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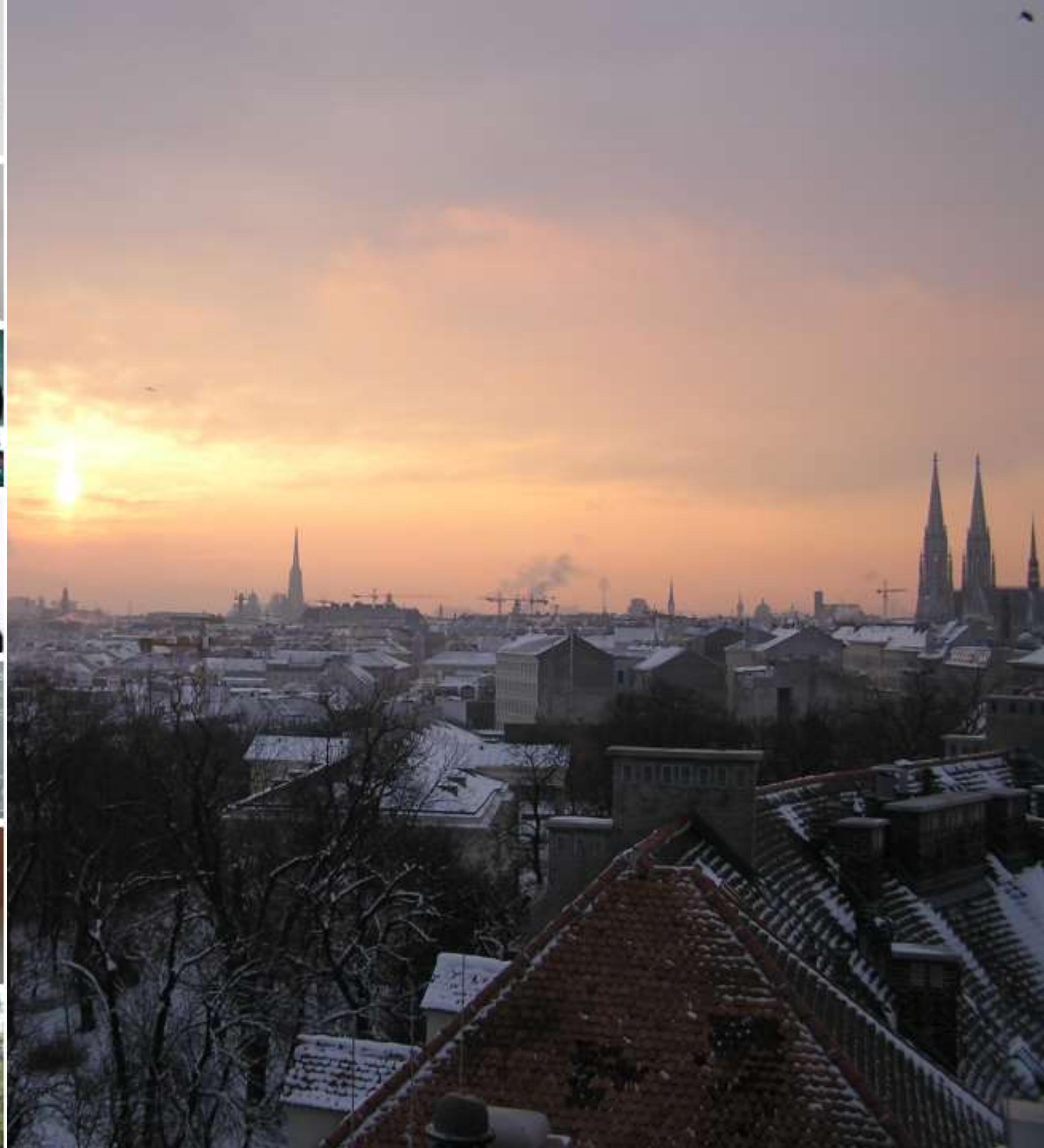
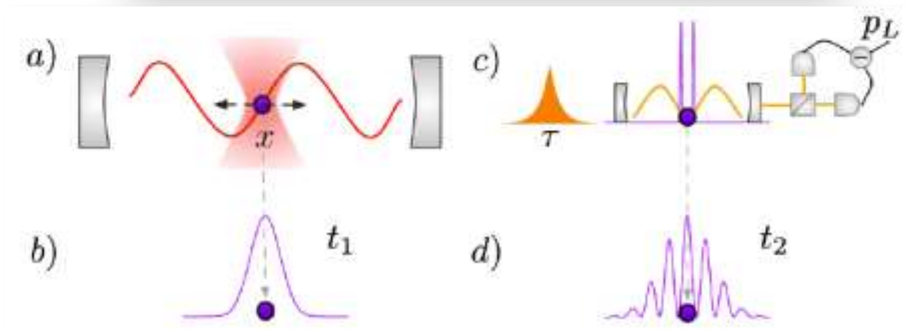
CoQuS ComplexQuantumSystems

Camerino
January 2014



Levitated Nanoparticles and Foundations of Quantum Physics

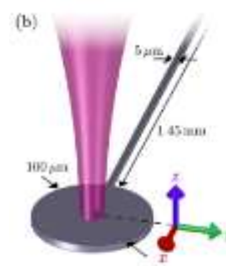
- Quantum control of levitated nanoparticles in high vacuum
- Macroscopic quantum superposition states and decoherence in the presence of gravity
- Design and proof-of-concept for a satellite-based experiment

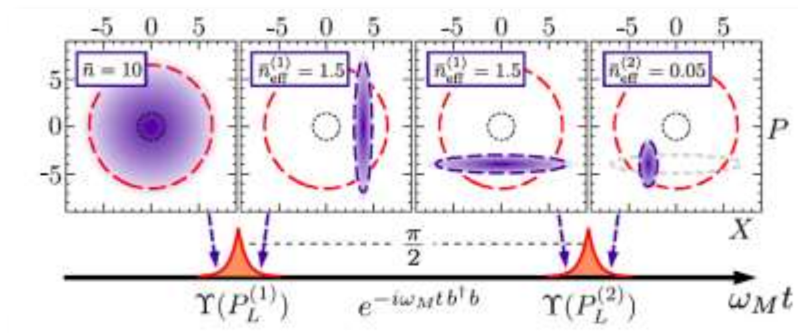


Nikolai Kiesel
Rainer Kaltenbaek

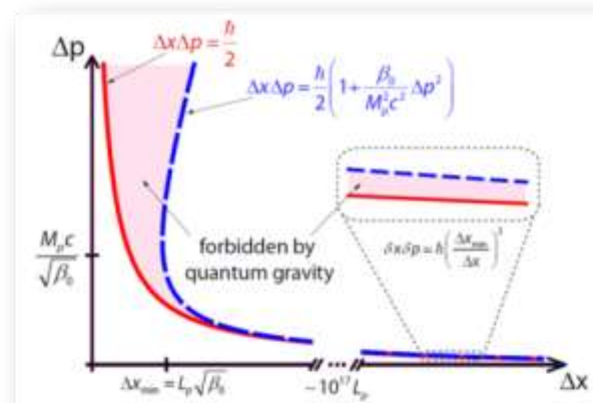
Quantum Non-Demolition Measurements and Tests of Quantum Gravity

- Quantum state control through quantum non-demolition measurements of macroscopic mechanical devices
- Towards low-energy tests of quantum gravity predictions





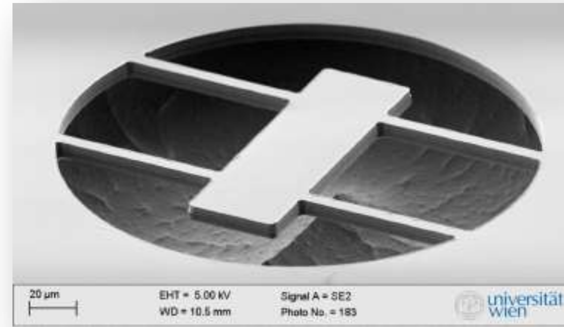
Sungkun Hong
Michael Vanner

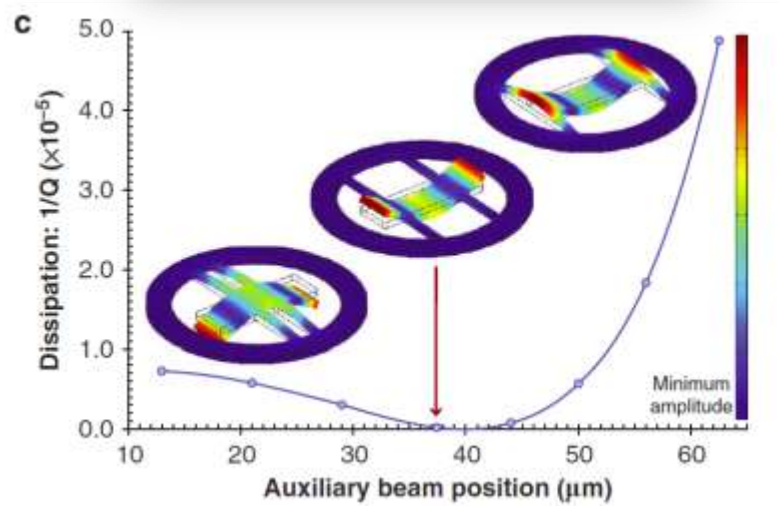


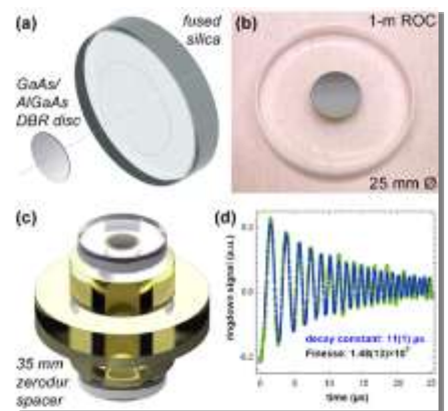
Fundamentals of Low-Noise Mechanical Resonators and Optical Coatings

- What are the ultimate stability and precision limits for lasers and gravitational wave detectors?
- What determines the ultimate low-temperature mechanical losses in multilayer mirrors?

Garrett D. Cole



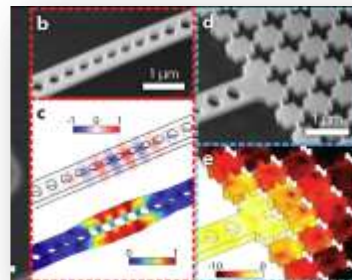


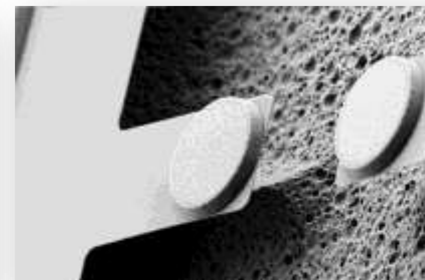


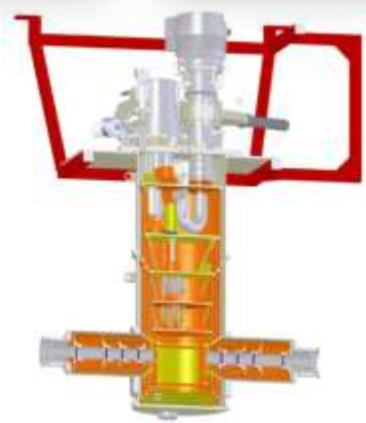
Solid-State Quantum Information Interfaces

- Quantum entanglement between light and micromechanics
- Single-photon control of micro- and nanomechanical devices
- Micro- and nano-optomechanics at ultra-low temperatures

Witlef Wieczorek
Simon Gröblacher

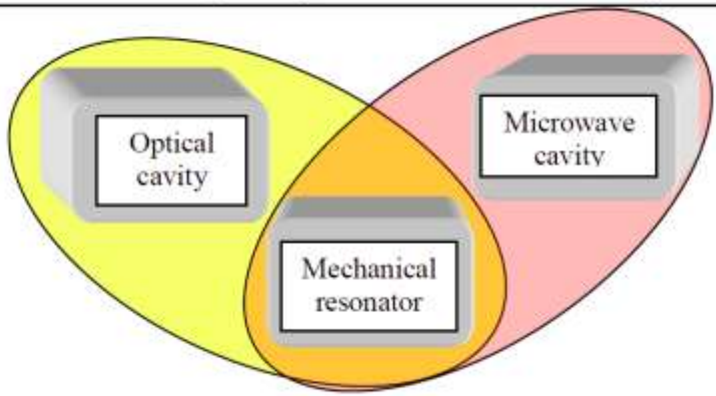






WP2: Photon-phonon interfaces

Main objective: implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons



Tasks:

Task 2.3: Optomechanical Correlations and Photon-Phonon Conversion

Task 2.4: Strong Optomechanical Coupling for Single Photons

Deliverables:

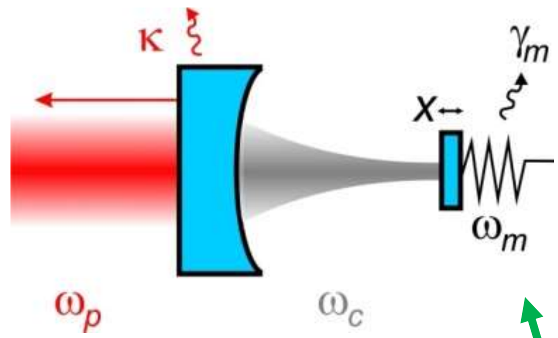
D2.3 Detection of optomechanical correlations by means of quantum filtering techniques (Month 24)

D2.4 Coherent photon-phonon conversion in an optomechanical system (Month 24)

D2.5 Demonstration of large single-photon optomechanical coupling rates (one order of magnitude improvement in g_0/κ) at cryogenic temperatures (Month 36)

Optomechanical quadratures

detection of correlations (entanglement)



light: amplitude and phase quadrature

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

direct measurement

via homodyne detection

mechanics: position and momentum

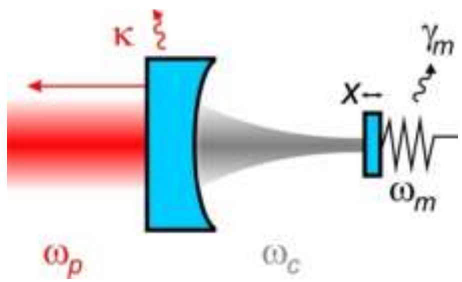
$$x_m(t,\theta) = x_m(t)\cos\theta + p_m(t)\sin\theta$$

only indirect determination

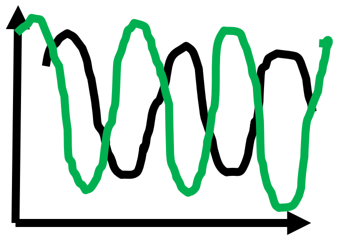
via measurements on light

field

Optomechanical state reconstruction

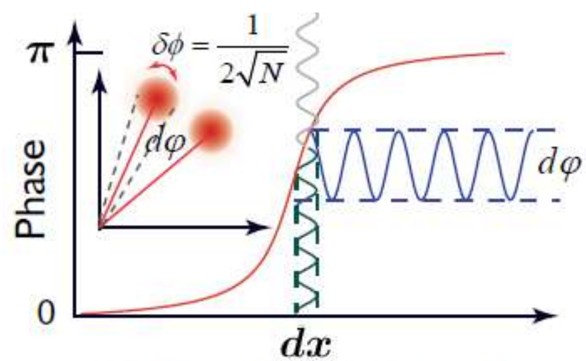


measurements on optical field



coupling to light is governed by
- *time-delay: cavity decay* κ
- *type of interaction: detuning of light* Δ
- *strength of interaction: OM coupling g*

simple example: resonant, adiabatically coupled optical drive



$\Delta = 0 \rightarrow x_m$ via y_l

$g, \omega_m \ll \kappa$

T. Briant et al., Eur. Phys. J. D 22 (03)
P. Verlot et al., PRL 102 (09)

Optomechanical quadratures

real-time determination of $x(t)$, $p(t)$ allows for feedback on mechanical system by optical field for

optical feedback cooling of mechanical motion

S. Mancini, et al., PRL 80 (1998)
J.-M. Courty et al., Eur. Phys. J. D 47 (2001)
C. Genes et al. PRA 77 (2008)

teleportation, entanglement swapping

Hofer, Wieczorek, Aspelmeyer, Hammerer PRA 84 (2011)
Hofer, Vasilyev, Aspelmeyer, Hammerer, PRL 111 (2013)

statistics of $x(t)$, $p(t)$, $x_l(t)$, $y_l(t)$ allows for determination of 1st and 2nd order moments for

reconstruction of Wigner function
characterization of optomechanical entanglement

D. Vitali et al, PRL 98 (2007)
M. Paternostro et al., PRL 99 (2007)

State estimation

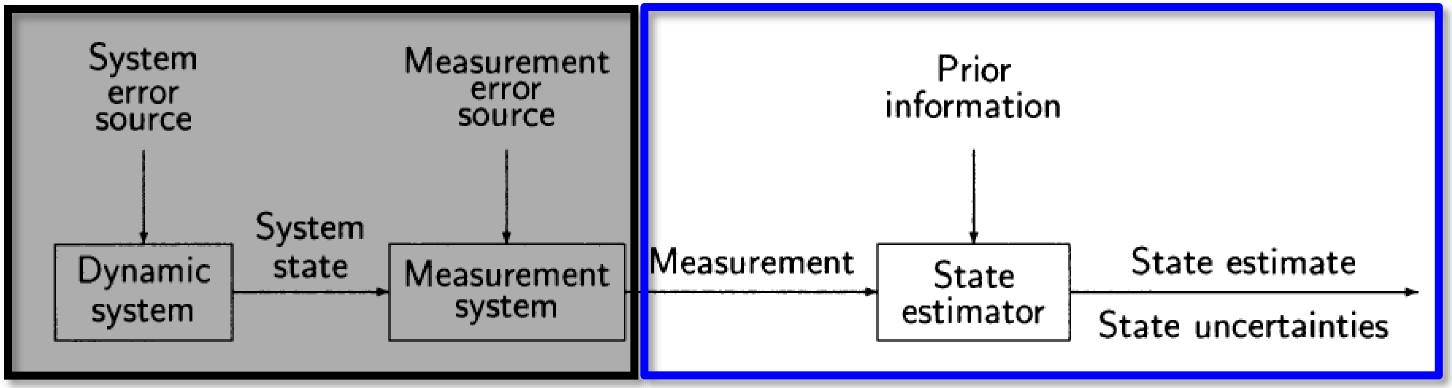
Estimation is the process of inferring the value of a quantity of interest from indirect, inaccurate and uncertain observations:

a parameter (time-invariant quantity)
the state of a dynamic system (evolving in time according to stochastic equations)

Filtering is the estimation of the state of a dynamic system ("filtering out the noise").

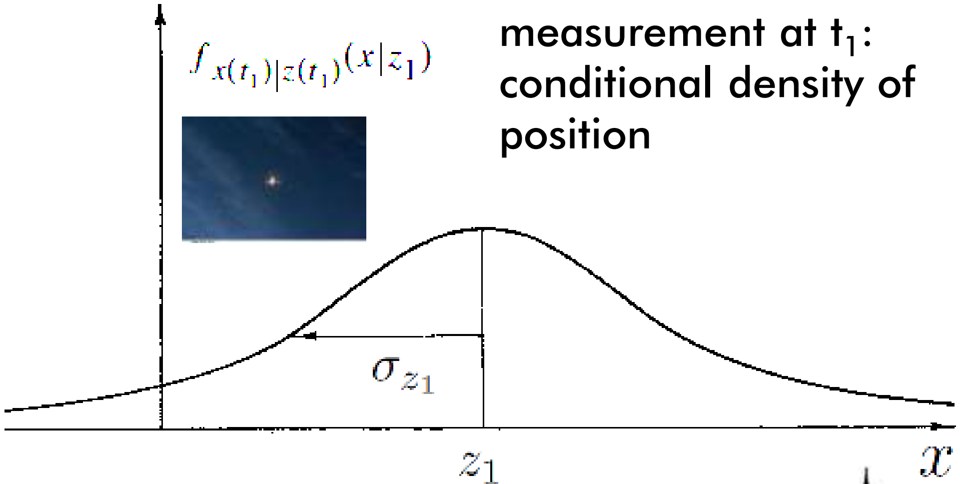
e.g. determination of planet orbits, tracking an aircraft

R. E. Kalman, Transactions of the ASME, 82 (1960)
Y. Bar-Shalom et al., Wiley (2001)
R. Stengel, Dover (1994)



State estimation: an example

State estimation: an example



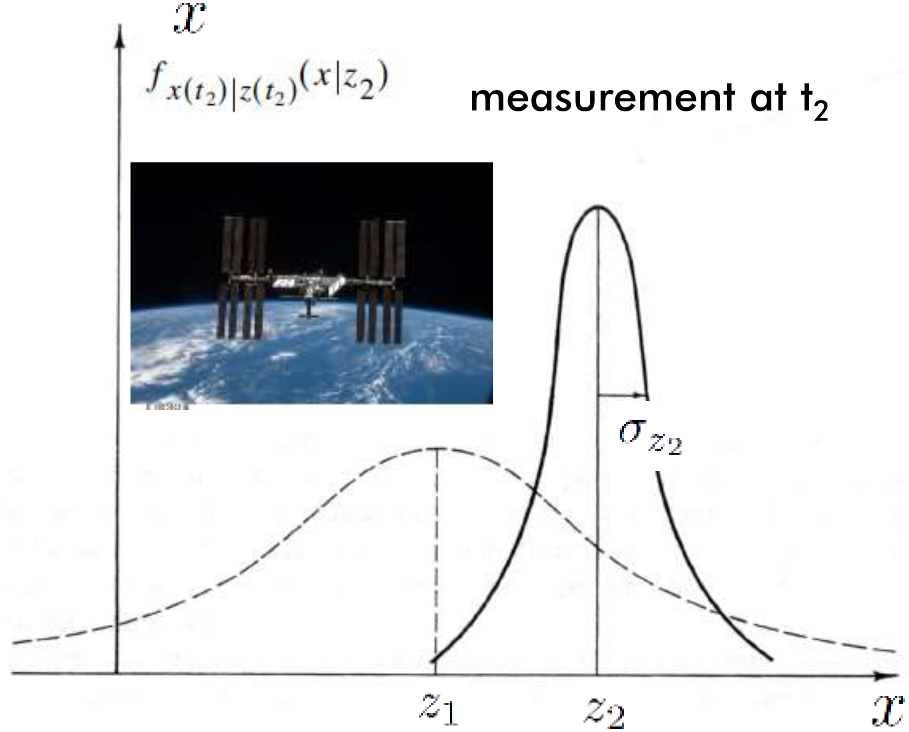
measurement at t_1: conditional density of position

best estimate and uncertainty due to measurement 1

$$\hat{x}(t_1) = z_1$$

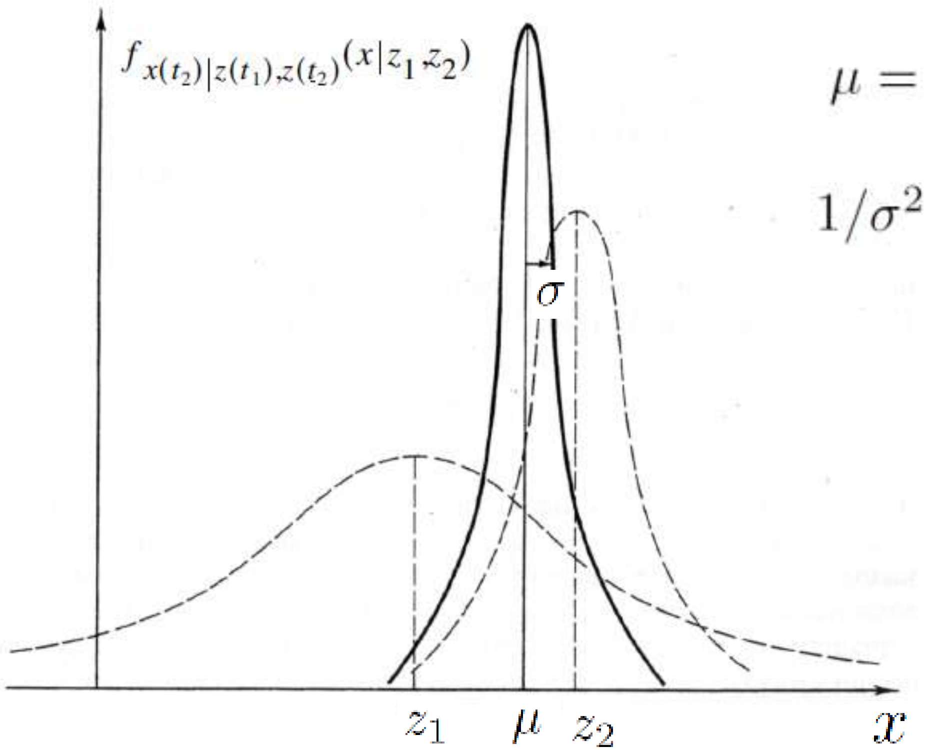
$$\sigma(t_1) = \sigma_{z_1}$$

measurement at t_2



see Maybeck, Stochastic models, estimation and control, Academic Press (79)

State estimation: an example



$$\mu = \frac{\sigma_{z_2}^2}{\sigma_{z_1}^2 + \sigma_{z_2}^2} z_1 + \frac{\sigma_{z_1}^2}{\sigma_{z_1}^2 + \sigma_{z_2}^2} z_2$$

$$1/\sigma^2 = 1/\sigma_{z_1}^2 + 1/\sigma_{z_2}^2$$

best estimate and uncertainty due to measurement 1 and 2

$$\hat{x}(t_2) = \mu$$

$$\sigma(t_2) = \sigma$$

predicted state, actual measurement, predicted measurement

$$\hat{x}(t_2) = \hat{x}(t_1) + K(t_2)[z_2 - \hat{x}(t_1)]$$

Kalman gain $K(t_2) = \frac{\sigma_{z_1}^2}{\sigma_{z_1}^2 + \sigma_{z_2}^2}$

see Maybeck, Stochastic models, estimation and control, Academic Press (79)

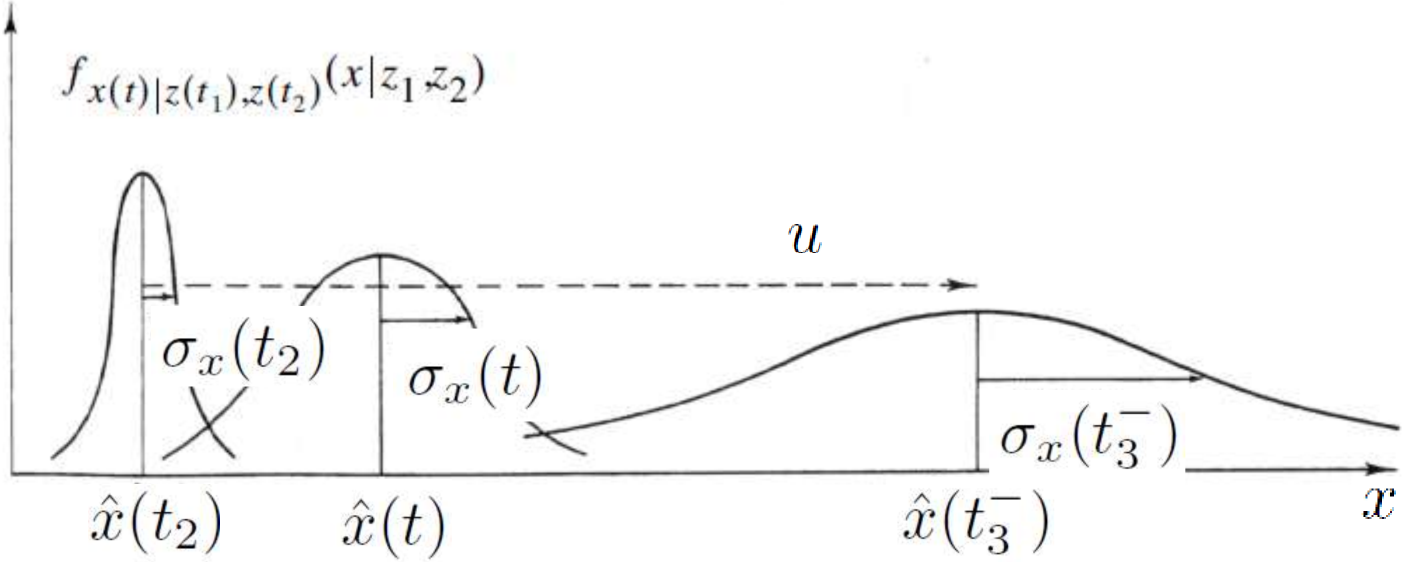
State estimation: an example

system dynamics:
move with constant, but somehow uncertain, velocity u

$$\frac{dx}{dt} = u + w$$

with white Gaussian noise

$$w \sim (0, \sigma_w^2)$$



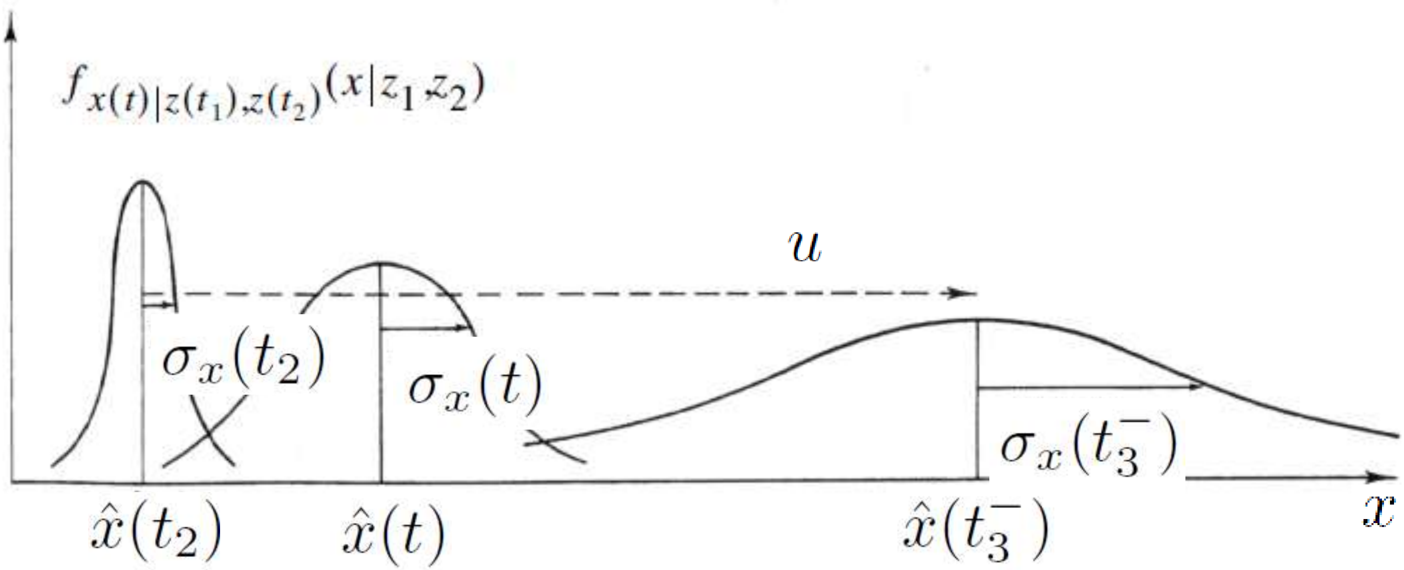
see Maybeck, Stochastic models, estimation and control, Academic Press (79)

State estimation: an example

best estimate and uncertainty
before measurement

$$\hat{x}(t_3^-) = \hat{x}(t_2) + u \cdot (t_3 - t_2)$$

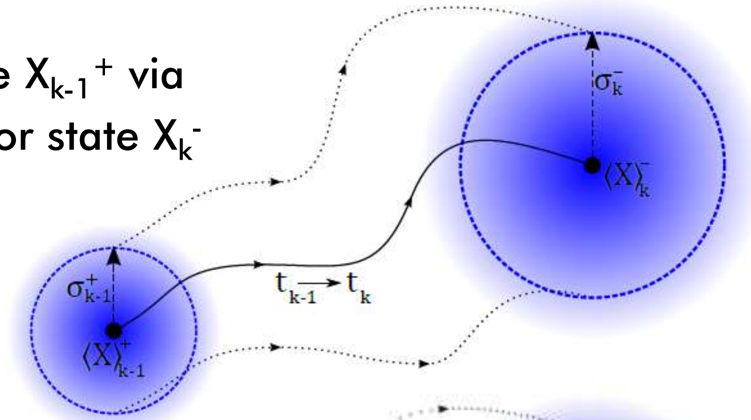
$$\sigma_x^2(t_3^-) = \sigma_x^2(t_2) + \sigma_w^2 \cdot (t_3 - t_2)$$



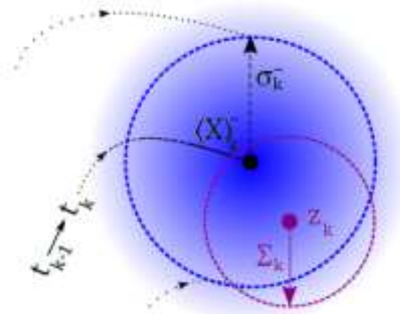
see Maybeck, Stochastic models, estimation and control, Academic Press (79)

Kalman-filter algorithm

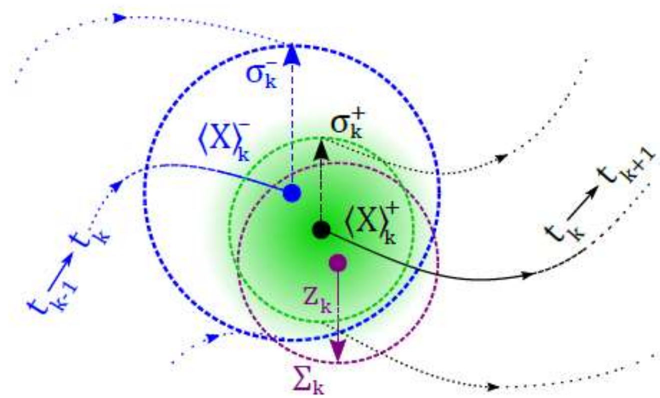
1) propagation of last estimate X_{k-1}^{+} via known system dynamics to prior state X_k^{-}



2) measurement Z_k takes place



3) measurement is taken into account to estimate posterior state X_k^{+}



Linear dynamic system: state space model

linear dynamic system with deterministic input u(t) and white Gaussian process noise w(t) and measurement noise v(t)

plant equation

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + w(t)$$
$$z(t) = C(t)x(t) + D(t)u(t) + v(t)$$

measurement equation

Kalman filter is optimal filter for linear Gaussian dynamic systems

posterior state estimate; actual measurement

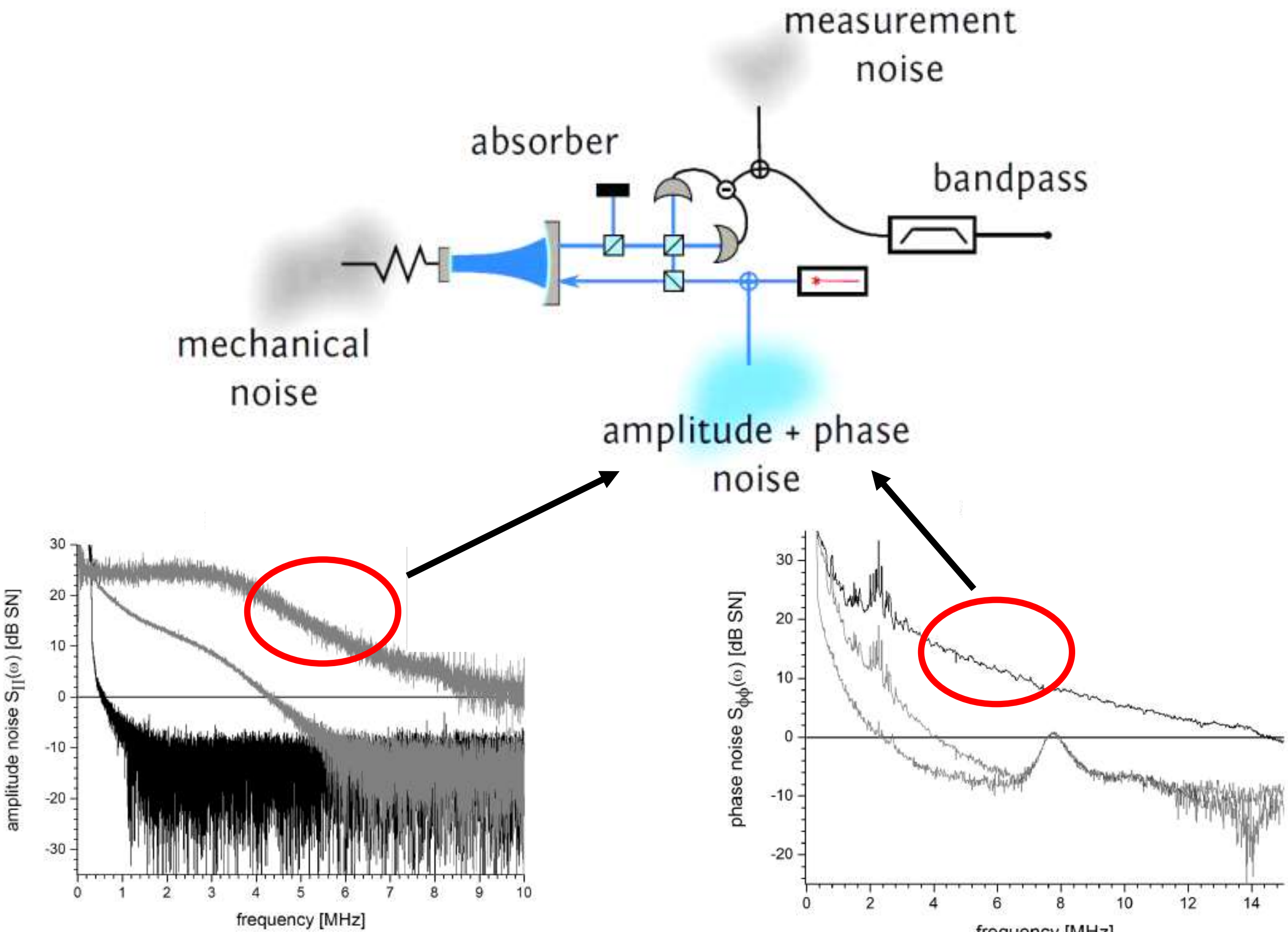
$$\hat{x}_k^+ = \underbrace{\left(A_{k-1}\hat{x}_{k-1}^+ + B_{k-1}u_{k-1}\right)}_{\hat{x}_k^-} + K_k[z_k - \underbrace{\left(C_{k-1}\hat{x}_k^- + D_{k-1}u_{k-1}\right)}_{\hat{z}_k}]$$

predicted state; Kalman gain; predicted measurement

minimizes mean estimation error covariance

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

Optomechanical state space model



Wieczorek, Hofer, Hoelscher-Obermaier, Hammerer, Aspelmeyer, et al. in preparation

Optomechanical state space model

OM system

(linearized Langevin equations and zero-mean Gaussian white process noise)

+

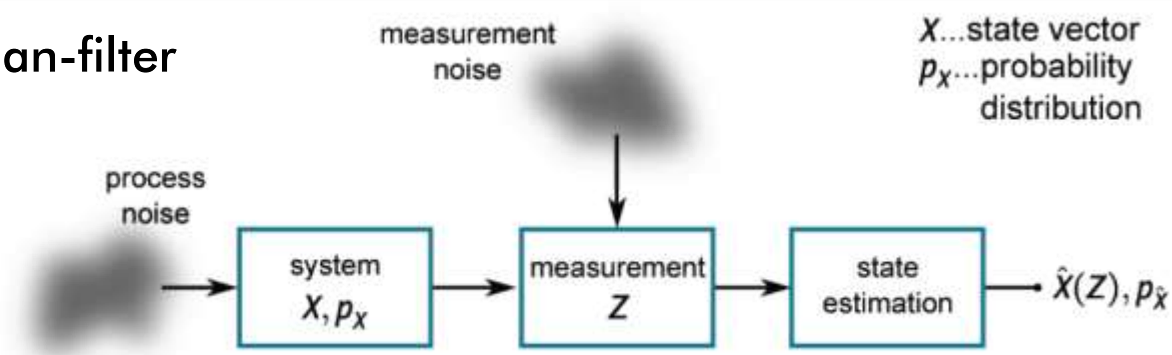
linear measurement

(includes zero-mean Gaussian white measurement noise)

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

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

Kalman-filter



R. E. Kalman, Transactions of the ASME, 82 (1960)

Y. Bar-Shalom et al., Wiley (2001)

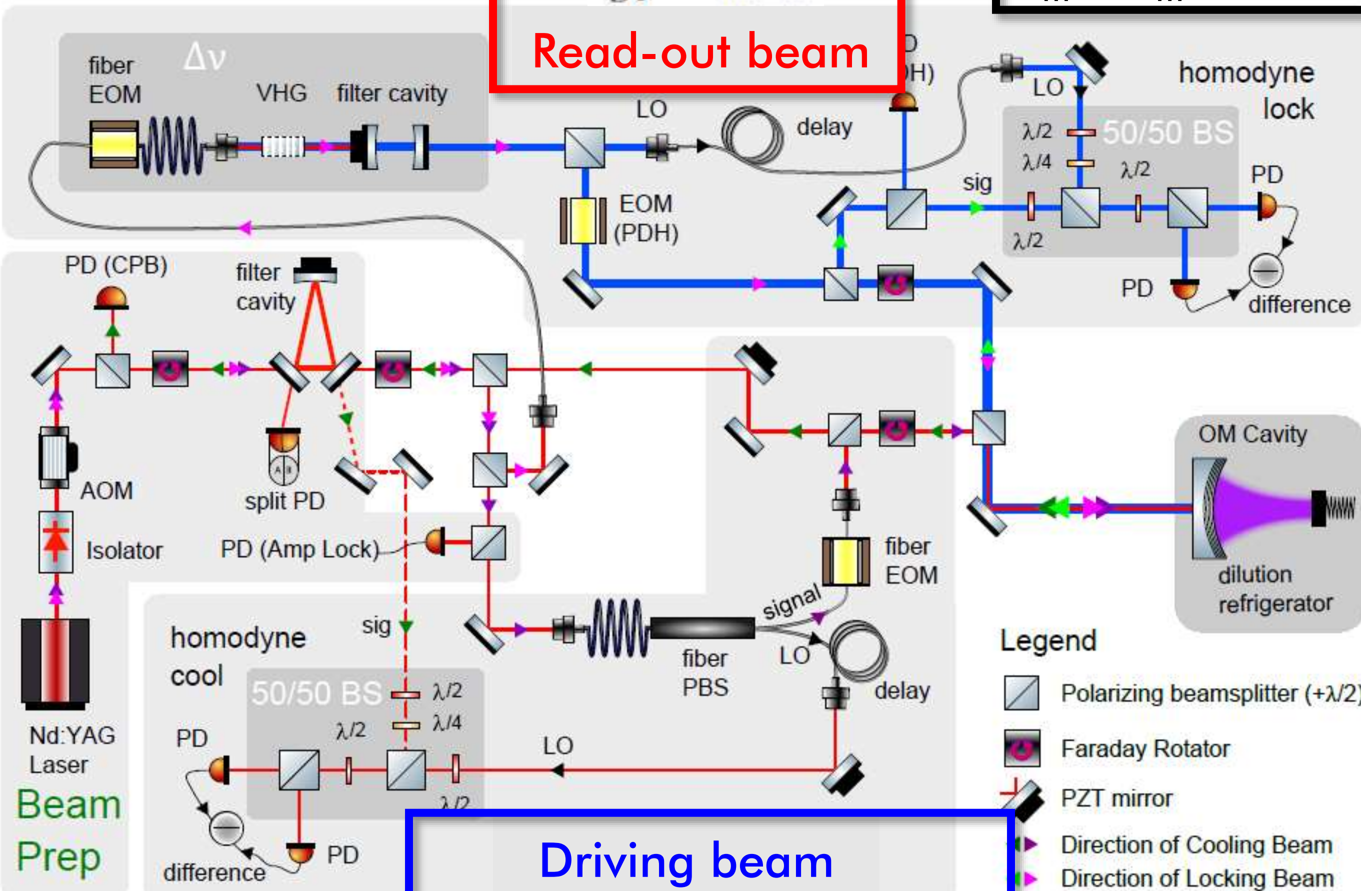
R. Stengel, Dover (1994)

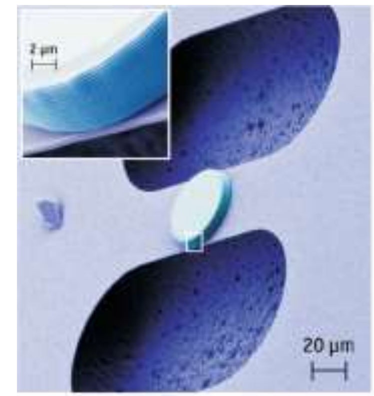
Experiment

optical control of cavity-OM system via two optical beams

$$\Delta_l = 0$$
$$g_l = 0.2\kappa$$

Read-out beam → mechanical quadratures $x_m(t), p_m(t)$





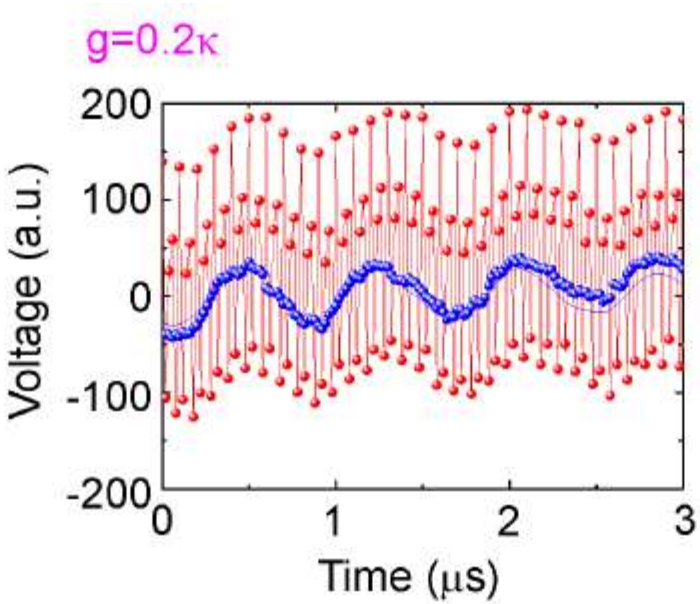
Driving beam

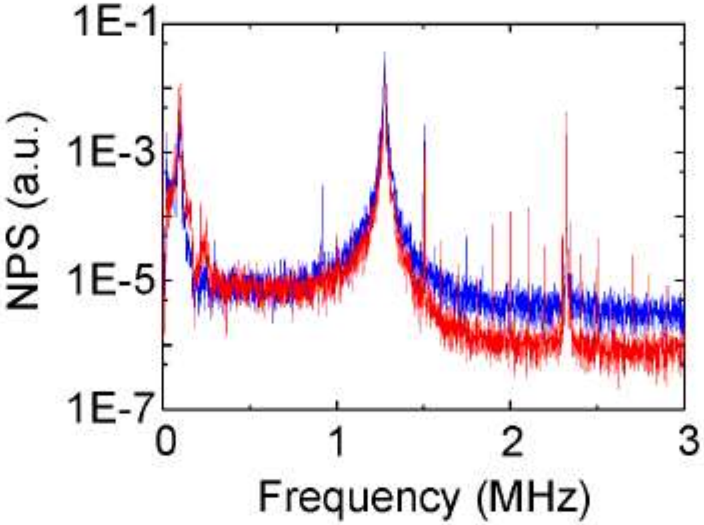
$$\Delta_c = \omega_m$$
$$g_c = 0.2\kappa \longrightarrow g_c = 1.6\kappa$$

→ optical quadratures $x_c(t), y_c(t)$

Measurements $Z(t)=(z_{\Delta=0}(t), z_{\Delta=\omega_m}(t))$

weak coupling

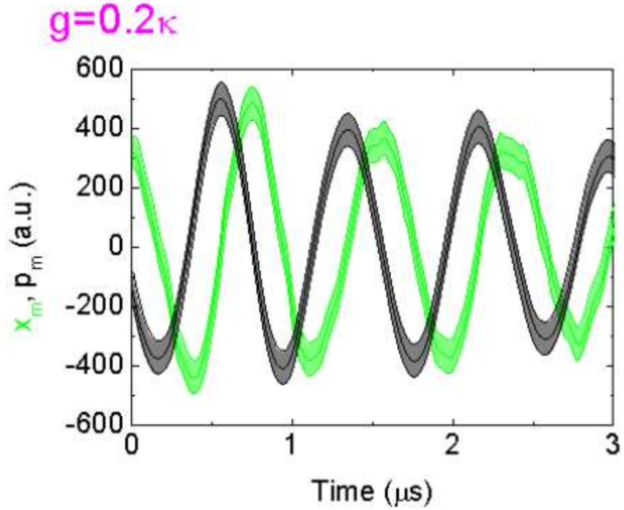


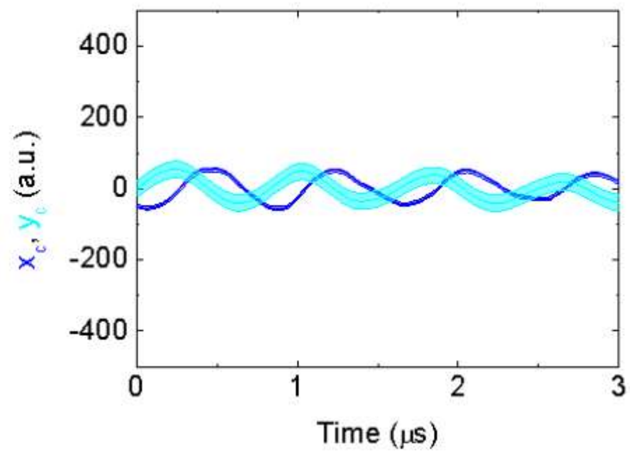


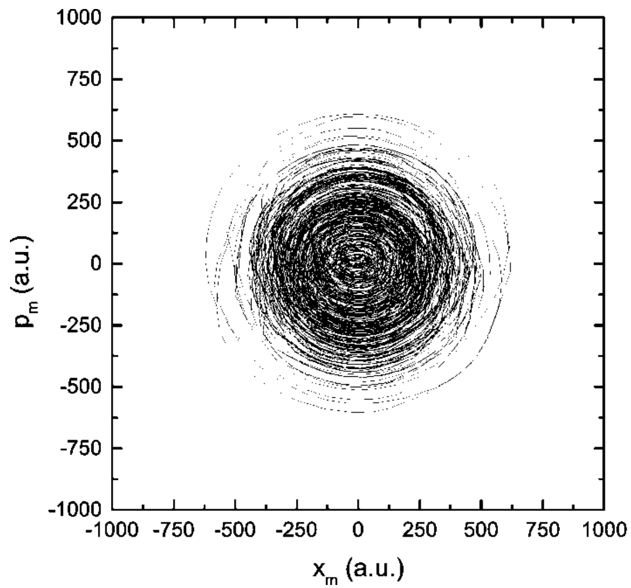
Wieczorek, Hofer, Hoelscher-Obermaier, Hammerer, Aspelmeyer, et al. in preparation

Estimated mechanical and optical quadratures $X(t)=(x_m(t),p_m(t),x_c(t),y_c(t))^T$

weak coupling





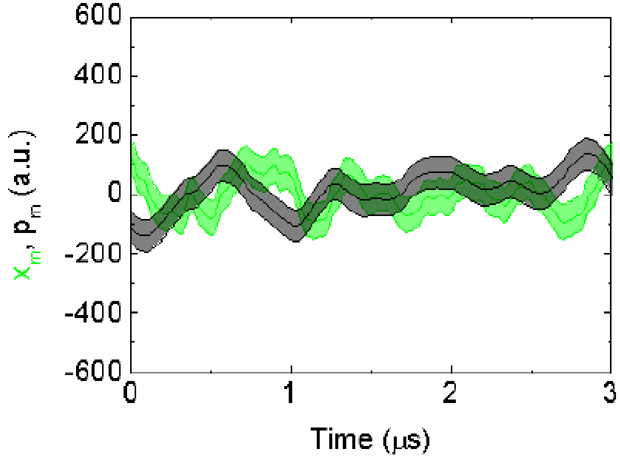


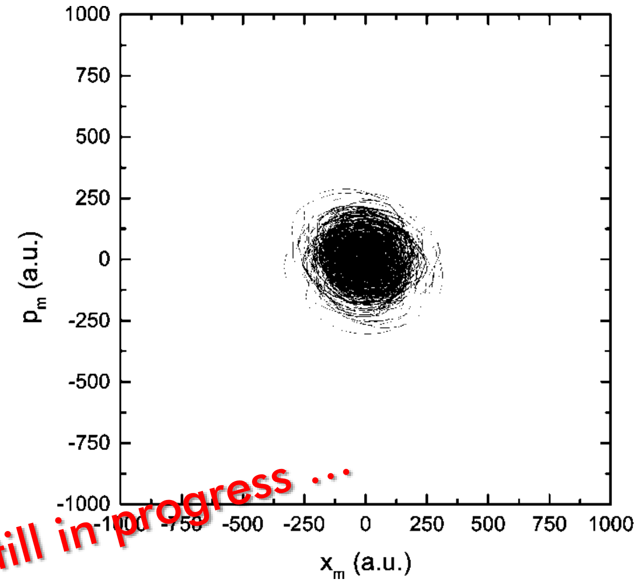
Wieczorek, Hofer, Hoelscher-Obermaier, Hammerer, Aspelmeyer, et al. in preparation

Estimated mechanical and optical quadratures $X(t)=(x_m(t),p_m(t),x_c(t),y_c(t))^T$

intermediate coupling

$g=0.86\kappa$

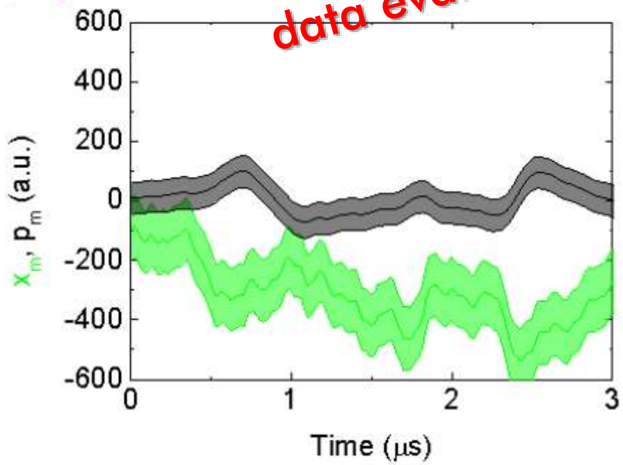


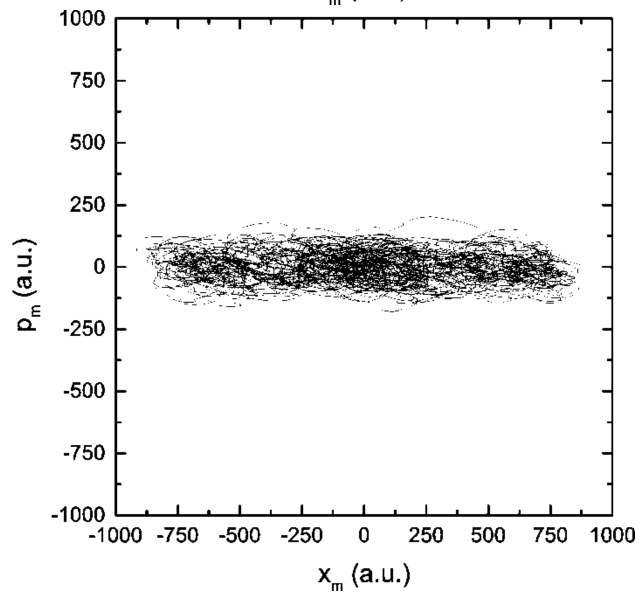


data evaluation still in progress ...

strong coupling

$g=1.6\kappa$

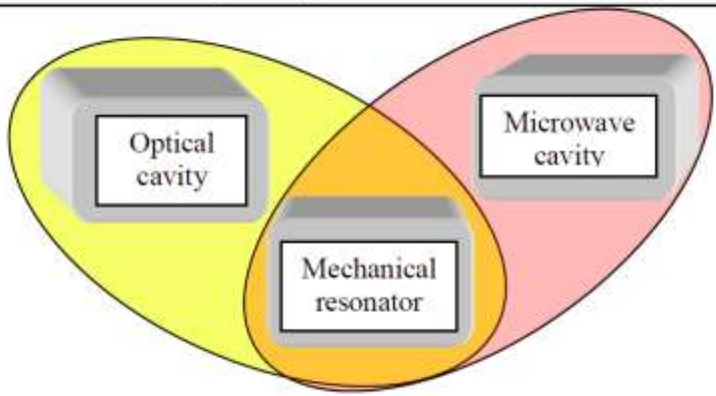




Wieczorek, Hofer, Hoelscher-Obermaier, Hammerer, Aspelmeyer, et al. in preparation

WP2: Photon-phonon interfaces

Main objective: implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons



Tasks:

Task 2.3: Optomechanical Correlations and Photon-Phonon Conversion

Task 2.4: Strong Optomechanical Coupling for Single Photons

Deliverables:

D2.3 Detection of optomechanical correlations by means of quantum filtering techniques (Month 24)

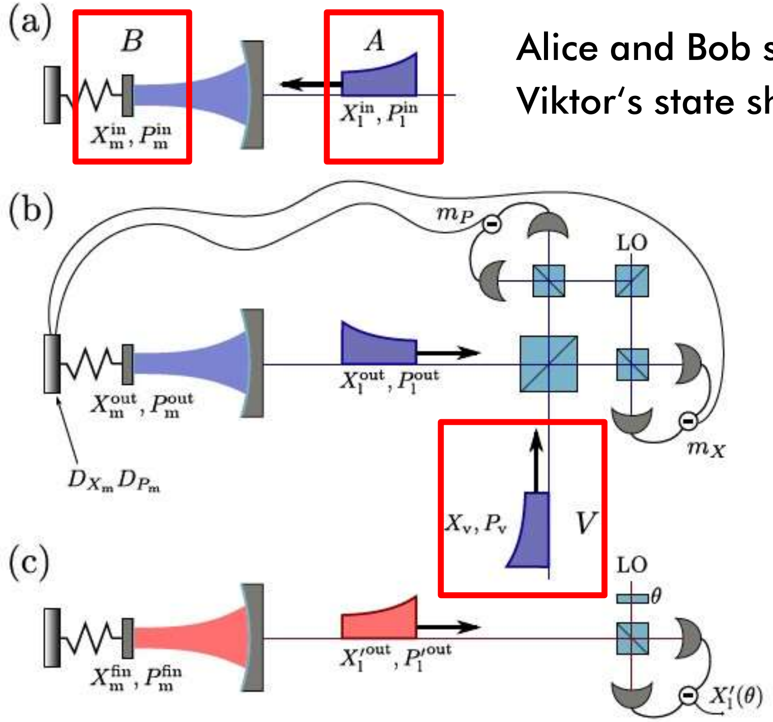
D2.4 Coherent photon-phonon conversion in an optomechanical system (Month 24)

D2.5 Demonstration of large single-photon optomechanical coupling rates (one order of magnitude improvement in g_0/κ) at cryogenic temperatures (Month 36)

Optomechanical teleportation

state transfer

Hofer, Wieczorek, Aspelmeyer, Hammerer, PRA 84 (2011)
Entanglement part: Palomaki et al., Science (2013)



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

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References

Levitated Nanoparticles and Foundations of Quantum Physics

Kiesel, Blaser, Delic, Grass, Kaltenbaek, Aspelmeyer, PNAS USA (2013):
Cavity cooling of an optically levitated nanoparticle
Kaltenbaek, Hechenblaikner, Kiesel, Romero-Isart, Schwab, Johann, Aspelmeyer, Exp. Astron. (2012):
Macroscopic quantum resonators (MAQRO)

Quantum Non-Demolition Measurements and Tests of Quantum Gravity

Vanner, Hofer, Cole, Aspelmeyer, Nature Communications (2013):
Cooling-by-measurement and mechanical state tomography via pulsed optomechanics
Pikovski, Vanner, Aspelmeyer, Kim, Brukner, Nature Physics (2012):
Probing Planck-scale physics with quantum optics

Solid-State Quantum Information Interfaces

Safavi-Naeini, Groeblacher, Hill, Chan, Aspelmeyer, Painter, Nature (2013):
Squeezed light from a silicon micromechanical resonator
Hofer, Vasilyev, Aspelmeyer, Hammerer, PRL 111 (2013):
Time-Continuous Bell Measurements
Hofer, Wieczorek, Aspelmeyer, Hammerer, PRA 84 (2011):
Quantum entanglement and teleportation in pulsed cavity optomechanics

Fundamentals of Low-Noise Mechanical Resonators and Optical Coatings
Cole, Zhang, Martin, Ye, Aspelmeyer, Nature Photonics (2013):
Tenfold reduction of Brownian noise in high-reflectivity optical coatings
Cole, Wilson-Rae, Werbach, Vanner, Aspelmeyer, Nature Communications (2011):
Phonon-tunnelling dissipation in mechanical resonators

Thank you for your attention!