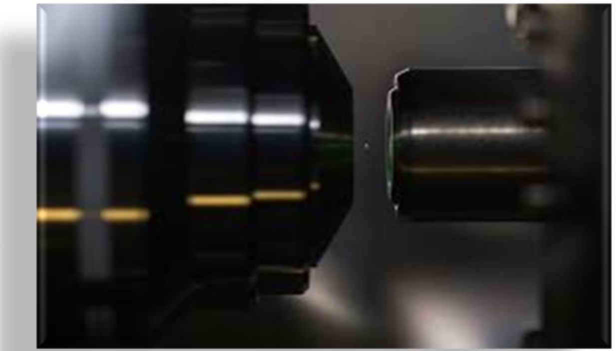
2019

Flying lasers for sound



*Courtesy J. Adam Fenster & A. N. Vamivakas

Levitated
Optomechanics

Optics & Photonics News **27** 42 (2016)

R. Pettit[1,2], W. Ge[3], P. Kumar[3], K. Xiao[3], L. Neukirch[1,2], D. Luntz-Martin[1], J. Schulz[1,2], Mishkat Bhattacharya[2,3,4] and A. N. Vamivakas[1,2]

[1]Institute of Optics & [2]Center for Coherence and Quantum Optics
University of Rochester
[3]School of Physics and Astronomy & [4]Future Photon Initiative
Rochester Institute of Technology

R·I·T

Office of Naval Research
ONR
Science & Technology

University of Rochester

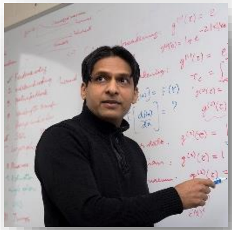
2019

AMO Theory group @ RIT

Rochester Institute of Technology: 20,000students+1100 faculty
School of Physics and Astronomy: ~38 fulltime faculty,
PhD Program in Astrophysics
MS in physics started in 2018

THEORY (RIT)

mxbsps@rit.edu



MB

Brandon. R.

Wenchao Ge

Pardeep K.

Kewen. X

Sandeep S.

Arpita P.

EXP (UofR)

University of Rochester

Nick V.

Levi Neukirch

Robert Pettit

nick.vamivakas@rochester.edu

Talk outline

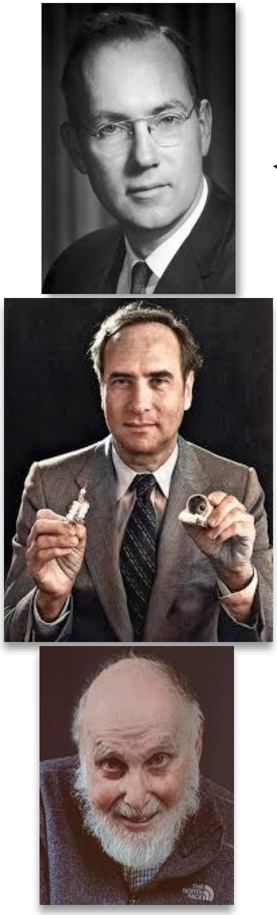
- Introduction
- Theory
- Experiment
- Conclusion

B. Rodenburg, L. P. Neukirch, A. N. Vamivakas and **M. Bhattacharya** Quantum model of cooling and force sensing with an optically trapped nanoparticle, *Optica* **30**, 318 (2016).

*R. M. Pettit, W. Ge, P. Kumar, D. R. Luntz-Martin, J.T. Schultz, L. P. Neukirch, **M. Bhattacharya** and A. N. Vamivakas, An Optical Tweezer Phonon Laser, *Nature Photonics* **13**, 402 (2019).

* News and Views, R. Huang & H. Jing, *Nature Photonics*, **13**, 371 (2019)
* Optics and Photonics News, May 2019, Breakthroughs of 2019,Dec 2019.

Optical laser



Laser history

1. Maser invented by Townes in 1953.
2. Laser proposed by Townes and Schawlow in 1958.
3. Laser built in 1960 by T. Maiman.
4. Quantum theory proposed in 1960s (Haken, Lamb, Lax…)
5. *Multiple Nobel prizes*
   - 1981 Bloembergen, Schawlow
   - 1997 Chu, Cohen-Tannoudji, Phillips
   - 2001 Cornell, Wieman, Ketterle
   - 2005 Hansch, Hall, Glauber
   - 2012 Haroche, Wineland
   - 2017 Weiss, Thorne, Barish
   - 2018 Ashkin, Morou, Strickland

   ….

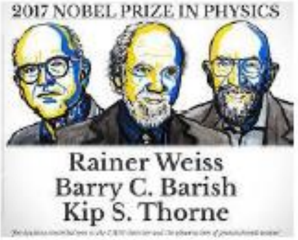
Edible laser with jello..

$10B industry

The Laser Inventor (Springer, 2018)

Cavity optomechanics: Displacement sensing

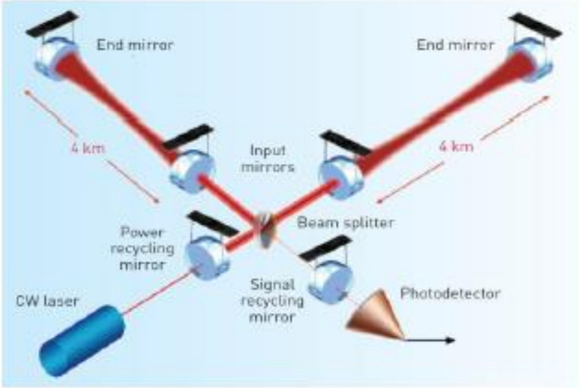
PRL **116,** 061102 (2016)   PHYSICAL REVIEW LETTERS   12 FEBRUARY 2016

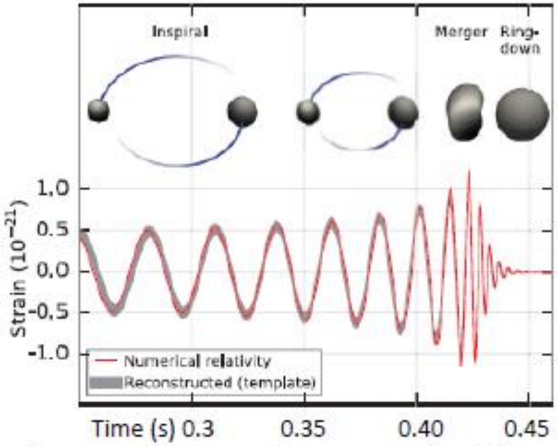

2017 NOBEL PRIZE IN PHYSICS
Rainer Weiss
Barry C. Barish
Kip S. Thorne

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)





Also...

Accelerometry
A. G. Krause, M. Winger, T. D. Blasius, Q. Lin and O. Painter, *Nat. Photon.* 6 768 (2012)

Magnetometry
S. Forstner et. al, *PRL* **108** 120801 (2012)

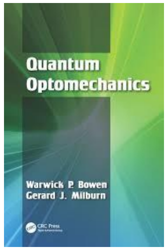
Thermometry
J. Millen et. al, *Nat. Nano.* 9 425(2012)

→ LIGO is a cavity optomechanical device !!

Displacement = Strain x Length of int. arm

$$\approx 10^{-18} m$$

Quantum-classical interface, sensing, transduction, Slow light, OMIT, memory.


Quantum Optomechanics
Warwick P. Bowen
Gerard J. Milburn

Photons and phonons

Photons ~ Phonons

Both are realizations of the harmonic oscillator

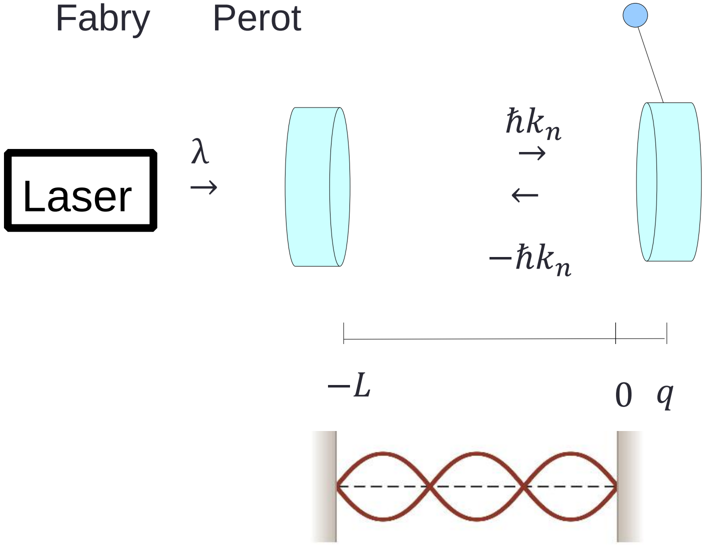
(E, B) ~ (Q,P)

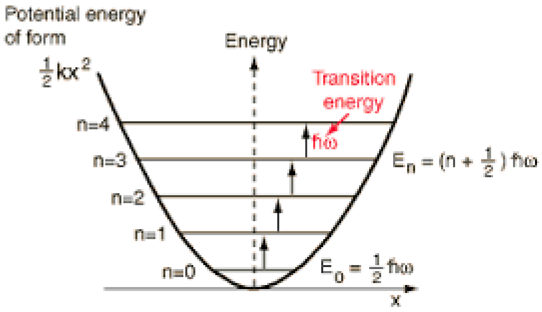
→ Can we make a laser for phonons?

The role of feedback

Fabry

Perot





Radiation Force $\propto$ *optical intensity*

Light-matter interaction energy

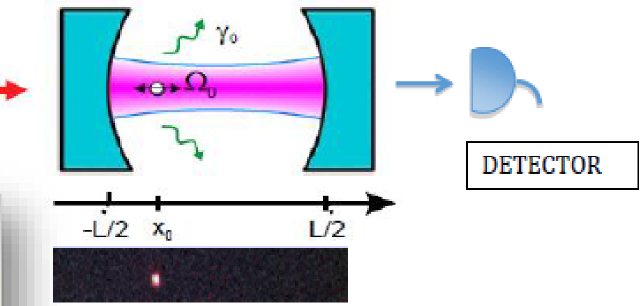
$\propto$ *optical intensity* $\times q$

$$\downarrow$$

$$a^\dagger a$$

- C. K. Law, PRA **51**, 2537(1995).
- MB, et. al, AJP **81**, 267 (2013).

Cavity optomechanics: Levitation



Theory: D. E. Chang et. al, PNAS **107**, 1005 (2007)
O. Romero-Isart….I. Cirac, PRL **107**, 020405 (2011)

Expmt: N. Keisel…M. Aspelmeyer et al., PNAS **110**, 14180 (2013): 64 K
J. Millen…P. Barker et. al, PRL **114**, 123602 (2015): 10 K

Limitations

1. Manipulation only possible along cavity axis
2. Physical access to particle limited
3. Scaling is complicated
4. Optical wavelengths have to be resonant with the cavity
5. Interaction is given

Question:

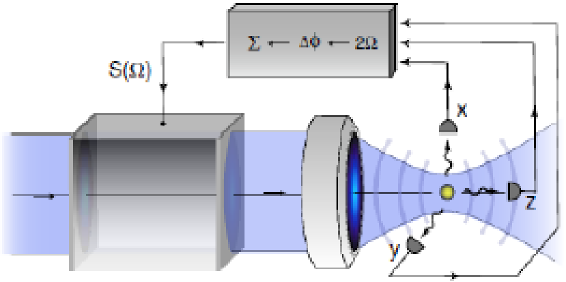
Can we do optomechanics without cavities?

→ Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E. & Chu, S. *Observation of a single-beam gradient force optical trap for dielectric particles*. Opt. Lett. **11**, 288–290 (1986)

O. Romero-Isart et al. PRL **107**, 020405 (2011)
P Asenbaum, S Kuhn, S Nimmrichter, U Sezer, M Arndt, Nat. Comm **4**, 111 (2013)

Cavity*less* optomechanics: Levitation

Single beam nanoparticle trapping



$$E = E_t e^{-a\, q^2}$$

Gaussian beam

Optical force on a Rayleigh particle ($r \ll \lambda$)

= Gradient force + ~~Scattering~~ force

$$V_t = -d.E$$

Trapping potential

$$= -\frac{\alpha E^2}{2} \sim b I_t q^2$$

Harmonic trap along each spatial direction

Note: All manipulation of the nanoparticle will be done by modulating I_t.

J. Gieseler, B. Deutsch, R. Quidant, and L. Novotny, PRL **109** 103603 (2012)

L. Neukirch, E. von Hartmann, J. M. Rosenholm, and A. N. Vamivakas, Nat. Phot. **9**, 653–657 (2015).

J. Millen, T. Deesuwan, P. Barker, J. Anders, Nat. Nanotech. **9**, 425 (2914)

M Rashid…H. Ulbricht, PRL **117**, 273601 (2016).

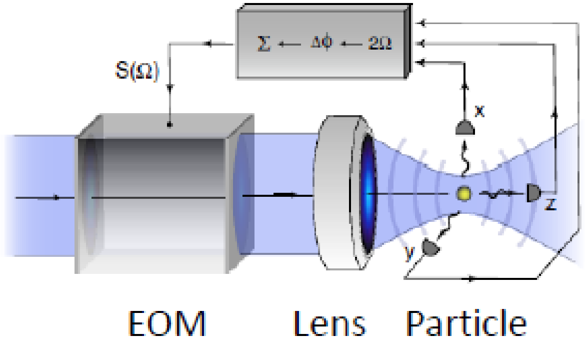
R. Gambhir…A. A. Geraci, PRA **91**, 051805(R) (2015).

Thai M. Hoang…Tongcang Li. Nat. Comm**.** **7**, 12550 (2016)

G. Conangla…N.Meyer,…R. Quidant, PRL **122**, 223602 (2019).

Cavityless optomechanics: Feedback

Cavity*less* optomechanics: Feedback



Linear damping: $F_l \propto -p$

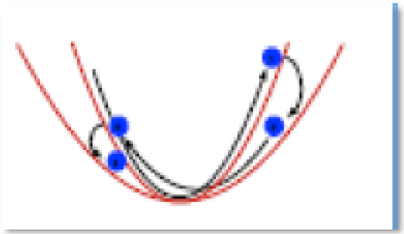
- This is present due to collisions with gas particles
- It can also be engineered using parametric feedback

Measure q
Calculate p

Modulate the trap laser $V_t \sim (I_t + \epsilon_l \frac{p}{q}) q^2$

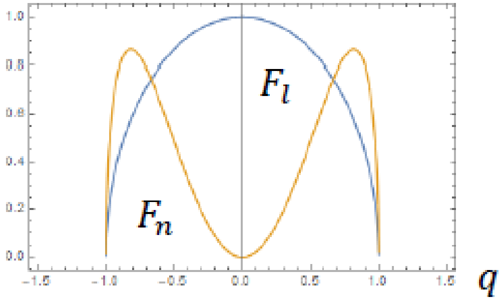
$F_l = -\partial V_t / \partial q \;\propto -\epsilon_l p$

Nonlinear damping: $F_n \propto -q^2 p$



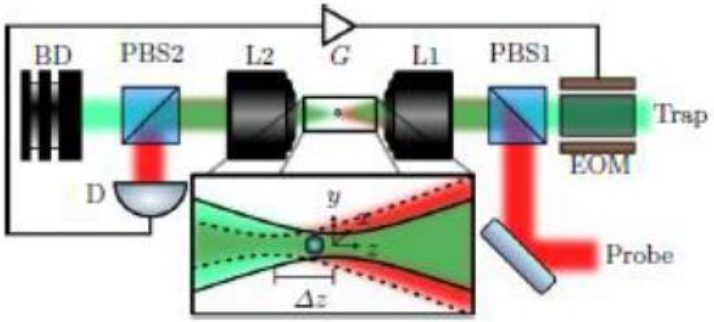
Measure q
Calculate p
Modulate the trap laser $V_t \sim (I_t + \epsilon_n p q) q^2$

$F_n = -\partial V_t / \partial q \;\propto -\epsilon_n q^2 p$



Theoretical model: microscopic Hamiltonian

A theorist's view of the experiment



$$\boxed{H = H_m + H_f + H_{int}}$$

Kinetic energy

$$H_m = |\mathbf{p}|^2/2m$$

Field energy

$$H_f = \varepsilon_0 \int |\mathbf{E}(\mathbf{r})|^2 \mathrm{d}^3\mathbf{r}$$

Interaction energy

$$H_{\mathrm{int}} = -\int_V \mathbf{P}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r}) \mathrm{d}^3\mathbf{r}/2$$

Total field

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_\mathbf{t} + \mathbf{E}_\mathbf{p} + \mathbf{E}_\mathbf{b}$$

Polarizable nanoparticle

$$\mathbf{P}(\mathbf{r}) = \alpha\, \mathbf{E}(\mathbf{r})$$

Procedure: Eliminate bath modes using Born-Markov approximation
Trace over probe field and *x*, *y* motion
Add suitable terms for gas collisions
Add Markovian feedback and backaction

A. C. Pflanzer, O. Romero-Isart, J. I. Cirac, PRA **86**, 013802 (2012)

Theoretical model – Master equation

$\dot{\rho}$

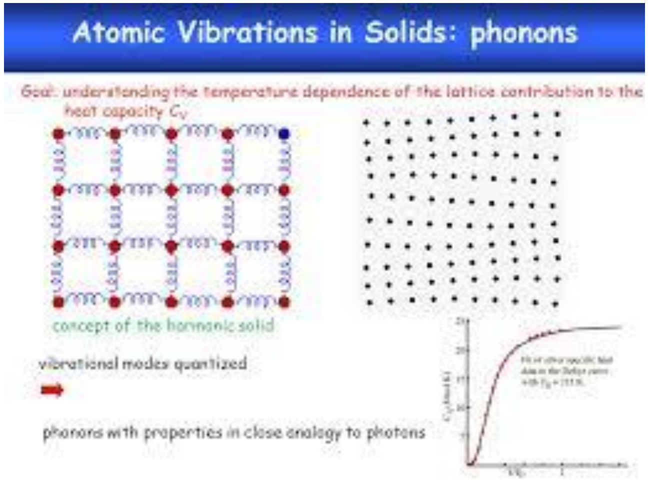
$= -i\left[\omega_m b^\dagger b, \rho\right]$	Unitary dynamics
$-\frac{\left(A_t + D_p\right)}{2} D[q]\rho$	Position diffusion
$-\frac{D_q}{2} D[p]\rho$	Momentum diffusion
$-i\frac{\gamma_g}{2}[q,\{p,\rho\}]$	Gas damping
$-i\gamma_f[q^3,\{p,\rho\}]$	Nonlinear feedback cooling
$-\Gamma_f D[q^3]\rho$	Backaction
$+i\gamma_l[q,\{p,\rho\}]$	Linear heating
$-\Gamma_l D[q]\rho$	Backaction

L. Diosi, Quantum master equation of a particle in a gas environment *Europhysics Letters* **30**, 63 (1995)

H. M. Wiseman and G. J. Milburn, Quantum theory of optical feedback via homodyne detection *Physical Review Letters* **70**, 548 (1993)

$$D[O]\rho = O^\dagger O\rho + \rho O^\dagger O - O\rho O^\dagger$$

Phonons



Atomic Vibrations in Solids: phonons

Goal: understanding the temperature dependence of the lattice contribution to the heat capacity C_V

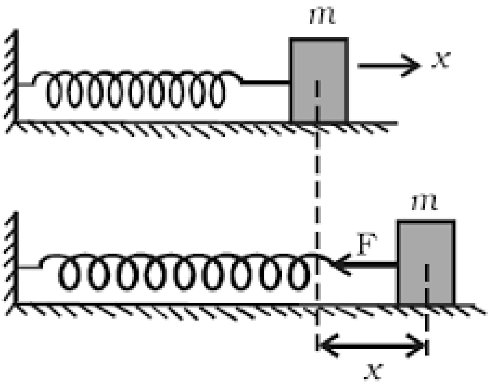
concept of the harmonic solid

vibrational modes quantized

➡

phonons with properties in close analogy to photons

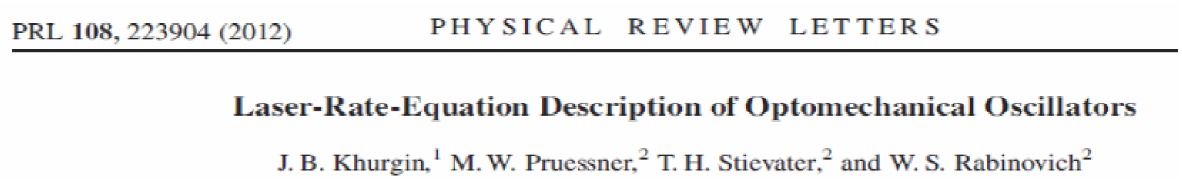
Center of mass vibrations



Linear harmonic oscillator

Phonon lasers in cavity optomechanics

(Lots of work in
the solid state!!)



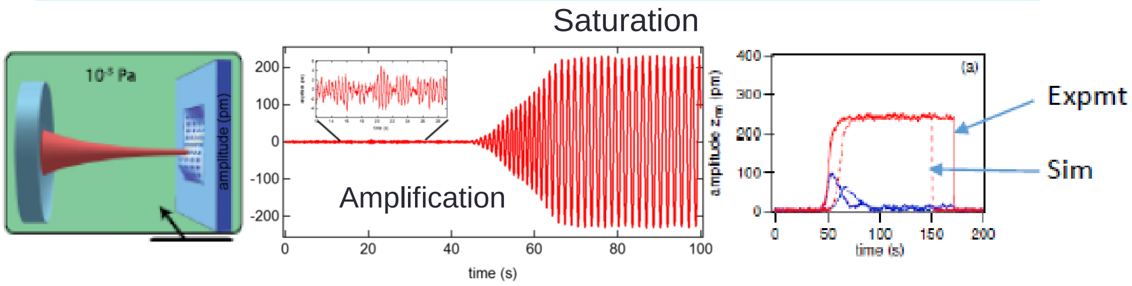
PRL 108, 223904 (2012) PHYSICAL REVIEW LETTERS

Laser-Rate-Equation Description of Optomechanical Oscillators

J. B. Khurgin,[1] M. W. Pruessner,[2] T. H. Stievater,[2] and W. S. Rabinovich[2]

"Optomechanical systems in which optically furnished gain enables self-sustained mechanical oscillation are properly called phonon lasers."

Mode competition and Anomalous Mode cooling in a Multimode Phonon Laser
- Kemiktarak et. al, PRL **113**, 030802(2014)



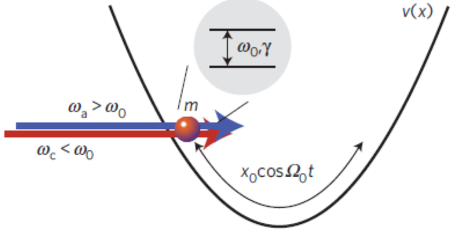
*H. Jing, et al.
PRL **113**, 053604 (2014)

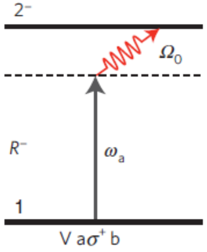
*D. Navarro-Urrios et al.,
J. Opt.**18**, 094206 (2016)

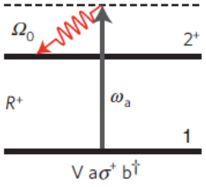
Phonon lasers in cavity optomechanics, K. Vahala et al.,
OSA Technical Digest (2010).

Levitated optomechanics: Phonon laser with a trapped ion

Using a trapped Mg^+ ion



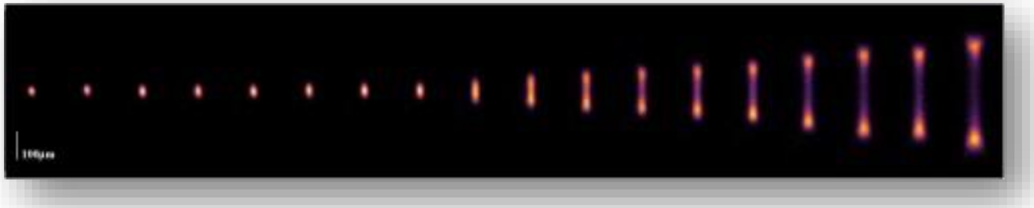




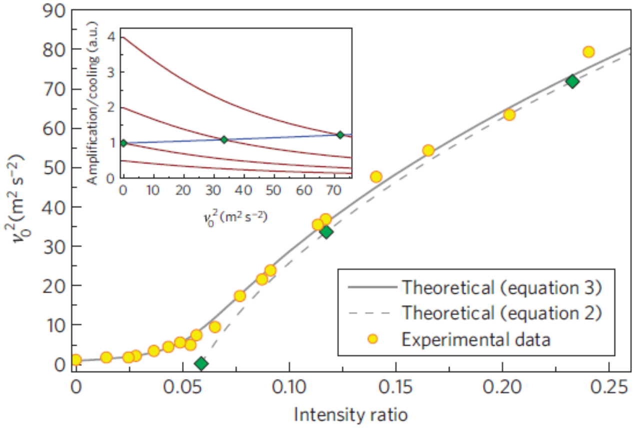
Cooling

Amplification

Threshold Behavior



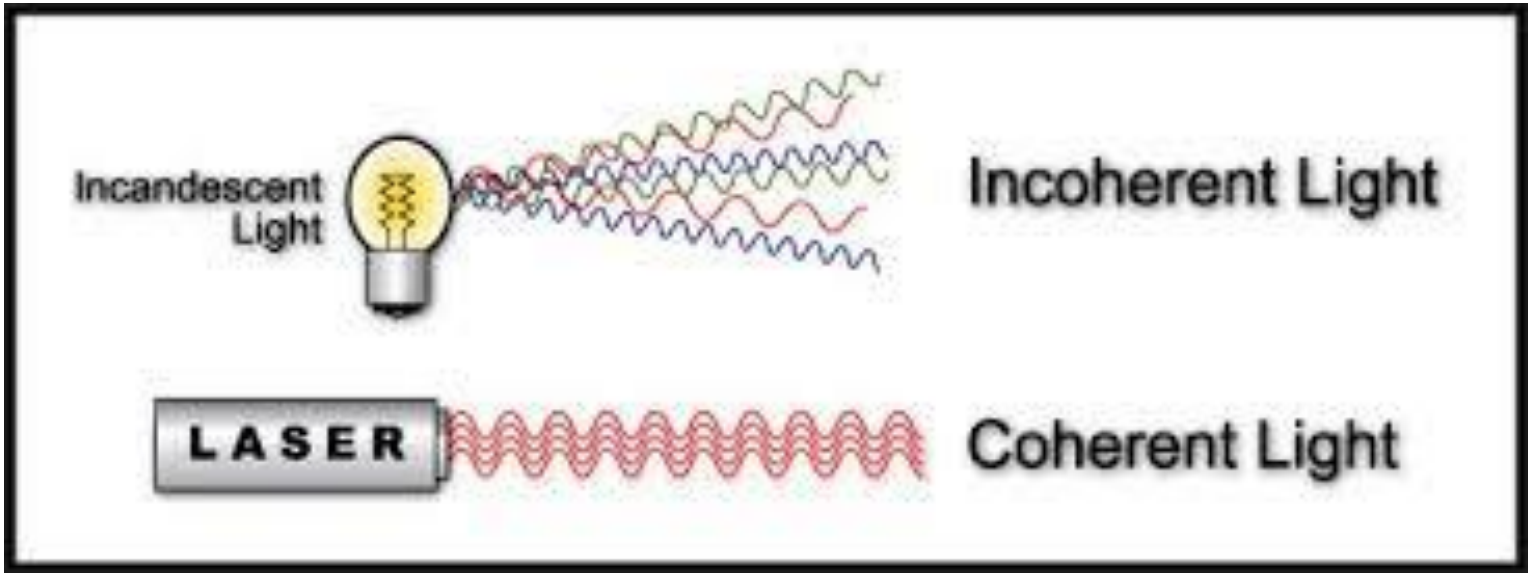
Nobel
Prize
2005



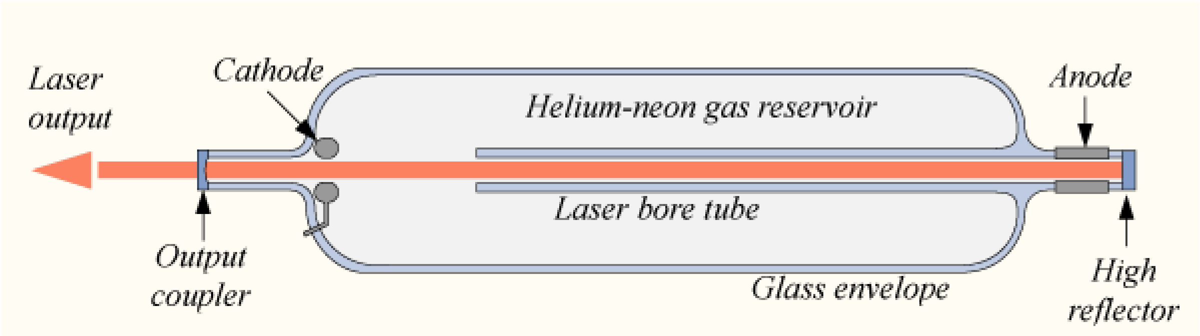
A phonon laser, K. Vahala et. al, Nature Physics **5,** 682 (2009)

Phonon lasing from optical frequency comb…Michael Ip et al., PRL **121**, 04320 (2018)

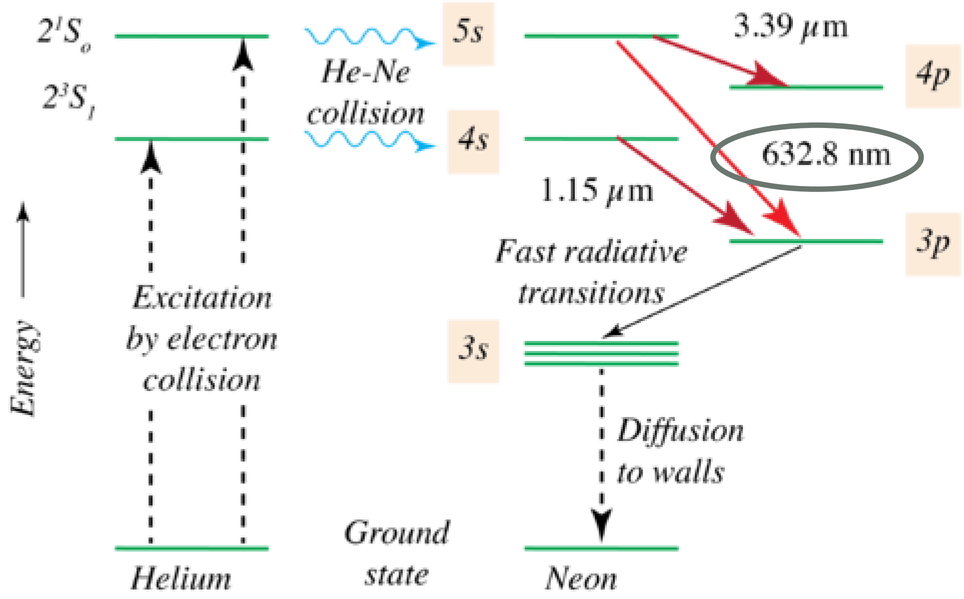
Optical laser

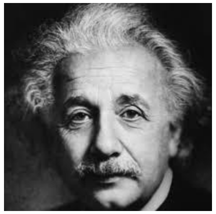


Optical laser

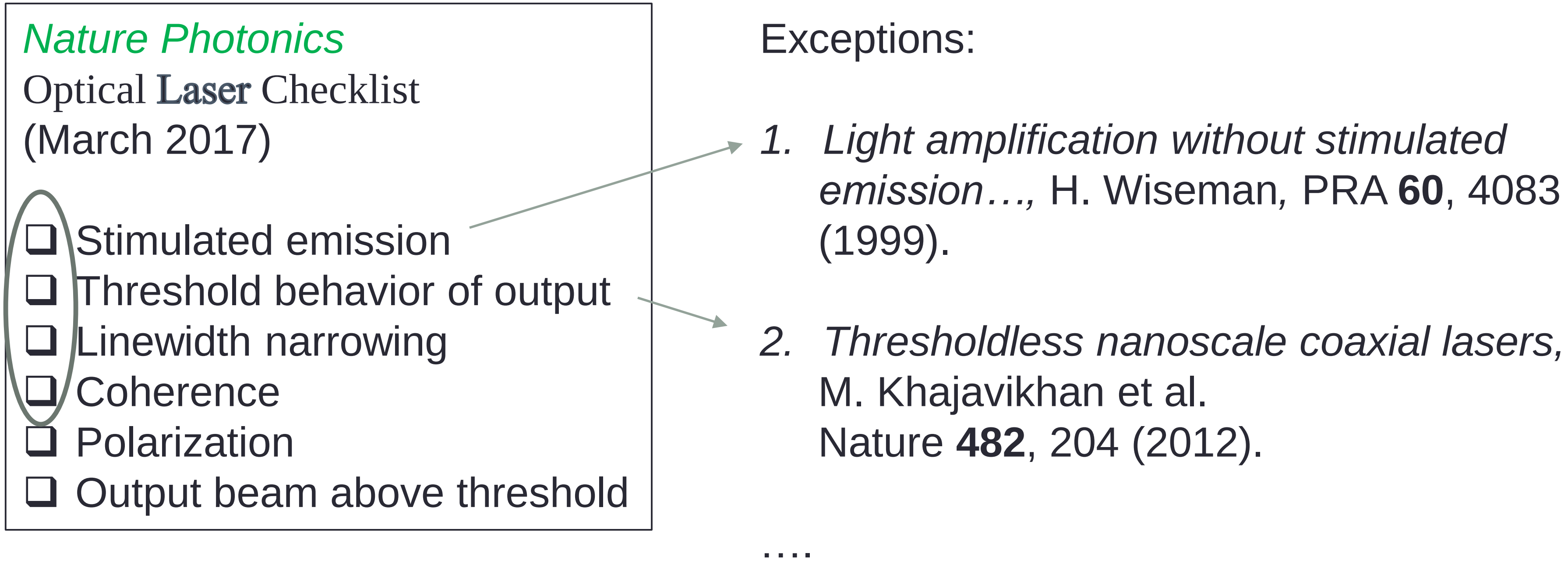


GAIN MEDIUM





What is a (phonon) laser?



Nature Photonics
Optical **Laser** Checklist
(March 2017)

- ☐ Stimulated emission
- ☐ Threshold behavior of output
- ☐ Linewidth narrowing
- ☐ Coherence
- ☐ Polarization
- ☐ Output beam above threshold

Exceptions:

1. *Light amplification without stimulated emission…*, H. Wiseman, PRA **60**, 4083 (1999).

2. *Thresholdless nanoscale coaxial lasers*, M. Khajavikhan et al. Nature **482**, 204 (2012).

….

*In principle, the last two can also be demonstrated, but need more experimental work.

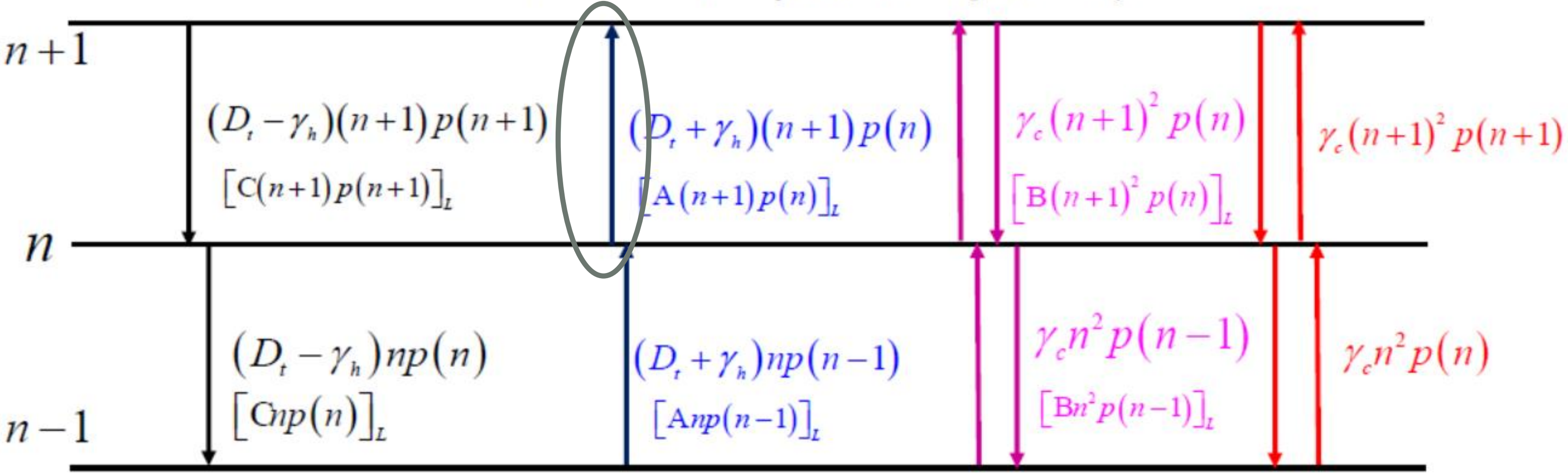
Note: There is no explicit mention of a quantized gain medium

Stimulated emission

$$\dot{p}(n) = -(D_t+\gamma_h)(n+1)p(n) + (D_t+\gamma_h)np(n-1) + \gamma_c(n+1)^2 p(n) - \gamma_c n^2 p(n-1)$$

$$-(D_t-\gamma_h)np(n) + (D_t-\gamma_h)(n+1)p(n+1) + \gamma_c(n+1)^2 p(n+1) - \gamma_c n^2 p(n)$$

$$D_t = A_t + 2\Gamma_l + D_p;\ \gamma_h = \gamma_l - \gamma_g;\ \gamma_c = 6\gamma_f$$

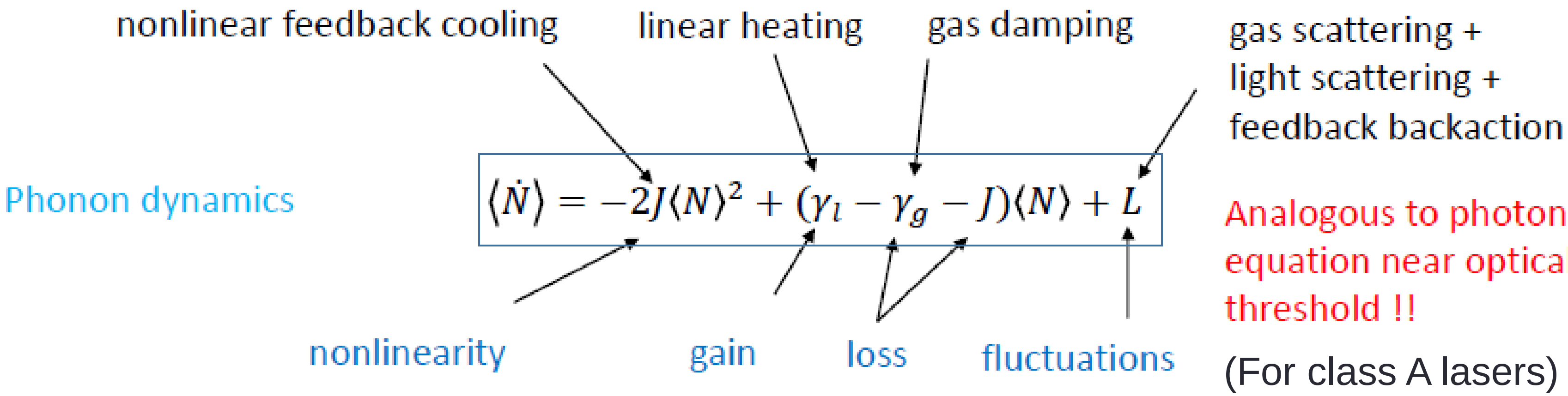


* *Quantum Optics* by Scully and Zubairy

2019

Phonon dynamics

$$\langle N\rangle = \frac{m\omega_m^2\langle q_{rms}^2\rangle}{\hbar\,\omega_m}$$



nonlinear feedback cooling

linear heating

gas damping

gas scattering +
light scattering +
feedback backaction

Phonon dynamics

$$\boxed{\langle\dot N\rangle = -2J\langle N\rangle^2 + (\gamma_l - \gamma_g - J)\langle N\rangle + L}$$

nonlinearity

gain

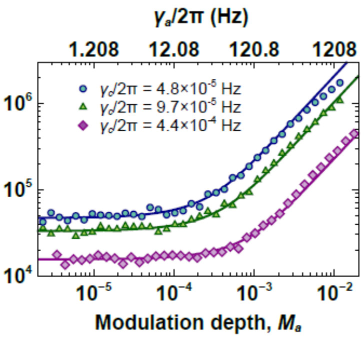
loss

fluctuations

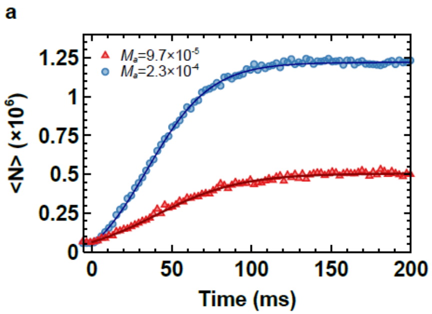
Analogous to photon number equation near optical laser threshold !!

(For class A lasers)

Threshold

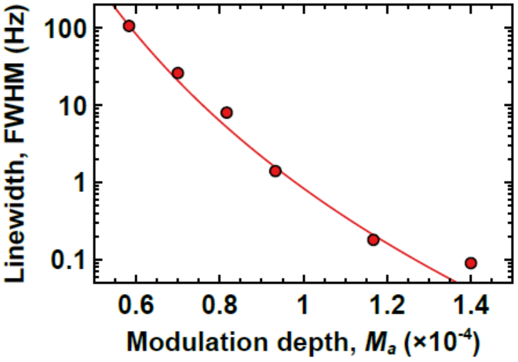


Phonon number transient



$$\langle N(t)\rangle = -\frac{(24\gamma_c + 2\gamma_g - 2\gamma_a)}{48\gamma_c} + \frac{1}{24\gamma_c\tau}\tanh\left[\frac{t}{\tau} + \theta\right]$$

Linewidth narrowing



* *Quantum Optics* by Scully and Zubairy

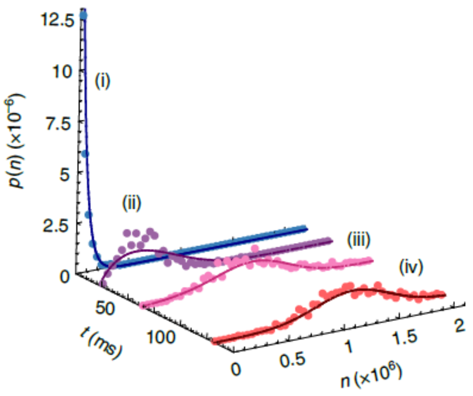
2019

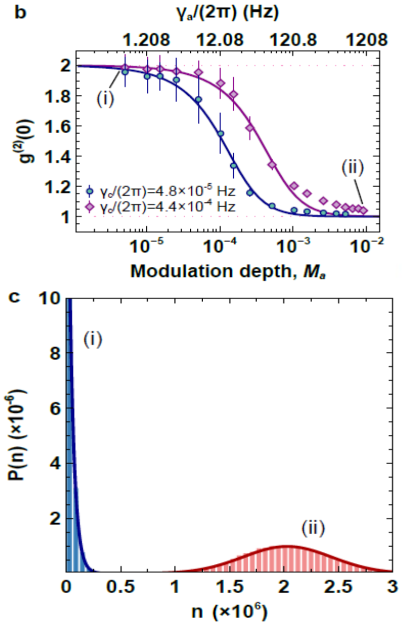
Phonon statistics

Time transient

Coherence: $g^2(0)$

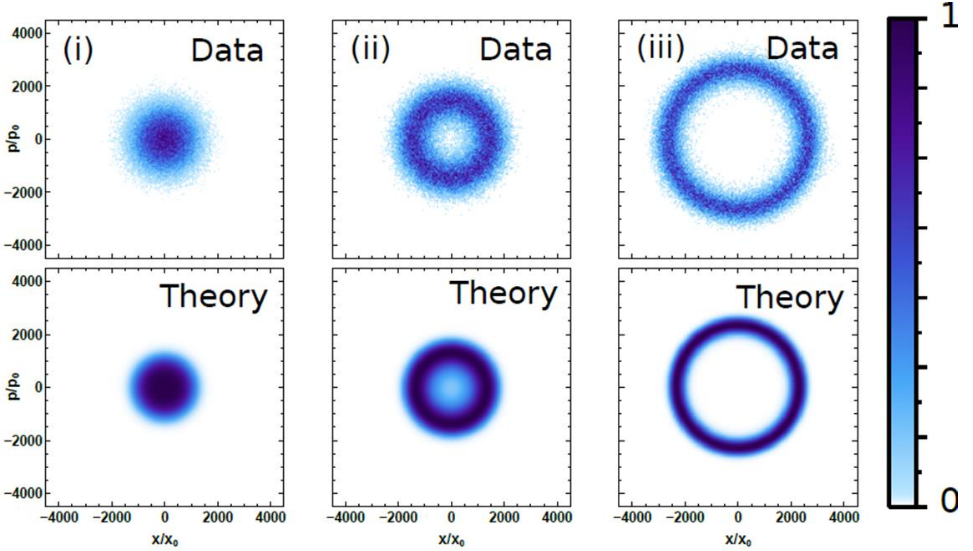
Phase space portrait





Brownian

Coherent



Boltzmann distribution

P function

Subthermal number squeezing
(Poissonian for lower pressures)

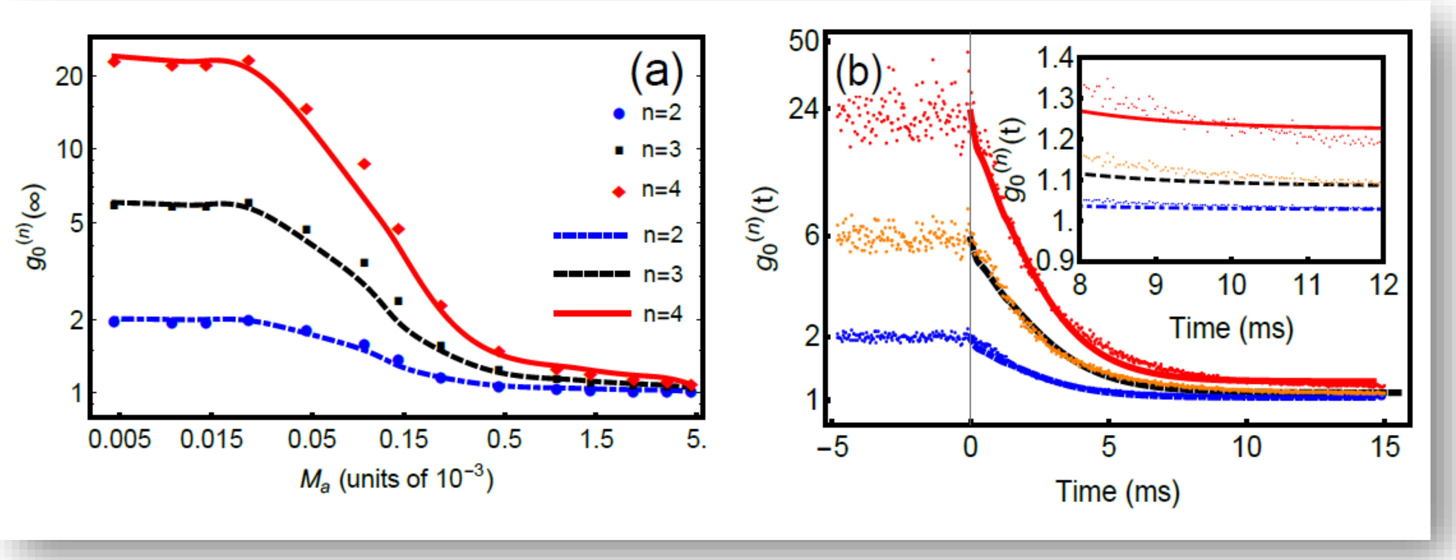
*R. M. Pettit et al., *Nature Photonics* **13**, 402 (2019).

2019

More recent work: Higher order correlations

Equal time correlation functions

$$g^{(n)}(t,0)=\frac{\langle \hat{a}^{\dagger n}(t)\hat{a}^{n}(t)\rangle}{\langle a^{\dagger}(t)a(t)\rangle^{n}}$$

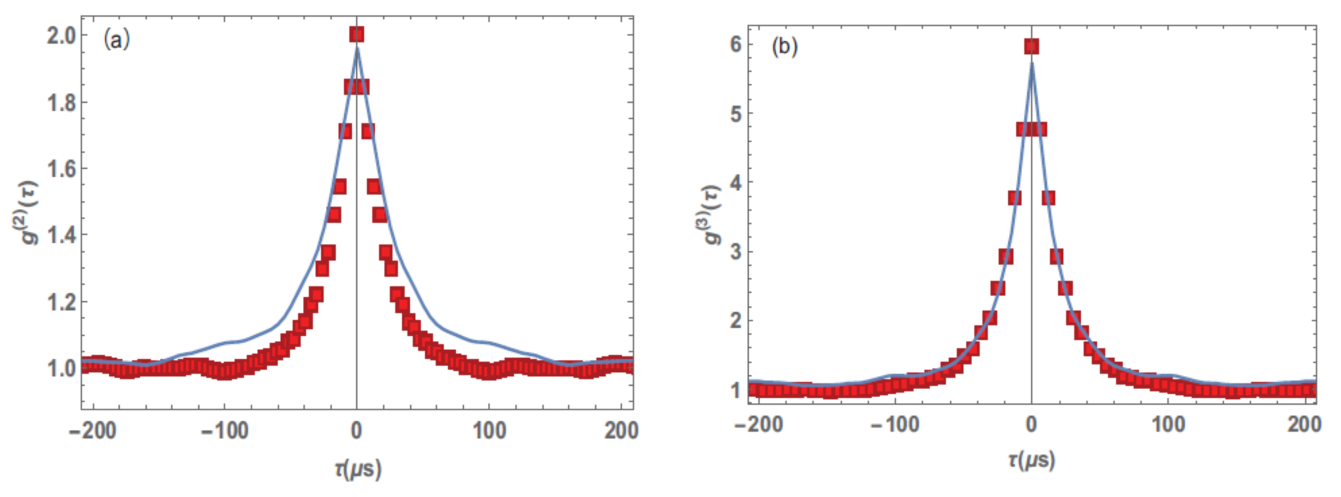


More recent work: Higher order correlations

Unequal time correlation functions

$$g^{(2)}(t,\tau) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t)\rangle}{\langle a^\dagger(t)a(t)\rangle^2}$$

$$g^{(3)}(t,\tau_1,\tau_2) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)\rangle}{\langle a^\dagger(t)a(t)\rangle^3}$$



$$\tau_1 = \tau_2 = \tau$$

More recent work: Higher order correlations

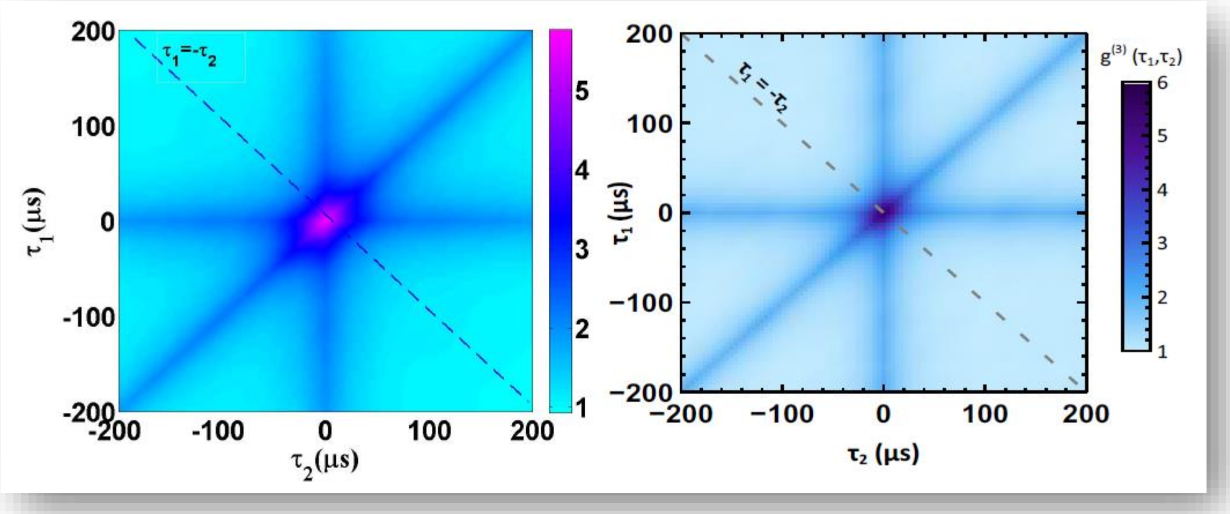
Unequal time correlation functions

$$g^{(3)}(t,\tau_1,\tau_2) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)\rangle}{\langle a^\dagger(t)a(t)\rangle^3}$$

$$g^{(3)}(\tau_1,\tau_2)$$

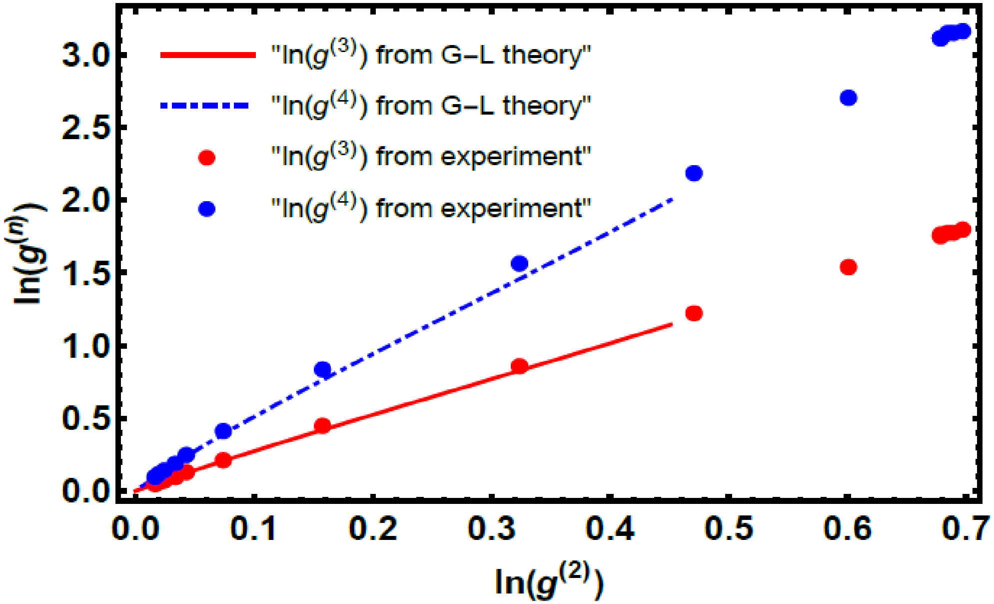
Theory

Experiment



$\tau_1 \neq \tau_2$

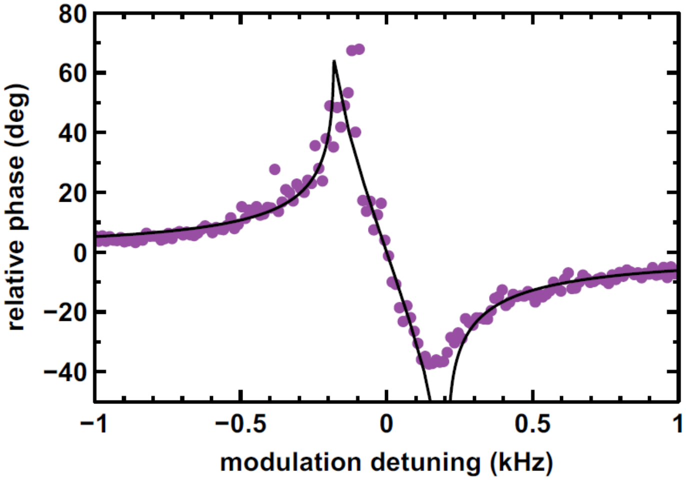
Comparison with Landau-Ginsburg theory

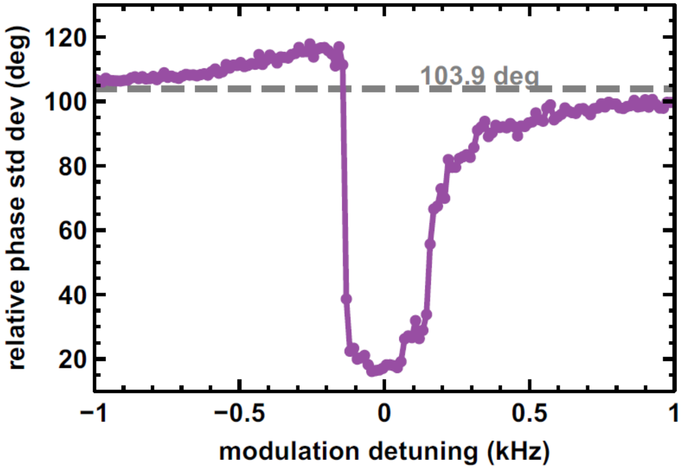


*Probing the Ginzburg-Landau potential for lasers using higher-order photon correlations, N. Takemura et al., arxiv:1908. 08679v1 (2019)

More recent work: Injection locking

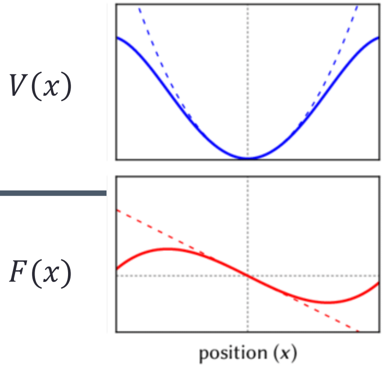
The phase of the free-running phonon laser can be locked to an external modulation



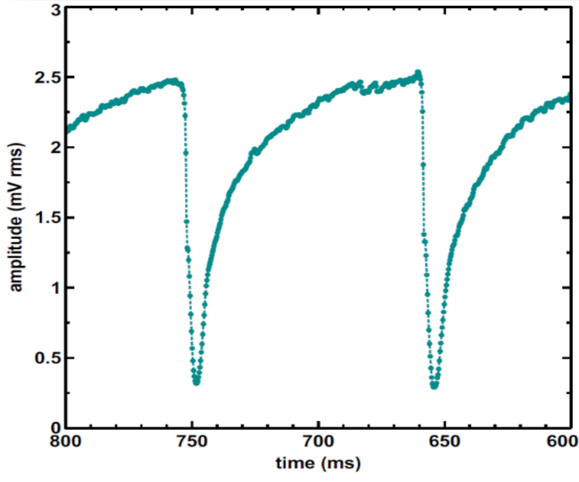


- *Injection locking of a trapped ion phonon laser,* S. Knunz et al. PRL **105**, 013004 (2010).
- PhD Thesis, Jan Gieseler.

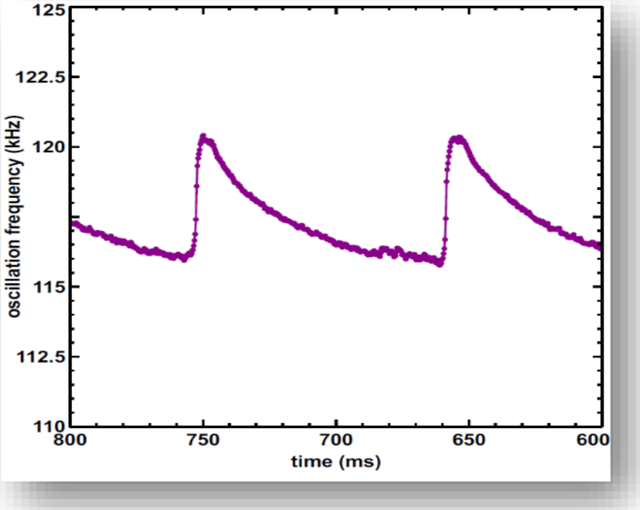
More recent work: Q-switching ??



Amplitude



Frequency



*Observed in the regime where mechanical amplitude ~ ω_0

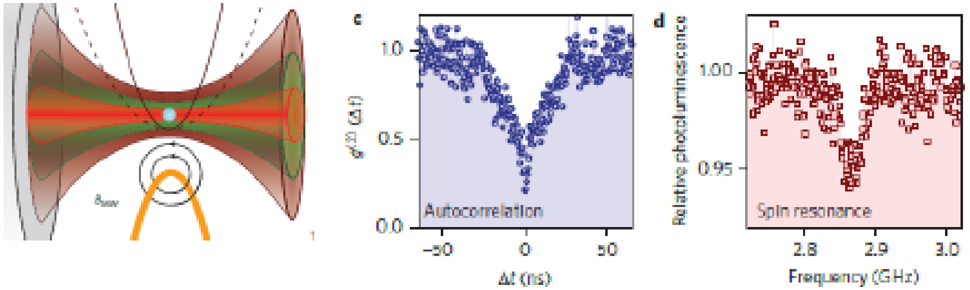
Looks like the Duffing nonlinearity could be responsible

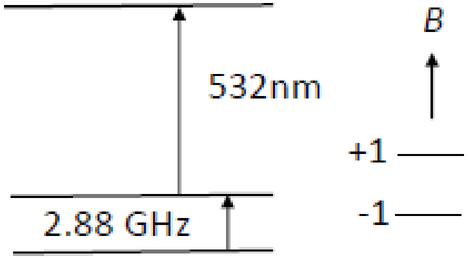
Pulsed phonon lasing in trapped ions

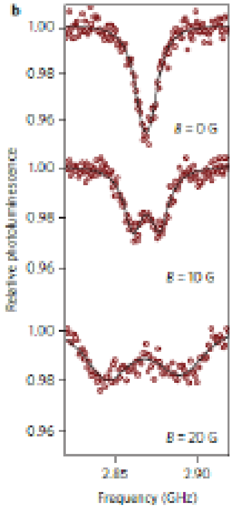
Y. Xie, W. Wan, H. Y. Wu, F. Zhou, L. Chen and M. Feng

Phys. Rev. A **87**, 053402 (2013).

Levitated quantum emitters: spin+mechanics







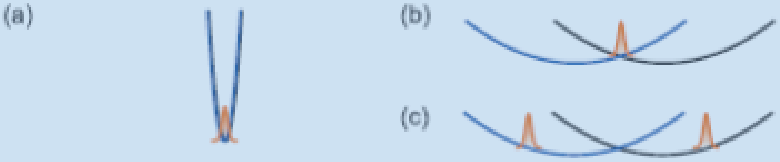
Multi-dimensional single-spin nano-optomechanics with a levitated nanodiamond

Levi P. Neukirch[1,2]*, Eva von Haartman[3], Jessica M. Rosenholm[3] and A. Nick Vamivakas[2,4]*

Nature Photonics

Large quantum superpositions of a levitated nanodiamond, Yin et al., PRA **88**, 033614 (2013)

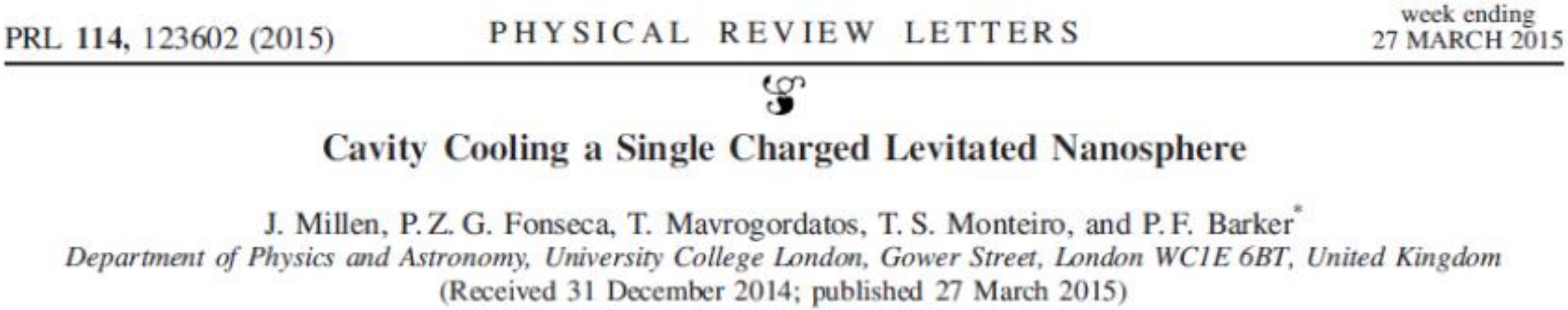
$$H_c = -\mu . B_z \sim S_z \frac{\partial B}{\partial z} Q_z$$



Single and two-mode mechanical squeezing of an optically levitated nanodiamond via dressed-state coherence, W. Ge and MB, NJP **18**, 103002 (2016)

Generating spin squeezing states….*PRB **94, 205118 (2016), K. Xia and J. Twamley

Cavity optomechanics: charged dielectrics

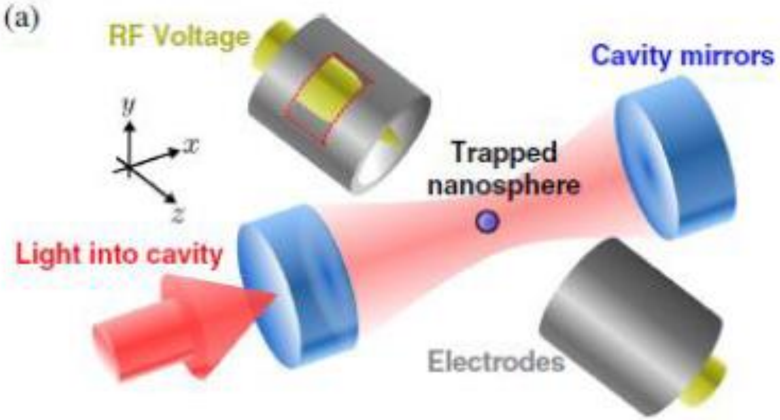


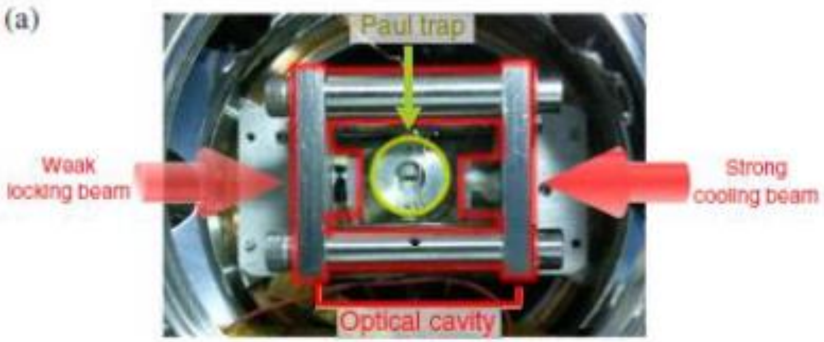
PRL 114, 123602 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

Cavity Cooling a Single Charged Levitated Nanosphere

J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, T. S. Monteiro, and P. F. Barker*
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 31 December 2014; published 27 March 2015)

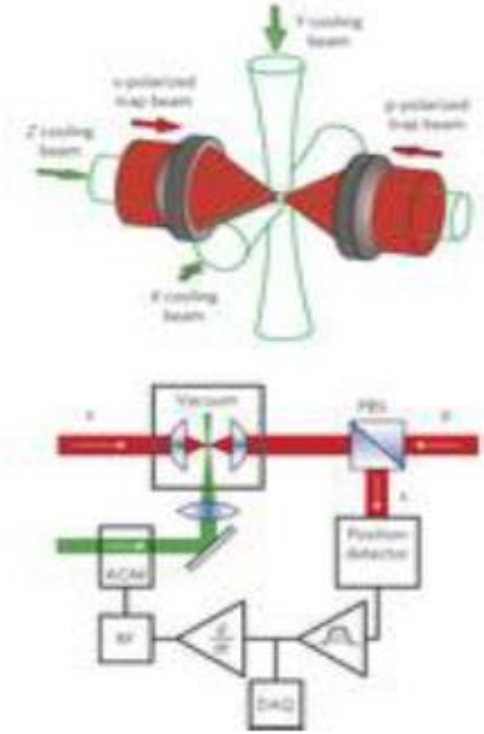




Larger objects: Mie regime

$r = 2\mu m$

300K → 1 mK



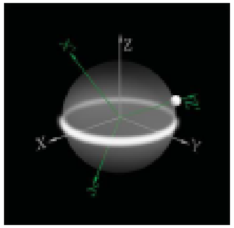
Millikelvin cooling of an optically trapped microsphere in vacuum
T. Li, S. Kheifets & M. G. Raizen
Nature **7**, 527 (2011)

Cooling the Motion of Diamond Nanocrystals in a Magneto-Gravitational Trap in High Vacuum

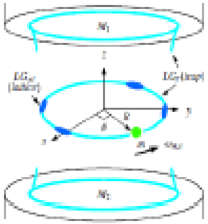
J. –F. Hsu et. al, Scientific Reports **6**, 30125 (2016)

Rotation

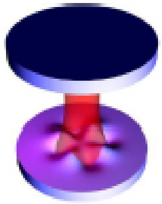
Rotational motion



- J. T. Rubin and L. I. Deych
  PRA **84**, 023844 (2011)
- L. Deych and V. Shuvayev
  PRA **92**, 013842 (2015)



- MB, JOSA B **32**, B55 (2015)



- Briant et al., PRA **68**, 033823 (2003)
- H. Shi and M. Bhattacharya,
  J. Phys. B, **46** 151001 (2013)

Focus:
The Fastest Spinners
July 20, 2018•
Physics 11,73.

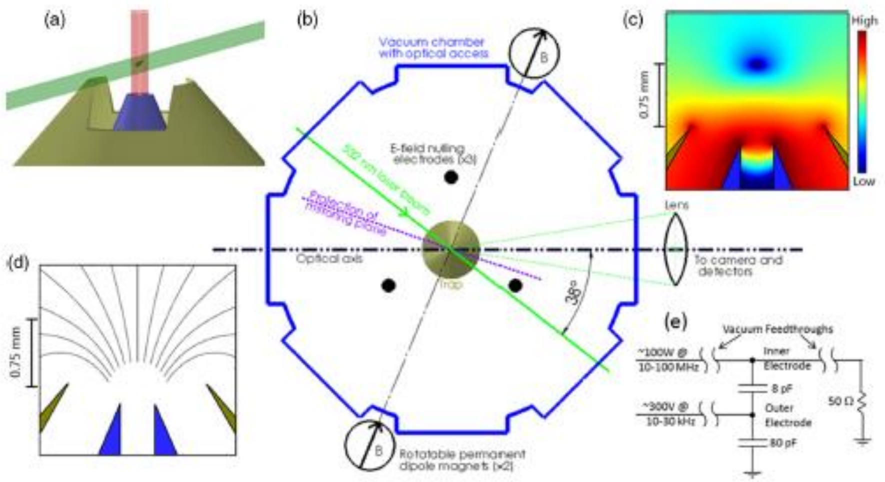
GHz Rotation of an Optically Trapped Nanoparticle in Vacuum
René Reimann et. al
PRL **121**, 033602 (2018)

Optically Levitated Nanodumbbell Torsion Balance and GHz Nanomechanical Rotor,
Jonghoon Ahn et. al
PRL **121**, 033603 (2018)

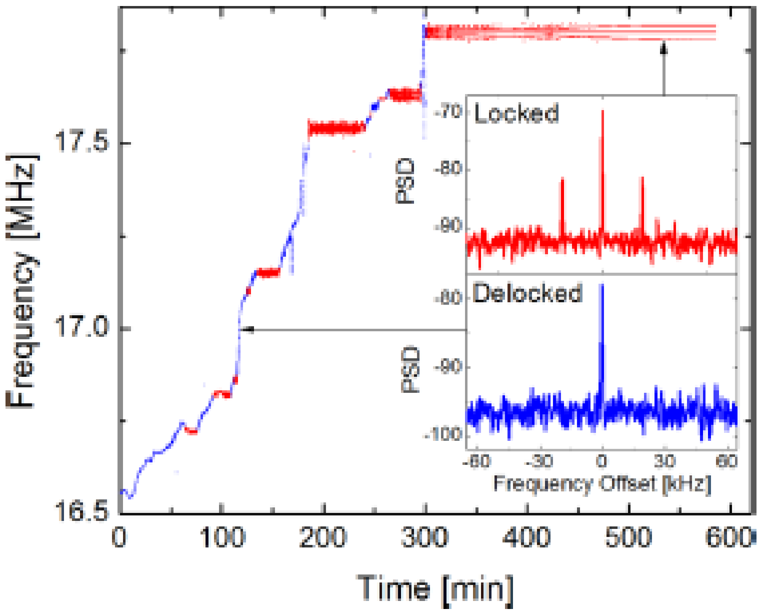
2019

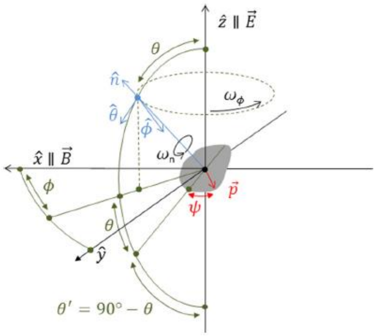
Rotation – Graphene nanoplatelets

B. E. Kane et. al, Phys. Rev. B **82**, 115441 (2010), Phys. Rev. B **96**, 035402 (2017)



Levitation

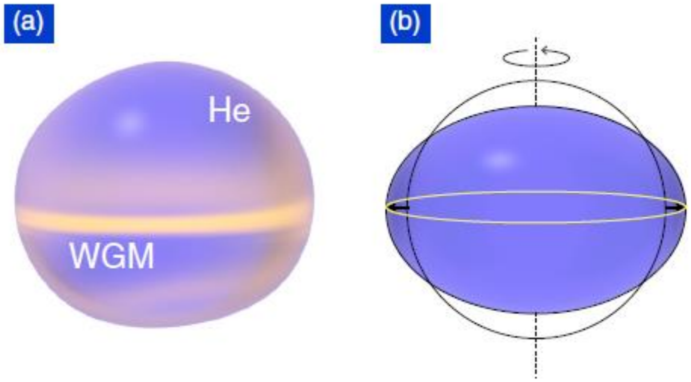




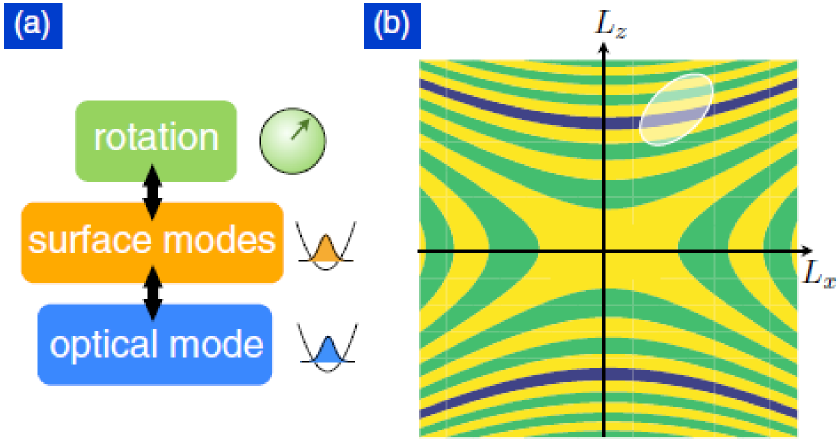
Frequency locking

Rotation – **Cavity optomechanics in a levitated helium drop**

L. Childress et. al, PRA **96**, 063842 (2017)



Magnetic levitation

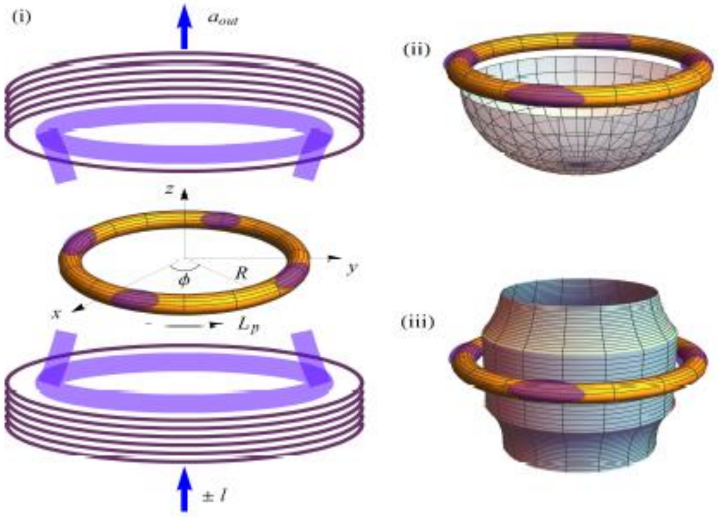


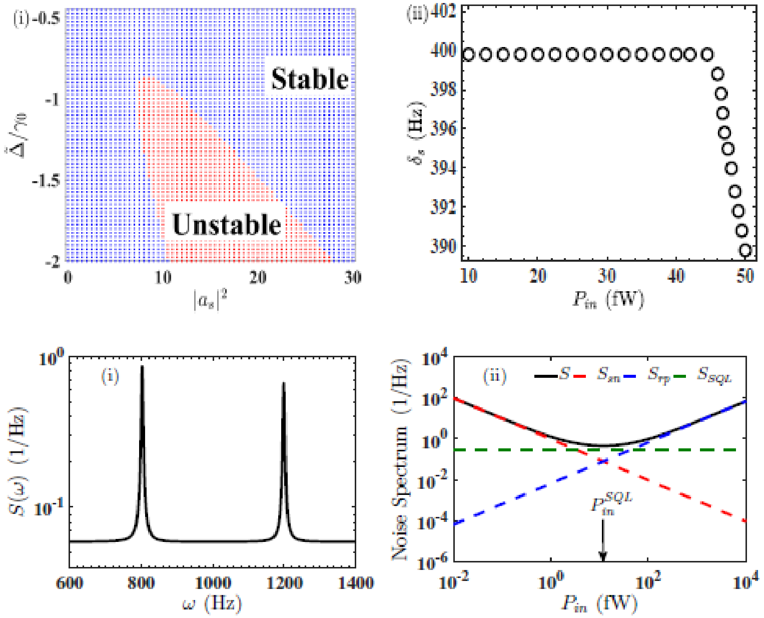
Cavity resonance as a function of L

$$\hat{H}_{\mathrm{QND}} = \hbar g_L \left(\frac{\hat{L}_z}{\hbar} \right)^2 \hat{a}^\dagger \hat{a}$$

Non-demolition measurement of angular momentum

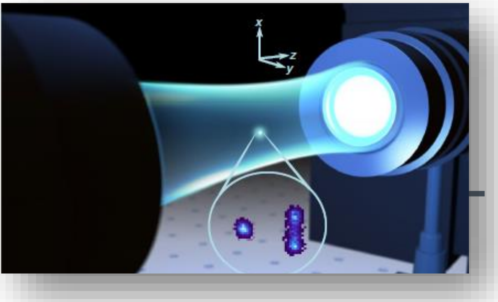
Rotation – **Cavity optomechanics with a rotating BEC**

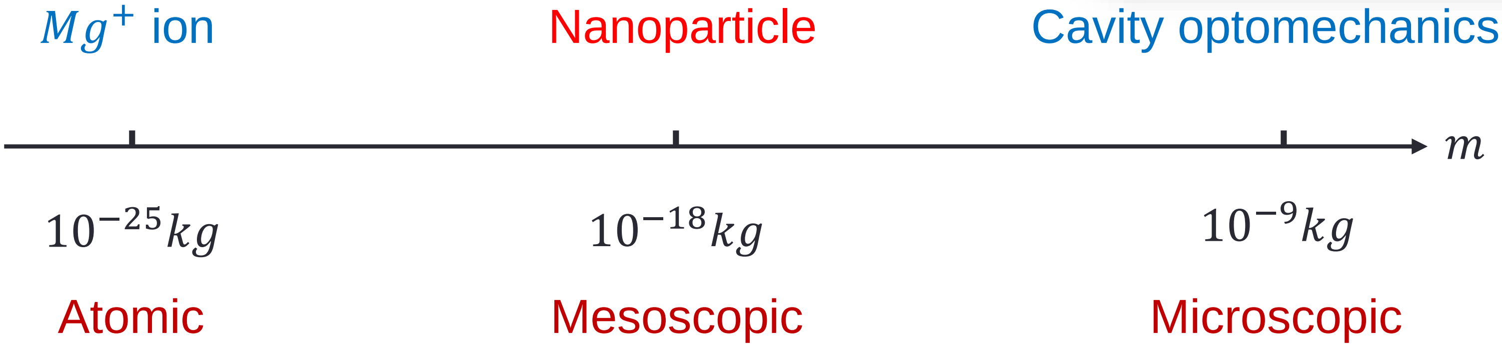




*P. Kumar, T. Biswas, K. Feliz, R. Kanamoto, M. S. Chang, A. K. Jha and MB, In review.

Conclusions





Mg^+ ion — Nanoparticle — Cavity optomechanics

m

$10^{-25}kg$ — $10^{-18}kg$ — $10^{-9}kg$

Atomic — Mesoscopic — Microscopic

1. Generate coherent states with good fidelity: Schrodinger cat state.
2. Nonlinear force measurement across the lasing transition.
3. Mie particles.
4. Our technique is very general and applies to any harmonic oscillator. All it requires is position measurement + feedback.

THANKS !!!

Optical Tweezer Phonon Laser: FAQs

Q. What constitutes the phonon in your case ?

A. The center of mass oscillations of the nanoparticle along one direction in space.

Optical Tweezer Phonon Laser: FAQs

Q. Can standard cavity optomechanics theory be used to describe your system?

A. No.

- There is no cavity.
- The light-matter interaction is single-pass.
- …

Optical Tweezer Phonon Laser: FAQs

Q. Why do you use a quantum model? There is nothing quantum in the experiment…??

A. The theory came first, is valid in the quantum regime, and needs to be verified in that limit.

A fully quantum theory is required for predicting ground state occupation.

The quantum model helps us establish the presence of stimulated emission. In that sense something quantum *is* happening in our phonon laser.

Optical Tweezer Phonon Laser: FAQs

Q. Why do you have both heating and cooling?

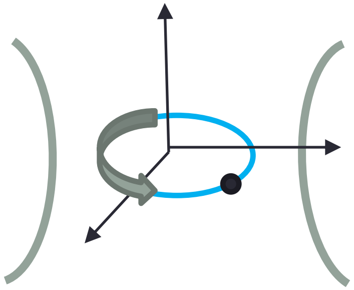
A. → Heating supplies gain

→ Cooling supplies nonlinearity

Optical Tweezer Phonon Laser: FAQs

Q. How about polarization and an output beam ?

A. Polarization



B. Output beam

We are in the zero dimensional limit of no vibronic output coupling, but…