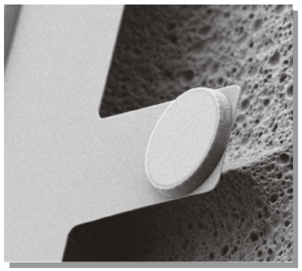
Quantum Control in Cavity Optomechanics: Theory and Experiment

Sebastian Hofer

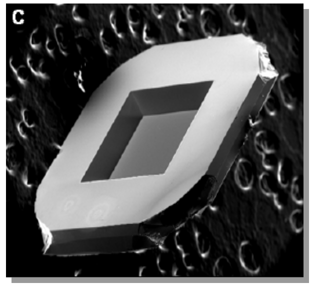
Aspelmeyer group (Vienna)
Klemens Hammerer (Hannover)

Cavity optomechanical systems



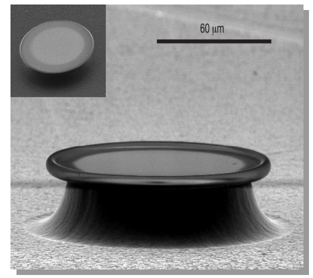
Micromirrors

Aspelmeyer (Vienna)
Heidmann (Paris)
Bouwmeester
(St Barbara, Leiden)



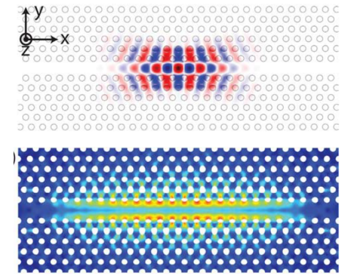
Micromembranes

Harris (Yale)
Kimble (Caltech)
Treutlein (Basel)



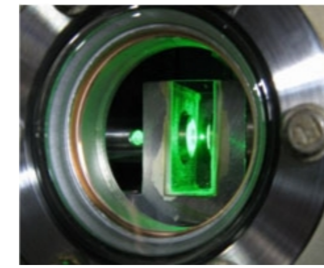
Microtoroids

Kippenberg (MPQ)
Weig (LMU)
Vahala (Caltech)
Bowen (UQ)



Optomechanical Crystals

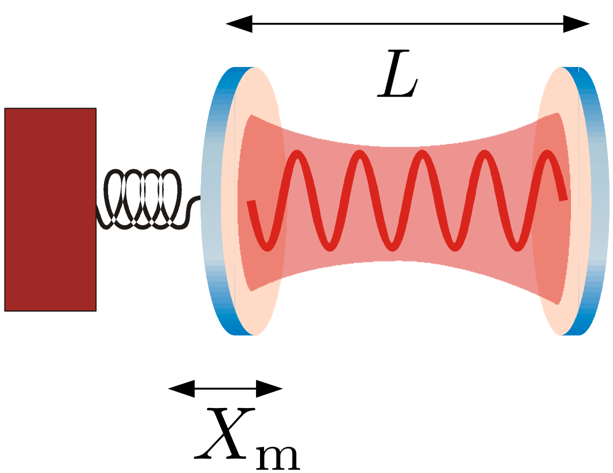
Gröblacher (Delft)
Painter (Caltech)
Tang (Yale)



Levitated nano-objects

Raizen (Austin)
Barker (London)
Aspelmeyer

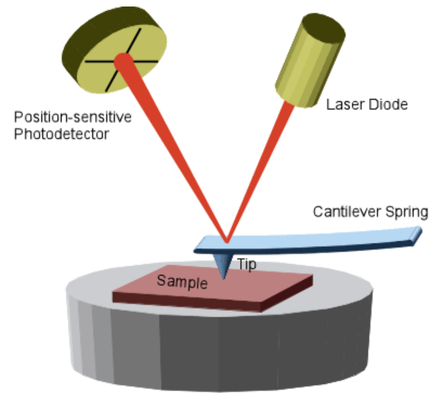
+ more massive systems (e.g., GW detectors)
+ electromechanical setups (microwave)



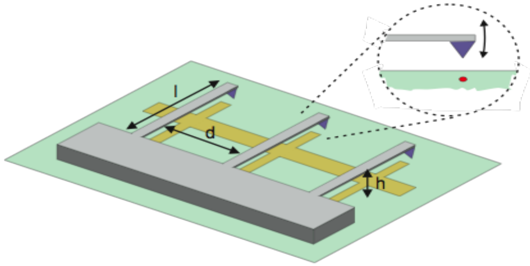
simple model:
optical + mechanical resonator coupled via radiation pressure

Applications

- quantum limited sensing
  - force ~ 10^{-21} N
  - mass ~ 10^{-24} g
  - displacement ~ 10^{-18} m

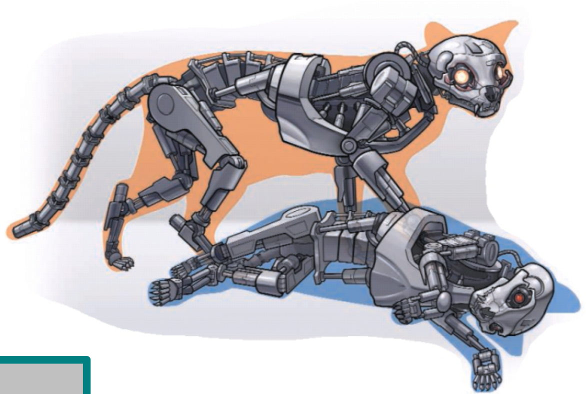


- quantum information
  - mechanical transducers → photons (optical + mw), atoms, charge, magnetic flux



Rabl et al., Nature Physics 6, 602 (2010)

- quantum foundations
  - Schrödinger cat states
  - test of decoherence models
  - connection to gravity



Cho, Science 327, 516 (2010)

Overall goal: push sytems into quantum regime!

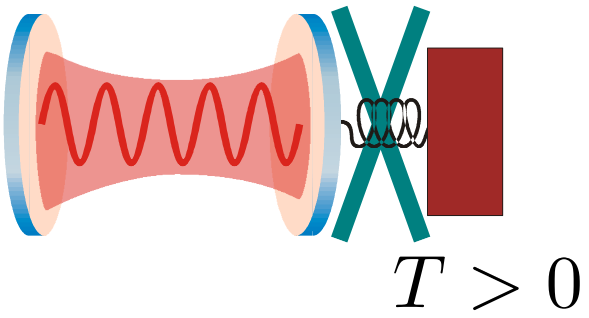
Observed quantum effects

- quantum coherent state transfer — O'Connell et al., Nature 464, 697 (2010); Palomaki, Nature 495, 210 (2013)
- ground state cooling — Chan, Nature 478, 89 (2011); Teufel, Nature 475, 359 (2011)
- quantum coherent coupling — Verhagen, Nature 482, 63 (2012)
- ponderomotive squeezing — Safavi-Naeini, arXiv:1302.6179 (2013); Brooks, Nature 488, 476 (2012)
- back-action noise in position sensing — Purdy, Science 339, 801 (2013)
- optomechanical entanglement — Palomaki, Science 342, 710 (2013)
- feedback control within decoherence time — Wilson, arXiv:1410.6191 (2014)

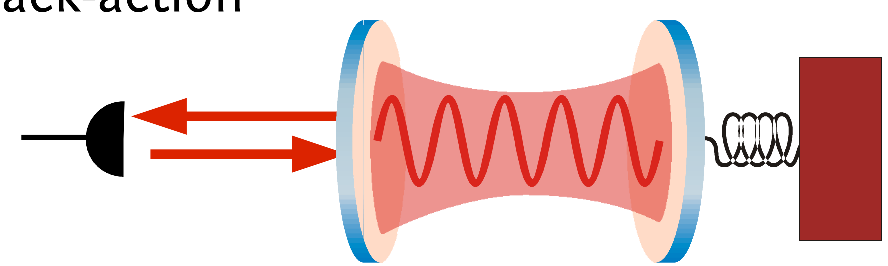
Challenges + (possible) solutions

Quantum protocols need...

- Overcome coupling to environment
  - passive cooling of bath
  - cut ties to environment by *levitation*
  - environment engineering, shape mode spectrum
  - ...



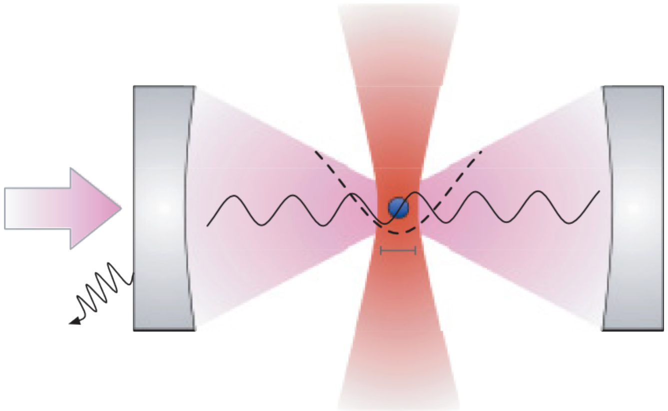
- Accurate read-out of mechanical state
  - clever data processing: *Kalman filtering* (CW)
  - *pulsed* read-out: beating the SQL and back-action



- ...and much more...

Levitating nanospheres

- Motivation
  - eliminate clamping
    - high Q: Q > 10^{10} @ p < 10^{-9} mbar
    - low dissipation/decoherence
  - high mass ~ 10^{9} amu
  - control over trap parameters
  - free-fall experiments, matter-wave interferometry

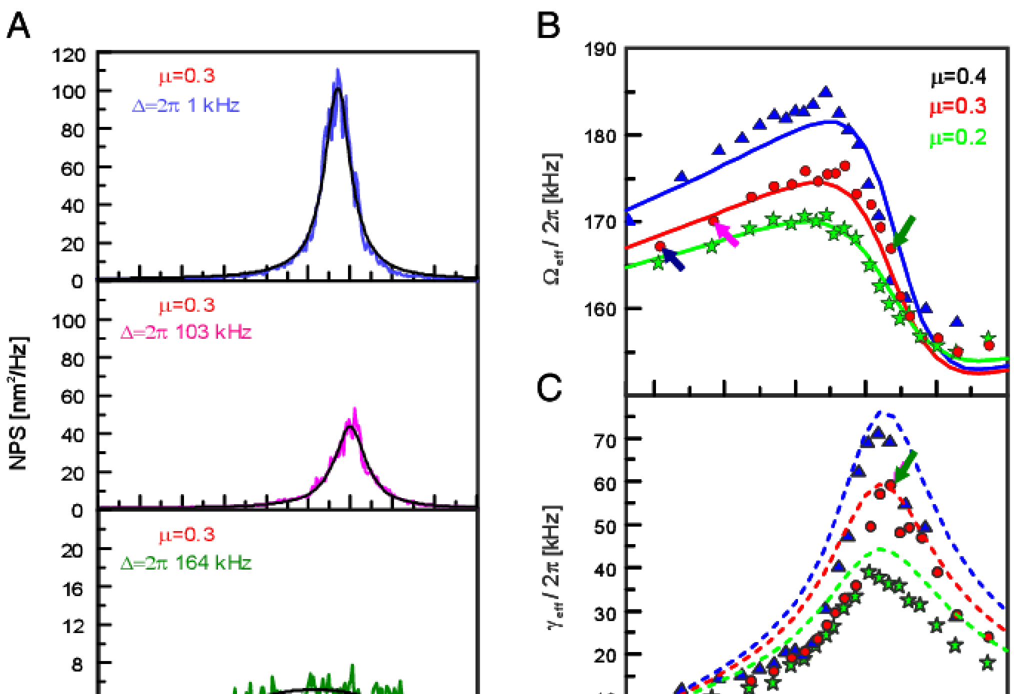


Romero-Isart et al., NJP 12, 033015 (2010)
Chang et al., PNAS 107, 1005 (2010)
P. F. Barker et al., PRA 81, 023826 (2010)

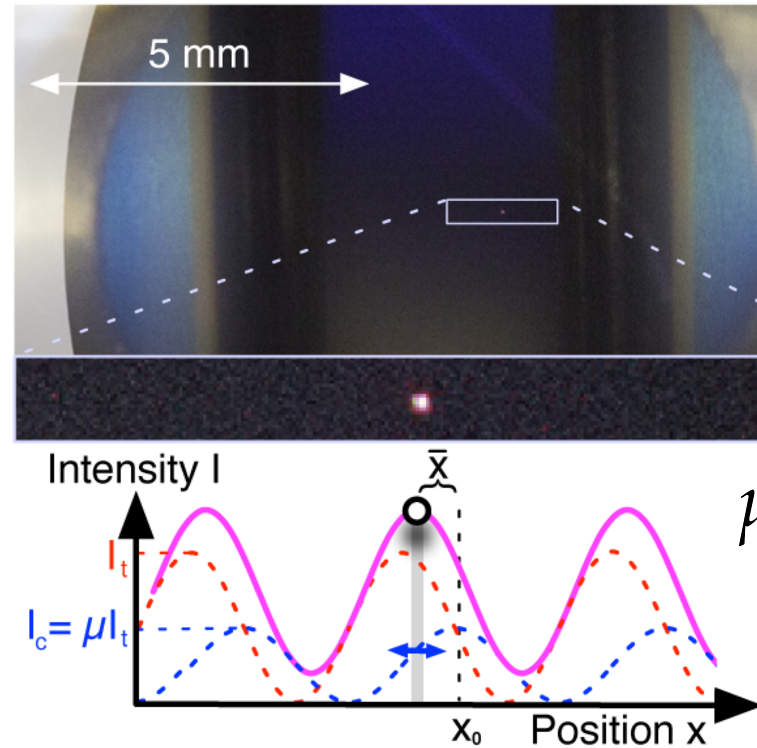
in principle: Quantum experiments @ 300K with macroscopic objects!

Levitating nanospheres

- 1d cavity cooling
  - in axial direction
  - room temperature
  - ~4 mbar



Rates comparable to standard cavity optomechanics setups, but...



$$\mu = \frac{I_c}{I_t}$$

- What we want: low pressure!

$Q \sim 25$ @ 4 mbar

$Q \sim 10^9$ @ 10^{-7} mbar

ground state cooling for $p < 10^{-7}$ mbar

Levitating nanospheres

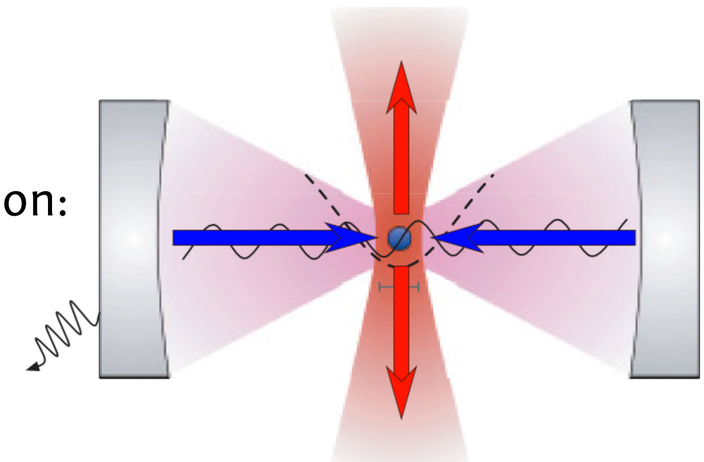
- No particle has been trapped in UHV so far!

	particle size	**final pressure**	**cooling**
Ashkin et al. APL, 19(8):283, 1971	20μm	10^{-6} mbar	3d fb cooling
Li, *PhD thesis*, University of Texas, 2011	1-5μm	10^{-6} mbar	3d fb cooling
Gieseler et al. *PRL 109*, 103603, 2012	140nm	10^{-6} mbar	3d fb cooling
Asenbaum et al. *Nature Comm 4*, 2743 2013	100nm-1μm	10^{-8} mbar	1d cavity cooling (no trapping)
Kiesel et al. PNAS 110, 14180-14185, 2013	254nm	1 mbar	1d cavity cooling
Monteiro et al. *NJP*, 15:015001, 2013.	20-500nm	5 mbar	no
Millen et al. *Nature Nano*, 9:425–429, 2014	50nm-2.56μm	1 mbar	no
Moore et al. *PRL* 113, 251801	5μm	10^{-7} mbar	3d fb cooling

Levitating nanospheres

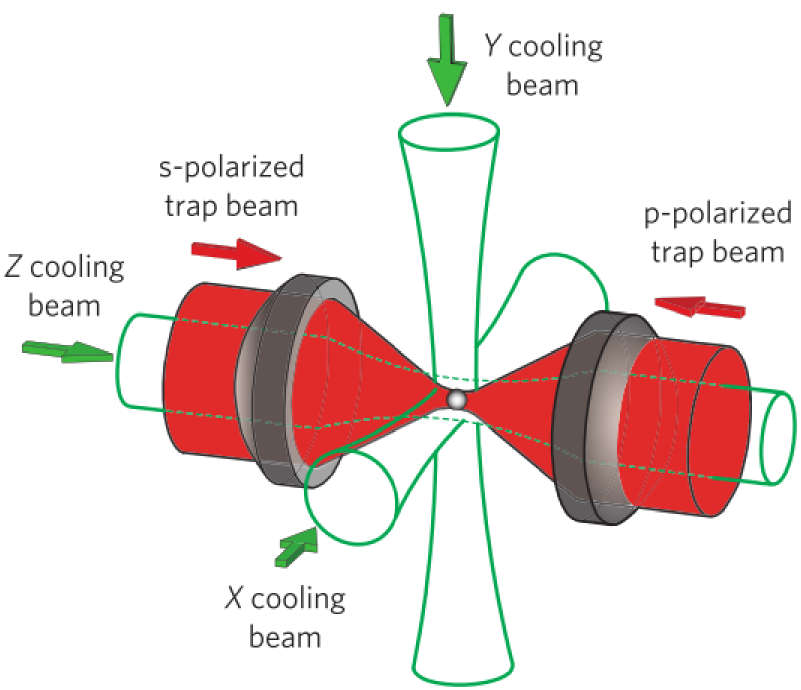
- particles lost at low pressures

axial direction:
cooled



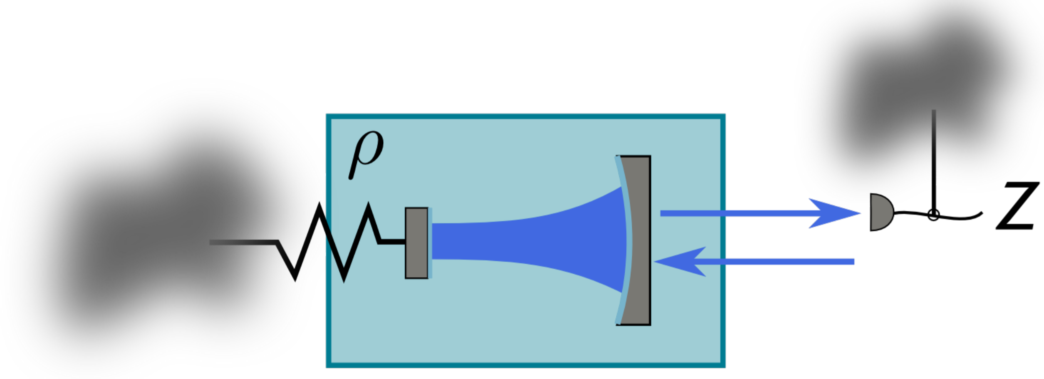
radial direction:
thermally activated escape

- solution: 3d feedback cooling



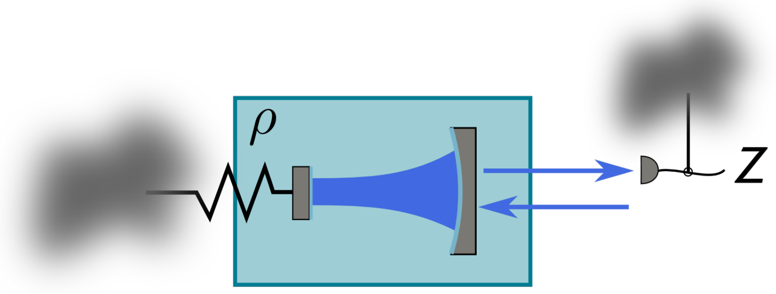
Li et al., Nature Physics 7, 527 (2011)
Gieseler et al., PRL 109, 103603 (2012)

Real-time optimal state estimation



Real-time optimal state estimation

- Goal: find optimal estimate of full quantum state
- CW measurement
- reconstruction of mechanical state from measuring light



R.E. Kalman (1960)

KF for mechanical systems:
Finn et al., PRD 63, 062004 (2001)
Iwasawa et al., PRL 111, 163602 (2013)

KF for quantum systems:
Yonezawa et al., Science 337:1514 (2012)
Geremia et al., PRL 91, 250801 (2003)

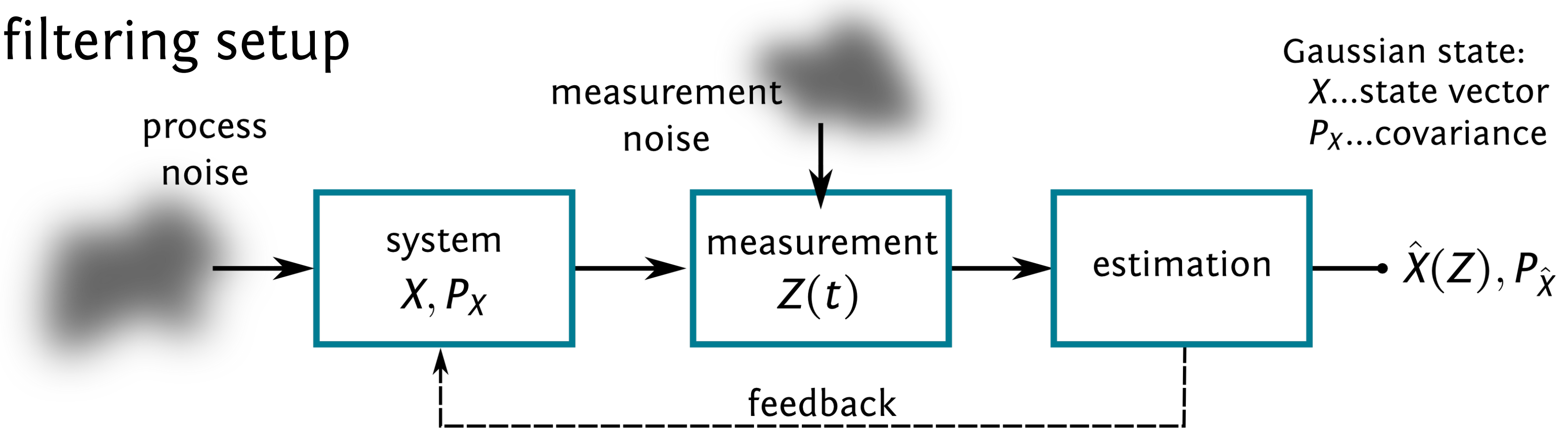
- Kalman filter
  - *Gaussian* systems: KF = optimal estimator (minimum-mean-square error)
  - real-time estimator → feedback
  - based on dynamical model of system

V.P. Belavkin (1980)

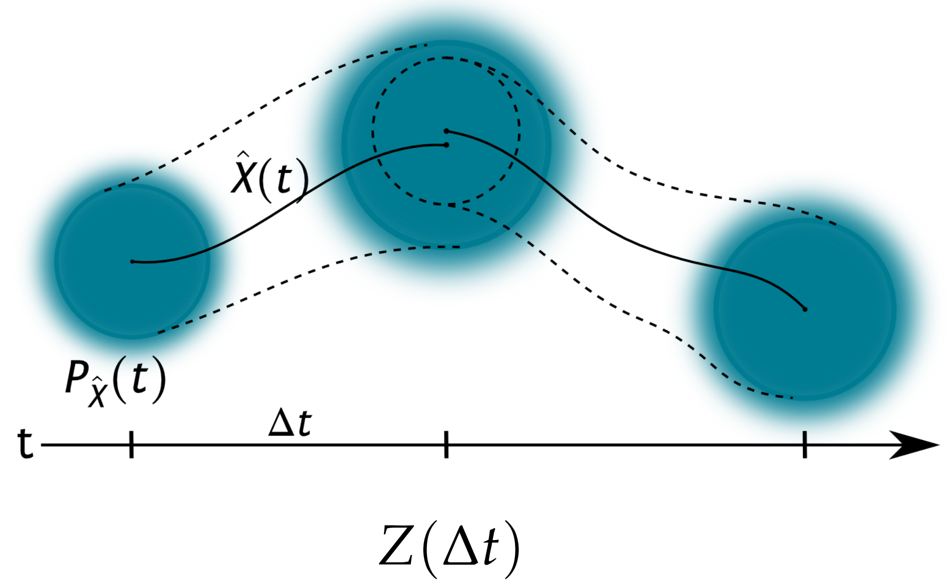
- Quantum filter
  - *Gaussian* systems: KF solves the *stochastic master equation* (for homodyne detection)
  - obtain *conditional quantum state*

Kalman filter in a nutshell

- filtering setup



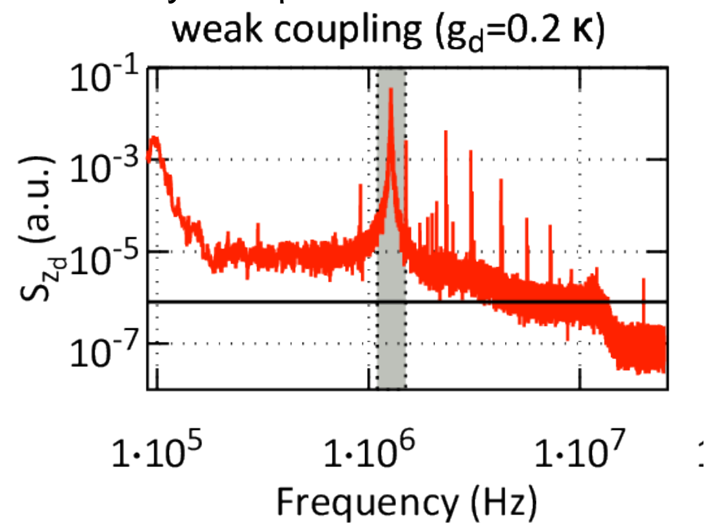
- algorithm
  0) initial state
  1) propagation = prediction
  2) measurement update
     (Bayesian conditioning)



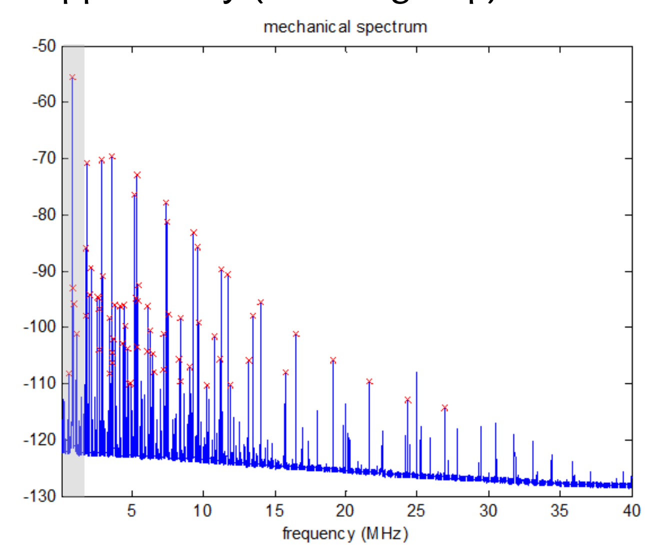
Kalman filter Vienna system

- requires accurate system and measurement model
- must account for:
  - thermal noise
  - technical noise sources
    - broadband, colored laser noise
    - narrowband noise peaks
  - multimode structures
- model must be validated against measurements

SiN doubly clamped beam

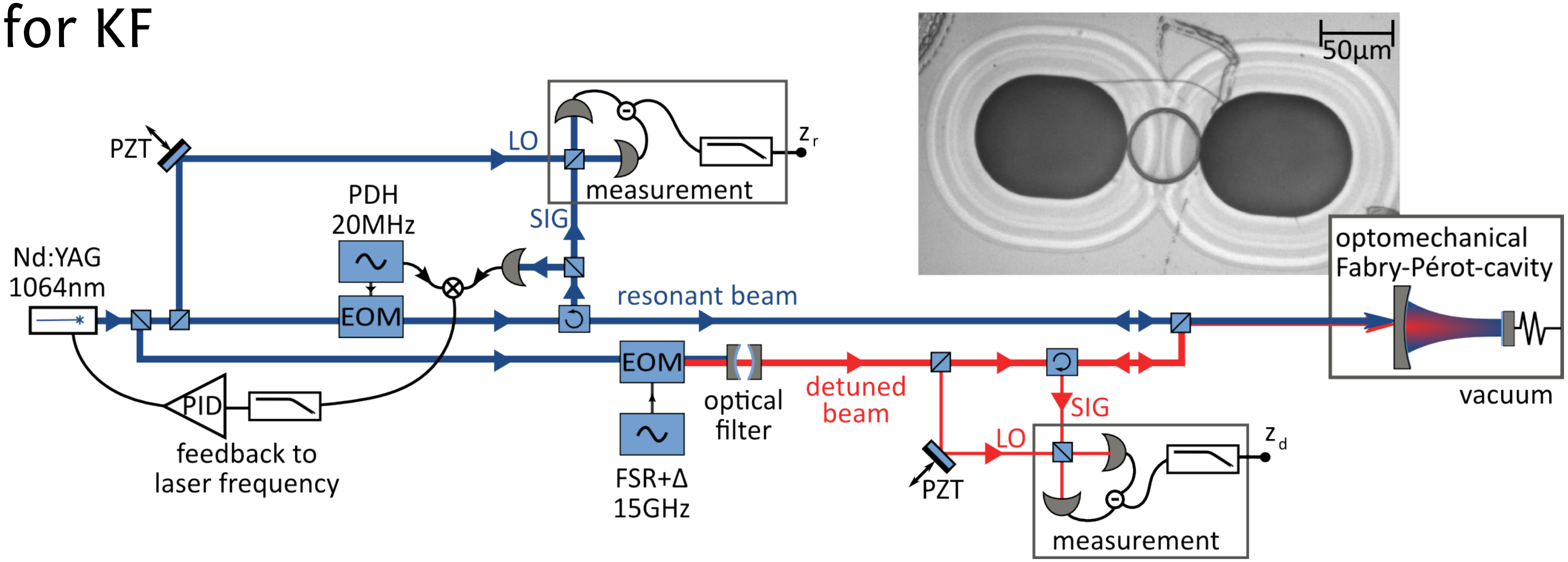


OM zipper cavity (Painter group)



Kalman filter Vienna system

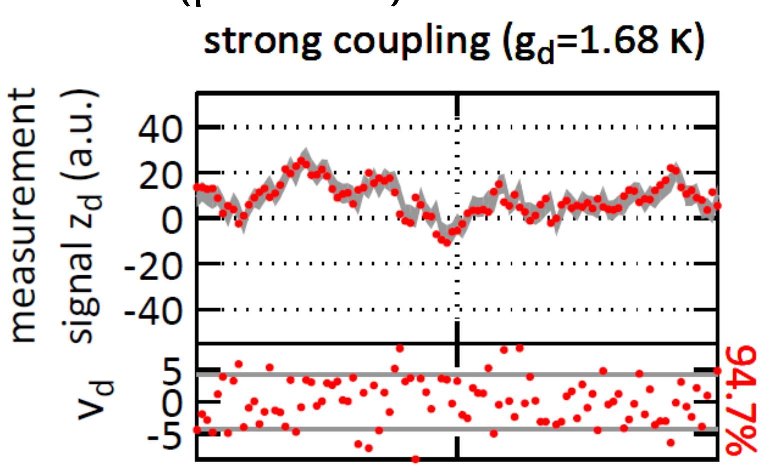
- model for KF

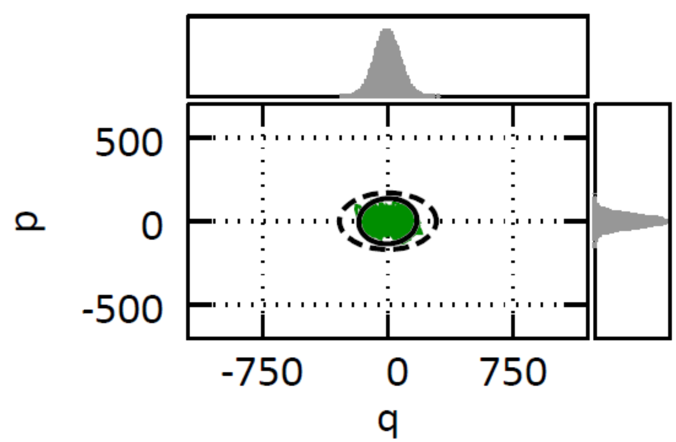


- results

(predicted) measurements

reconstructed mechanical state

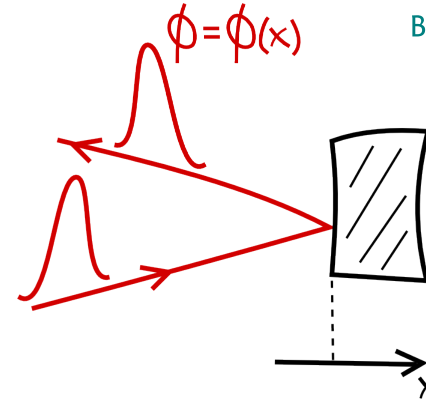




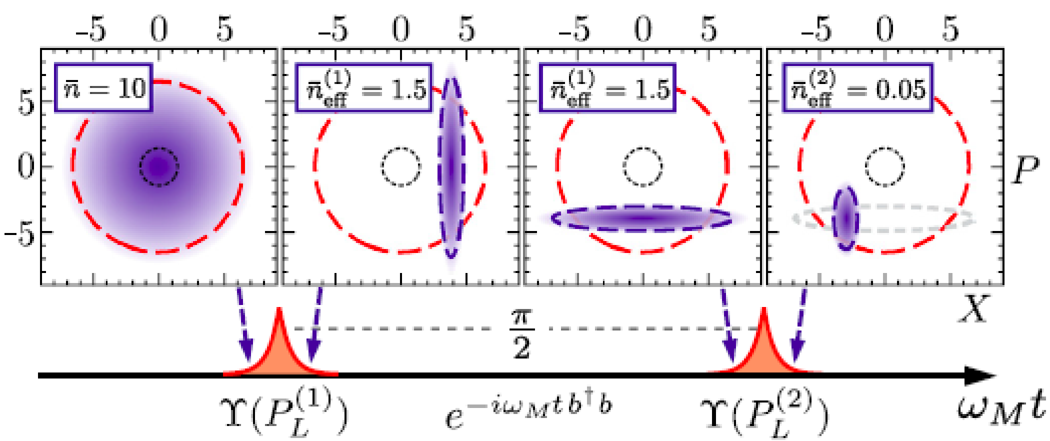
W. Wieczorek, SH et al.,
submitted (2015)

Beating the SQL by QND

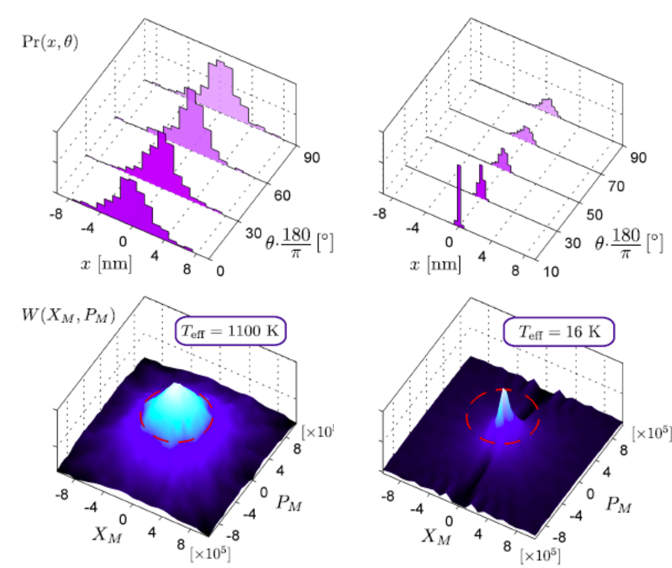
- Pulsed state state tomography
  - stroboscopic measurement of x_m
  - measurement back-action on p_m
  - operated on resonance, for a bad cavity



Braginsky, Thorne,...



M. Vanner et al., PNAS 108, 16182 (2011)

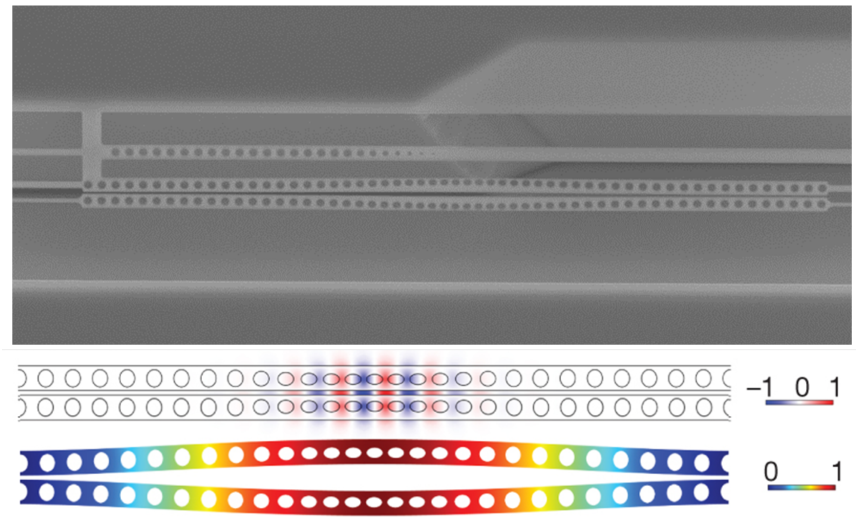


M. Vanner et al.,
Nature Communications 4 (2013)

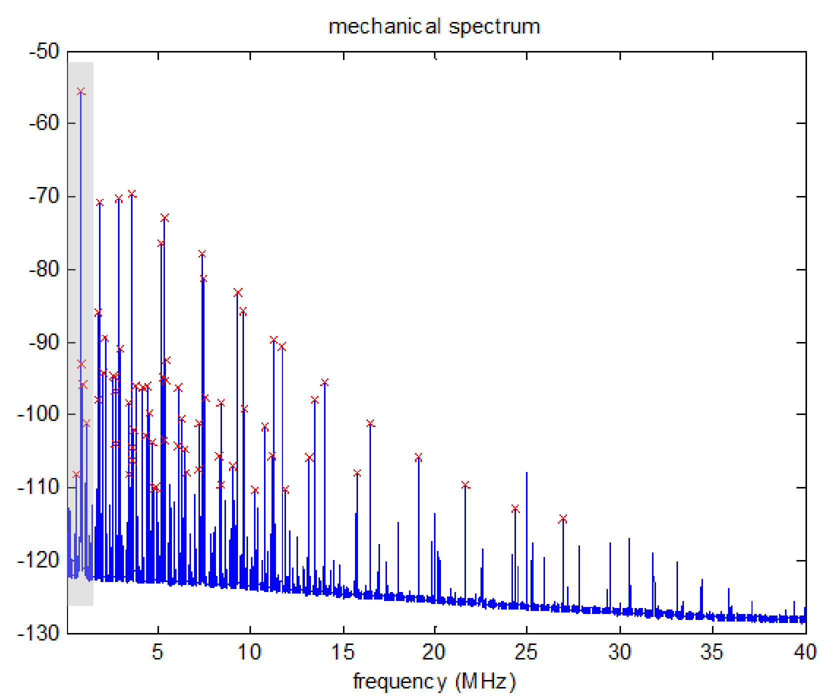
- "Cooling by measurement"
  - = conditional reduction of variance
  - interaction strength (no cavity) $\chi \approx 1/\sigma_x \approx 10^{-4}$

Beating the SQL by QND

- Goal: $\chi > 1 \Leftrightarrow \sigma_x < 1$
  - conditionally squeezed state
- How?
  - large single-photon coupling
  - interaction enhanced by cavity
  - $\chi \approx 4$
- Problem:
  - diffusion due to multiple modes!

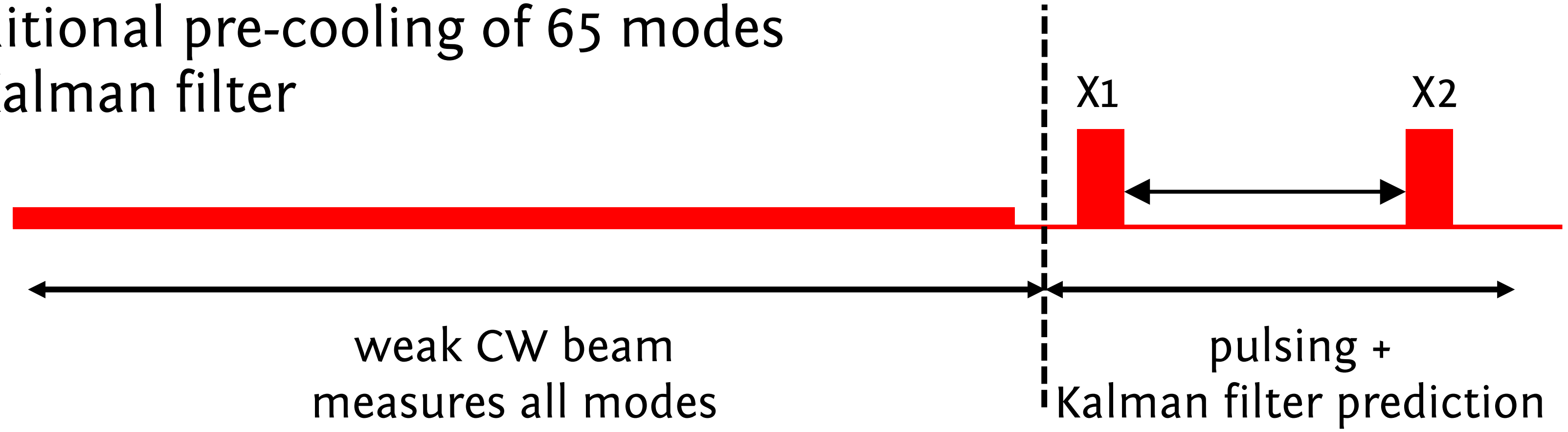


A. Safavi-Naeini et al., Nature 500, 185 (2013)

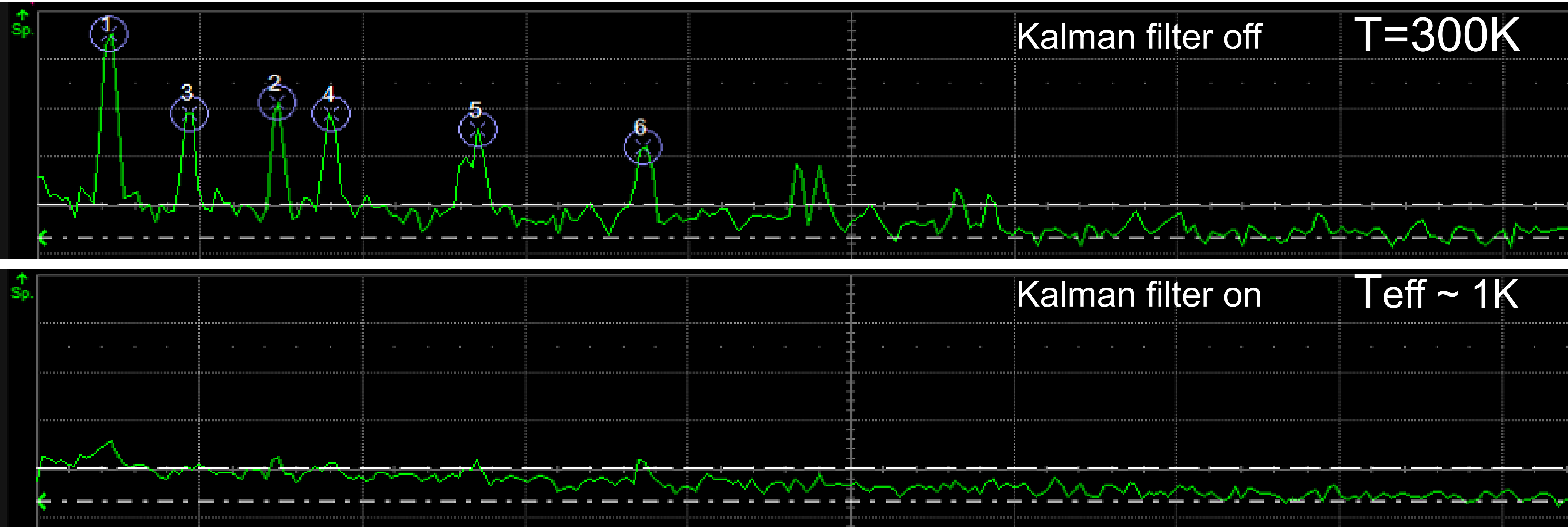


Beating the SQL by QND

- conditional pre-cooling of 65 modes via Kalman filter



- subtract predictions from measurements



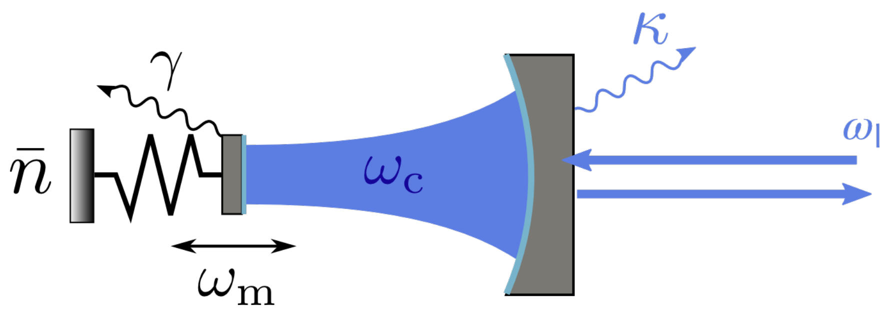
Hamiltonian

- optomechanical cavity

$\kappa = \frac{c\pi}{2LF}$

$\bar{n} \simeq \frac{k_B T}{\hbar\omega_m}$

$\Delta = \omega_c - \omega_l$



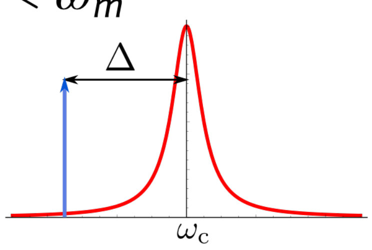
- linearised interaction Hamiltonian (for strong driving)

cooperativity:

$$C = \frac{4g^2}{\kappa\gamma(\bar{n}+1)}$$

$$H_{rp} = g(a_c + a_c^\dagger)(a_m + a_m^\dagger)$$
$$= g(a_c a_m^\dagger + a_c^\dagger a_m) + g(a_c a_m + a_c^\dagger a_m^\dagger)$$

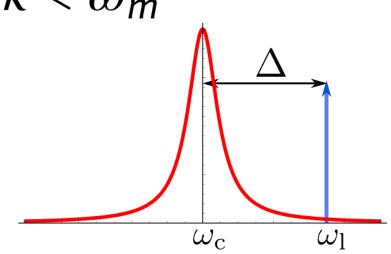
red $\Delta = +\omega_m$
$\kappa < \omega_m$



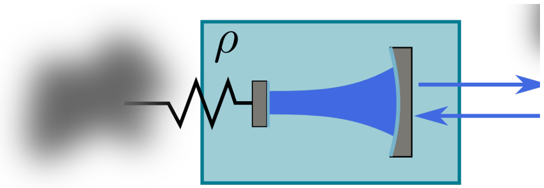
"beam splitter"
= state transfer

2-mode-squeezing
= entangling

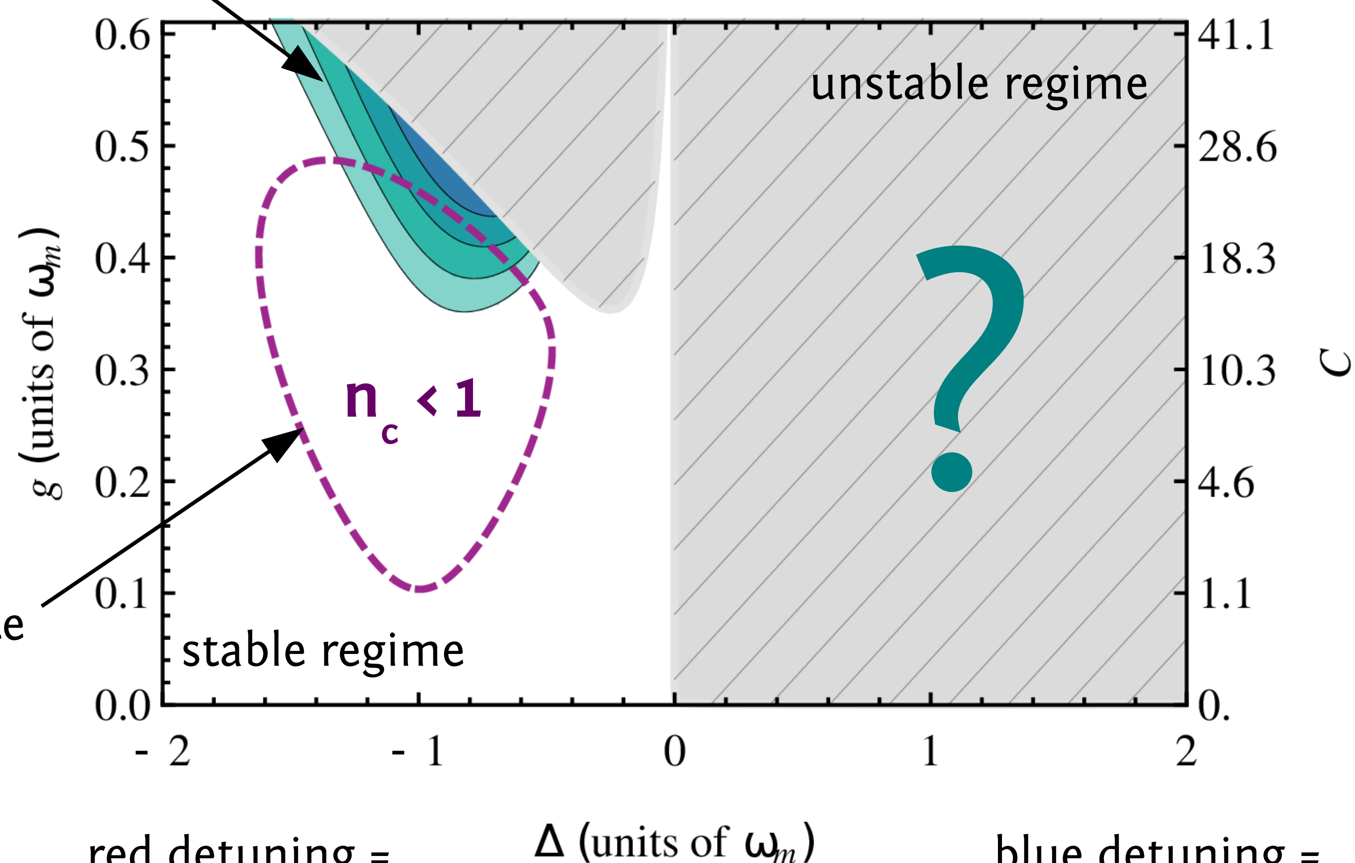
blue $\Delta = -\omega_m$
$\kappa < \omega_m$



Steady-state phase diagram



entanglement between mechanics and intracavity field



ground state cooling

red detuning = cooling

blue detuning = heating

$Q = 10^7$

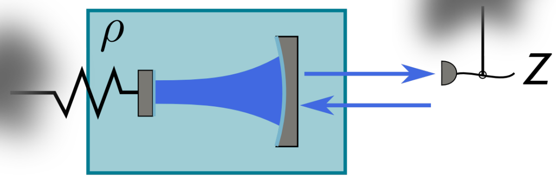
$n_{bath} = 3.5\ 10^5$

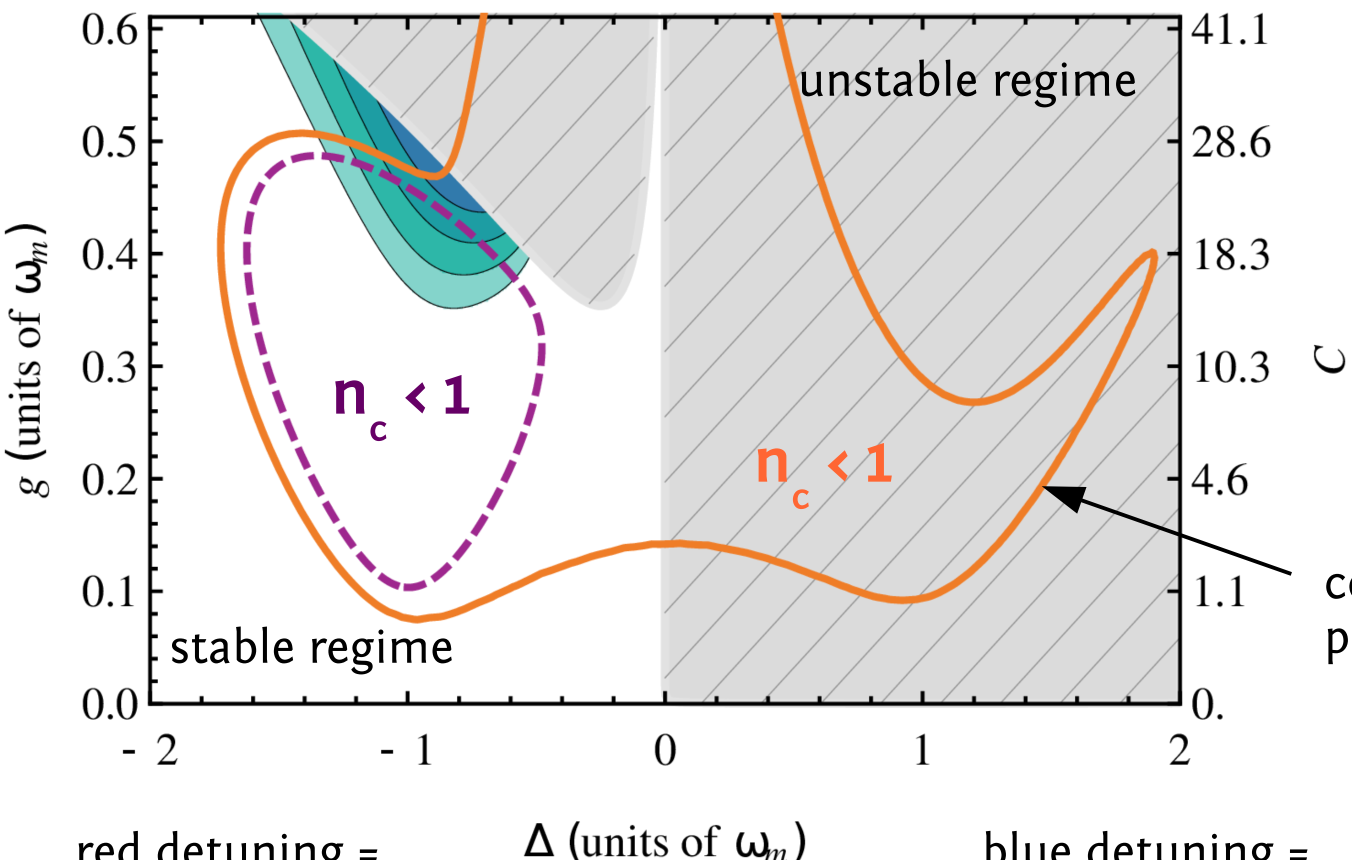
$\kappa = \omega_m/4$

Genes et al.,
PRA 77, 033804 (2008)
PRA 78, 032316 (2009)

Conditional-state phase diagram

- conditioned on homodyne detection of phase quadrature





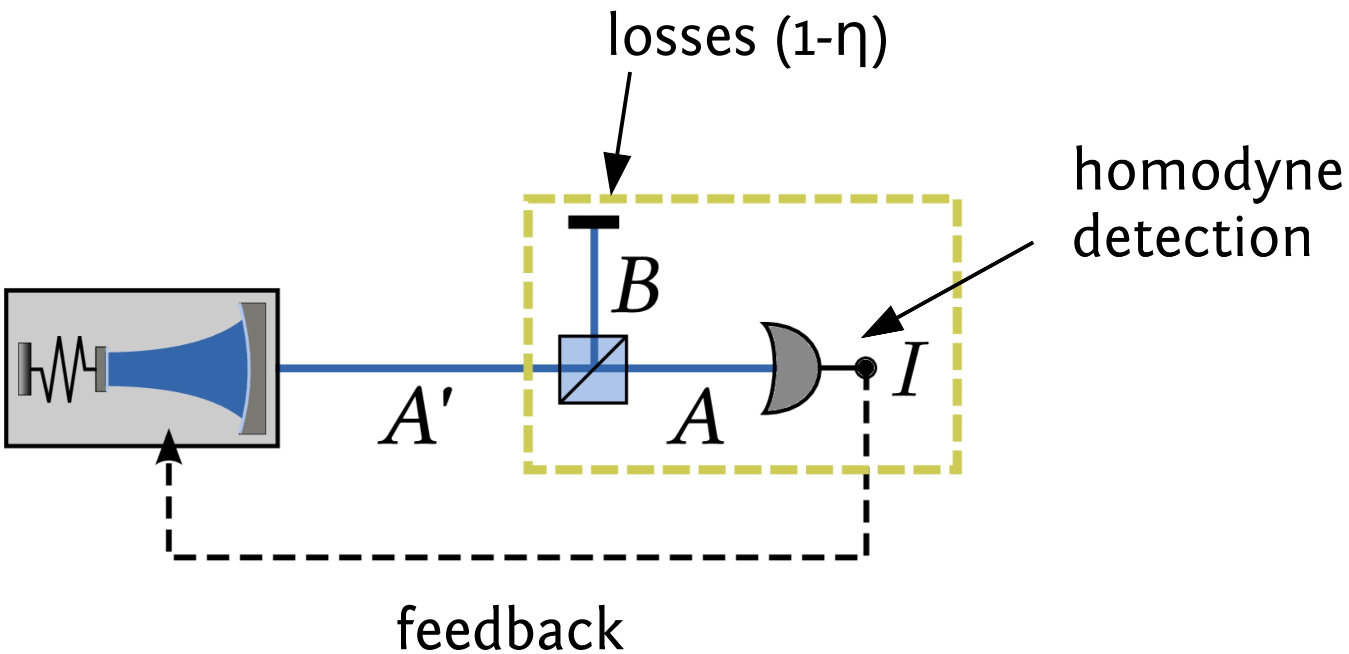
$Q = 10^7$
$n_{bath} = 3.5\ 10^5$
$\kappa = \omega_m/4$

red detuning = cooling

blue detuning = heating

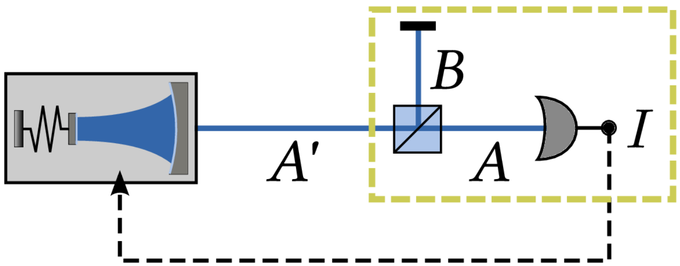
Hofer & Hammerer, accepted in PRA, arXiv:1411.1337

Feedback cooling (homodyne detection)



Feedback cooling with a twist

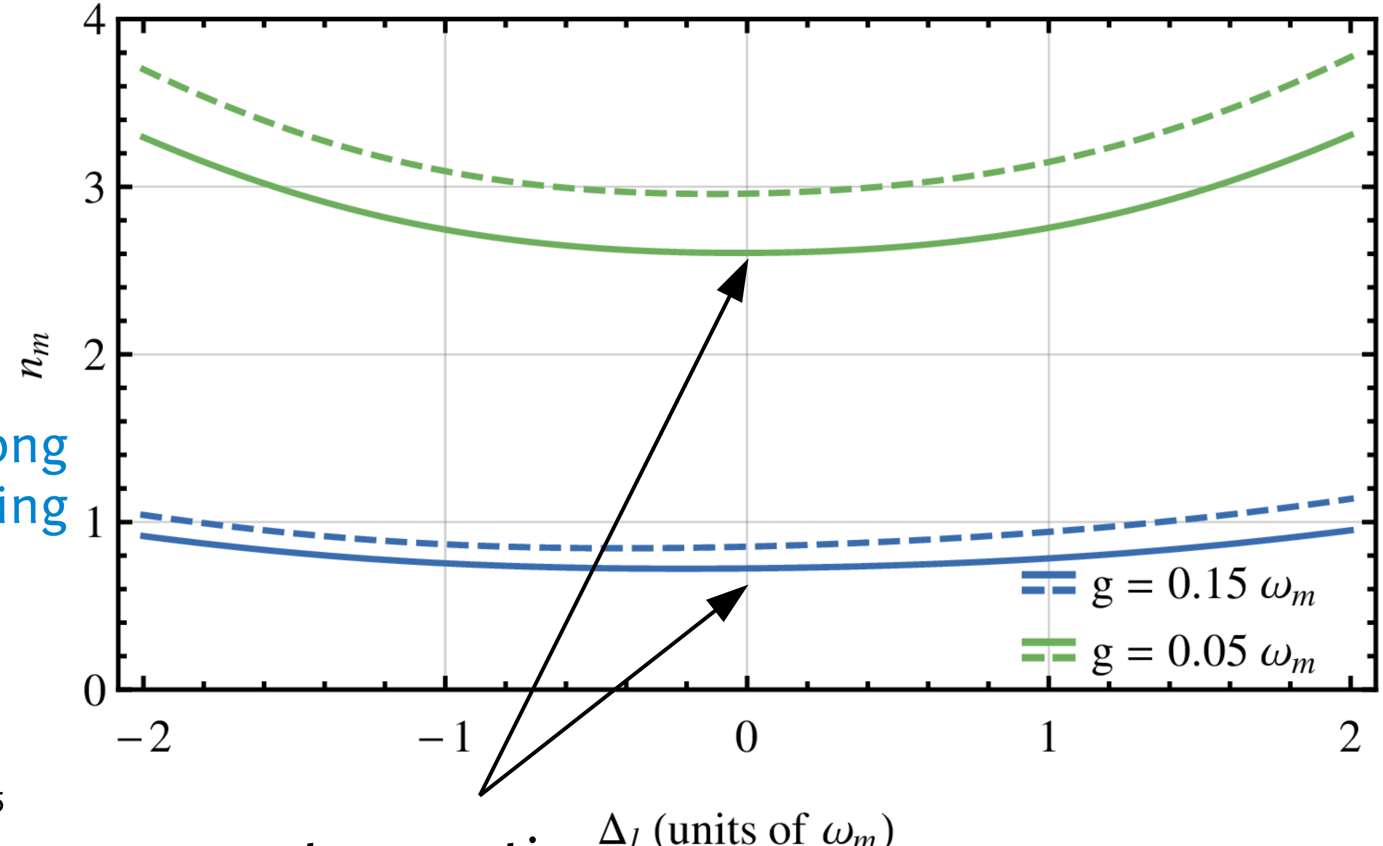
- bad-cavity regime $\kappa > \omega_m$
  + LQG control



weak coupling

η=0.8

η=1



strong coupling

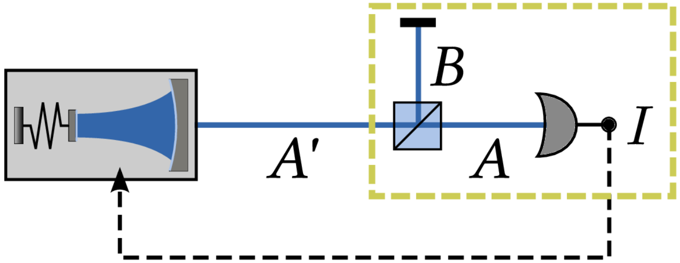
$Q = 10^7$
$n_{bath} = 3.5\ 10^5$
$\kappa = 2\ \omega_m$

resonant operation is optimal

Hofer & Hammerer, accepted in PRA, arXiv:1411.1337

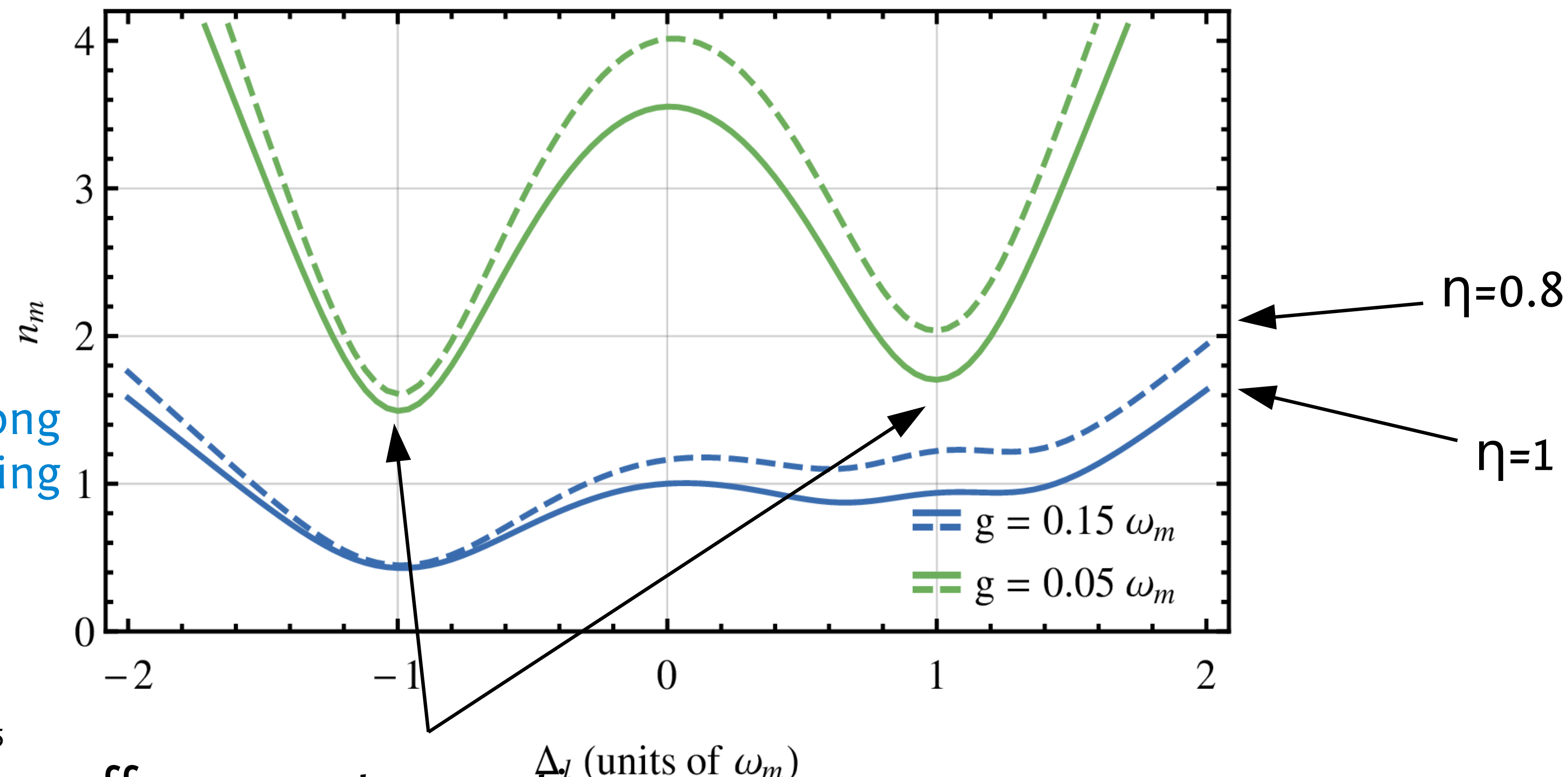
Feedback cooling with a twist

- sideband-resolved regime $\kappa < \omega_m$
  + LQG control



weak coupling

strong coupling



$Q = 10^7$

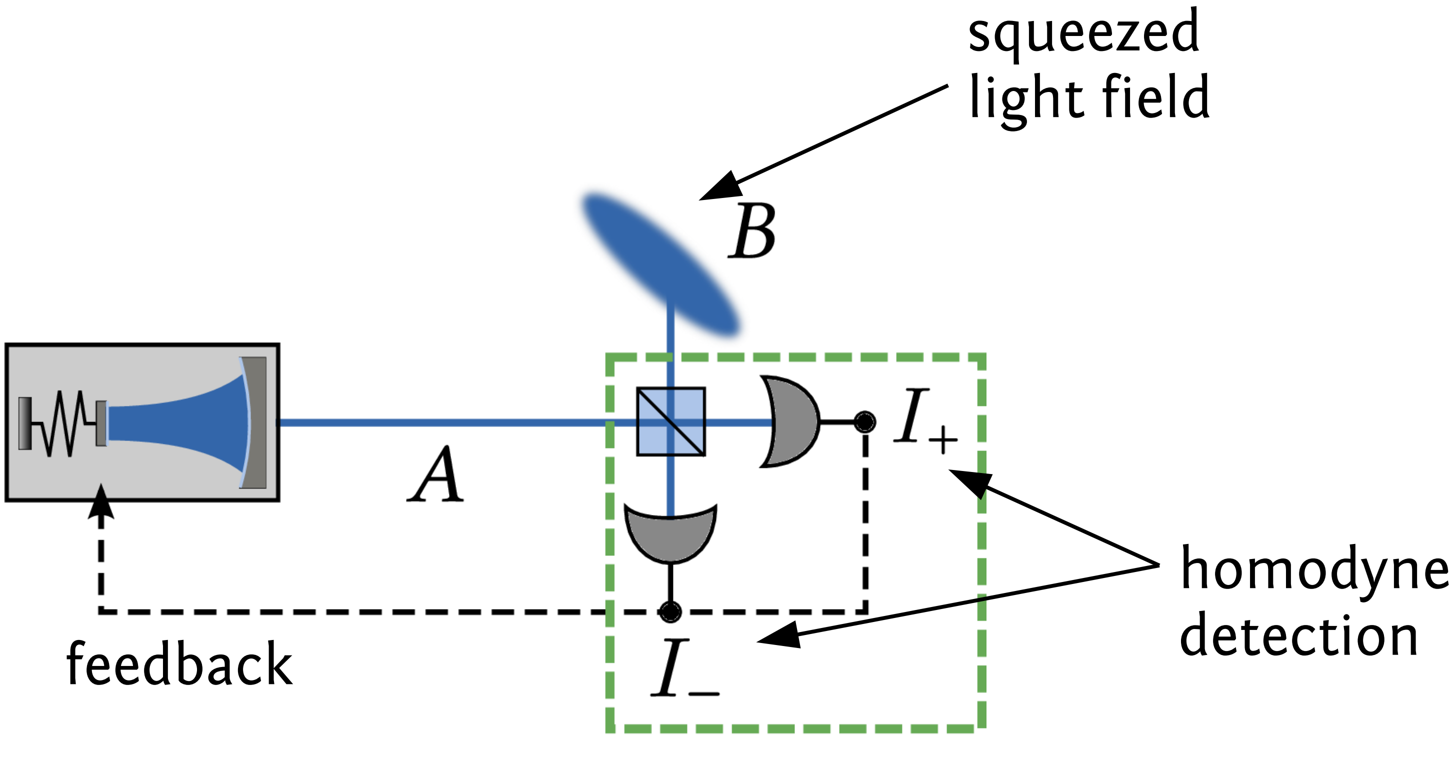
$n_{bath} = 3.5\ 10^5$

$\kappa = \omega_m/4$

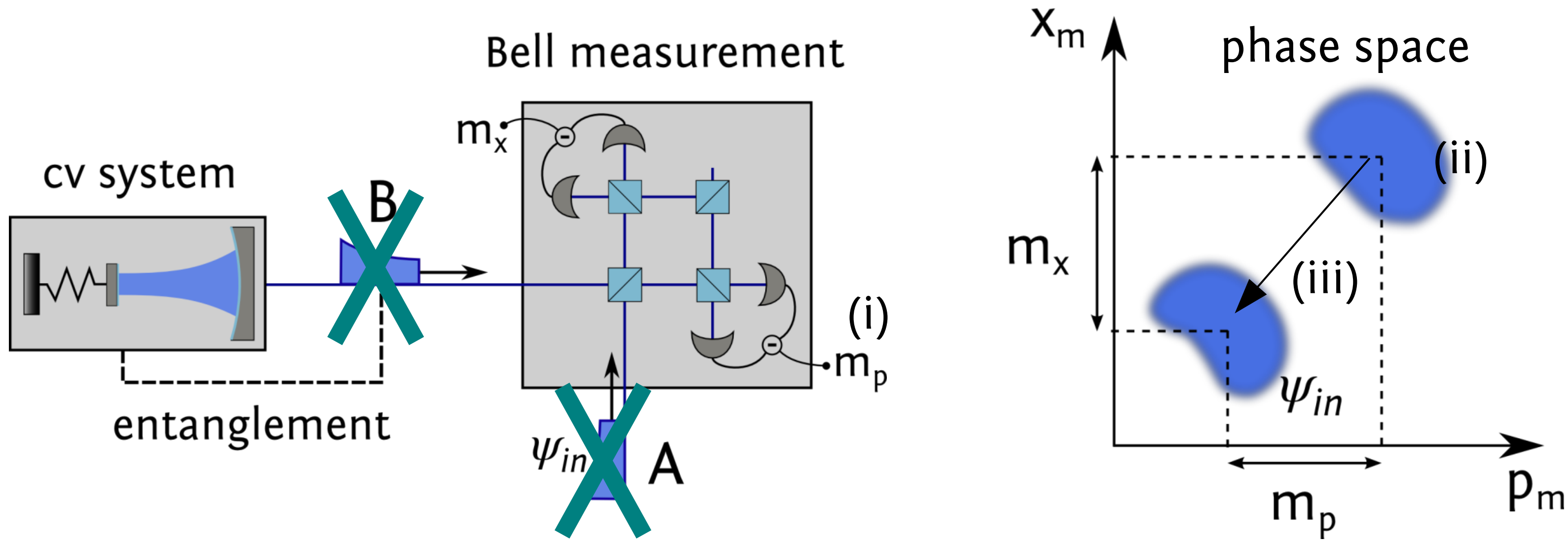
off-resonant operation is optimal

Hofer & Hammerer, accepted in PRA, arXiv:1411.1337

Time-continuous teleportation



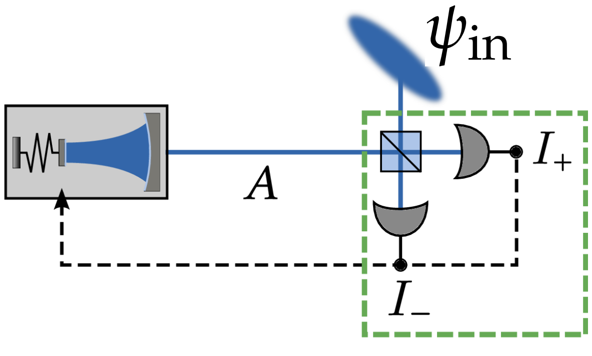
CV Bell measurement/teleportation



- CV Bell measurement = 2 homodyne detectors + beam splitter
  - measures EPR quadratures $X_- = X_A - X_B \quad P_+ = P_A + P_B$
    with outcomes m_x and m_p
- CV teleportation
  - Bell measurement projects mechanics onto into displaced input state
  - displacement by m_x and m_p recovers input state

Hofer et al. PRA 84, 052327, (2011)
Palomaki et al., Science 342, 710 (2013)

Time-continuous teleportation



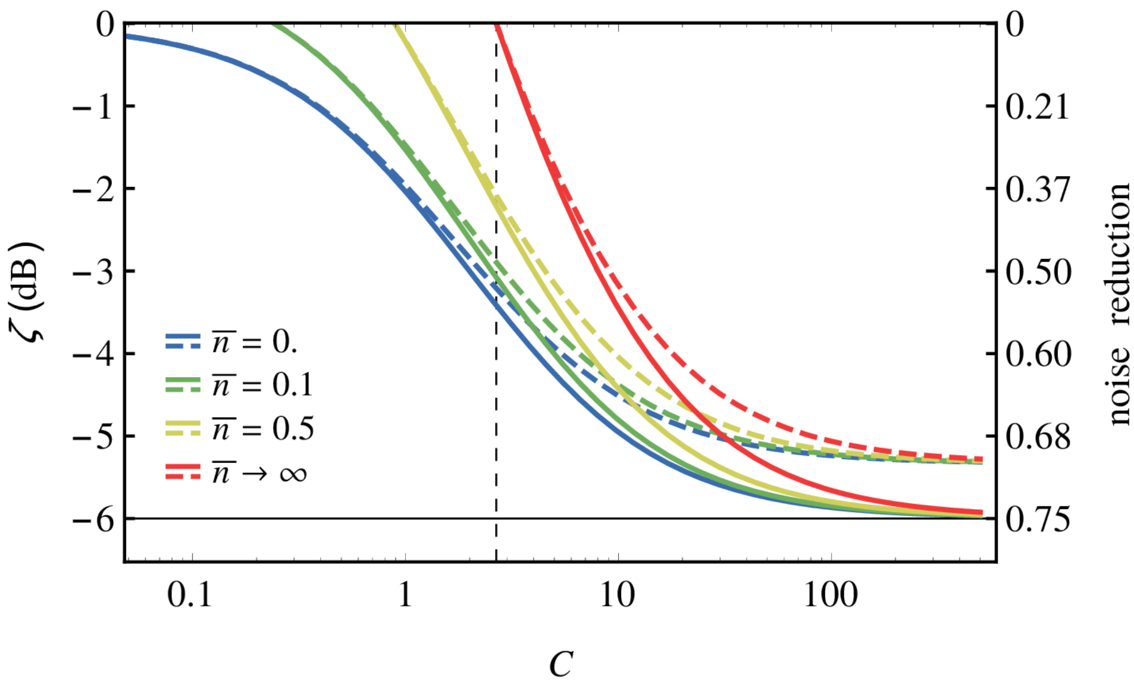
- continuous operation of teleportation
  CW, no pulses
- dissipative remote state preparation

$$\dot{\rho} = \mathcal{D}[J]\rho \qquad J|\psi_{\rm in}\rangle = 0 \quad \xrightarrow{t \to \infty} \quad \rho_{\rm ss} = |\psi_{\rm in}\rangle\langle\psi_{\rm in}|$$

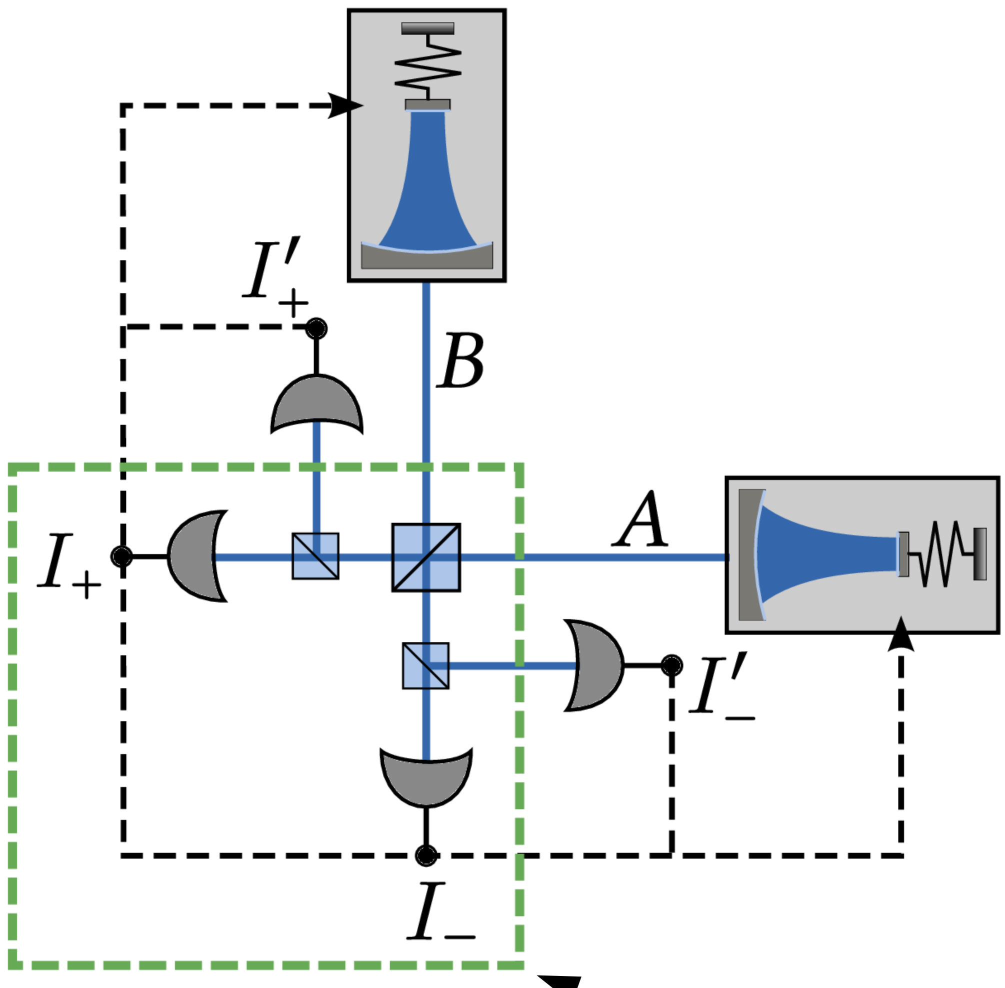
- teleportation of a squeezed state

needs strong cooperativity!

$$C = \frac{4g^2}{\kappa\gamma(\bar{n}+1)} > 1$$



Time-continuous ent. swapping



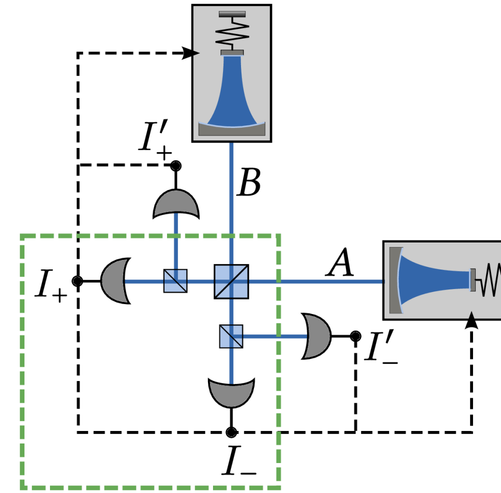
Bell measurement

Time-continuous ent. swapping

- create steady-state entanglement between two mechanical oscillators
- dissipative remote state preparation

$$\dot{\rho} = \mathcal{D}[J]\rho \quad \xrightarrow{t \to \infty} \quad \rho_{\mathrm{ss}} \approx |\psi_{\mathrm{EPR}}\rangle\langle\psi_{\mathrm{EPR}}|$$

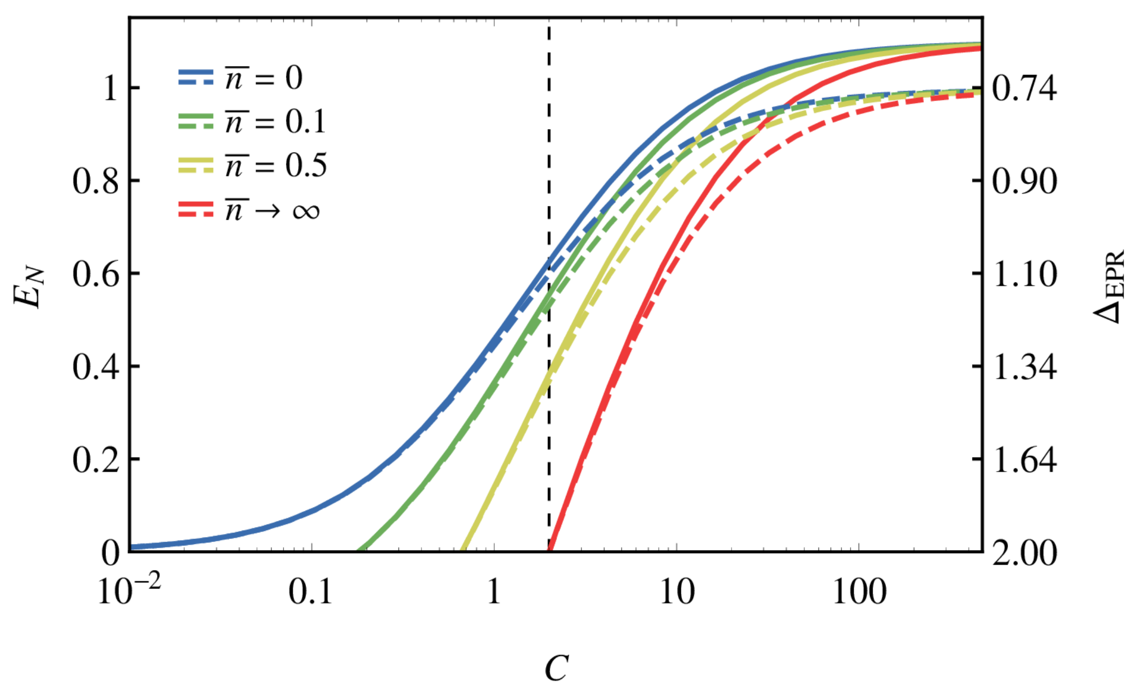
$$J|\psi_{\mathrm{EPR}}\rangle \approx 0$$



- bipartite mechanical entanglement

needs strong cooperativity!

$$C = \frac{4g^2}{\kappa\gamma(\bar{n}+1)} > 1$$



Acknowledgements