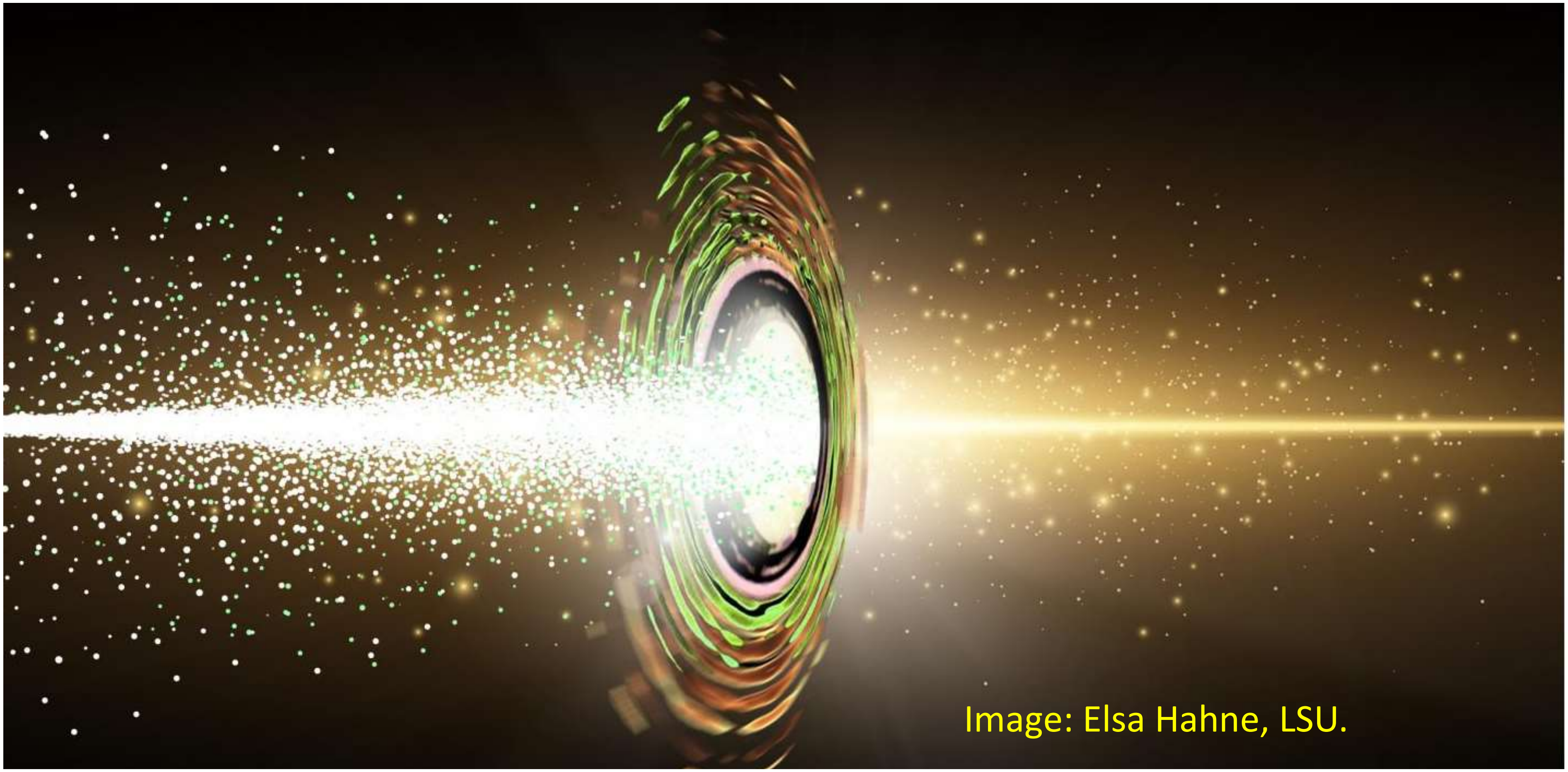
Optomechanical (ponderomotive) squeezing at room temperature

Thomas Corbitt (LSU)

GWADW 2019

N. Aggarwal, T. Cullen, J. Cripe, G. D. Cole, R. Lanza, A. Libson, D. Follman, P. Heu, T. Corbitt, N. Mavalvala, arXiv:1812.09942.



From my talk at GWADW in 2006..

LIGO

The experimental concept

- A "tabletop" interferometer to generate squeezed light as an alternative to nonlinear optical media and to explore radiation pressure effects
- Relies on intrinsic quantum physics of optical field–mechanical oscillator correlations
- Squeezing produced even when the sensitivity is far worse than the (free mass) SQL
  - Due to noise suppression of optical springs

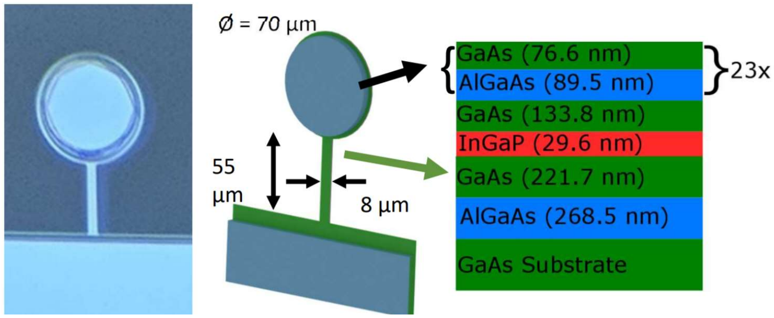
From my talk at GWADW in 2006..

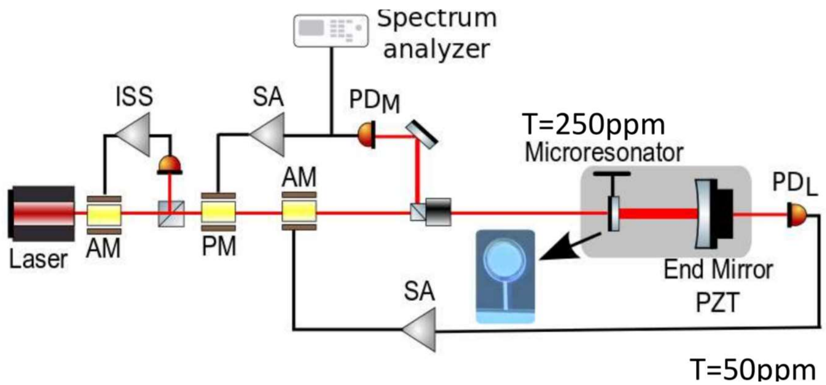
Outline

- Goals of experiments
  - Explore radiation pressure effects
    - Ponderomotive squeezing
    - Optical spring / parametric instability
- Path to goals
  - Phase I experiment – completed!
    - See some RP effects.
  - Phase II experiment – almost completed!
    - See extreme RP effects.
  - Phase III – ongoing.
    - See ponderomotive squeezing.

Optomechanics at LSU

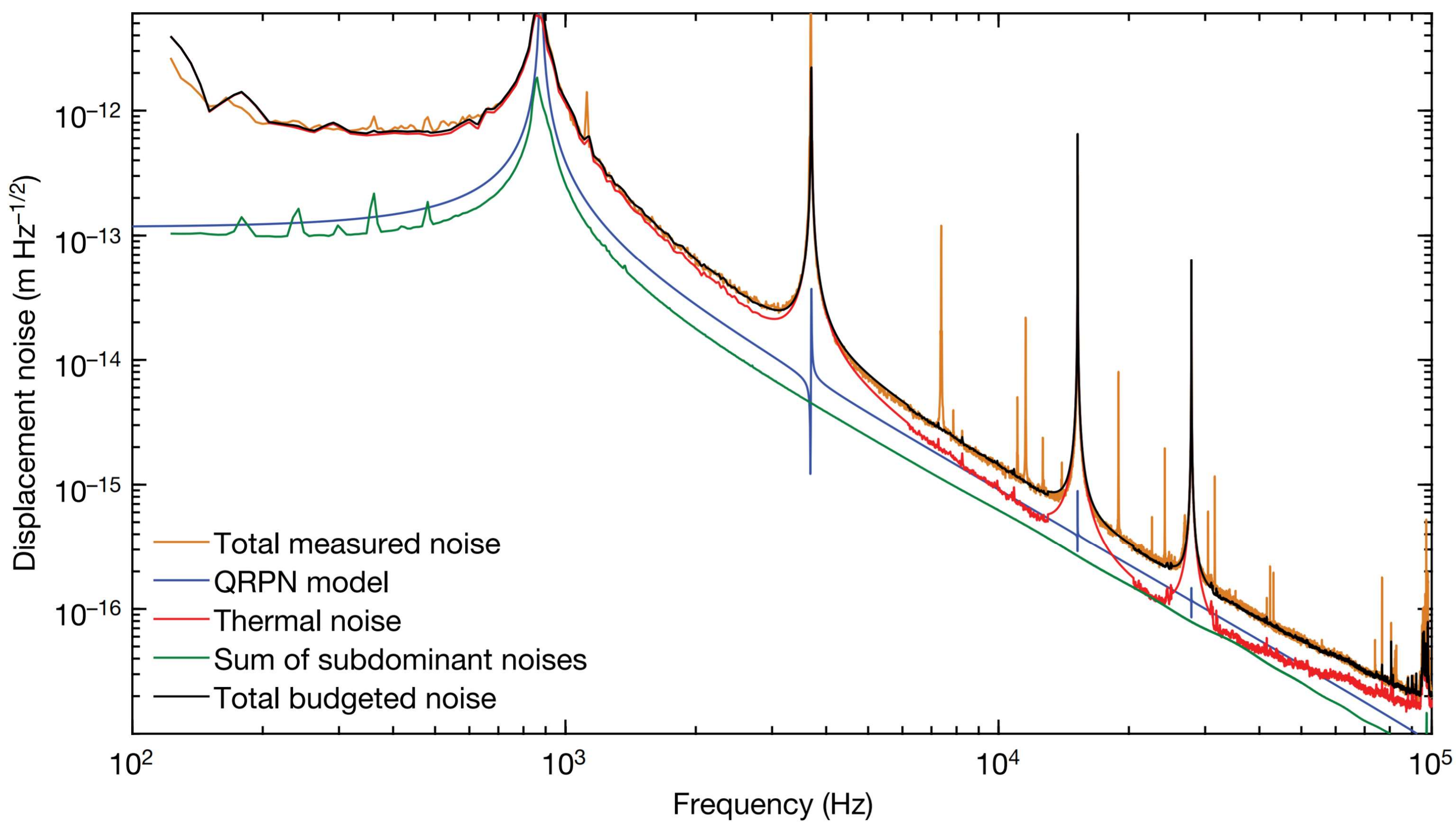
- Very light (50 ng) microfabricated mirror
- Suspended as quasi-free mass
- Study optomechanics and quantum noise in a system with similar features to GW interferometers
- Micro-mirror forms one mirror in optical cavity
- Typically operated with a very high optical spring frequency (150 kHz)





Prior results

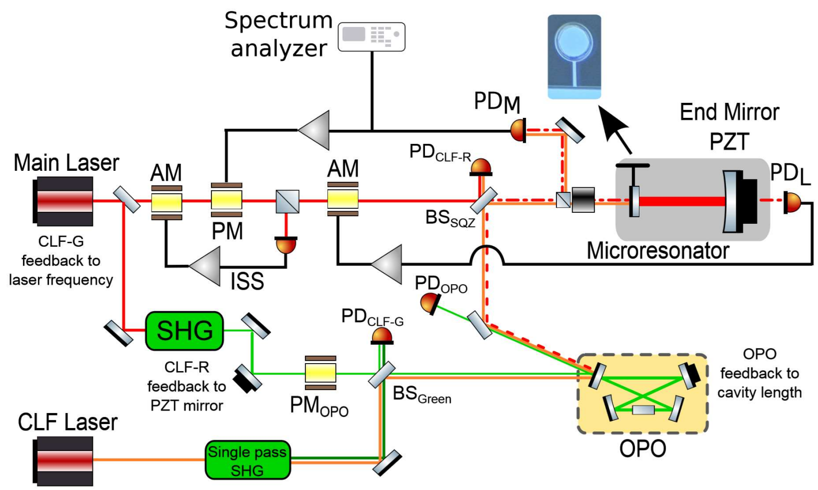
Quantum radiation pressure noise measured at room temperature in late 2017/early 2018!

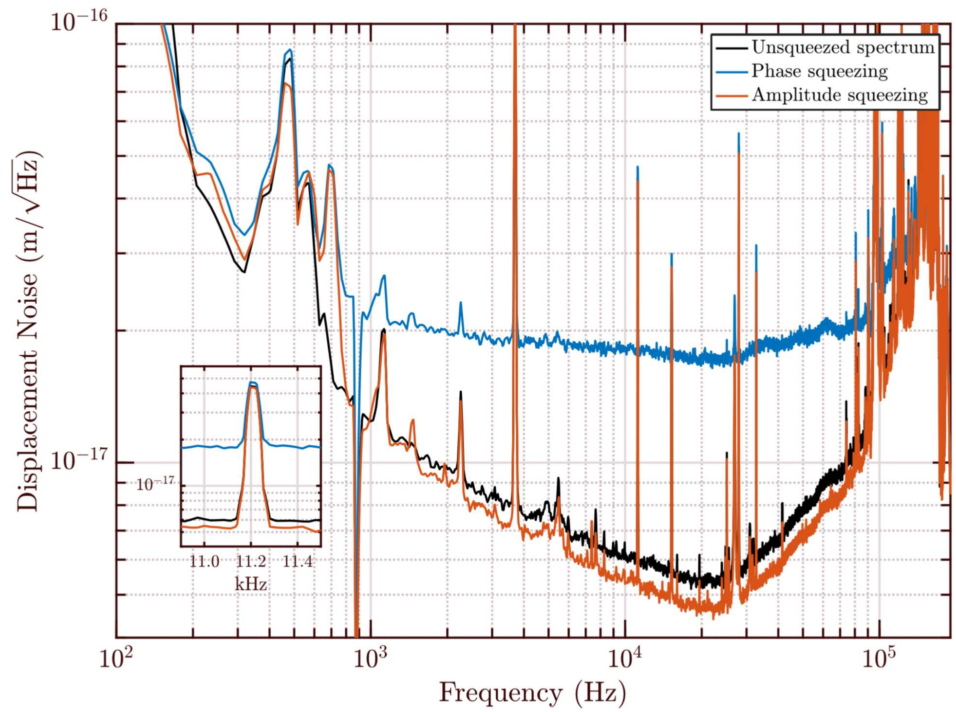


J. Cripe, N. Aggarwal, R. Lanza, A. Libson, R. Singh, P. Heu, D. Follman, G. D. Cole, N. Mavalvala & T. Corbitt, *Nature* **568** 364-367 (2019).

Prior results

Quantum radiation pressure noise reduced with squeezed light! Collaboration with ANU.



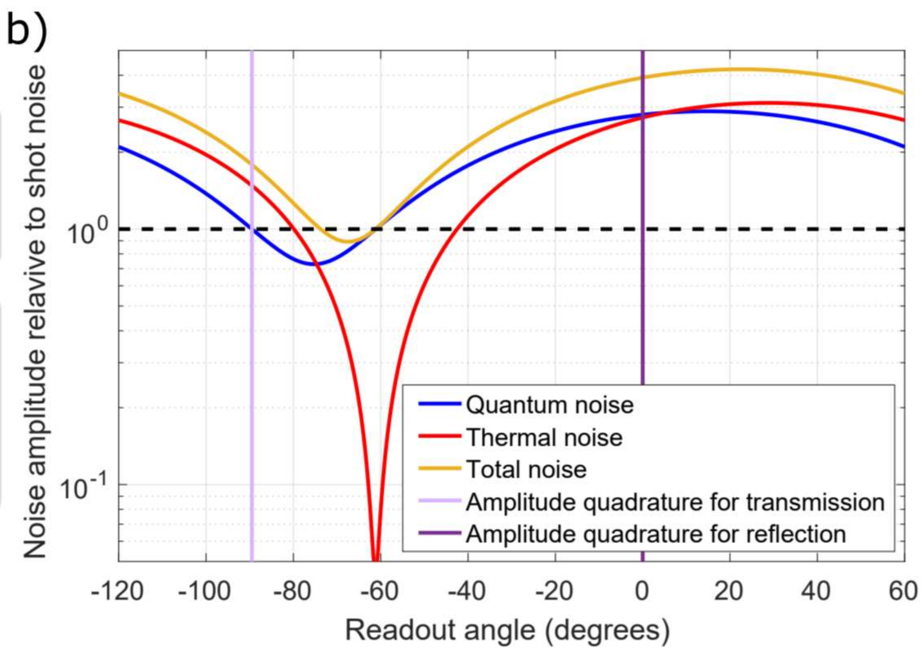


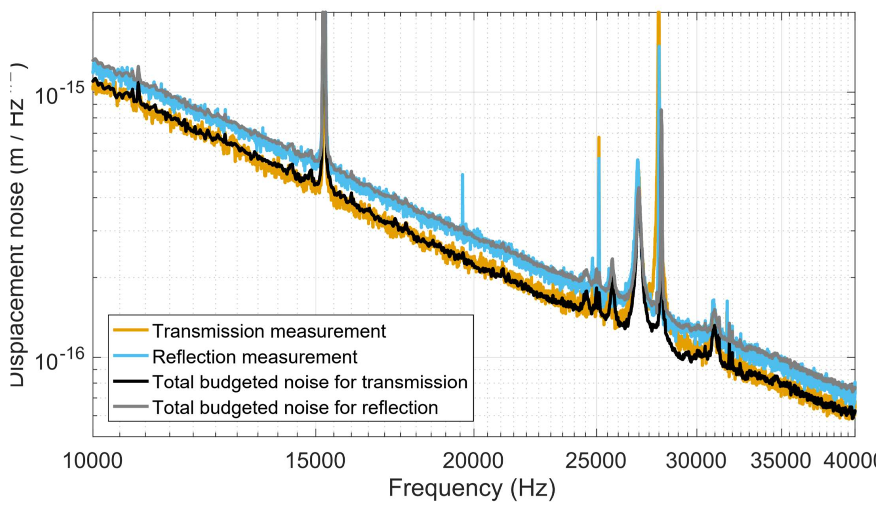
Optical spring response not removed in this plot.

M. J. Yap, J. Cripe, G. L. Mansell, T. G. McRae, R. L. Ward, B. J.J. Slagmolen, D. A. Shaddock, P. Heu, D. Follman, G. D. Cole, D. E. McClelland, and T. Corbitt, arXiv:1812.09804v1.

Prior results

Quantum radiation pressure noise coherently cancelled (variational readout). Also: quantum noise free measurement of thermal noise



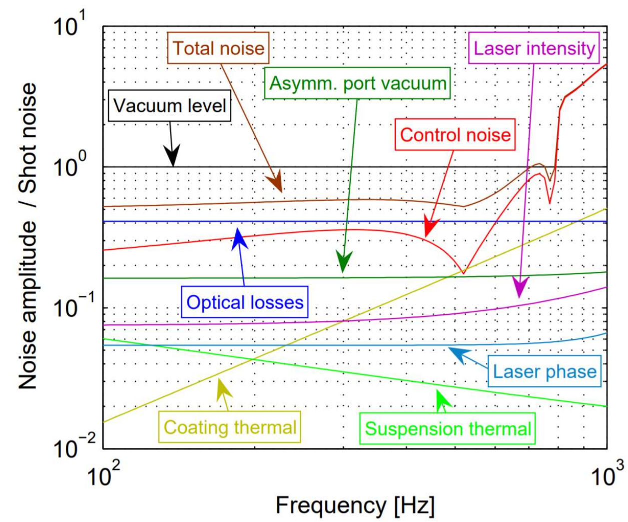


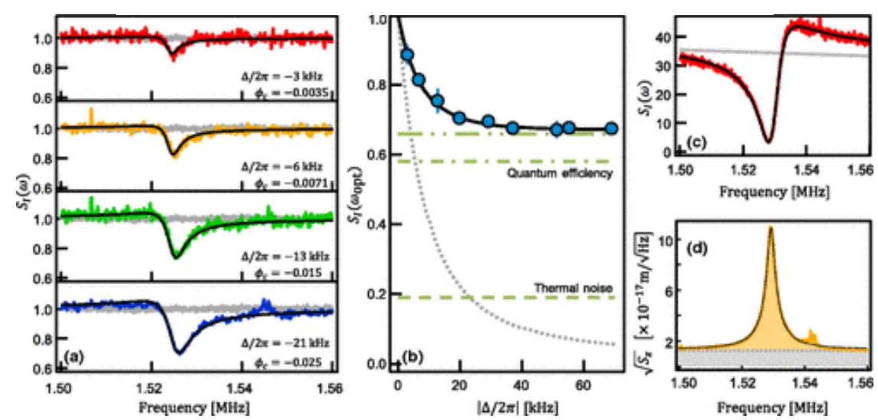
J. Cripe, T. Cullen, Y. Chen, P. Heu, D. Follman, G. D. Cole, and T. Corbitt, arXiv:1812.10028v1

Optomechanical squeezing experiment

$$\begin{pmatrix} b_A \\ b_P \end{pmatrix} = \begin{pmatrix} 1 & \\ -2\mathcal{K}(\Omega) & 1 \end{pmatrix} \begin{pmatrix} a_A \\ a_P \end{pmatrix}$$

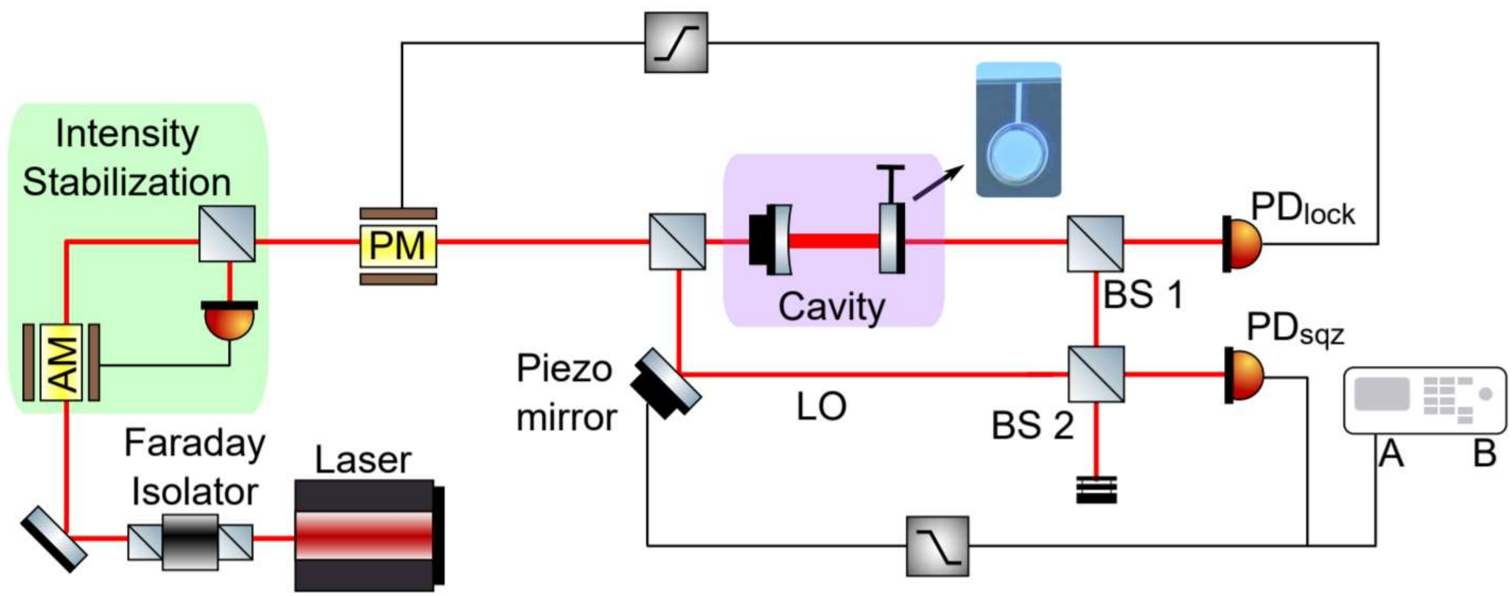
- **Goal:** show that an optical cavity with a movable mirror produces squeezed light via radiation pressure.
    - We expected gravitational wave interferometers to exhibit this effect – could be exploited
    - Demonstrate that we understand how quantum noise behaves in these systems
    - Potential new source for squeezed light
- Idea for ponderomotive squeezer with strong optical spring: T. Corbitt, Y. Chen, F. Khalili, D. Ottaway, S. Vyatchanin, S. Whitcomb, and N. Mavalvala, Phys. Rev. A **73**, 023801 (2006)
- Has been observed before near mechanical resonance frequency, for example: T. P. Purdy, P. L. Yu, R. W. Peterson, N. S. Kampel, and C. A. Regal, Phys. Rev. X 3, 031012 (2013).





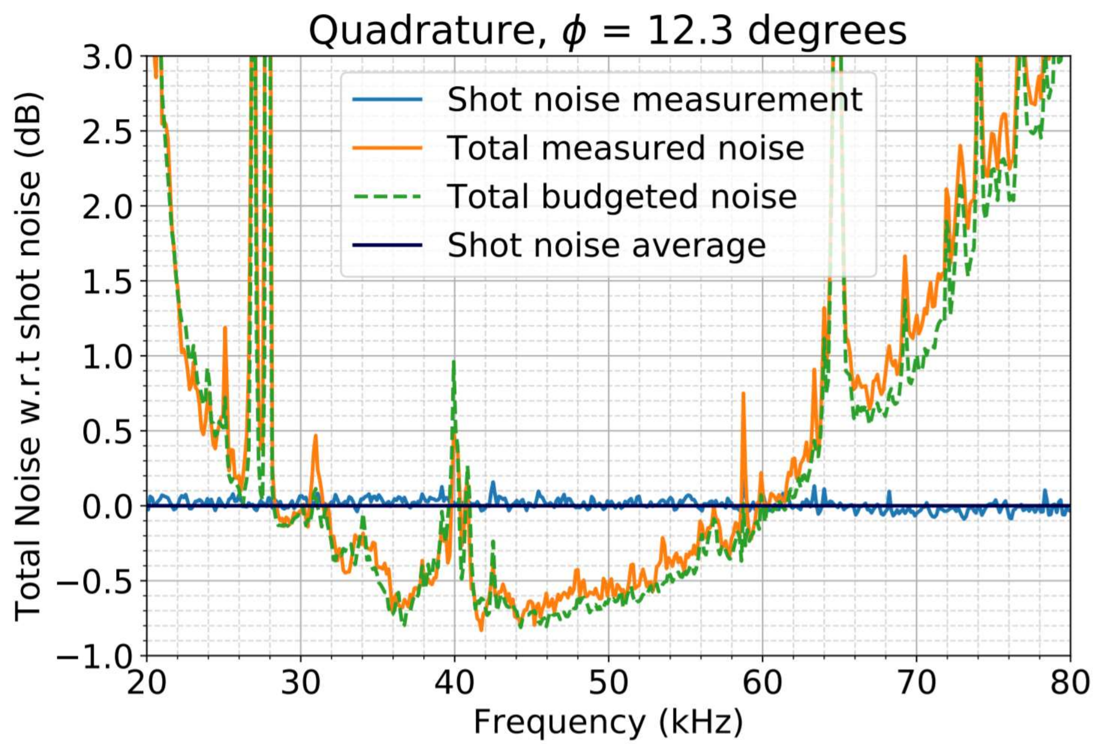
The experiment

- Performed at LSU with Nancy Aggarwal (MIT)
- Challenges:
  - Homodyne detection for squeezed light
  - How to lock cavity while leaving (bright) squeezed beam available for measurement?
  - Understanding noise couplings



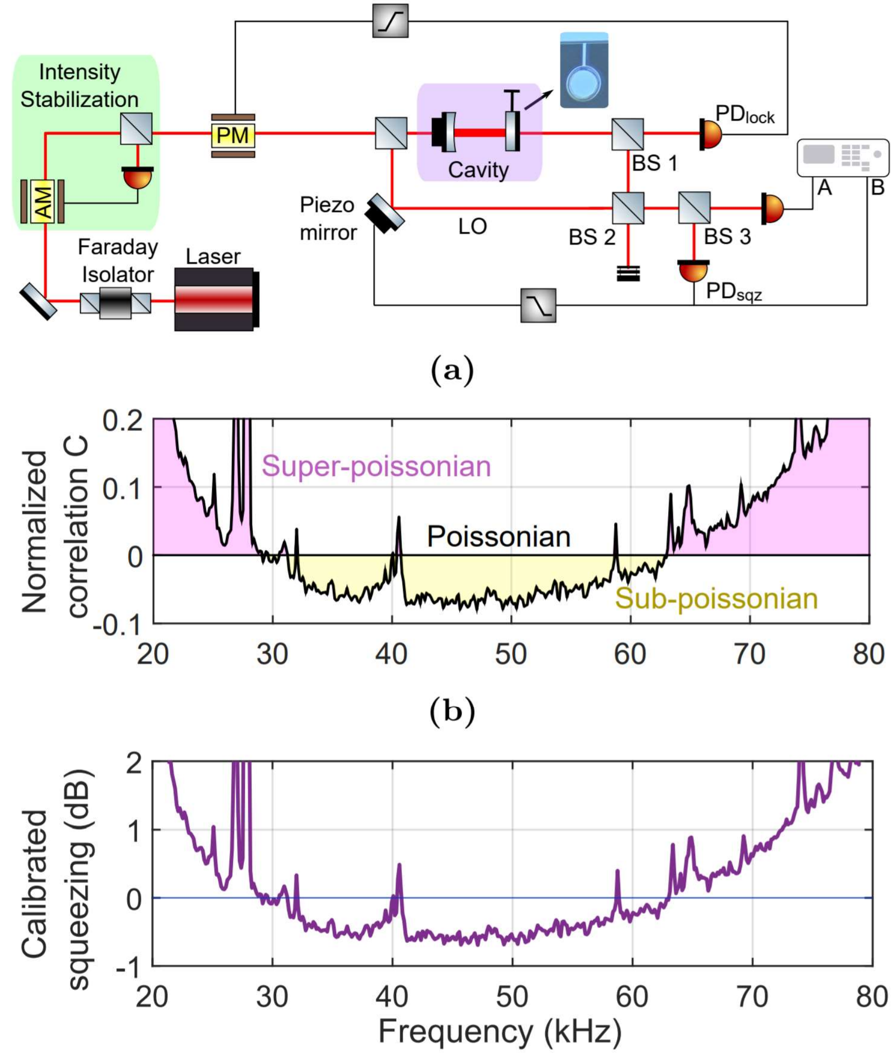
Squeezed light!

- At frequencies below the optical spring resonance (150 kHz), we expect frequency independent squeezed light.
- Measure noise spectrum at single quadrature to observe squeezing.
- Limitations to squeezing:
  - Optical losses
  - Thermal noise
  - Feedback noise
  - Phase noise between LO and squeezed beam



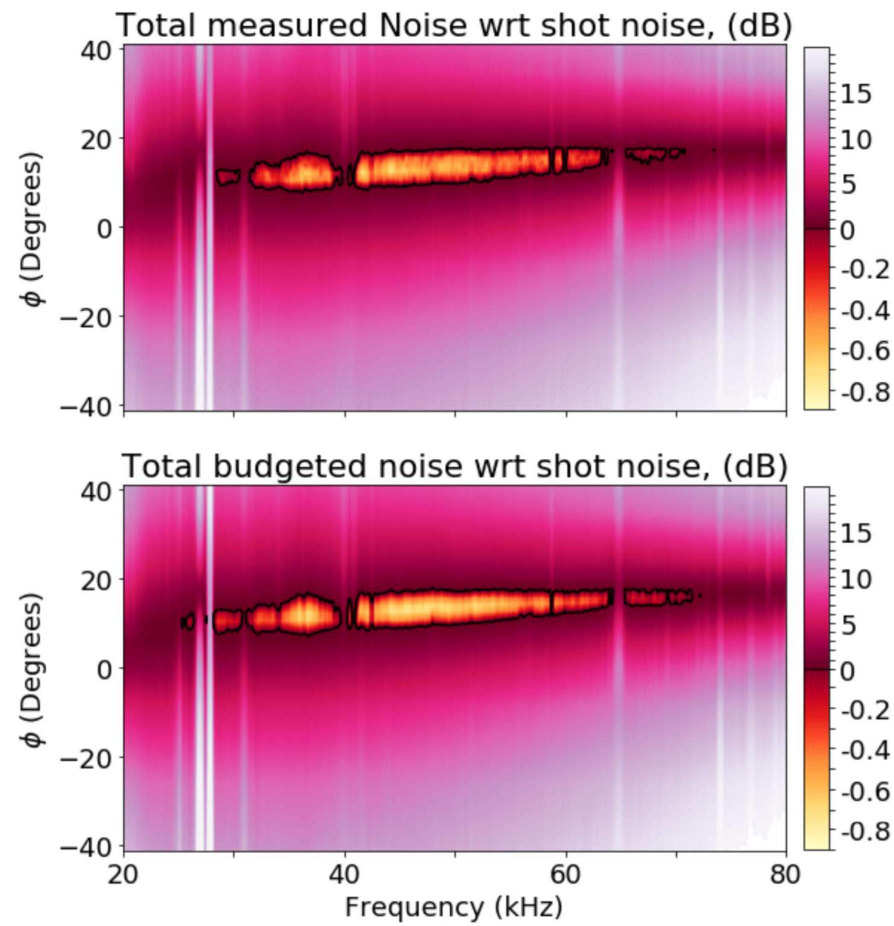
Is it really squeezed?

- Small amount of squeezing might raise skepticism
  - How well is shot noise calibrated?
- Perform independent proof of squeezing using correlation measurements
- Split amplitude squeezed field on beamsplitter, and measure correlations between two detectors
  - Shot noise limited beam: no correlations
  - Classical noise limited beam: positive correlations
  - Amplitude squeezed beam: *negative* correlations
- Inferred squeezing agrees with other measurements



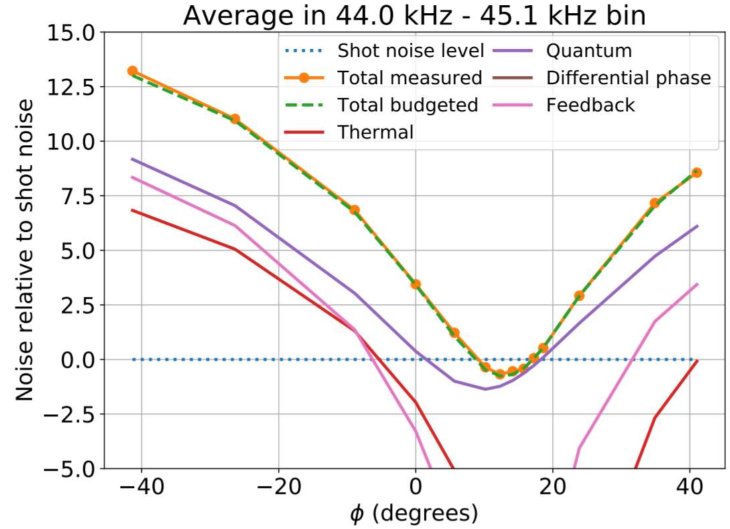
Other quadratures

- Measurements performed at many quadratures.
- Noise is well understood.
- Bright lines correspond (mostly) to mechanical resonances of cantilever.
- Squeezing is very impure (anti-squeezing >> squeezing).

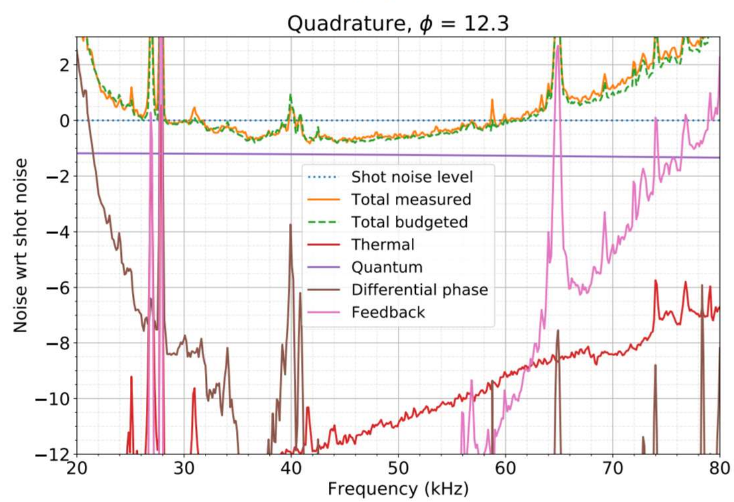


What are the limitations?

- Quantum noise
  - Reduce losses
  - Operate at smaller detuning
- Thermal noise
  - Cryogenic operation
- Feedback noise
  - Subtract
- Differential phase noise (LO – squeezing)
  - Keep LO in vacuum

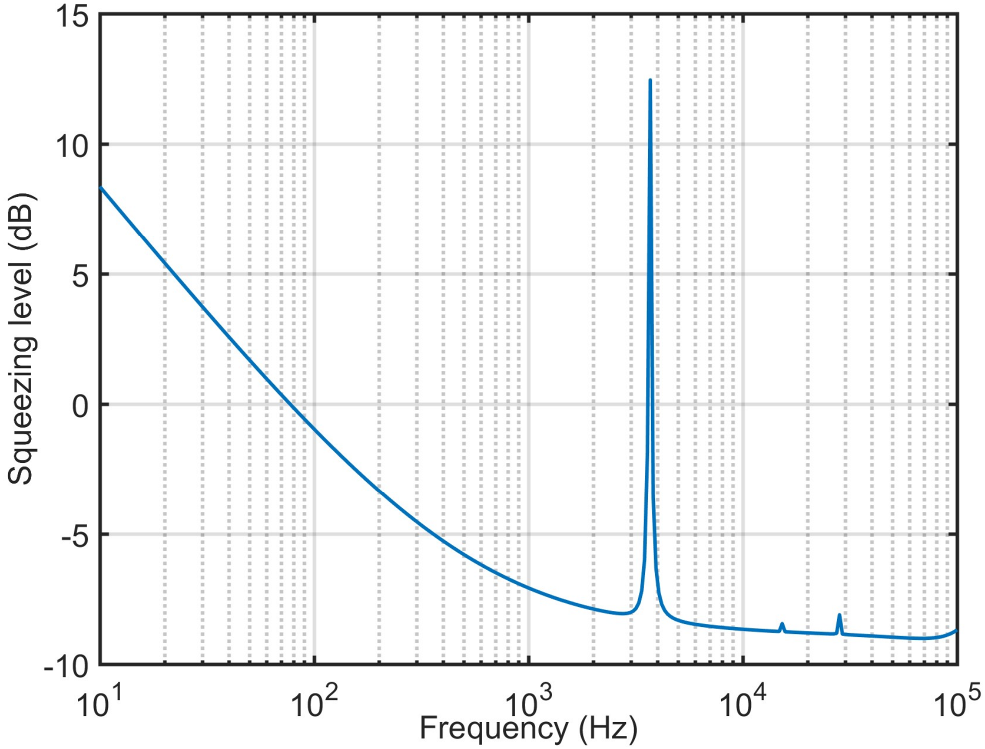


(a)



What if..

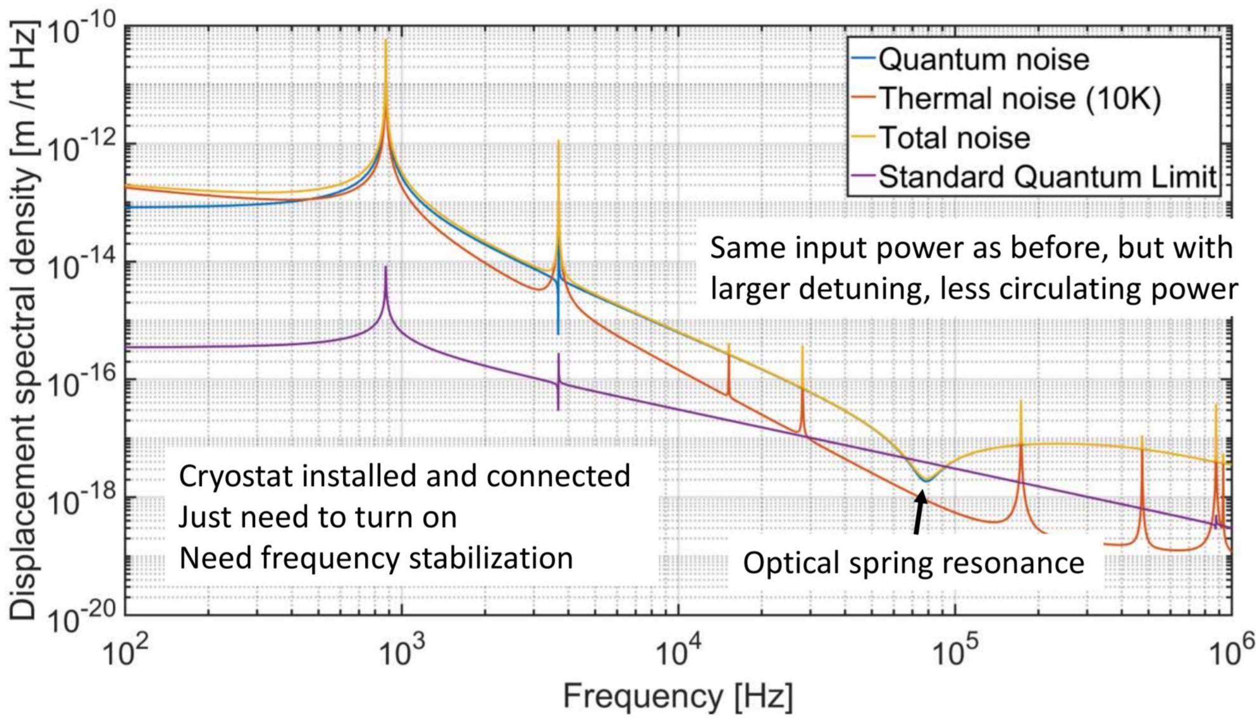
- We use our current devices, but:
- Reduce losses by factor of 10 (not too crazy)
- Operate at 10K (demonstrated base temperature of cantilever with current cryostat)
- Eliminate feedback and LO phase noise



…need different cantilever design for very low frequency

What's next?

- Measure squeezing in double optical spring configuration – eliminates need for feedback
- Measure ponderomotive entanglement
- Sub-SQL experiments



Conclusions

- Operating prototype at this scale is very flexible! In one year:
  - Measured QRPN.
    - J. Cripe, N. Aggarwal, R. Lanza, A. Libson, R. Singh, P. Heu, D. Follman, G. D. Cole, N. Mavalvala & T. Corbitt, *Nature* **568** 364-367 (2019).
  - Reduced QRPN with squeezed light.
    - M. J. Yap, J. Cripe, G. L. Mansell, T. G. McRae, R. L. Ward, B. J.J. Slagmolen, D. A. Shaddock, P. Heu, D. Follman, G. D. Cole, D. E. McClelland, and T. Corbitt, arXiv:1812.09804v1.
  - Coherently cancelled QRPN.
    - J. Cripe, T. Cullen, Y. Chen, P. Heu, D. Follman, G. D. Cole, and T. Corbitt, arXiv:1812.10028v1.
  - Measured ponderomotive squeezing.
    - N. Aggarwal, T. Cullen, J. Cripe, G. D. Cole, R. Lanza, A. Libson, D. Follman, P. Heu, T. Corbitt, N. Mavalvala, arXiv:1812.09942.
- If one wants to study quantum noise, it might make sense to think about prototypes on this scale.