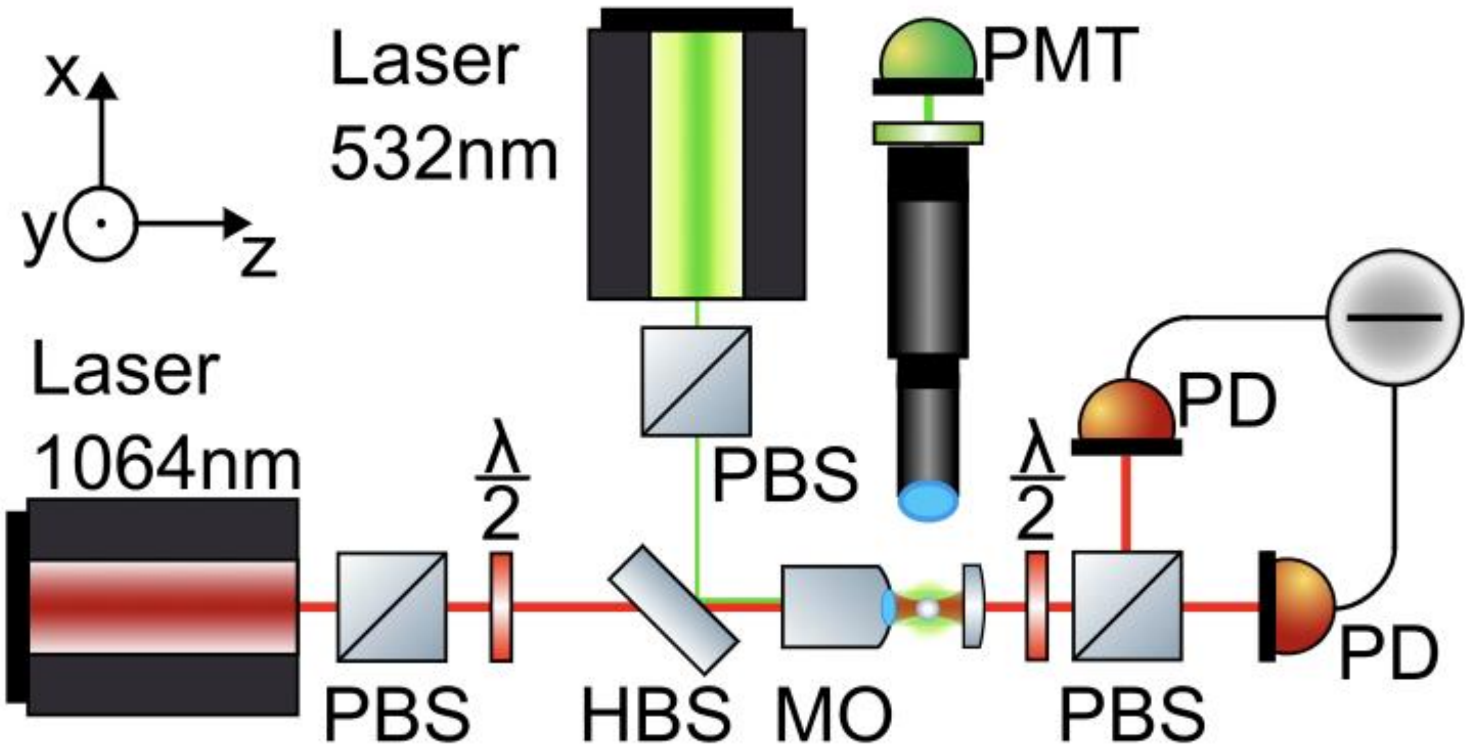


Levitodynamic spectroscopy

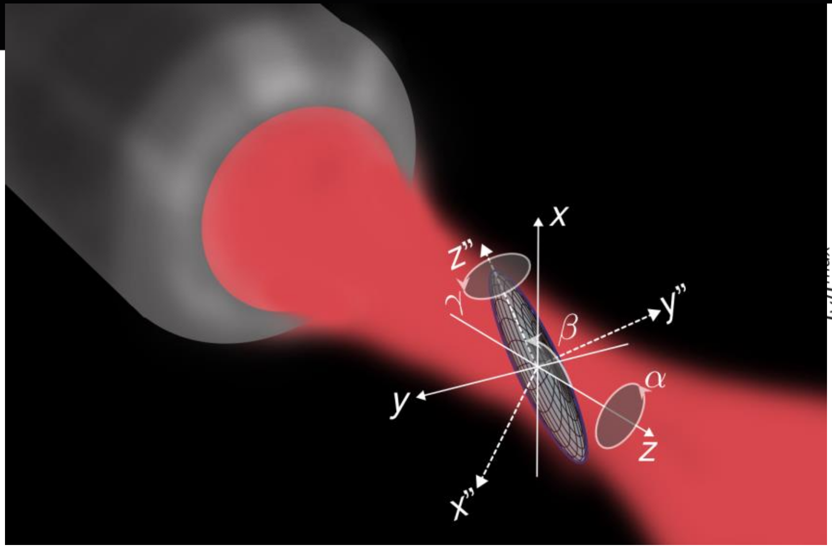


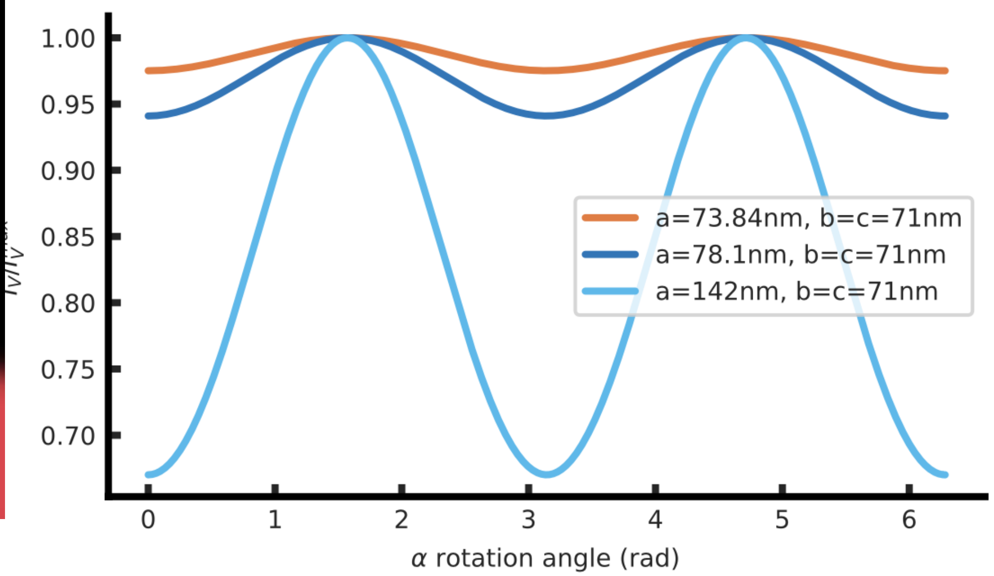
nm resolution possible

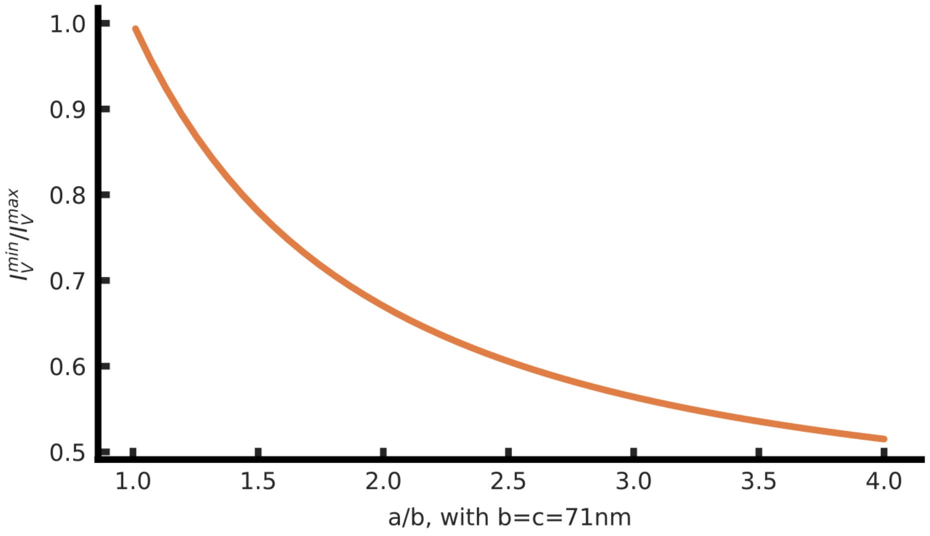
Angular scattering



Ellipsoid







Measurement of single nanoparticle anisotropy by laser induced optical alignment and Rayleigh scattering for determining particle morphology

Cite as: Appl. Phys. Lett. **121**, 221102 (2022); doi: 10.1063/5.0128606
Submitted: 29 September 2022 · Accepted: 11 November 2022 ·
Published Online: 28 November 2022

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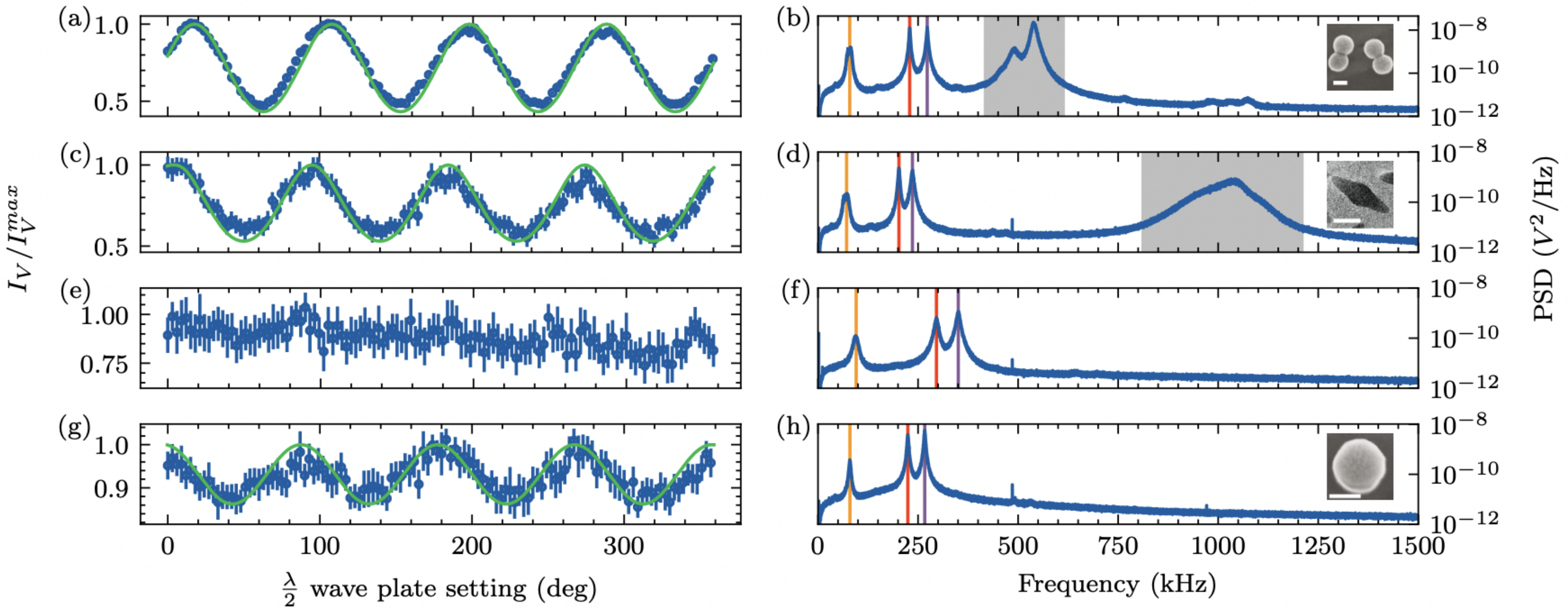
Markus Rademacher,[1] Jonathan Gosling,[1] Antonio Pontin,[1] Marko Toroš,[2] Jence T. Mulder,[3] Arjan J. Houtepen,[3] and P. F. Barker[1,a)]

Single nanoparticle characterisation



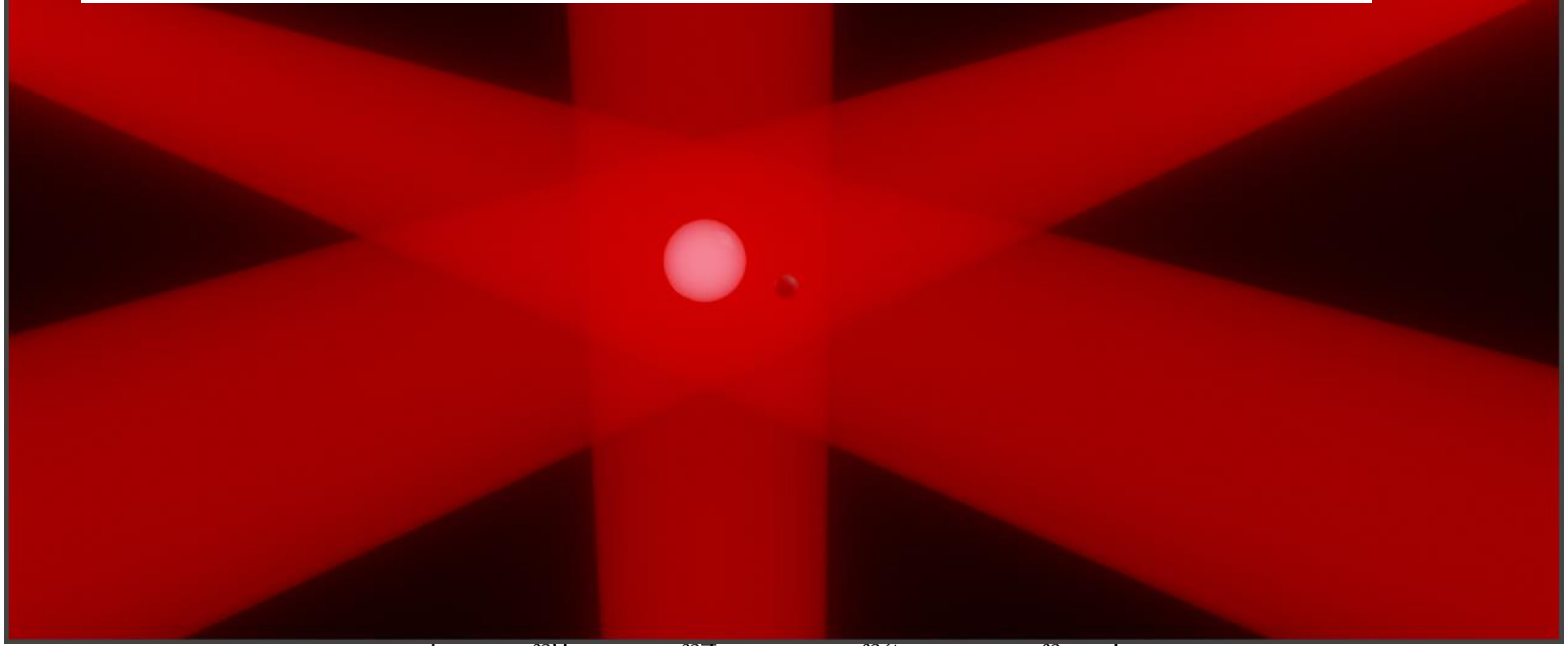
Comments

- Can cool using coherent scattering and feedback
- Motional decoherence from light scattering and internal heating challenging
- What more general technique could we use to cool and control?

Cooling via collisions

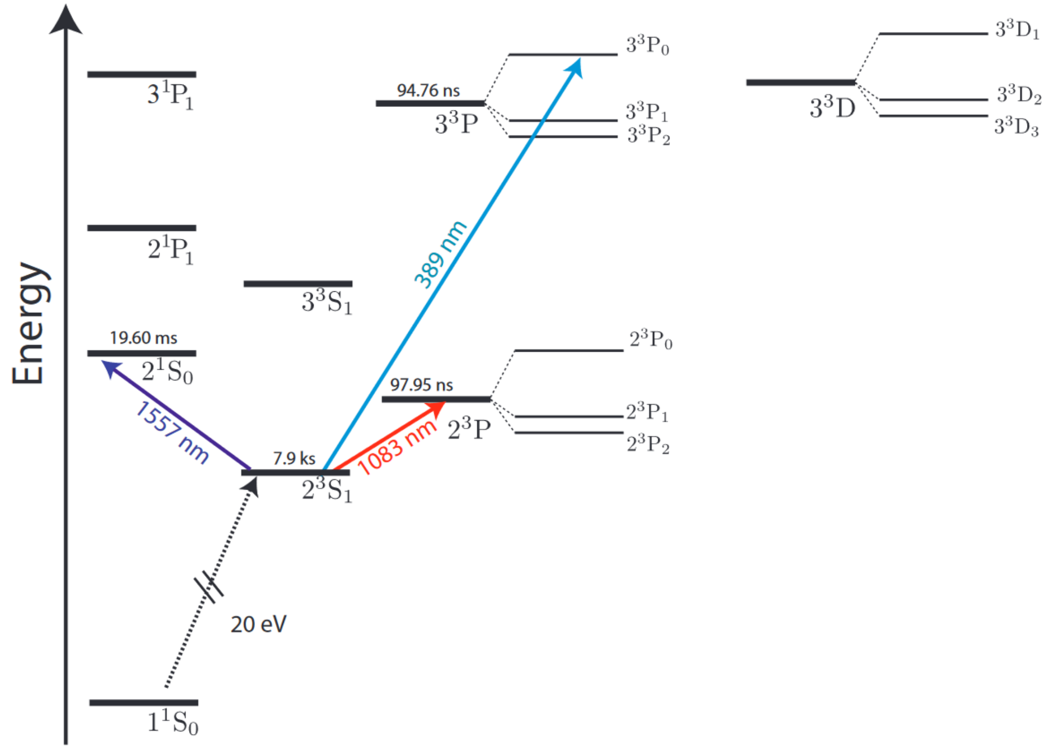
A levitated atom-nanosphere hybrid quantum system

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



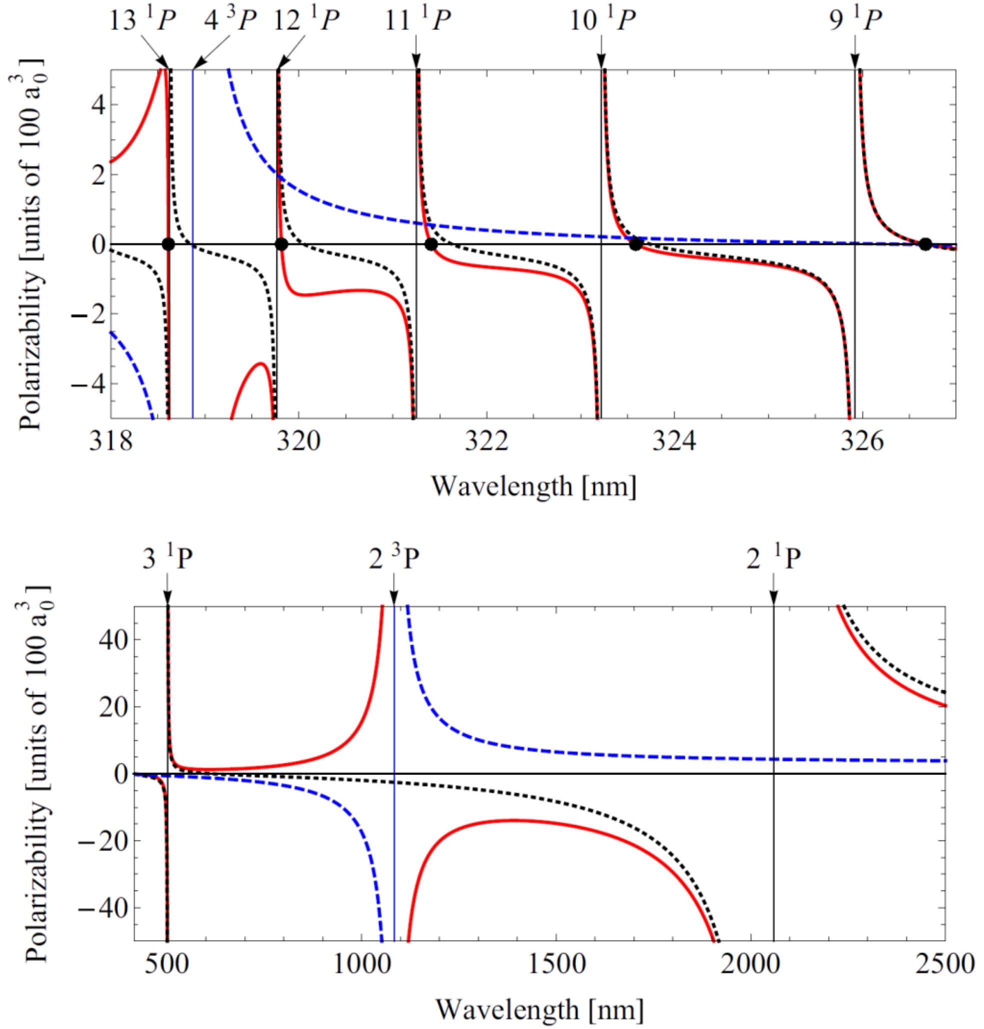
$$C = a^3(n^2+1)/(n^2+2)$$

Cold atoms - He*



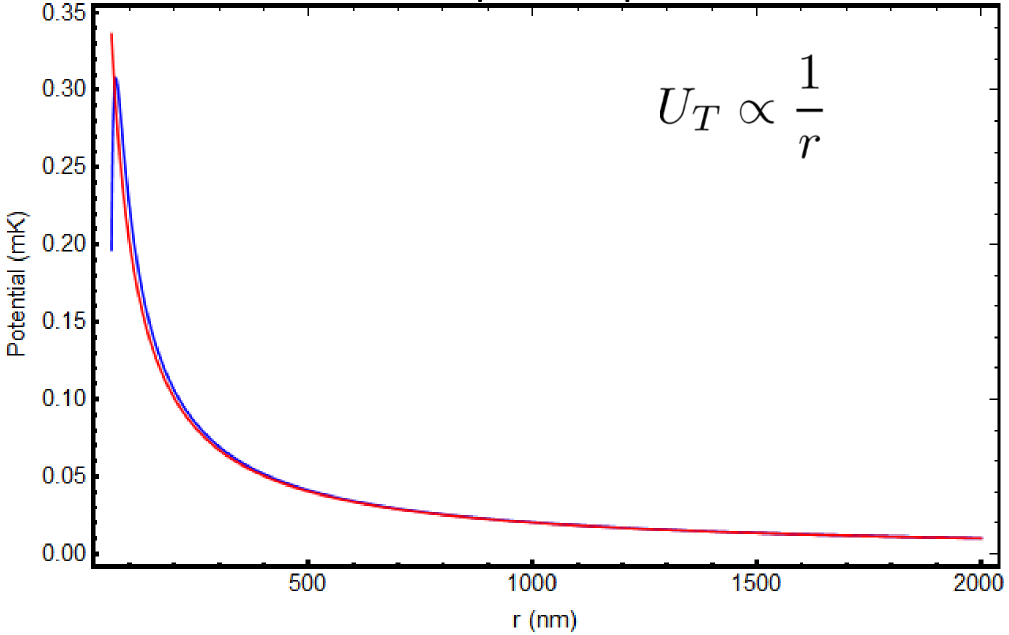
Magic wavelengths for the 2 ³S → 2 ¹S transition in helium

R. P. M. J. W. Notermans,[1] R. J. Rengelink,[1] K. A. H. van Leeuwen,[2] and W. Vassen[1,*]



Repulsive potential

Very long-range Coulomb like repulsive potential

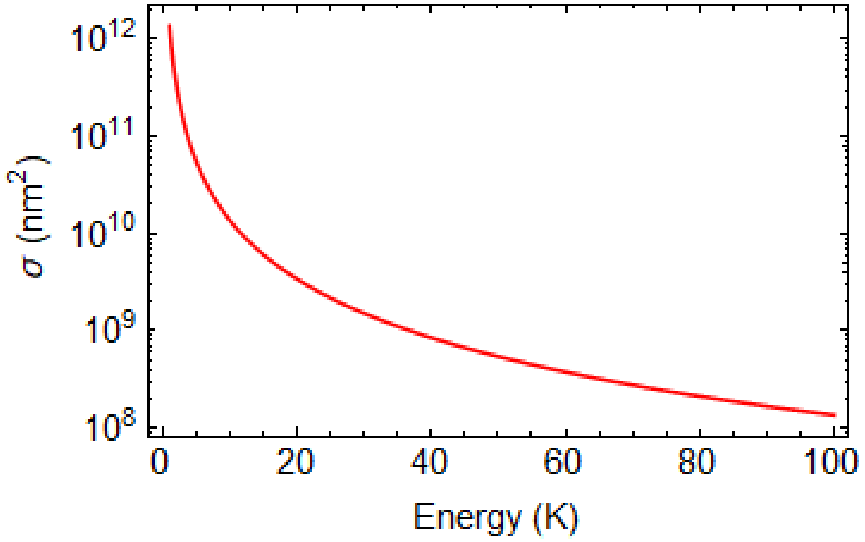


Cross section is 6 orders larger than physical cross-section

$$I_3 = I_0 \left[3 + \frac{6C}{r^6} + \frac{2C^2k^2}{r^4} + \frac{2C^2k^4}{r^2} + \frac{4Ck^2}{r} \right]$$

$$U_{Opt} \propto \alpha I_3$$

$$U_{CP} = -\frac{\hbar}{8\pi^2\epsilon_0} \sum_{l=0}^{\infty} (2l+1)(l+1) \times \frac{a^{2l+1}}{r^{2l+4}} \int_0^{\infty} d\zeta \alpha(i\zeta) \frac{\epsilon(i\zeta) - 1}{\epsilon(i\zeta) + [(l+1)/l]}$$



Sympathetic cooling

Damping rate

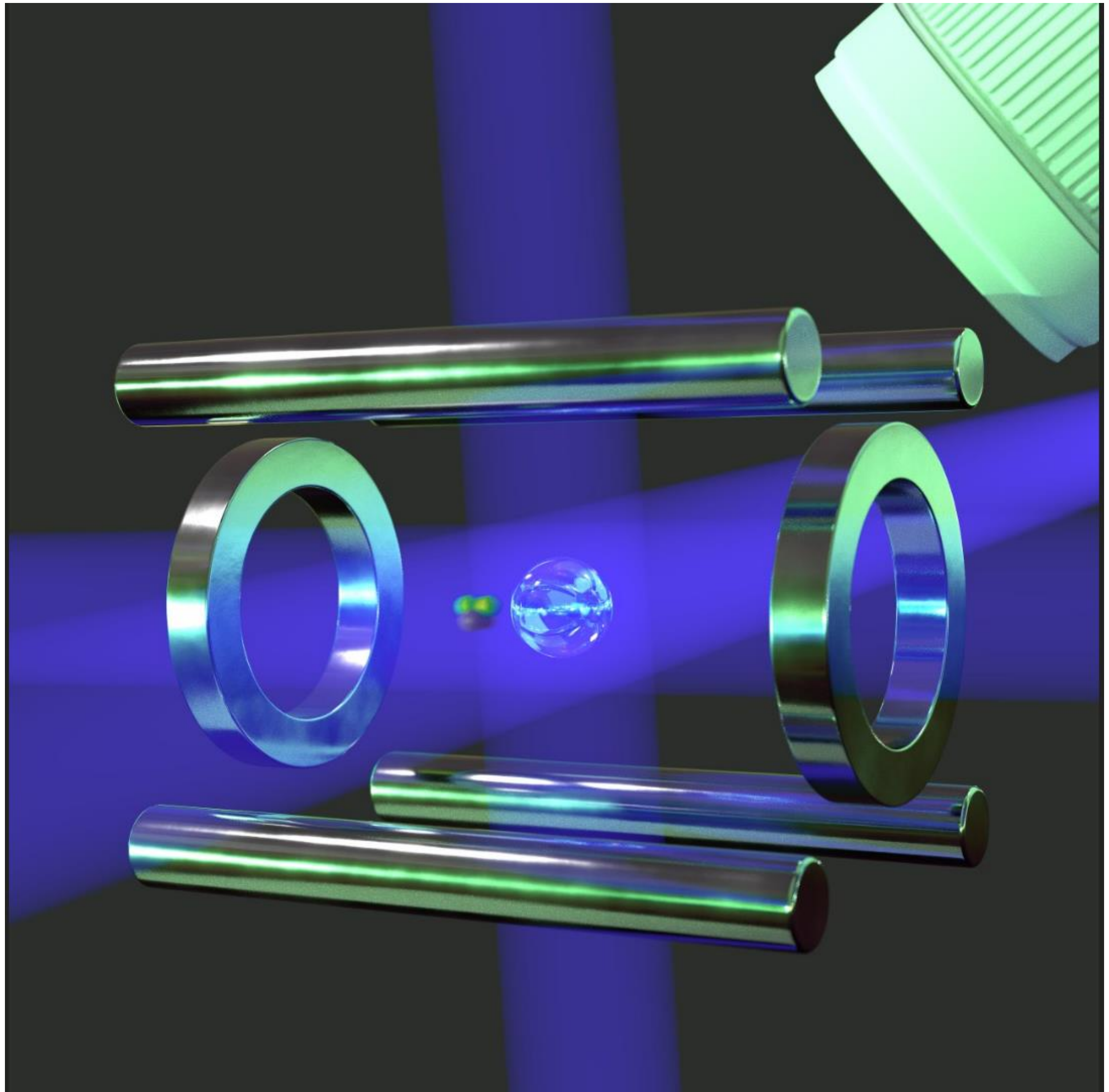
$$\gamma_C = \frac{\xi}{\alpha_c} n \sigma v_{th}$$

$$\xi = \frac{4 m_n m_a}{(m_n + m_a)^2}$$

10 orders difference in mass BUT cooling rates in excess of 10 kHz

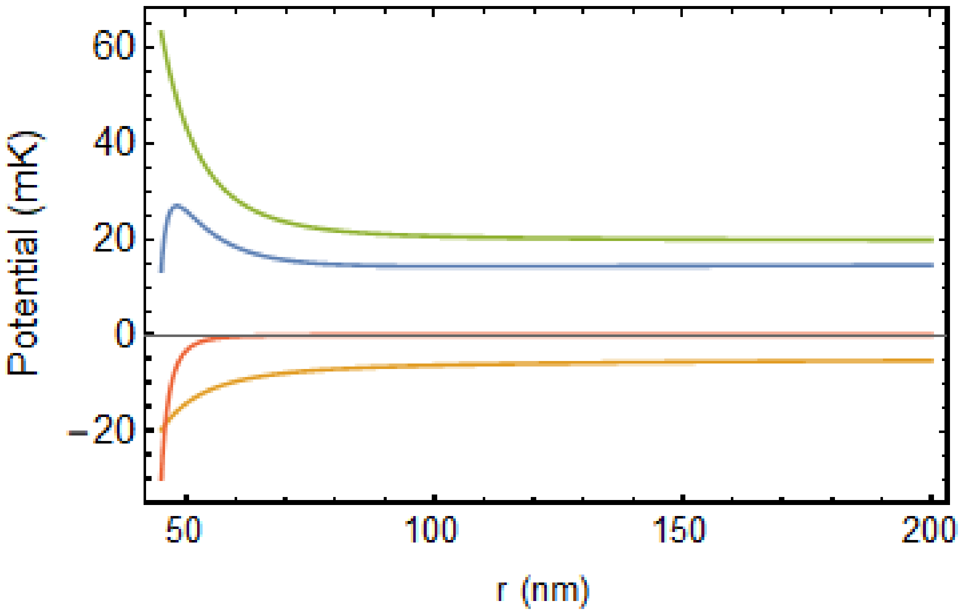
Primary source of heating due to voltage noise 10 nv/Sqrt[Hz]

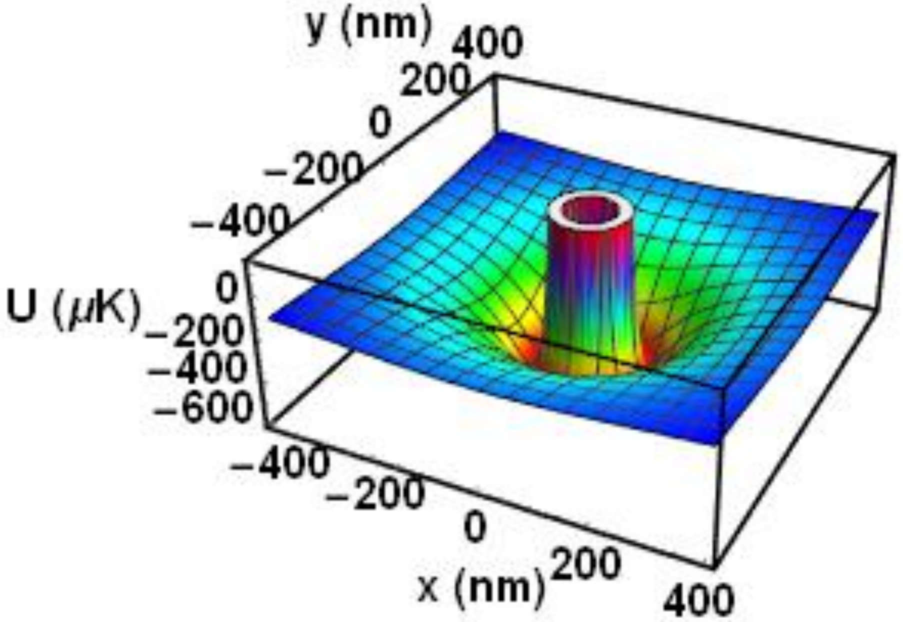
Temps below 10 μK appear feasible



Bound states

Combining repulsive and attractive potentials





$$U_0(r) = 3(U_R - U_A) + 6\frac{U_R C_R^2 - U_A C_A^2}{r^6} + 2\frac{U_R C_R^2 k_R^2 - U_A C_A^2 k_A^2}{r^4} + 2\frac{U_R C_R k_R^4 - U_A C_A k_A^4}{r^2} + 4\frac{U_R C_R k_R^2 - U_A C_A k_A^2}{r^1}$$

Casimir-Polder

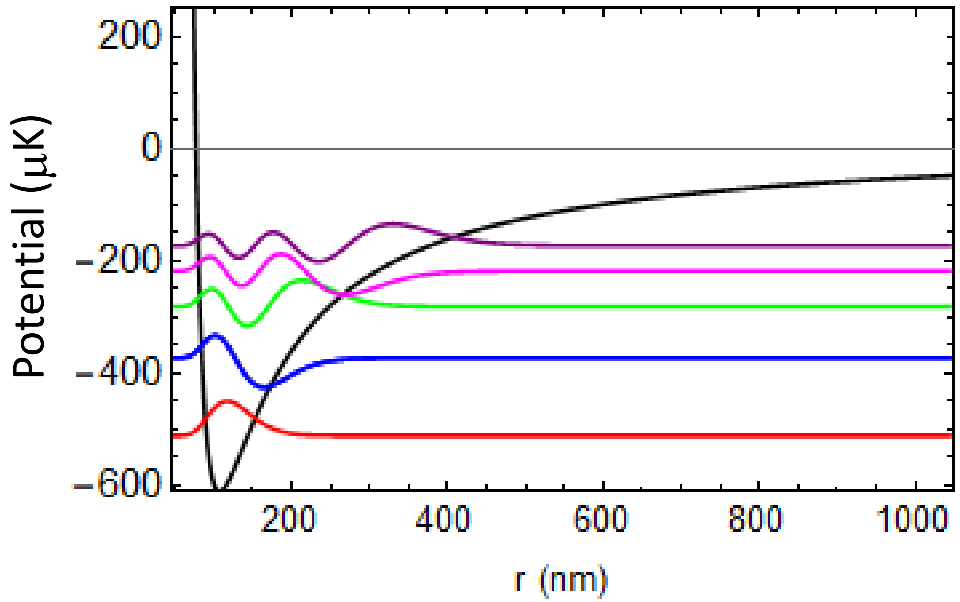
$$U_A \propto \frac{1}{r^6}$$

Optical

$$U_R \propto \frac{1}{r}$$

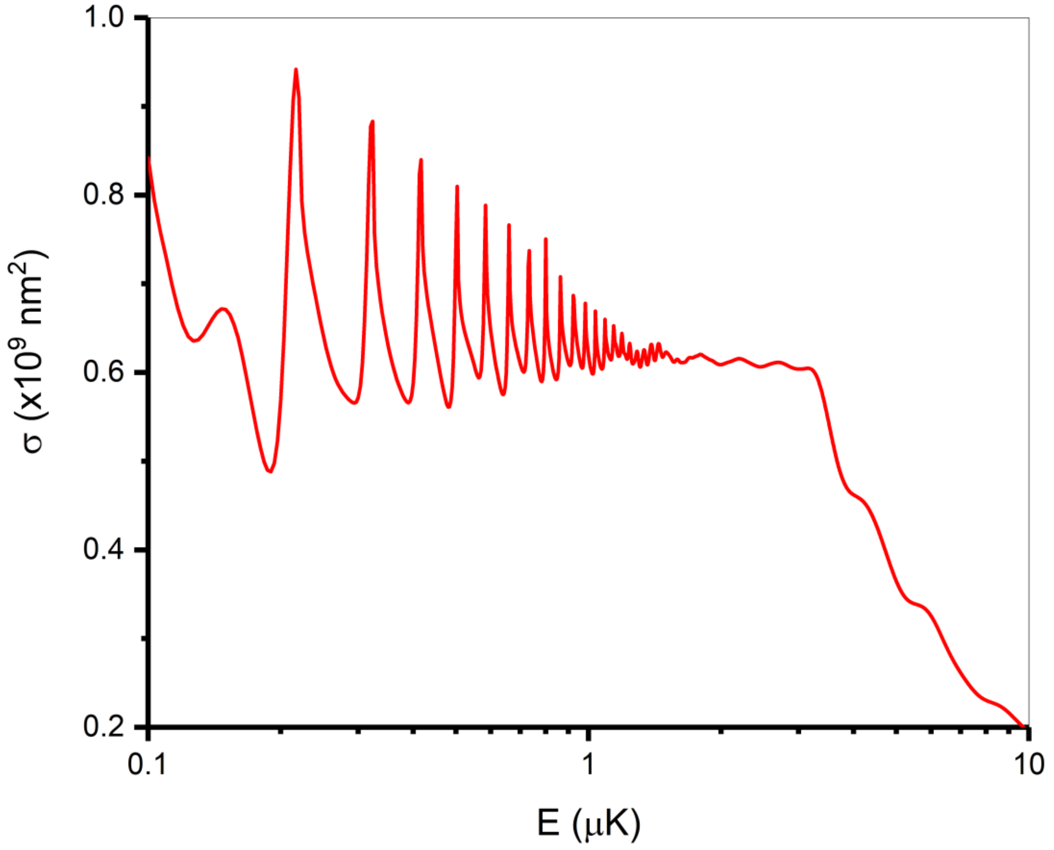
$$k_R^2 < k_A^2$$

Bound states



Tightly bound system with nanosphere-atom trap frequencies of 100 -1000 kHz

Lifetime limited by detuning from optical resonances and vibrational noise



Interferometry?

He* $J=1, M_z=-1,0,1$

Trap freq 100 Hz -10 KHz

Particle oscillation of a few microns is much less than optical field extension

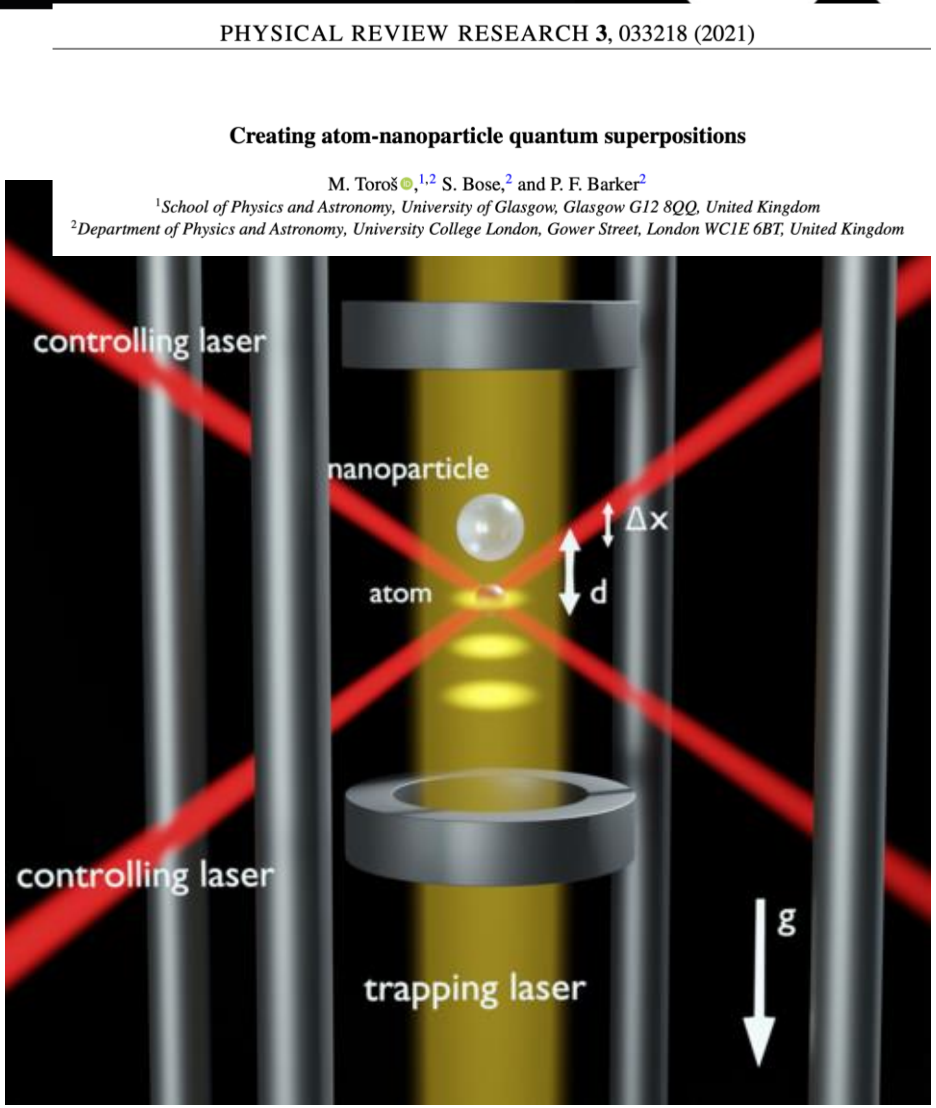
B gradient field for transverse S-G

Creation superposition of $M_z = 1,-1$

Allow to fall in trap

S-G creates COM superposition

Close interferometer and measure phase change


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

Creating atom-nanoparticle quantum superpositions

M. Toroš,[1,2] S. Bose,[2] and P. F. Barker[2]

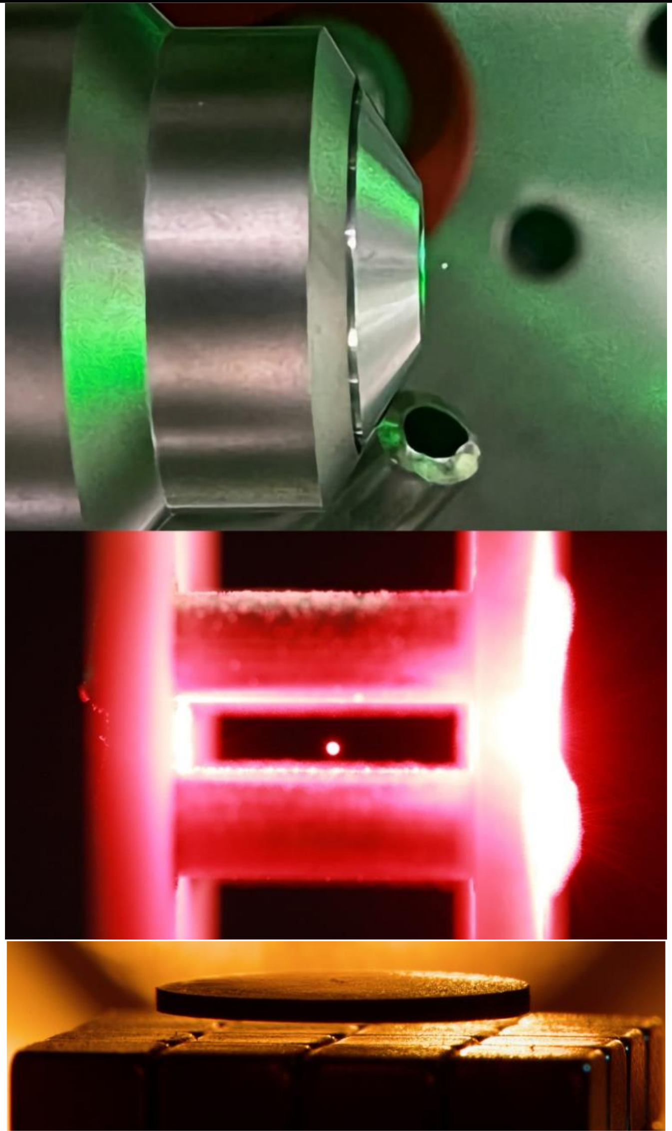
[1]*School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

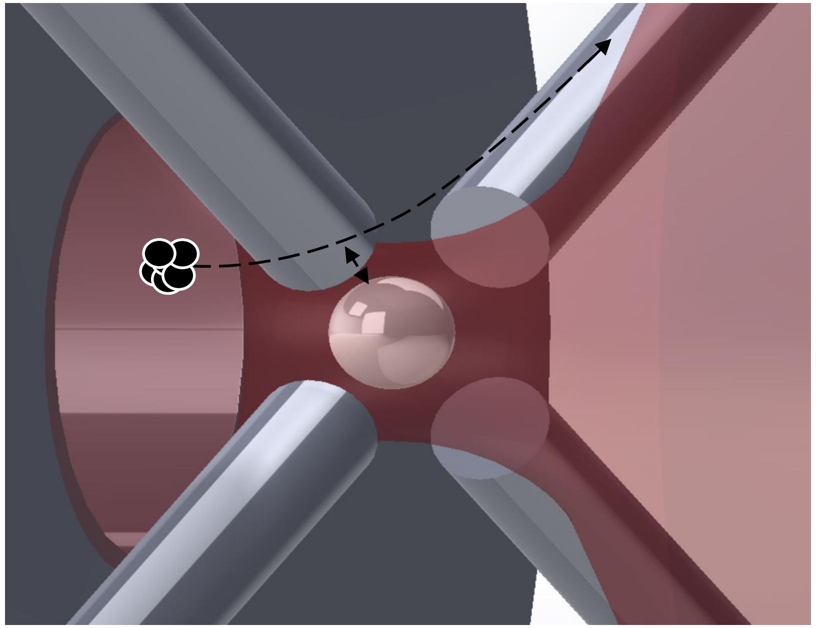
[2]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*

Comments

- hybrid quantum system
- highly tunable-system with the potential to use different cold atomic species (Cs)
- sympathetic cooling – center-of-mass motion, internal ?
- can turn off cooling rapidly
- creation of tightly bound atoms with spin
- could we replace NV for SG or other nanoparticle interferometry
- can we cool rotational motion and internal motion

Impulsive force detection

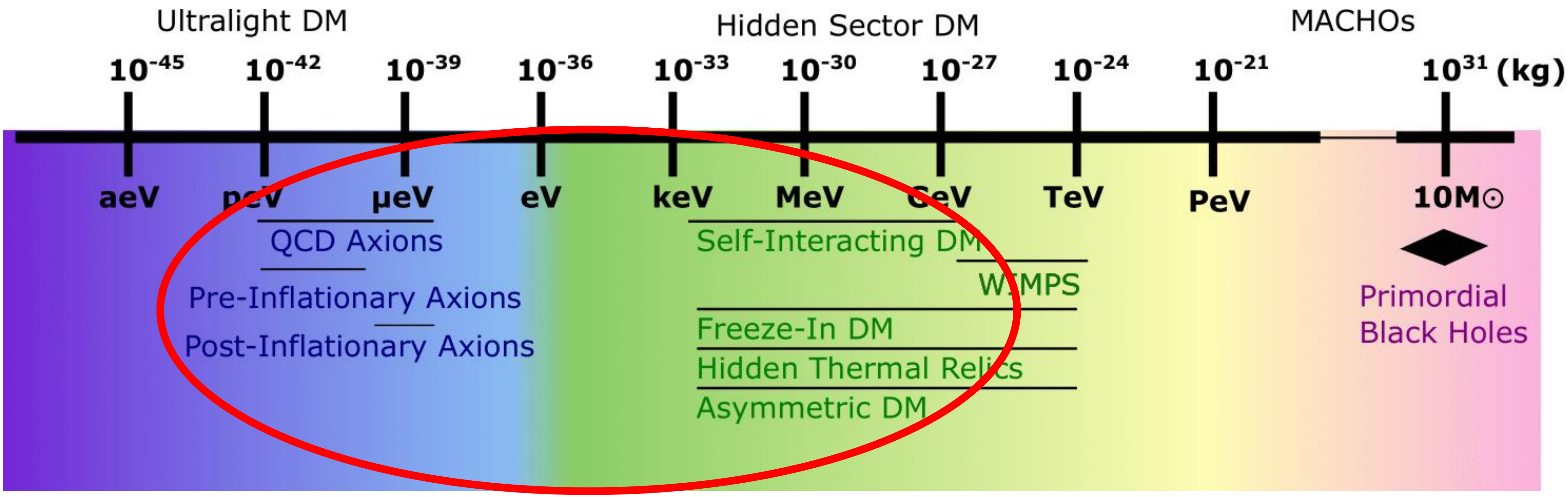




Collisions with:

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

Dark matter landscape



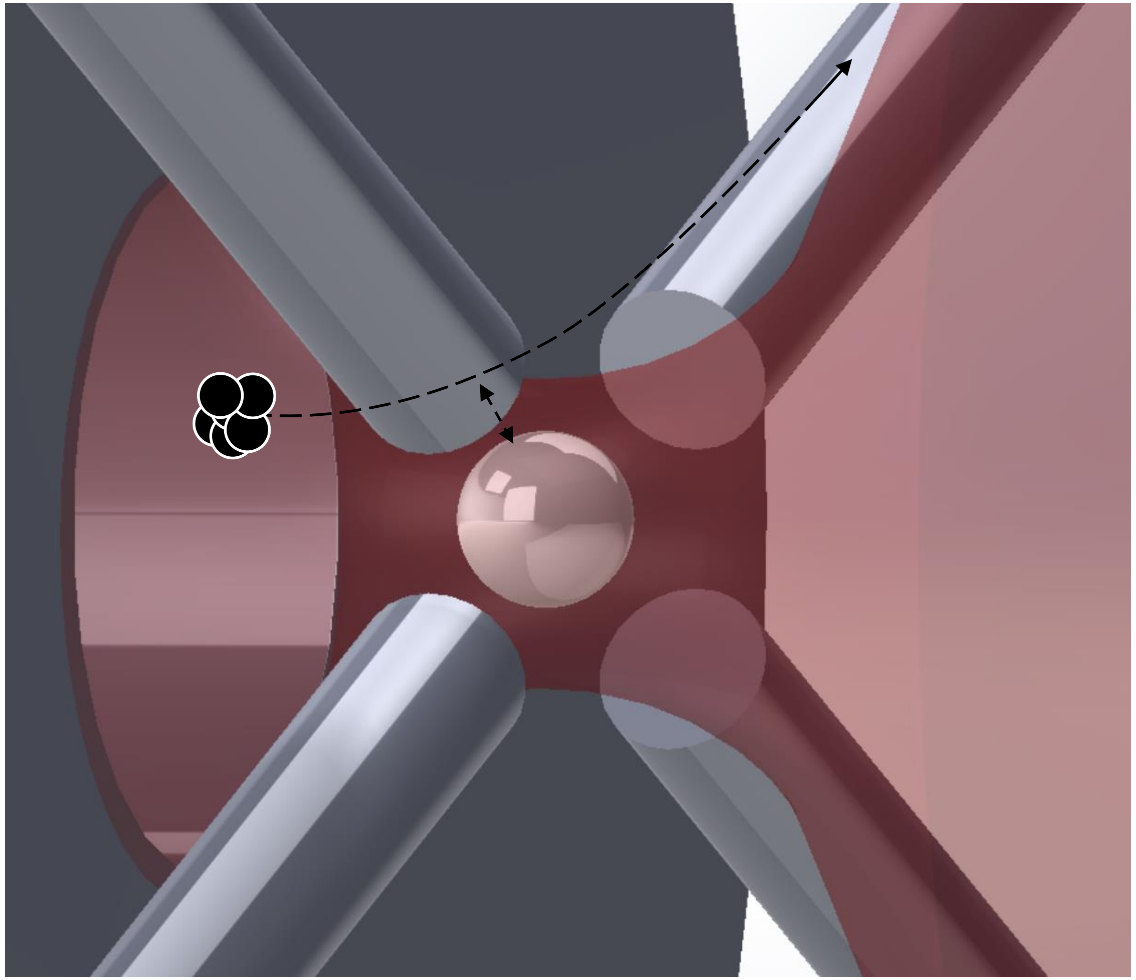
Dark matter nuggets

- 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.

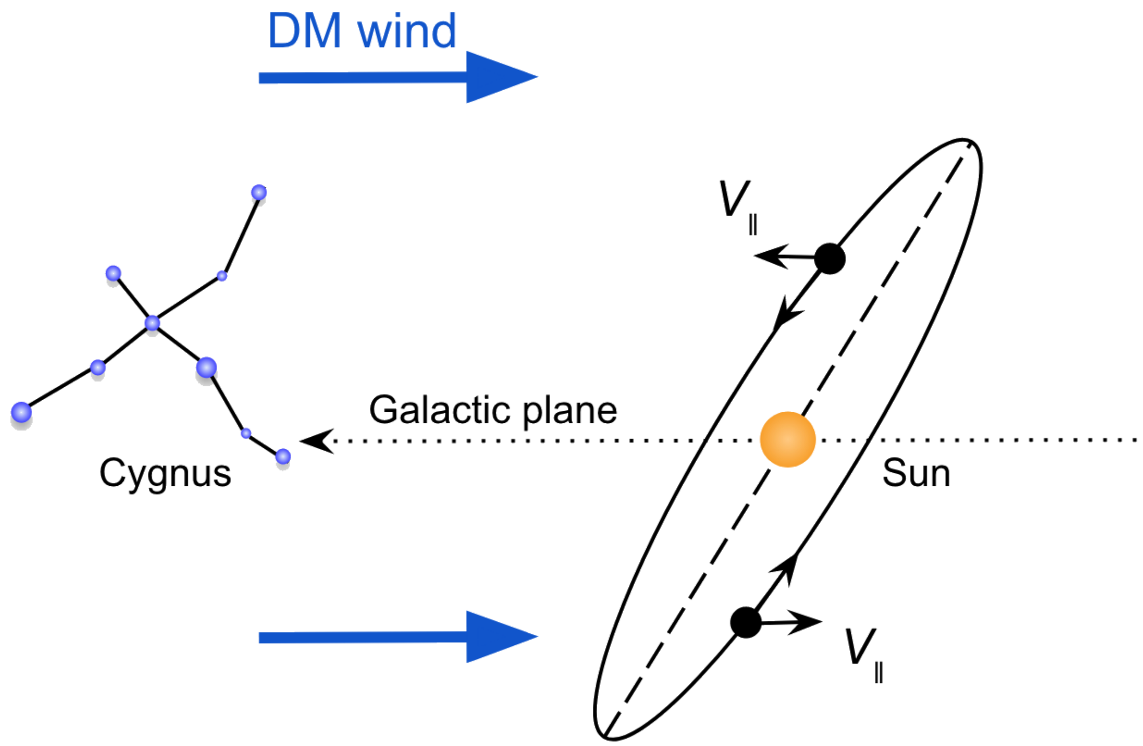
$$V(\vec{r}) = \frac{g_\chi N_\chi g_n N_n}{4\pi} \frac{1}{|\vec{r}|} e^{-m_\phi |\vec{r}|}$$

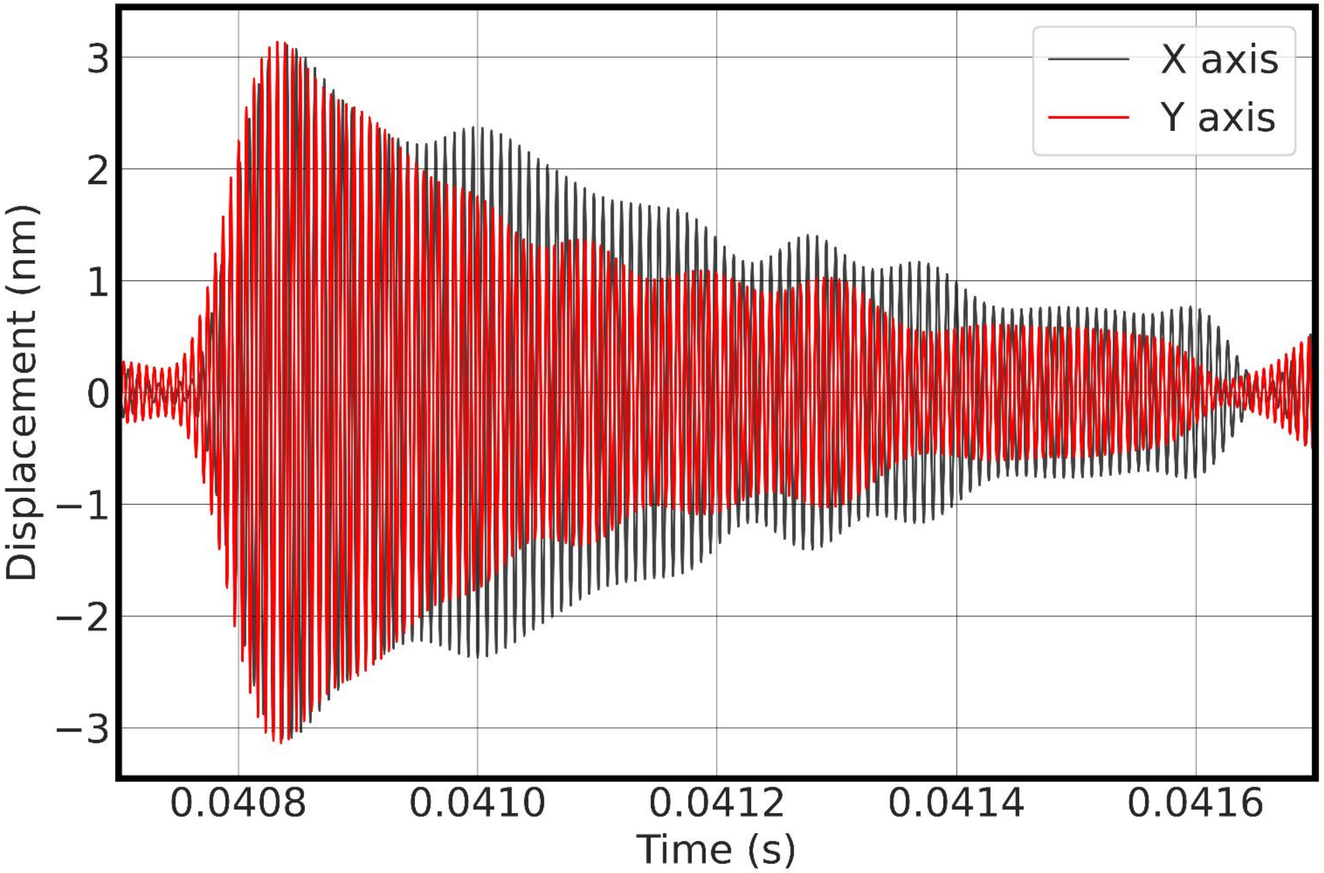
Long-range, small-angle scattering

m_ϕ <eV

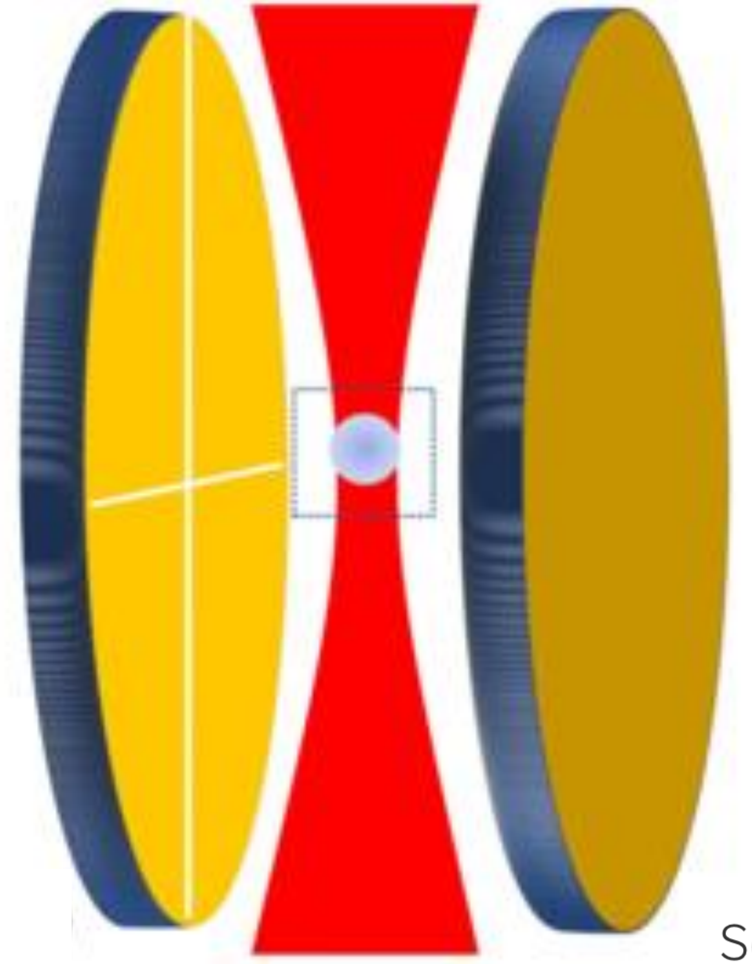


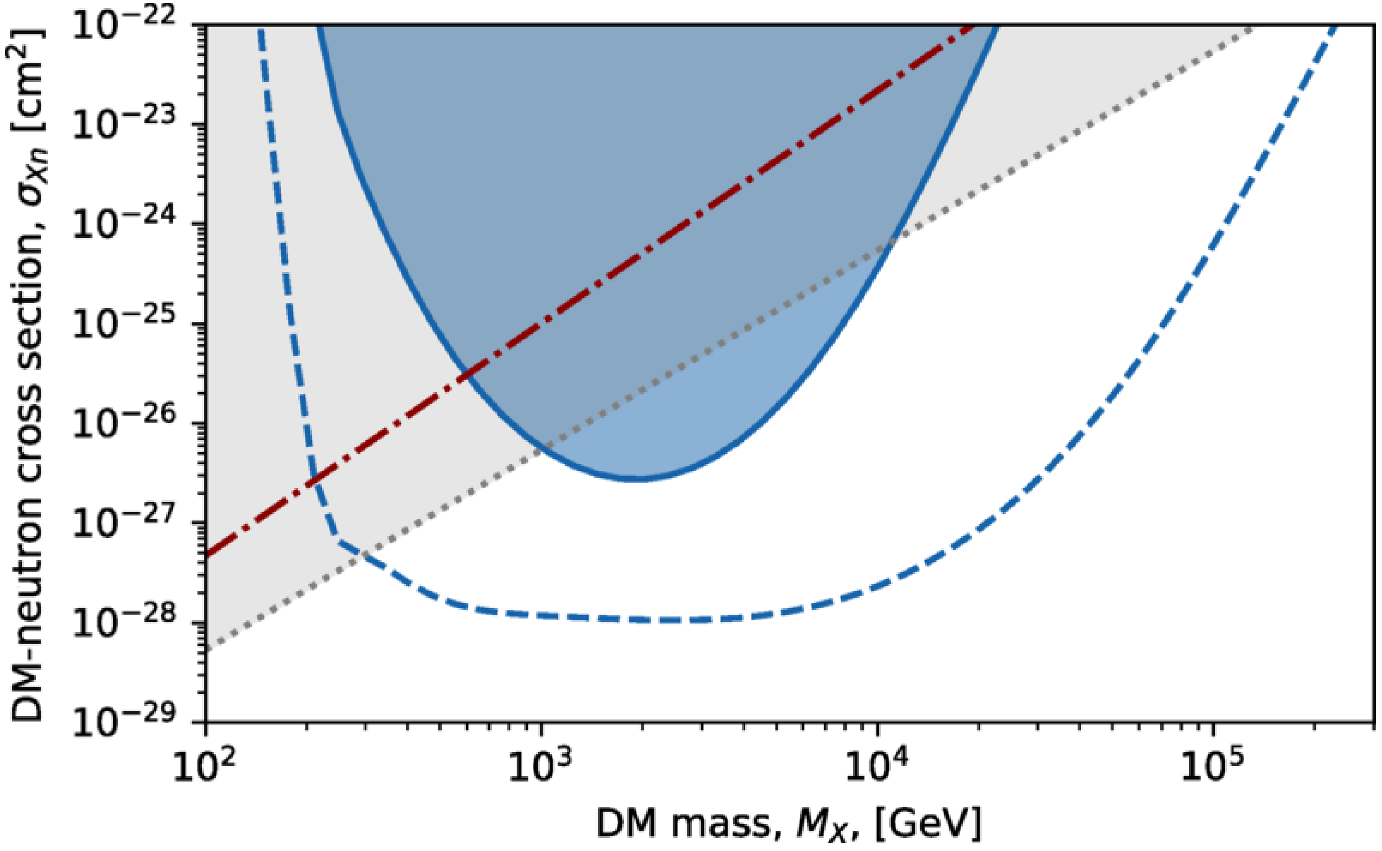
Directionality





State-of-the-art

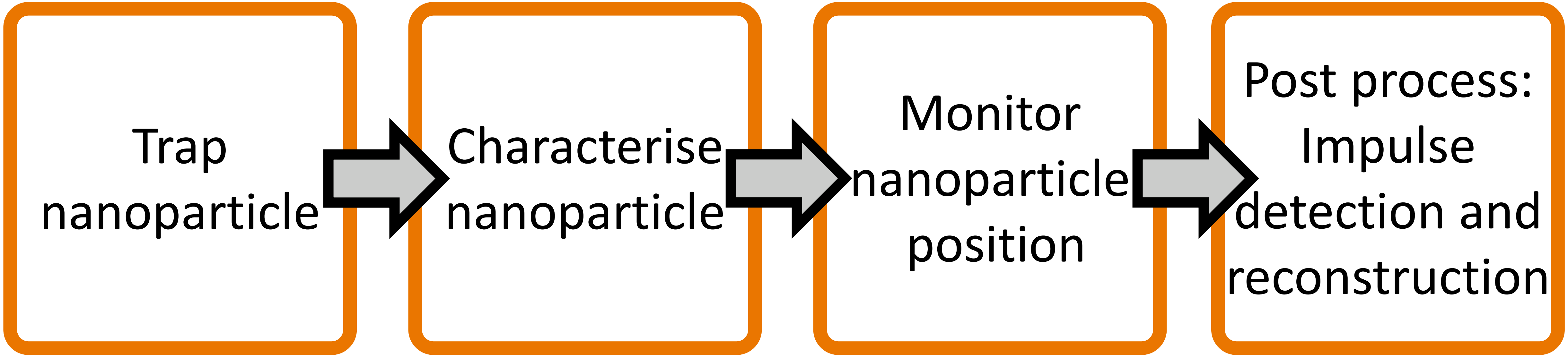




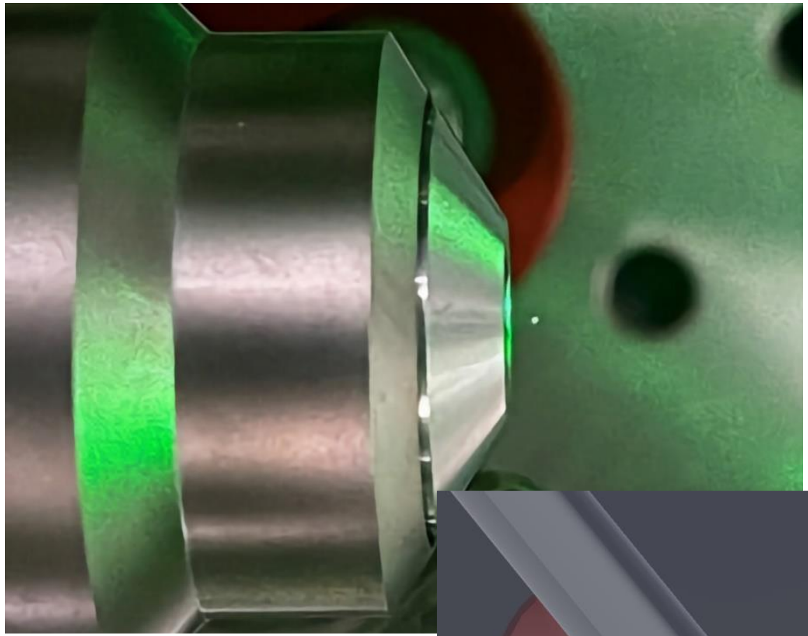
Search for Composite Dark Matter with Optically Levitated Sensors

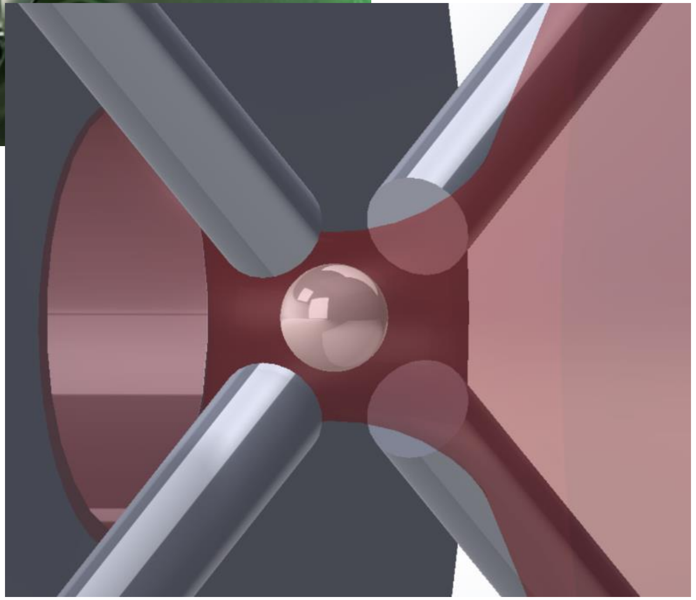
Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore
Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020

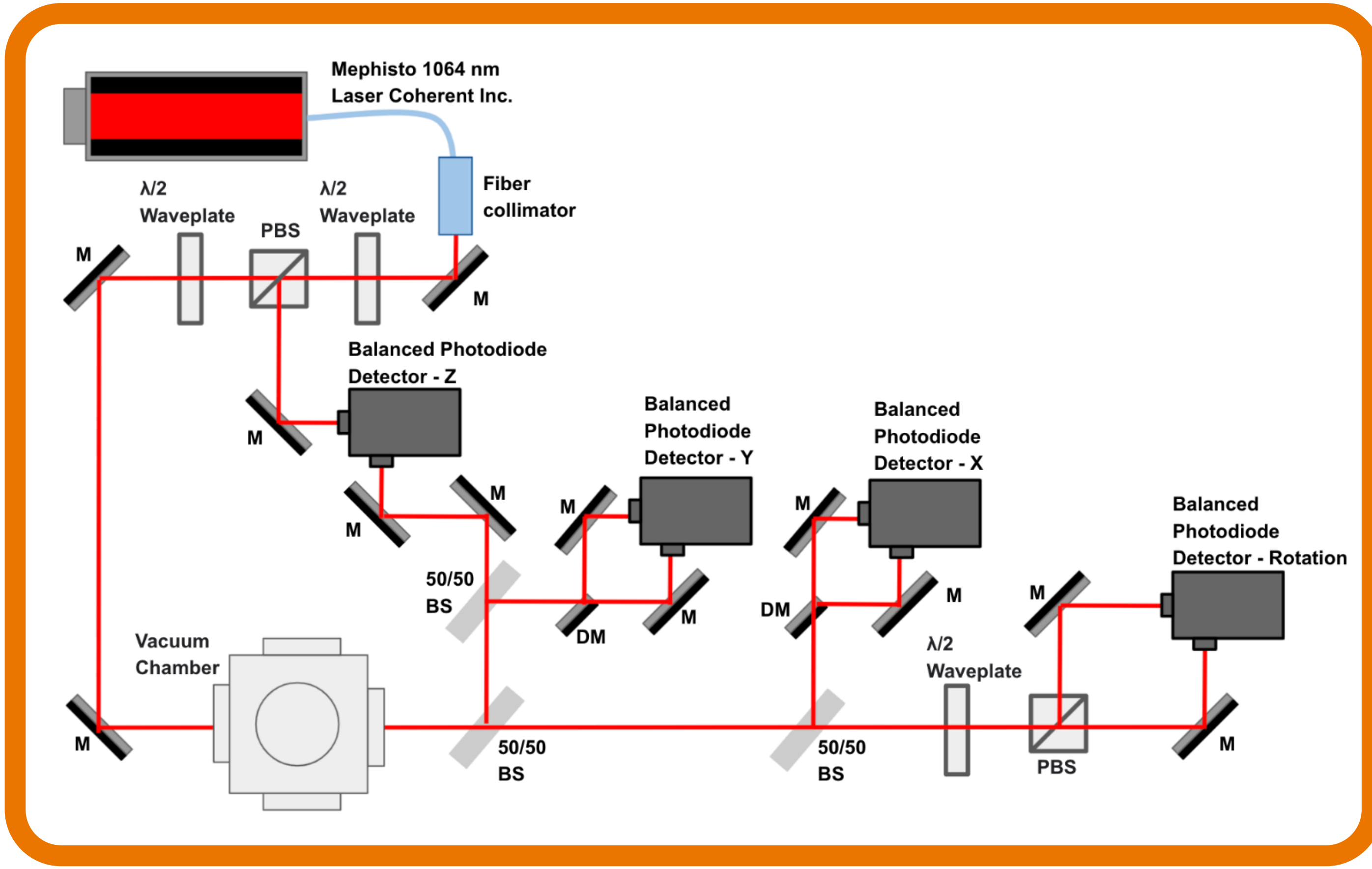
Experimental Procedure



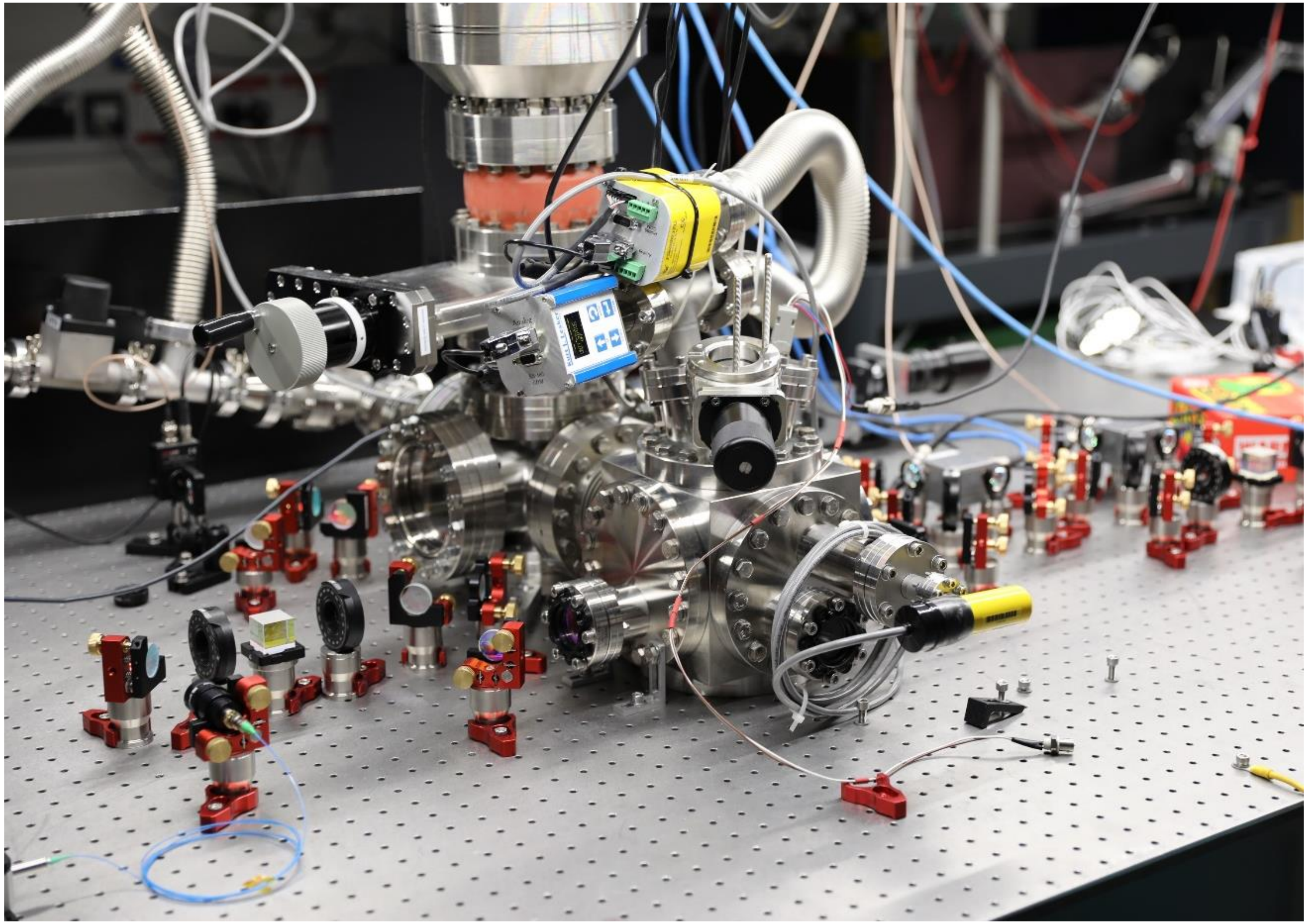
Experimental Setup



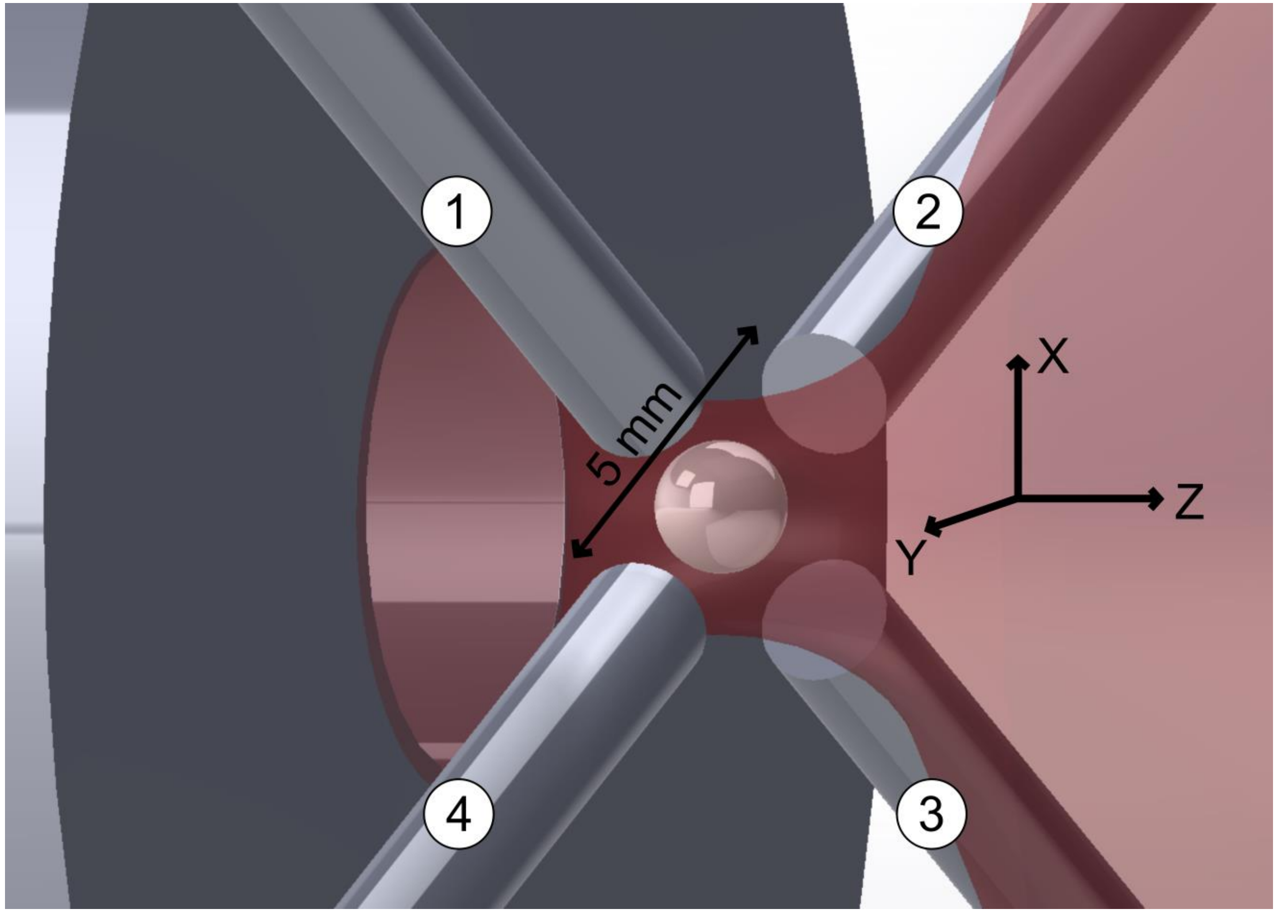


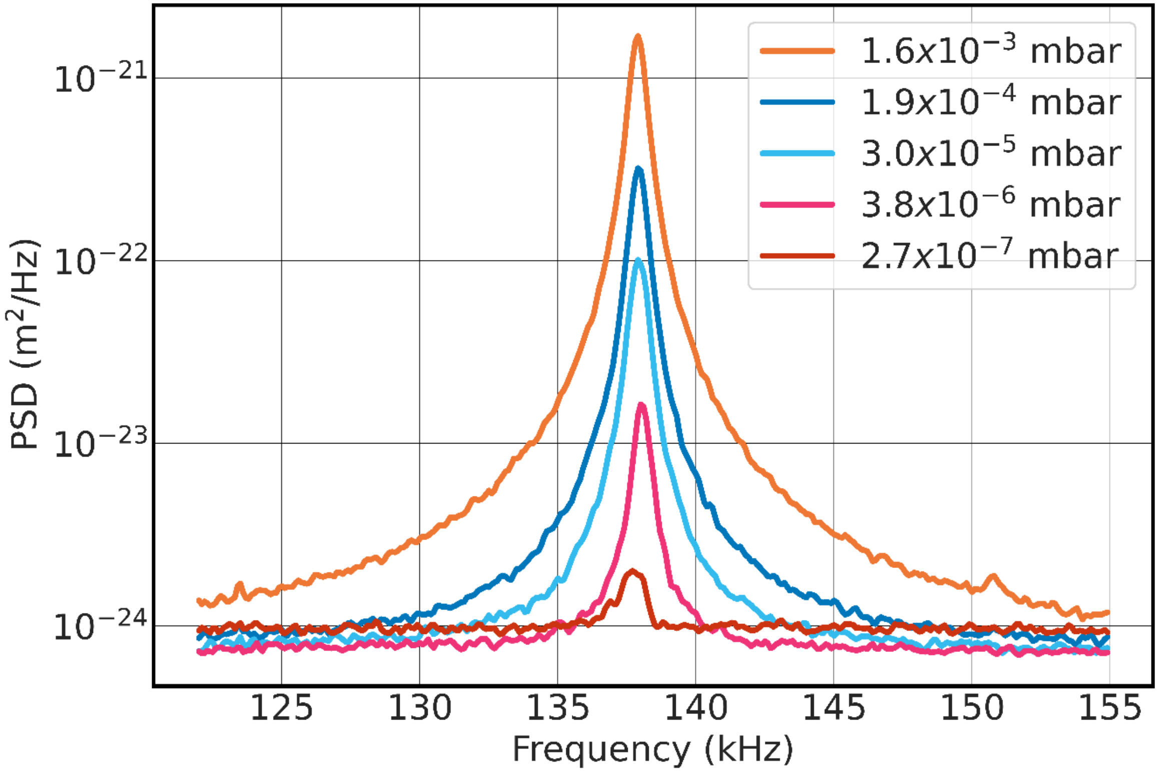


Experimental Setup

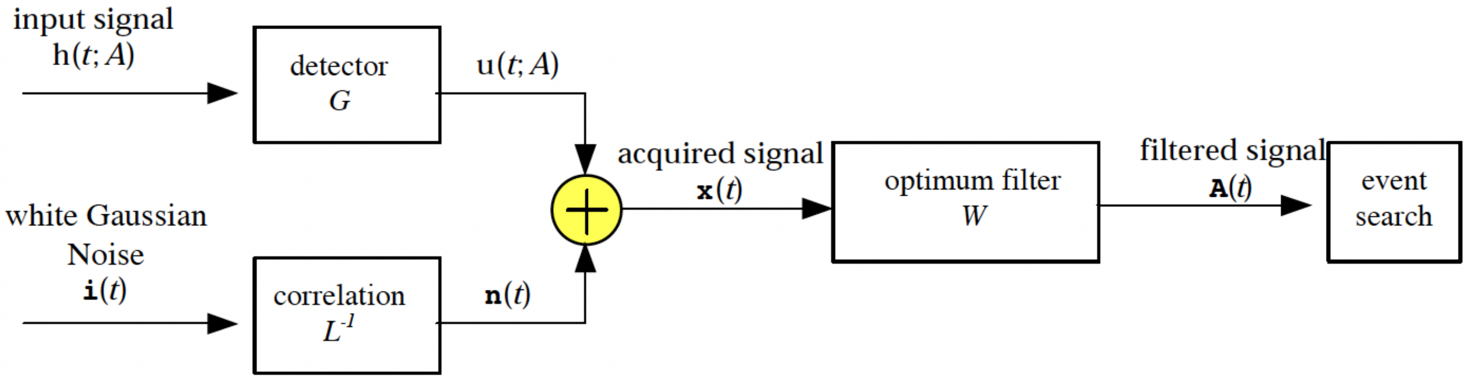


Feedback Cooling





Impulsive event detection



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

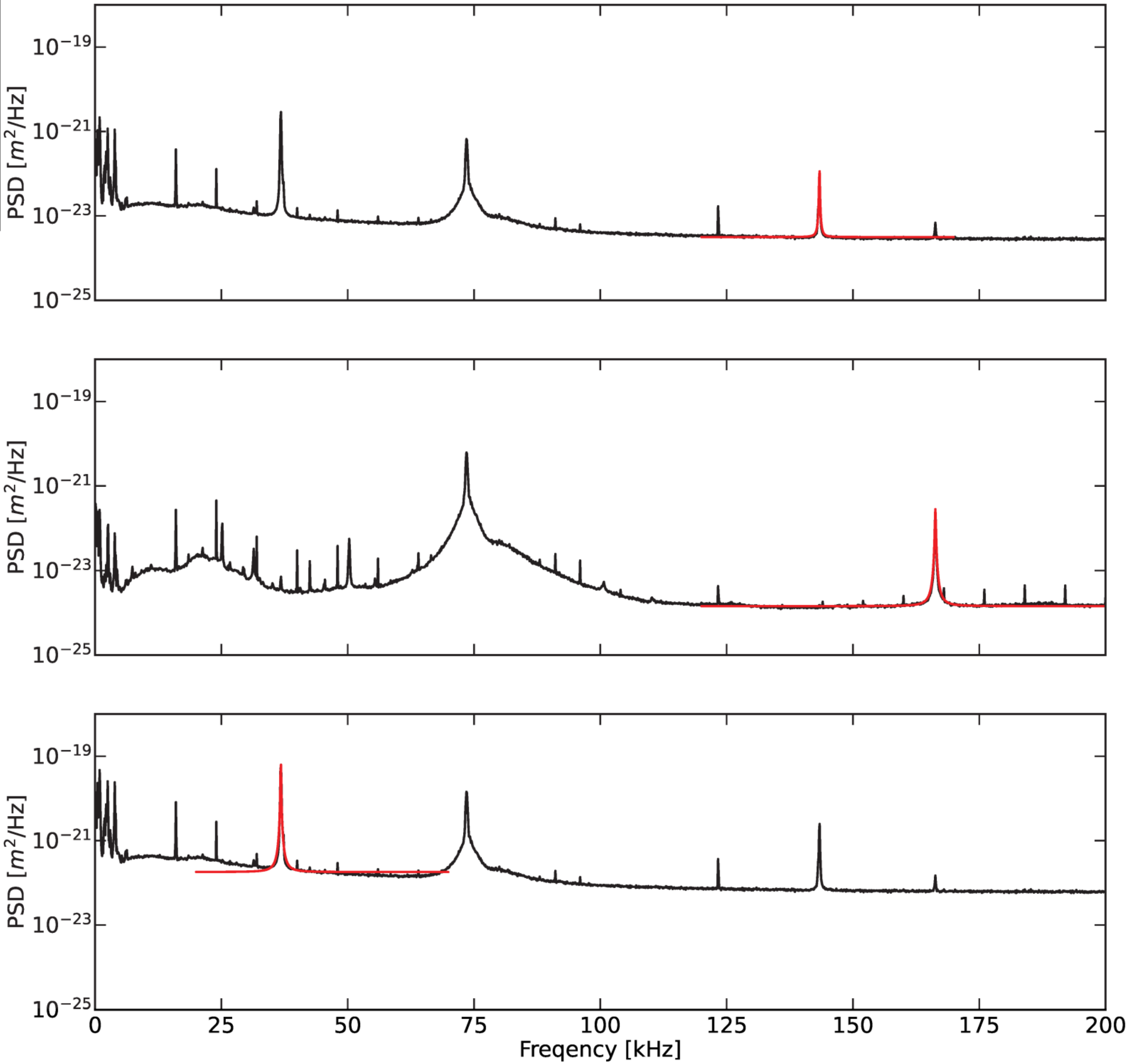
Product of 3 filters

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

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

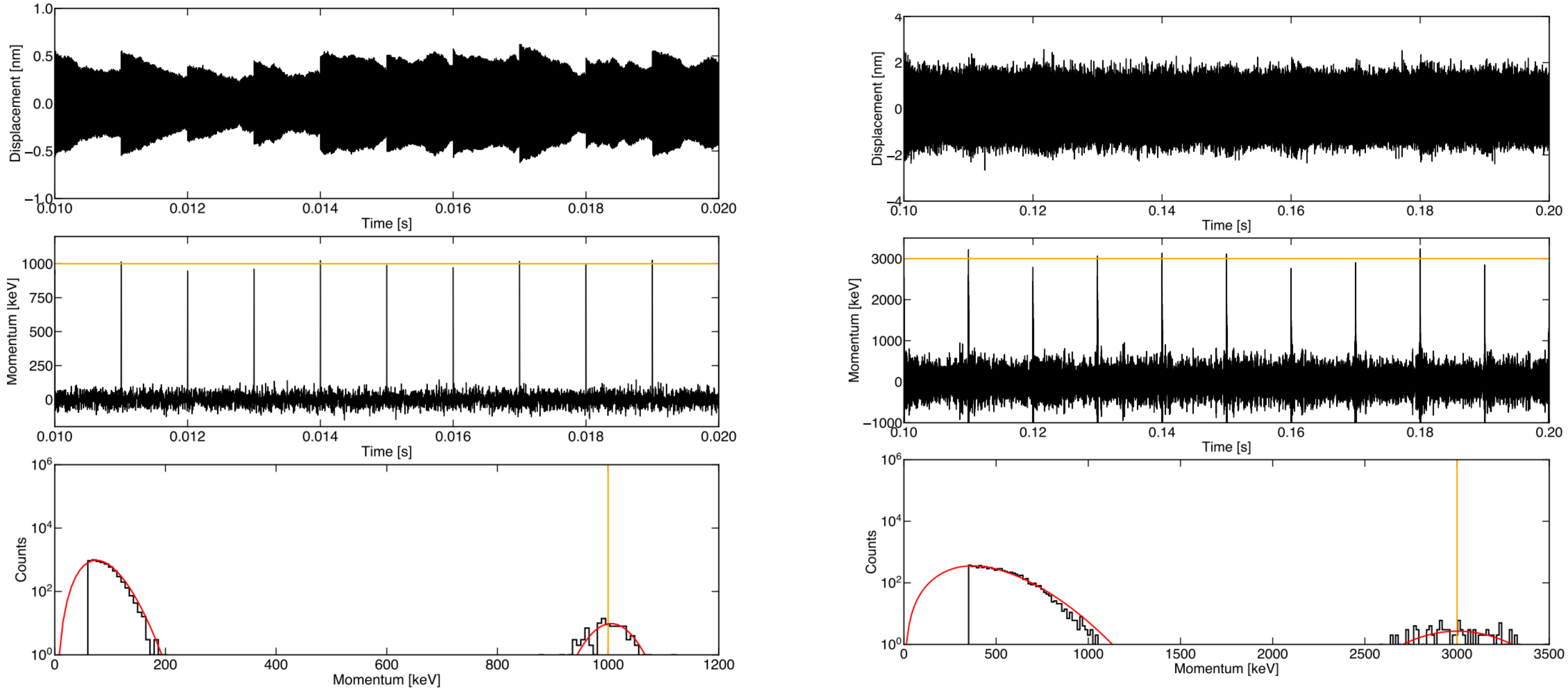
$F^*(\omega)$

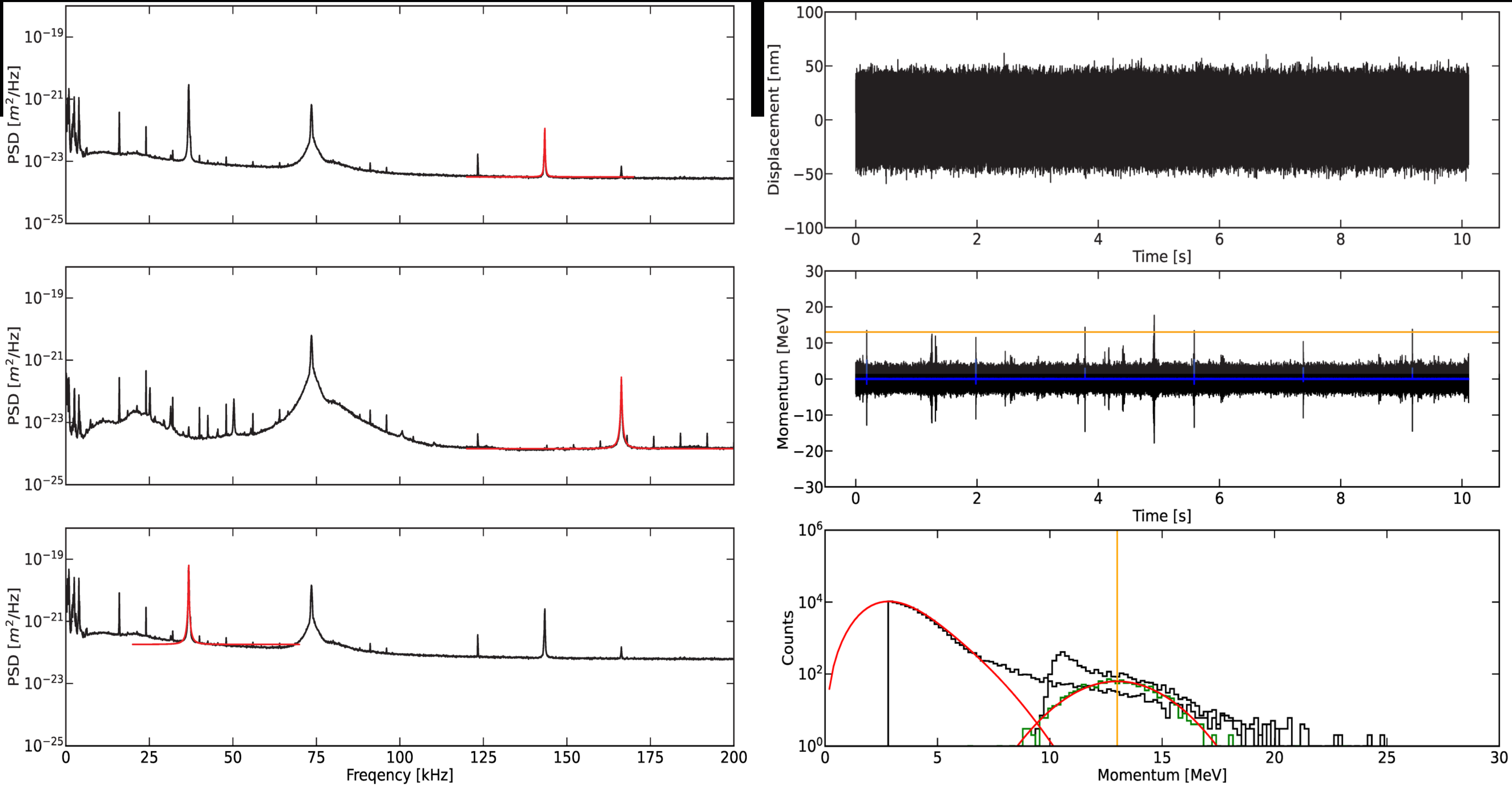
A. Ortolan et al, Gravitational waves. Proceedings, 2nd Edoardo Amaldi Conference, Geneva, Switzerland, July 1-4, 1997, 204-215



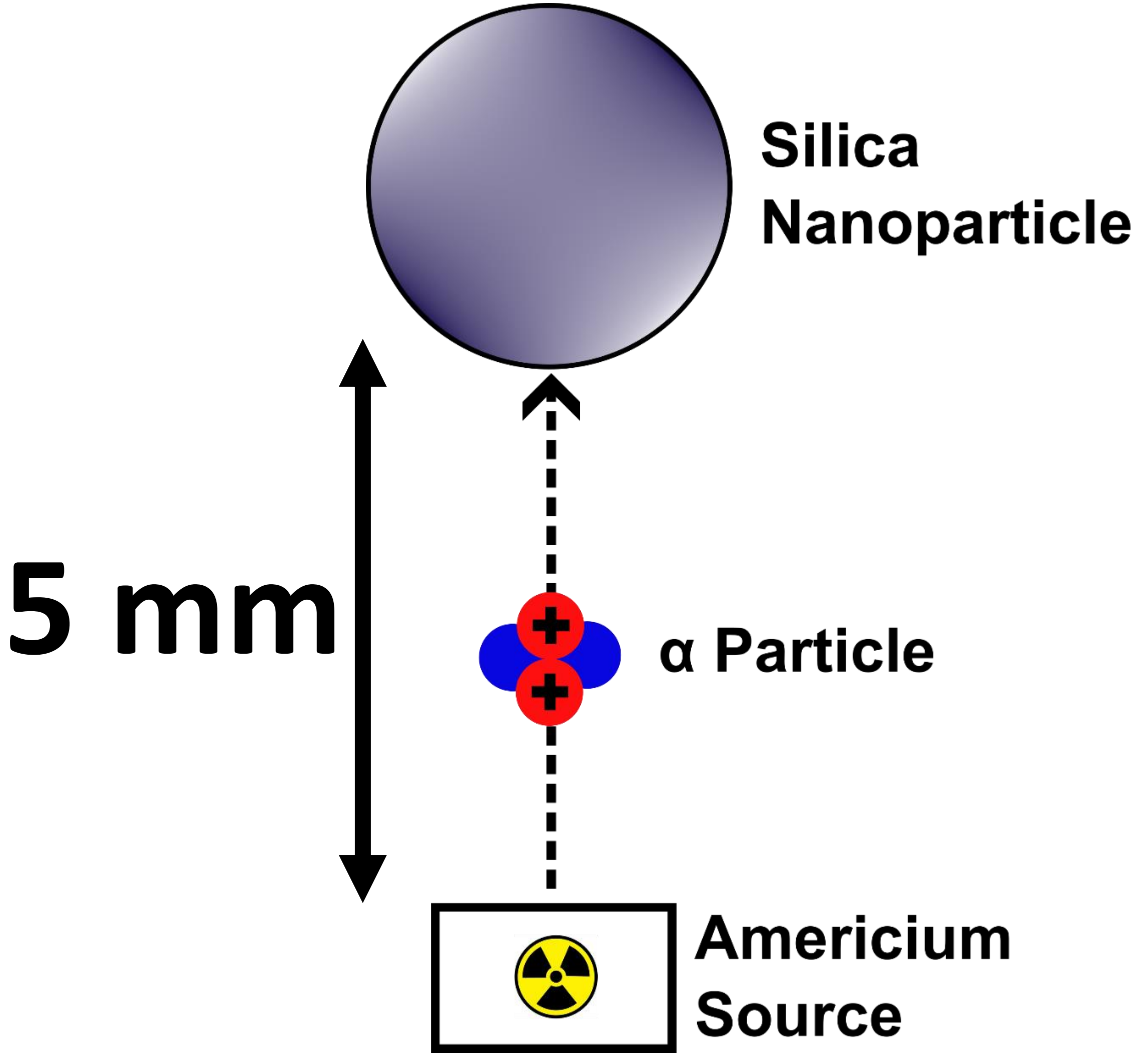
PSD [m^2/Hz]
10^-19
10^-21
10^-23
10^-25
0
25
50
75
100
125
150
175
200
Freqency [kHz]

Experimental Procedure

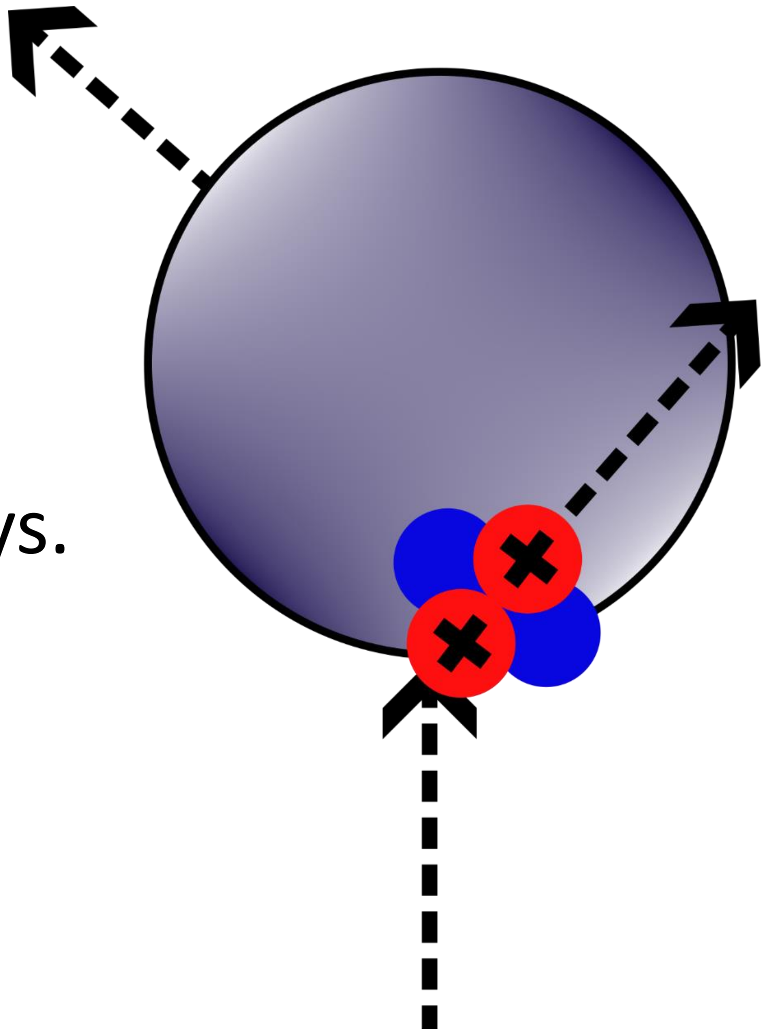



PSD [m^2/Hz]
10^{-19}
10^{-21}
10^{-23}
10^{-25}
0
25
50
75
100
125
150
175
200
Freqency [kHz]
Displacement [nm]
100
50
0
−50
−100
Time [s]
2
4
6
8
10
Momentum [MeV]
30
20
10
−10
−20
−30
Counts
10^6
10^4
10^2
10^0
5
15
20
30

Application to alpha particles



Application to Alpha Particles



4.6 MeV Alpha
- deposit 14 keV

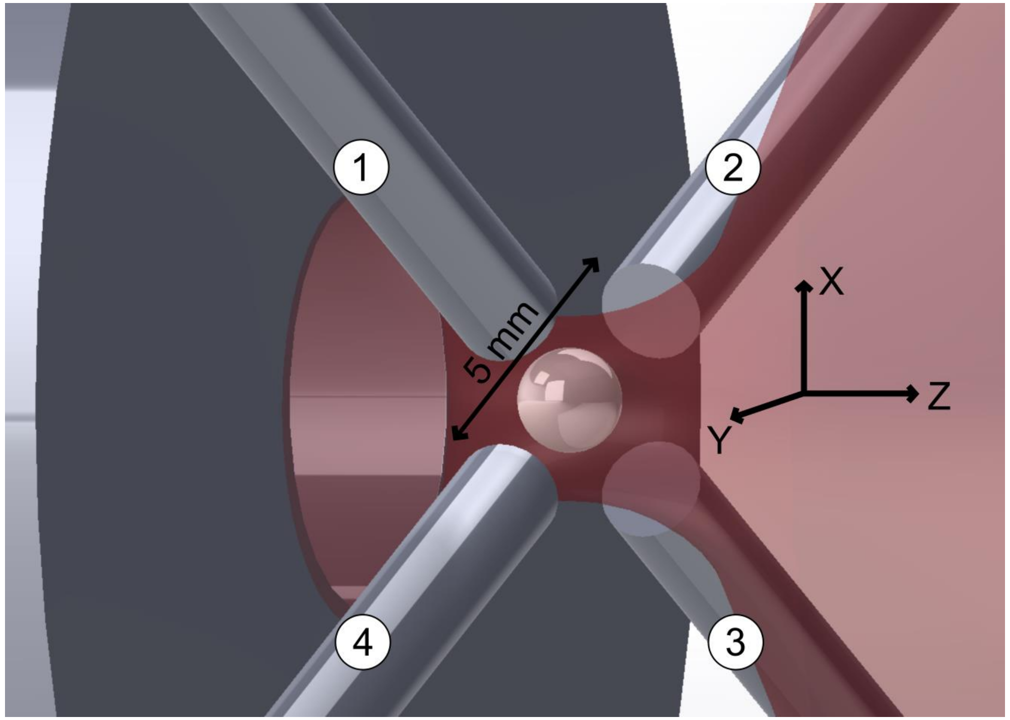
Maximum momentum –
~ 200 MeV

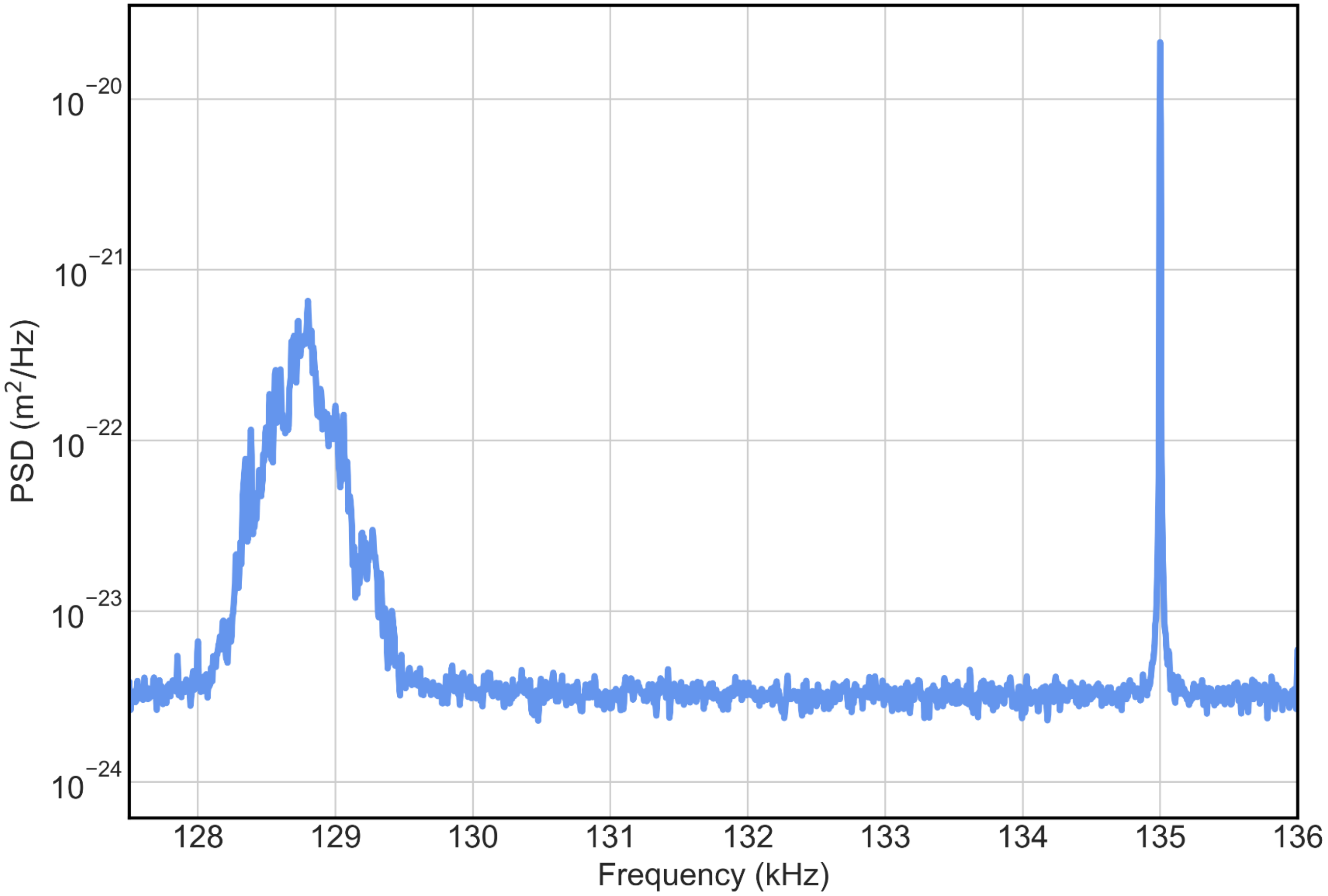
Applications to Nuclear spectroscopy:
Malyzhenkov et al., Phys. Rev. A 98, 052103

Sterile Neutrino searches:
Carney et al., PRX Quantum 4, 010315

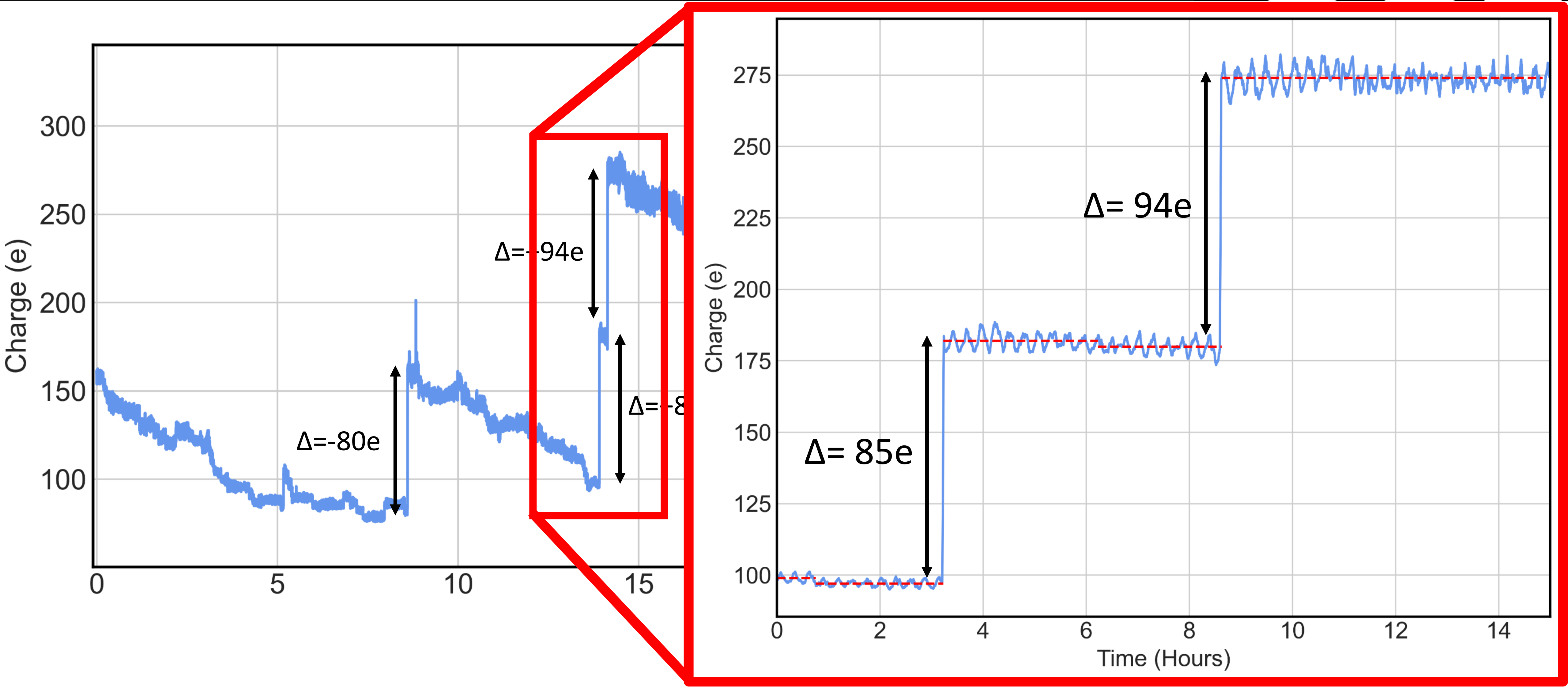
Mechanical detection of nuclear decays:
Wang et al., arXiv:2402.13257

Charge Monitoring





Charge Monitoring (40 days)



Conclusions

- Review of what is possible and potentially useful
- Cooling all DOF by cavity cooling and by collisions
- Characterisation of particles via their motion in traps
- Impulsive sensing of collisions and charge

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Peter Barker

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Eva Kilian

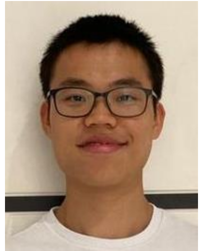
Amy Hopper

Hayden Fu

Fiona Alder

Marko Toros

Antonio Pontin



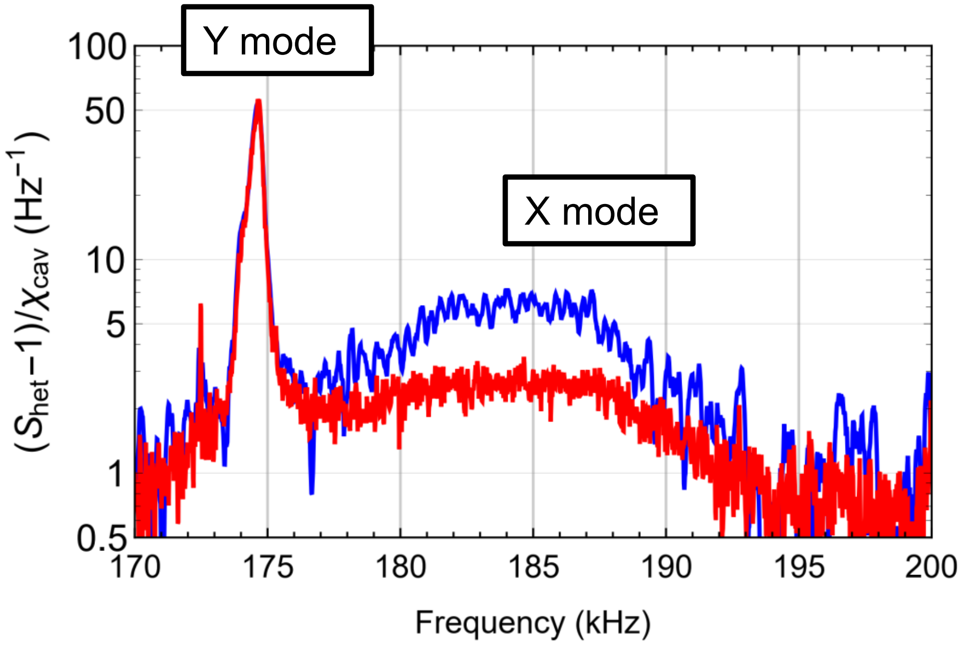
Robert James

Heterodyne measurement - ground state

Ratio of Stokes to anti-Stokes transition

$$R = e^{\frac{\hbar w_m}{T k_B}} = \frac{n_{th} + 1}{n_{th}}$$

Clear signature of quantum behavior



At the ground state

$n_{th} \sim 1$

EPSRC
Engineering and Physical Sciences Research Council

Displacement calibration

Calibration via gas collisions:

$$R = \frac{m_g v_t P_g (1 + \frac{\pi}{8})}{\rho k_B T \Gamma_g}$$

Displacement calibration

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Calibration via interference fringes:

- 640 nm laser used to form interference fringes at the nanoparticle.
- Utilise linear region to get a calibration of voltage to displacement.

Displacement calibration

Calibration via gas collisions:

$$R = \frac{m_g v_t P_g (1 + \frac{\pi}{8})}{\rho k_B T \Gamma_g}$$

Calibration via interference fringes:

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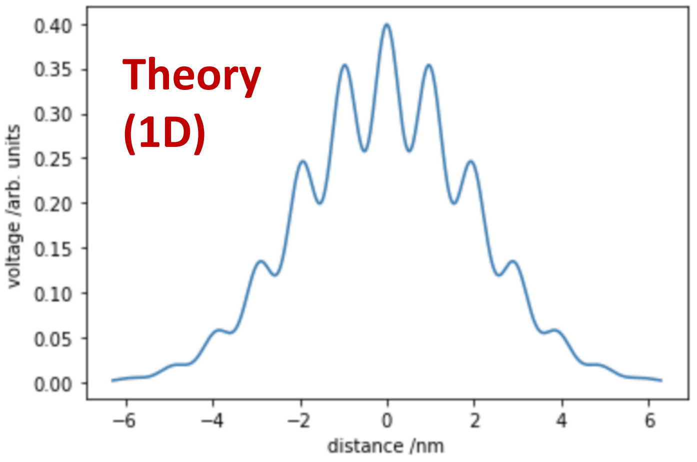
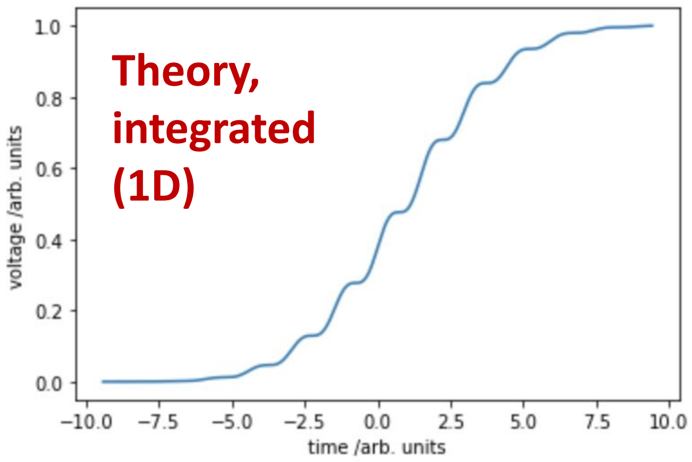
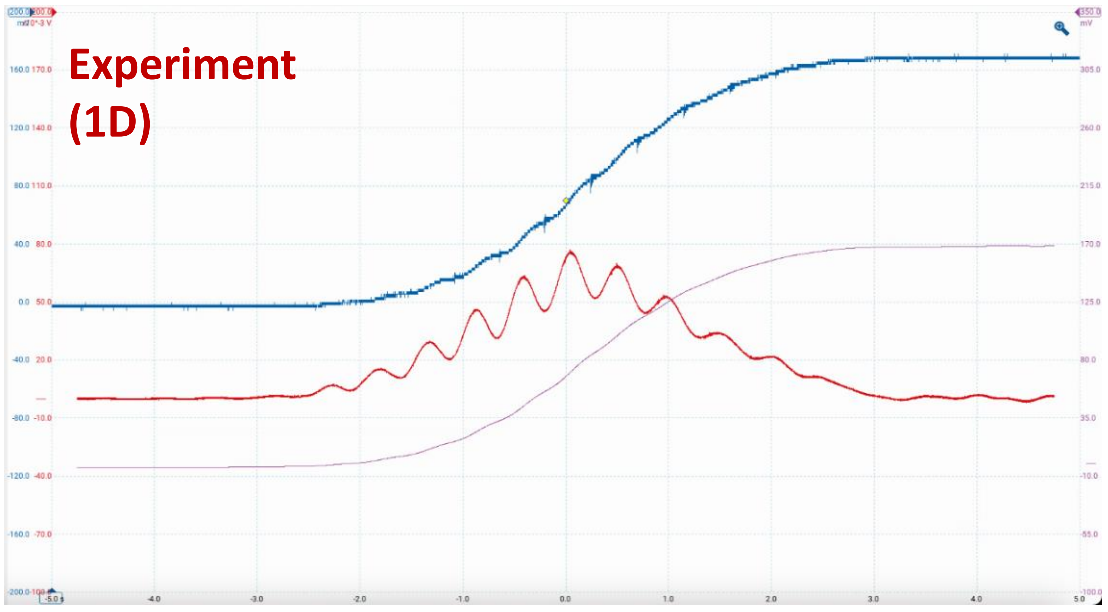
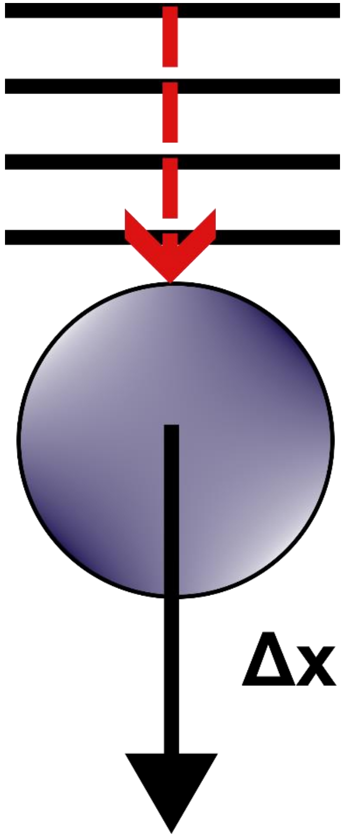






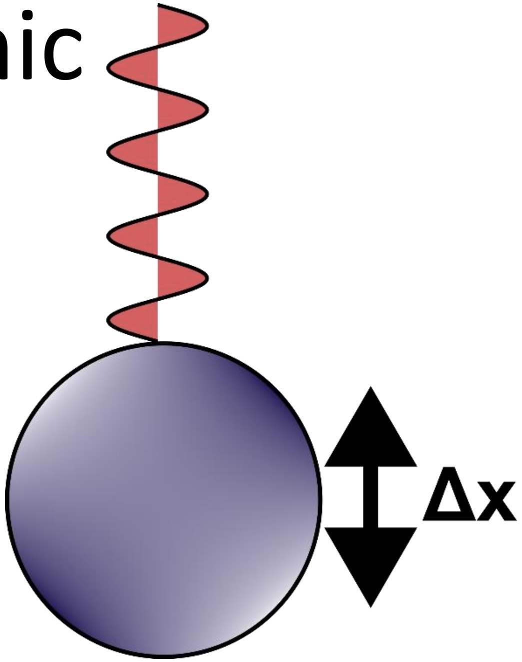
Types of forces

Constant force:



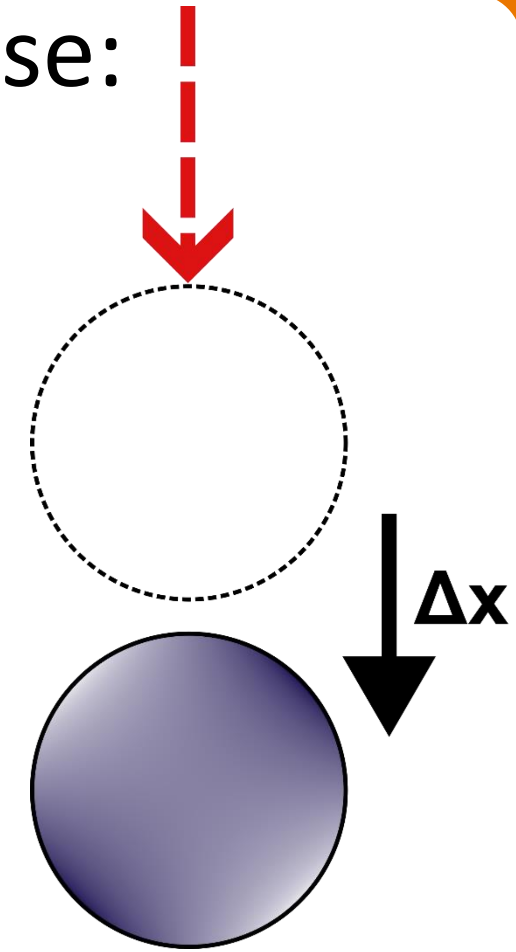
Hebestreit et al., Phys. Rev. Lett. 121, 063602
Rider et al., Phys. Rev. Lett. 117, 101101

Harmonic force:



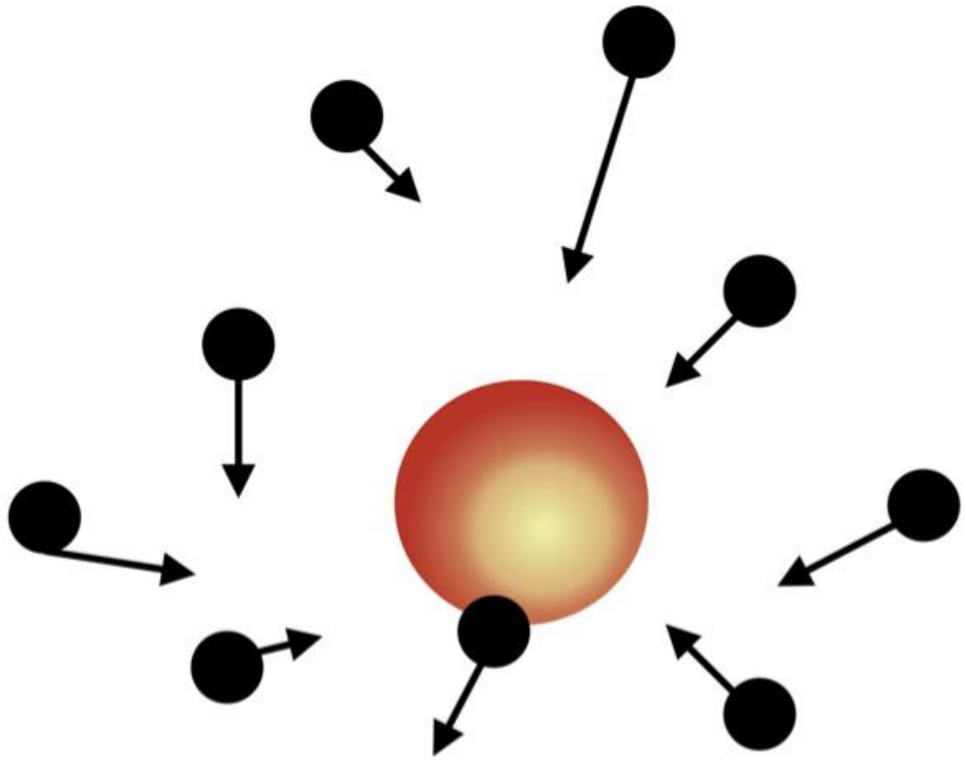
Ranjit et al., Phys. Rev. A 93, 053801
Liang et al., Fundamental Research 3 (2023) 57–62

Impulse:

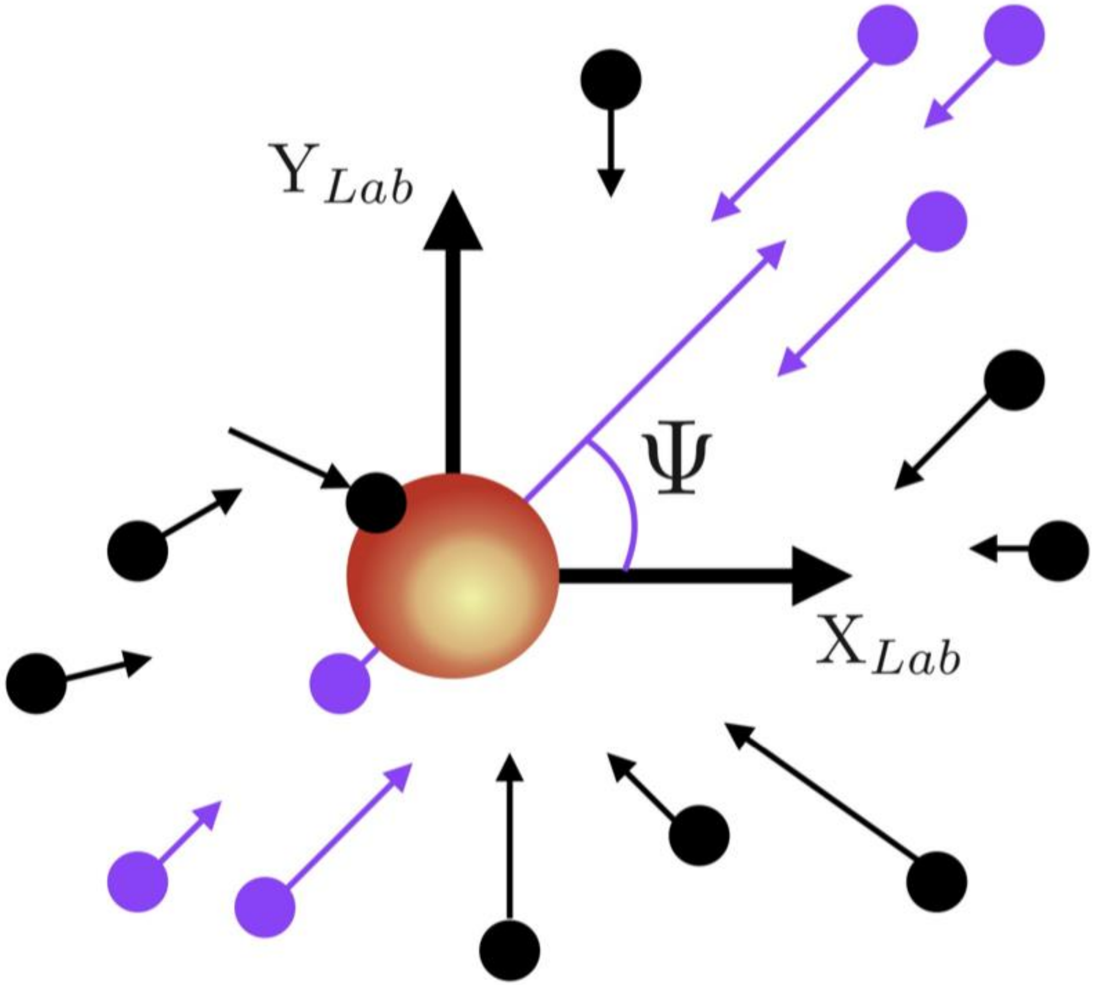


Monteiro et al., Phys. Rev. Lett. 125, 181102
Dania et al., Phys. Rev. Lett. 132, 133602

Stochastic forces



Stochastic forces



Cross-correlation

Cross-correlation

Cross-correlation mechanical spectra:

$$S_{xy}(\omega) = \frac{1}{2}\left(\left\langle [\hat{x}]^\dagger \hat{y} \right\rangle + \left\langle [\hat{y}]^\dagger \hat{x} \right\rangle\right)$$

Cross-correlation

Cross-correlation mechanical spectra:

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PSD under directed force:

$$S_{xx}(\omega) = |\chi_x(\omega)|^2 S_{th}(1 + \beta^2\cos^2\Psi)$$

$$S_{yy}(\omega) = \left|\chi_y(\omega)\right|^2 S_{th}(1 + \beta^2\sin^2\Psi)$$

Cross-correlation

Cross-correlation mechanical spectra:

$$S_{xy}(\omega) = \frac{1}{2}\left(\langle[\hat{x}]^{\dagger}\hat{y}\rangle + \langle[\hat{y}]^{\dagger}\hat{x}\rangle\right)$$

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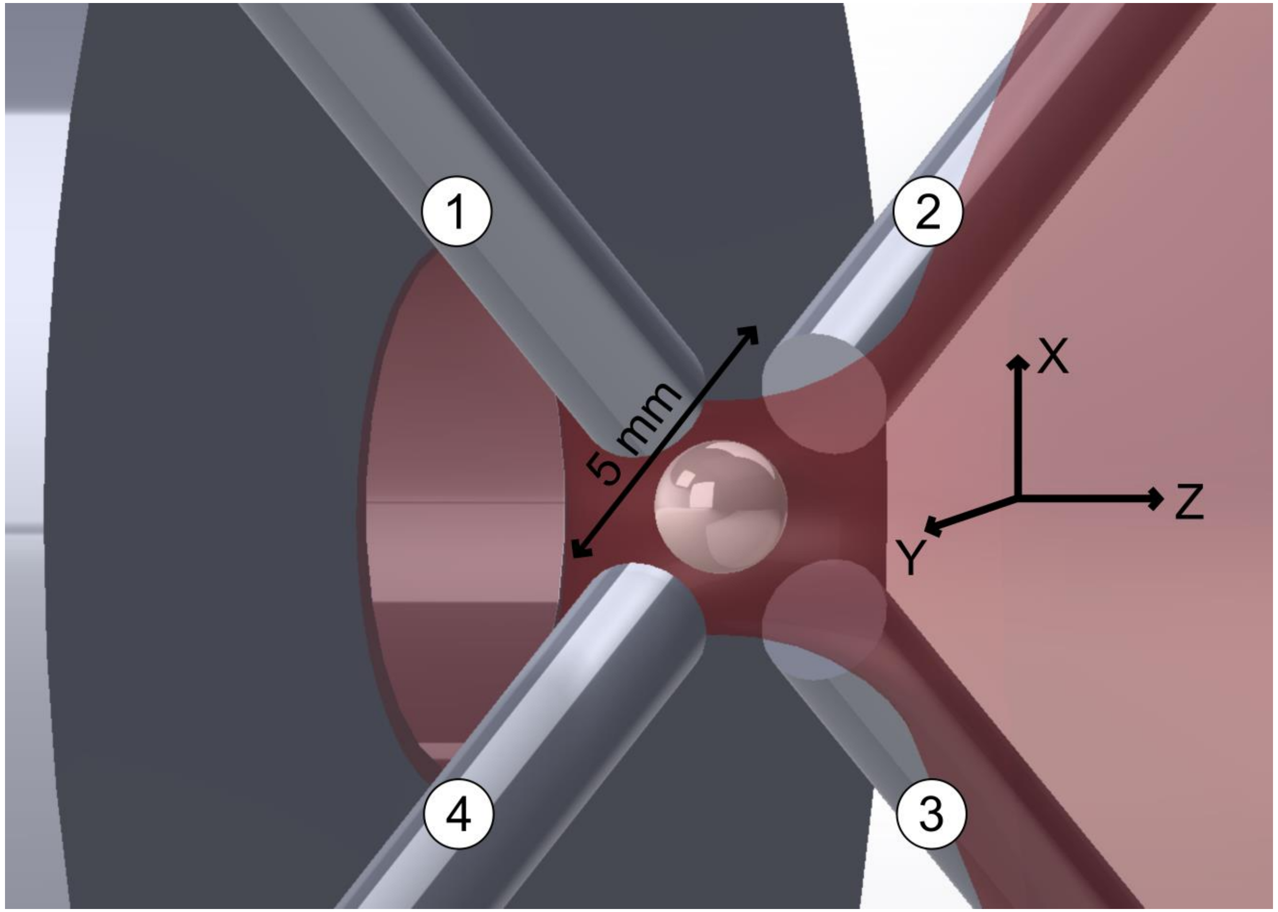
CSD under directed force:

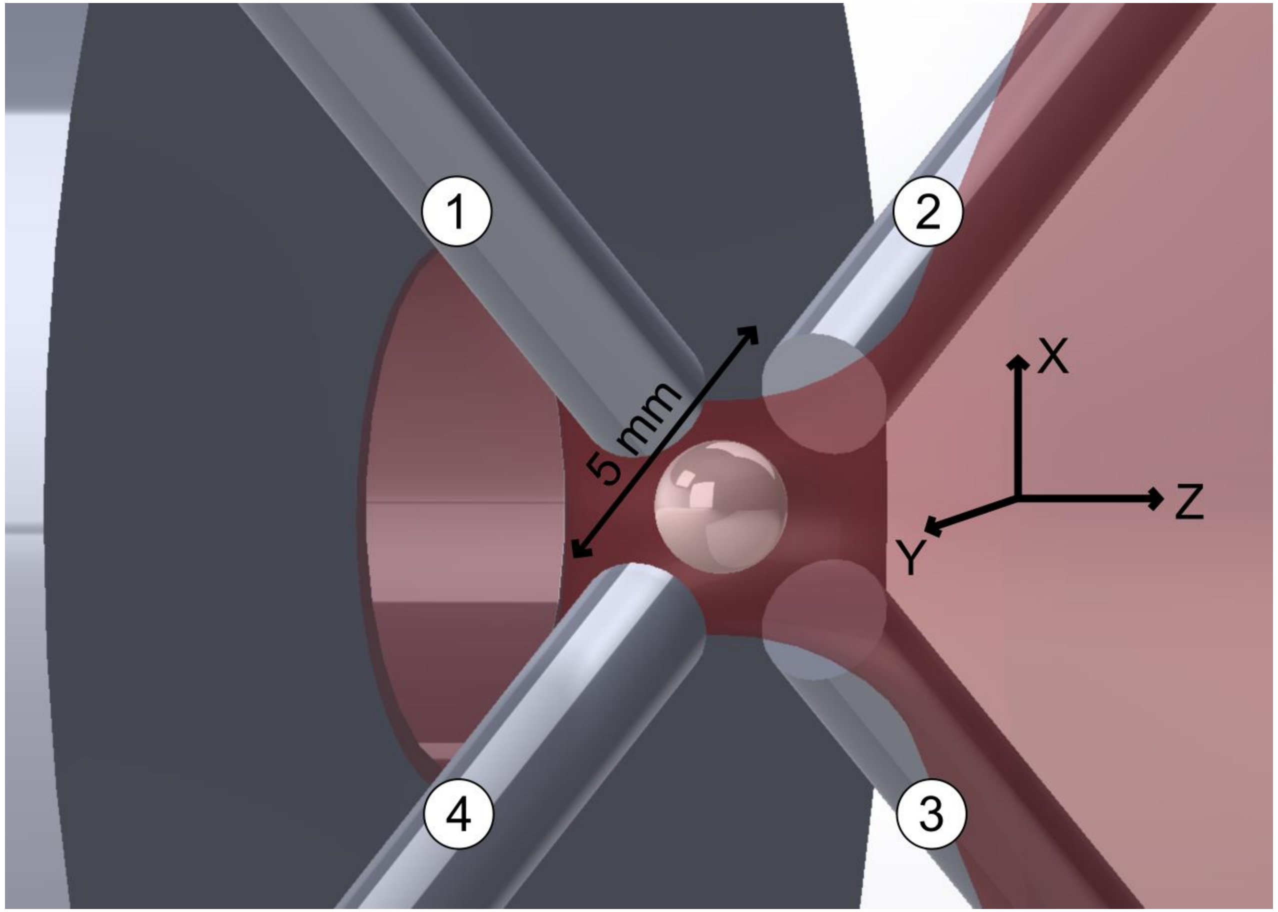
$$S_{xy}(\omega) = \mathrm{Re}\left[\chi_x^*(\omega)\chi_y(\omega)\right] S_{th}\beta^2 \cos\Psi \sin\Psi)$$

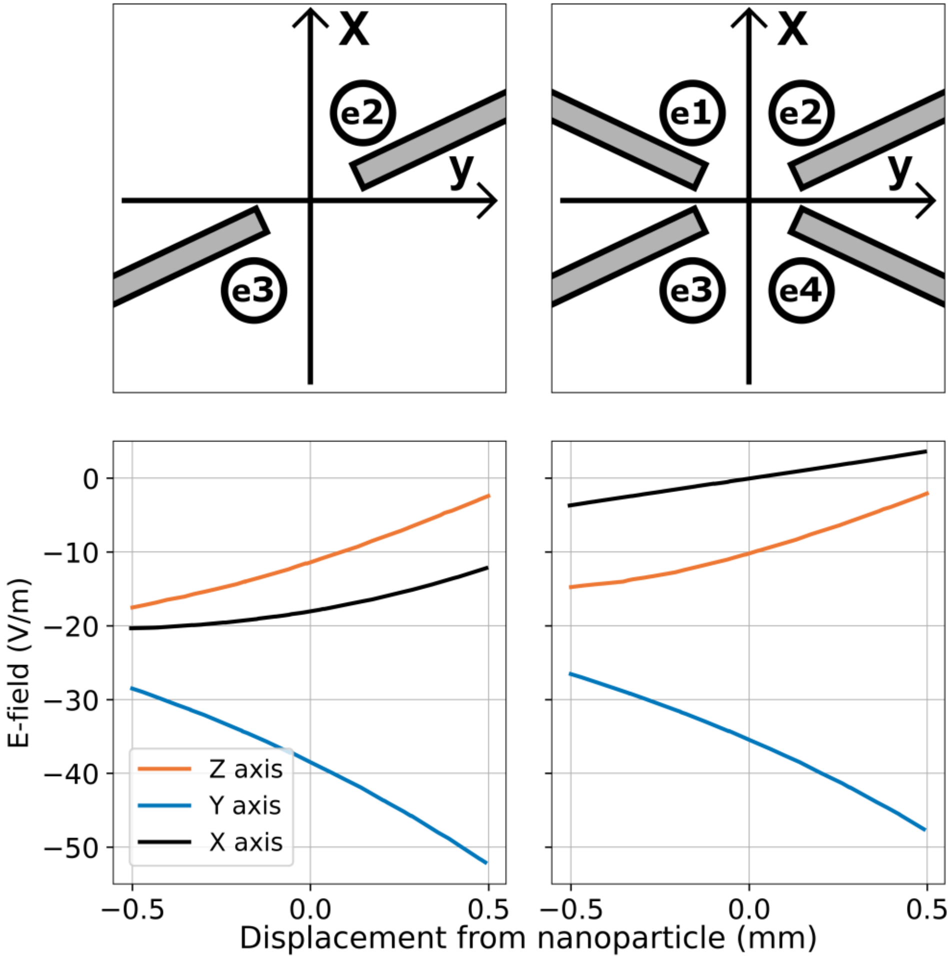
$$\beta^2 = S_{ff}^{dir}/S_{th}$$

Experiment setup

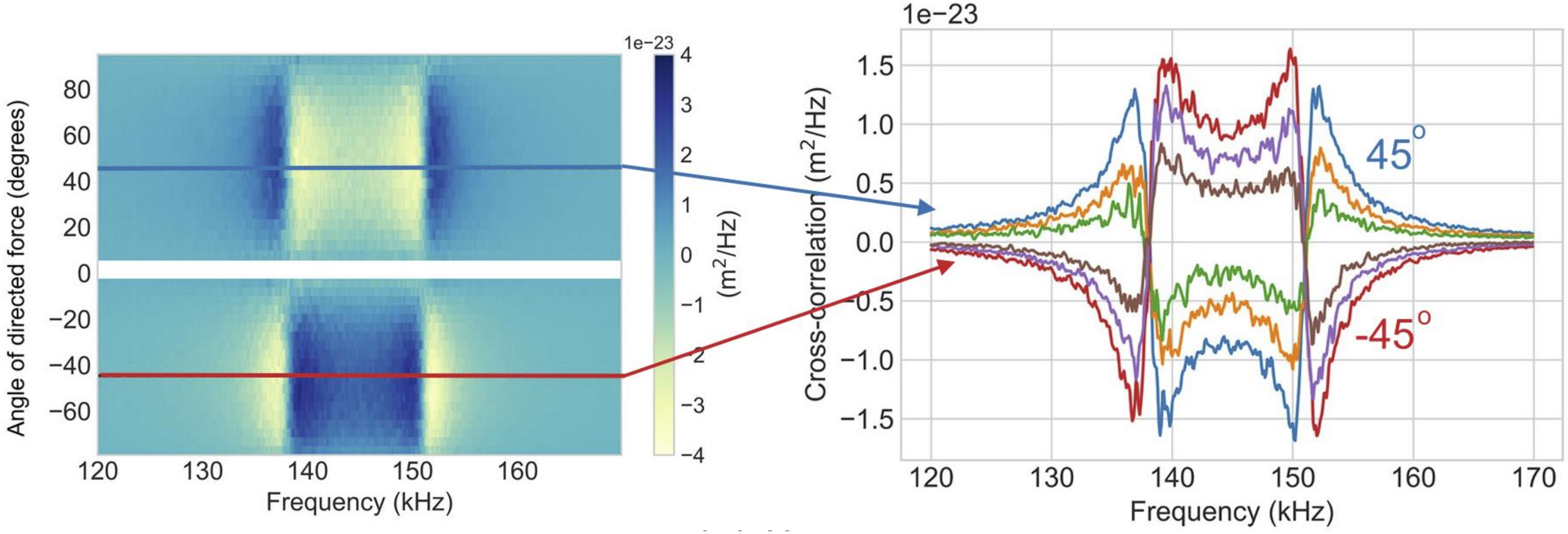


Experiment setup



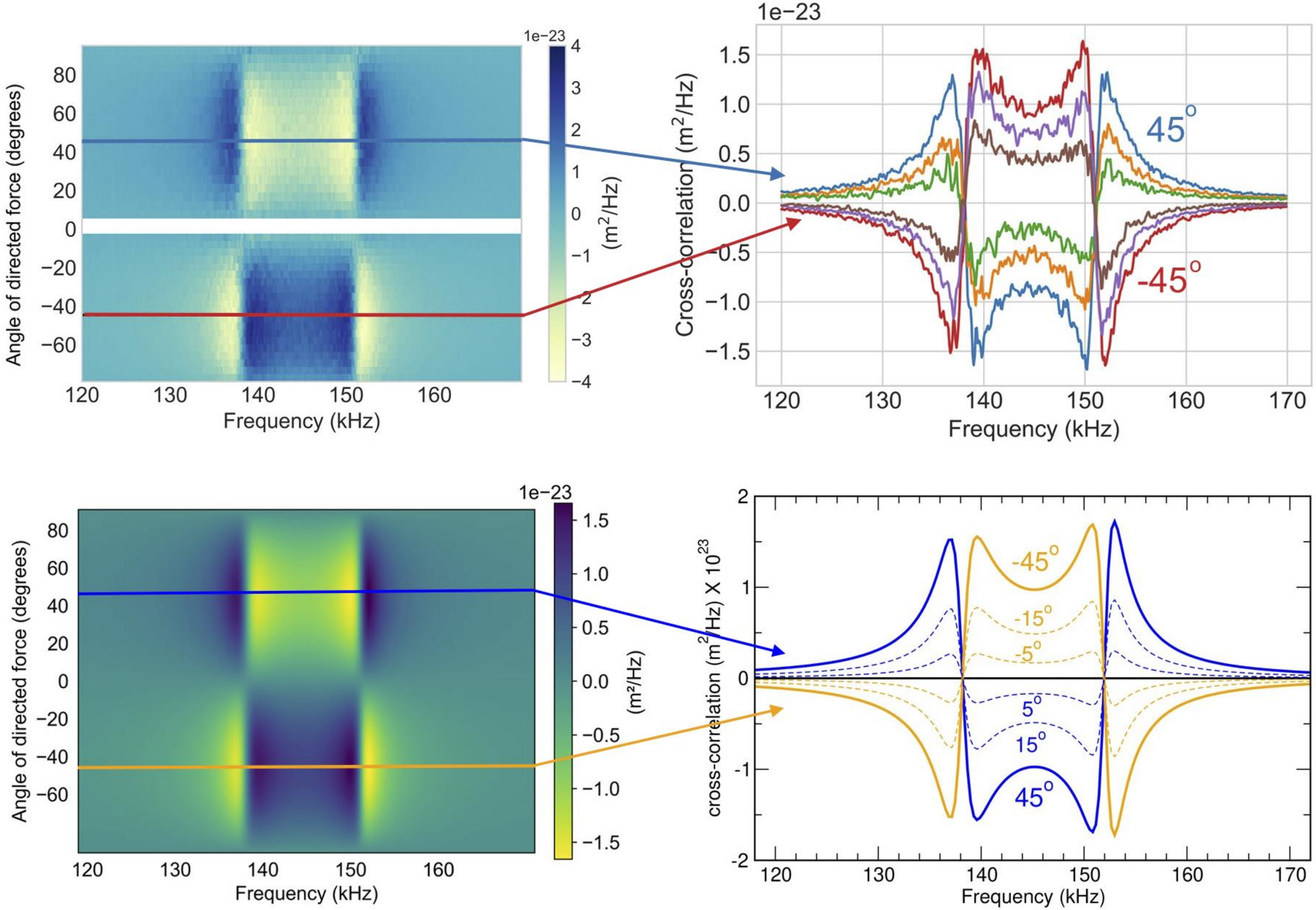


Results

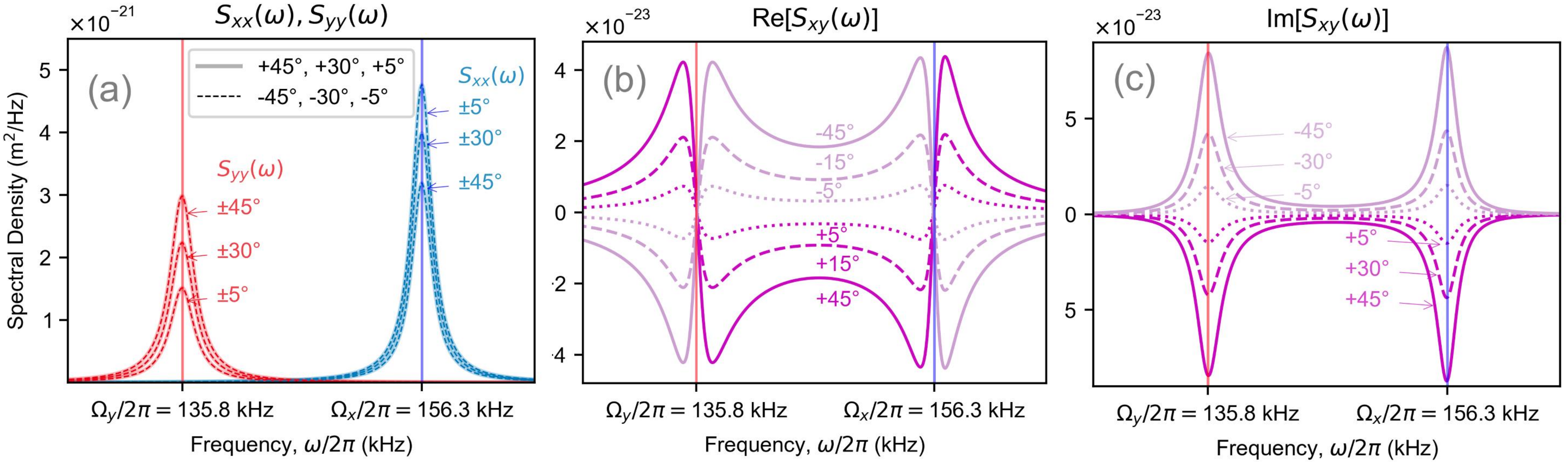


Angle of directed force (degrees)
Frequency (kHz)
1e−23
(m²/Hz)
Cross-correlation (m²/Hz)
45°
-45°

Results

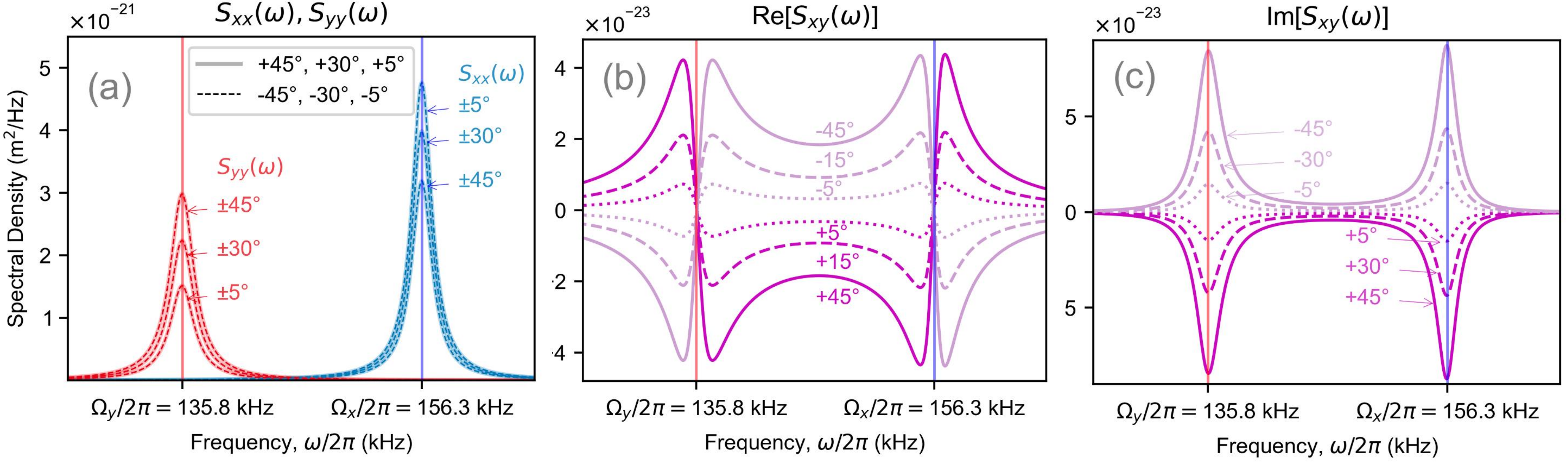

1e−23
Angle of directed force (degrees)
Frequency (kHz)
(m²/Hz)
Cross-correlation (m²/Hz)
45°
-45°
-15°
-5°
5°
15°
cross-correlation (m²/Hz) X 10²³

Results



$S_{xx}(\omega), S_{yy}(\omega)$
$\times 10^{-21}$
Spectral Density (m^2/Hz)
(a)
+45°, +30°, +5°
-45°, -30°, -5°
$S_{xx}(\omega)$
±5°
±30°
±45°
$S_{yy}(\omega)$
±45°
±30°
±5°
$\Omega_y/2\pi = 135.8$ kHz
$\Omega_x/2\pi = 156.3$ kHz
Frequency, $\omega/2\pi$ (kHz)
Re[$S_{xy}(\omega)$]
$\times 10^{-23}$
(b)
-45°
-15°
-5°
+5°
+15°
+45°
$\Omega_y/2\pi = 135.8$ kHz
$\Omega_x/2\pi = 156.3$ kHz
Frequency, $\omega/2\pi$ (kHz)
Im[$S_{xy}(\omega)$]
$\times 10^{-23}$
(c)
-45°
-30°
-5°
+5°
+30°
+45°
$\Omega_y/2\pi = 135.8$ kHz
$\Omega_x/2\pi = 156.3$ kHz
Frequency, $\omega/2\pi$ (kHz)

Results



$\times 10^{-21}$
$S_{xx}(\omega), S_{yy}(\omega)$
(a)
+45°, +30°, +5°
-45°, -30°, -5°
$S_{xx}(\omega)$
±5°
±30°
±45°
$S_{yy}(\omega)$
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-45°
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-5°
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+30°
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