The Abdus Salam
International Centre
for Theoretical Physics

2445-08

Advanced Workshop on Nanomechanics

9 - 13 September 2013

Measuring force sensitivity at the standard quantum limit

Sydney Schreppler
Ultracold Atomic Physics Group
UC Berkeley

Measuring force sensitivity at the standard quantum limit

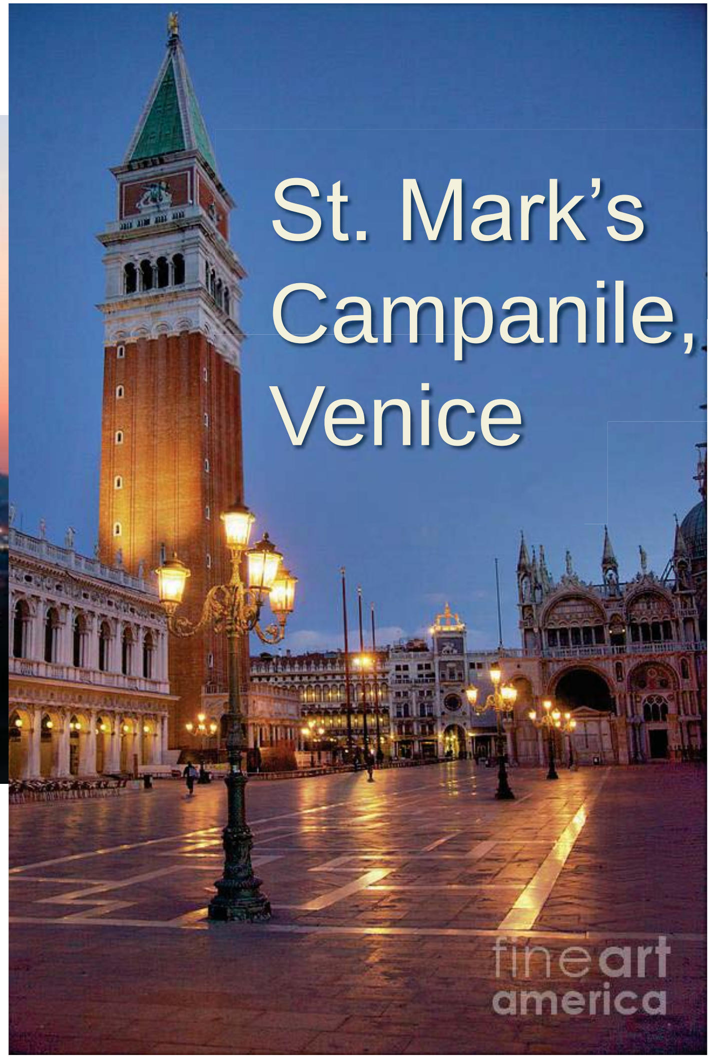
Sydney Schreppler

Ultracold Atomic Physics Group, UC Berkeley
PI: Dan Stamper-Kurn

ICTP Frontiers of Nanomechanics, 10 September, 2013

From Berkeley, CA to the ICTP

Sather Tower, Berkeley



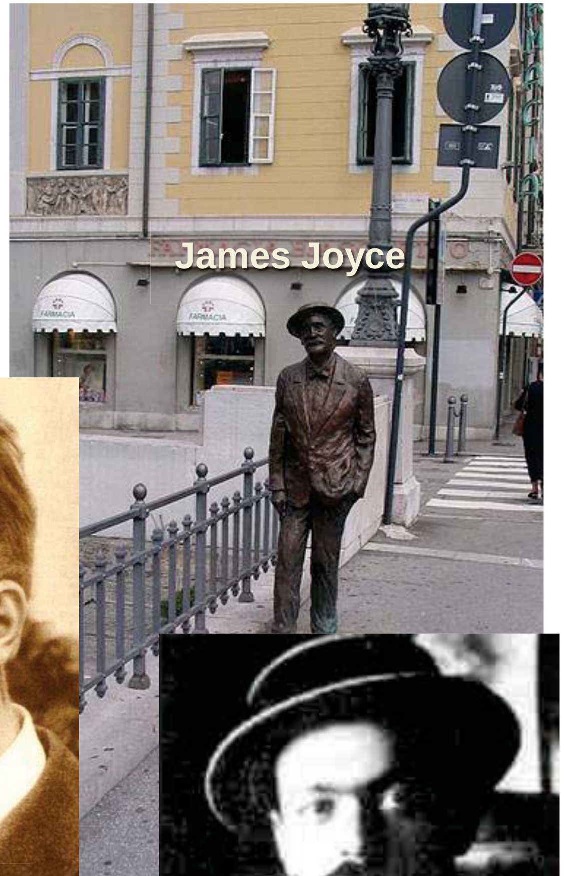
St. Mark’s Campanile, Venice

From Berkeley to the ICTP

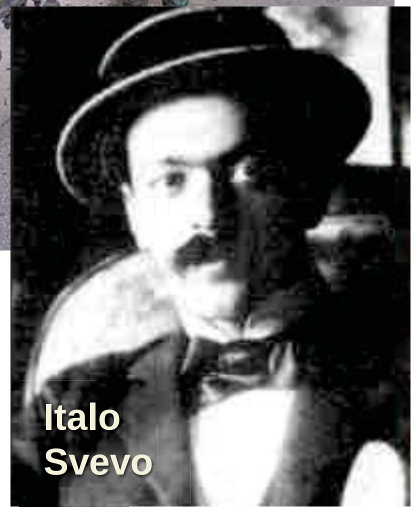
San Francisco, USA


Allen Ginsberg, Harold Norse, Jack Hirschman, Michael McClure & Bob Kaufman

Trieste, Italy


James Joyce


Rainer Maria Rilke

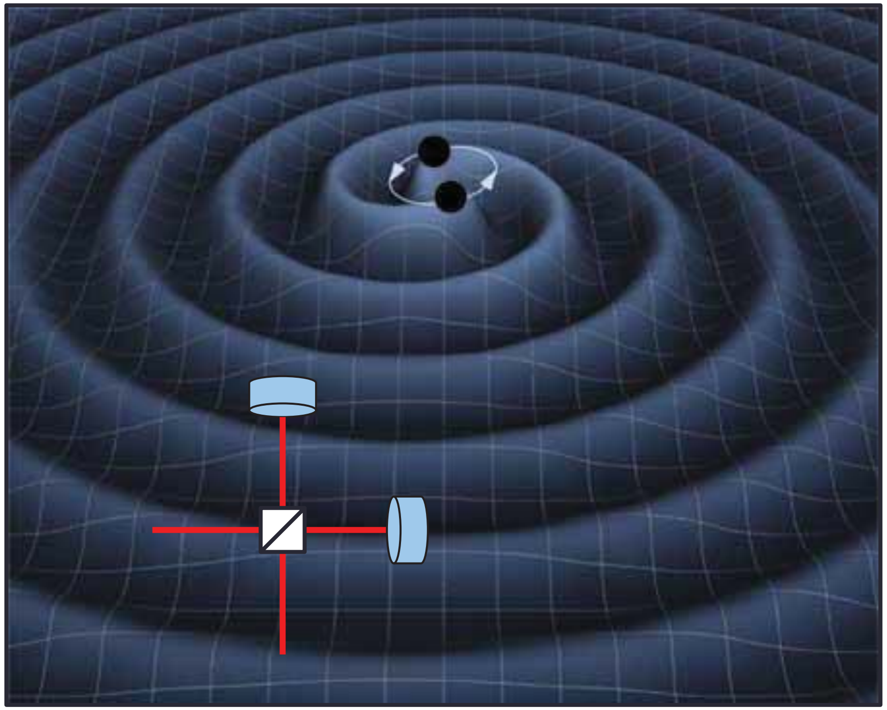

Italo Svevo

Summary

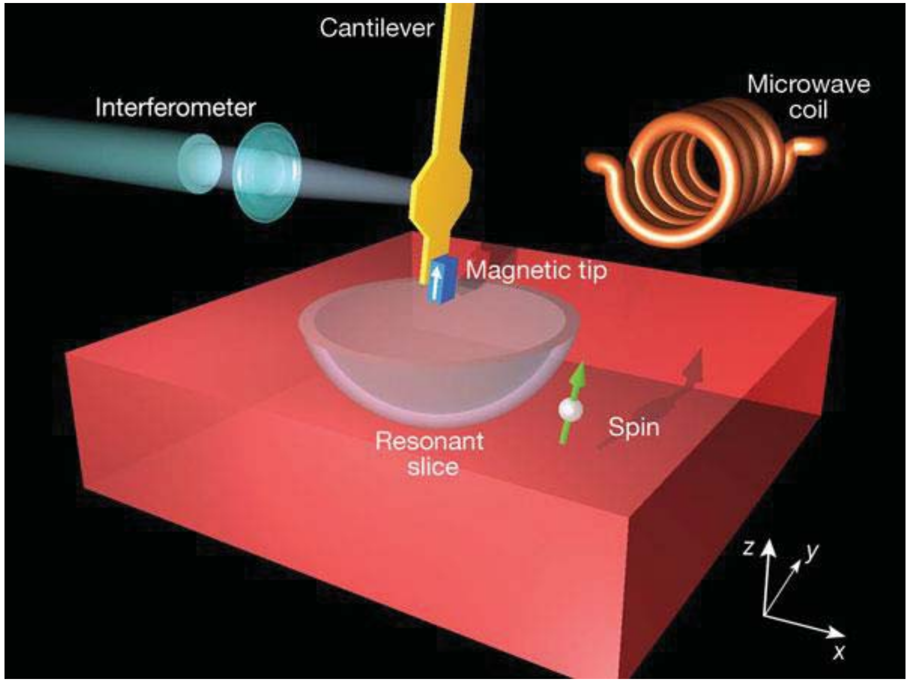
- Standard quantum limit
- Cold atoms for optomechanics
- Measuring force sensitivity
- The phase-space picture

Limits on measuring forces

Accuracy of measurement limited to zero-point-fluctuations in one damping period [see Clerk et al., RMP **82**, 1155 (2010)]

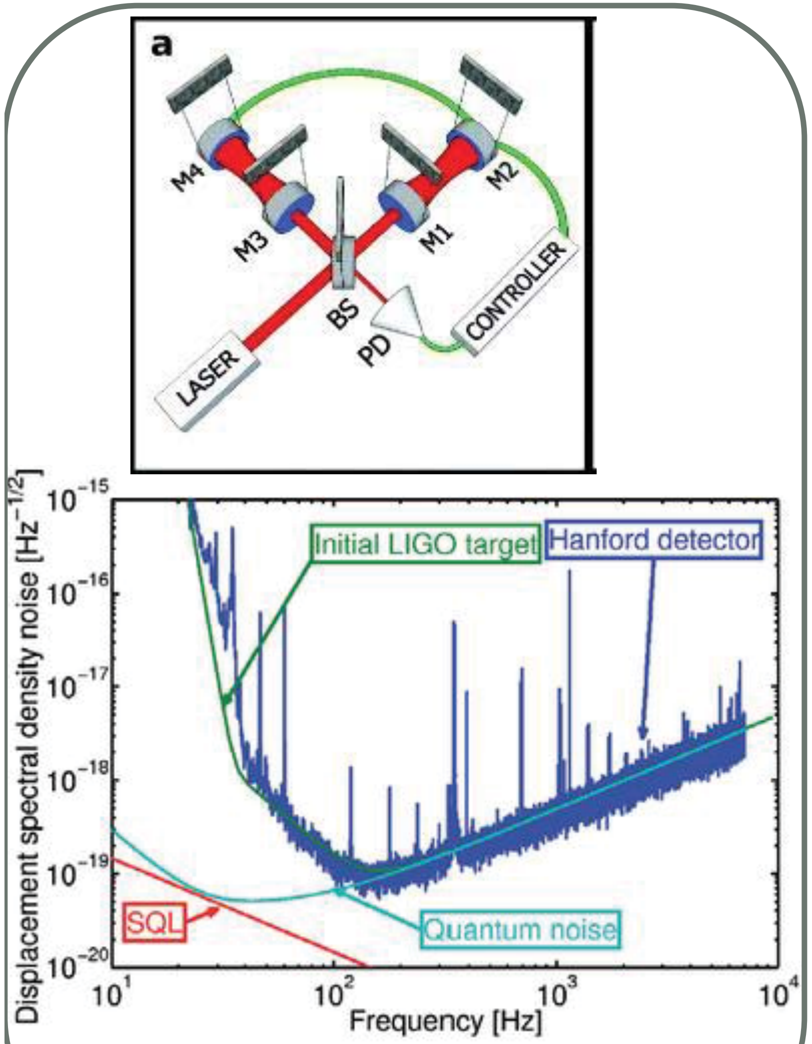


LIGO/VIRGO

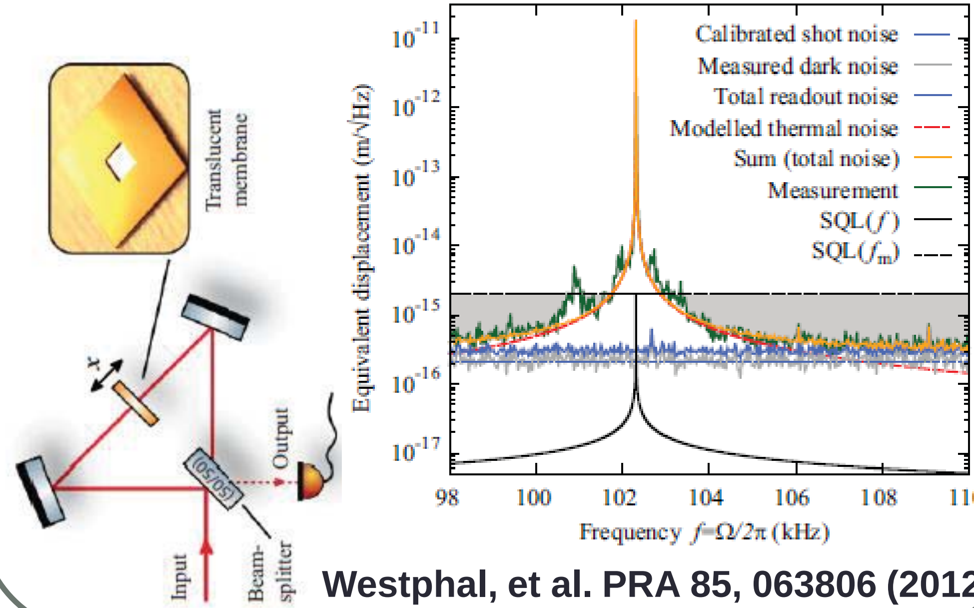


Single spin NMR
Rugar et al., Nature **430**, 329 (2004)

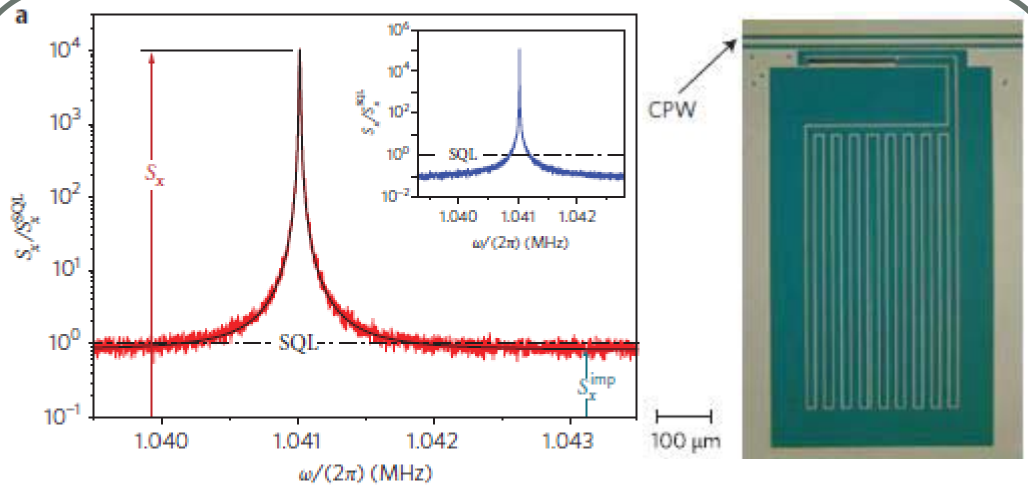
The effort so far



Abbott et al., NJP 11, 073032 (2009)

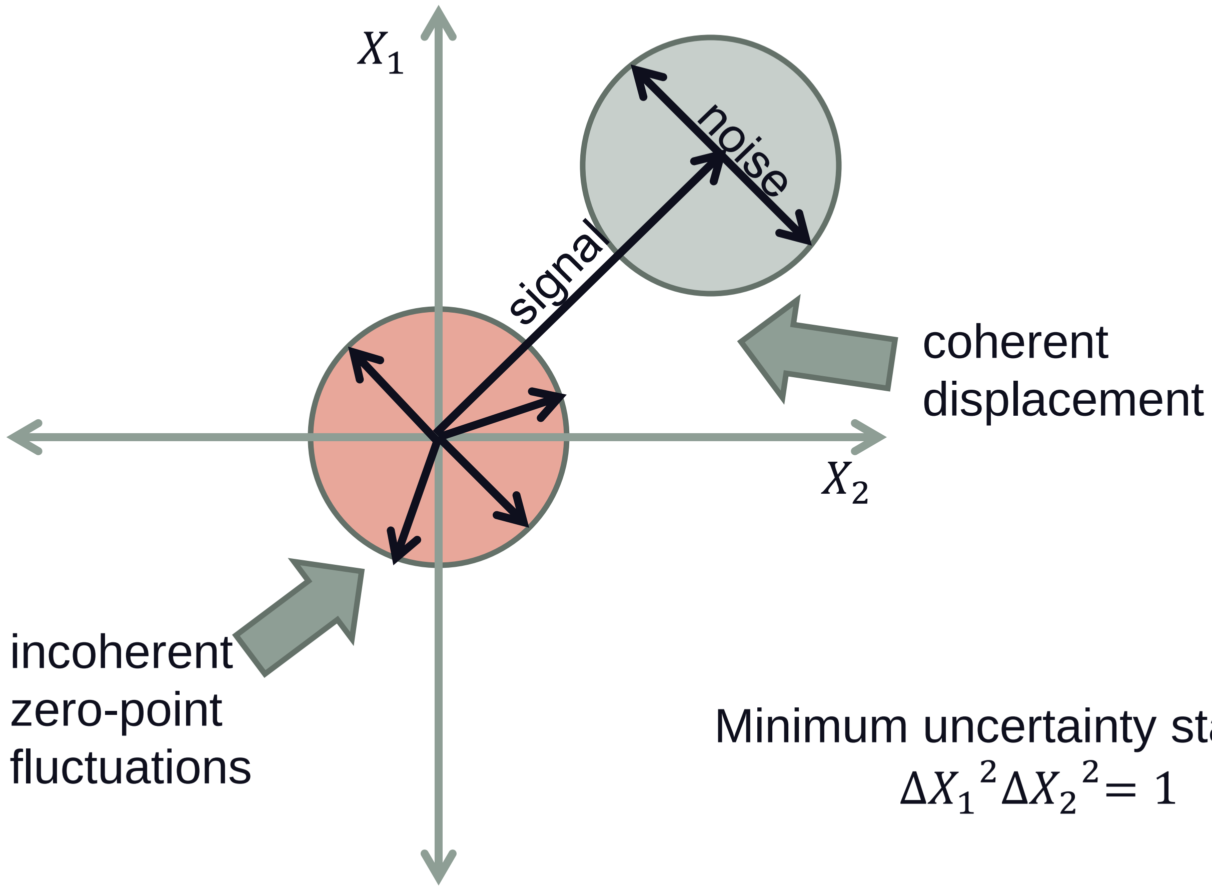


Westphal, et al. PRA 85, 063806 (2012)



Teufel, et al. Nature Nano 4, 820 (2009)

Quadrature-sensitive measurement

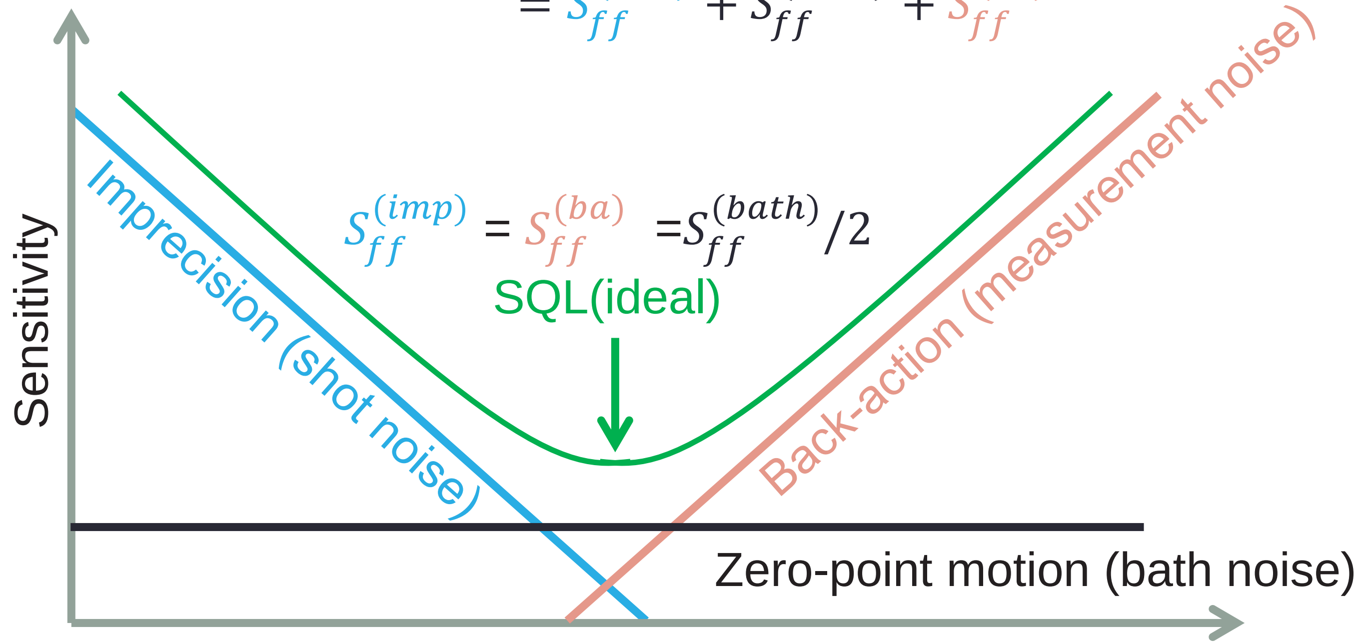


Minimum uncertainty state:

$$\Delta X_1{}^2 \Delta X_2{}^2 = 1$$

Standard quantum limit

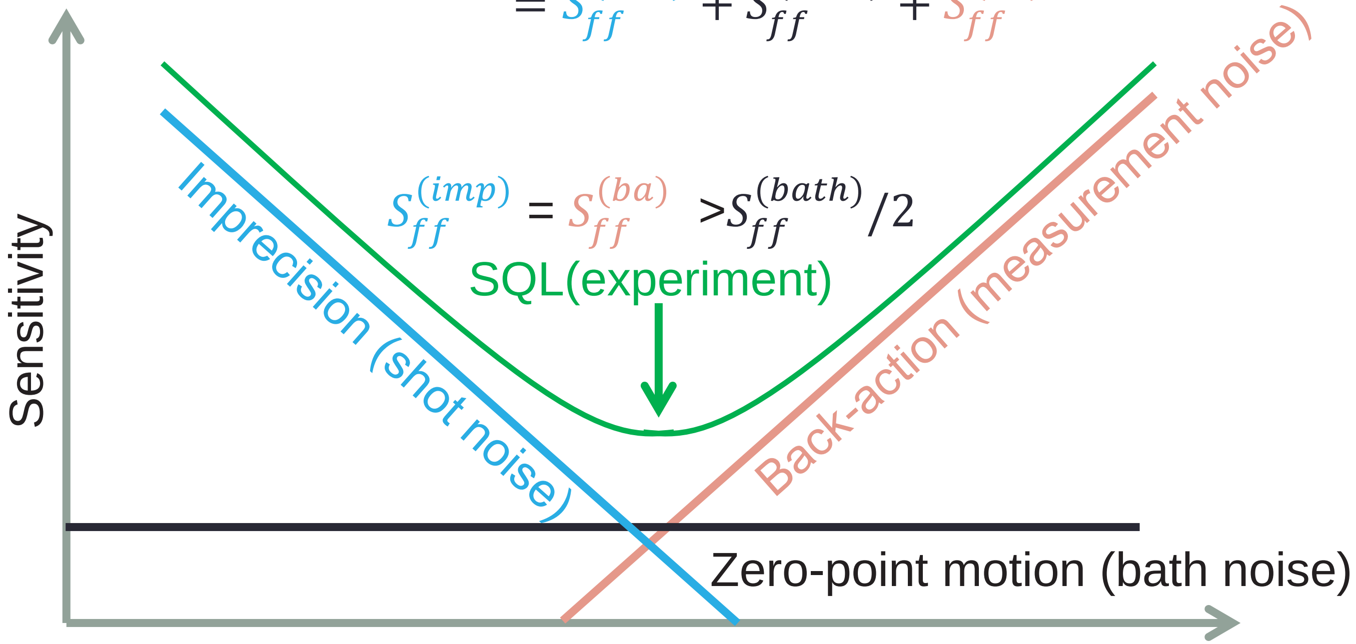
$$S_{ff}^{(tot)} = 2\Gamma {p_{HO}}^2 \left[\frac{1}{4\ C_{OM}} + 1 + C_{OM} \right]$$
$$= S_{ff}^{(imp)} + S_{ff}^{(bath)} + S_{ff}^{(ba)}$$



$$C_{OM} = \frac{4n{g_{OM}}^2}{\kappa\,\Gamma}$$

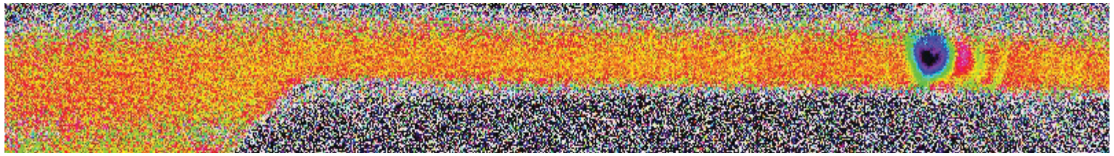
Standard quantum limit

$$S_{ff}^{(tot)} = 2\Gamma {p_{HO}}^2 \left[\frac{1}{4\epsilon C_{OM}} + 1 + C_{OM} \right]$$
$$= S_{ff}^{(imp)} + S_{ff}^{(bath)} + S_{ff}^{(ba)}$$



$$C_{OM} = \frac{4n{g_{OM}}^2}{\kappa\,\Gamma}$$

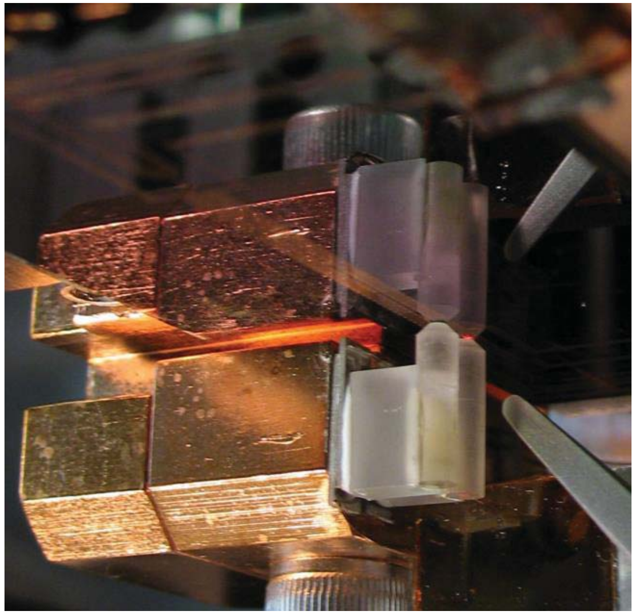
Cold atoms for optomechanics



- **Decoupling from environment**: atoms trapped in 845 nm standing-wave optical dipole trap

- **Dispersive measurement**: probe light is detuned from atomic transition at 780 nm by $\Delta_{CA} \gg \sqrt{N} g$
  - Atoms collectively shift cavity resonance $\Delta_N \propto g^2 \sin^2(kz)$

- **Mechanical ground state**: shot-noise limited probe allows interrogation with no added technical noise



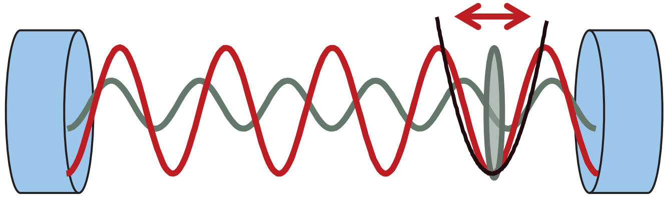
(images + apparatus construction credit: Tom Purdy!)

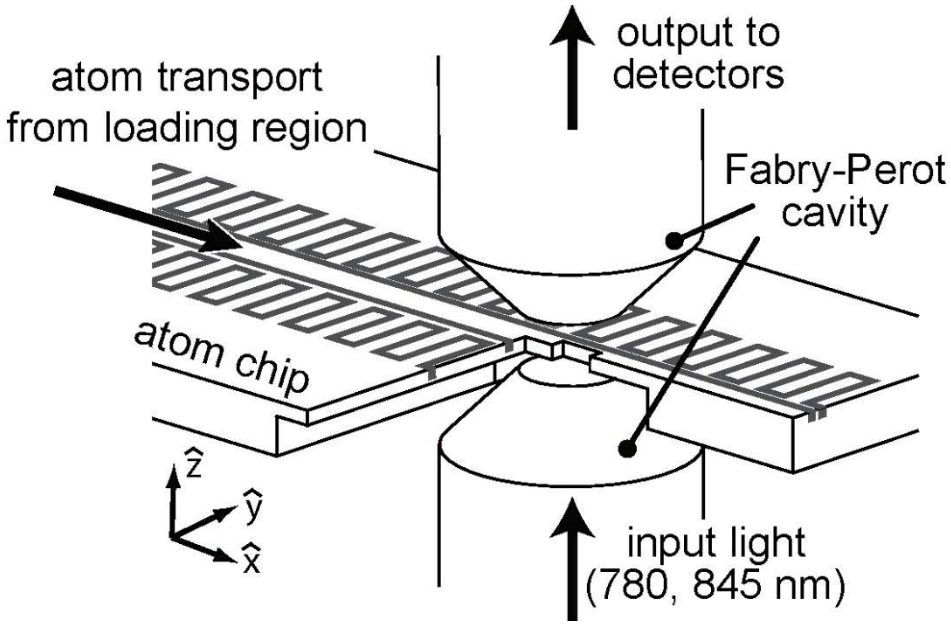
Cold atoms for optomechanics

- Atom chip allows precise cloud positioning
- Collective atomic motion = mechanical degree of freedom

$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b}$$

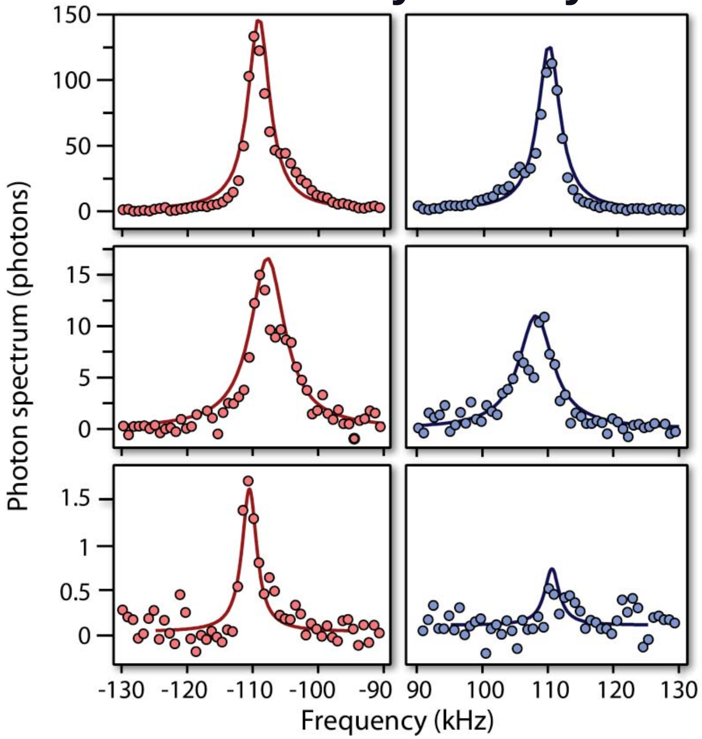
$$+\hbar g_{OM} \underbrace{(\hat{b} + \hat{b}^\dagger)}_{\hat{z}_{COM}} \underbrace{\hat{a}^\dagger \hat{a}}_{n}$$





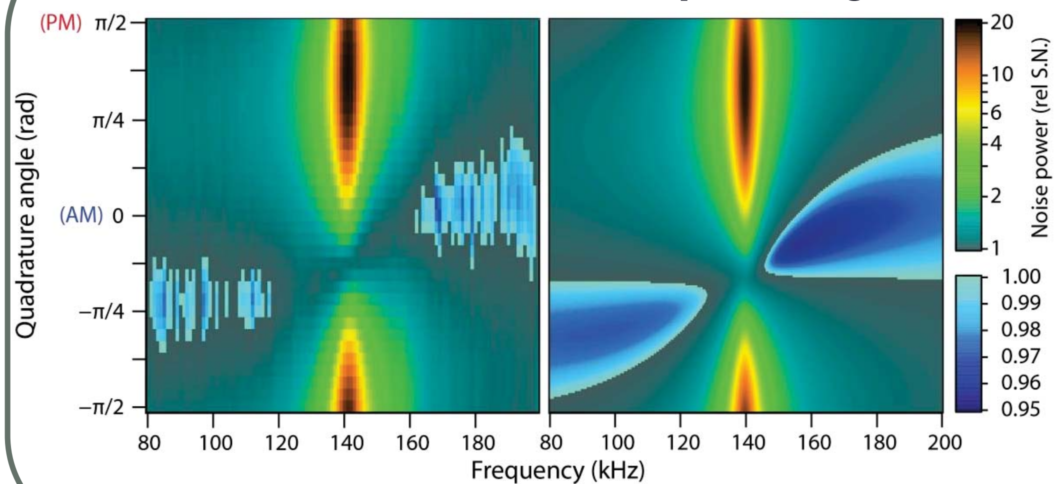
Cold atoms for optomechanics

Stokes Asymmetry



*Brahms et al., PRL **108**, 133601 (2012)*

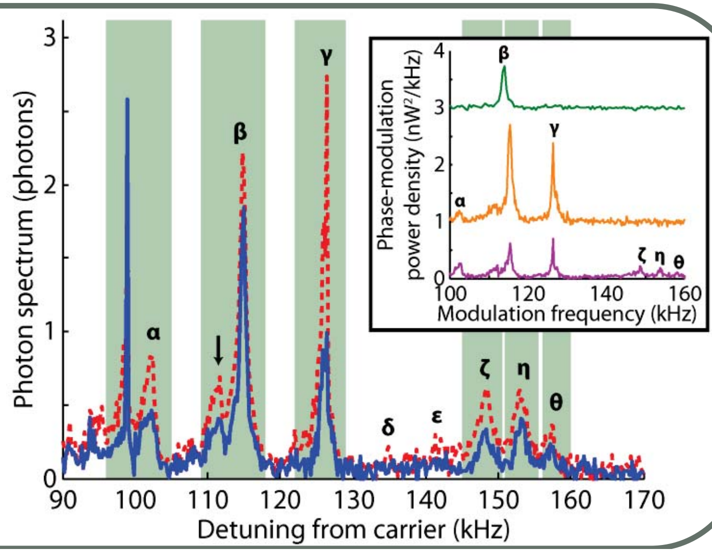
Ponderomotive squeezing



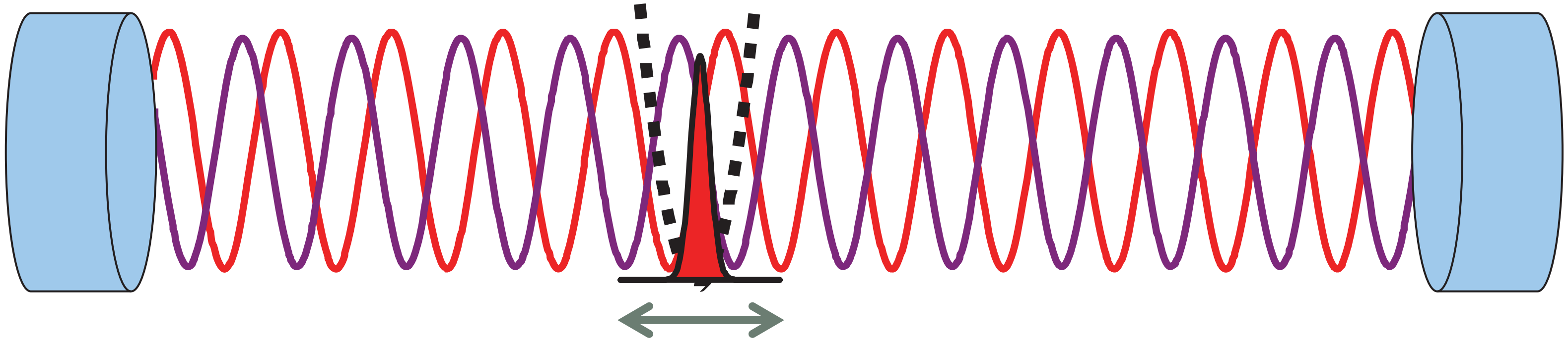
*Brooks et al., Nature **488**, 476 (2012)*

Ground-state oscillator arrays

*Botter et al., PRL **110**, 153001 (2013).*



Applying a force

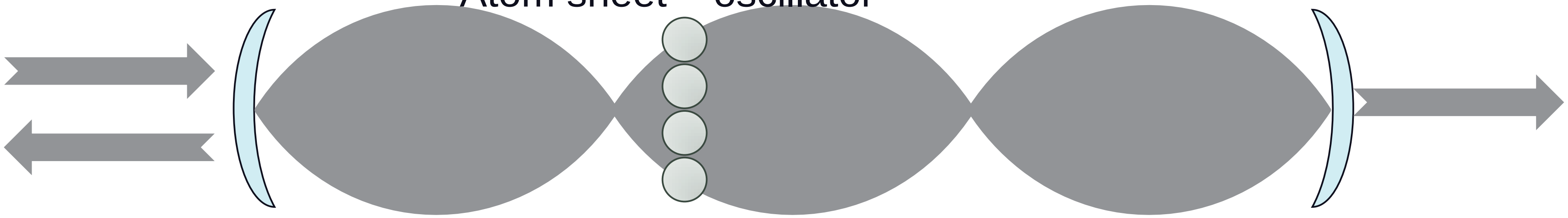


$$z = \chi_M(\omega) F_{ext}(\omega)$$

- AC trap intensity modulation shifts atoms center-of-mass

$$\frac{dz}{dF} = \chi_M(\omega) \cong \frac{1}{2M\omega_m} \frac{1}{-(|\omega| - \omega_m) - i\Gamma/2}$$

Measuring applied force

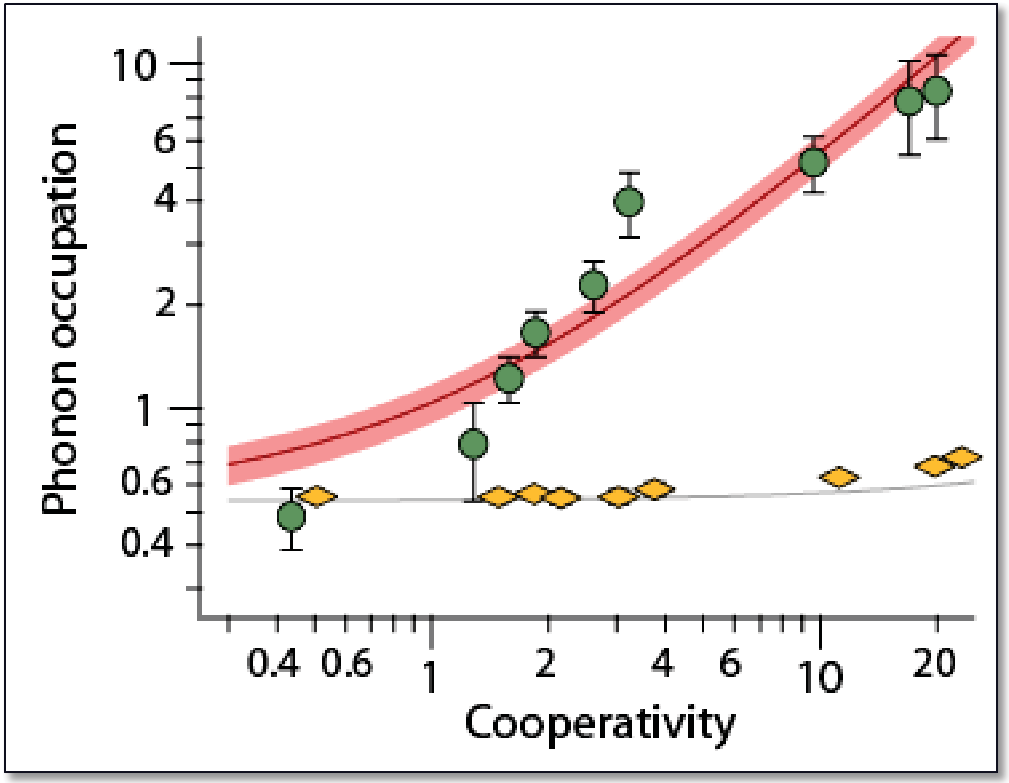


- On cavity resonance, atomic motion recorded in phase of probe

$$\phi = \frac{g_{OM}}{\kappa z_{HO}} z$$

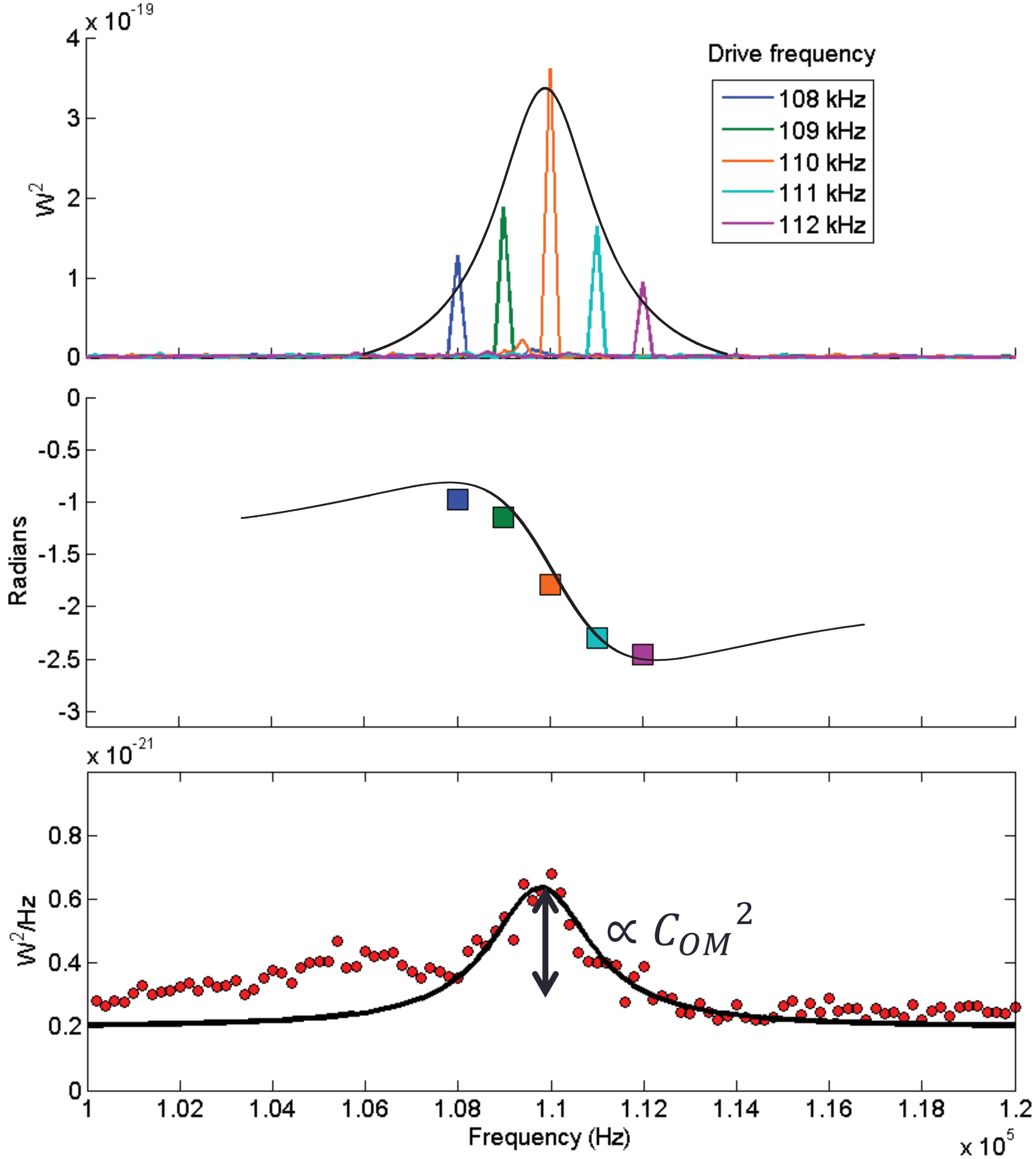
- Measurement produces back-action

$$H_{int} = \underbrace{\hbar g_{OM}}_{\text{force per photon}} \hat{z}\hat{a}^{\dagger}\hat{a}$$



Measuring applied force

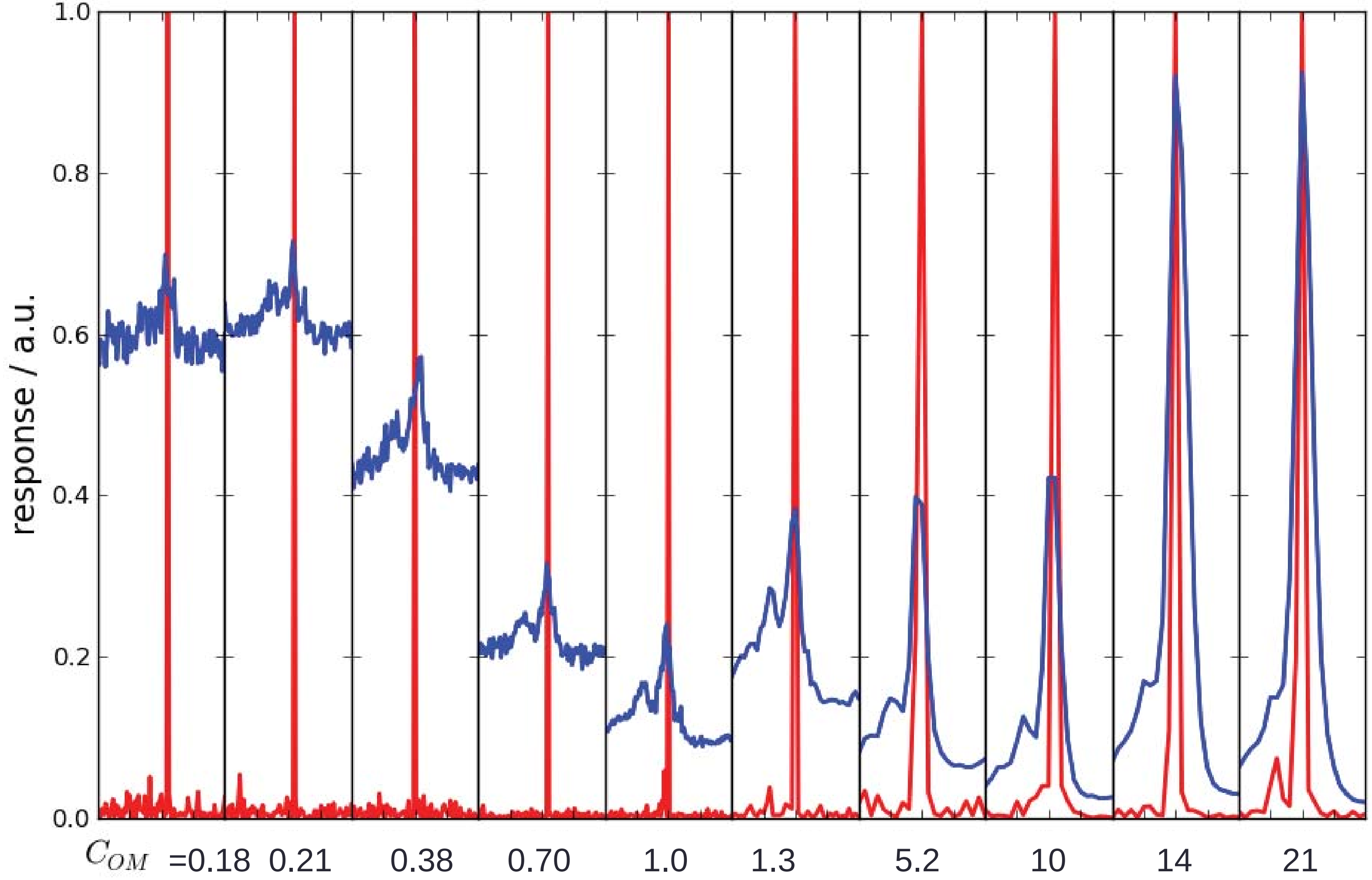
- Apply coherent classical force of fixed strength at incremental frequencies
- Coherent response = average Fourier transform at driven frequency
- Incoherent response = average noise power spectrum



Signal and noise spectra

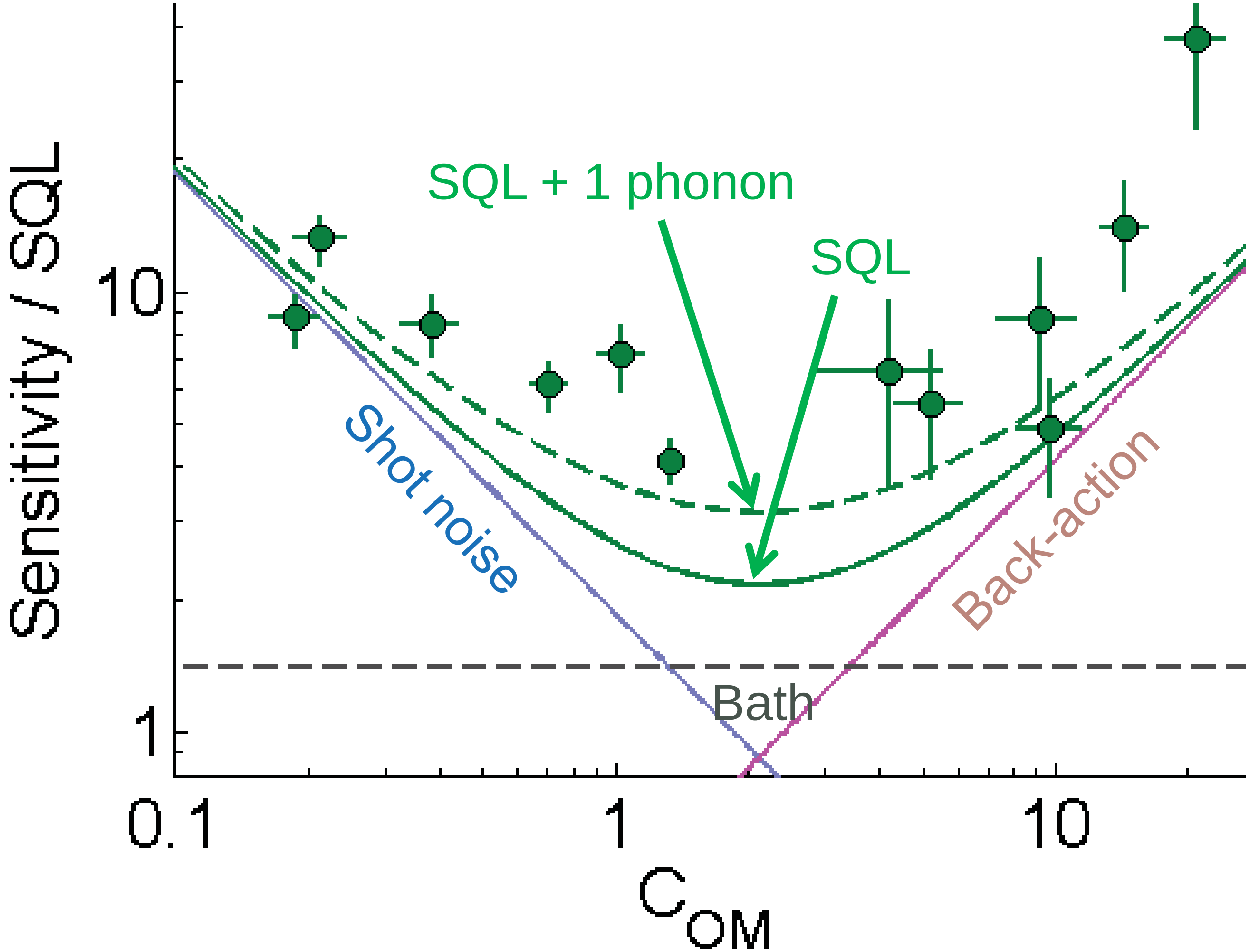
Normalized coherent response to constant applied force

Normalized noise spectrum x 140

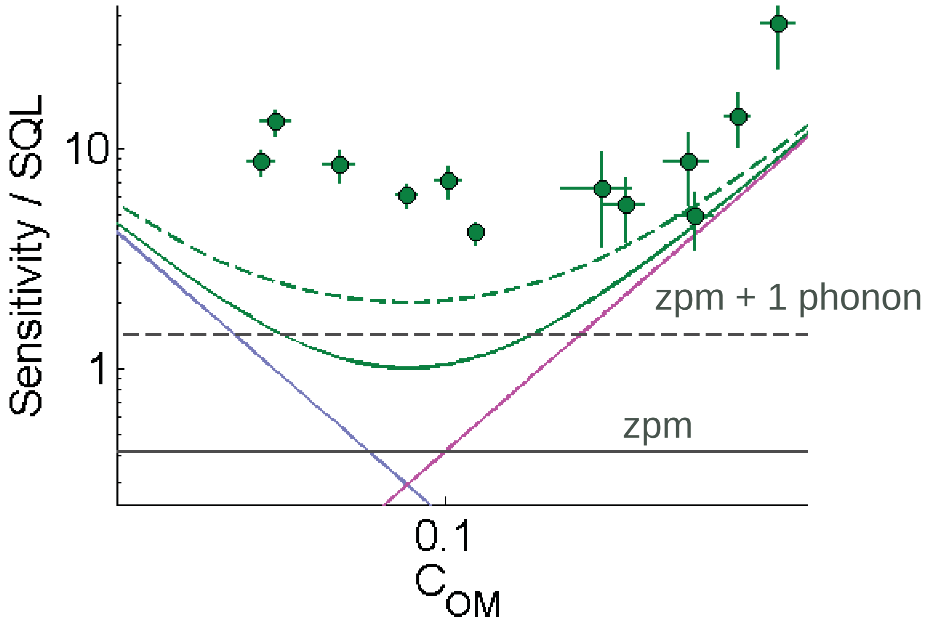


Measured sensitivity

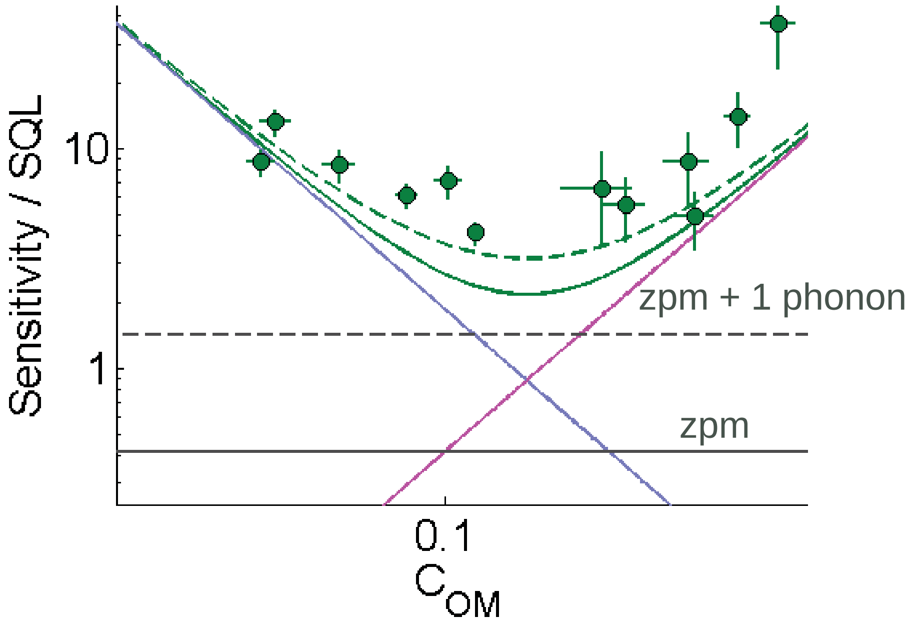
For typical oscillator,
$\sqrt{SQL} \approx 3 \times 10^{-23}\ N/\sqrt{Hz}$
$\approx 16\ m\,\mathrm{g}/\sqrt{Hz}$



Ideal vs. experimental SQL



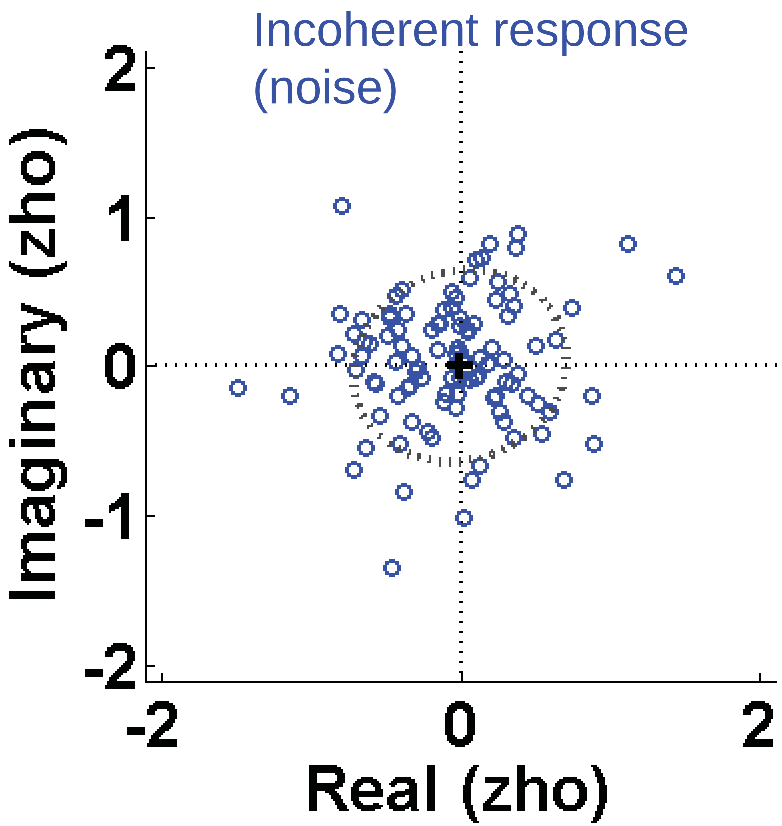
Perfect detection efficiency
$\epsilon \rightarrow 1$

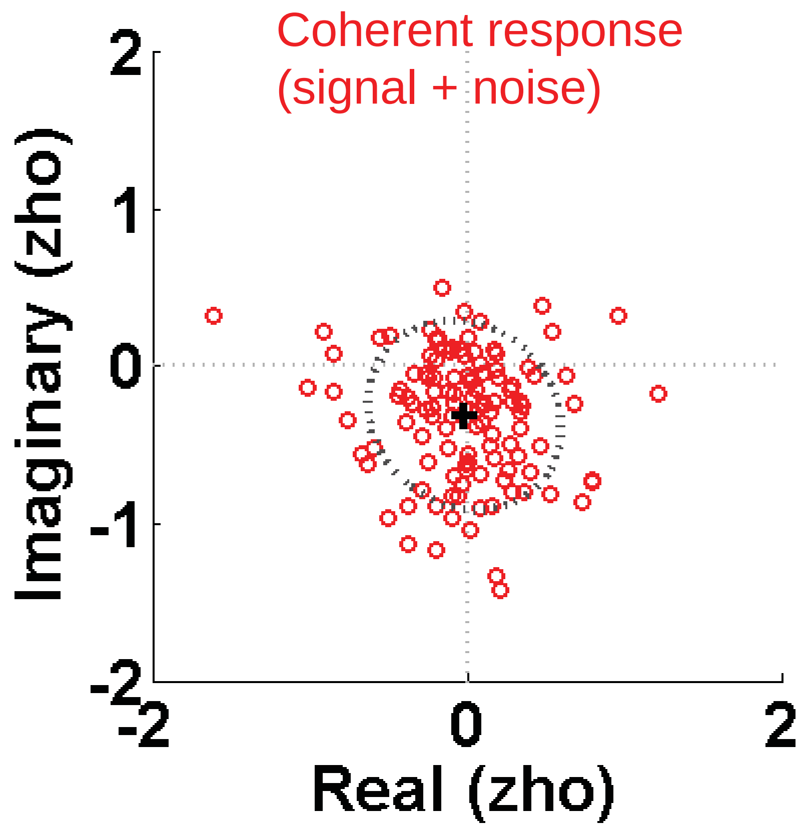


Actual detection efficiency
$\epsilon \rightarrow 0.12$

Phase-space response

Prepare and measure sample ~1000 times at each measurement strength

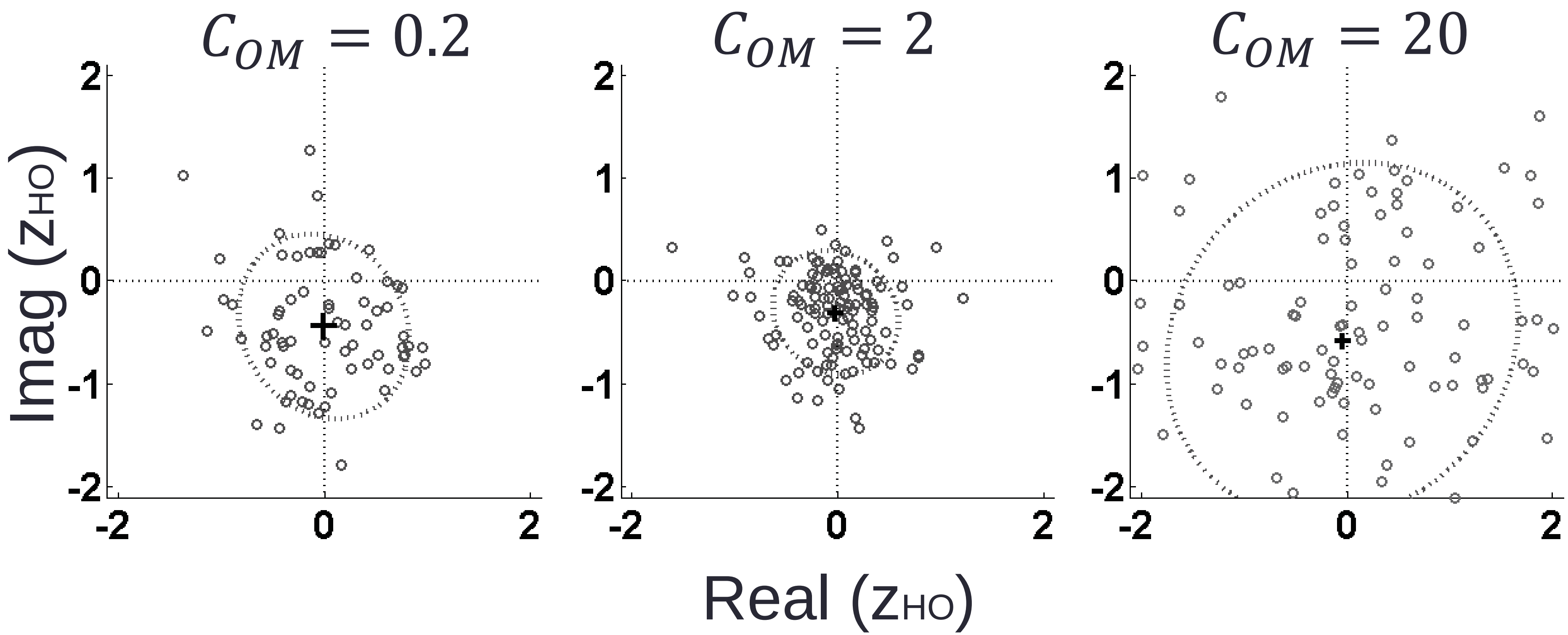




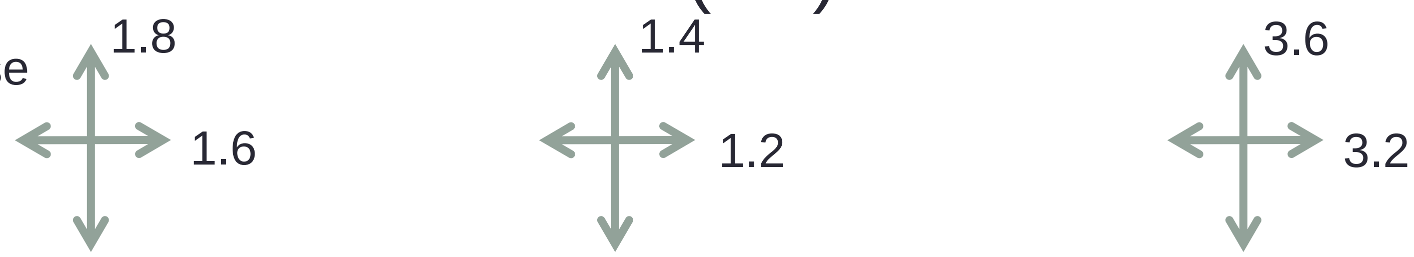
$$\Delta X_{Re}{}^2 \Delta X_{Im}{}^2 \geq \frac{1}{\epsilon \tau \gamma_m} \approx 1.3$$

Expect diameters of ~ 1.1 zho at SQL

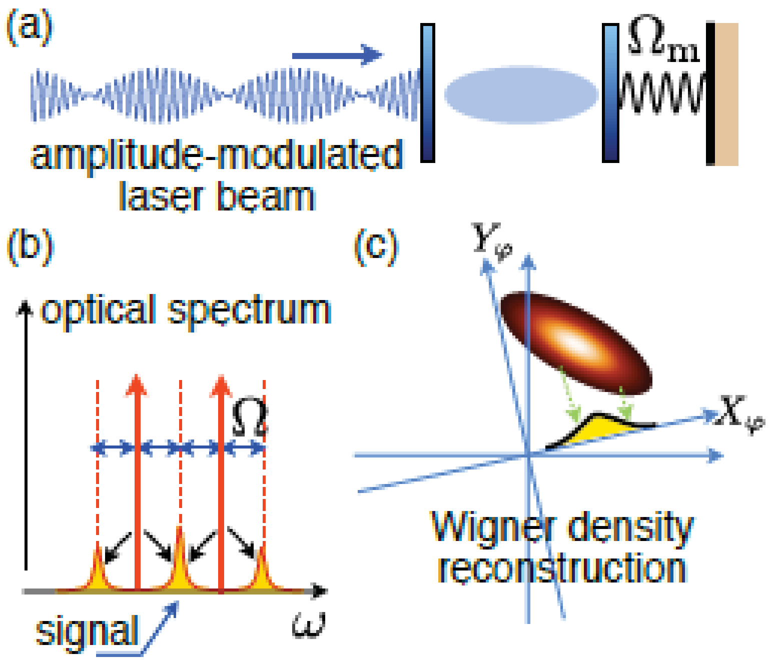
Phase-space response



1σ error ellipse axes
(units of z_{HO})



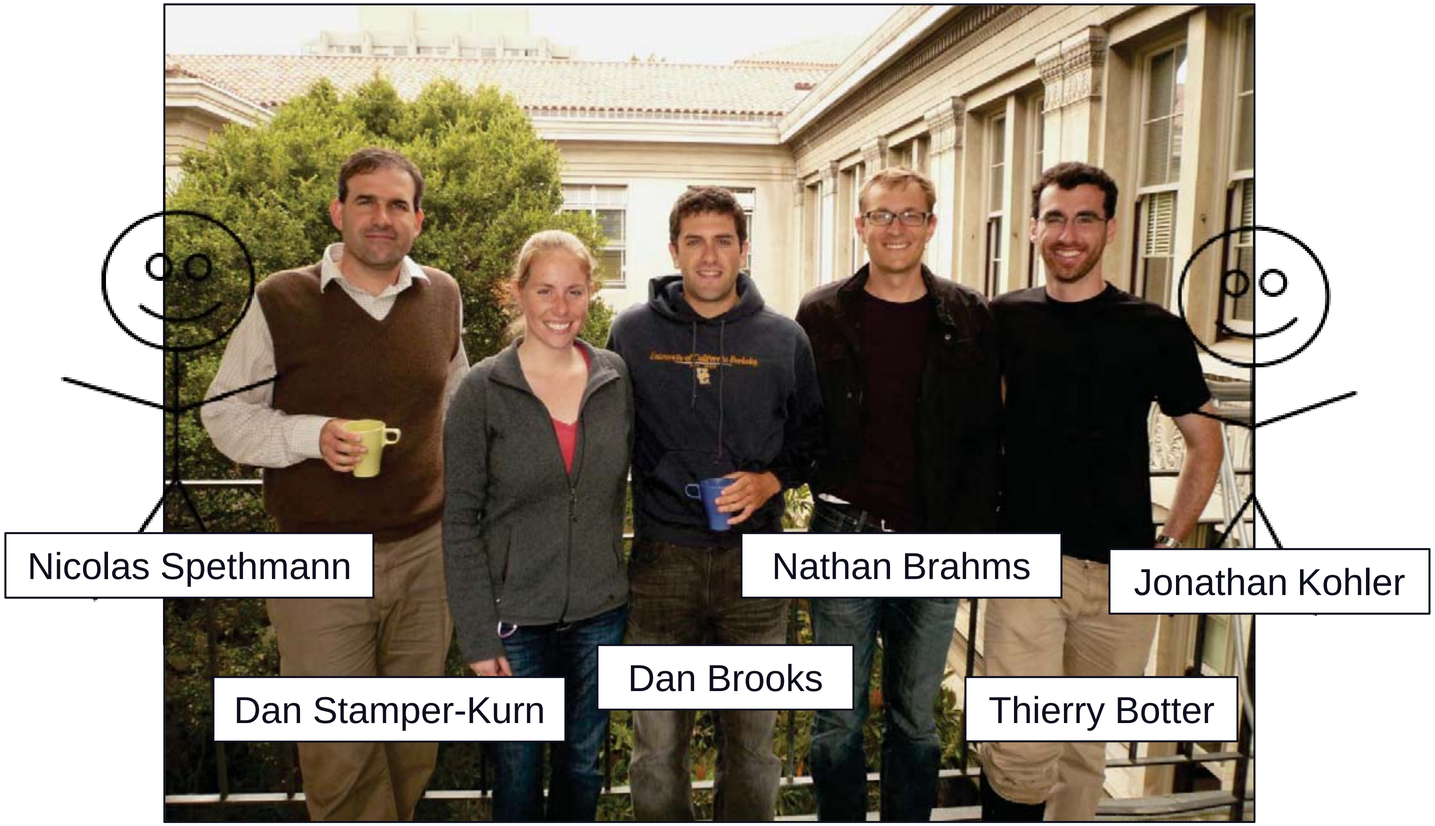
What's next



Stroboscopic QND measurements

Aspelmeyer et. al, arXiv:1303.0733v1 (2013)

Thanks to:


Nicolas Spethmann
Nathan Brahms
Jonathan Kohler
Dan Stamper-Kurn
Dan Brooks
Thierry Botter

Force calibration