2449-8

38th Conference of the Middle European Cooperation in Statistical Physics - MECO38

25 - 27 March 2013

Towards Quantum Optics Experiments with Cavity-Optomechanical Systems

Witlef WIECZOREK
Faculty of Physics
University of Vienna
Austria

Towards quantum optics experiments with cavity-optomechanical systems

Witlef Wieczorek

Faculty of Physics,
University of Vienna,
Austria

VCQ
Vienna Center for Quantum Science and Technology

universität wien

MECO38
25^{th}-27^{th} March 2013
ICTP

1) Introduction to cavity optomechanics

2) Mechanical state preparation

mechanical mode cooling

optomechanical strong coupling

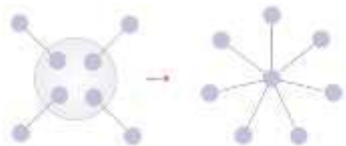
3) Optomechanical state reconstruction

4) Outlook: quantum optomechanics

quantum optics / quantum information with … (not complete)

AMO

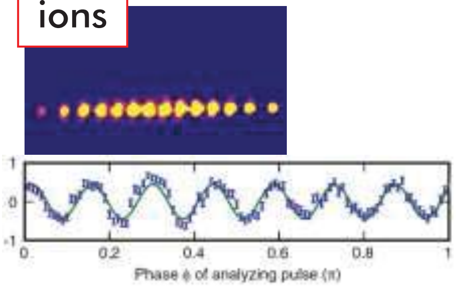
photons



X.-C. Yao et al.,
Nature Photonics 6 (12)

$\sim 10^1$ photons

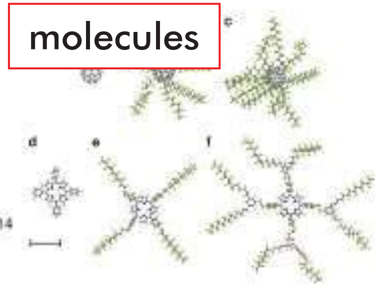
ions



T. Monz et al.,
PRL 106 (11)

$\sim 10^1$ ions

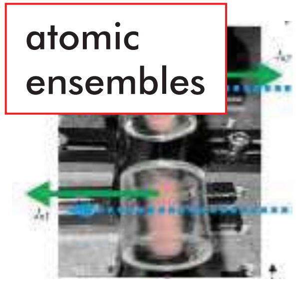
molecules



S. Gerlich et al.,
Nature Comm. 2 (11)

$\sim 10^3$ atoms

atomic ensembles

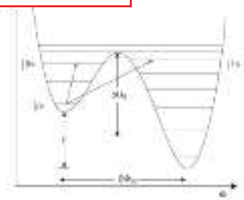


B. Julsgaard et al.,
Nature 413 (01)

$\sim 10^{12}$ atoms

Solidstate-based

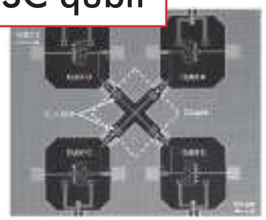
SQUID



J. R. Friedman et al.,
Nature 406 (00)

$\sim 10^9$ cooper pairs

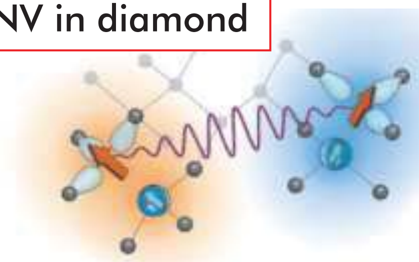
SC qubit



M. Neeley et al.,
Nature 467 (10);
L. DiCarlo, Nature 467 (10)

$< 10^1$ SC qubits

NV in diamond

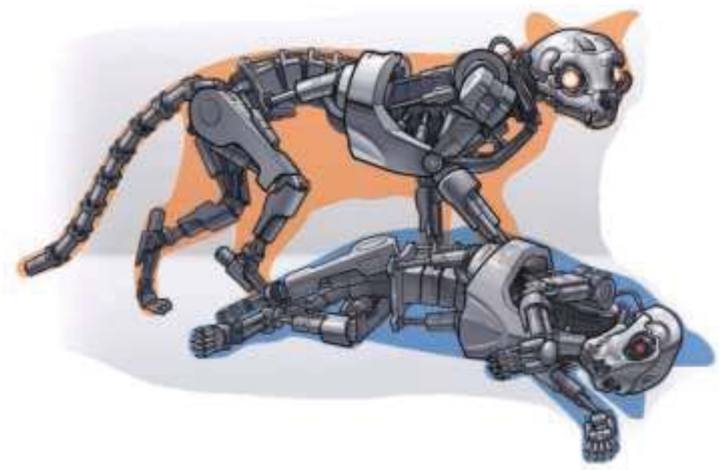


F. Dolde et al.,
Nature Physics 9 (13)

$< 10^1$ NV centers

towards macroscopic, mechanical objects

mechanical oscillator



$>10^{14}$ atoms

g – kg

Hz

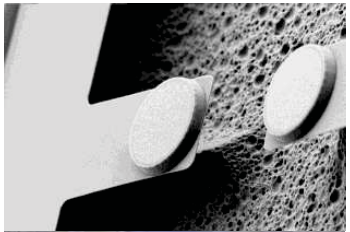
cm

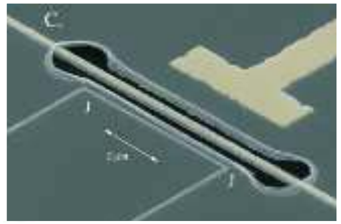
mass

ng -mg

kHz – MHz

μm





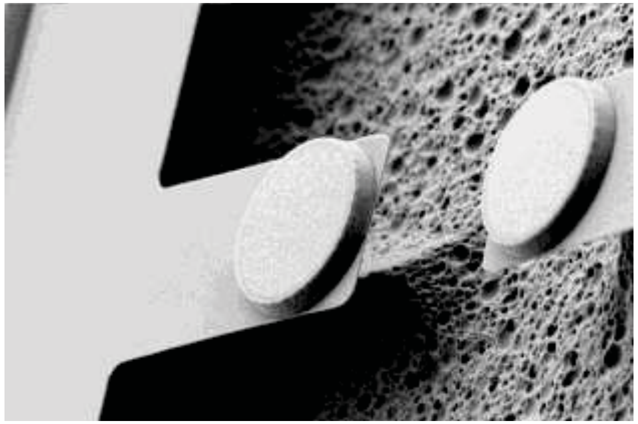
frequency

pg -ng

MHz – GHz

nm

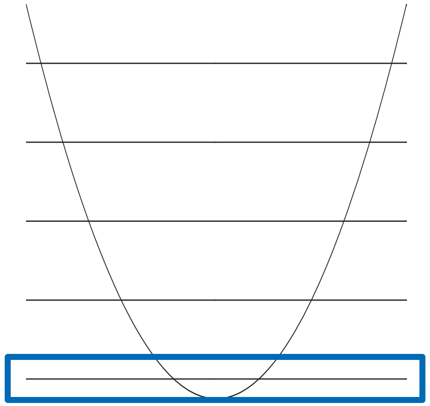
M. Aspelmeyer, T. Kippenberg, F. Marquardt,
arXiv:1303.0733 [quant-ph] (2013)



undesired damping (energy loss to environment)

$$\dot{x} = p/m$$
$$\dot{p} = -\omega_m^2 m x - \gamma_m p - \sum_i f_i(t)$$

thermal noise force
external forces

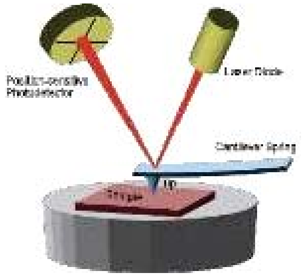


experimental challenge:

$$\langle E \rangle = \hbar\omega_m(\langle n \rangle + \tfrac{1}{2})$$
$$\langle n \rangle = (\exp(\hbar\omega_m/k_B T) - 1)^{-1}$$

example
frequency 1MHz, n<1: T<70μK

What can be done with "quantum"-controlled mechanical oscillators?

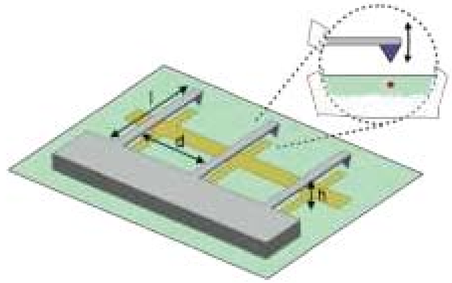


Mechanical sensing

present performance: yoctogram, yoctonewton, attometer, etc.
What are the quantum limits to mechanical sensing?

Quantum foundations

macroscopic superpositions involving up to 10^{20} atoms
Is there a limit to the size of Schrödinger cats?



Quantum information

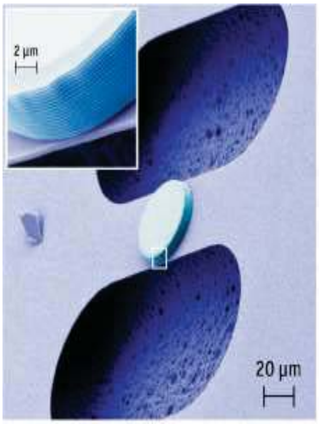
potential hybrid quantum information architectures on a chip
Can mechanical systems serve as a quantum bus / memory?

Realization by combining
tools of quantum optics
with high-performance micro/nanomechanical systems

How to control a mechanical oscillator?

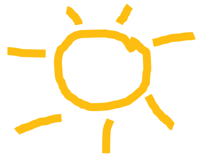
photon momentum

$\hbar k$

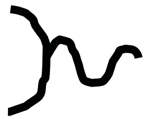


S. Gröblacher et al.,
Nature Physics 5 (09)

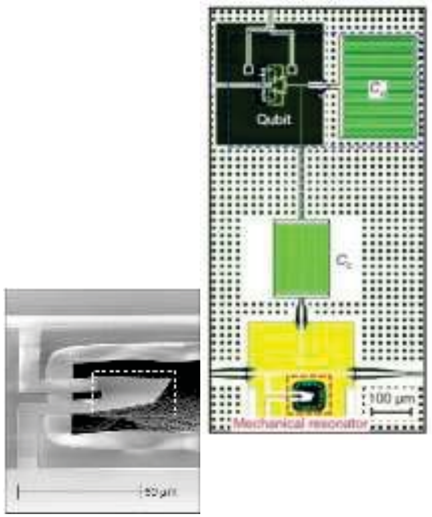
optical light fields



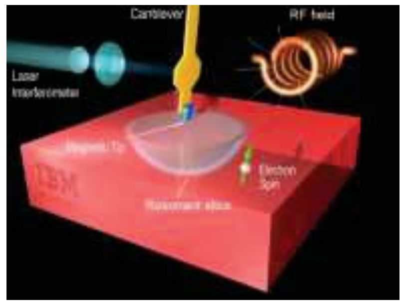
coherent states
squeezed states
single photons



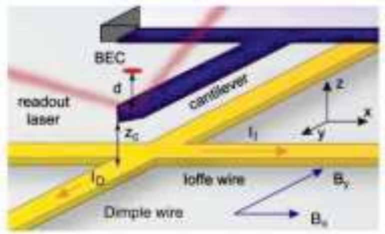
homodyne/heterodyne detection
single photon counting



A. O'Connell et al.,
Nature 464 (10)

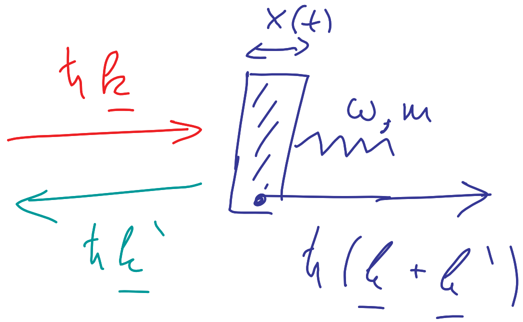


D. Rugar et al.,
Nature 430 (04)



D. Hunger et al.,
PRL 104 (10)

interaction via radiation pressure:
effect of a single photon



energy conservation:

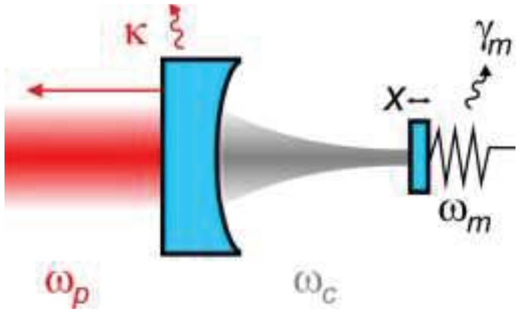
$$\Delta x^2 = \frac{\Delta p^2/2m}{m\omega_m^2/2}$$

1MHz, 50ng, 1064nm: $\frac{\Delta x}{x_{\rm zp}} = 8\pi\frac{x_{\rm zp}}{\lambda} \sim \mathcal{O}(10^{-8})$

$$x_{\rm zp} \sim 10^{-16}\mathrm{m}$$

increase by interaction with coherent state $n_c \gg 1$

qualitatively and quantitatively new:
cavity-optomechanics



$$\Delta p = \frac{\mathcal{F}}{\pi} \cdot 2\hbar k \longrightarrow \frac{\Delta x}{x_{\mathrm{zp}}} = 8\mathcal{F}\frac{x_{\mathrm{zp}}}{\lambda}$$

Finesse up to 10^4 … 10^5

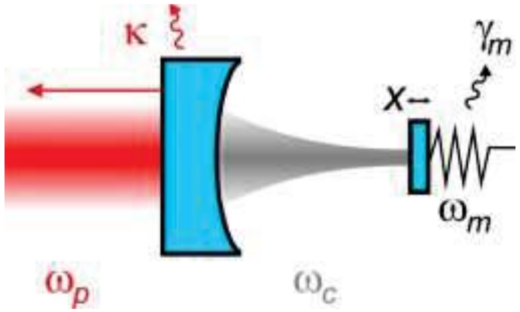
further increase by pumping with coherent input states: $n_c \gg 1$

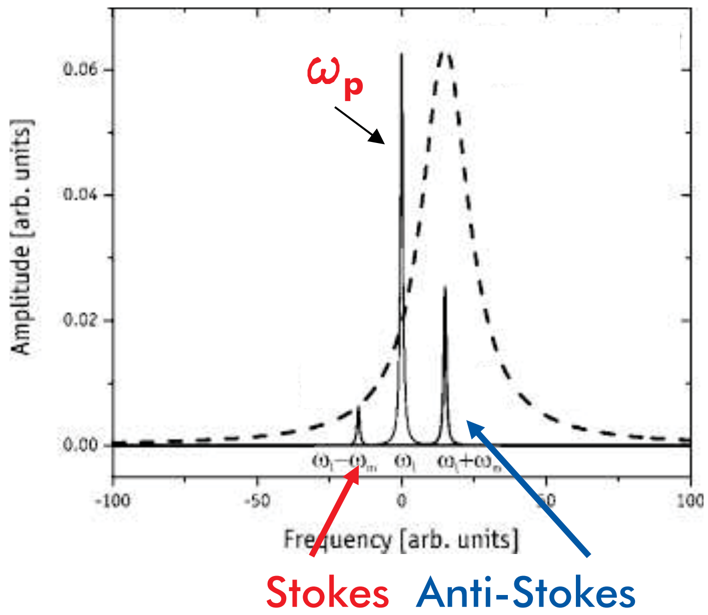
$$\hat{\mathcal{H}} = \boxed{\hbar\omega_c \hat{a}^\dagger \hat{a}} + \frac{1}{2}\hbar\omega_m(\hat{p}^2 + \hat{x}^2) \boxed{- \hbar g_0 \hat{a}^\dagger \hat{a}\hat{x}} + \boxed{i\hbar E(\hat{a}^\dagger e^{-i\omega_p t} - \hat{a}e^{i\omega_p t})}$$

cavity | OM interaction | drive

M. Aspelmeyer, T. Kippenberg, F. Marquardt, arXiv:1303.0733 [quant-ph] (2013)

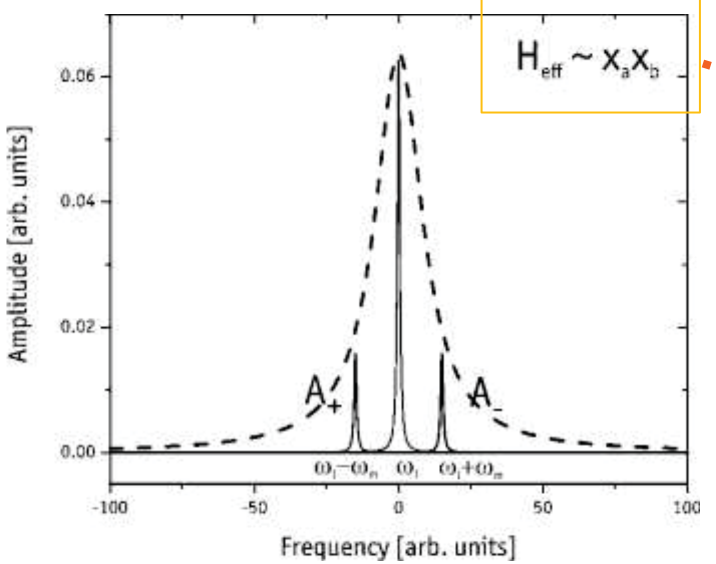
$$\hat{\mathcal{H}} = \boxed{\hbar\omega_c \hat{a}^\dagger \hat{a}} + \frac{1}{2}\hbar\omega_m(\hat{p}^2 + \hat{x}^2) - \hbar g_0 \hat{a}^\dagger \hat{a}\hat{x} + i\hbar E\boxed{\left(\hat{a}^\dagger e^{-i\omega_p t} - \hat{a} e^{i\omega_p t}\right)}$$



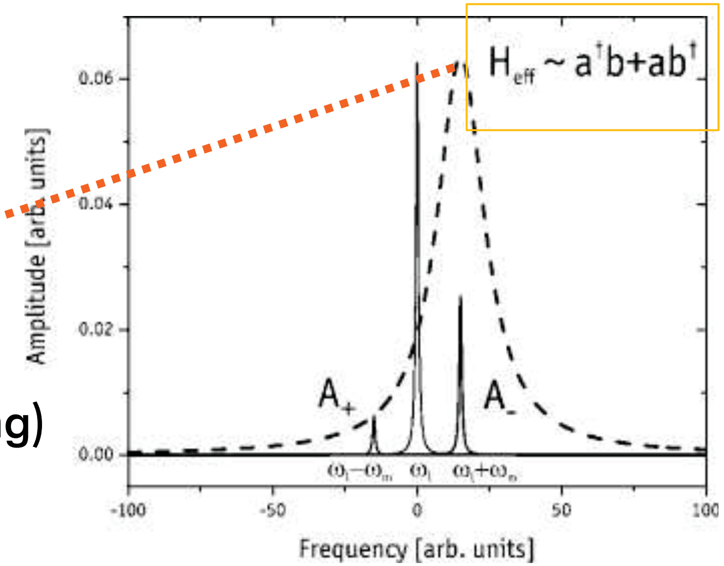


T. Kippenberg, K. Vahala, Science 321 (08)
M. Aspelmeyer, K. Schwab, NJP 10 (08)
F. Marquardt, S. Girvin, Physics 2 (09)

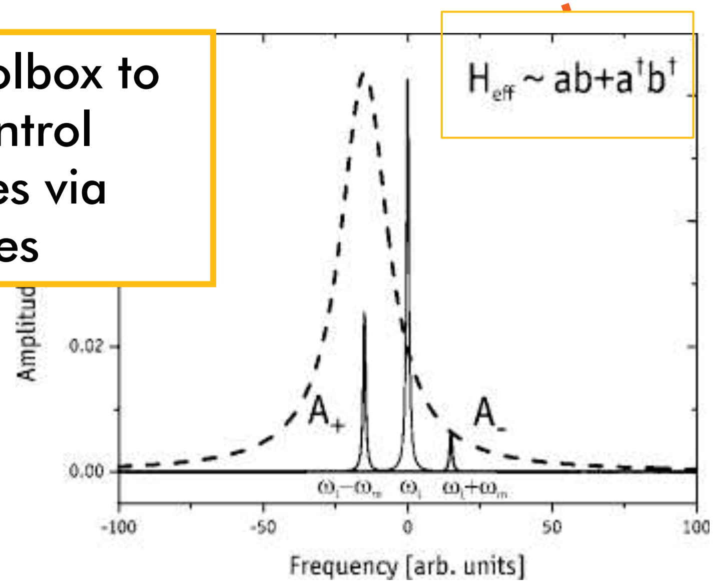
M. Aspelmeyer, T. Kippenberg, F. Marquardt, arXiv:1303.0733 [quant-ph] (2013)



- QND (photon number)
- Beamsplitter (cooling)
- TM squeezer (parametric driving)



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



approximations:

- $n_c \gg 1$
- $g \ll \omega_m$

J. Zhang et al., PRA 68 (03)
M. Aspelmeyer et al., JOSAB 27 (10)

What is the quantum regime of a mechanical oscillator?

state initialization

minimum entropy mechanical states
(e.g. ground state via side-band cooling)

A. O'Connell, Nature 464 (10)
J. Teufel et al., Nature 475 (11)
J. Chan et al., Nature 478 (11)
E. Verhagen et al., Nature 482 (12)

$$\langle n \rangle \lesssim 1$$

coherent photon-phonon exchange

(strong optomechanical coupling)

S. Gröblacher et al., Nature 460 (09)
J. Teufel et al., Nature 471 (11)
E. Verhagen et al., Nature 482 (12)

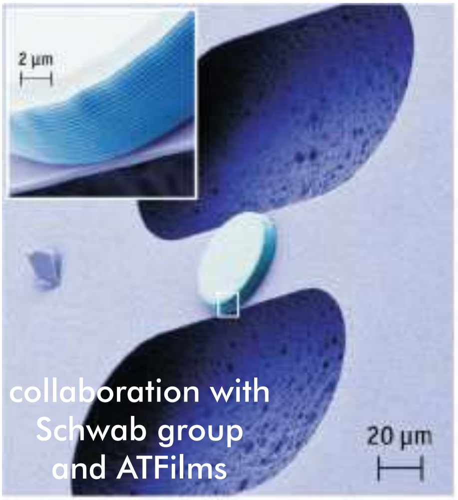
$$\Gamma_m \ll \kappa \ll \omega_m, g$$

state preparation and verification

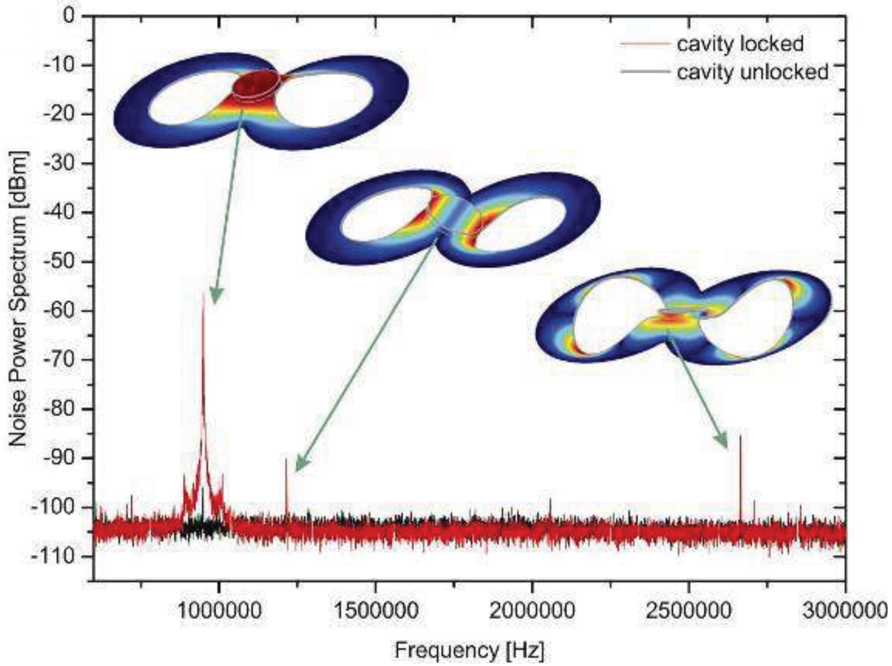
Palomaki et al., Nature 495 (13)

Cavity-optomechanics in practice with a 1MHz mechanical oscillator

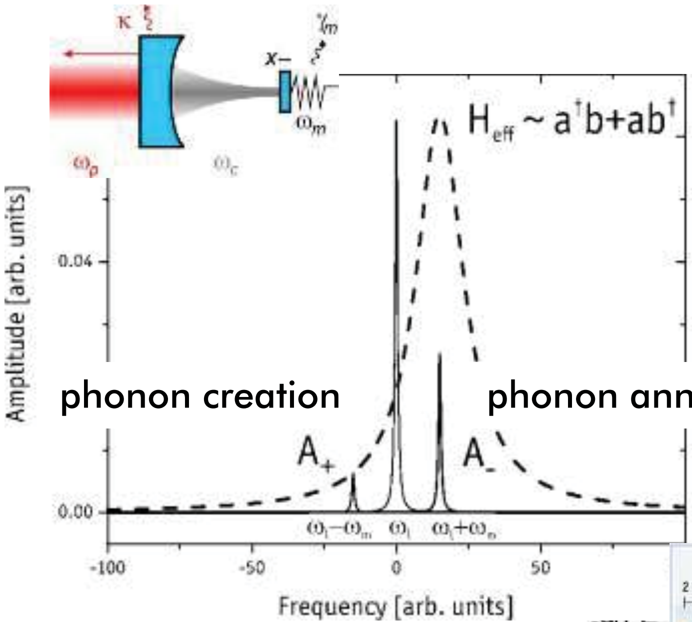
Hybrid Si_3N_4 & Ta_2O_5/SiO_2



dimensions: 150 x 50 x 1 μm^3
reflectivity > 0.9999 (absorption <0.4ppm)
Finesse ~ 20000, up to $\kappa \sim 0.2\omega_m$
Q_m ~ 30000 at low T, m_{eff}~50ng



S. Gröblacher et al., Nature Physics 5 (09)

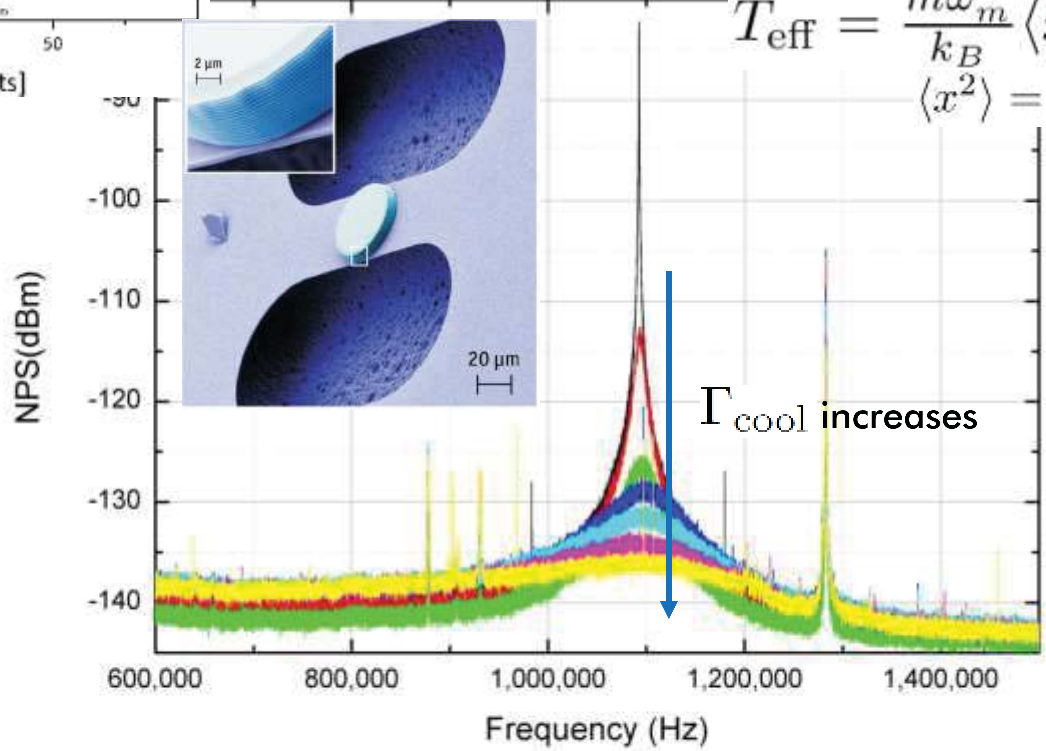


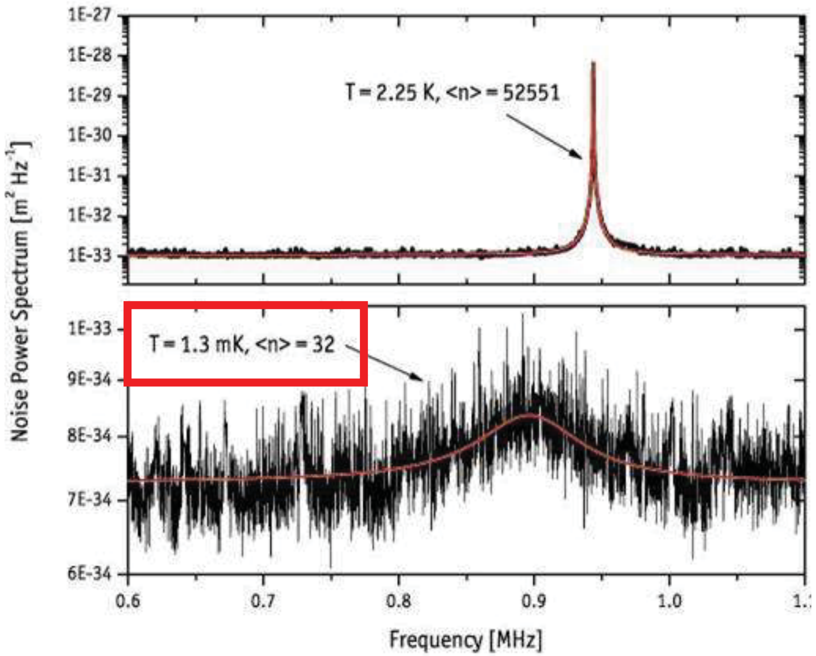
$$\Gamma_{\text{cool}} = A_- - A_+$$

$$\langle n \rangle_{eff} = \frac{\gamma_m \bar{n} + A_+}{\gamma_m + \Gamma_{\text{cool}}}$$

$$T_{\text{eff}} = \frac{m\omega_m^2}{k_B} \langle x^2 \rangle$$

$$\langle x^2 \rangle = \int \mathrm{d}\omega S_{xx}(\omega)$$





S. Gröblacher et al., Nature Physics 5 (09)

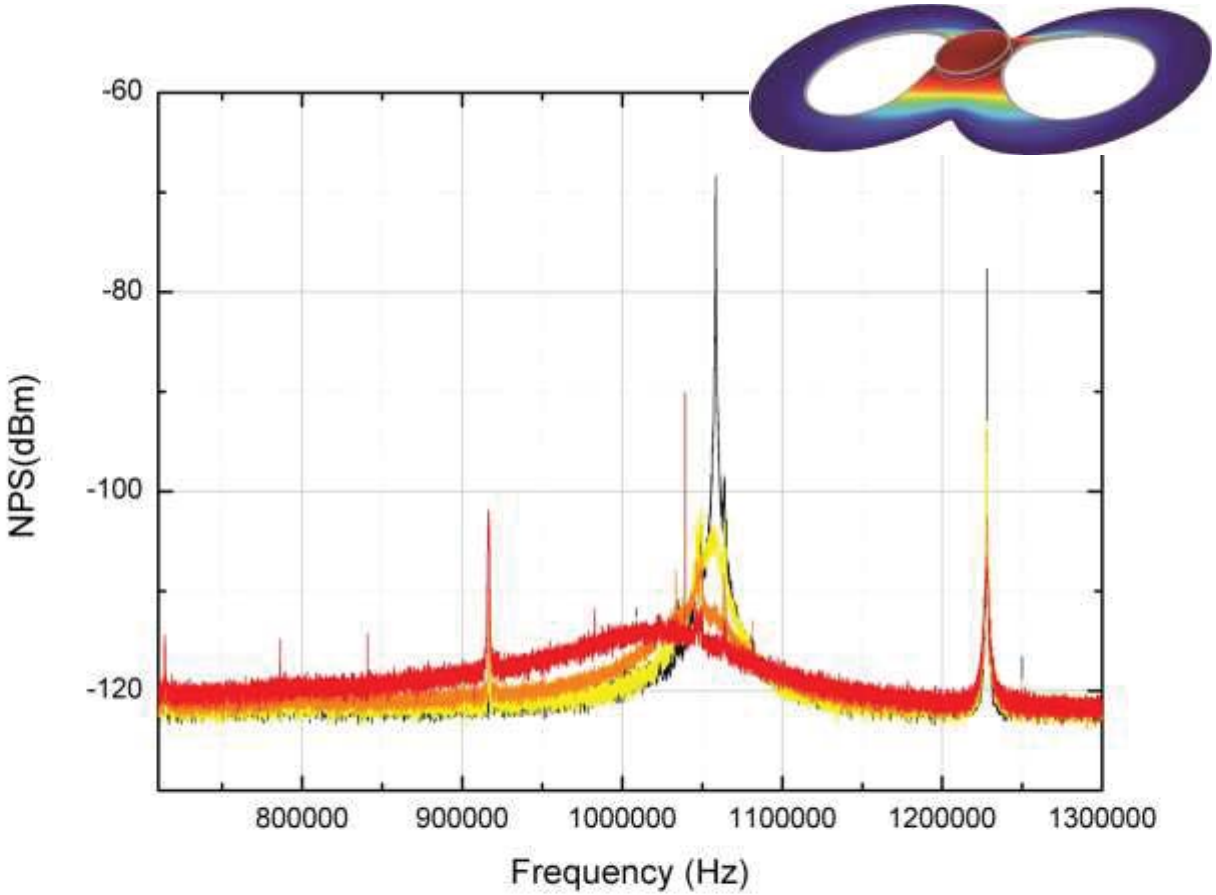
$$\langle n \rangle_{eff} = \frac{\gamma_m \overline{n} + A_+}{\gamma_m + \Gamma_{\mathrm{cool}}}$$

reduction of bath occupation via lower bath temperatures (mostly also decrease in γ_m)

T	<n> for $\omega_m/2\pi$=1MHz
4.2K	87000
20mK	420

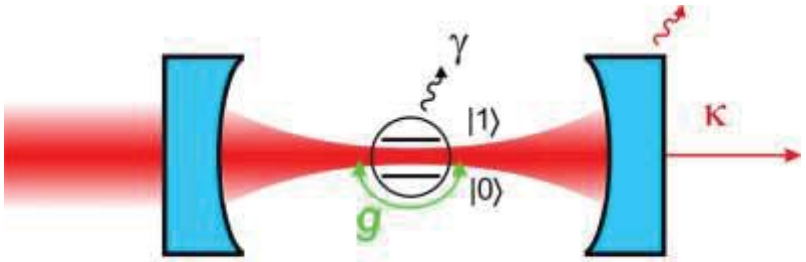
preliminary data

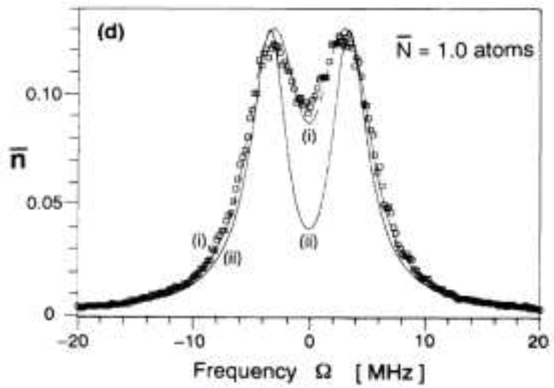
Finesse ~ 17000, T ~ 200mK, m_{eff}~350ng



strong coupling $g > \kappa, \gamma_{\mathrm{m}}$

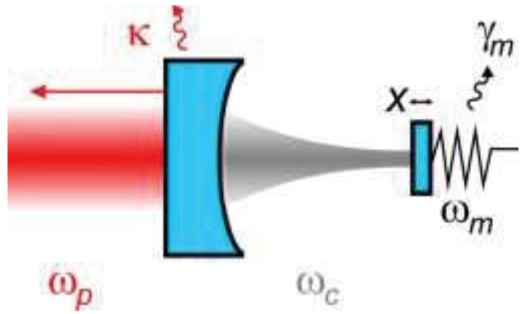
cavityQED





R. J. Thompson et al., PRL 68 (92)

optomechanics



mechanical oscillator: ω_m

light: effective harmonic oscillator at

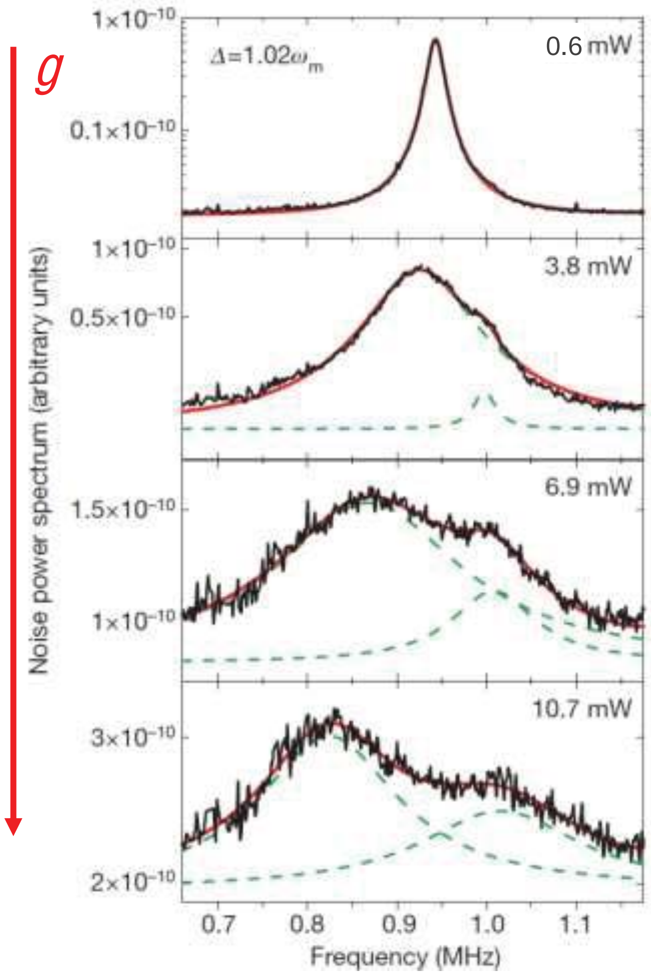
$$|\Delta| = |\omega_p - \omega_c| = \omega_m$$

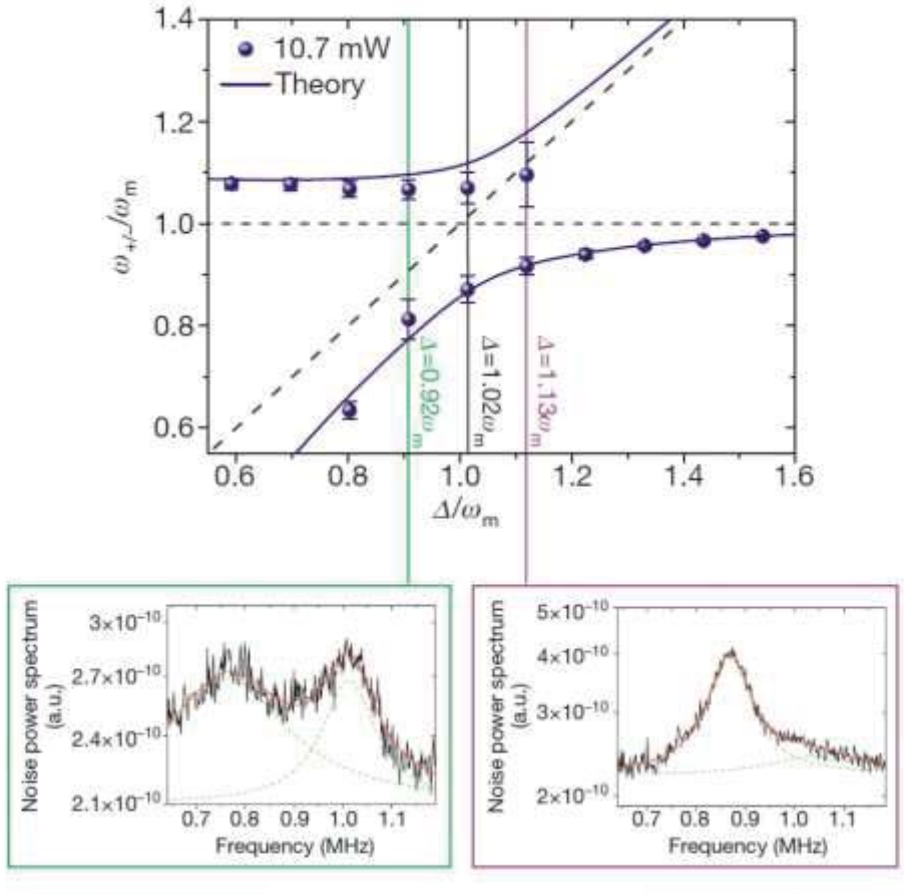
coherent interaction:

signature normal mode splitting

F. Marquardt et al., PRL 99 (07)
J. Dobrindt et al., PRL 101 (08)

optomechanical normal mode splitting @ RT



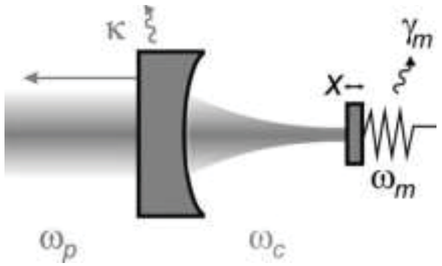


Finesse 14000, Q_m = 6700 at RT, m_{eff}=145ng

$g \approx 2\pi \times 325\ kHz$
$\kappa = 2\pi \times 215\ kHz$
$\gamma_m = 2\pi \times 140\ Hz$

S. Gröblacher et al., Nature 460 (09)

optomechanical state reconstruction
verification of prepared optomechanical states



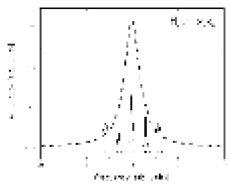
$$x_m(\theta) = x_m \cos\theta + p_m \sin\theta$$

(x_m,p_m) - only indirect read-out via light field

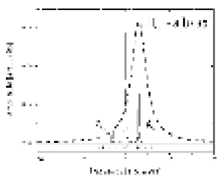
$$x_l(\phi) = x_l \cos\phi + y_l \sin\phi$$

(x_l,y_l) – direct read-out

different regimes:

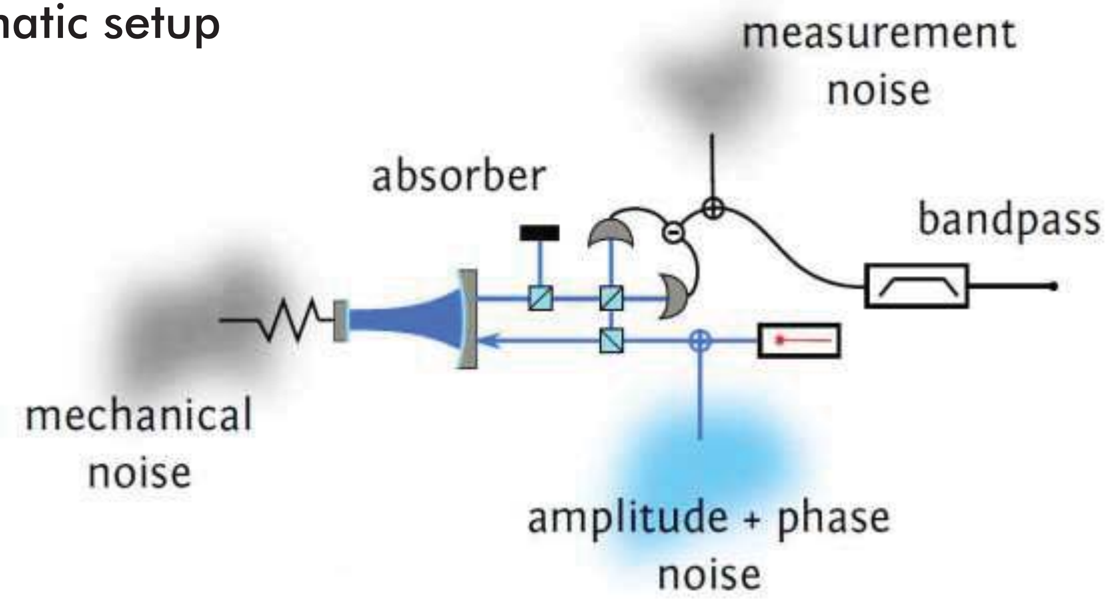


$\Delta = 0 \rightarrow x_m(\theta(\kappa, \omega_m))$ via y_l



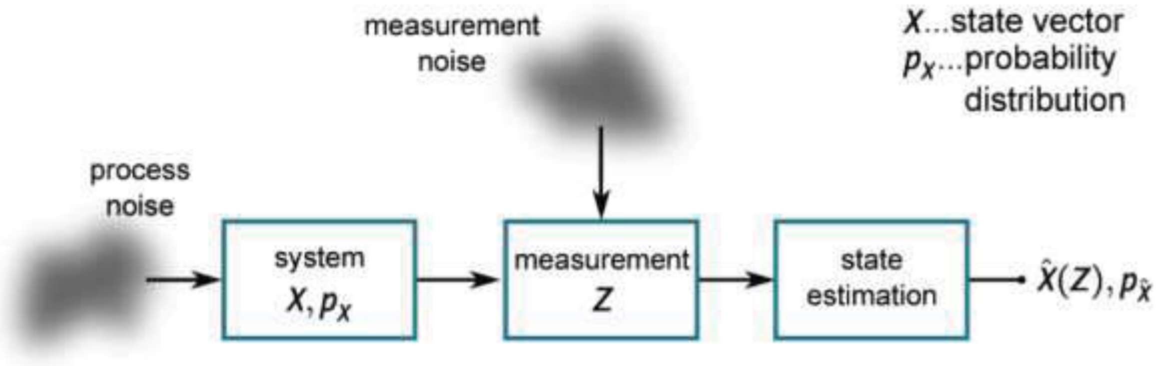
$$\Delta = \omega_m \rightarrow x_l x_m + y_l p_m$$

Schematic setup



Kalman-filter

known from classical signal processing and used for state estimation



Physical model

$$X = \begin{cases} \dot{x}_m = \omega_m p_m \\ \dot{p}_m = -\omega_m x_m - \gamma_m p_m - g(a_c + a_c^\dagger) - \sqrt{2\gamma_m}\xi \\ \dot{a}_c = -i\Delta a_c - \kappa a_c - igx_m + \sqrt{2\kappa}a_{\text{in}} \end{cases}$$

Gaussian

$$Z = \{ \quad x_{\text{out}} = \sqrt{2\kappa}x_c(\phi) + x_{\text{in}}(\phi)$$

Reconstruction
via Kalman filter

$\Longrightarrow$ find $\hat{X}(t)$

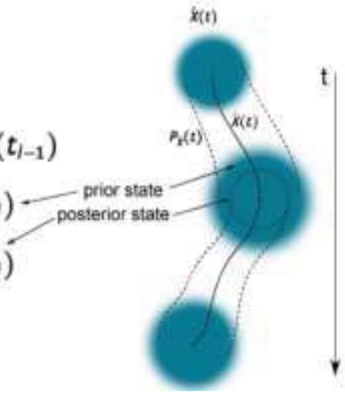
- Kalman filter discrete time

$t_{i+1} = t_i + \Delta t$

0) initial estimate $\hat{X}^{(+)}(t_{i-1}), P_{\hat{X}}^{(+)}(t_{i-1})$

1) propagation $\hat{X}^{(-)}(t_i), P_{\hat{X}}^{(-)}(t_i)$

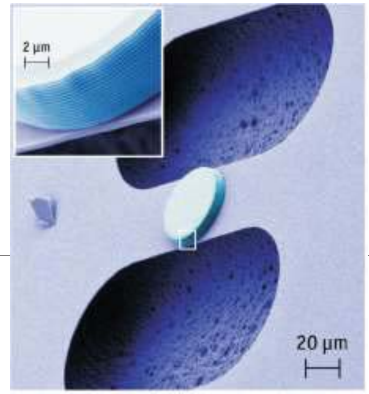
2) Bayesian update $\hat{X}^{(+)}(t_i), P_{\hat{X}}^{(+)}(t_i)$



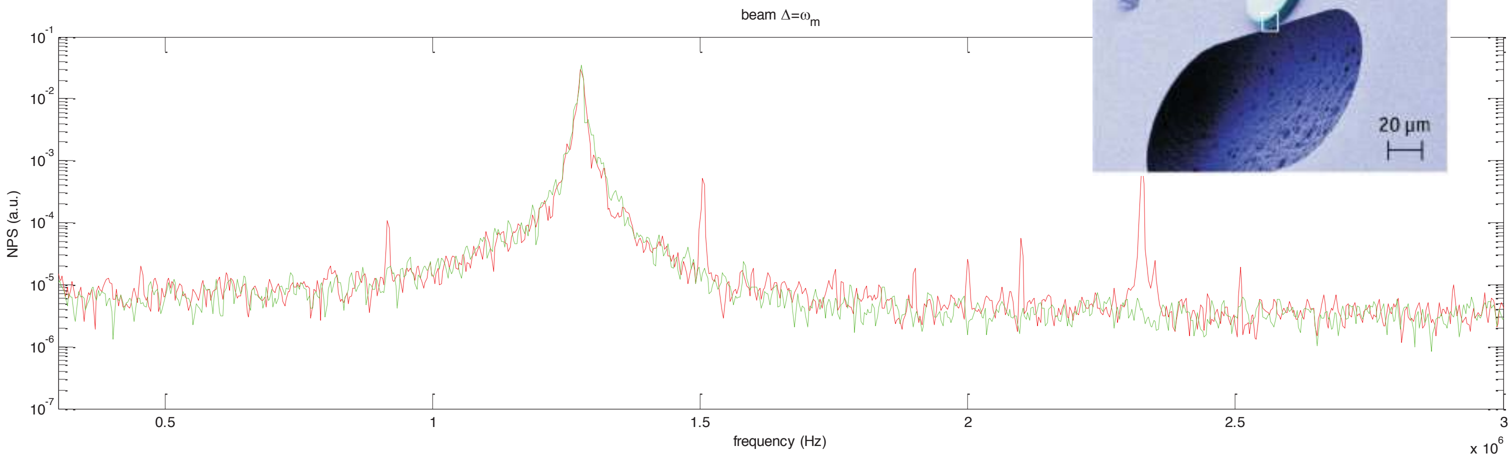
minimizes error covariance

$$P = \langle [X - \hat{X}(Z)][X - \hat{X}(Z)]^T \rangle$$

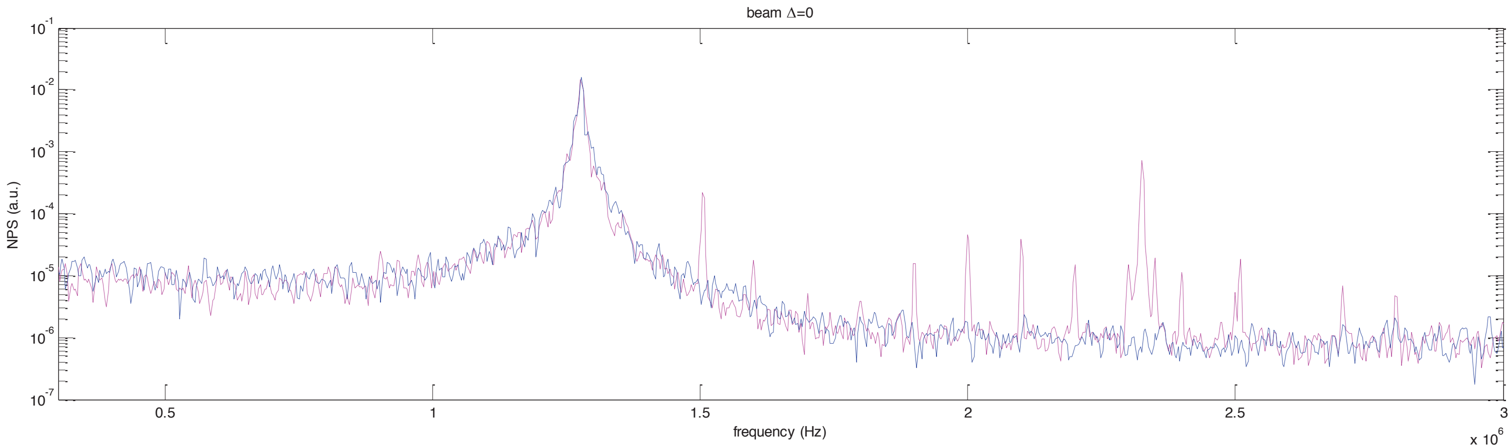
Comparison: NPS of simulated vs. real data



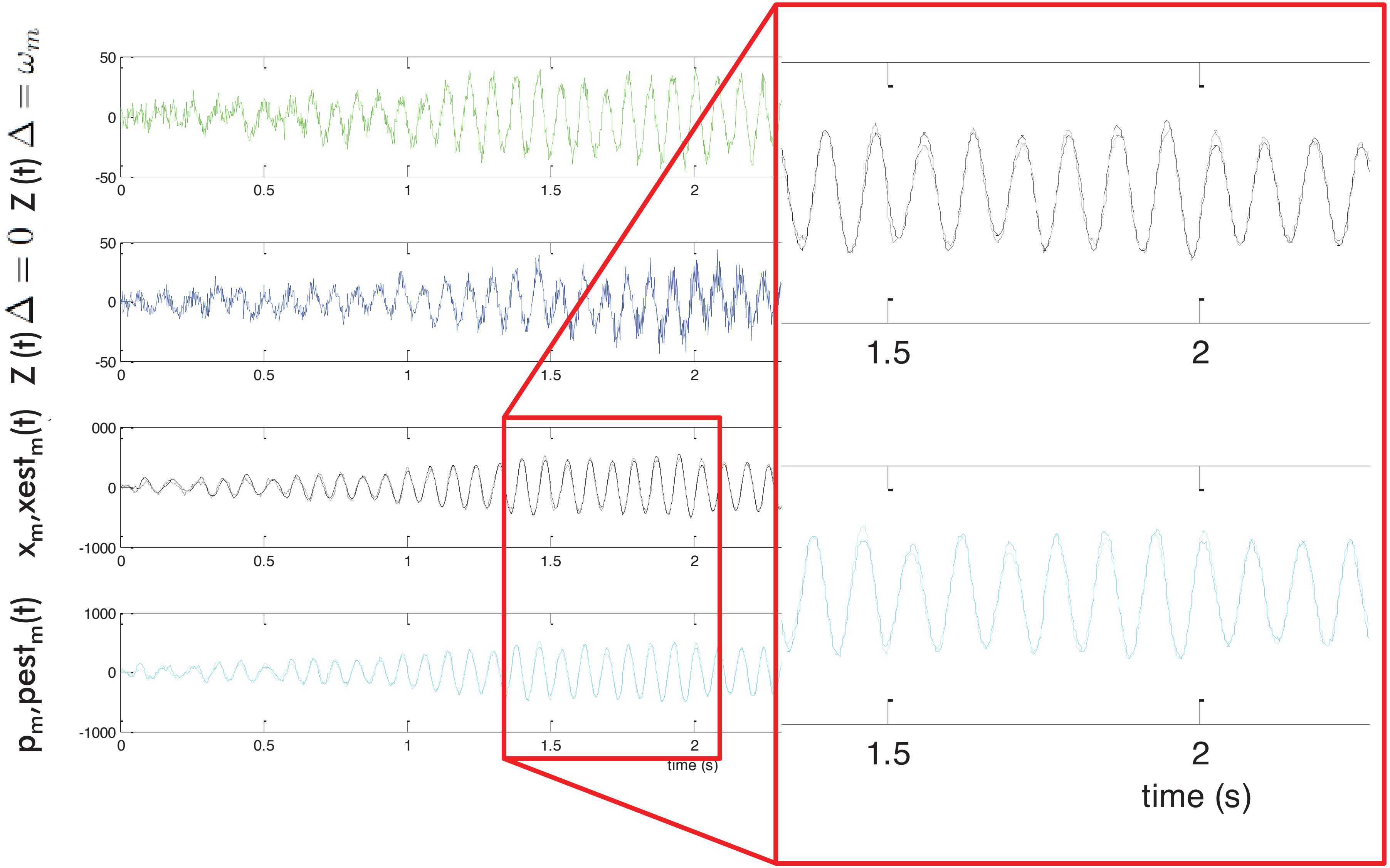
NPS $\Delta = \omega_m$



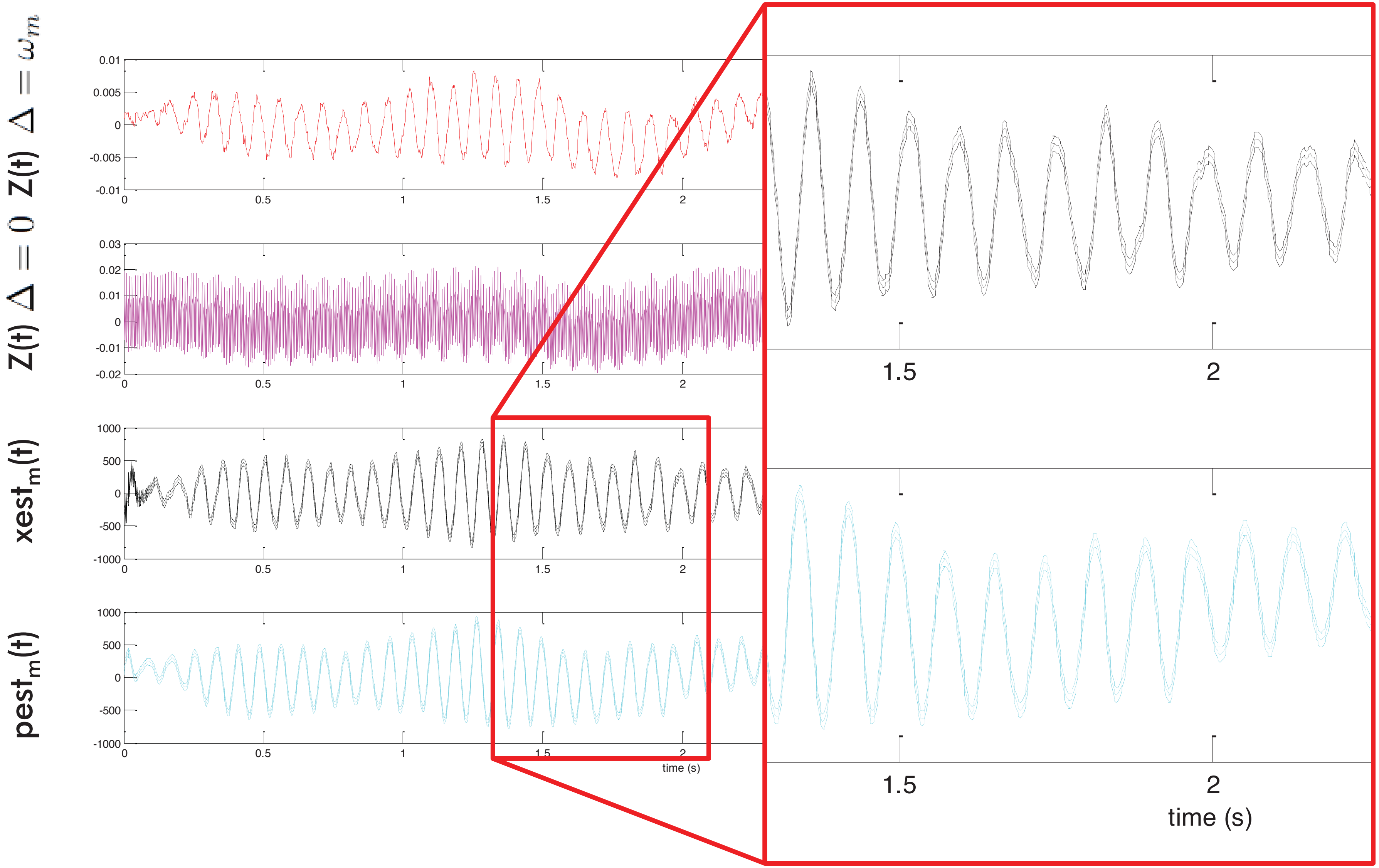
NPS $\Delta = 0$



Simulated data and its reconstruction



Real data and its reconstruction

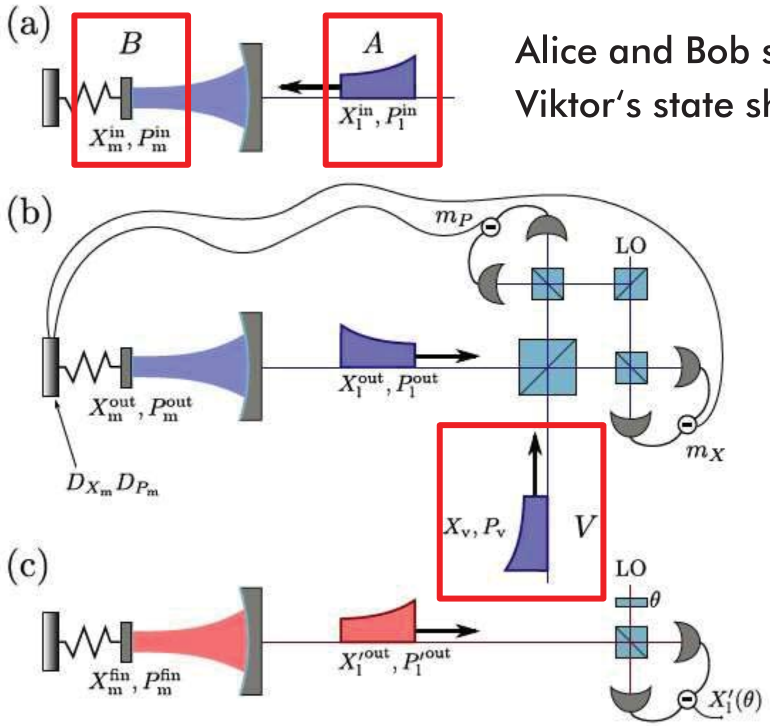


Where do we want to go?

Optomechanical teleportation

state preparation

collaboration with K. Hammerer, University of Hannover
Hofer et al., PRA 84 (2011)



Alice and Bob share an entangled state
Viktor's state shall be teleported to Bob

teleportation fidelity

$$F_{tp} = (1 + \Delta_{EPR}/2)^{-1}$$

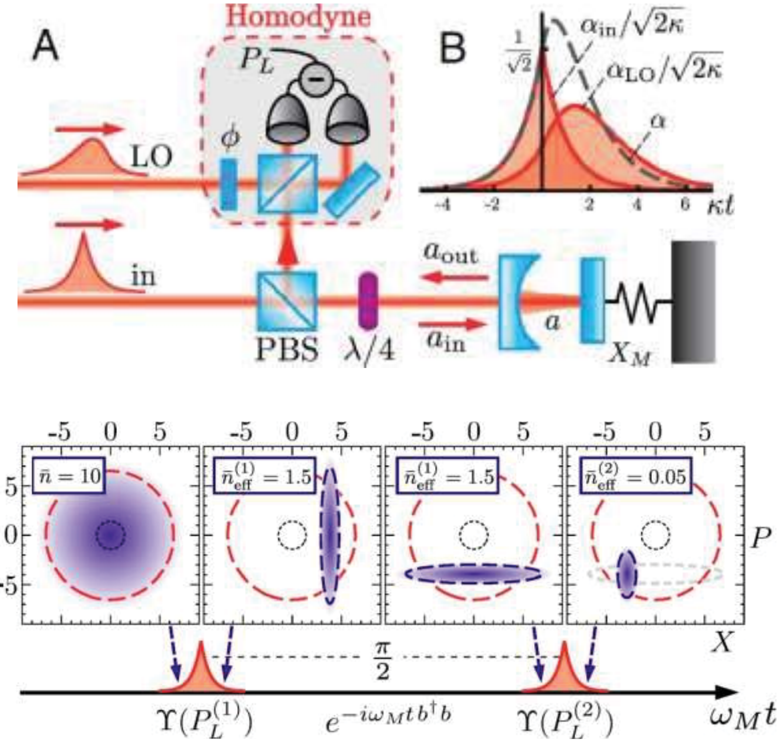
better than classical, if

$$\Delta_{EPR} < 2$$

$\omega_m/2\pi$	Q_m	T_{bath}	$\bar{n}$	n_0	$g_0/2\pi$	$\kappa_{opt}/2\pi$	τ_{opt}	P_{opt}	$g_{opt}/2\pi$	Δ_{EPR}
3.8 MHz	10^5	200 mK	1100	0.0	4.8 Hz	3.2 MHz	2.5 μs	30 mW	0.97 MHz	0.7
3.7 GHz	10^5	200 mK	0.7	0.7	910.0 kHz	0.26 GHz	0.41 μs	6 μW	0.032 GHz	0.1
3.7 GHz	10^5	1 K	3.7	3.7	910.0 kHz	0.31 GHz	0.30 μs	8 μW	0.040 GHz	0.5

Optomechanical quantum control

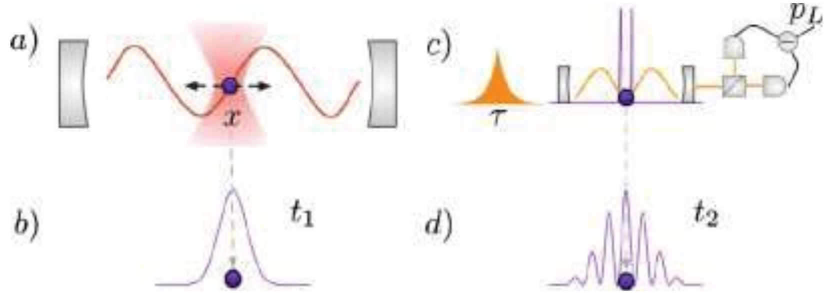
mechanical state preparation
and characterization

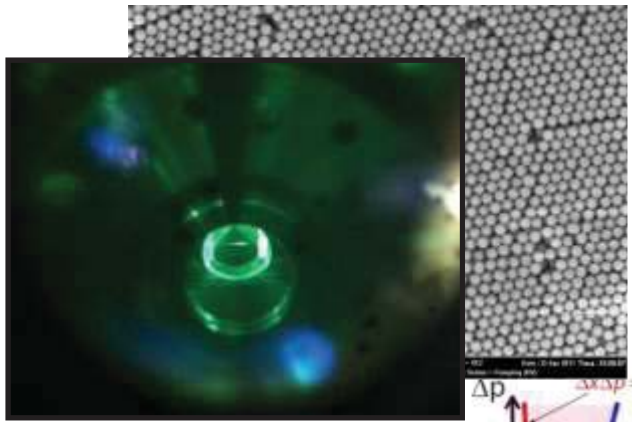


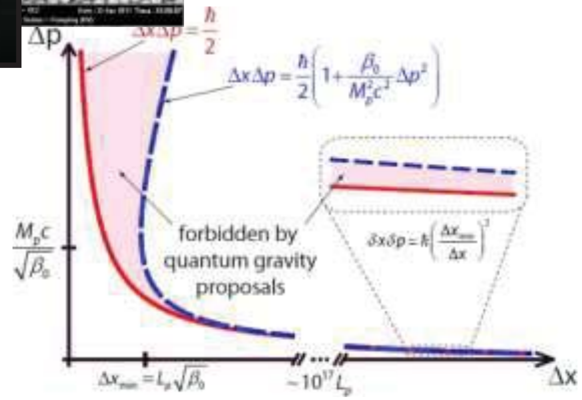
e.g.:
M. R. Vanner et al., PNAS 108, 16182-16187 (2011)
M. R. Vanner et al. arXiv:1211.7036 [quant-ph] (2012)

Foundational questions

testing collapse models
testing predictions of quantum gravity







e.g.:
O. Romero-Isart et al.,
PRL 107, 020405 (2011)
I. Pikovski et al.,
Nature Physics 8, 393 (2012)

Summary

Cavity optomechanical systems as new building blocks in quantum optics

state initialization:

- low-entropy state

state preparation:

- by means of strong coupling and state transfer
- teleportation
- pulsed optomechanics

state read-out and verification:

- reconstruction via Kalman filter

Markus Aspelmeyer
Garrett D. Cole
Michael Vanner
Simon Gröblacher
Witlef Wieczorek
Sebastian Hofer
Jason H-Obermaier
Ralf Riedinger
Karoline Siquans

STREP MINOS
IIF IQOS
ERC Starting Grant

Our Collaborators & Discussion Partners

<u>Foundations of quantum physics:</u>
Caslav Brukner (Vienna, Austria)
Anthony J. Leggett (UIUC, USA)
Anton Zeilinger (Vienna, Austria)
Oriol R. Isart, Anika Pflanzer,
Ignacio Cirac (Munich, Germany)

<u>Quantum optical control and quantum information (theory):</u>
Jens Eisert (Berlin, Germany)
K. Hammerer (Hannover, Germany)
G. Milburn (Queensland, Australia)
Frank Verstraete (Vienna, Austria)
Peter Rabl (Vienna, Austria)
Peter Zoller (Innsbruck, Austria)

<u>Micro- and nanomechanics and quantum interfacing:</u>
Oskar Painter (Caltech, USA)
I. Wilson-Rae (Munich, Germany)
Keith Schwab (Caltech, USA)