Levitated optomechanics and optical fibres

COST Action QTSpace, March 2017

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Introduction

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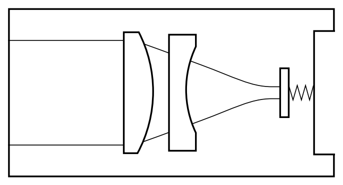
Overview

Optomechanics

Coupling mechanical motion to light [1]

e.g.

- Aspelmeyer (Vienna)
- Painter (Caltech)
- Gröblacher (TU Delft)
- Kippenberg (EPFL)
- LIGO (Caltech & MIT)



Vast scope; considerable fabrication challenges; cryogenics

[1] Aspelmeyer, Kippenberg, Marquardt Rev. Mod. Phys. 86 1391 (2014)

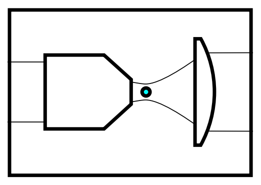
Overview

Optomechanics	Typical numbers
Levitated Optomechanics	Why it's interesting
...with Fibre Optics	Why it's difficult

Levitated Optomechanics

Decouple mechanical mode by *levitating* a.k.a. dipole trap [2]

e.g.



- Novotny (ETH)
- Quidant (ICFO)
- Arndt (Vienna)
- Barker (UCL)
- Ulbricht (Southampton)
- Bateman (Swansea)

Remarkably low damping; exceptionally high Q; thermally decoupled

[2] Gieseler, Deutsch, Quidant, Novotny PRL 109 103603 (2012)

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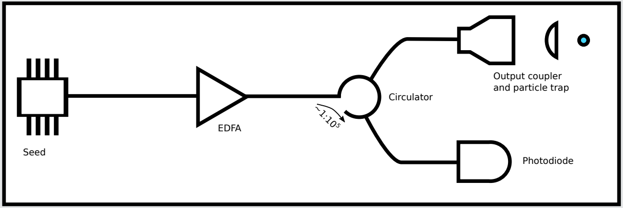
Overview

- Optomechanics
- Levitated Optomechanics
- ...with Fibre Optics
- Typical numbers
- Why it's interesting
- Why it's difficult

... with Optical Fibres



Technical advantages

- Stability (spatial, not in phase)
- Collection efficiency
- Integral amplification
- Increased complexity feasible

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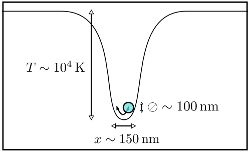
Overview

Typical numbers

- Particle typically $\sim 100\,\mathrm{nm}$ SiO_2 sphere
- Particle mass $M \sim 10^{-17}\,\mathrm{kg} \sim 10^9\,\mathrm{u}$
- Trap depth $\sim 10\,000\,\mathrm{K}$
- Trap frequency $\sim 50\,\mathrm{kHz}$
- Localisation at $T = 300\,\mathrm{K}$ is $\lesssim \lambda/10$



Overview

Optomechanics	Typical numbers
Levitated Optomechanics	Why it's interesting
. . . with Fibre Optics	Why it's difficult

Why it's interesting

Meso-scopic system in which can approach QM limits

Cooling *towards* ground-state[3]

$$T \sim 450\,\mathrm{\mu K} \text{ and } \langle n \rangle = \frac{1}{e^{\hbar\omega/k_B T} - 1} \lesssim 63$$

cf. $T \sim 300\,\mathrm{K}$ and $\langle n \rangle \sim 10^8$

Switchable spring-constant: towards mechanically squeezed states

[3] Jain, Gieseler, Moritz, Dellago, Quidant, Novotny PRL 116 243601 (2016)

Overview

Why it's interesting

Meso-scopic system in which can approach QM limits

Cooling *towards* ground-state[4]

$$T \sim 450\,\mu\mathrm{K} \text{ and } \langle n \rangle = \frac{1}{e^{\hbar\omega/k_B T} - 1} \lesssim 63$$

cf. $T \sim 300\,\mathrm{K}$ and $\langle n \rangle \sim 10^8$

Switchable spring-constant: towards mechanically squeezed states

Why it's difficult

Material purity: only pure SiO_2 so far at low vacuum
Small scattering cross-section: typically $\sim 10^{-5}$
Feedback cooling required to reach low pressures

[4] Jain, Gieseler, Moritz, Dellago, Quidant, Novotny PRL 116 243601 (2016)

Achievements in the field

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Towards ground-state cooling

First demonstrations of mK temperatures:
Raizen (Texas) [5] and Novotny (ETH) [6]

Follows a theoretical description which suggests that ground-state feasible [7]

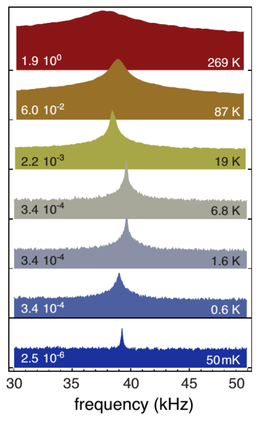
Parametric Feedback cooling

- monitor particle position
- reduce trap intensity when particle *away* from centre
- modulate at 2ω with phase shift

Limited by

- heating from residual gas
- position resolution

Limitation: *Shot-Noise from Rayleigh Scatter* (more later)



[5] Li, Kheifets, Raizen Nat. Phys 7 527 (2011)
[6] Gieseler, Deutsch, Quidant, Novotny PRL 109 103603 (2012)
[7] Chang, Regal, Papp, Wilson, Ye, Painter, Kimble, Zoller PNAS 107 1005 (2010)

Towards Squeezed states

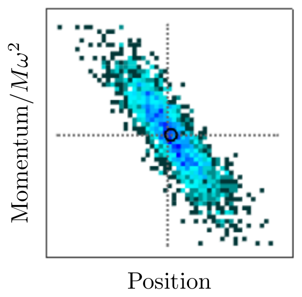
"Squashing" of the Mechanical State [8]

Free-evolution is rigid-body rotation
of distribution in $(x, p/m\omega^2)$

Switch fast switching of spring constant
changes basis; distribution becomes ellipsoidal

Allow 1/4 rotation and switch back

Demonstrated for thermal state;
works without modification for quantum state



Quantum Thermodynamics

Review by Millen and Xuereb [9]

COST Action MP1209 "Thermodynamics in the Quantum Regime"

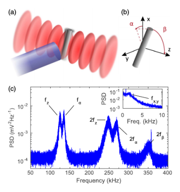
[8] Rashid, Tufarelli, Bateman, Vovrosh, Hempston, Kim, Ulbricht PRL 117 273601 (2016)
[9] Millen & Xuereb, New J. Phys 18 011002 (2016)

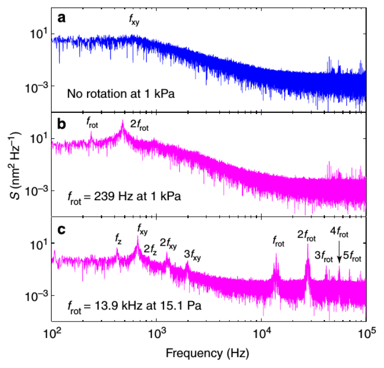
Spinning

5MHz spinning (and 40K cooling) [10] from Dholakia (St Andrews, UK)

Torsional force sensing [11]

"...full control over the rotational and translational dynamics of an optically levitated silicon nanorod" (mbar, clean N_2; Vienna) [12]





[10]Arita, Mazilu, Dholakia Nat. Comm. 4 2374 (2013)
[11]Hoang, Ma, Ahn, Bang, Robicheaux, Yin, Li arXiv:1605.03990
[12]Kuhn, Kosloff, Stickler, Patolsky, Hornberger, Arndt, Millen Optica 4 356 (2017)

Propspects for fundamental tests

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Stochastic Extensions to QM

Proposed extensions to Schrödinger equation[13]; adds a fundamental stochastic term

Depends on Mass, Separation, and Time[14]

Proposed levitated nanoparticle test[15] (Challenges akin to OTIMA[16])

Proposal description

Trap and cool particle

Drop through phase-grating

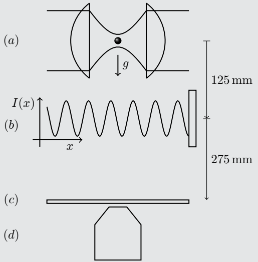
Observe distribution

Time-scale $\propto M^2$

$M \lesssim 10^6\,\mathrm{u}$ limited by free-fall height

Includes realistic decoherence

Experimental schematic



[13] Bassi, Lochan, Satin, Singh, Ulbricht RMP 85 471 (2013)
[14] Nimmrichter and Hornberger PRL 110 160403 (2013)
[15] Bateman, Nimmrichter, Hornberger, Ulbricht Nat. Commun. 5 4788 (2014)
[16] Haslinger, Dörre, Geyer, Rodewald, Nimmrichter, Arndt Nature Phys 9 144 (2013)

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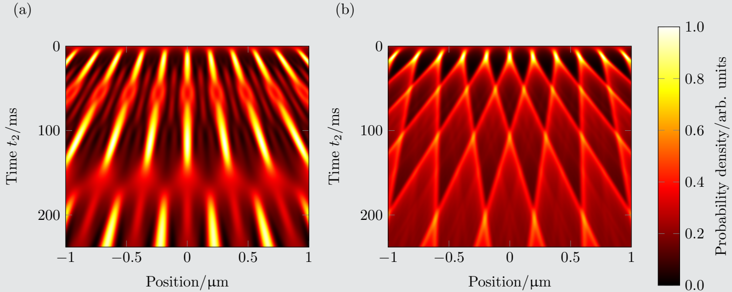
Predicted distribution



(a) Quantum and (b) Classical probability densities t_2 after the grating pulse

MAQRO

Geometry adopted by MAQRO [17]

Largely based on available optical space technology; ideally Lagrange L1 or L2 [18]

[17] Kaltenbaek et al. EPJ Quantum Technology 3 5 (2016)

[18] http://maqro-mission.org/

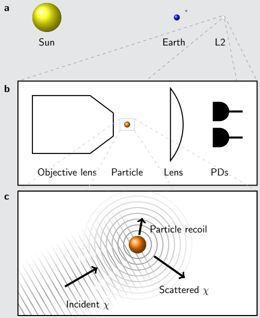
Dark Matter

Small feasible low-mass window[19]: $m \sim 100\,\mathrm{eV/c^2}$

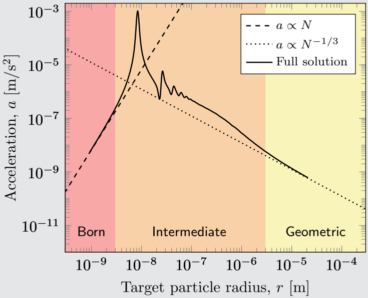
Long wavelength $\implies$ coherent scattering from normal matter (cf. *neutron optics*)

Space-based measure of anomalous accelleration: nanoparticle optimum size

Experimental schematic



Anomalous Acceleration



[19] Bateman, McHardy, Merle, Morris, Ulbricht Sci. Rep. 5 8058 (2014)

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Schrödinger–Newton

What is the gravitational field of a superposition? [20]

Perhaps gravity does not need to be quantized: fundamentally semi-classical theory.

Add self-gravity of wavefunction to Schrödinger

($\|\psi\|^2$ interpreted as mass-distribution)

Proposal description

Cryogenic linear Paul trap

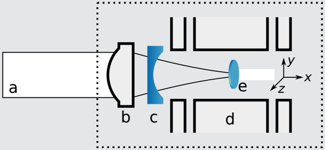
Levitated superconducting disc

Self-gravity adds anharmonicity

Optomechanical position readout

Larger masses accessible in space

Experimental schematic



Frequency $\sim 10\,\mathrm{Hz}$

Frequency shift $\sim 0.1\,\mathrm{mHz}$

[20] Großardt, Bateman, Ulbricht, Bassi PRD 93 096003 (2016)

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Short-range gravity

Experimental tests to guide development of Quantum Gravity

One avenue is deviations from $1/r^2$ at short lengths

Geraci proposed measuring short-range gravity via levitated optomechanics[21]

(Milligram-scale proposals[22]; cold atoms constrain $\alpha < 10^{-3}$ at $\lambda \sim \mathrm{mm}$ [23])

Proposal description

Particle, in standing wave, near surface

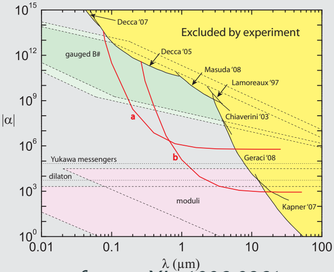
Behind screen, oscillate local mass-density at trap frequency

Drive nanoparticle motion resonantly

Yukawa parameterisation:

$$V = -\frac{GMm}{r}\left[1 + \alpha e^{-r/\lambda}\right]$$

Experimentally excluded regions



from arXiv:1006.0261

[21] Geraci, Papp, Kitching PRL 105 101101 (2010)
[22] Schmöle, Dragosits, Hepach, Aspelmeyer Class. & Quant. Grav. 33 125031 (2016)
[23] Biedermann, Wu, Deslauriers, Roy, Mahadeswaraswamy, Kasevich PRA 91 033629 (2015)

Challenges & Techniques

Overview

Detection: Position resolution & Collection efficiency

Technical: Stability & Calibration

Fundamental: Process Noise

Detection: Position resolution & Collection efficiency

- Particle Rayleigh scatters:
  - position information
  - momentum kicks
- Want to approach Standard Quantum Limit
  - $\implies$ collect large fraction of scatter

- Free space
  - mm scale beams and 100 $\mu\mathrm{m}$ scale detectors
  - $\lesssim 1\%$ of scatter
- Fibre optics
  - couple $\sim 60\%$ back-scatter into single mode fibre
  - all of collected light usable at detector

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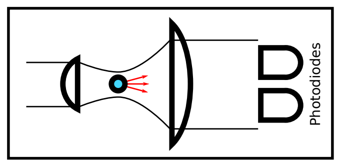
Forwards scatter

Technique by Gieseler et al.[24]



Focussed Gaussian beam has Gouy shift (π relative to plane wave)

Scattered light not subject to Gouy shift

Phase difference between laser and scatter

Phase throughout focus

$$\phi(z) = kz - \arctan(z/z_R)$$

Phase difference (z_R is Gouy shift)

$$\Delta\phi(z) = kz - \phi(z) = \arctan(z/z_R)$$

Sensitivity of phase difference at focus

$$[\partial_z \Delta\phi|_{z\to 0} = z_R^{-1}$$

Very stable; looking for tiny signal atop entire laser signal.

[24] Gieseler, Deutsch, Quidant, Novotny PRL 109 103603 (2012)

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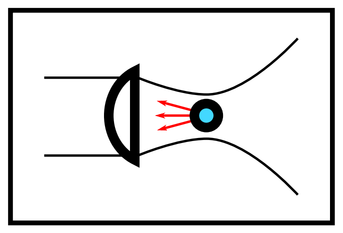
Backwards scatter

Gouy shift remains in laser focus

$$\phi(z) = kz - \arctan(z/z_R)$$

Phase difference is now sum of delay to particle and delay back



$$\Delta\phi = kz + \phi(z) = 2kz - \arctan(z/z_R)$$

Phase sensitivity at focus

$$\partial_{\Delta\phi}\big|_{z\to 0} = 2k - z_R^{-1}$$

(cf. forward scatter $\partial_z \Delta\phi|_{z\to 0} = z_R^{-1}$.)

Diffraction limit constrains Rayleigh range $z_R \gtrsim \lambda$

Therefore, back-scattered is $\gtrsim 11\times$ more sensitive.

Same optic as focusses laser collects the scatter

Reference field follows macroscopically different path $\implies$ phase-drift θ

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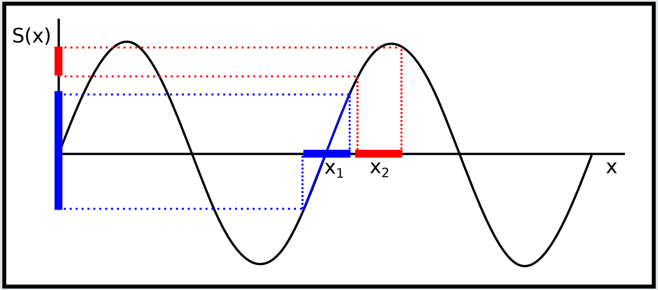
Interferometric response curve



If $\langle x \rangle = x_1$, interferometric response $\approx$ linear

If $\langle x \rangle = x_2$ (equivalently, θ drifts), response is non-linear

Typical amplitude $2k\sqrt{\langle x^2 \rangle}$ is not small, so always somewhat non-linear

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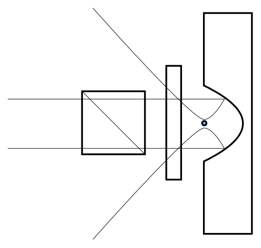
Parabolic Mirror

Developed at Southampton with Hendrik Ulbricht[25]



High Numerical Aperture $\mathrm{NA} \gtrsim 0.995$

Achromatic focusing

Reference field is diverging

Scattered field is collimated

Phase-offset stable (cm-scale in-vacuum)

and tunable via wavelength[26]

Place detector distance $\sim 1\,\mathrm{m}$ away

$\implies$ field amplitudes comparable

$\implies$ can use low-power detectors

$\implies$ maximal modulation

Sub-optimal detection: cm-scale beam and 100um-scale detector

$\implies$ small fraction of light used and alignment very sensitive

[25] Rashid, Tufarelli, Bateman, Vovrosh, Hempston, Kim, Ulbricht PRL 117 273601 (2016)

[26] arXiv:1603.02917

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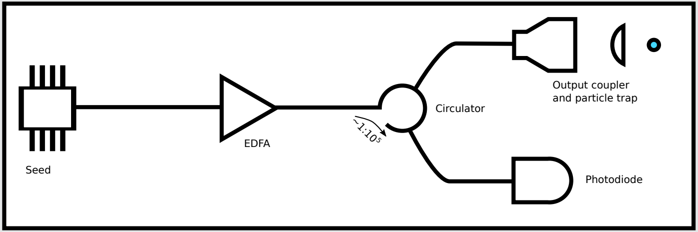
Fibre optics

Motivated by need for alignment stability and better light collection



Single-mode fibre so *very nearly* perfect Gaussian beam

Large fraction ($\sim 60\%$) of back-scatter usable at detector

Macroscopic path difference $\sim$ metres $\implies$ significant drift
(although, see prior-art using end-facet of fibre[27].)

e.g. Small fraction going wrong way through circulator

Polarisation the same *by construction*
(fibre propagation more like mirrors in 3D than drifting waveplates)

[27] Mestres, Berthelot, Spasenovic, Gieseler, Novotny, Quidant APL 107 151102 (2015)

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Overview

Detection: Position resolution & Collection efficiency

Technical: Stability & Calibration

Fundamental: Process Noise

Technical: Stability & Calibration

- Photodiode mapped to position via thermodynamics
    - Often assumes $T = 300\,\mathrm{K}$ at high pressure
    - Claims of low temperature/phonon occupation
    - Some more sophisticated techniques[28]
- Detection is interferometric
    - Phase-drift in free-space is tolerable
- Fibre optics (prior-art [29])
    - spatially stable (single mode)
    - significant phase drift (metre-scale path differences)
- Tackling phase-drift leads to new position measurement technique

[28] Millen, Deesuwan, Barker, Anders Nature Nanotech. 9 425 (2014)

[29] Mestres, Berthelot, Spasenović, Gieseler, Novotny, Quidant Appl. Phys. Lett. 107 151102 (2015)

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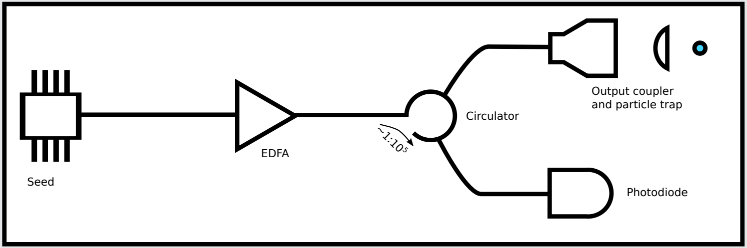
Significant phase drifts

Ideally, want detection linear in position z

Interferometric detection gives $\sin(2kz + \theta) \approx 2kz$ for $\theta = 0$ and $kz \ll \pi$.



- Forward scatter:
  - $\theta = 0$ by construction
- Backwards scatter:
  - Parabolic mirror: θ stable and tunable to 0
  - Fibre optics: θ drifts fast 2π in $\sim 100\,\mathrm{ms}$.

But. . . kz not $\ll \pi$ for many situations

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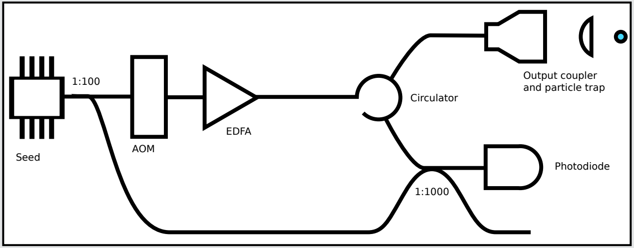
(Super-)heterodyne detection

Alignment stability and light collection make this worth pursing

Harmonic particle motion $\implies$ sinusoidal phase modulation $\implies$ sidebands

When centred on $\omega = 0$, *interference* between -ve & +ve sidebands
$\implies$ sideband amplitudes depend on phase offset, θ

Offset from $\omega = 0$ by *heterodyne* detection (RF techniques)



- Shift optical frequency by 80 MHz via AOM
- Match ratio via tap-couplers and interfere
- Down-shift $\sim$ 80 MHz with RF mixer

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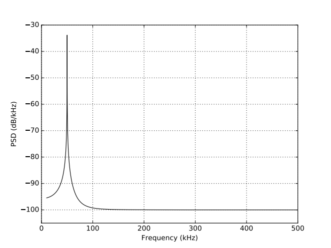
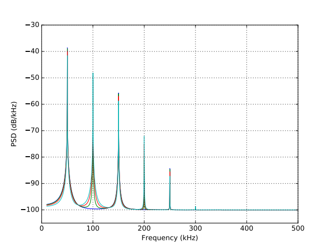
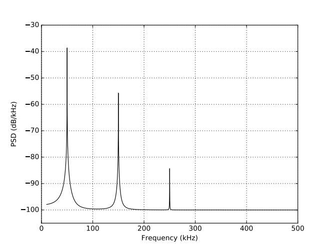


Position PSD (50 kHz, 100 Hz wide)

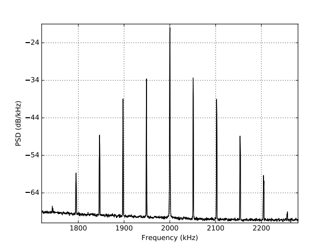


Example backward-scatter: θ drifting



Typical forward-scatter for $T = 300\,\mathrm{K}$

Interference btwn -ve & +ve sidebands



Experimental heterodyne signal

θ dependence now absent

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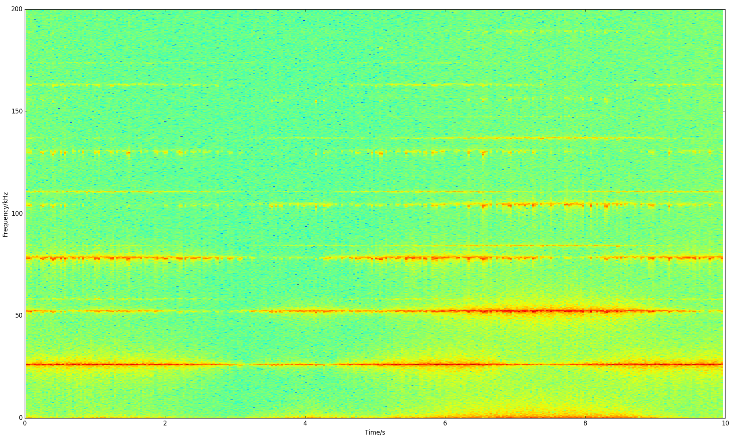

Example Homodyne PSD-spectrogram showing drift of θ

Each vertical slice is PSD for short time-interval

Sidebands spaced by 26 kHz; Odd/even orders drift in/out over $\sim$ seconds

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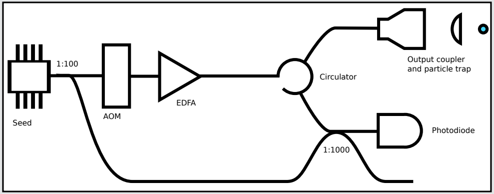
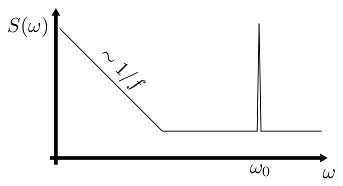
Phase Lock Loop

Large oscillation amplitude $kz \sim \pi$ motivates Phase Lock Loop approach



Shift optical frequency by 80 MHz via AOM
Match ratio via tap-couplers and interfere
Down-shift $\sim 80\,\mathrm{MHz}$ with RF mixer

Low-pass filter and signal $\propto \sin(2kz + \theta)$
Phase-lock-loop via feedback to AOM drive
Low-frequency $\sim 1/f$ thermal drift
Single peak linear in position and calibrated
cf. $\int$ *PSD peak, assuming* $T = T_{env}$



Effect of signal degradation in mixer etc not clear

Entropy vs Temperature

Impressive demonstrations have been for cold and low occupation

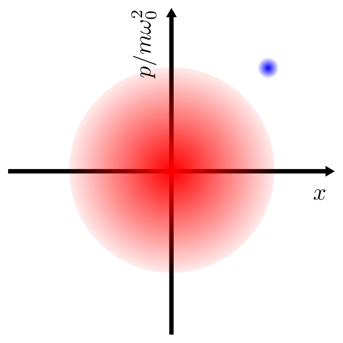
Phase-space (Wigner-function) representation

Seeking low phase-space volume

- achieve by either cooling
- or measuring really well

Kalman filter

- predict state based on dynamics
- updated based on measurements
- provably optimal for Gaussian noise
- Quantum generalisations [30]



[30] Wieczorek, Hofer, Hoelscher-Obermaier, Riedinger, Hammerer, Aspelmeyer PRL 114 223601 (2015)

Overview

Detection: Position resolution & Collection efficiency

Technical: Stability & Calibration

Fundamental: Process Noise

Fundamental: Process noise

- Gas collisions
  - require UHV
- Blackbody radiation
  - absorption/emission; scattering negligible
  - Influences material choice (e.g. Si, SiO_2, Diamond)
  - Requires cryogenics for Schrödinger–Newton
- Rayleigh scattering
  - hence free-fall for Matterwave interferometer(s)
  - proposals to minimize free-flight [31]
  - or space-based (e.g. MAQRO) to remove g

[31] Wan, Scala, Morley, Rahman, Ulbricht, Bateman, Barker, Bose, Kim PRL 117 143003 (2016)

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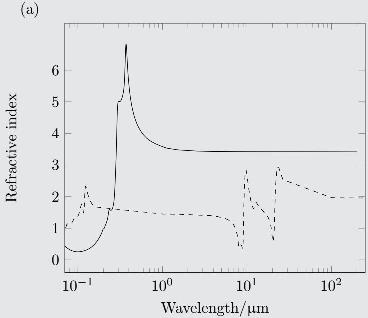
Silica vs Silicon spectra



Dashed line silica; solid line silicon; Laser $\lambda_{\mathrm{L}} \sim 1.5\,\mu\mathrm{m}$; Blackbody $\lambda_{\mathrm{Bb}} \sim 50\,\mu\mathrm{m}$

Diamond *very much like* silicon $\implies$ nanodiamonds at low pressure very difficult

- possibly material purity, but perhaps limited by Bb[32]
- demonstrations[33] and recent progress[34]

[32] Rahman, Frangeskou, Kim, Bose, Morley, Barker Sci. Rep. 6 21633 (2016)
[33] Kuhn, Kosloff, Stickler, Patolsky, Hornberger, Arndt, Millen Optica 4 356 (2017)
[34] Frangeskou, Rahman, Gines, Mandal, Williams, Barker, Morley arXiv:1608.04724

Challenges/Blackbody radiation

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Bb/Decoherence

Thermal photons leak information to environment

$\lambda_{\mathrm{Bb}} \sim hc/k_B T \sim 50\,\mu\mathrm{m}$ at $300\,\mathrm{K}$

one or two don't matter, but $\sim 10^3$ are a problem

both absorption & emission (cryogenics for Schrödinger–Newton proposal)

Bb/Cooling!

Blackbody radiation necessary to stop particle melting

At $\lesssim 10^{-2} mbar$, negligible gas conduction

Usable materials limited by absorption properties

Bb/Material choice

Nanoparticle in *high intensity* laser wavelength λ_{L}

Require: low absorption at λ_{L} and good emissivity at λ_{Bb}

SiO_2 excellent emitter; Si very poor emitter

Experimentally, only SiO_2 *so far* at low pressure

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Swansea University

Rayleigh scattering

Shot-noise in Rayleigh scattered light randomizes particle momentum

For typical numbers, dominates around 10^{-7} mbar

Fundamental limit to achievable sensitivities?

State-of-the-art

Direct Measurement of Photon Recoil[35]

Background gas:

$T_{\text{equlib}} = 300\,\mathrm{K}$ and *rate* $\gamma \propto \text{Pressure}$

Rayleigh scatter:

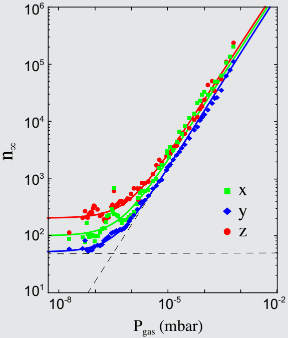
$T_{\text{equlib}} \sim \hbar\omega/k_B \sim 10^4\,\mathrm{K}$ and *rate* $\gamma = \text{constant}$

Feedback cooling:

$T_{\text{equlib}} \sim \mathrm{mK}$ and *rate* $\gamma = \text{constant}$

Plot mean occupation vs pressure

Photon scattering dominates below $\lesssim 10^{-7}$ mbar



[35] Jain, Gieseler, Moritz, Dellago, Quidant, Novotny PRL 116 243601 (2016)

Coherent feedback

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Overview

Rayleigh scatter suppression an example of coherent feedback

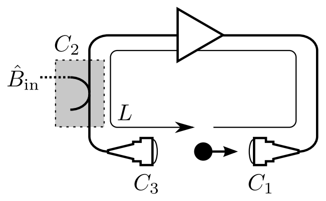
Emulate Cavity Optomechanics?

Amplified Unidirectional Ring Cavity

Cavity optomechanics might seem far-fetched given huge loss ($\sim 10^{-5}$)

However, low-noise amplification is possible

e.g. amplified unidirectional ring cavity[36]



Coherent feedback

Beat all measurement-based feedback [37]

Generally more scope for interesting types of feedback control[38]

[36] Xuereb et al., J. Mod. Opt. 58, 1342 (2011); arXiv:1101.0130
[37] New J. Phys 16 073036 (2014)
[38] Serafini ISRN Optics 275016 (2012); arXiv:1210.4186

Closing

Thank you

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PhD positions available

`swansea.ac.uk/science/research/dtc/`