Optomechanical quantum non-demolition measurement of optical field fluctuations

Antonio Pontin

Erice, 1 - 5 August 2016

Cavity opto-mechanics: why?

Unique capability to study the transition between classical and quantum mechanics…

- generation of squeezed light
- observation of the quantum states of a macroscopic mechanical oscillator
- quantum non demolition measurements of field quadratures
- creation of entangled states of light and one or more oscillators

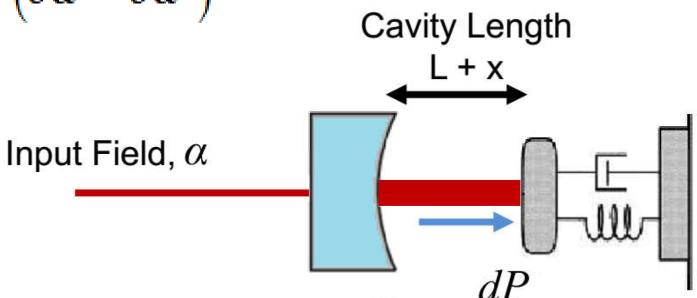
…but also useful sensors

Crucial properties:

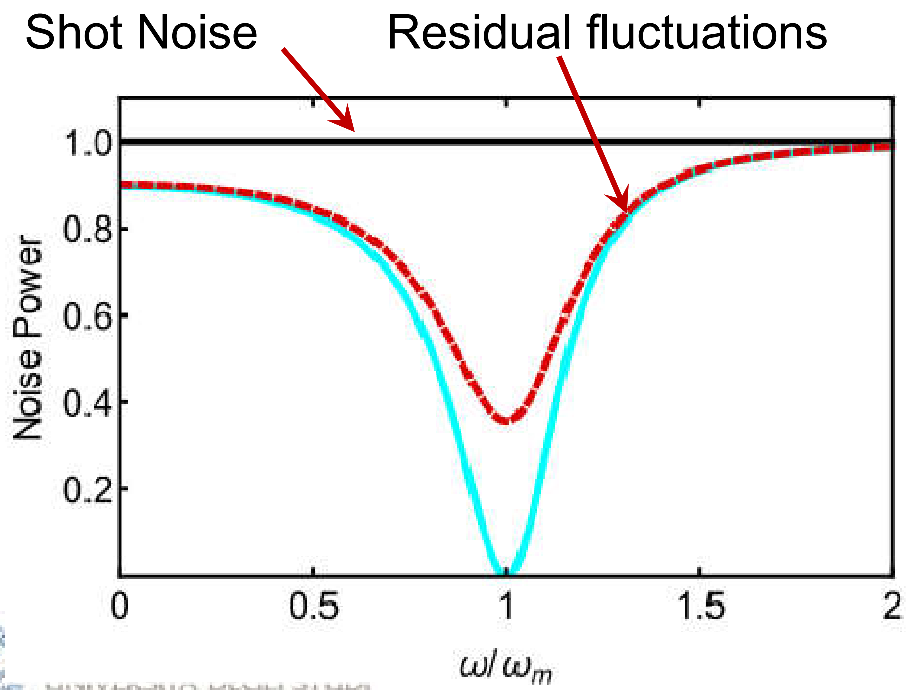
- low thermal noise → **high mechanical Q**
- high optical quality (cavity Finesse)

Ideal optomechanical QND

$$\delta X = \delta a^\dagger + \delta a$$
$$\delta Y = -i\left(\delta a - \delta a^\dagger\right)$$



$$F_{rad} \propto \frac{dP}{dL} x$$



<u>Amplitude quadrature (**Signal**)</u>

$$\delta X \longrightarrow \delta X$$

<u>Phase quadrature (**Meter**)</u>

$$\delta Y \longrightarrow \delta Y + \underbrace{\beta\, \delta X}_{\text{Back-action (RPSN)}} \pm \underbrace{\gamma\, \delta F_{th}}_{\text{Thermal noise}}$$

Quadratures are correlated

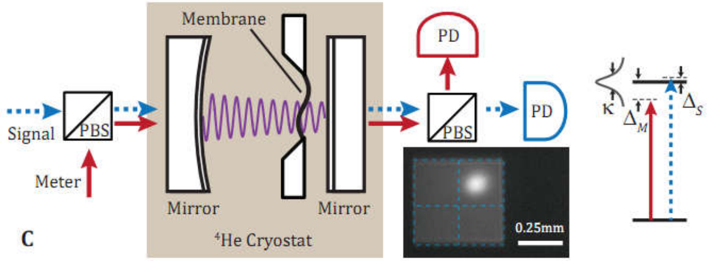
$$C_{XY} = \frac{|S_{XY}|^2}{S_{XX} S_{YY}} \neq 1$$

~~Perfect~~ QND

Science AAAS

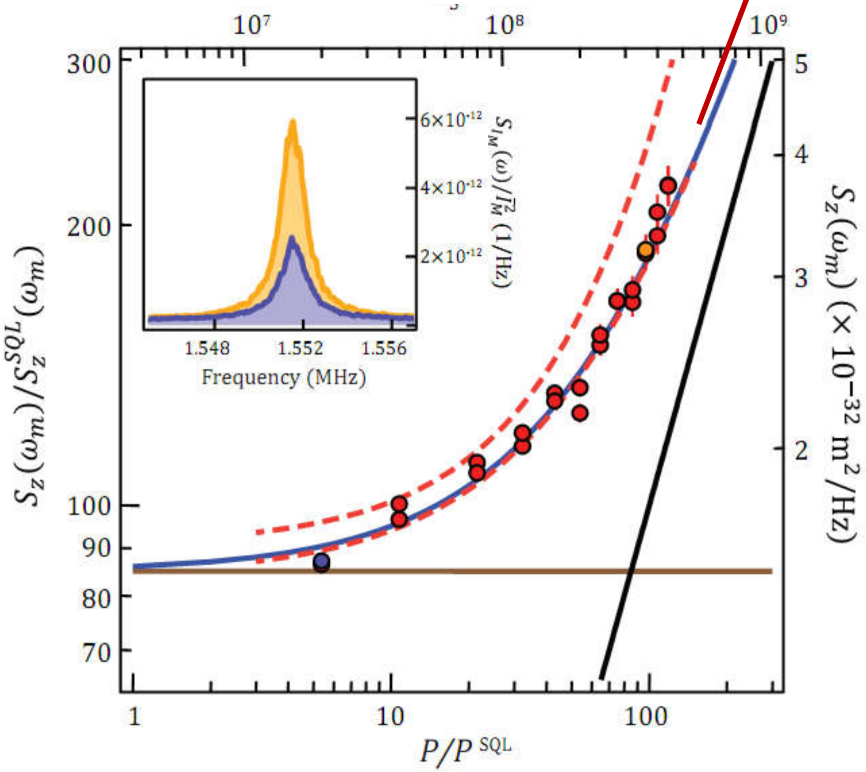
Observation of Radiation Pressure Shot Noise on a Macroscopic Object

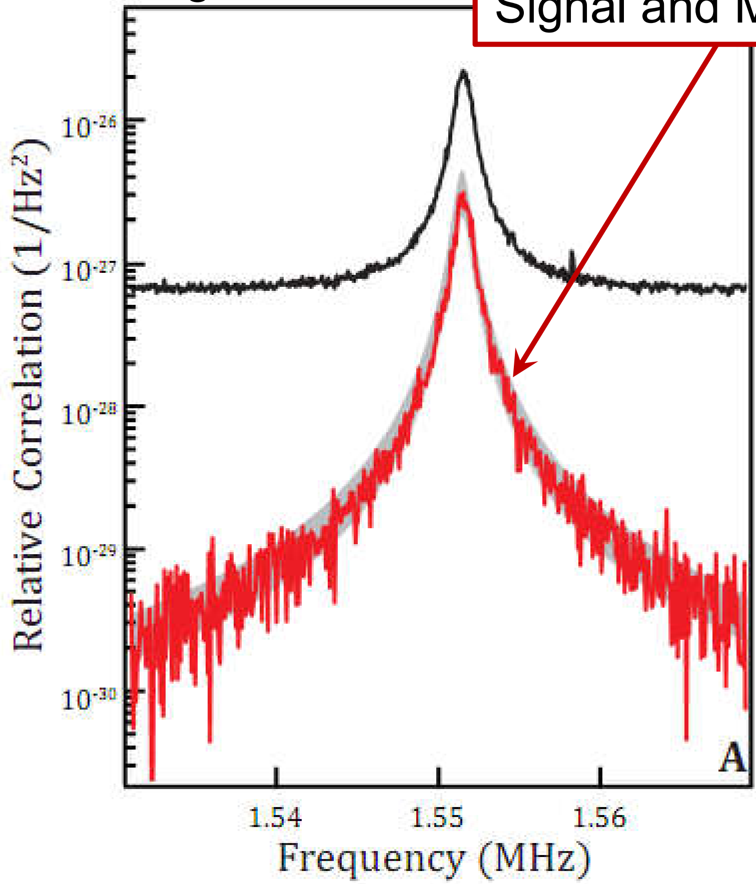
T.P. Purdy *et al*, Science **339**, 6121, 801 (2013)



Radiation Pressure induced heating

Correlation between Signal and Meter





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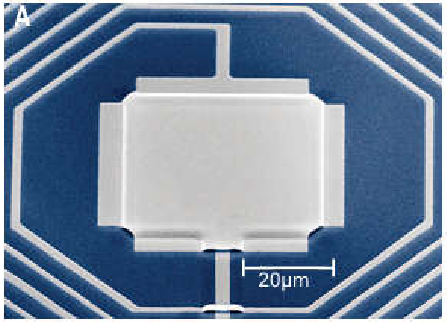
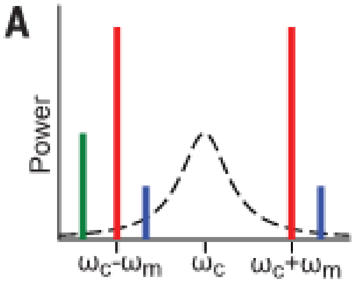
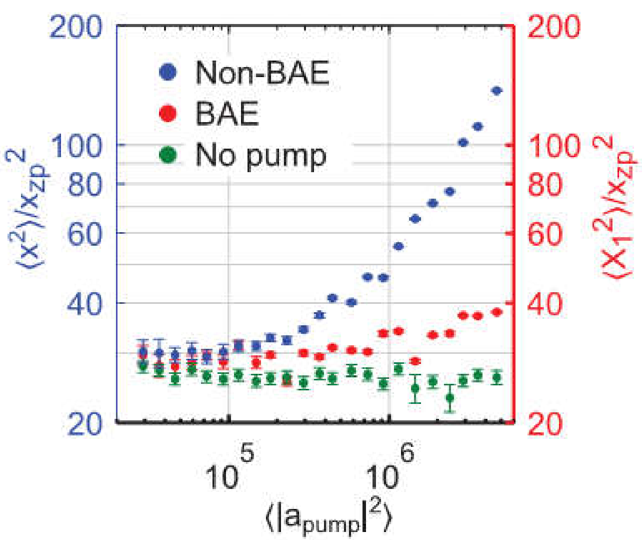
Mechanically detecting and avoiding the quantum fluctuations of a microwave field

J. Suh *et al*, Science **344**, 6189, 1262 (2014)



Two tones drive



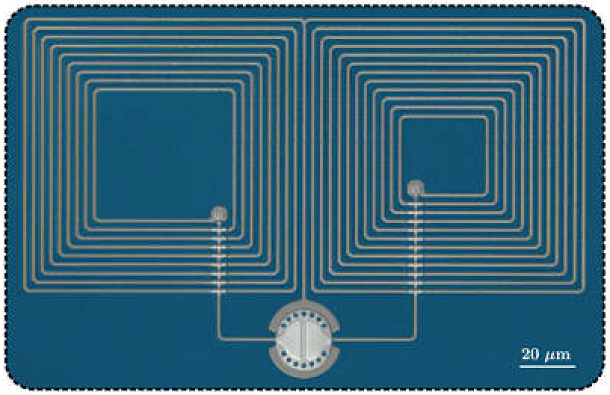


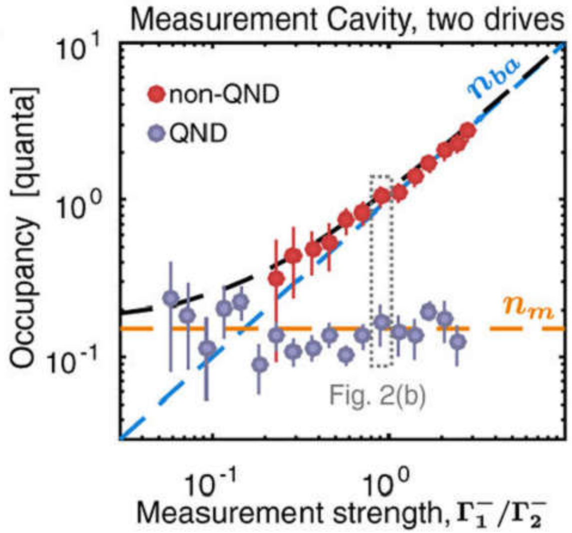
PHYSICAL REVIEW X

Quantum Nondemolition Measurement of a Nonclassical State of a Massive Object

F. Lecocq, J. B. Clark, R. W. Simmonds, J. Aumentado, and J. D. Teufe

Phys. Rev. X **5**, 041037 – Published 7 December 2015





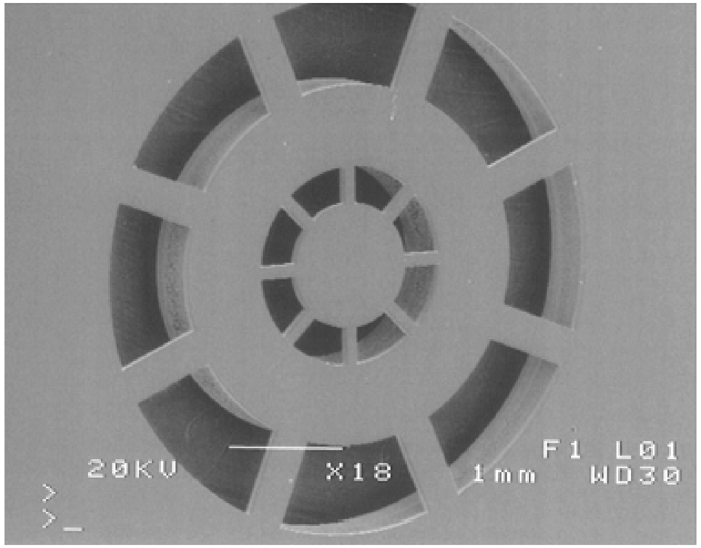
Both demonstrate a mechanical squeezed state

$$\frac{\langle X^2 \rangle}{\langle x_{zp}^2 \rangle} \sim 0.8$$

Outline

- Development of Micro Mechanical devices
- Experimental setup
- QND measurement of field quadratures

Micro-Mechanical devices



- SOI silicon wafer
- diameter of the central disk ~ 800-400 µm
- highly reflective coating Ta_2O_5/SiO_2
- external “wheel” oscillator for mechanical decoupling
- set of slightly different geometric parameters to cover a frequency range of 150 – 300 kHz

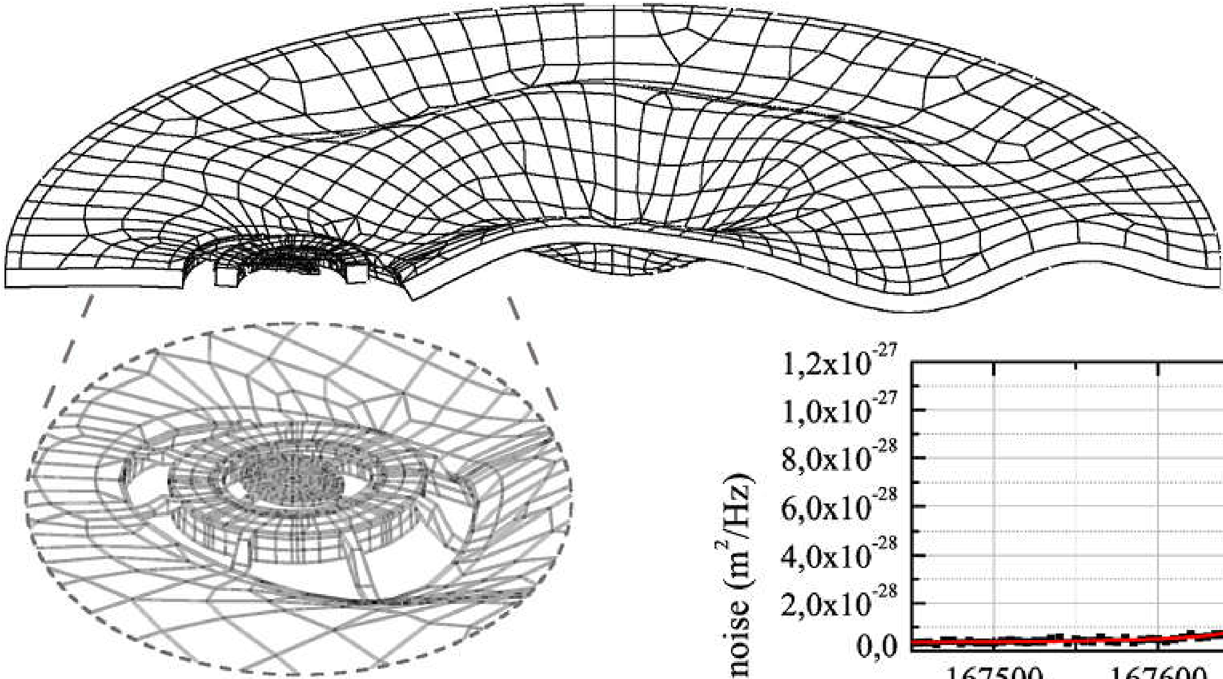
Understand (and reduce, where possible) every loss mechanism is crucial

Structural damping → Lattice imperfection
Bulk Si ϕ~ 10^{-9}
Coating ϕ~ (3-6) 10^{-4}

Thermoelastic damping → Elastic energy dissipated into heat

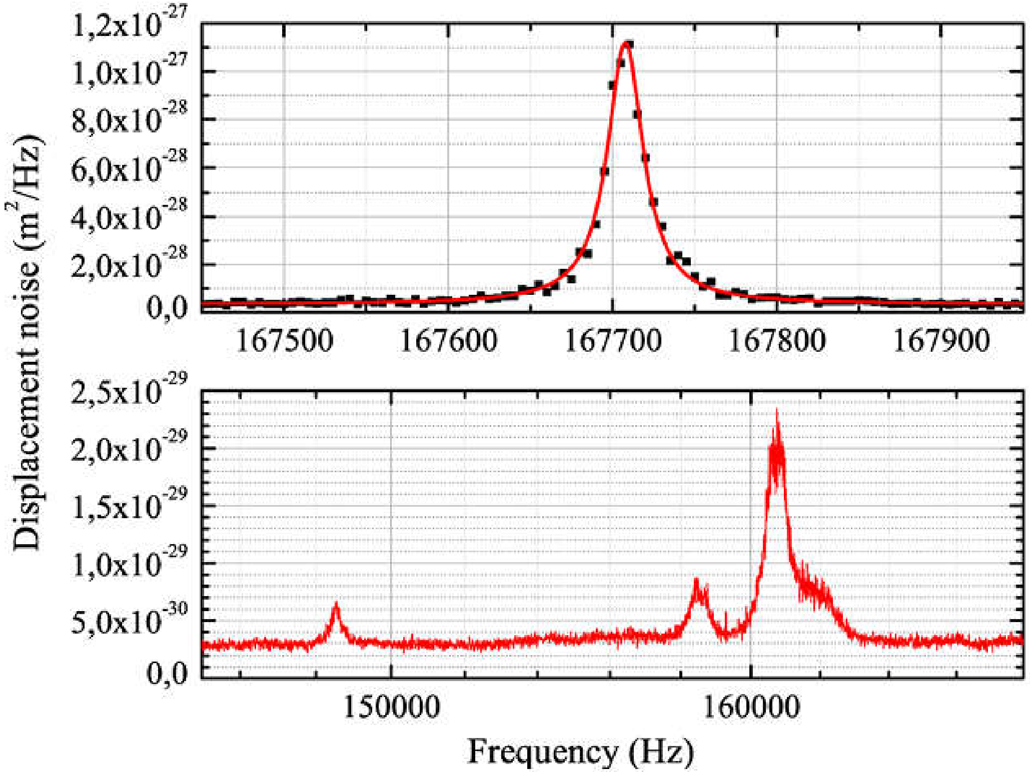
Coupling with a lossy environment

Decoupling wheel

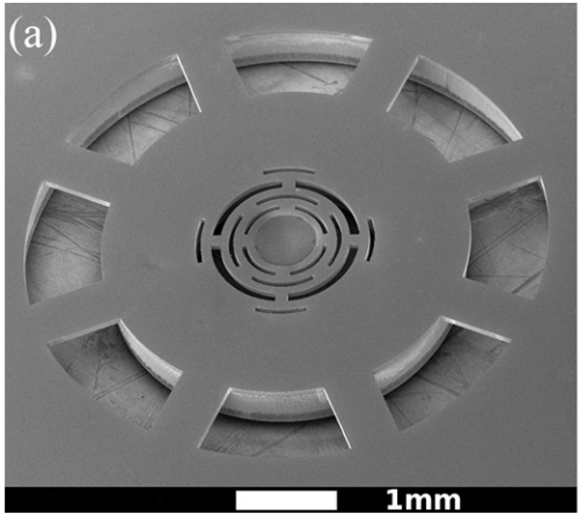


FEM simulation of
Micro-mirror + wafer

Without the external wheel there is mechanical coupling with low Q wafer modes

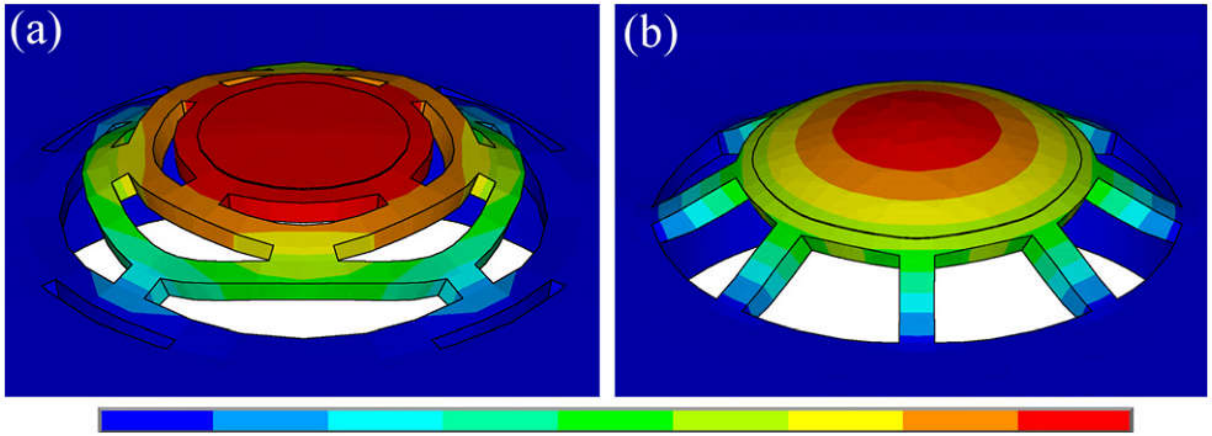


Low deformation micro-mirrors



Coating area reduced as much as possible

Succession of torsional and flexural beams to reduced as much as possible the deformation of the coating.



App.Phys.Lett. **101**, 071101 (2012)

UNIVERSITÀ DEGLI STUDI DI TRENTO

Università degli Studi di Firenze

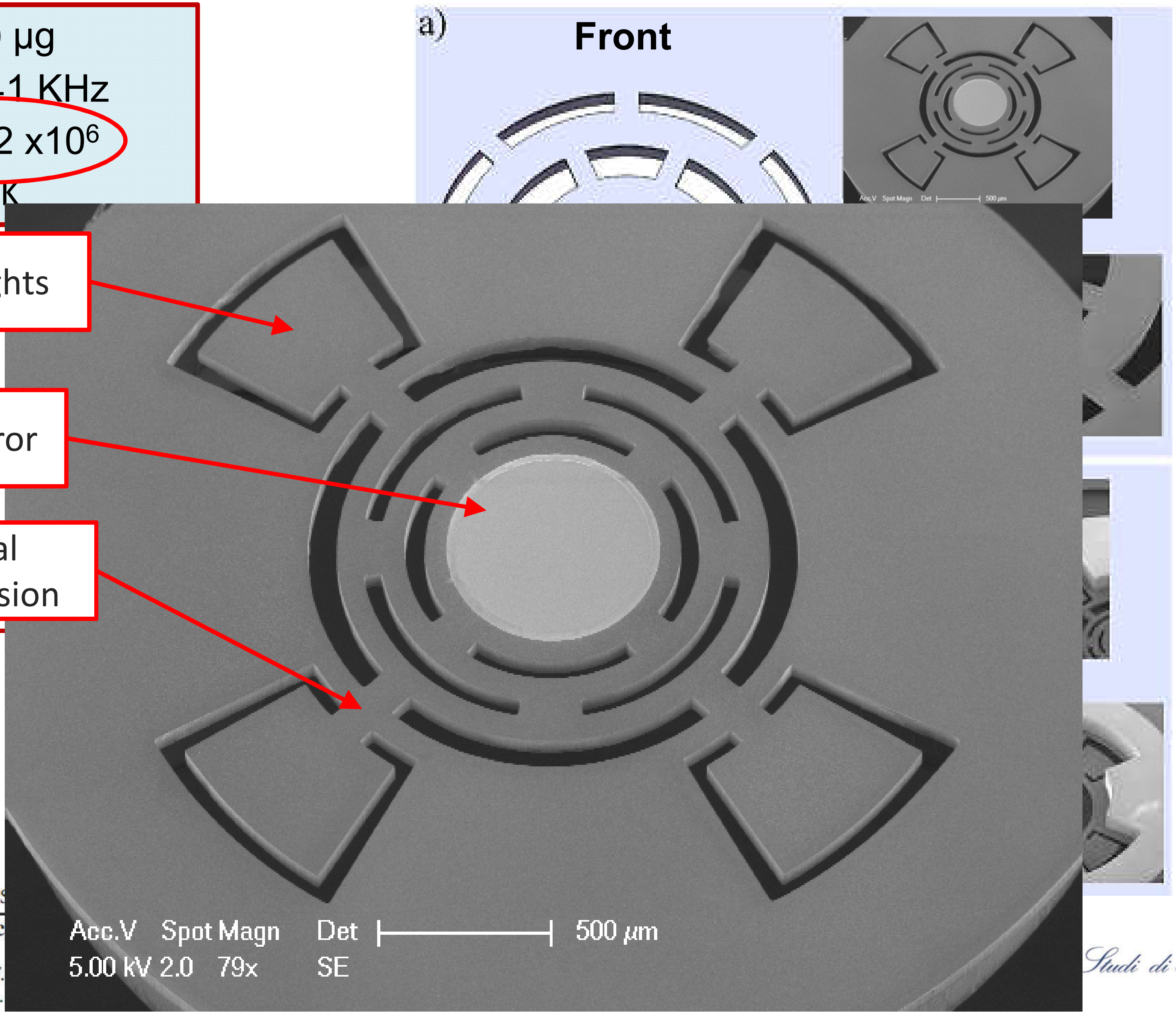
Latest generation

$m = 20\ \mu g$
$f_m = 141$ KHz
$Q = 1.2 \times 10^6$
$T = 4.3$ K

Counterweights

Mirror

Nodal Suspension



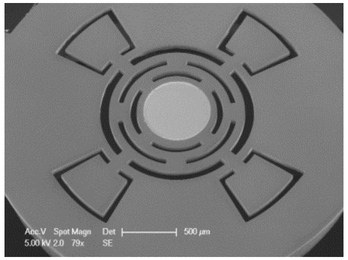
PHYS

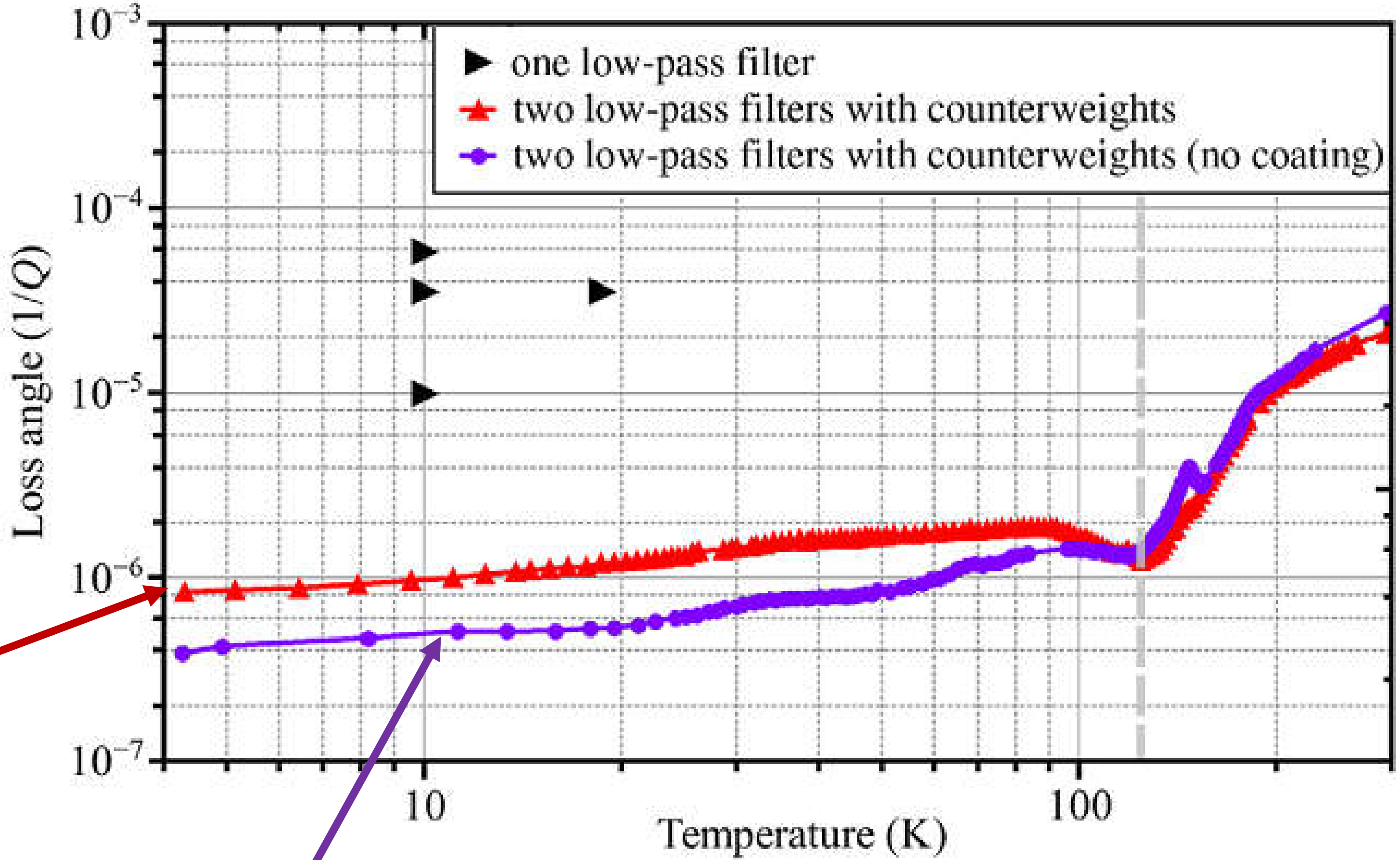
Low-Loss Optomec

A. Borrielli,[1,2] A. Pontin,[3,4] F.
G.

Studi di Firenze

Experimental characterization





With coating

Without coating

Thermoelastic dip

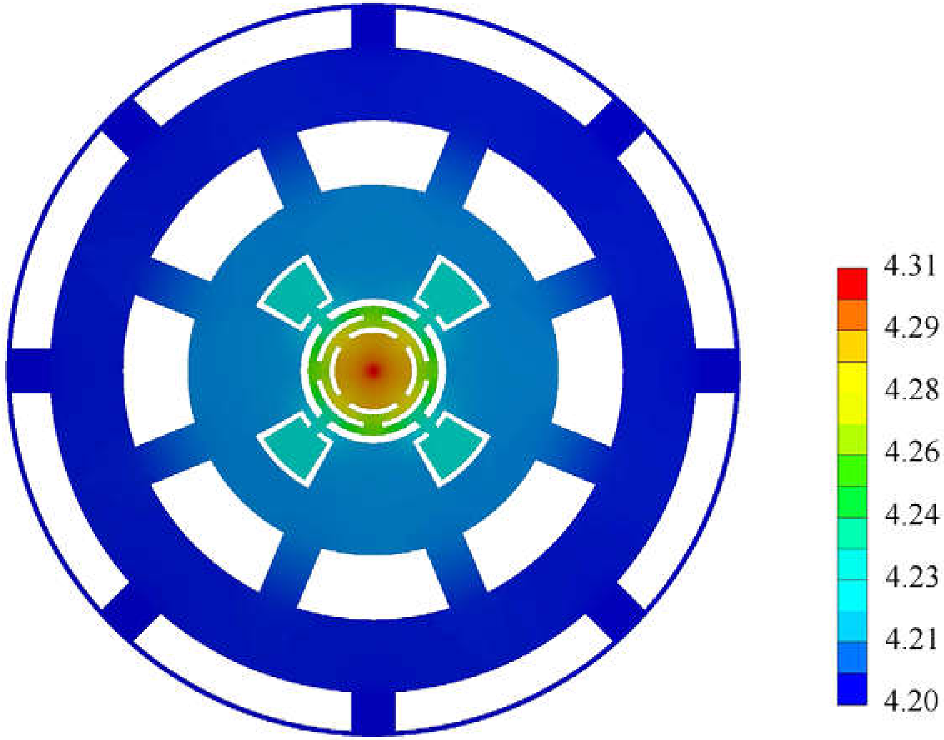
Temperature distribution in cryogenic samples

FEM simulations

$$T_{bath} = 4.2 \ \ K$$

$$P_{absorbed} = 1 \ \ mW$$

$$\boxed{P_{in} = 12 \ \ mW \quad \left(P_{cav} = 250 \quad W\right)}$$



Maximum temperature increase ~3%

Cavity parameters

Observed optical losses under optimal conditions as low as

$$\mathcal{L} \sim 20 \text{ ppm}$$

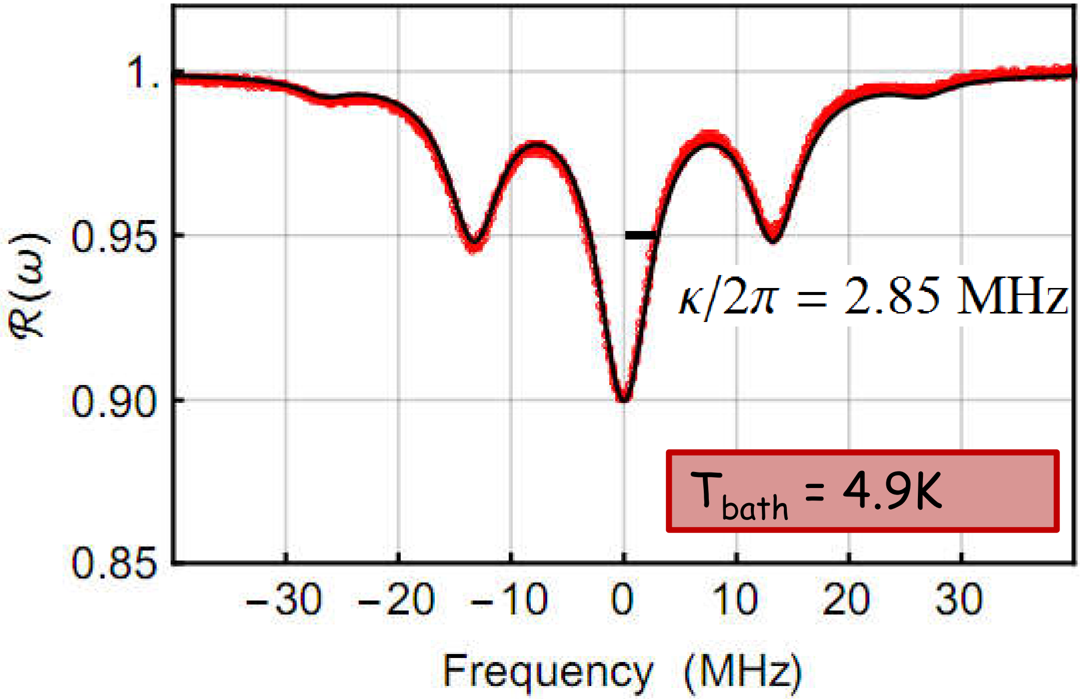
At low temperature

$$\boxed{\begin{array}{l}\mathcal{L} \sim 33 \text{ ppm} \\ \mathcal{T} \sim 315 \text{ ppm}\end{array}}$$

$$\mathcal{F} = 18000$$

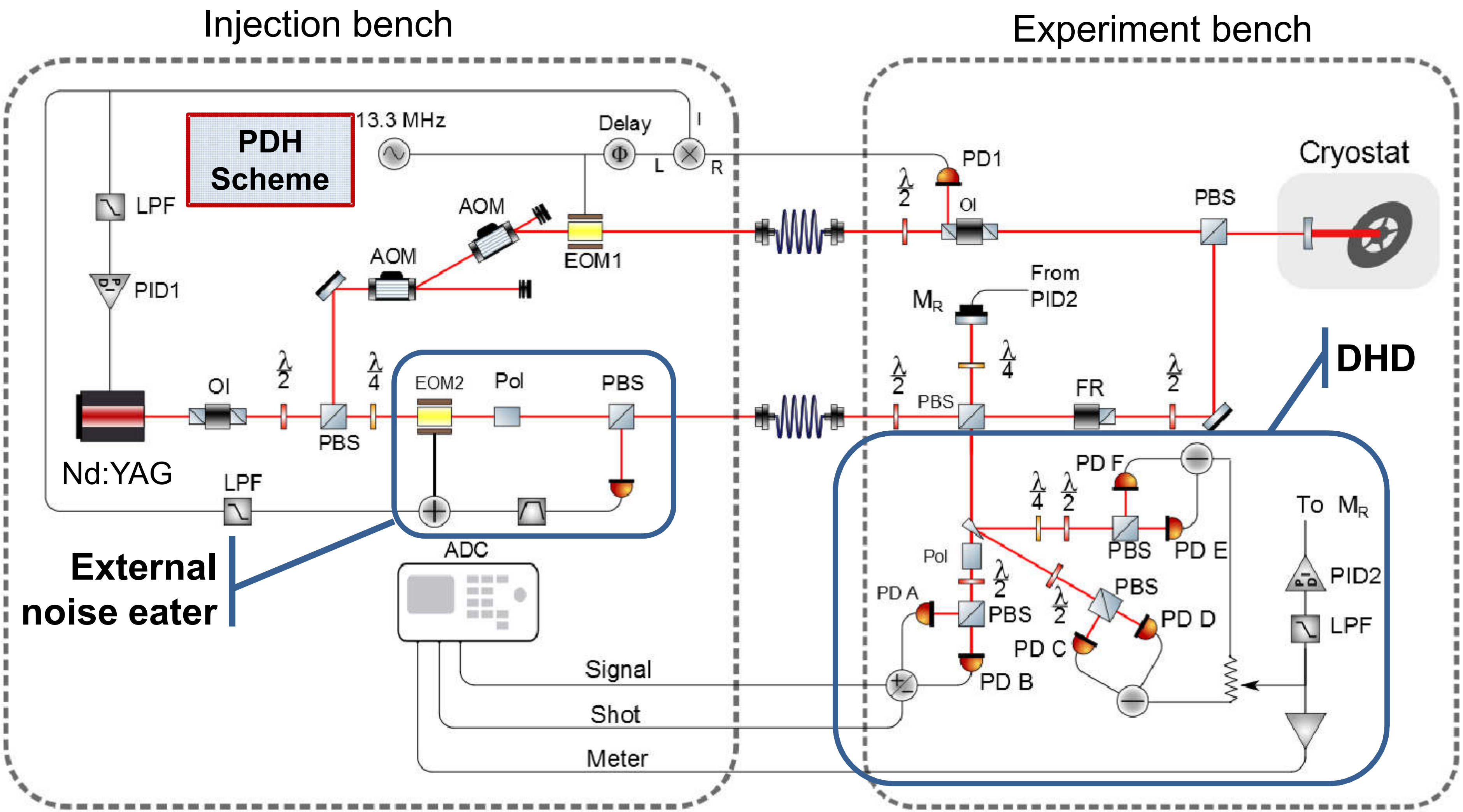
<u>Strongly overcoupled</u>

Reflection dips - PHD beam

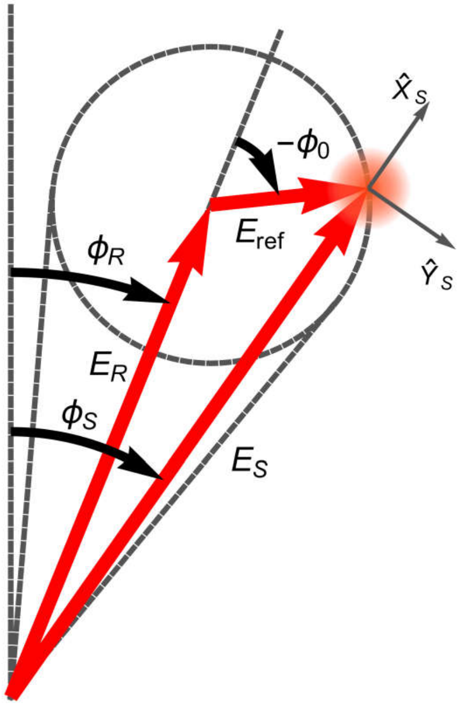


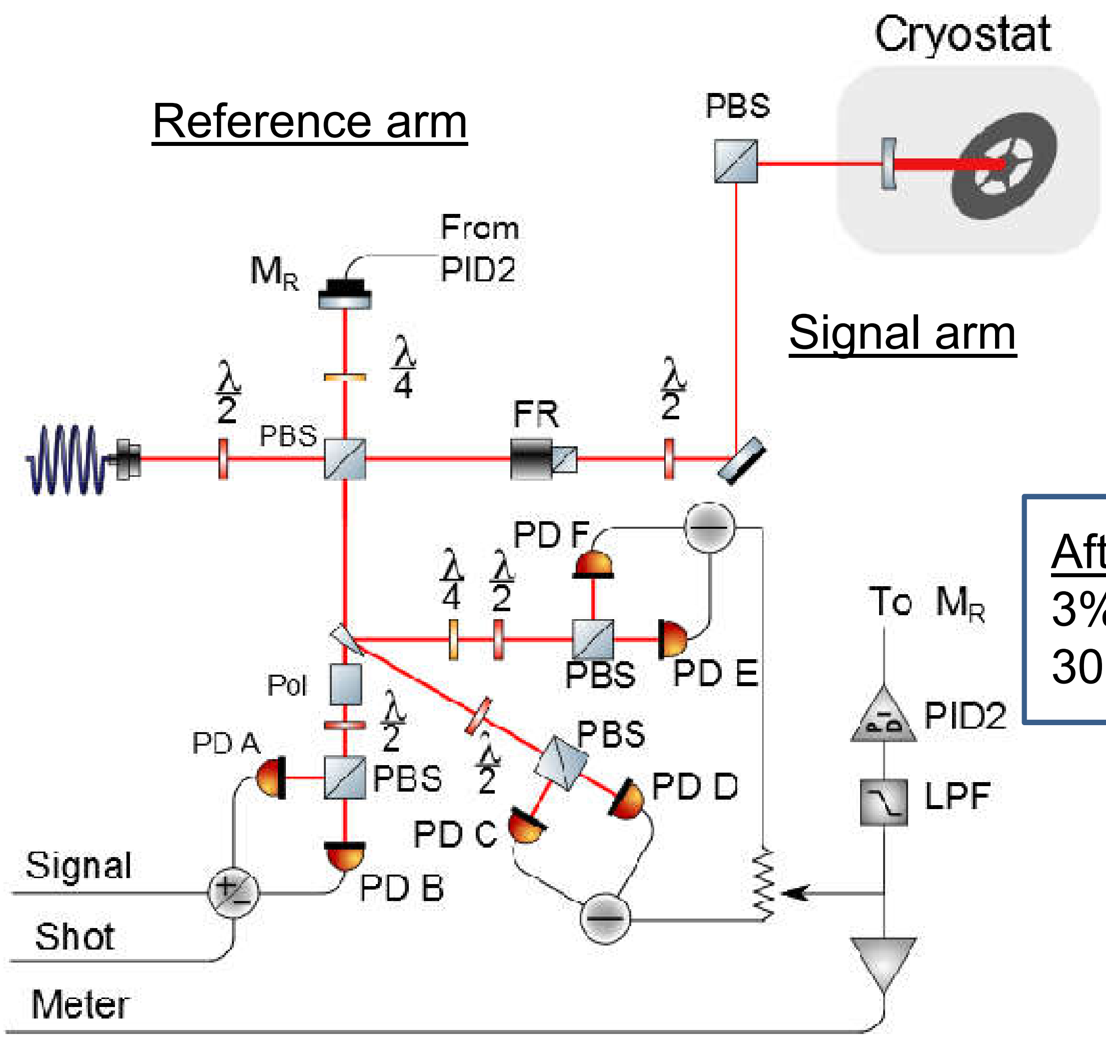
$$L_{cav} = 1.455 \text{ mm}$$

Experimental Setup



Double Homodyne Detection





After polarizer
99% Signal
3% Reference

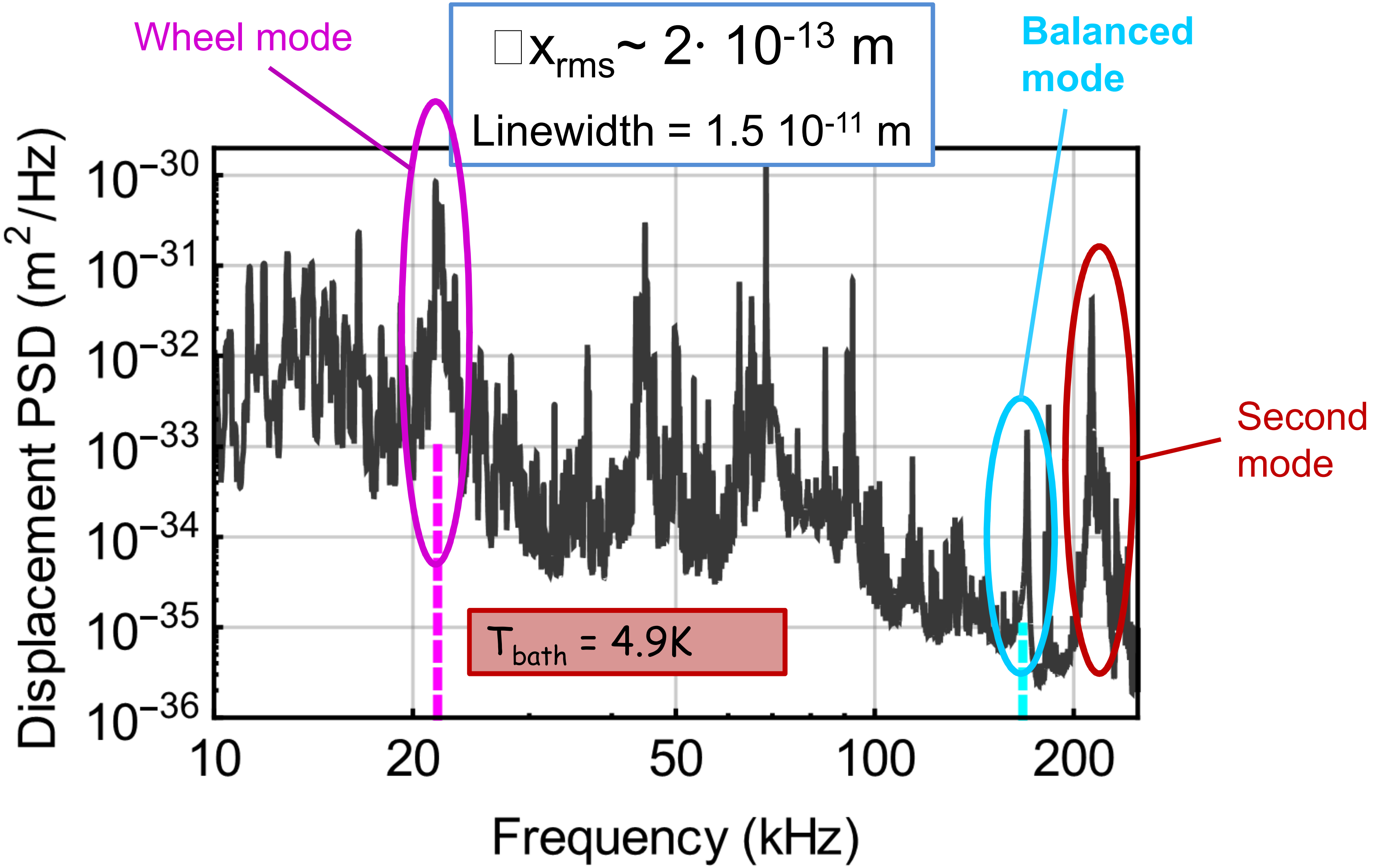
After wedge
3% Signal
30% Reference

Power Ratio
$\sim 10^{-2}$

Meter spectrum

□x_{rms}~ 2· 10^{-13} m

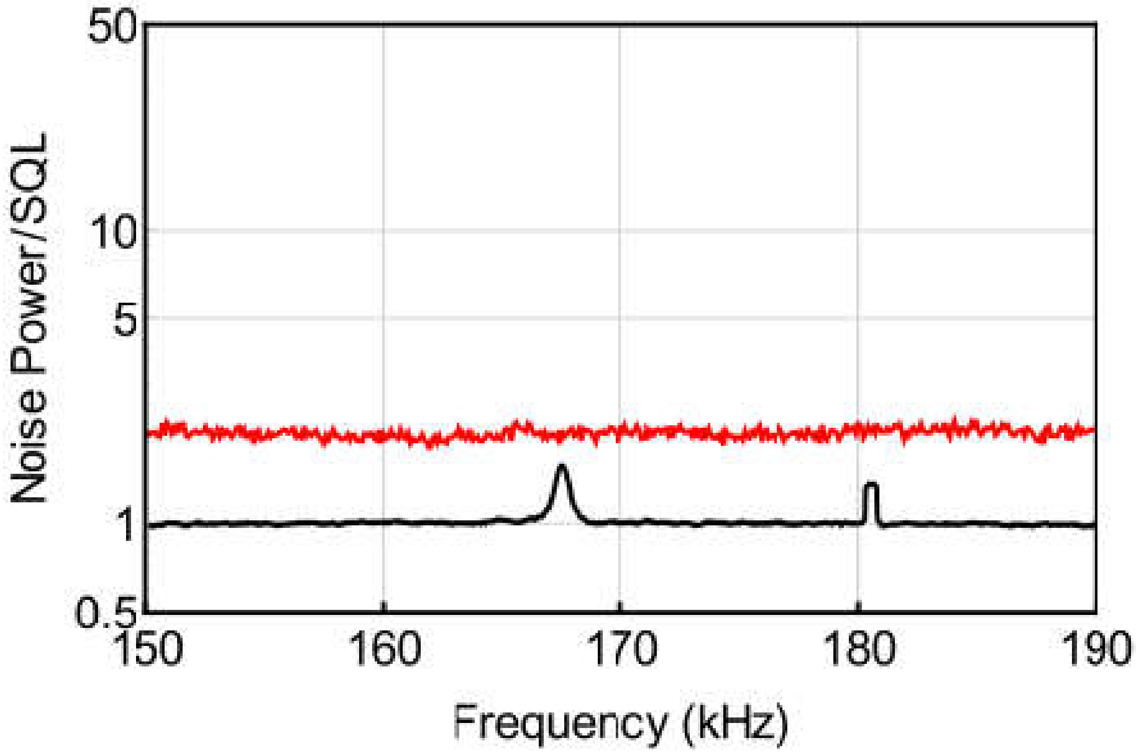
Linewidth = 1.5 10^{-11} m



Amplitude quadrature

Classical noise

Balanced mode $m_{\mathrm{eff}} = 250\ \mu\mathrm{g}$ → High intensities



Cavity input Power

$$P_{\mathrm{in}} \cong 38\ \mathrm{mW}$$

Excess intensity noise

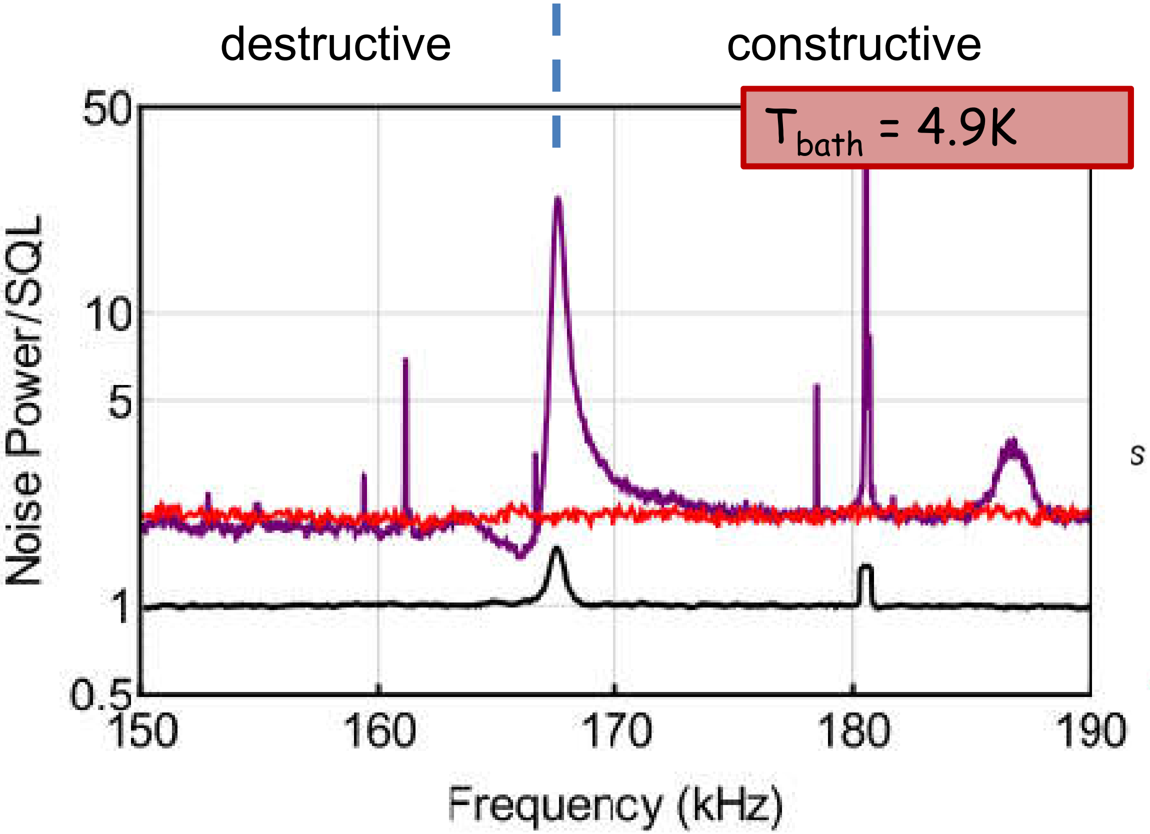
$$S_{\mathrm{II}} = 1 + \frac{P}{24\ \mathrm{mW}}$$

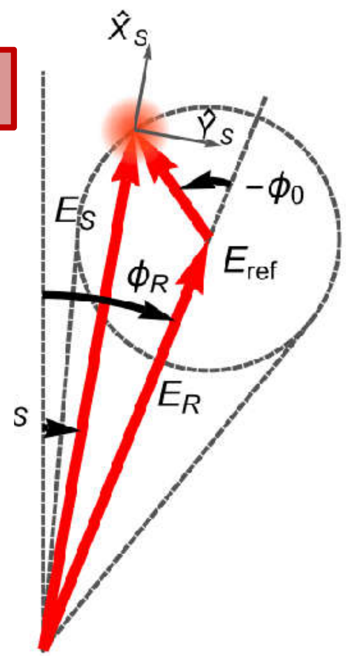
Quadrature spectrum

Interference

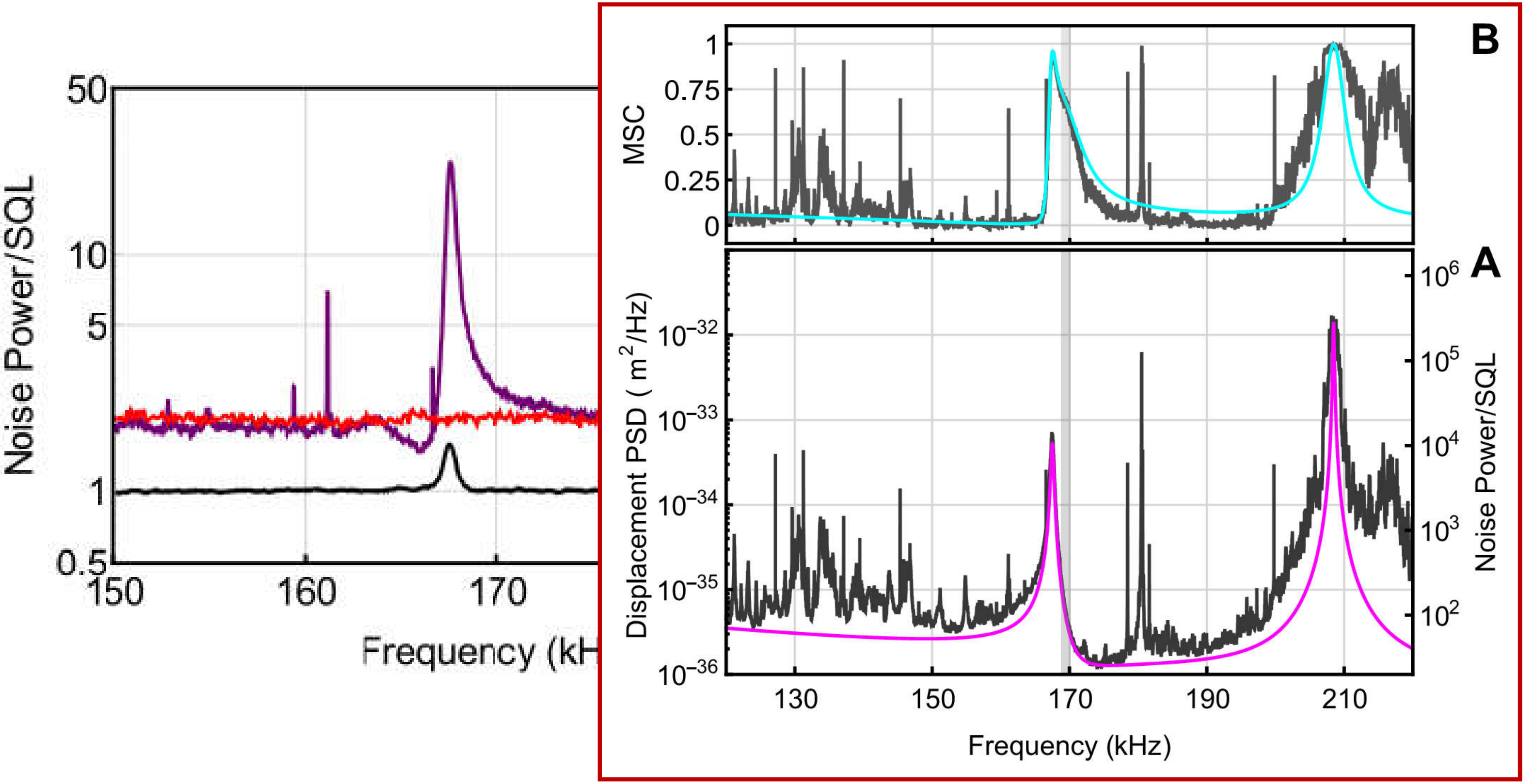
destructive

constructive





Signal and meter correlation



QND - Residual amplitude fluctuations

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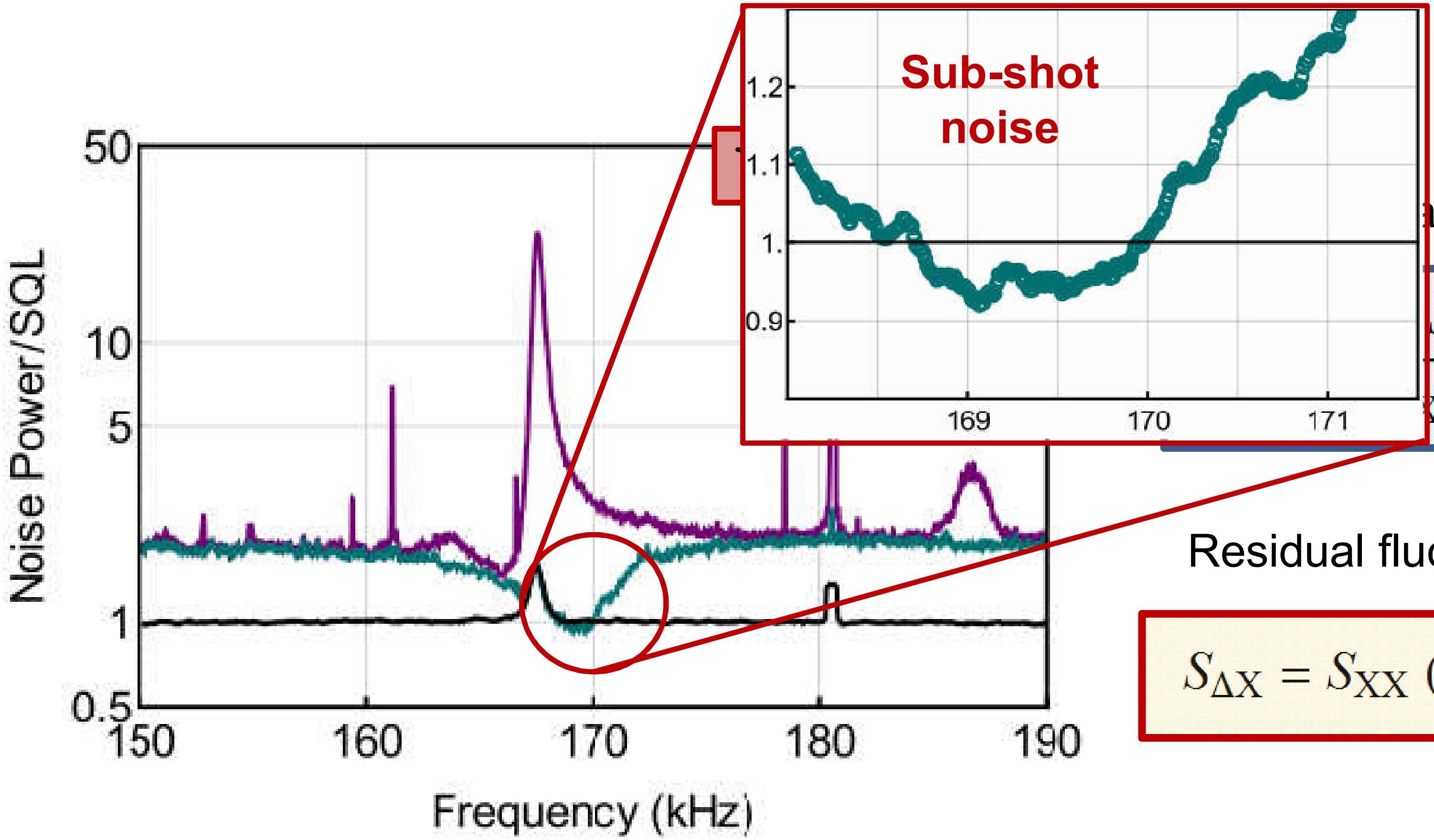


ation

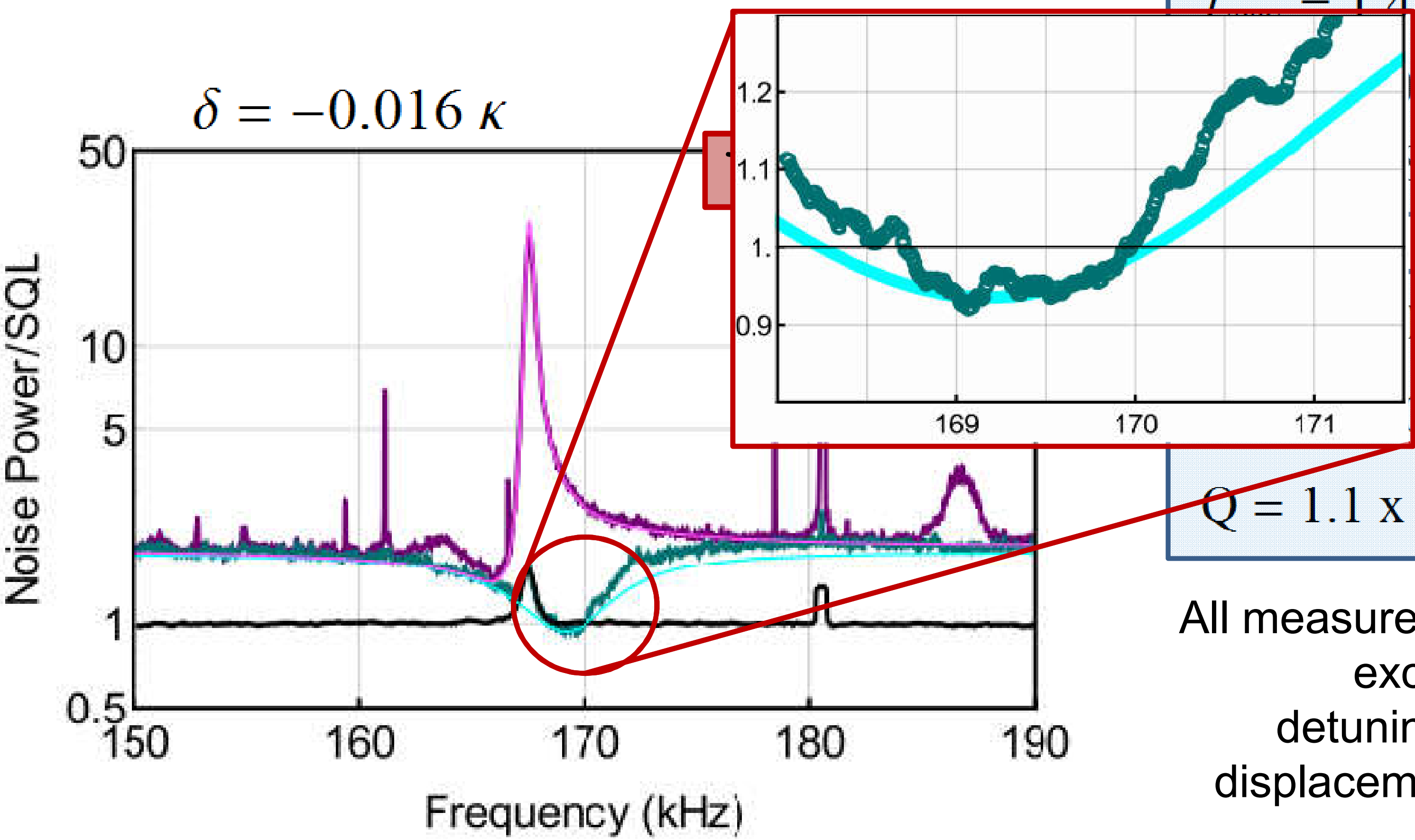
$S_{XY}|^2$

$XX\ S_{YY}$

Residual fluctuations

$$S_{\Delta X} = S_{XX}\,(1-C_{XY})$$

Model comparison



$L_{cav} = 1.455$ mm

0

35 MHz

169334 Hz

0 μg

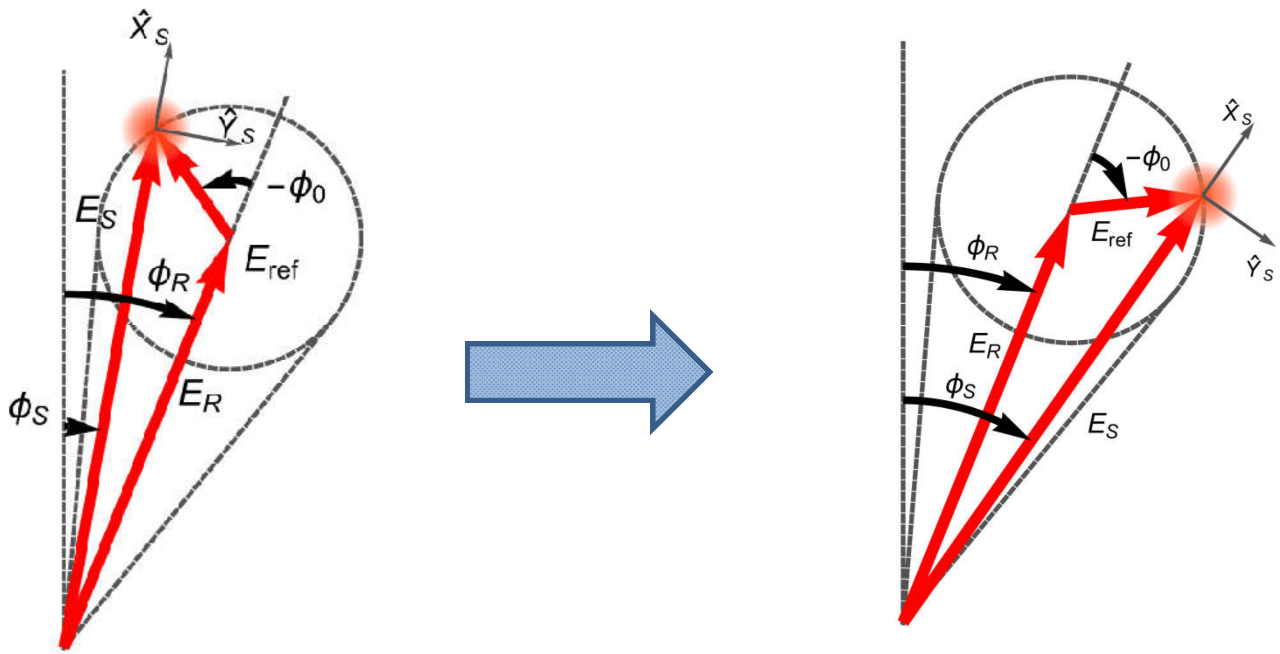
$Q = 1.1 \times 10^6$

All measured independently
except for:
detuning - phase -
displacement noise floor

Input Power	Intracavity Power	Effective coupling strength
$P_{in} = 38$ mW	$P_{cav} = 350$ W	$G/2\pi = -750$ kHz

Different quadrature

Opposite side of the reflected filed



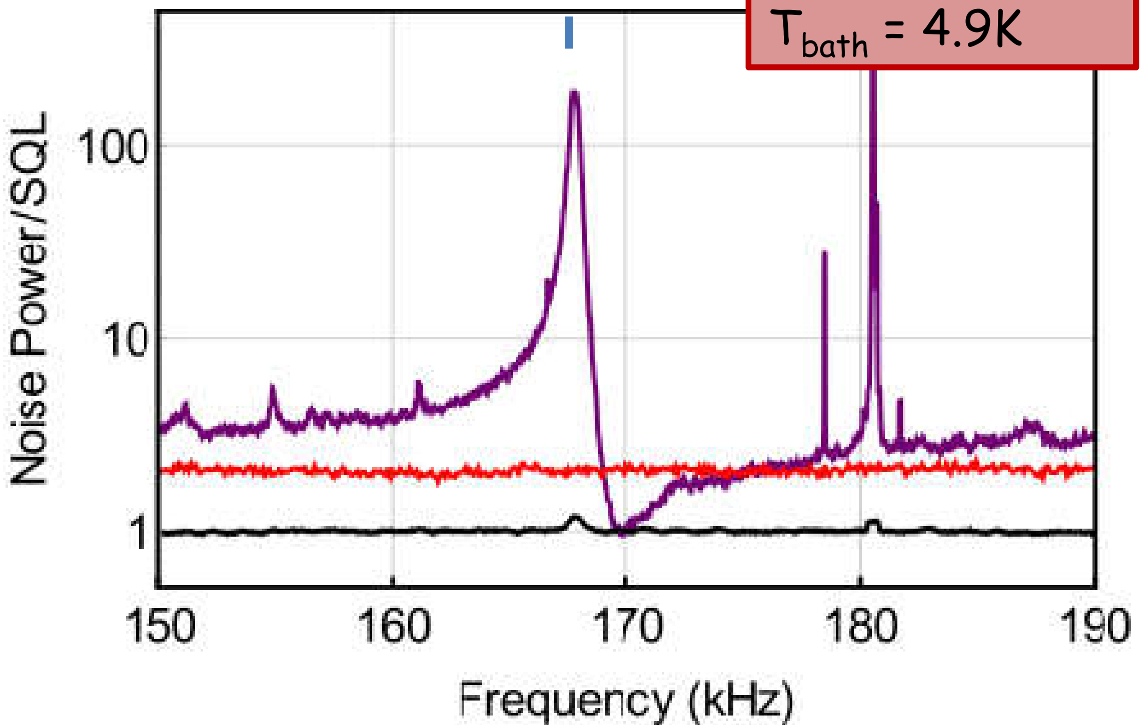
Different quadrature

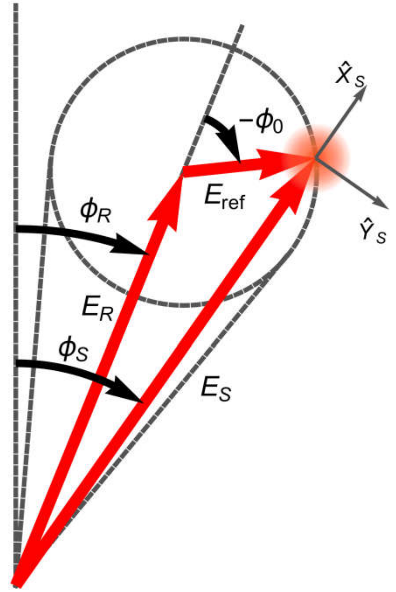
Interference

constructive

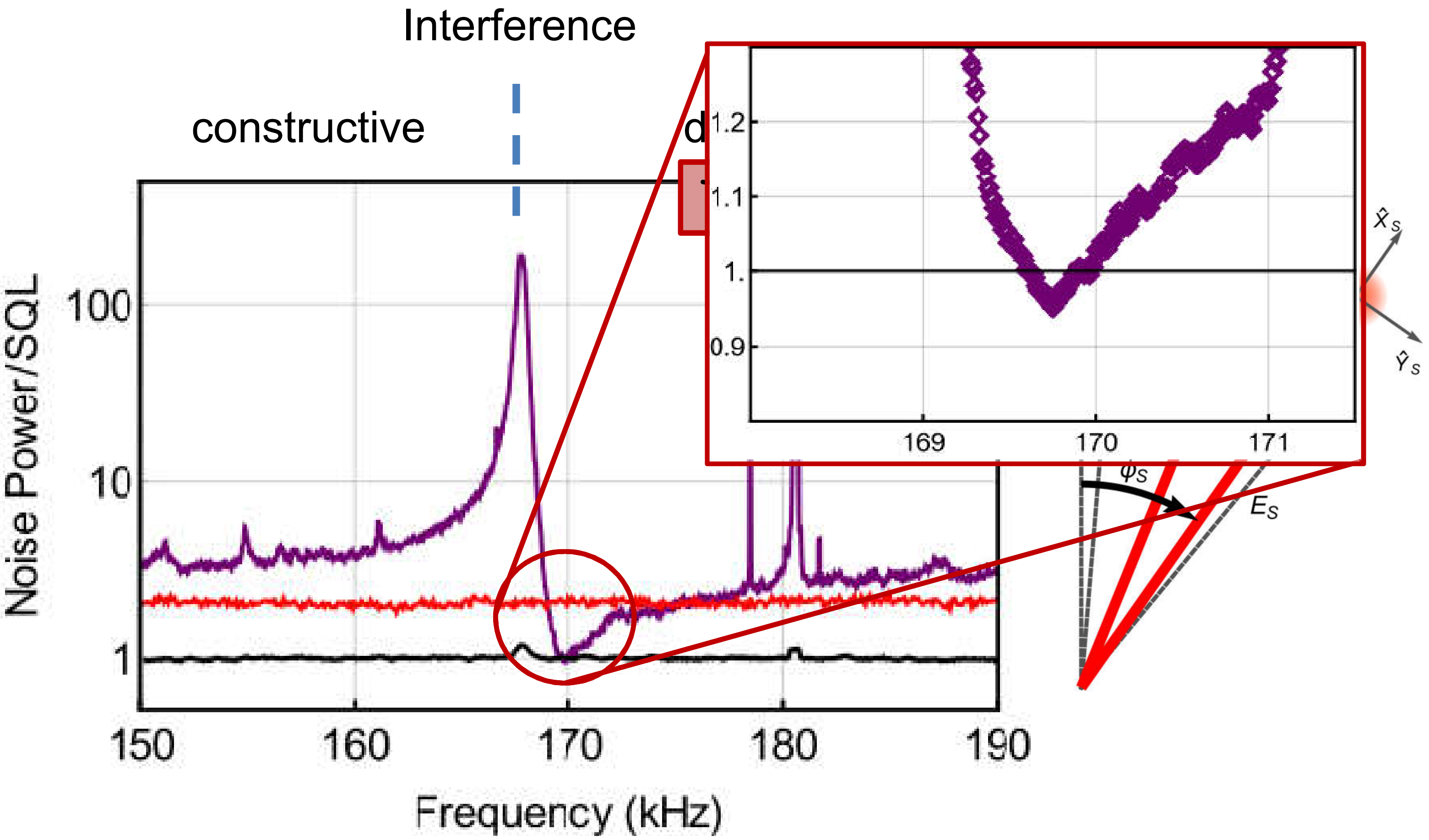
destructive

T_{bath} = 4.9K

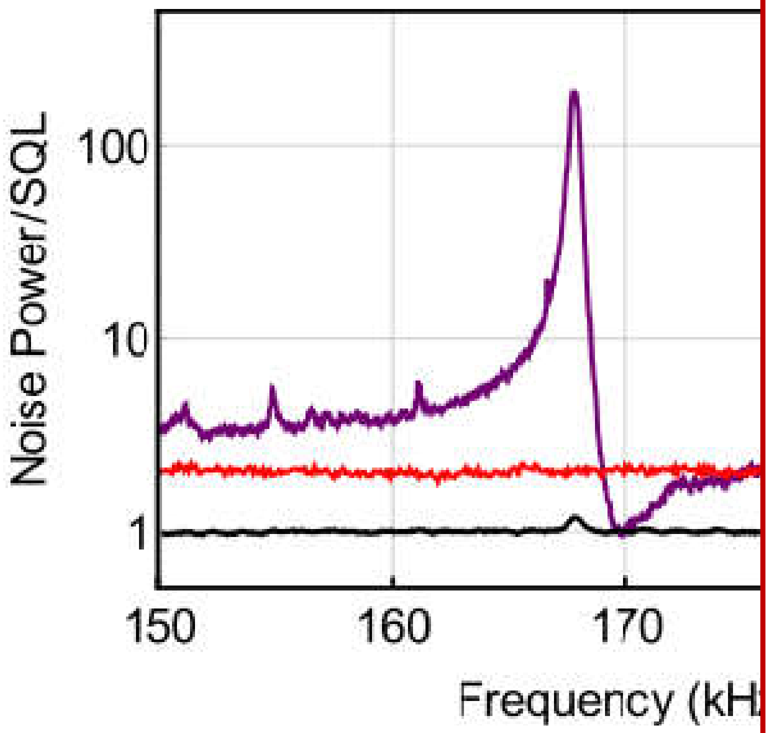


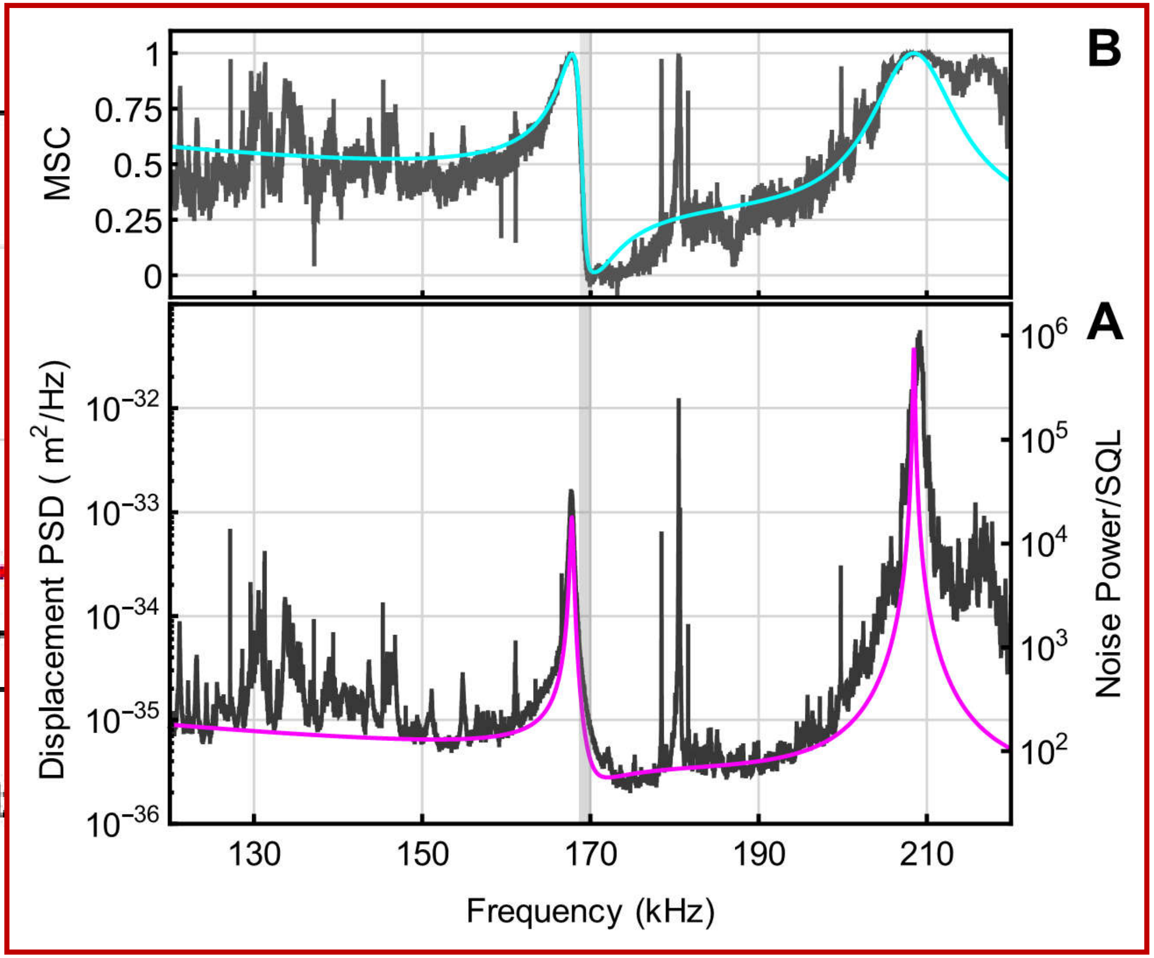


Ponderomotive squeezing

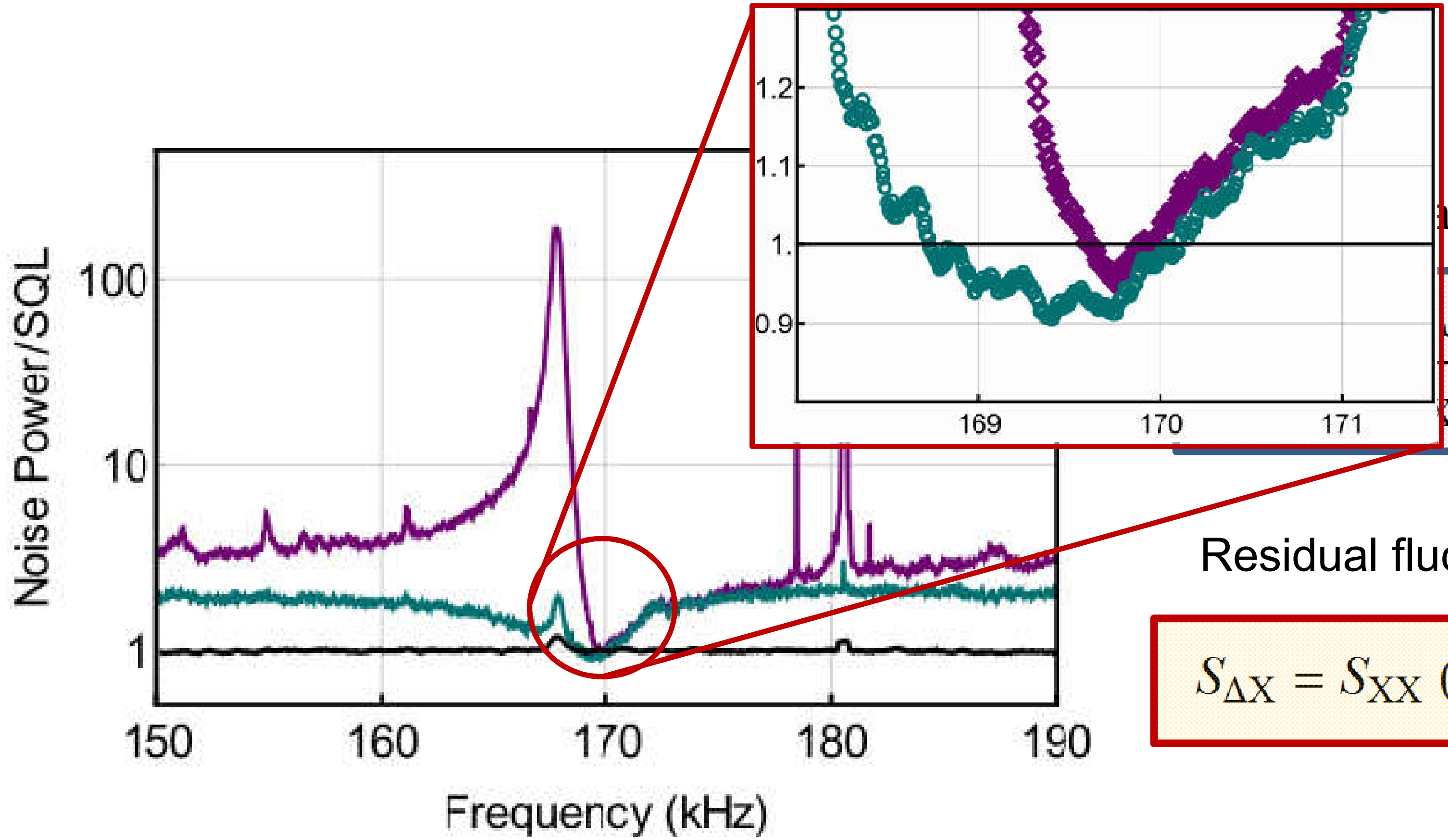


Signal and meter correlation





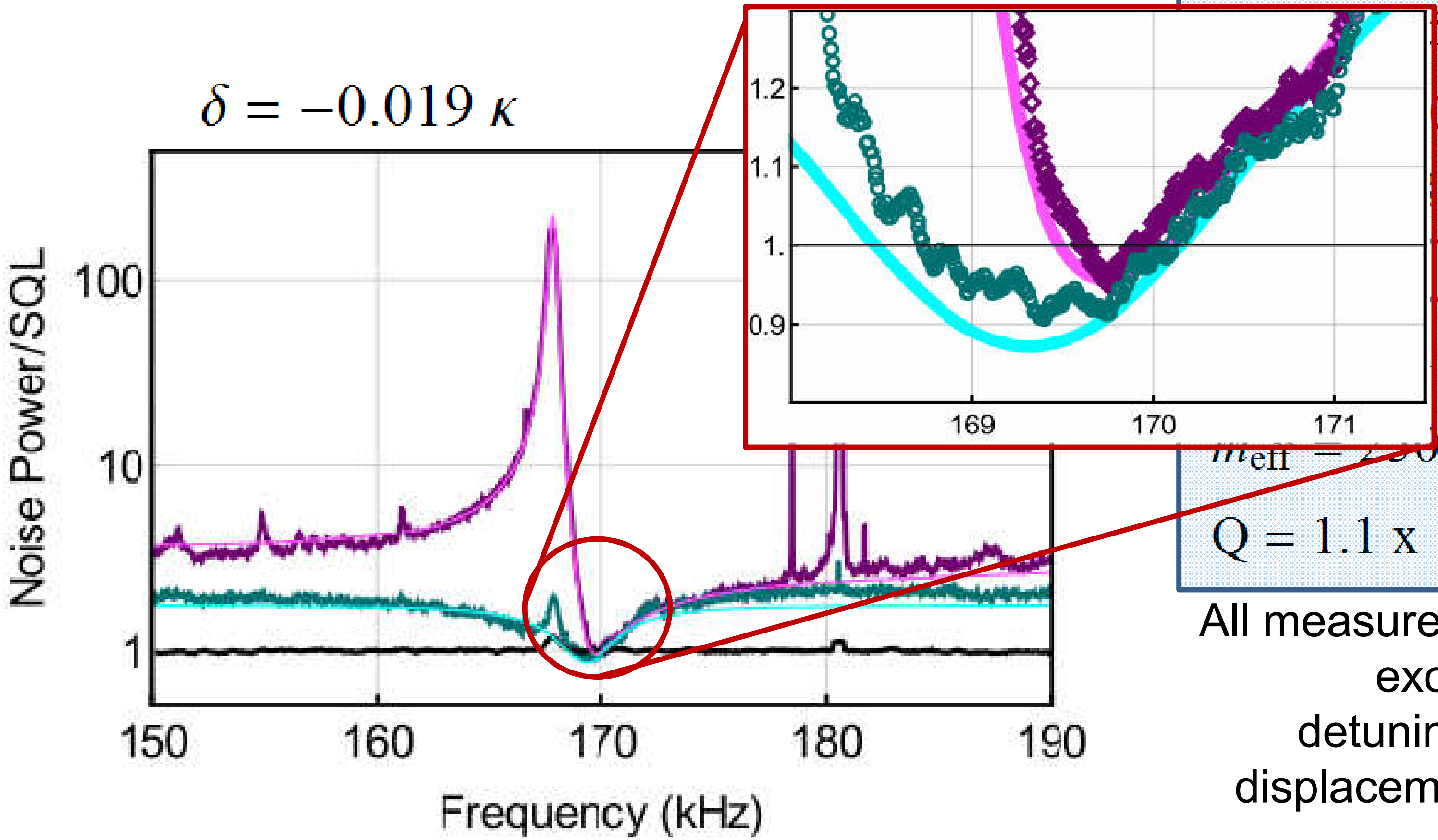
QND - Residual amplitude fluctuations



Residual fluctuations

$$S_{\Delta X} = S_{XX}\,(1 - C_{XY})$$

Model comparison



55 mm

0

5 MHz

69334 Hz

m_{eff} = 250 μg

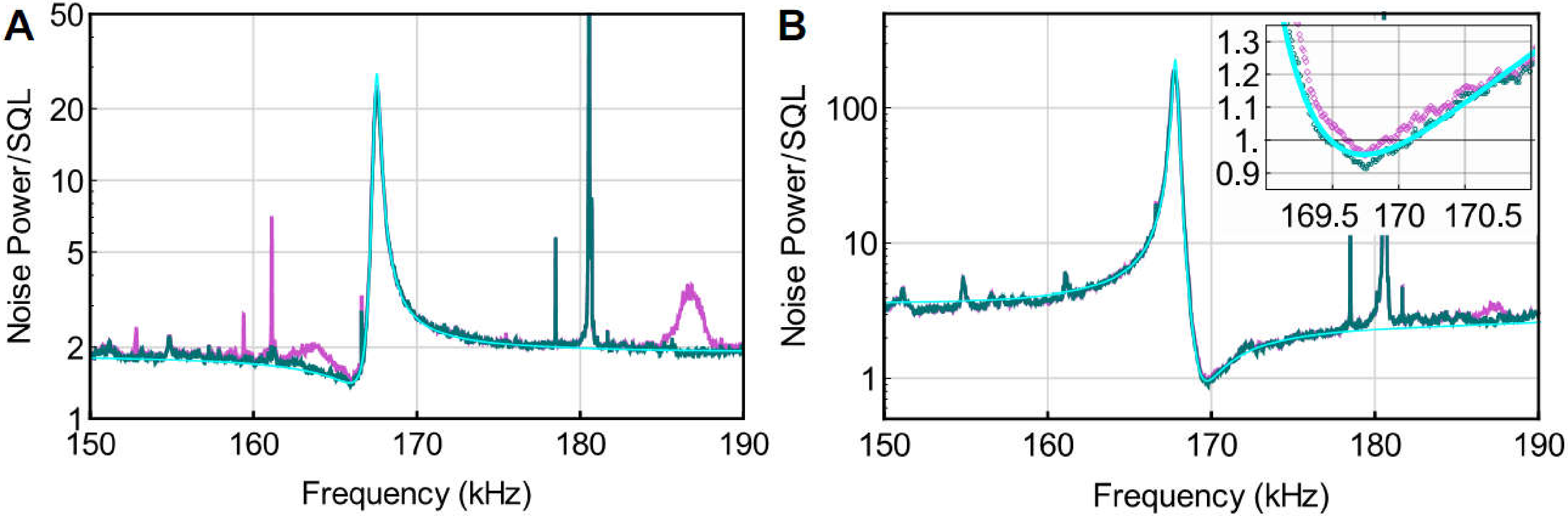
Q = 1.1 x 10^6

All measured independently except for:
detuning - phase - displacement noise floor

Input Power	Intracavity Power	Effective coupling strength
$P_{\mathrm{in}} = 38$ mW	$P_{\mathrm{cav}} = 350$ W	$G/2\pi = -750$ kHz

Non-linearity

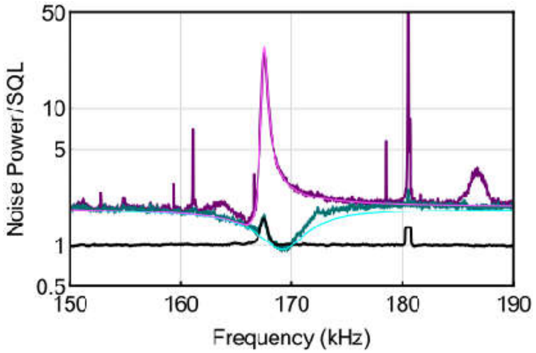
Non-vanishing correlation between X and Y^2



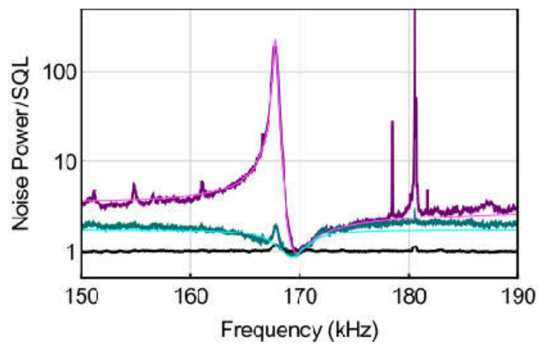
It is possible to isolate the linear contribution

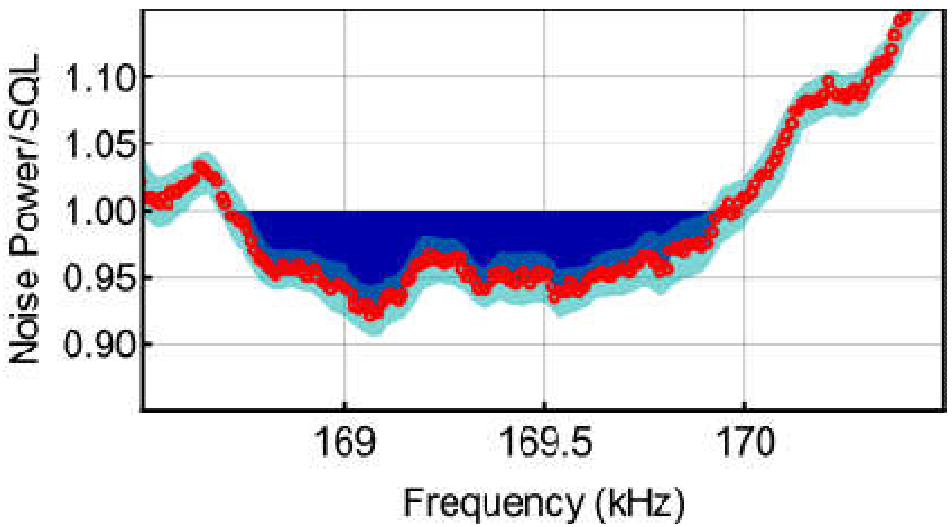
$$S_{\Delta X\,\mathrm{lin}} = S_{XX}\,(1 - C_{XY\mathrm{sqr}})$$

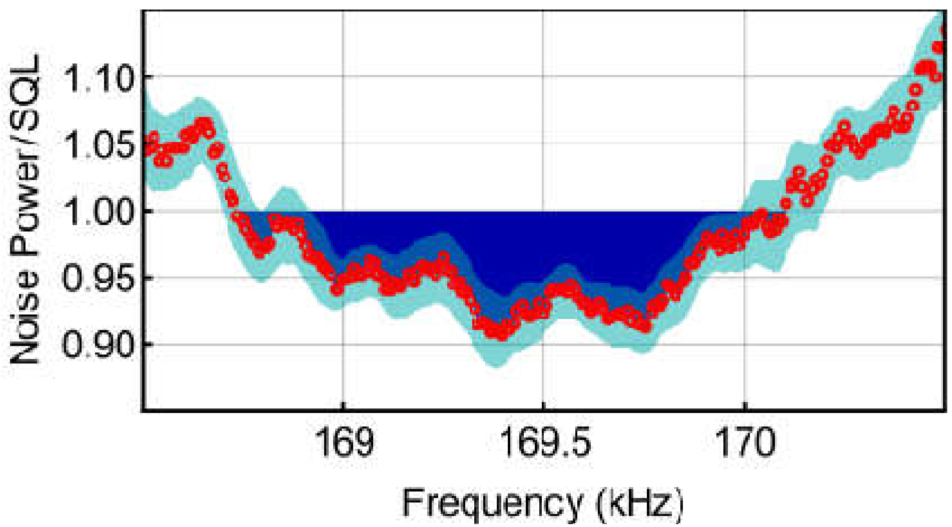
Statistical significance



Residual fluctuations shown
with 90% confidence belts







Minimum 0.921 ± 0.012 (σ) 0.906 ± 0.016 (σ)

Thanks!

Antonio Pontin