Exploring the thermodynamics of small systems with levitated optomechanics

Nikolai Kiesel [1]

[1] *VCQ, Faculty of Physics,*

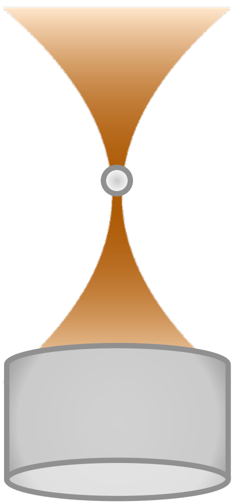
University of Vienna

KITP
Quantum Thermodynamics
29.06.2018

D. Grass[1], U. Delic[1], M. Aspelmeyer[1]
M. Rademacher[1], M. Debiossac[1], M. Ciampini[1],
A. Dechant[2], M. Konopik[3], E. Lutz[3]

[2] Department of Physics , Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
[3] Institute for Theoretical Physics II, University of Erlangen-Nürnberg, D-91058 Erlangen, Germany

Optical trapping in liquid - a great level of control !

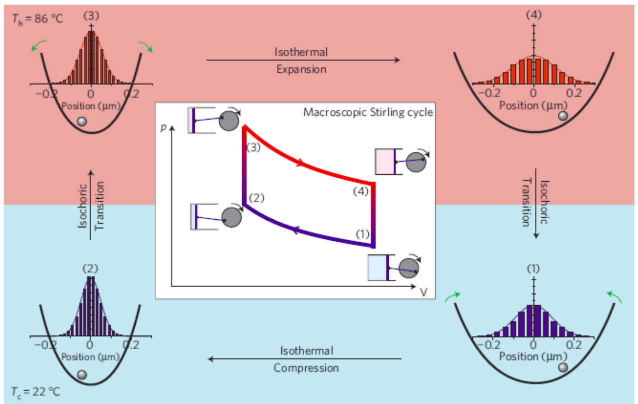


Real-life µ-Tetris was created by Theodoor Pielage, Bram van den Broek and Joost van Mameren.

Optical trapping in liquid
A paradigm in stochastic thermodynamics

Seifert, U. Rep. Prog. Phys. 75, 126001 (2012)

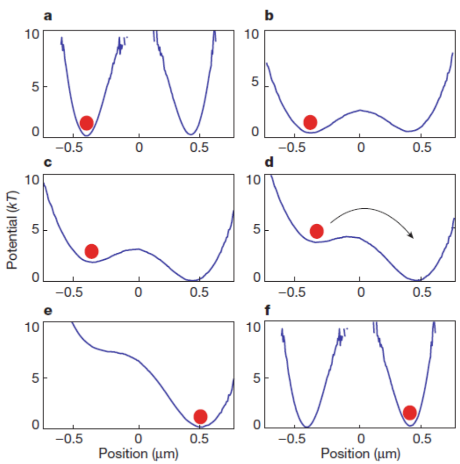
A microbead heat engine
Blickle, Bechinger,
Nat. Phys. 8, 143 (2011).

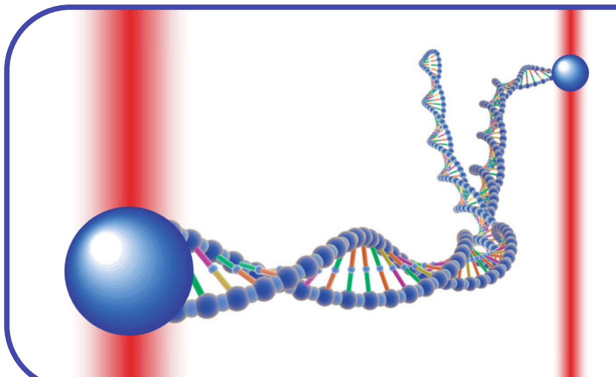


Experimental verification of Landauer's principle linking information and thermodynamics

Antoine Bérut[1], Artak Arakelyan[1], Artyom Petrosyan[1], Sergio Ciliberto[1], Raoul Dillenschneider[2] & Eric Lutz[3]†

Berut et al
Nature **483**,
187 (2012)





Gupta, A. N. et al.
Nature Phys. 7, 631–634 (2011)

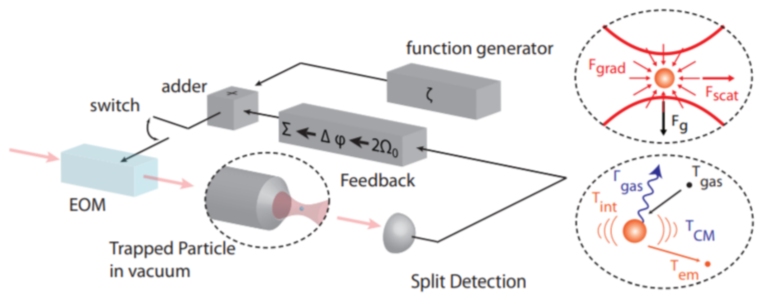
Christopher Jarzynski
Single-molecule experiments: Out of equilibrium
Nature Physics 7, 591 (2011)

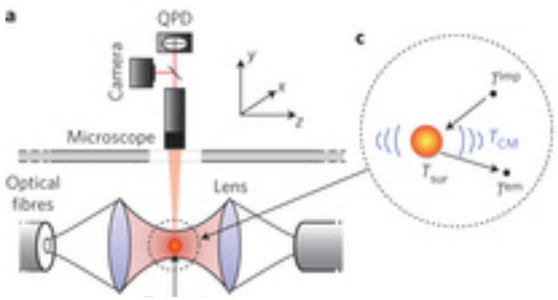
Many more examples…

Optical levitation and Thermodynamics

Dynamic relaxation of a levitated nanoparticle from a non-equilibrium steady state
Gieseler et. al. Nat. Nanotech. 9, 358 (2014)

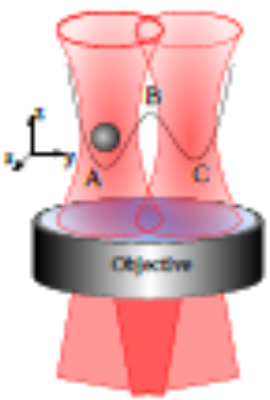
Nanoscale temperature measurements using non-equilibrium Brownian dynamics of a levitated nanosphere
Millen et. al. Nat. Nanotec. 9, 425 (2014)





Talk Wednesday by Rui Pan
T.M. Hoang, et al. PRL 120 (8), 080602 (2018)

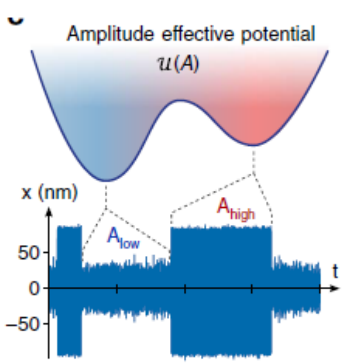
Optically levitated nanoparticle as a model system for Stochastic bistable dynamics
Ricci et al., Nat. Comm 8, 15141 (2016)



Reviews

Optomechanics of levitated dielectric particles
Zhang-Qi Yin, Andrew Geraci and Tongcang Li
Int. J. Mod. Phys. B 27, 1330018 (2013)

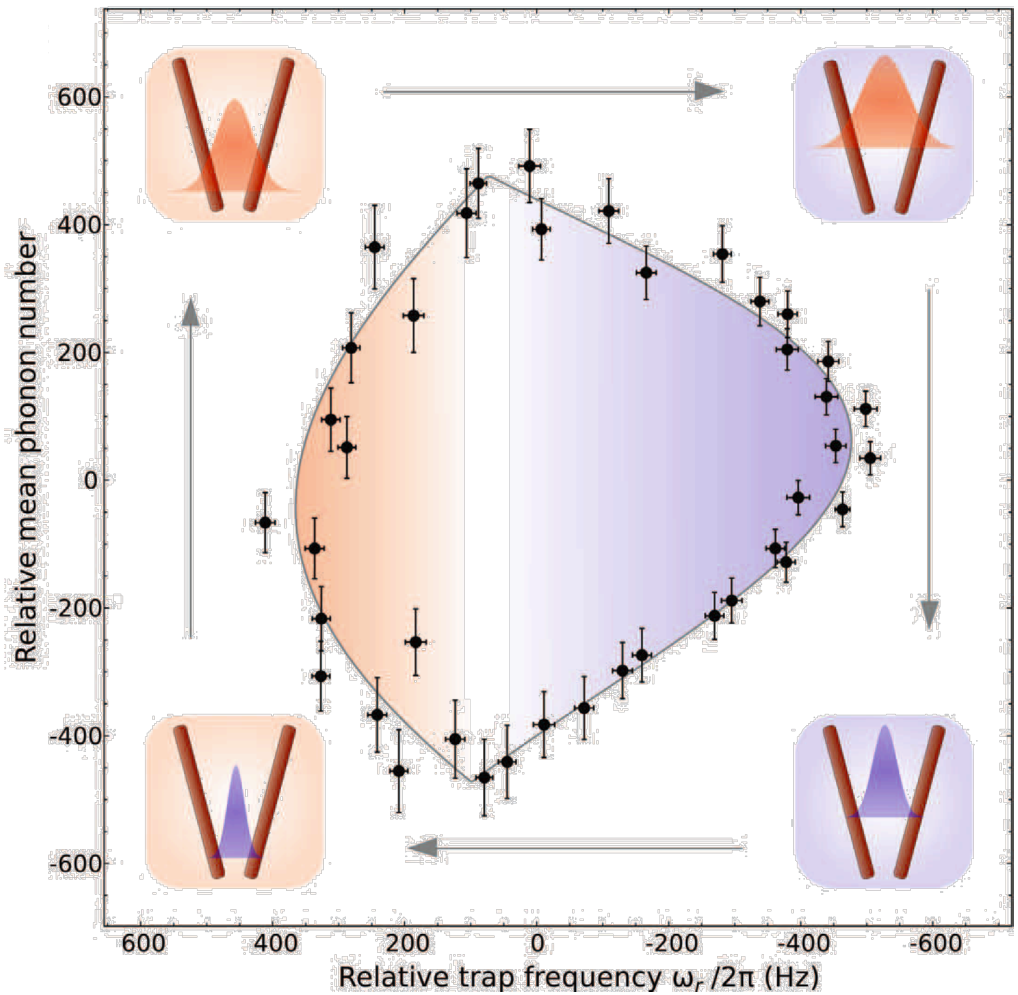
Levitated Nanoparticles for Microscopic Thermodynamics – A Review Jan Gieseler and James Millen
Entropy 2018, 20, 326 (2018)

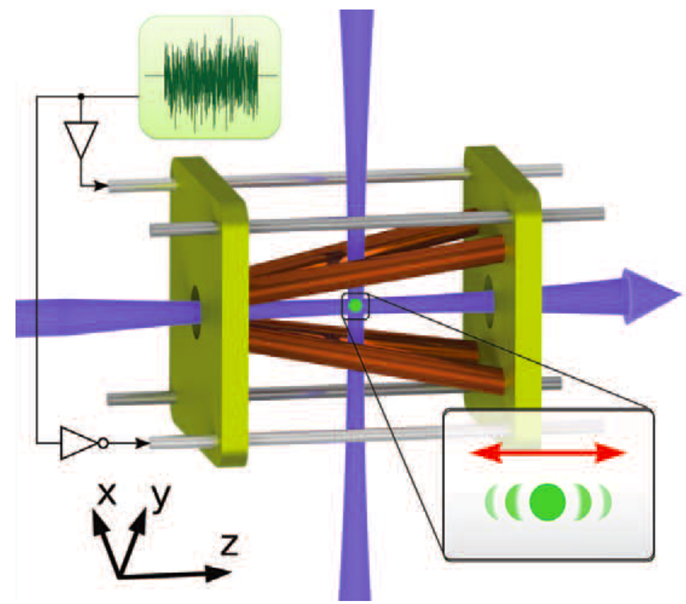


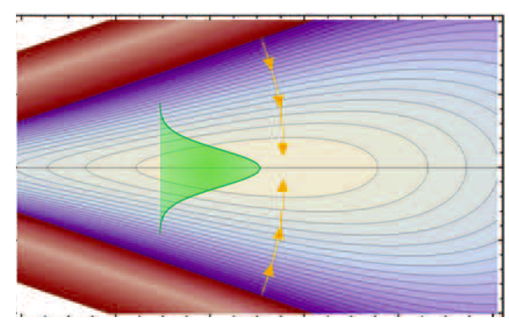
Direct measurement of Kramers turnover with a levitated nanoparticle
Rondin et al., Nat. Nano. 12, 1130 (2017)

Ion Engine

Roßnagel et al.,Science 352, 6283 (2016), Abah et al., PRL 109, 203006 (2012)

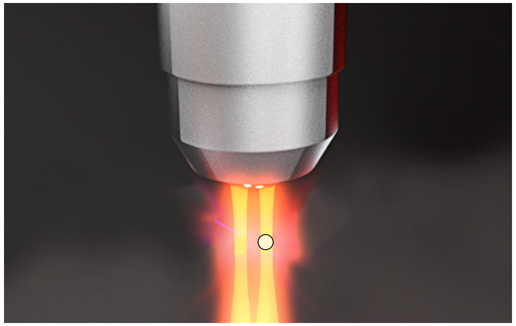






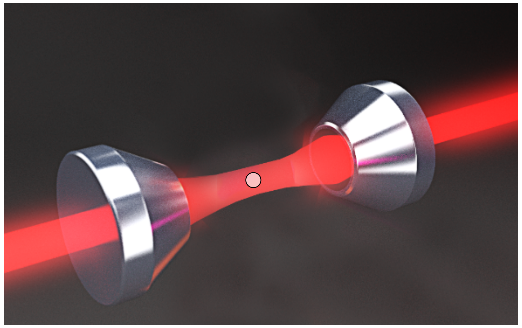
Underdamped clamped resonator beyond Carnot: Klaers et al., PRX, 7, 031044 (2017).

Experimental Platform



Optical tweezer

\+



Cavity Optomechanics

Control potential landscape
System

Control interaction with light
Reservoir

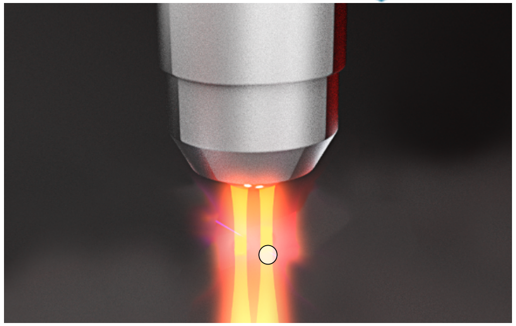
Remove thermal Reservoir
-> Levitation in vacuum

Add engineered reservoir
„Quantum baths“

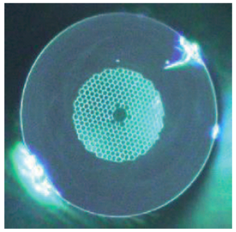
All-Optical: **Maximize spatial and temporal control**
over potential landscape and reservoir

Overview

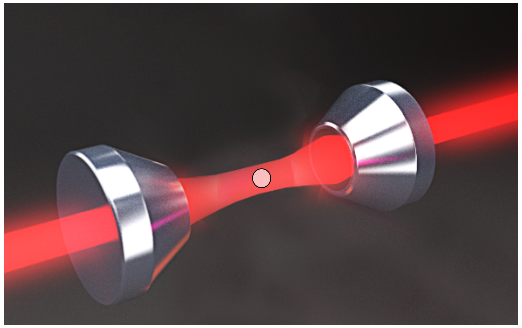
- Levitated Nanoparticles



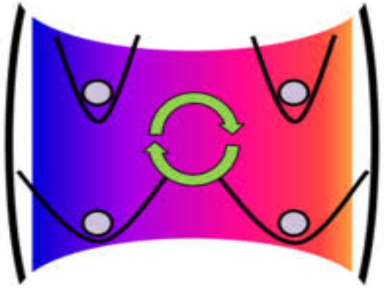
- Thermodynamics in a fiber



- Levitated Cavity Optomechanics



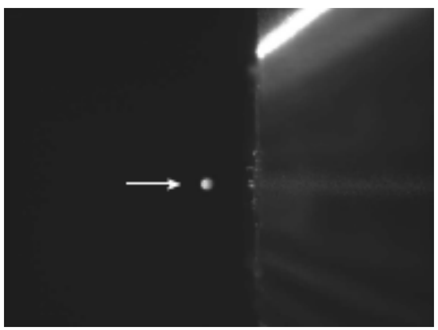
- Model for a heat engine

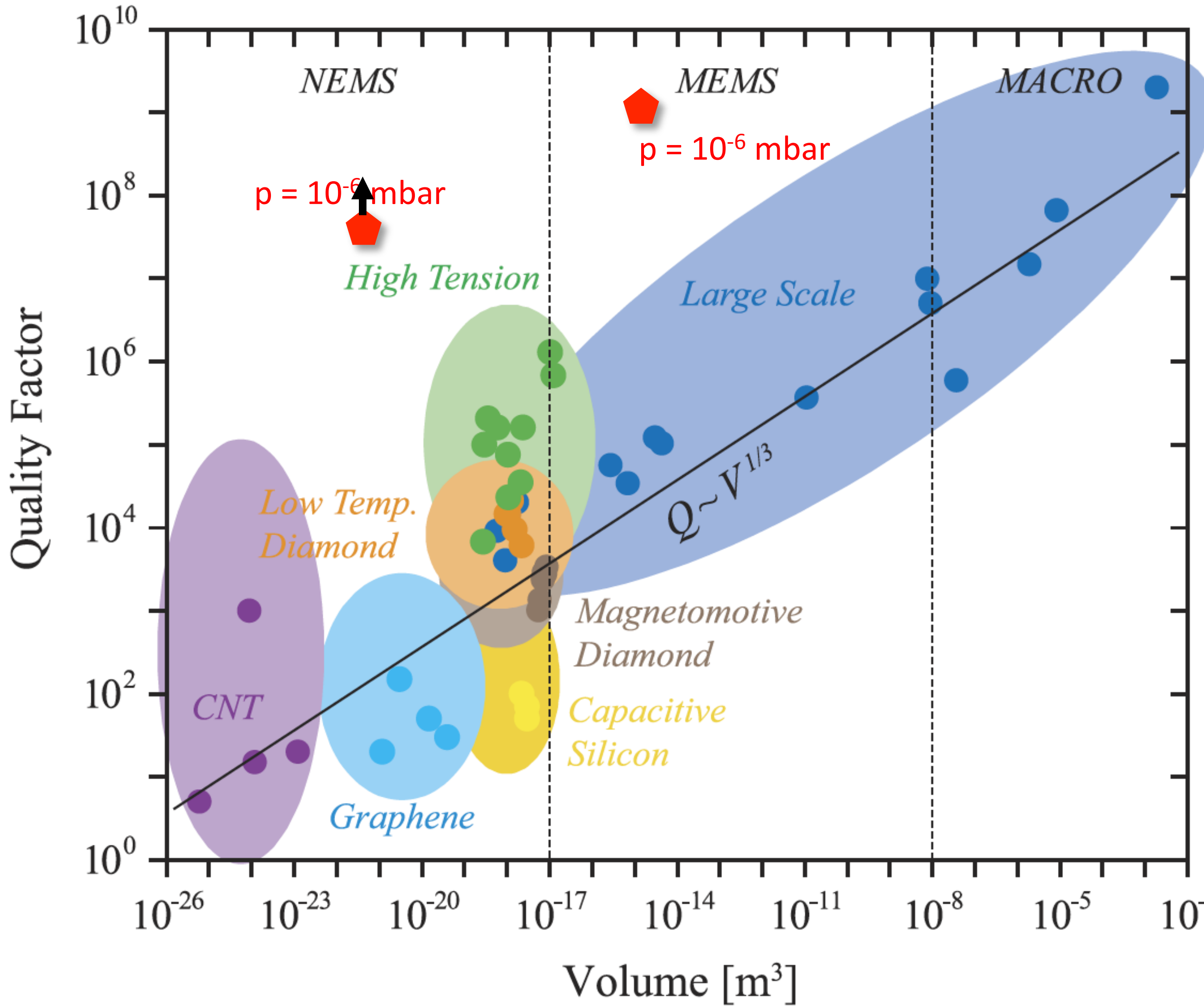


Optical Levitation for high-Q mechanics

- Ashkin & Dziedzic, APL 28, 333 (1976)(20um Si oil)

J. Gieseler, R. Quidant, C. Dellago, L. Novotny, Nature Nanotechnology 9, 358 (2014)
(70 nm SiO2)

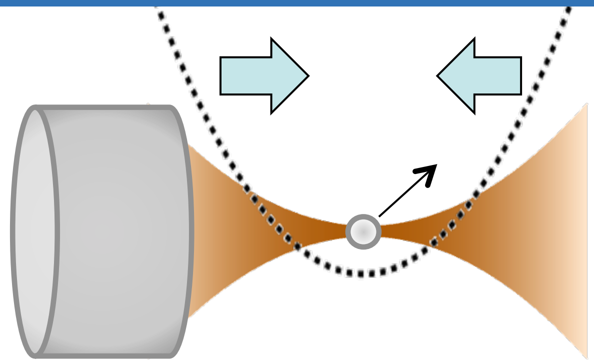




M. Imboden, P. Mohanty, Phys. Rep. 534, 89 (2014)

Feeback cooling and heating rate

Microscope objective



Parametric feedback cooling

$\omega_x \approx 2\pi \times 170$ kHz

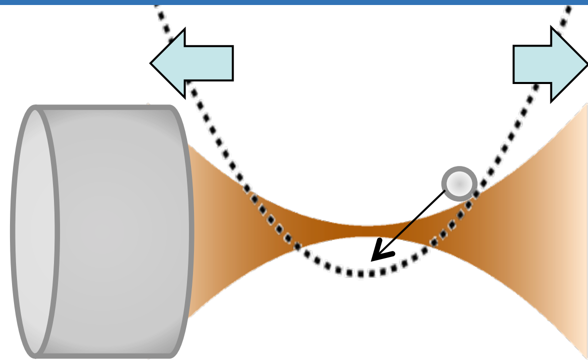
$\omega_z \approx 2\pi \times 40$ kHz

$\omega_y \approx 2\pi \times 190\ kHz$

See also Gieseler, J., et al., PRL 109, 103603 (2012).

Feeback cooling and heating rate

Microscope objective



Parametric feedback cooling

$\omega_x \approx 2\pi \times 170$ kHz

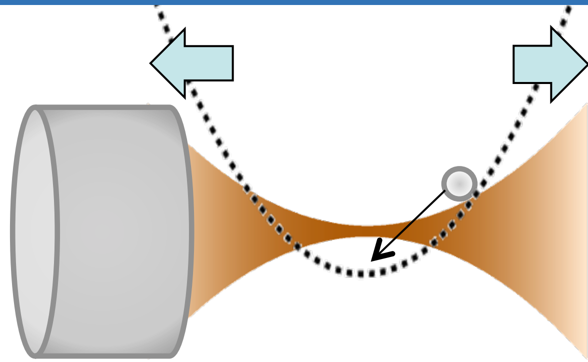
$\omega_z \approx 2\pi \times 40$ kHz

$\omega_y \approx 2\pi \times 190\ kHz$

See also Gieseler, J., et al., PRL 109, 103603 (2012).

Feeback cooling and heating rate

Microscope objective



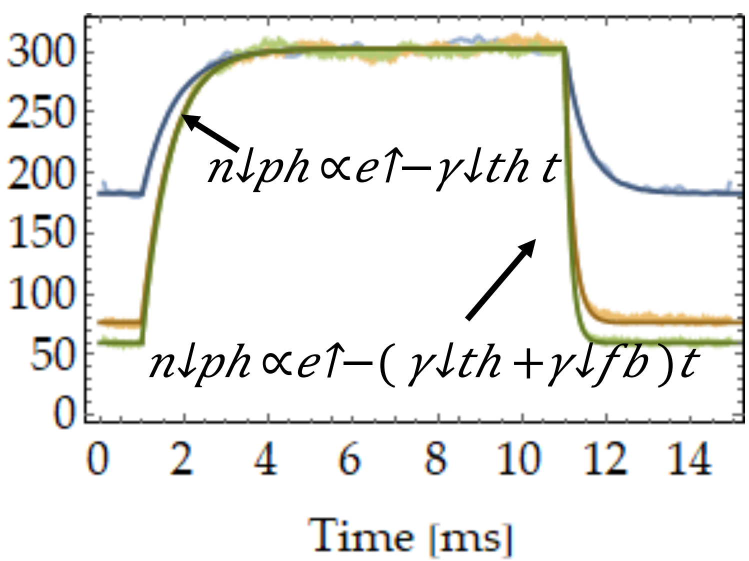
Parametric feedback cooling

$\omega_x \approx 2\pi \times 170$ kHz

$\omega_z \approx 2\pi \times 40$ kHz

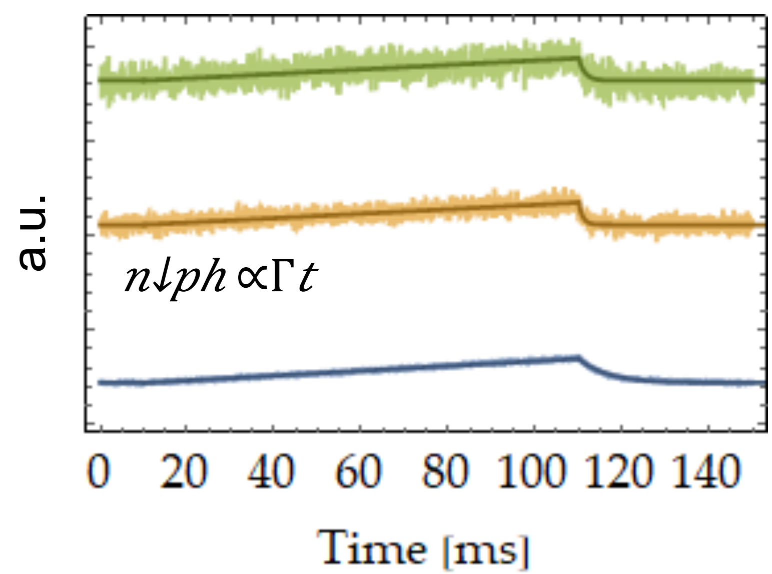
$\omega_y \approx 2\pi \times 190\ kHz$

Full equilibration at ~ 10^{-2}mbar

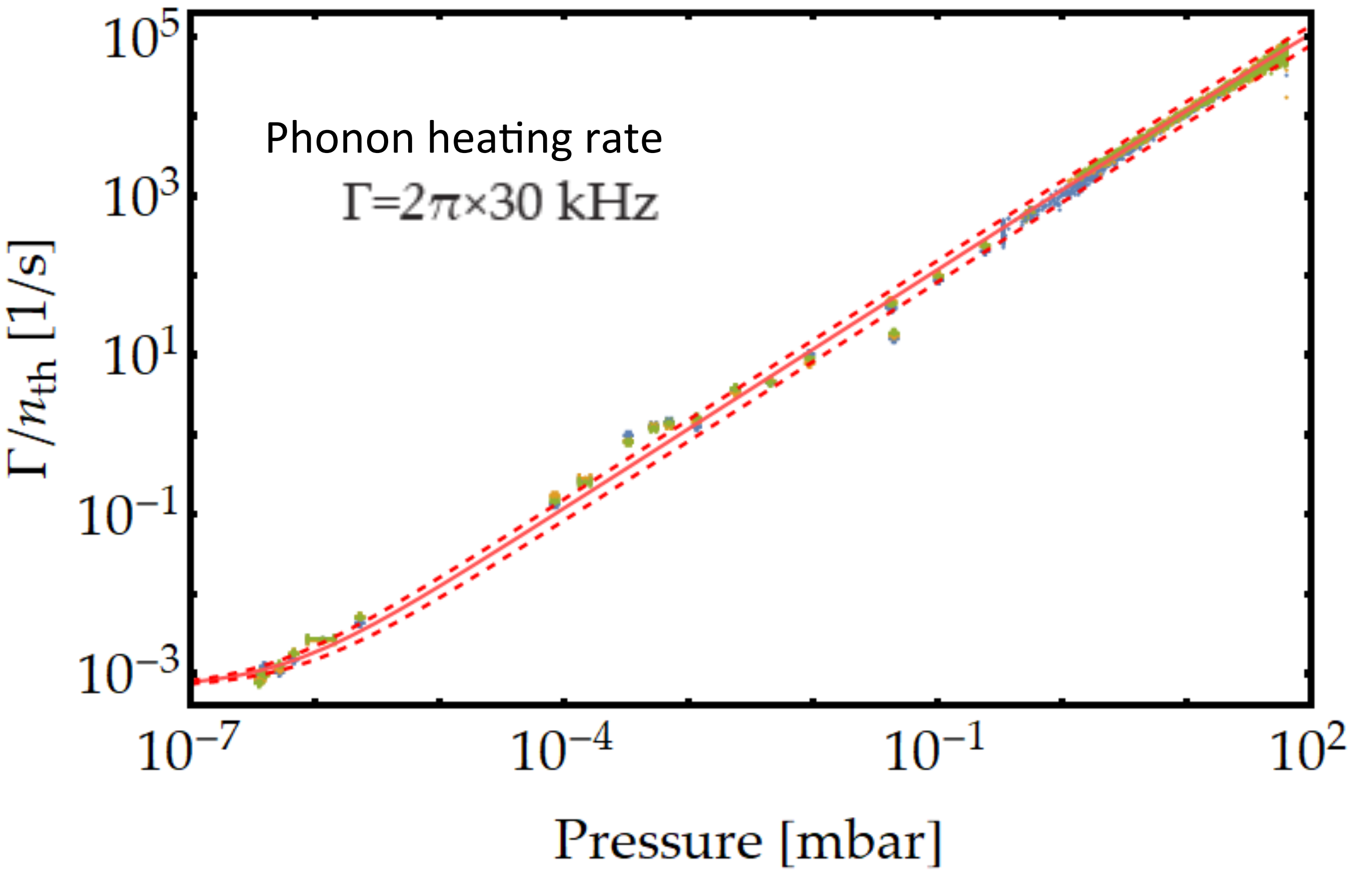


Linear onset of equilibration @ $4*10^{-7}$ mbar

$$n_{ph}(t)=n_{th}+(n_{cool}-n_{th})e^{-\gamma t}\approx n_{cool}+\Gamma t$$



Recoil Heating



First measurement of photon recoil:
Jain et al., Phys. Rev. Lett. 116, 243601 (2016)

Bath temperature in recoil limited regime:
$k_B T = \hbar\omega_{ph} \sim 10^4$ K

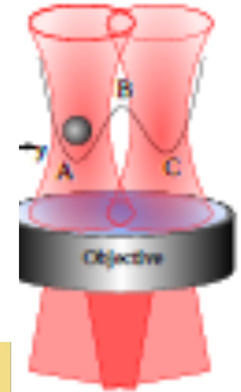
Record: Cooling to 60 phonons (actually <10 by now) – a few μK

Complex Potentials in levitation

LETTERS
PUBLISHED ONLINE: 23 OCTOBER 2017 | DOI: 10.1038/NNANO.2017.198
nature nanotechnology

Direct measurement of Kramers turnover with a levitated nanoparticle

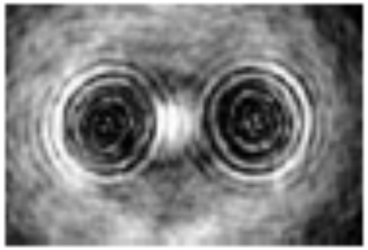
Rondin et al., Nat. Nano. 12, 1130 (2017)



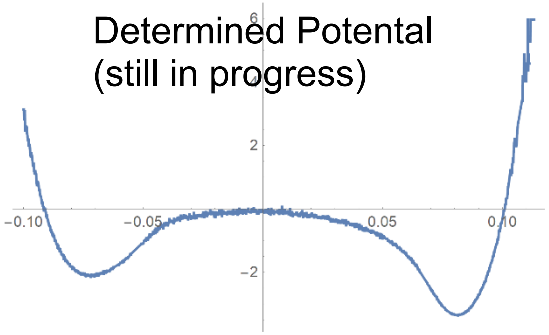
Optics Letters

Rotation of two trapped microparticles in vacuum: observation of optically mediated parametric resonances

Arita et al., Optics Letters 40, 4851 (2015)



Determined Potental
(still in progress)

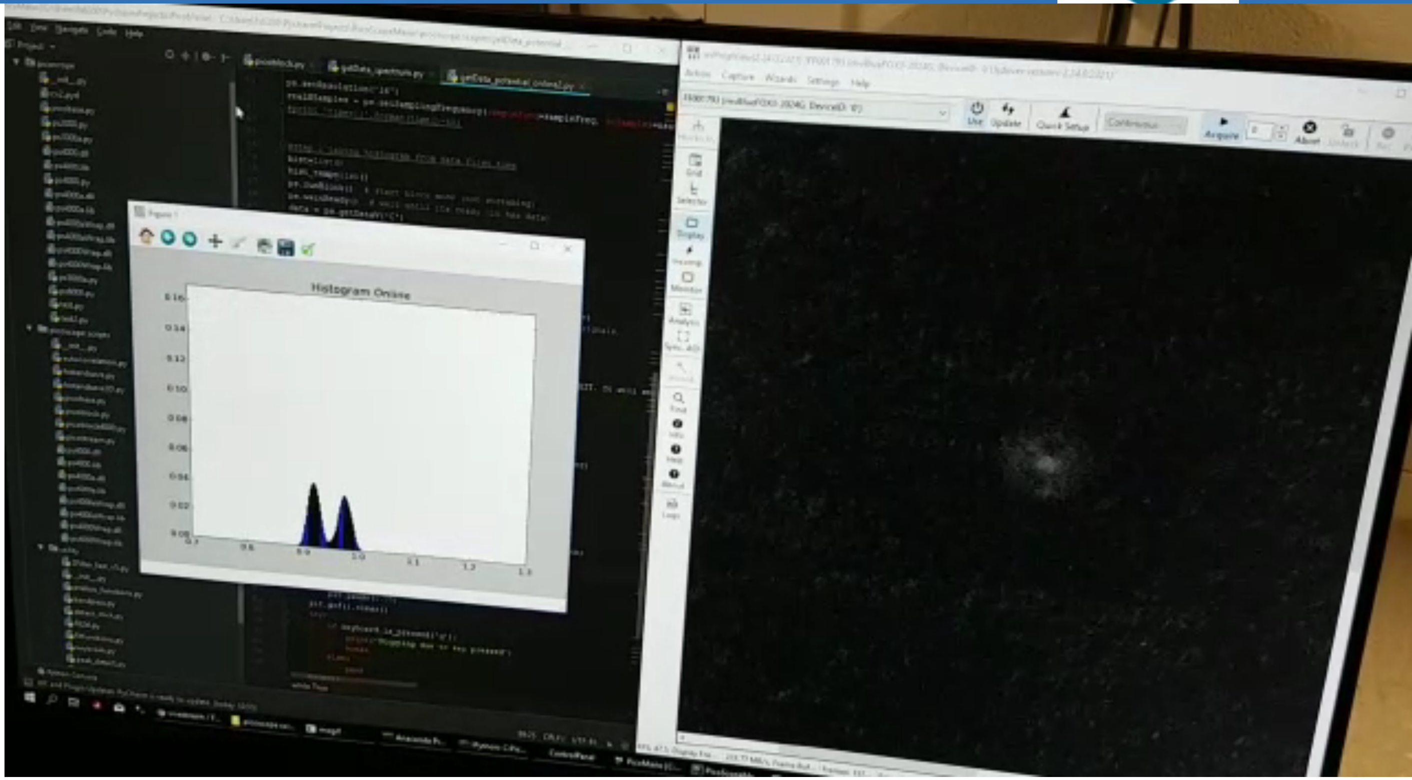


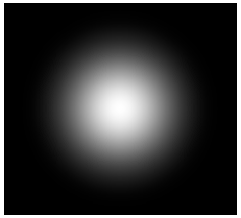
Nonequilibrium information erasure below kTln2
Konopik et al. (arXiv 1806.01034)

Experiment: Kiesel labs,
Ciampini et al.
work ongoing

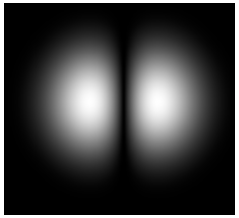
Tilted double well potential

70 nm particle
@ 1 mbar

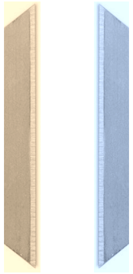




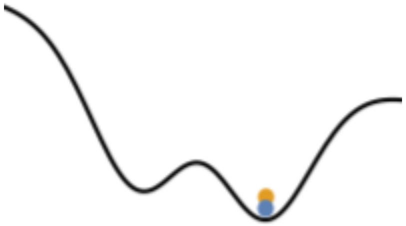
+



+



=



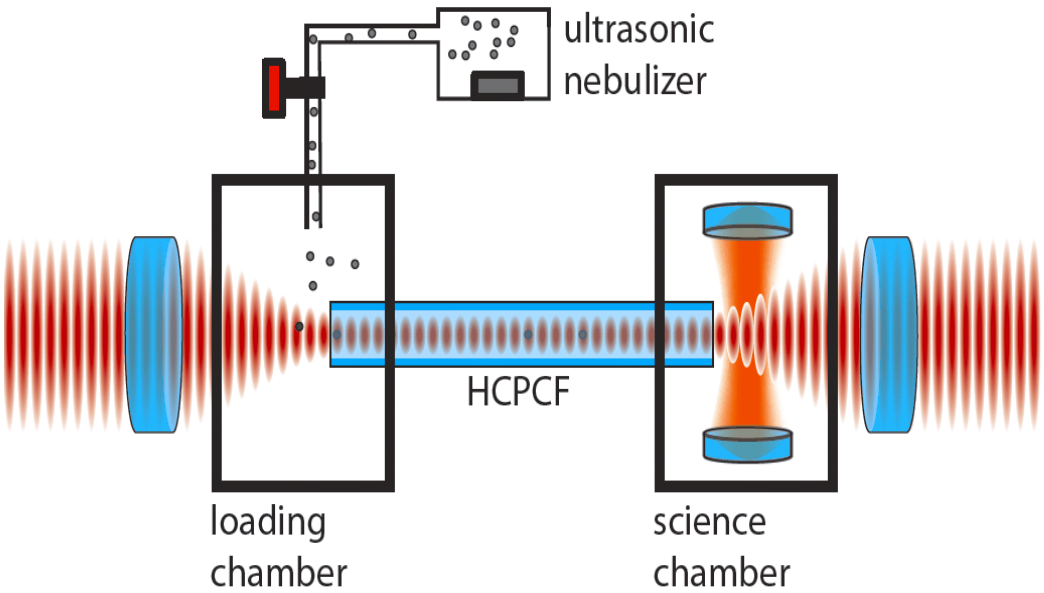
TEM 00 TEM 01
(W~1 μm)

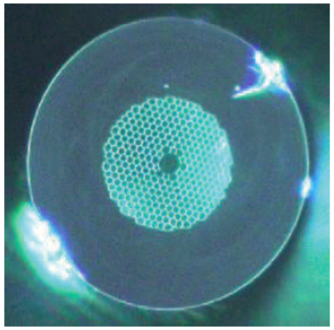
Electrodes
(D= 100 μm)

Optical control in HCPCF

Grass et al., APL 108, 221103 (2016)

HCPCF
(hollow core photonic crystal fiber)



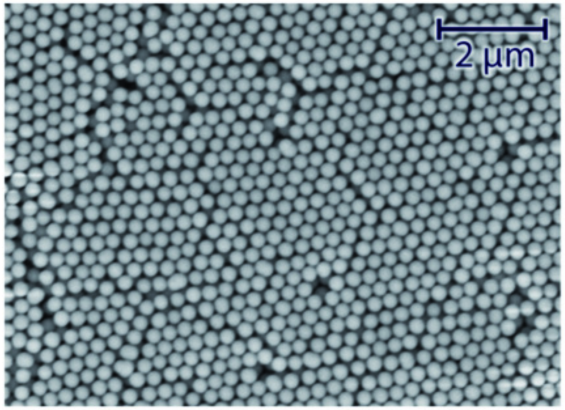


10µm air core

<0.1 db/m
@ 1060nm

7.5µm
mode field diameter

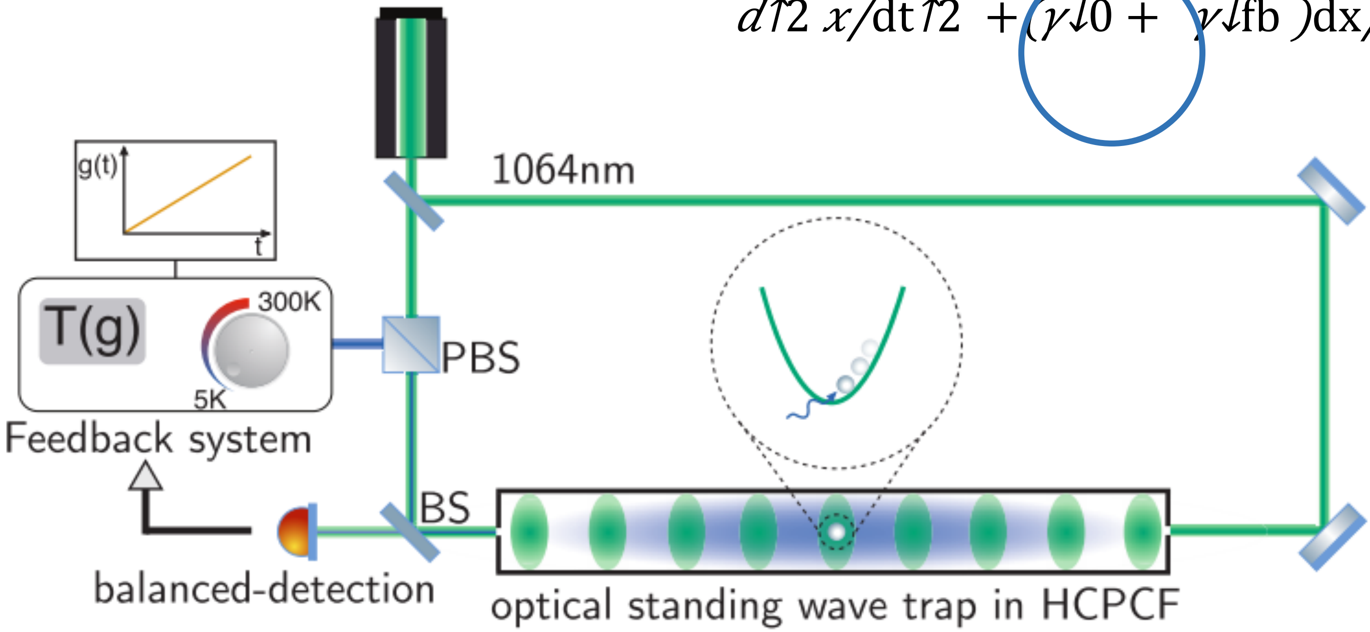
Silica : r=127 nm +/- 10%

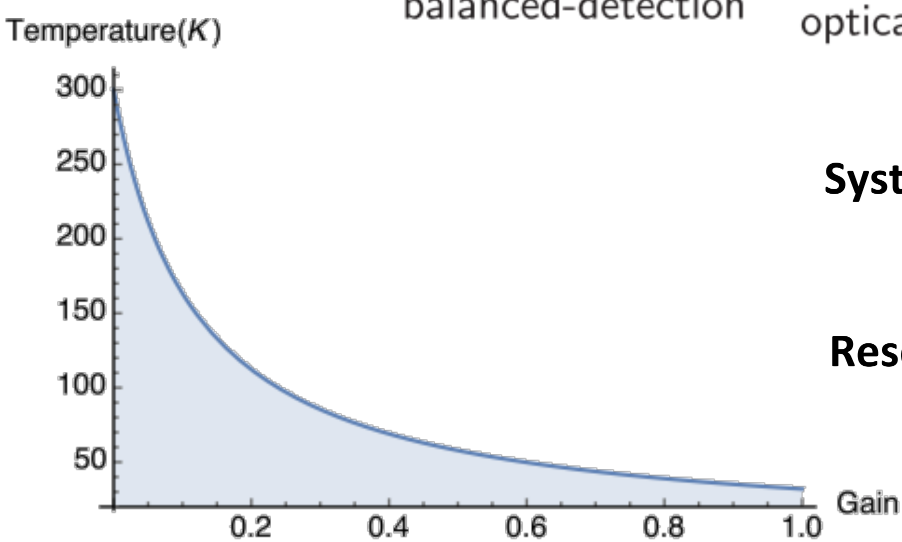


Renn et. al., PRL 82, 1574 (1999)
Kuhr, S. et al *PRL 91,* 213002 (2003)
Čižmár, T. et al *APL 86*, 174101 (2005)
Schmidt, O. et al Opt. Exp. 21, 2212 (2013)

Temperature Control in HCPCF

$$\frac{d^2 x}{dt^2} + (\gamma_0 + \gamma_{fb})\frac{dx}{dt} + \Omega^2$$





System: Nanoparticle (r=969nm) in a standing wave; near harmonic potential

Reservoir: Simulated by linear feedback cooling, gain tunes temperature

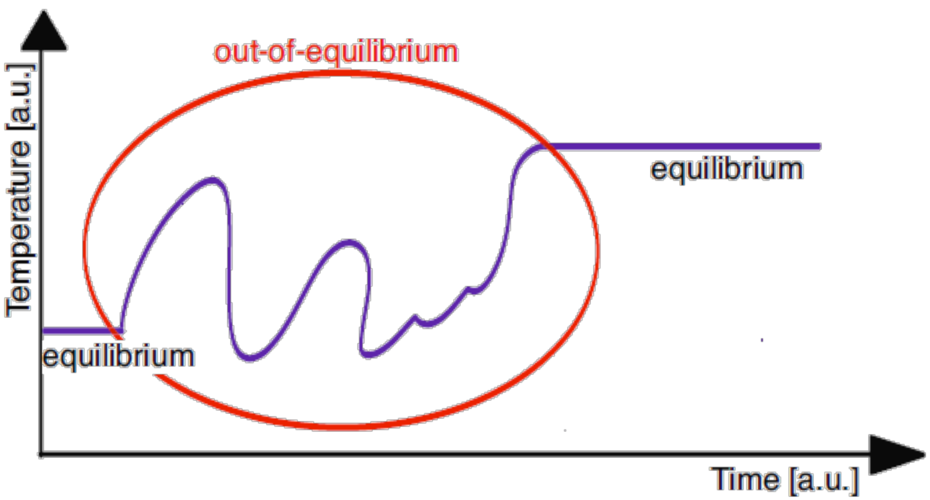
Thermal Driving out of Equilibrium

Mechanical Work drives a system:
Free energy difference can be determined even far from equilibrium

Jarzynski Equality:

$$e^{-\beta\Delta F} = \langle e^{-\beta W} \rangle$$

Theory: Jarzynski, C., PRL 78, 2690 (1997)
Experiment: Liphardt, Science 296, 1832 (2002)



Williams, D. J. Searles, and D. J. Evans,
PRL 100, 250601 (2008).

Thermal Drive
Williams Searles Evans Equality

$$e^{-\Delta(\beta F)} = \langle e^{-\int \dot{\beta}\, H(\lambda, x_t,}$$

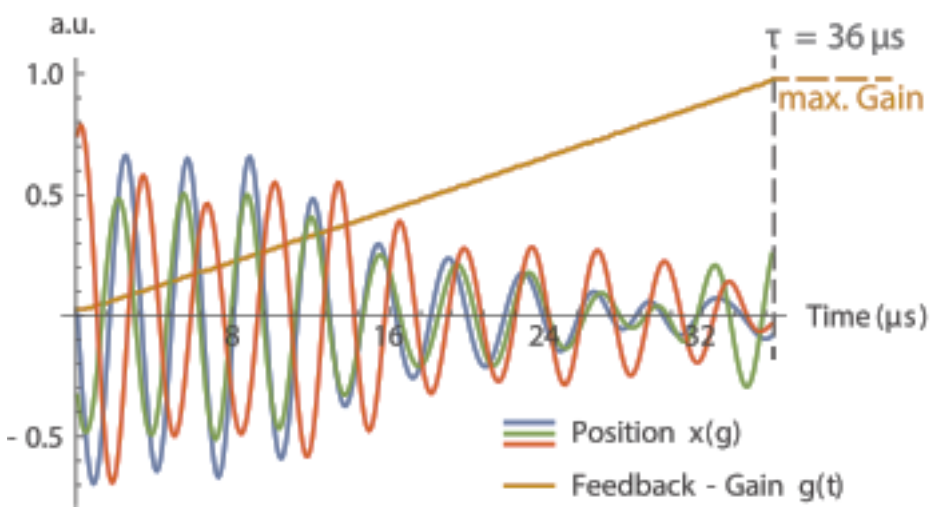
Thermal Driving out of Equilibrium

Mechanical Work drives a system:
Free energy difference can be determined even far from equilibrium

Jarzynski Equality:

Theory: Jarzynski, C., PRL 78, 2690 (1997)
Experiment: Liphardt, Science 296, 1832 (2002)

$$e^{-\beta\Delta F} = \langle e^{-\beta W} \rangle$$



Williams, D. J. Searles, and D. J. Evans,
PRL 100, 250601 (2008).

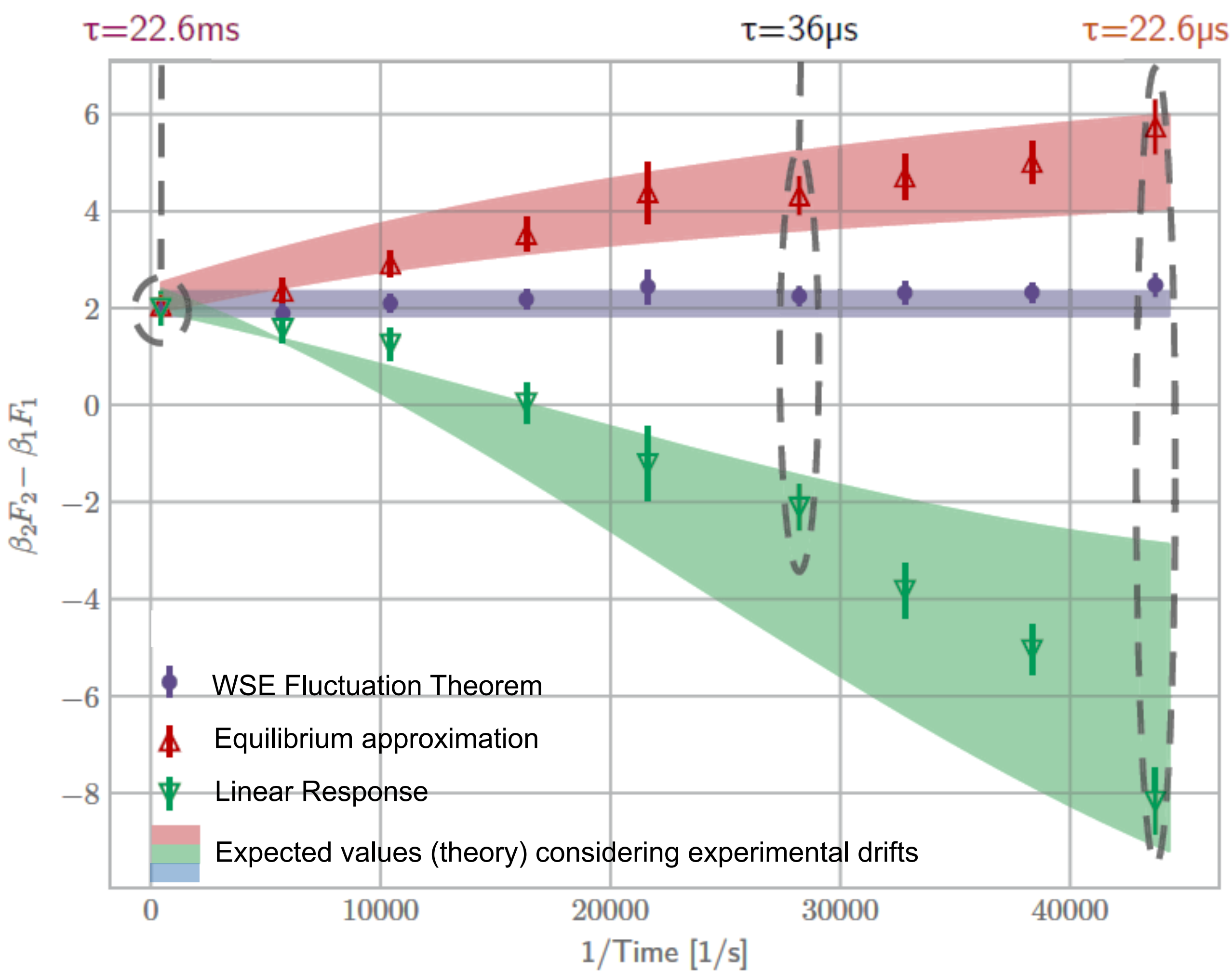
Thermal Drive
Williams Searles Evans Equality

$$e^{-\Delta(\beta F)} = \langle e^{-\int \beta \dot{H}(\lambda, x_t ,$$

Test of WSE Fluctuation Theorem

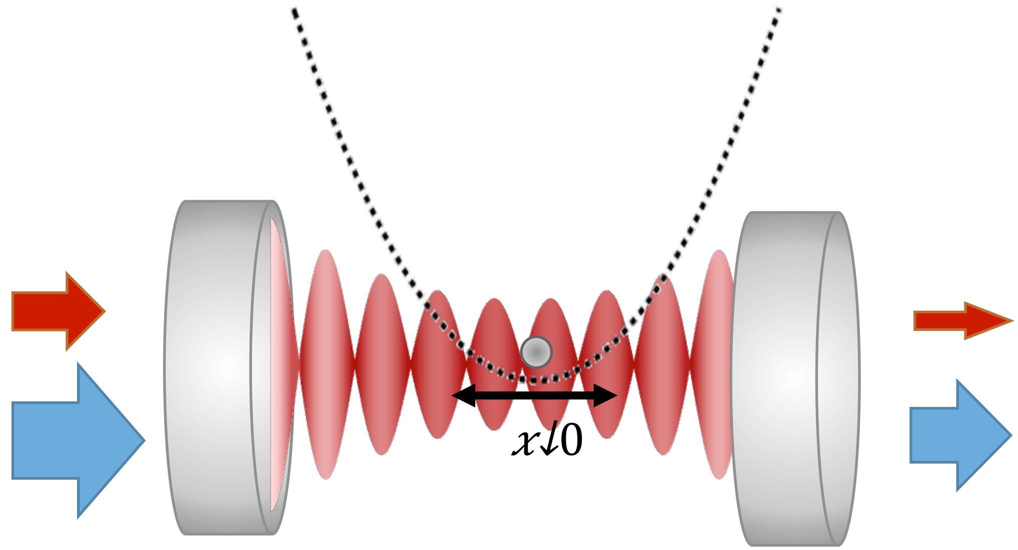
Thermal Drive
Williams Searles Evans Equality

$$e^{-\Delta(\beta F)} = \langle e^{-\int \beta \, H(\lambda, x_t, p_t)\, dt}$$

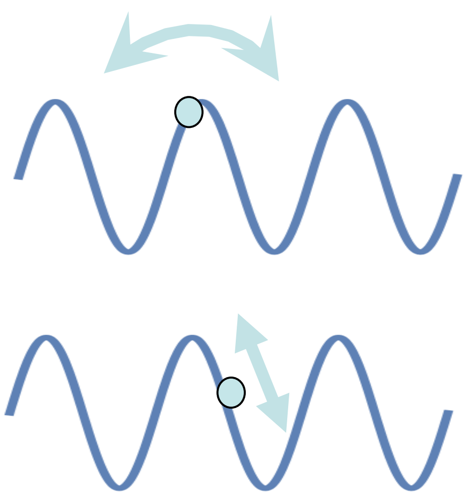


Coupling to a cavity

Driving



To detection



Cavity frequency shift vs. particle position

$$\hbar\omega_c(x) = -U_0 \sin^2(kx)$$

Dispersive linear coupling via

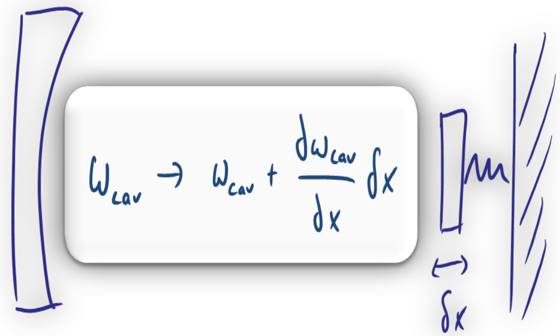
$$\omega_c(x) \approx \frac{d\omega_c}{dx} x$$

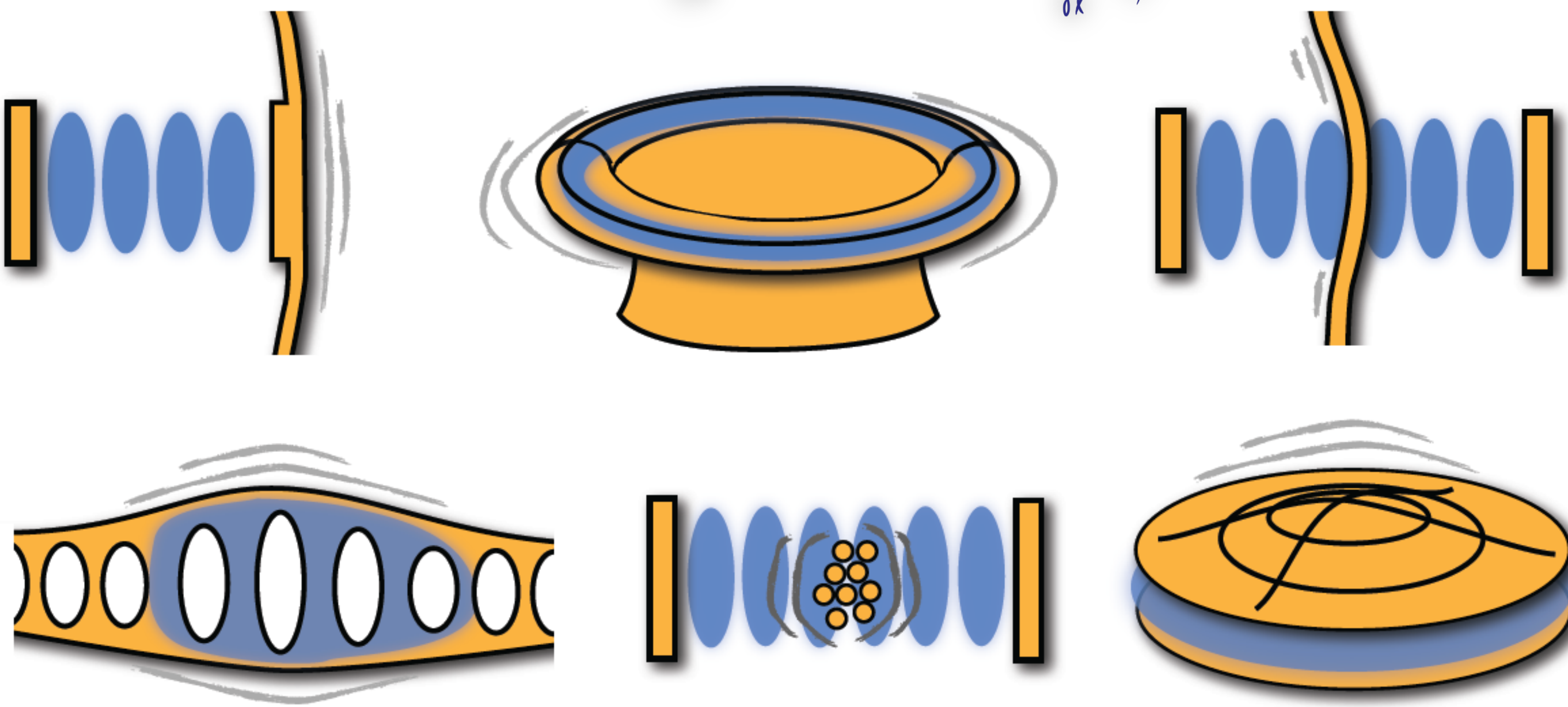
Optomechanical Systems

single-photon coupling |1> — $H_{int} \approx \hbar g_0\, a^{+} a\, x$

driven cavity |α> — $H_{int} \approx \hbar g_0 \alpha\, x_{cav} x$

still too small

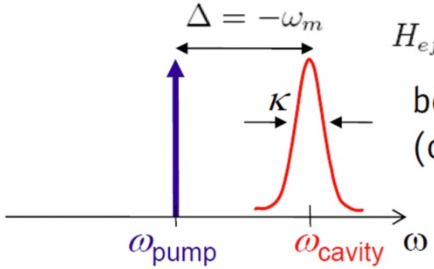




Rev. Mod. Phys. **86**, 1391 (2014)

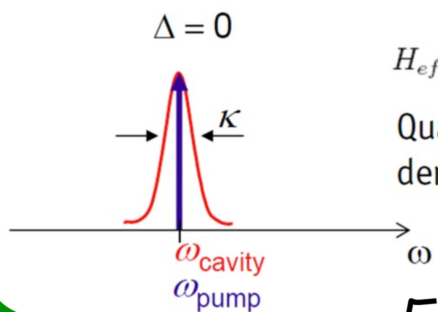
Quantum Optomechanics

Ideal case:
resolved sideband regime, RWA



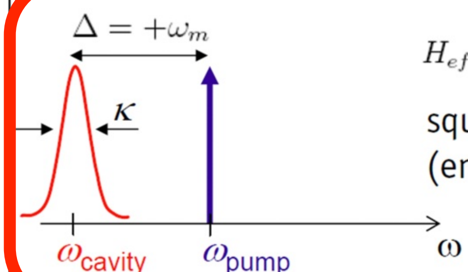
$H_{eff} \propto a^\dagger b + a b^\dagger$

beam-splitter (cooling)



$H_{eff} \propto x_a x_b$

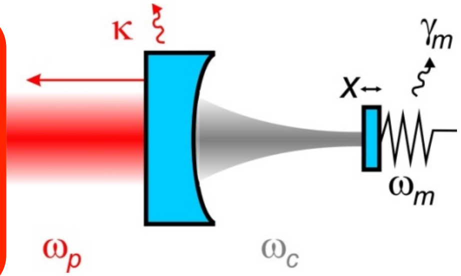
Quantum non-demolition QND



$H_{eff} \propto a^\dagger b^\dagger + ab$

squeezer (entanglement)

full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states



Requires:

Minmum entropy mechanical states (e.g. ground state)

+

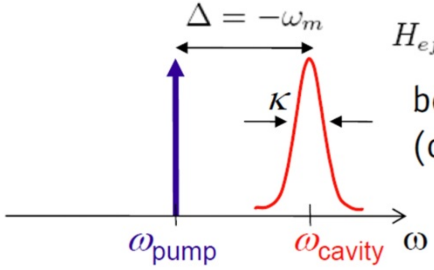
Strong cooperativity $C=g^2/\kappa \gamma\ n_{bath}$

g: OM coupling
κ: cavity decay
γ: mechanical damping
n_{bath}: bath phonon number

Early ideas:
Zhang, Peng, Braunstein, PRA **68**, 013808 (2003)
Aspelmeyer, Kippenberg, Marquardt, RMP **86**, 1391 (2014)

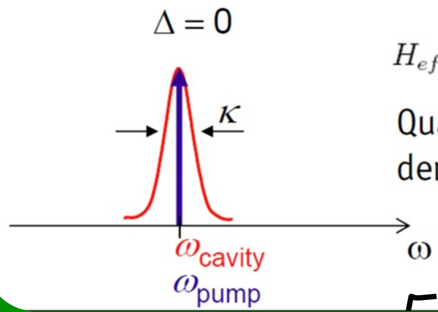
Quantum Optomechanics

Ideal case:
resolved sideband regime, RWA



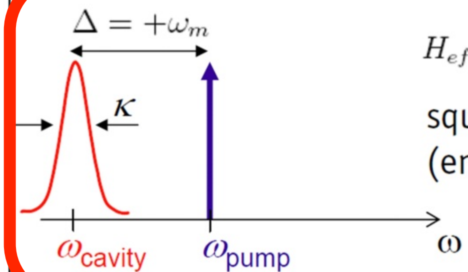
$H_{eff} \propto a^\dagger b + a b^\dagger$

beam-splitter (cooling)



$H_{eff} \propto x_a x_b$

Quantum non-demolition QND

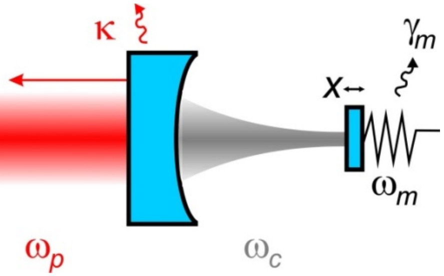


$H_{eff} \propto a^\dagger b^\dagger + ab$

squeezer (entanglement)

full **quantum optics toolbox**
to prepare and control
states
states

Teufel et al., Nature 2011
*Chan et al., Nature 2011**



Gröblacher et al., Nature 2009
Teufel et al., Nature 2011
Verhagen et al., Nature 2012

hanical states
(e.g. ground state)
+
Strong cooperativity $C = g↑2 / \kappa\, g\ nbath$

g: OM coupling

Brooks et al., Nature 2012
*Safavi-Naeini et al., Nature 2013**
Purdy et al., PRX 2013

nping
mber

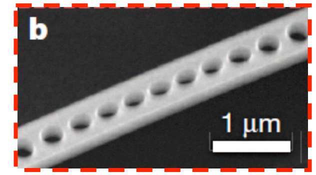
Palomaki et al., Science 2013
Riedinger et al., Nature 2016

Zhang, Peng, Braunstein, PRA **68**, 013808 (2003)
Aspelmeyer, Kippenberg, Marquardt, RMP **86**, 1391 (2014)

Quantum Optomechanics

Quantum ground state of motion

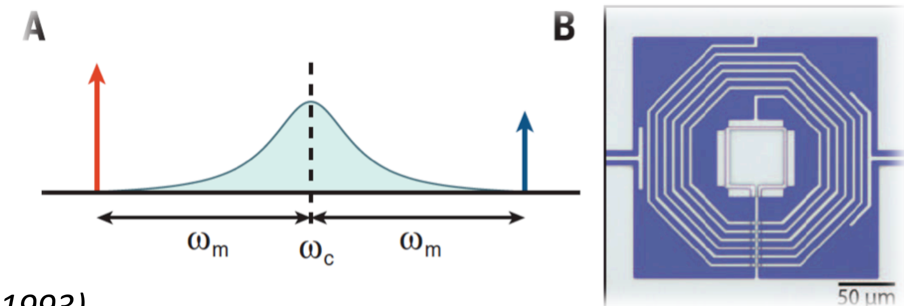
Microwave cavity cooling: Teufel et al., Nature 475, 359 (2011)
Laser cooling: Chan et al., Nature 478, 89 (2011)
... and many more around the world...

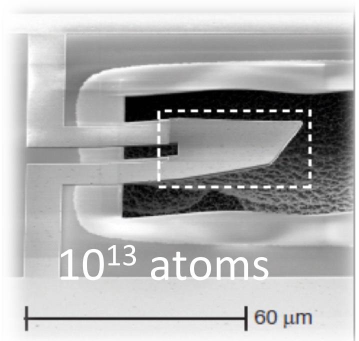


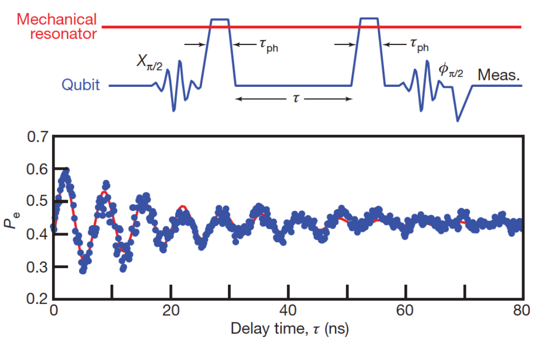
Quantum squeezed states of motion

Wollman et al., Science 349, 952 (2015)
J.-M. Pirkkalainen et al., PRL 115, 243601 (2015)
F. Lecocq et al., PRX 5, 041037 (2015)

„reservoir engineering“
(see also Cirac et al. PRL 70, 556 1993)

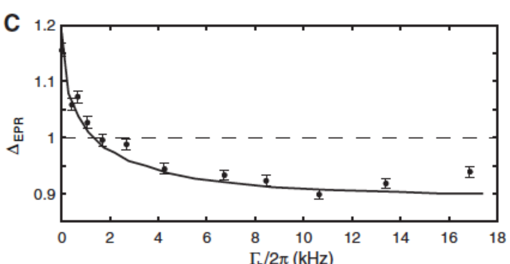


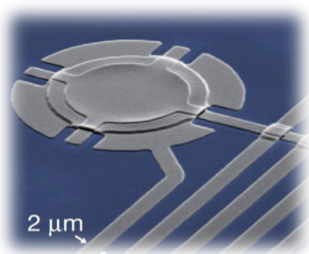




Non-Gaussian quantum states of motion

Phonon control through superconducting qubit:
O'Connell et al., Nature 464, 697 (2010)
Photon-phonon correlations:
Riedinger, Hong et al., Nature 530, 313 (2016)





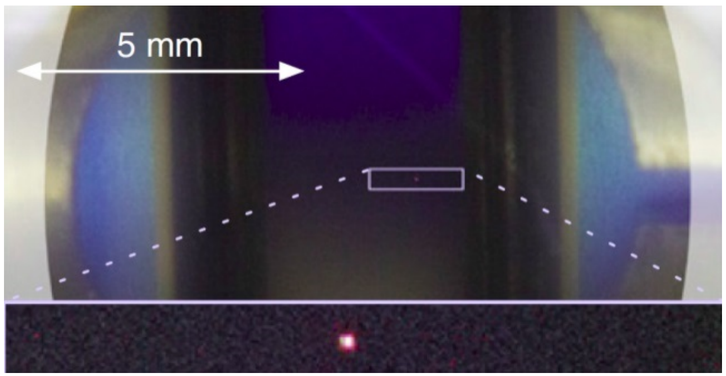
Quantum entanglement

EPR-type entanglement (MW):
Palomaki et al., Science 342, 710 (2013)
Bell-type entanglement (optical):
Lee et al., Science 334, 1253 (2011)

Nanoparticle in a cavity

Cavity cooling of a trapped sphere

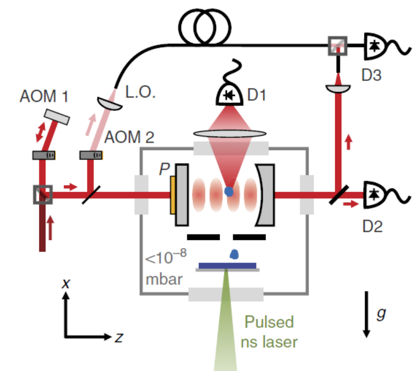
Uni Vienna



Kiesel, Blaser, Delic, Grass, Kaltenbaek, Aspelmeyer, PNAS 110, 14180 (2013)

Cavity cooling of a free particle

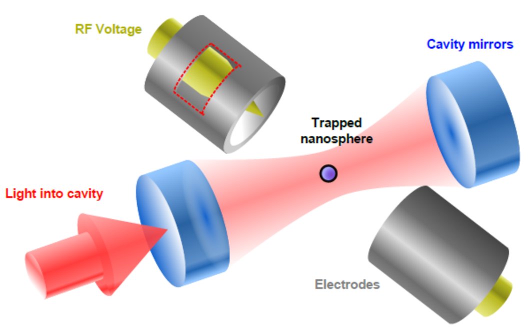
Uni Vienna



Asenbaum et al., Nature Communications 4, 2743 (2013)

Cooling in hybrid electro-optical trap

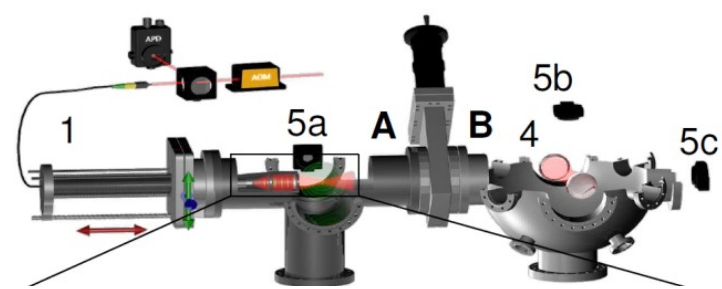
UCL



Millen et al., Phys. Rev. Lett. 114, 123602 (2015)

Transport and cavity transition in UHV

ICFO

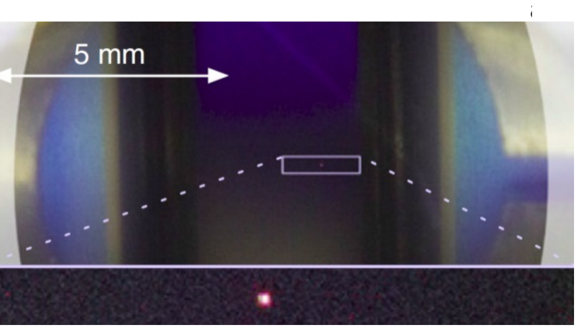


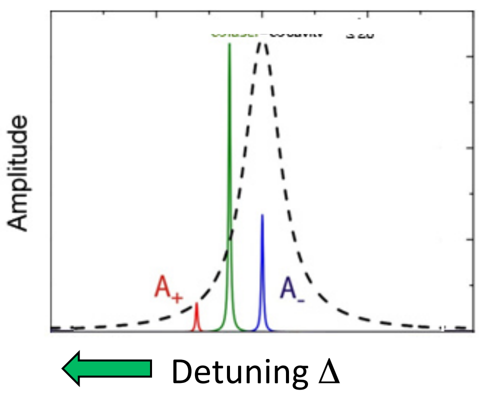
Mestres et al., Appl. Phys. Lett. 107, 151102 (2015)

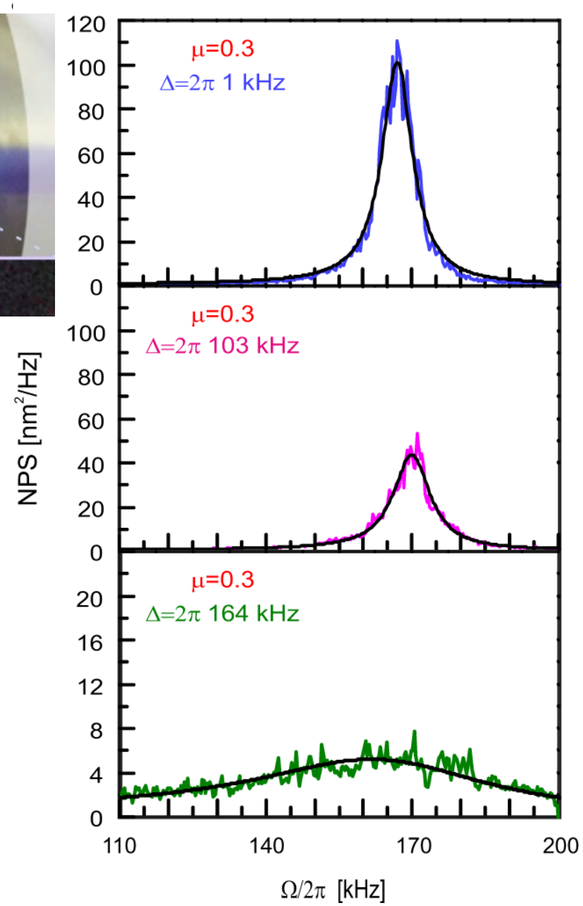
Cooling to approx. 50 K @ 4 mbar

Note: Probe beam = optical trap

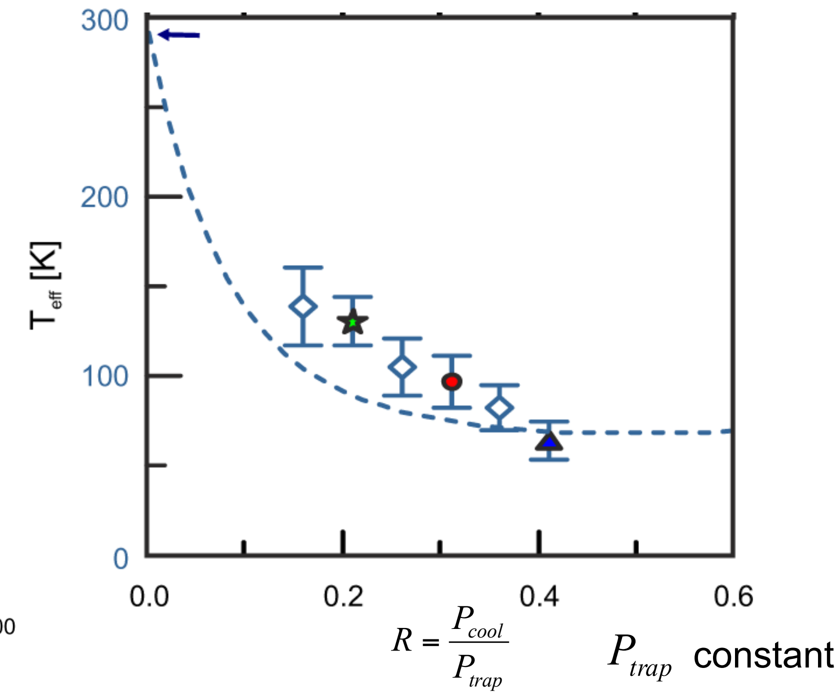
Kiesel, N. et al., *PNAS 110*, 14180 (2013)





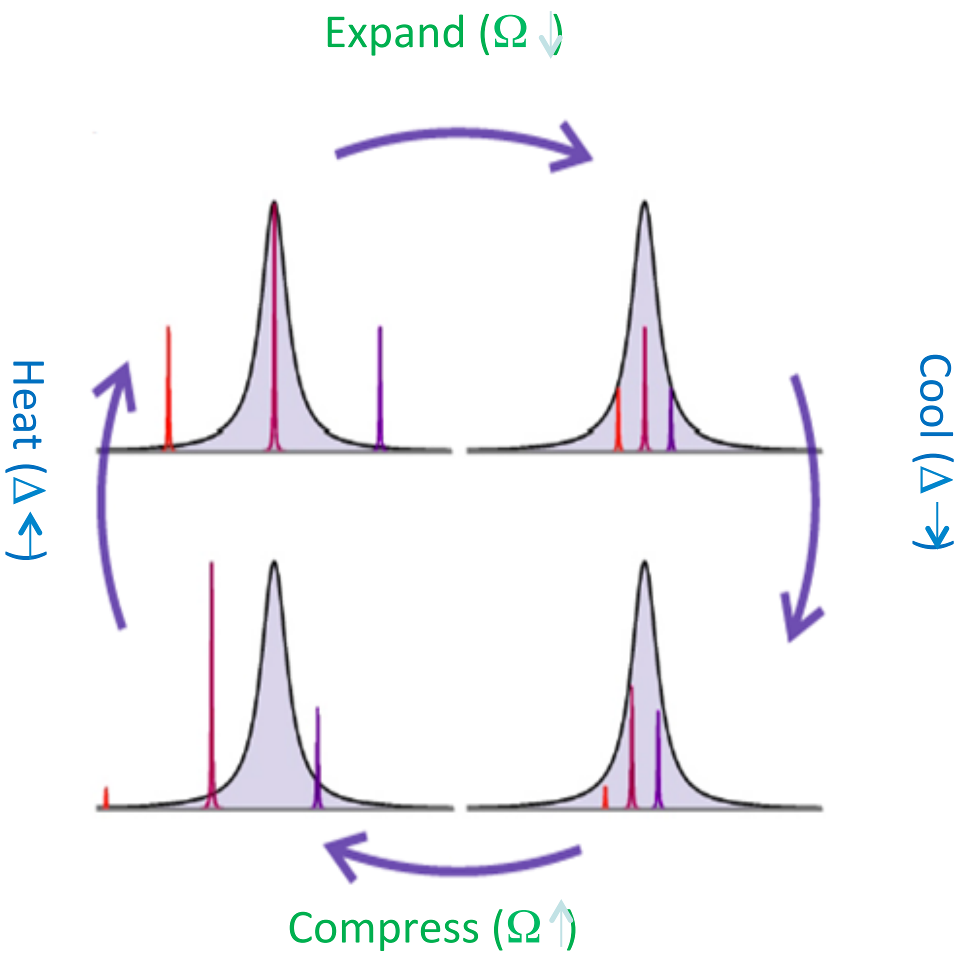


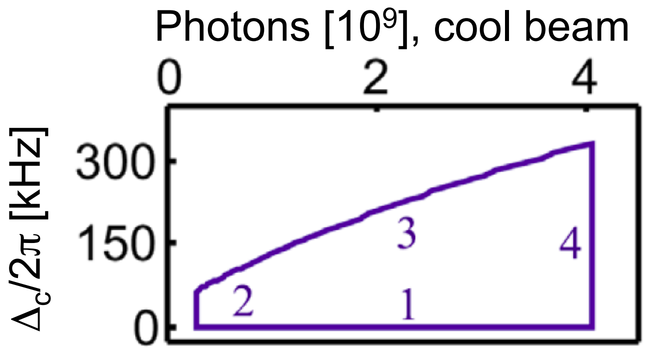
Optomechanical Cooling



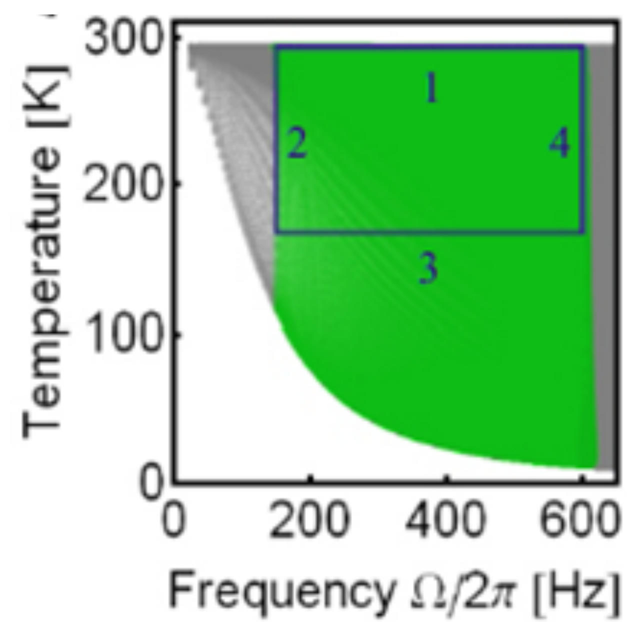
Cooling rate effectively
up to approx. 40 kHz

Implementing a Sterling cycle



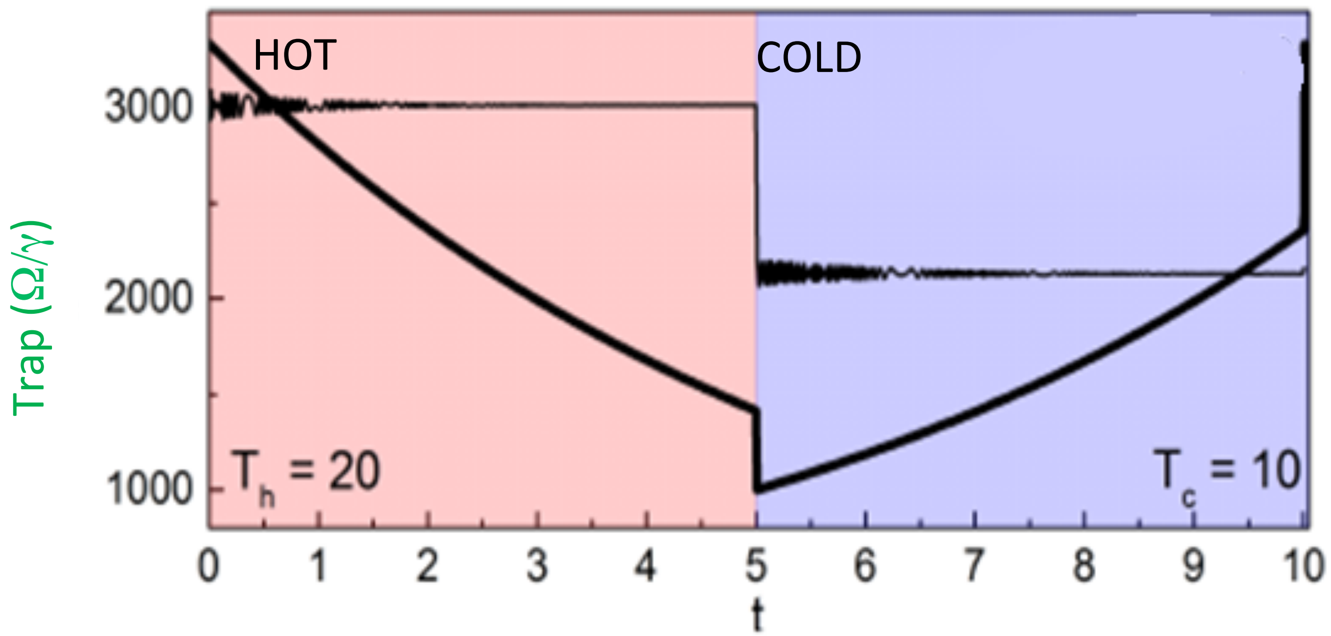


Requires <1mW power



Dechant et al., PRL 114, 183602 (2015), parameters based on Kiesel et al. PNAS 110, 14180 (2013).

Timing is everything - Optimization

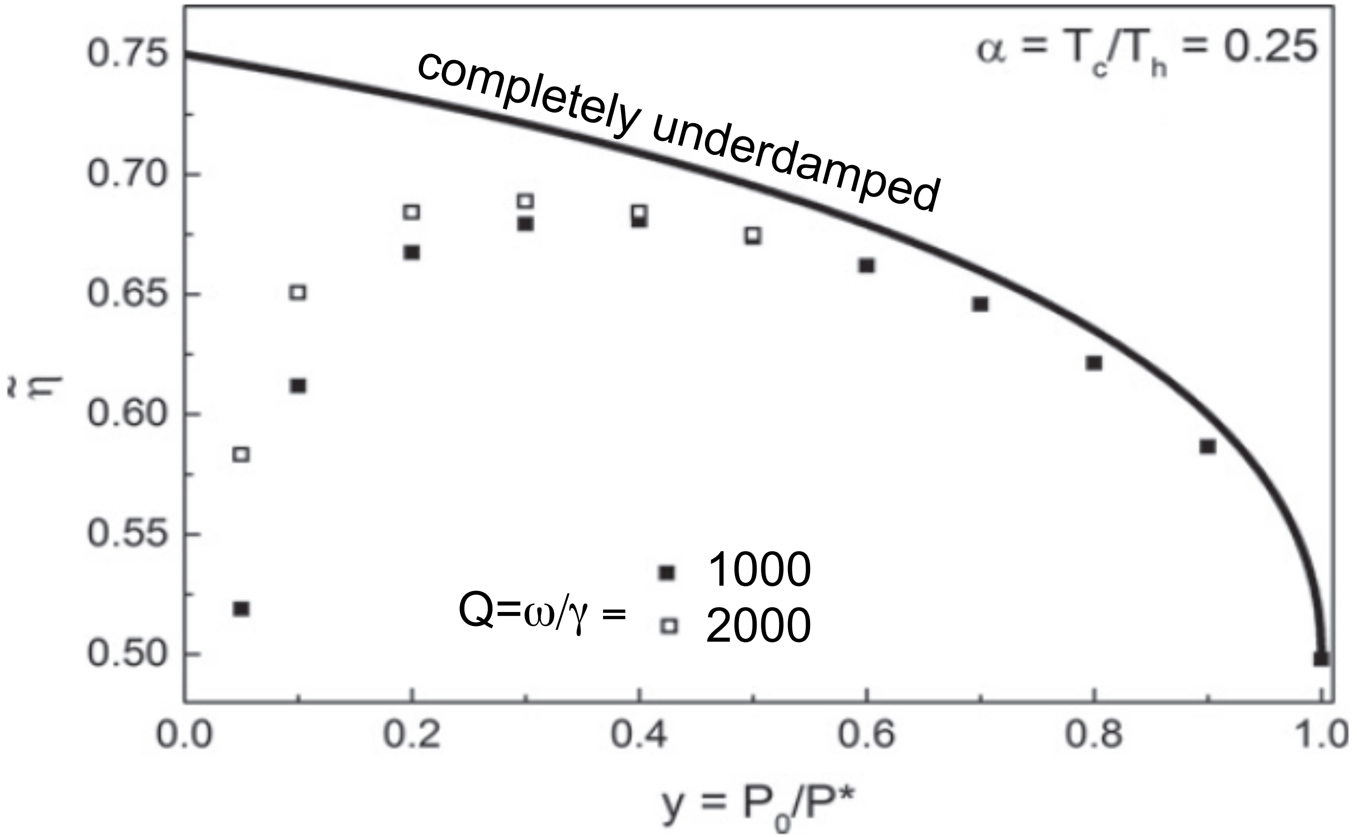


Optimize efficiency at fixed power output η - exponential protocol

Steps accomodate for temperature jumps

Dechant et al., EPL 119, 50003 (2017).

Timing is everything - Optimization



- Small deviations from max. Power result in strong efficiency increase
- Efficiency at max. power is
  general **for underdamped systems**

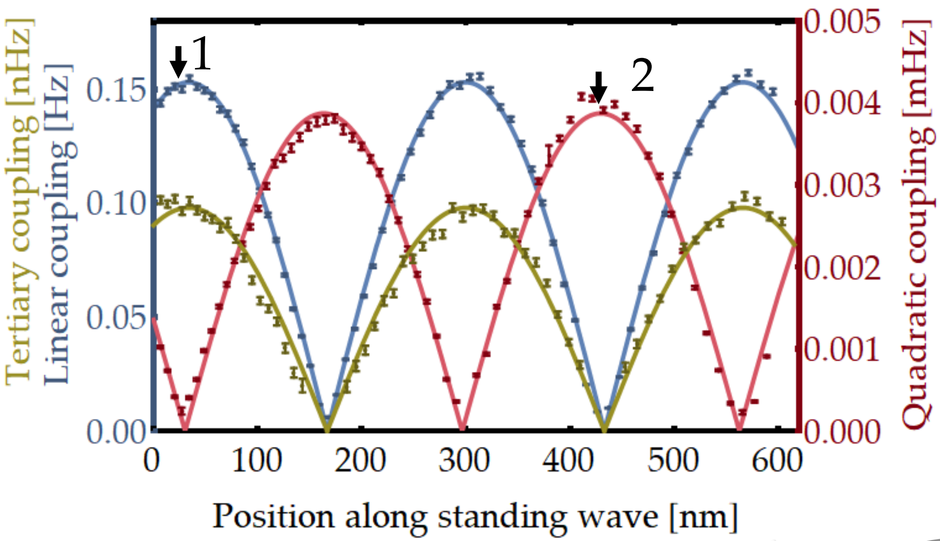
$$\eta = 1 - \sqrt{T_{COLD}/T_{HOT}}$$

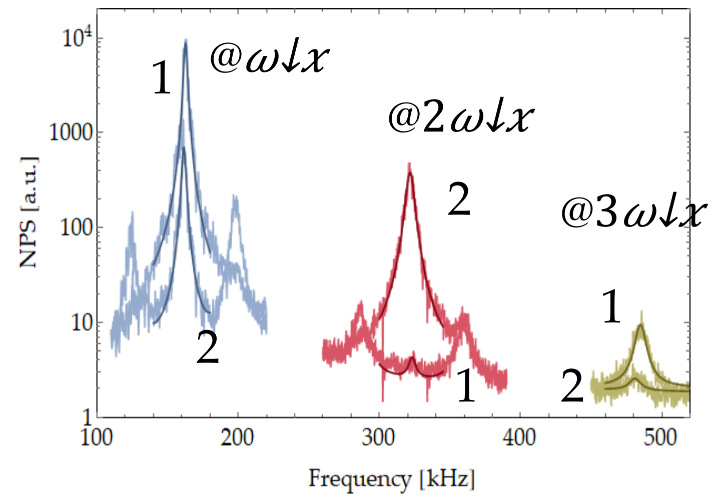
(Curzon Ahlborn bound)

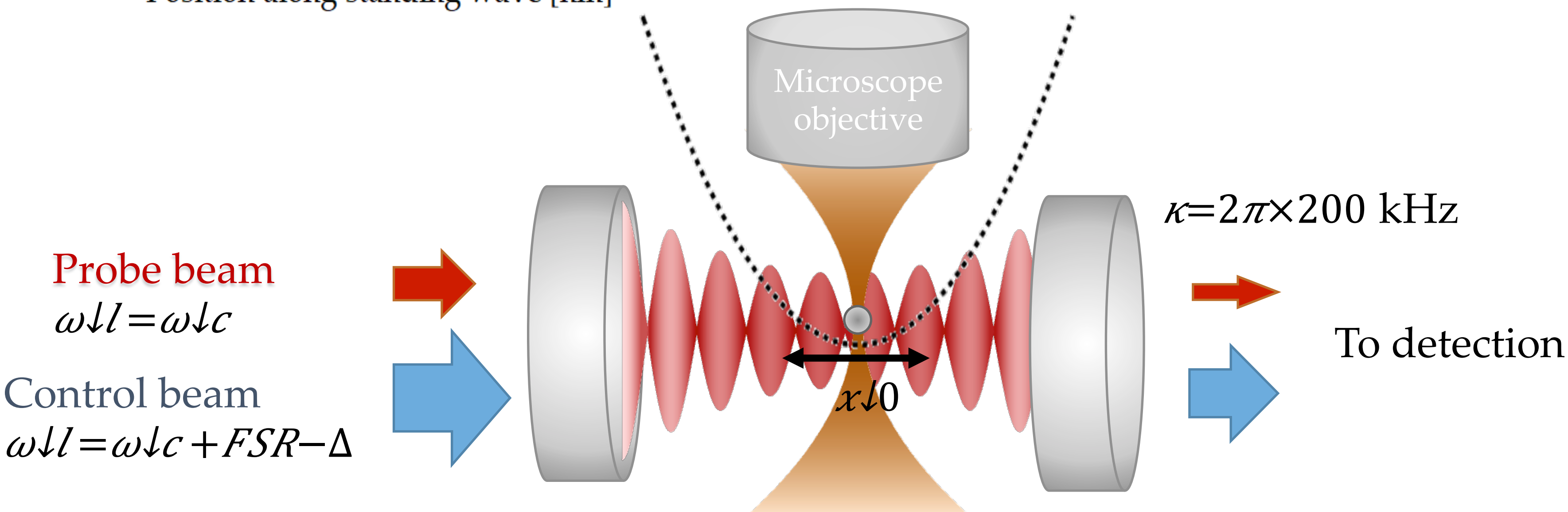
Dechant et al., EPL 119, 50003 (2017).

Coupling to a cavity

Optomechanical coupling



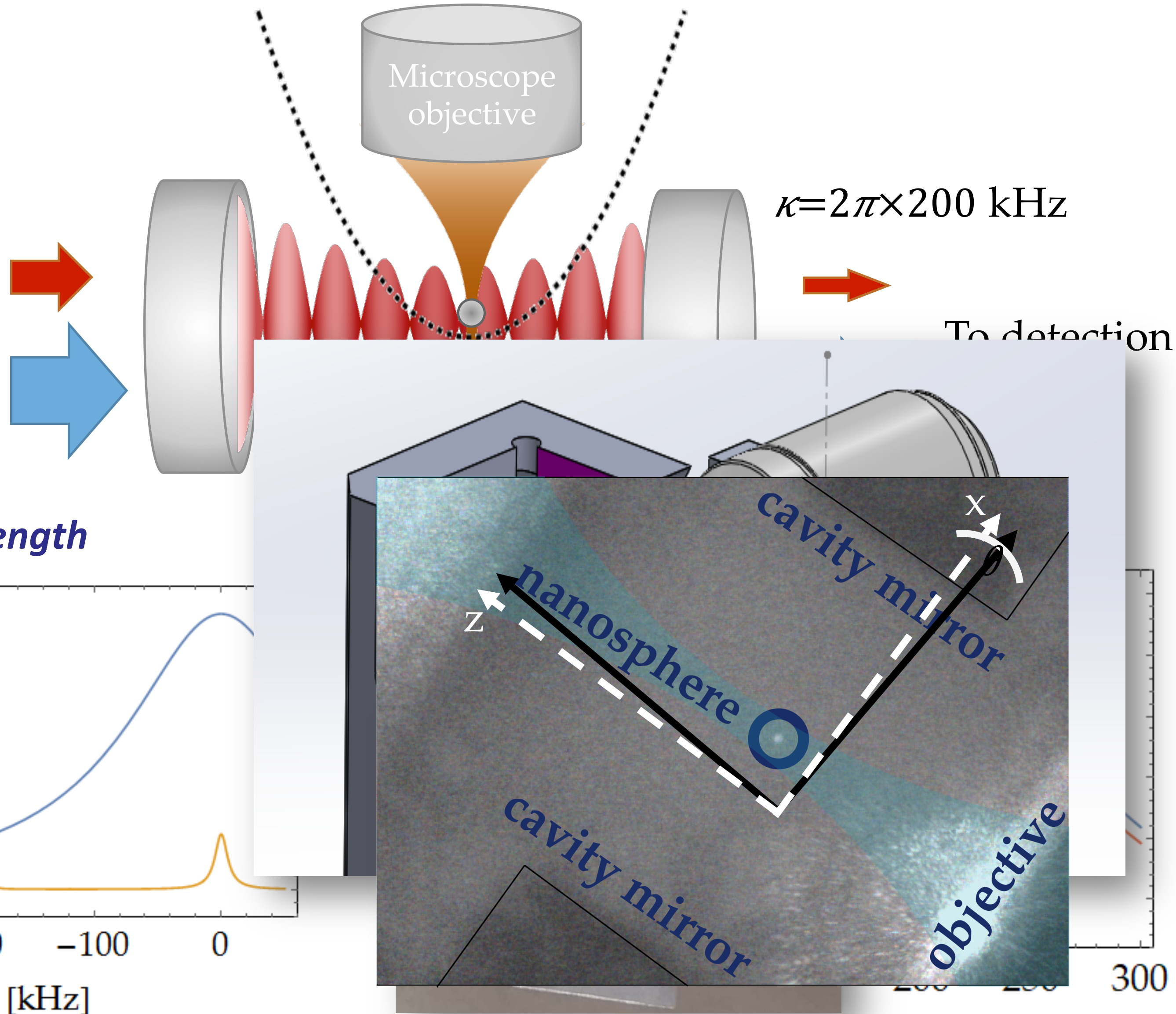




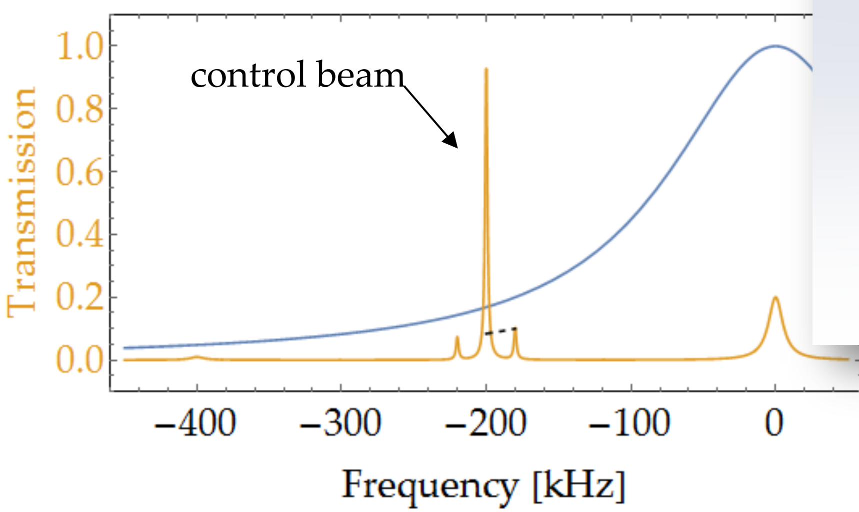
Optomechanical Coupling

Probe beam
$\omega_l = \omega_c$

Control beam
$\omega_l = \omega_c + FSR - \Delta$

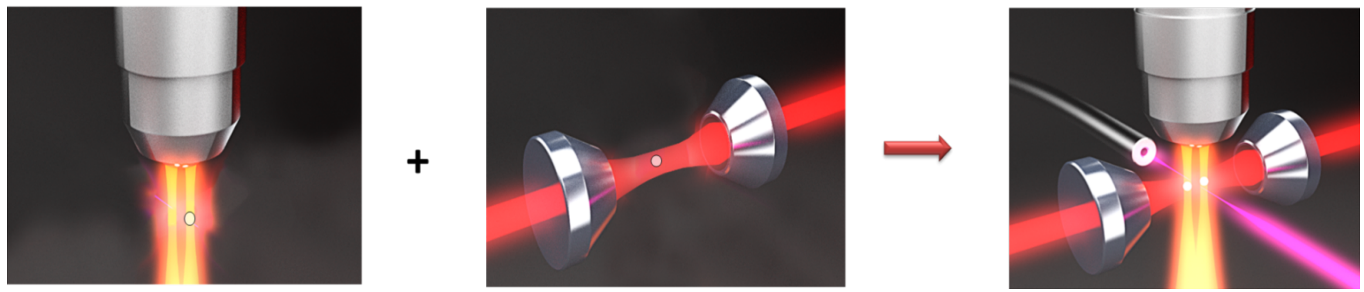


OMIT for coupling strength



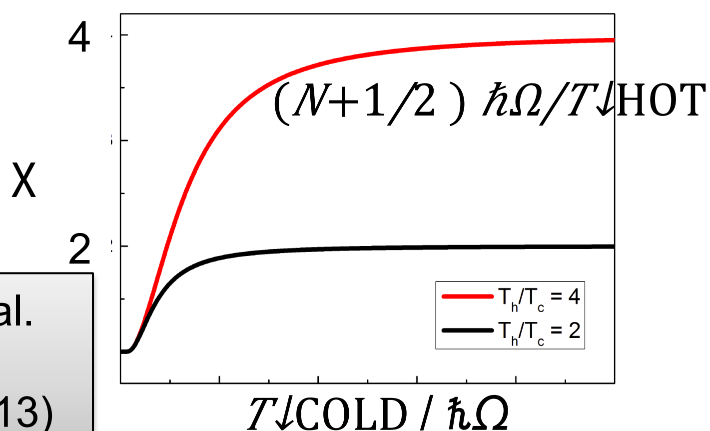
Weis et al., Science 330, 1520 (2010); Safavi-Naeini, Nature 472, 69 (2011)

Conclusion and Outlook

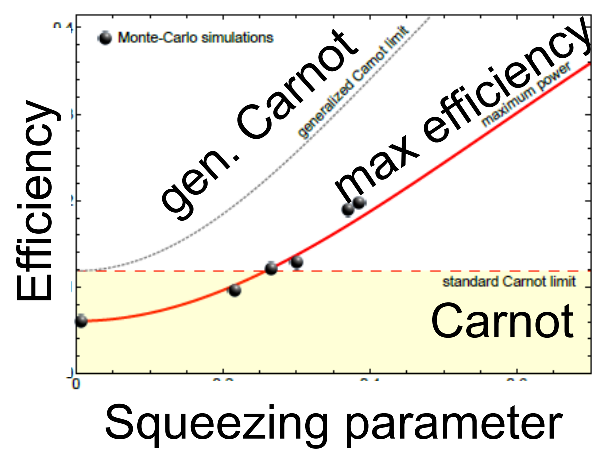


Optical levitation provides access to

- Complex POTENTIALS: Optimized geometry and use of multiple degrees of freedom
- FAST CONTROL: Far-from equilibrium and optimized thermodynamic protocols
- RESERVOIRS: Cavity Optomechanics as a versatile control tool
- QUANTUM THERMODYNAMICS: Natural extension into the quantum regime



Agarwal et al.
PRE 88,
012130 (2013)



Roßnagel et al.
PRL 112,
030602 (2014)

Acknowledgements

The cavity and HCPCF team


Uros Delic


David Grass


Manuel Reisenbauer


Markus Aspelmeyer

The young thermo team


Mario Ciampini

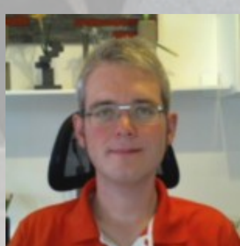

Maxime Debiossac

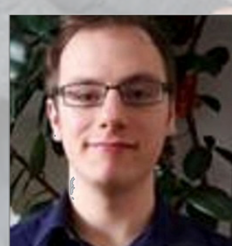

Markus Rademacher


Tobias Wenzl

TherMi
FWF Der Wissenschaftsfonds.
Alexander von Humboldt Stiftung/Foundation
erc European Research Council

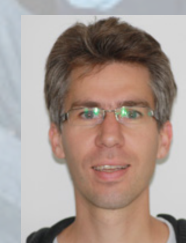
Collaborators: WSE, Heat engine (...), and Complex optical traps


Andreas Dechant


Michael Konopik


Eric Lutz


Monika Ritsch-Marte


Gregor Thalhammer

S: SAPIENTIAE VIENNENSIS STUDII