Advanced Characterization and Sensing with Squeezed Optomechanical Systems

Aspen winter workshop: Quantum Information Science for Fundamental Physics, 2/19/2020

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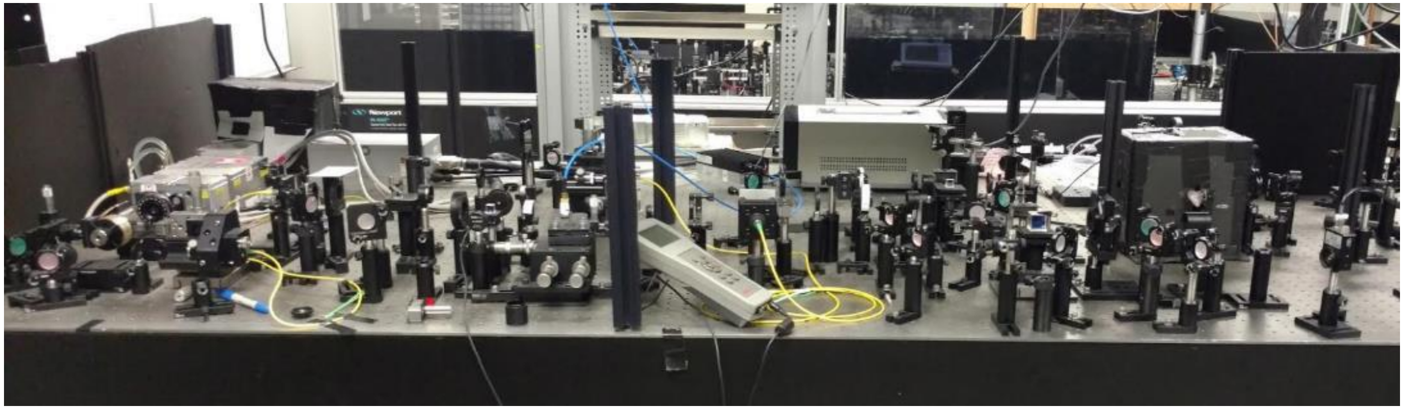
Goal: combine AFM with quantum noise reduction

Quantum optics



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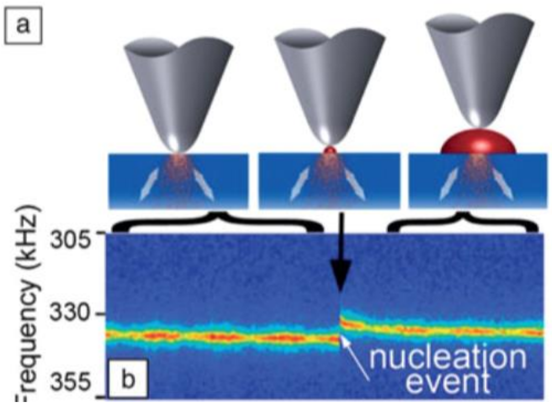
Conventional AFM

=

AFM of broadband material signatures hidden by the SQL in conventional resonance enhanced AFM operation.

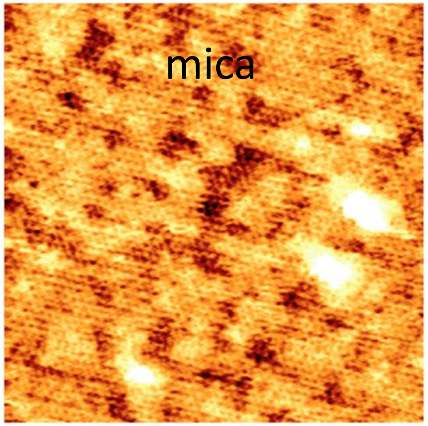
State of the Art of AFM

Resonance-enhanced
Imaging of battery action

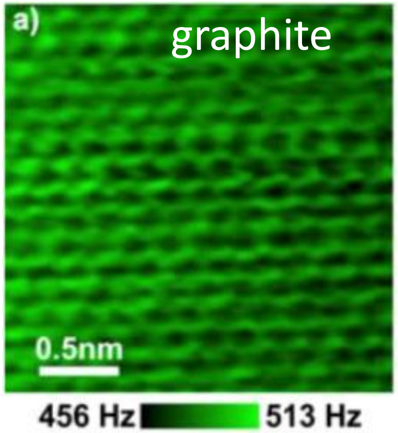


ORNL: Jesse/Balke

Atomic resolution: Resonance-enhanced imaging of atoms in liquid

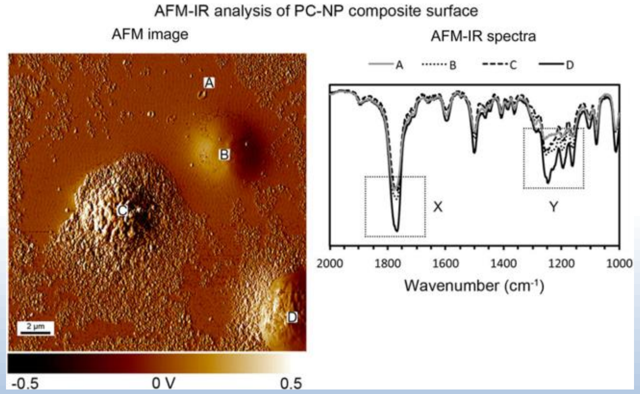


Appl. Phys. Lett. **87**, 034101 (2005)



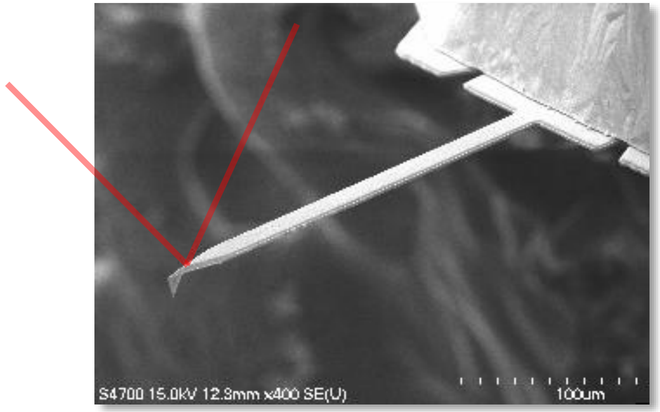
ACS Nano 5 (2014) 5233

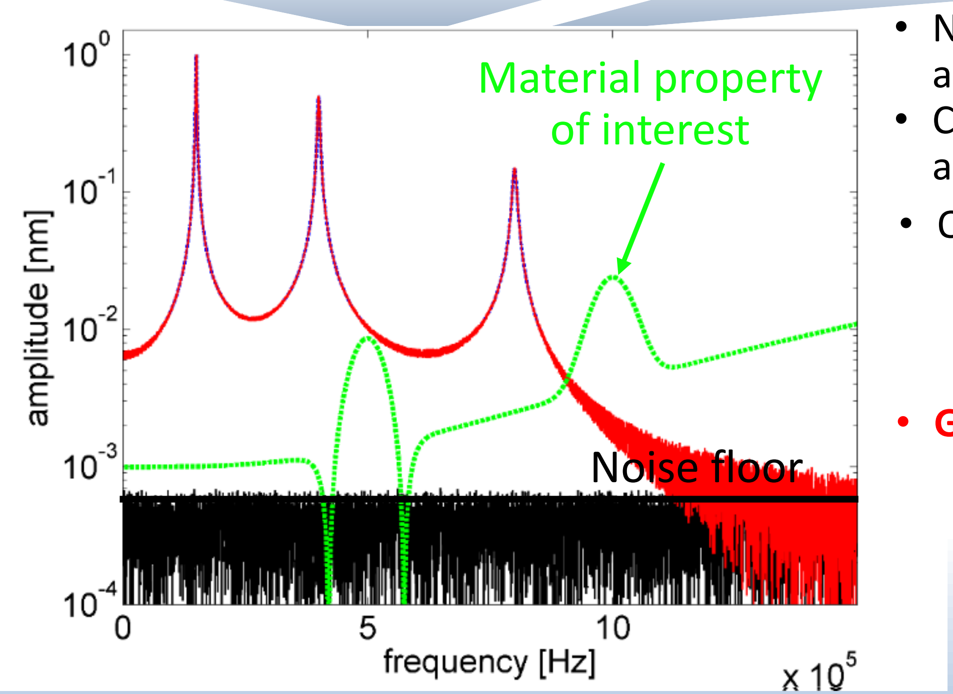
Chemical imaging:
Resonance-enhanced
nanoscale infrared spectroscopy



All of these measurements are made possible by resonance enhancement, but cannot address broadband materials response.

Breaking through the noise floor for broadband force microscopy





- Noise obscures all signals below certain amplitude
- Cantilever acts as a natural narrow band amplifier that works at a few fixed frequencies
- On-resonance measurements:
  - Drastically narrow frequency range
  - Slows measurements due to ringdown
  - Highly susceptible to non-linear dynamics
- **Goal: Lower noise floor to**
  - **Allow measurements at all frequencies (not just on resonances)**
  - Enable fast measurements
  - **Study material properties,**
  - **not cantilever properties!**

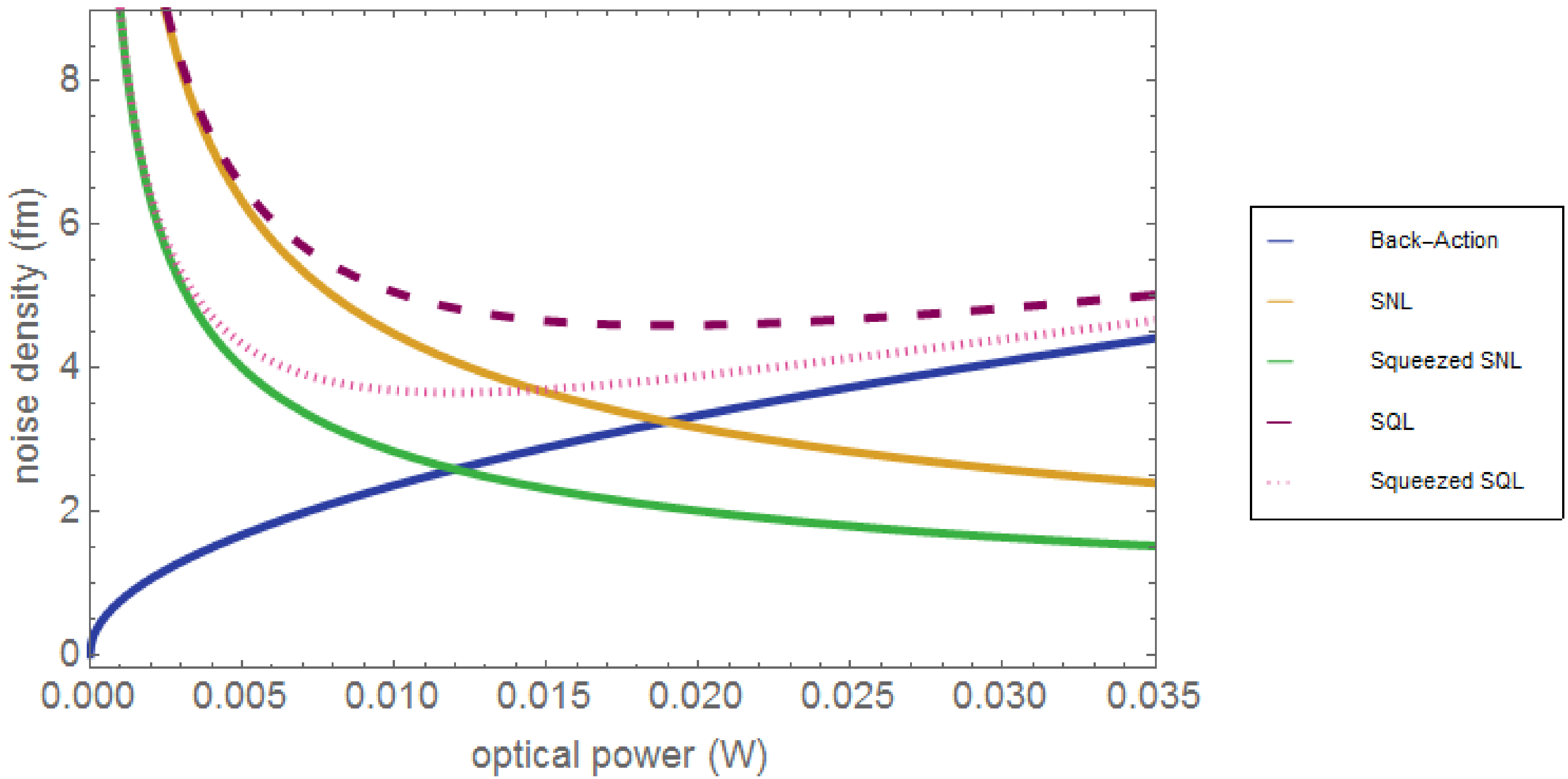
MEMS Noise

1. Thermal noise limit due to cantilever interactions with heat bath,
2. Shot noise limit due to photostatistics
3. Back-action noise limit due to fluctuations in radiation pressure imparted on cantilever.

On resonance, $\langle(\Delta x)^2\rangle_{th} > \langle(\Delta x)^2\rangle_{SQL} = \langle(\Delta x)^2\rangle_{shot} + \langle(\Delta x)^2\rangle_{back}$ above 1 μK.

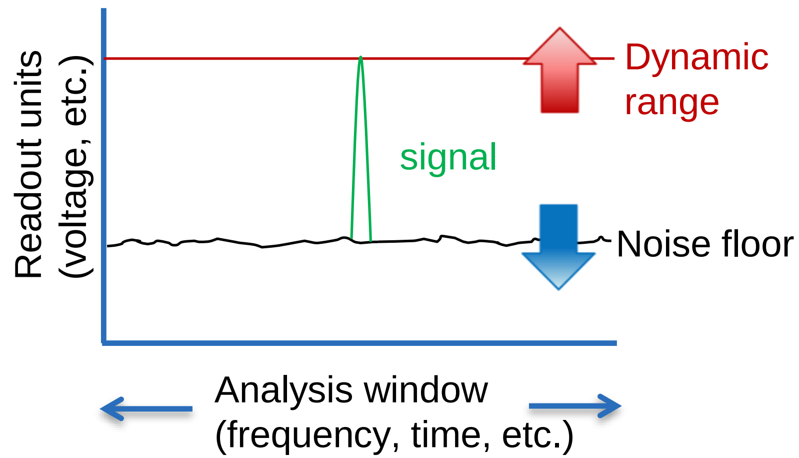
Off-resonance, $\langle(\Delta x)^2\rangle_{th} = \frac{2k_B T\Delta f}{k\pi f_0 Q}$,

$$\left\langle(\Delta x)^2\right\rangle_{shot} = \frac{hc\lambda\Delta f}{8\pi^2 P}, \text{ and } \left\langle(\Delta x)^2\right\rangle_{back} = \frac{8Ph\Delta f}{c\lambda k^2}$$



Detection Limits

- The *fundamental detection limit* is the noise floor of the full sensor as viewed at the backend after all filters and computational analysis

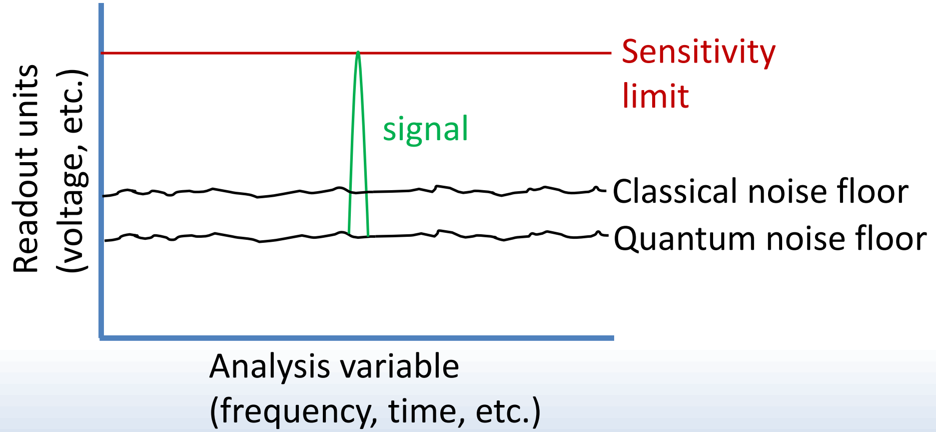


- Our approach increases the signal to noise (SNR) by decreasing the noise floor using **quantum noise reduction (QNR)** and increasing dynamic range using quantum signal modulation

Pushing the Sensing Limits – Quantum Noise Reduction

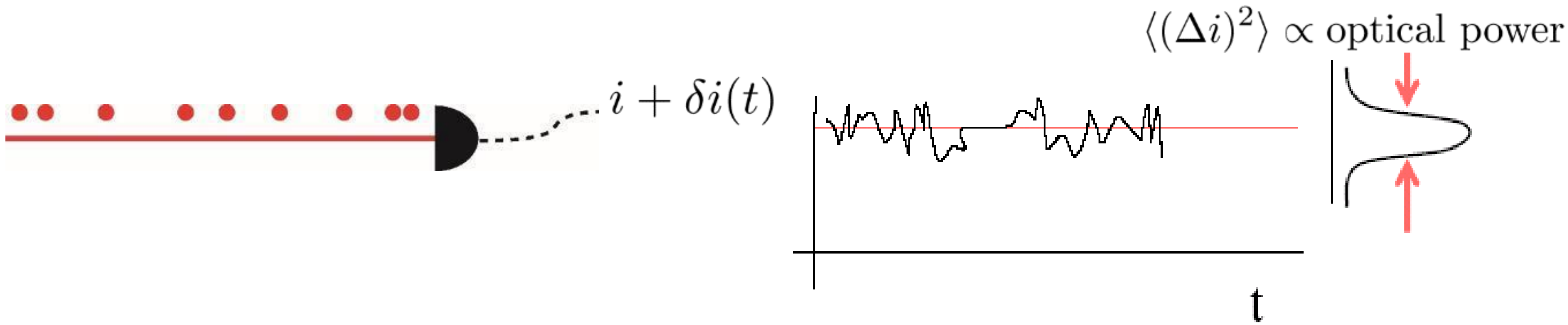
Quantum noise reduction - lowers the noise floor for a signal by exploiting quantum correlations

- In sensors that use light as readout method, quantum statistics of light field can dominate noise floor
- Classical limit determined by technical noise or shot noise of readout light
- Quantum statistics on readout light enables sub-shot noise signal to noise ratios



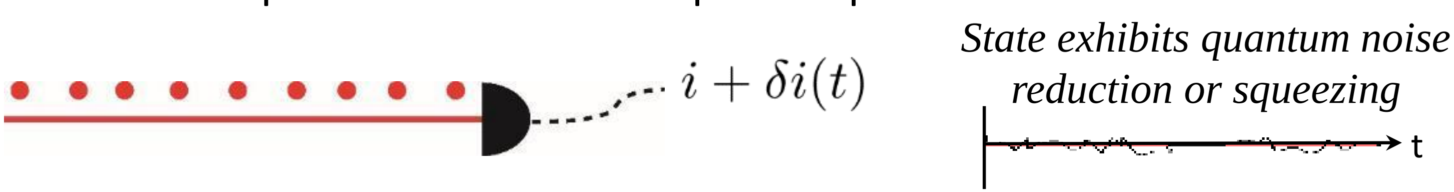
Quantum Noise Reduction

- Quantum noise can be viewed as a result of light being composed of discrete photons with a random temporal distribution.



- This noise represents the shot noise limit (SNL) and is the minimum noise level for a classical state of light.

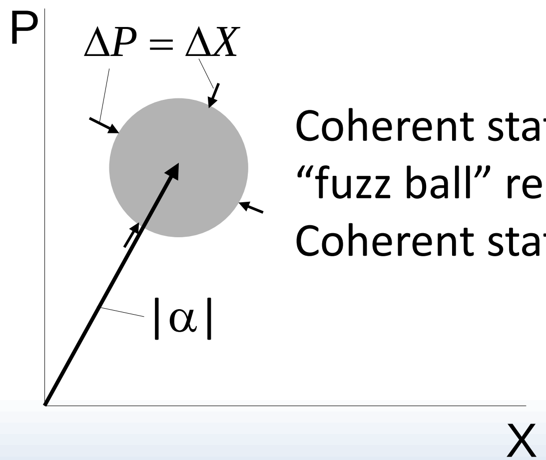
- Can generate states of light with less noise in amplitude through the use of a nonlinear process that can emit pairs of photons.



- Amount of quantum noise reduction increases with strength of nonlinearity.

Quantum noise reduction

- Aka: “squeezing”.
- The Heisenberg uncertainty principle is minimized
  - Squeezed states are minimum uncertainty states, like coherent states
  - $\Delta X \, \Delta P = 1$
- Examine the phase space for the quantum state:



Coherent state
“fuzz ball” represents uncertainty
Coherent state uncertainty = SQL

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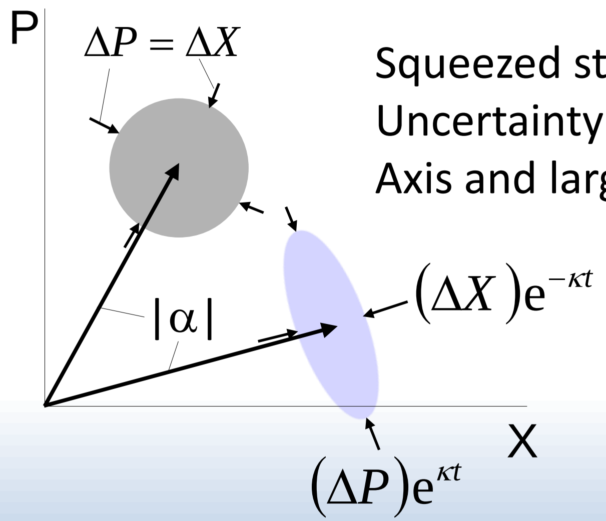
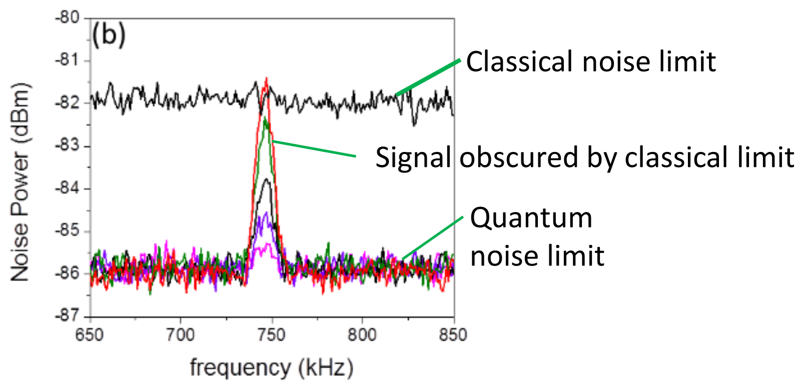


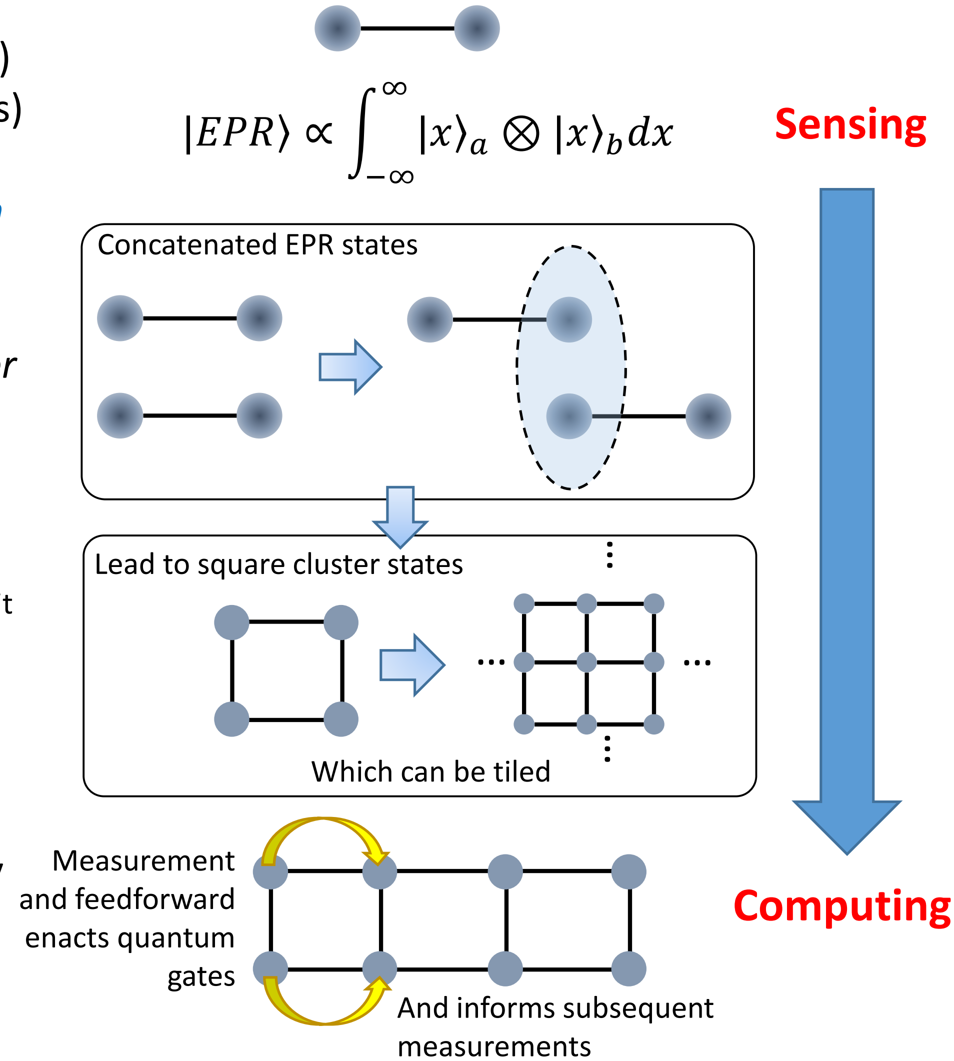
Squeezed state
Uncertainty ellipse is smaller along one
Axis and larger along the other

Quantum Sensing and Quantum Computing Across Quantum Networks

- Quantum networks are collections of qubits (nodes) connected by interactions, or quantum gates (edges)
- Simplest quantum network is the two qubit EPR state or Bell state, *which is a workhorse in quantum sensing*
    - The quantum correlations in EPR quantum networks can be used to *reduce the noise floor in measurements* – **quantum metrology**



- Indefinitely large quantum networks can be built by concatenating EPR states – *the same network is a resource for measurement-based quantum computing and distributed quantum sensors*

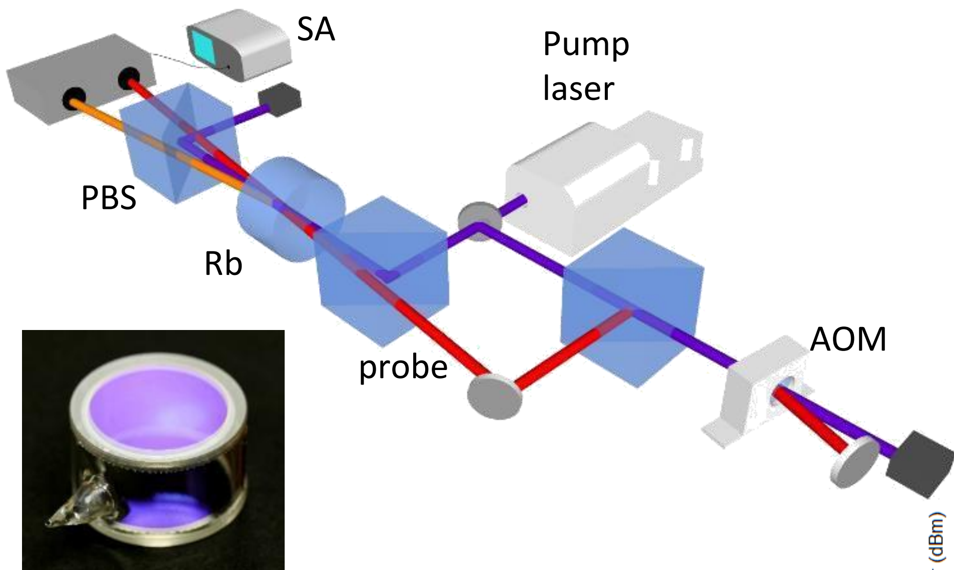


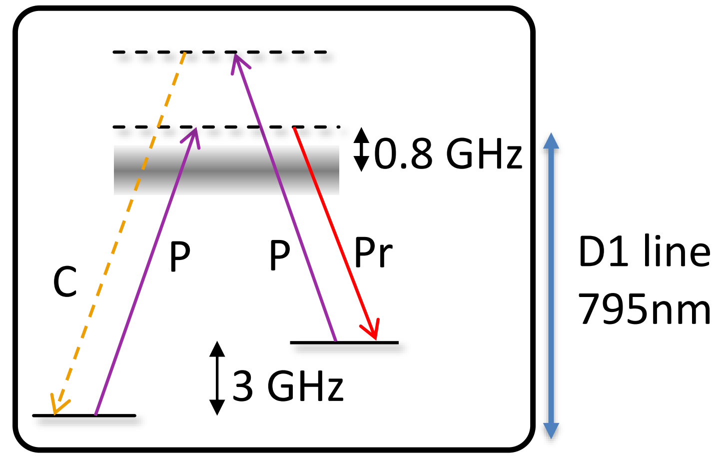
The know-how in generating long range entanglement for quantum sensing lends itself to building quantum computers. This is because in order to make these quantum sensors, one must build a *quantum network* with a *two qubit gate* interaction between the nodes.

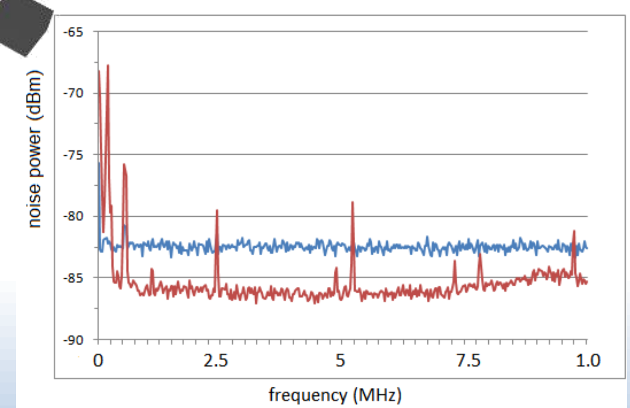
Four wave mixing for CV quantum optics

Generate quantum noise reduction via nonlinear interactions:

Force light fields to interact with themselves via nonlinear optics near atomic resonance in Rb vapor. *Differential detection allows quantum noise reduction*.







10 dB available noise reduction in this system

Science **321**, 544-547
Nature **457**, 859-862

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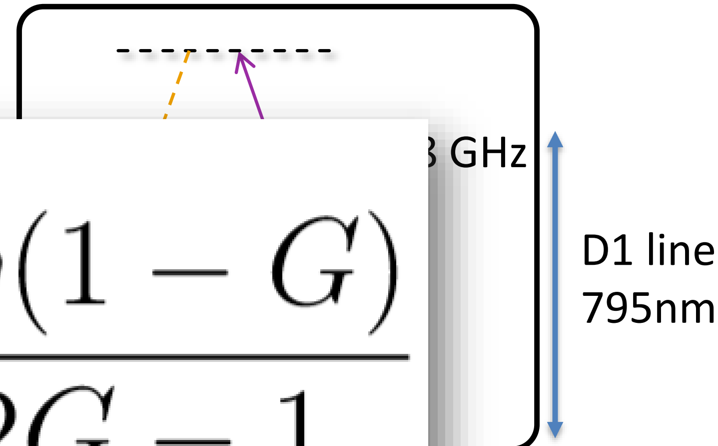
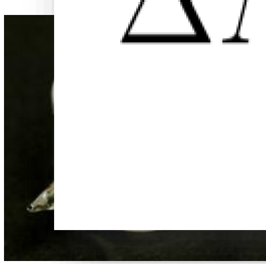
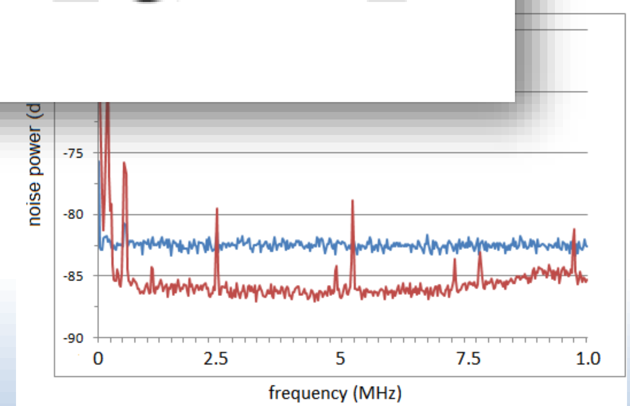
Force light fields to interact with themselves via nonlinear optics near atomic resonance in Rb vapor. *Differential detection allows quantum noise reduction*.



$$\Delta N^2_{-,n} = 1 + \frac{2\eta(1-G)}{2G-1}$$





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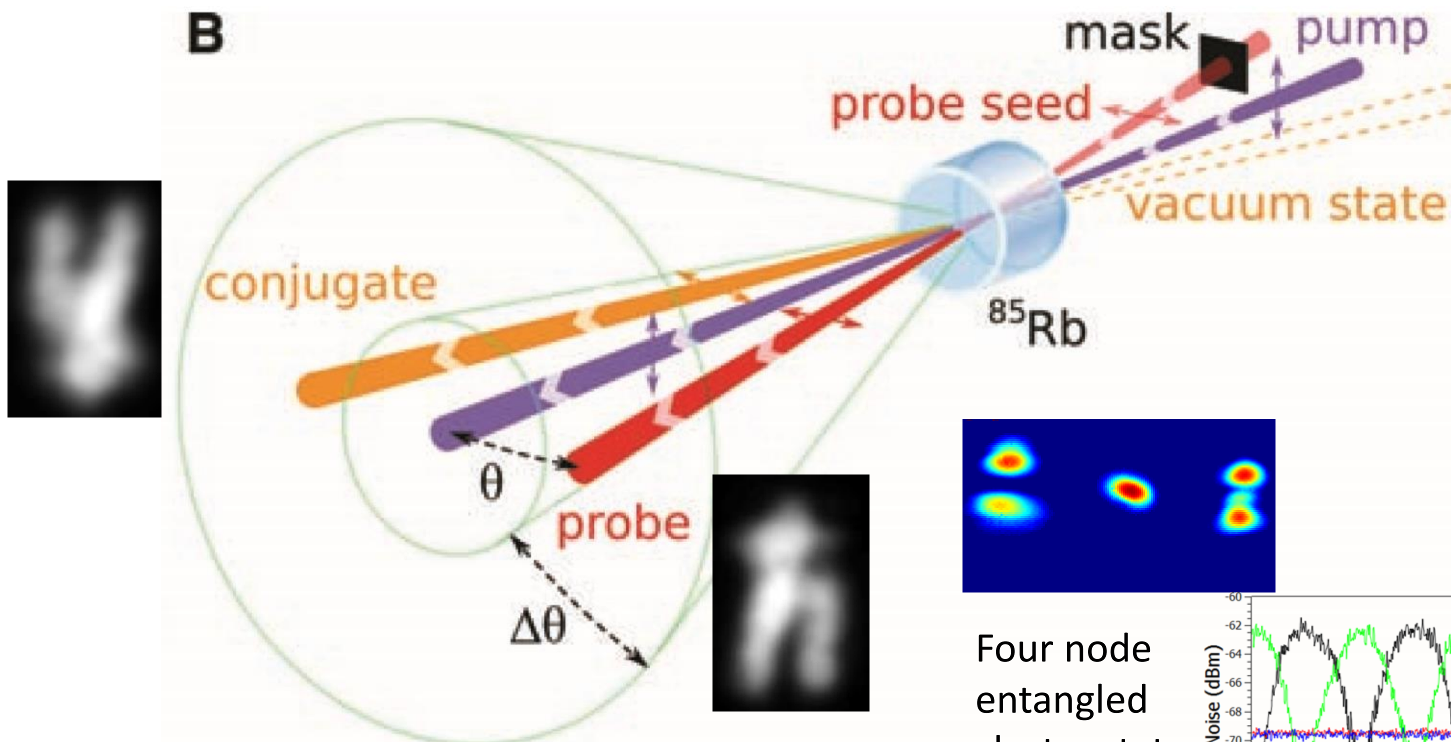
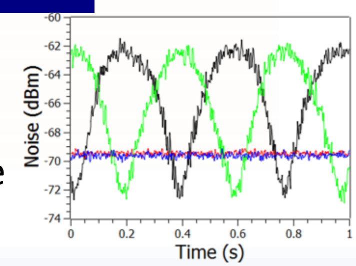
Pretty pictures are possible



Four node entangled cluster state



"anything you can do in the time domain you can do in the spatial domain"

Interferometric Readout

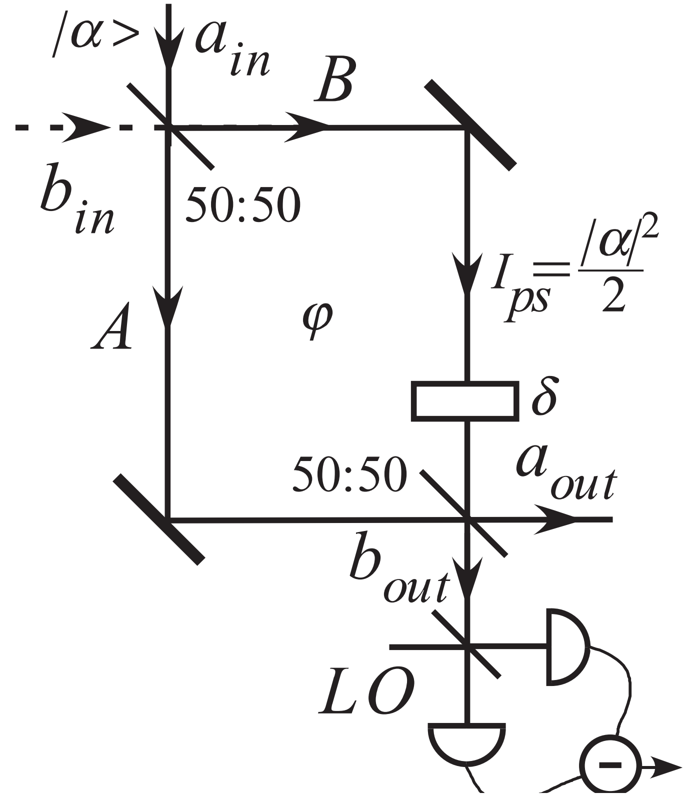
- Linear Interferometry (LI) improves sensitivity (A&P)
  - Ultimate sensitivity governed by the laws of physics: "The Standard Quantum Limit" (SQL)
  - Phase sensitivity (for $N = 2\, I_{PS}$ photons):

$$\delta_{\mathrm{SQL}} = 1/\sqrt{N}$$

  - Most useful metric:

    Signal to Noise Ratio (SNR):

$$\mathrm{SNR}_{\mathrm{LI}} = 2 I_{ps}\,\delta^2$$

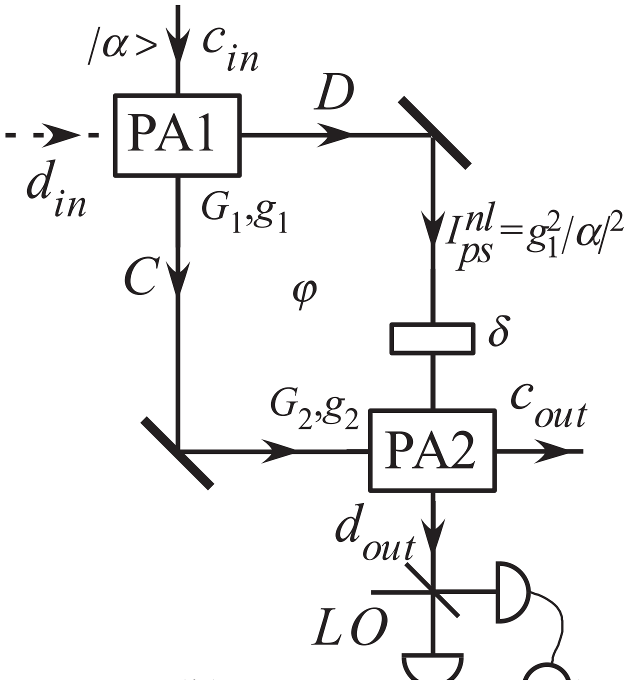


Z. Y. Ou, Phys. Rev. A **85**, 023815 (2012)

Recent Theoretical Innovation

- Non Linear Interferometry (NLI) improves sensitivity over LI:
  - Replace beam splitters with parametric amplifiers (PA)
  - Second PA becomes phase sensitive improves sensing signal
  - Does not change noise, improving SNR
  - For amplitude gain G, the SNR is:

$$G^2 g^2 (4|\alpha|^2 + 2)\delta^2/1 \approx 4G^2 I_{ps}^{nl}\delta^2 \quad \text{for } |\alpha|^2 \gg 1$$

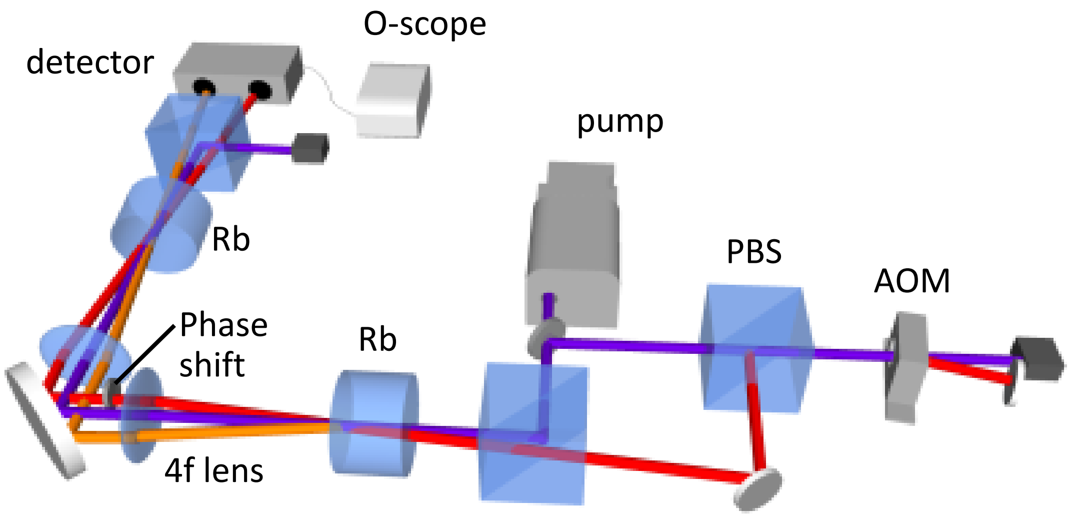


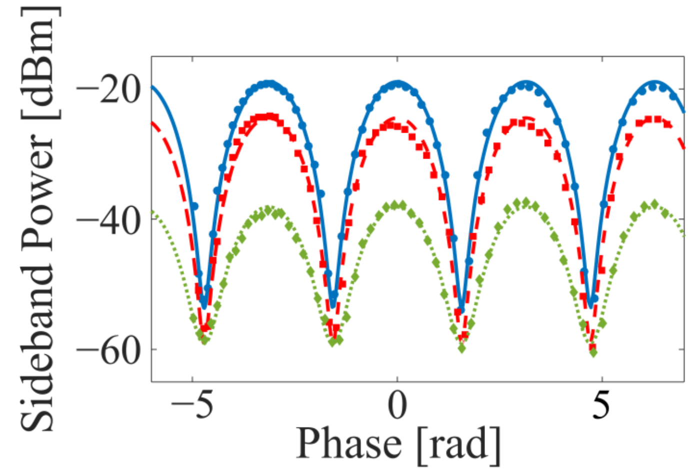
Z. Y. Ou, Phys. Rev. A **85**, 023815 (2012)

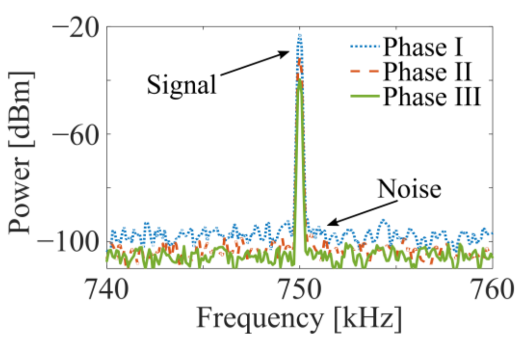
- In this limit, the SNR improvement relative to LI is:

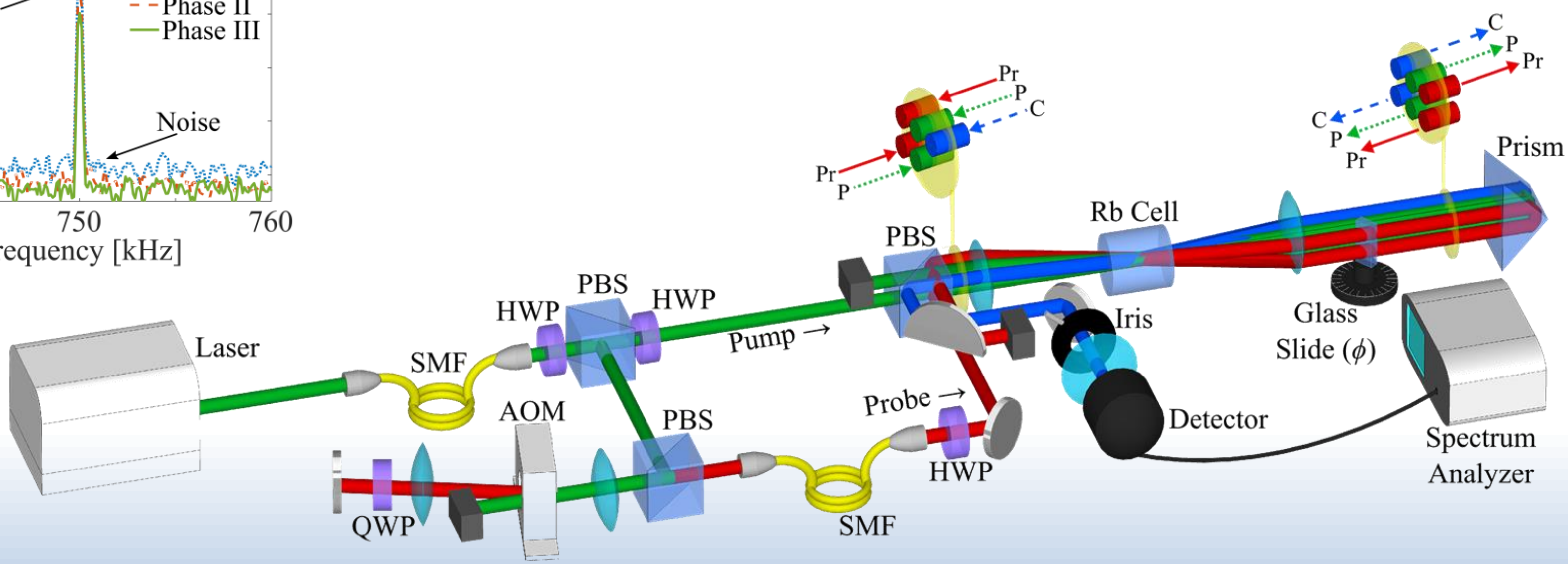
$$SNR_{NLI}/SNR_{LI} \approx 2\,G^2$$

Nonlinear interferometer in Rb vapor





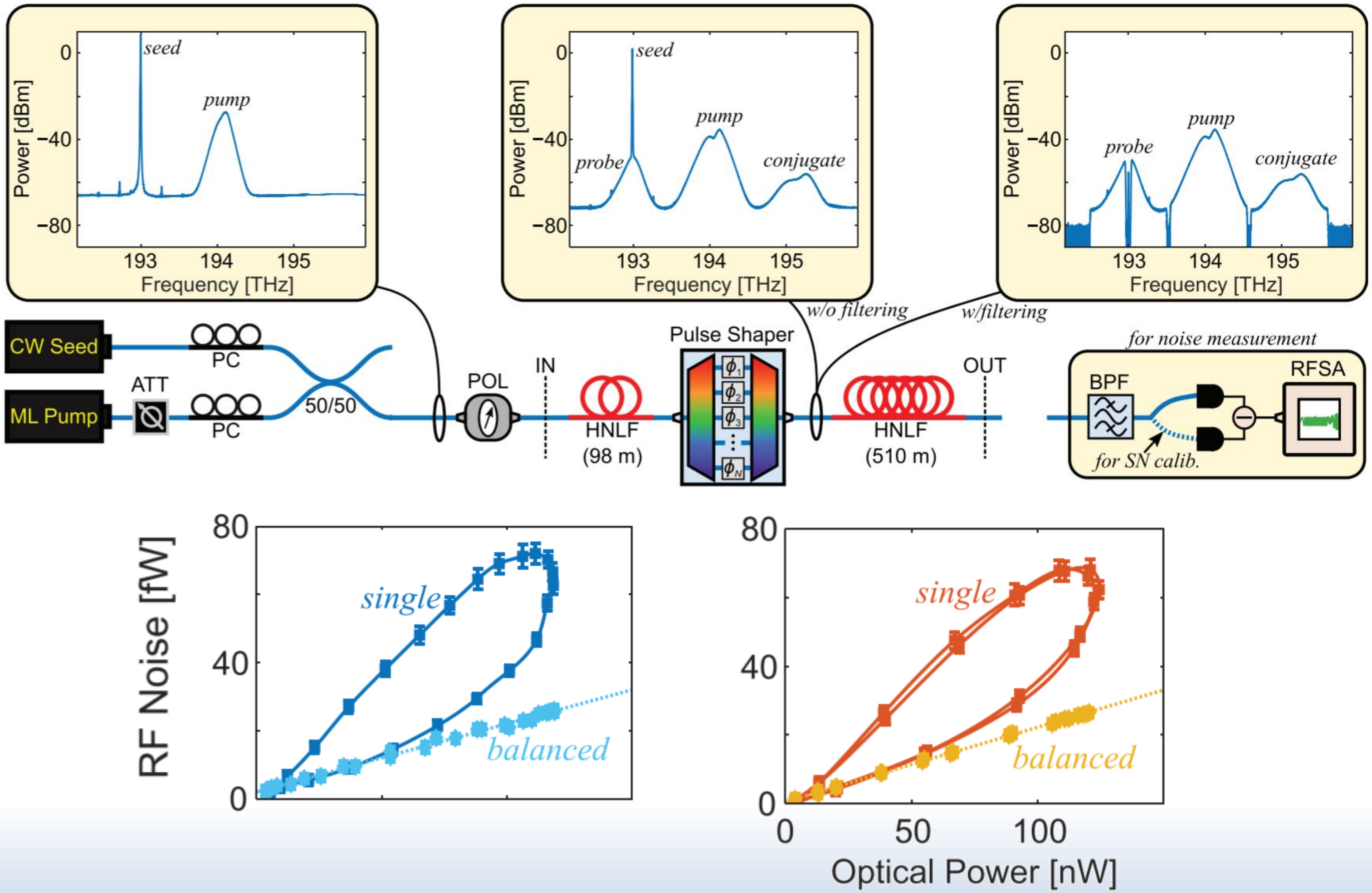




Lukens, Joseph M.; Peters, Nicholas A.; Pooser, Raphael C. Optics Letters 41, 5438-5441 (2016).

Nonlinear interferometer in highly nonlinear fiber

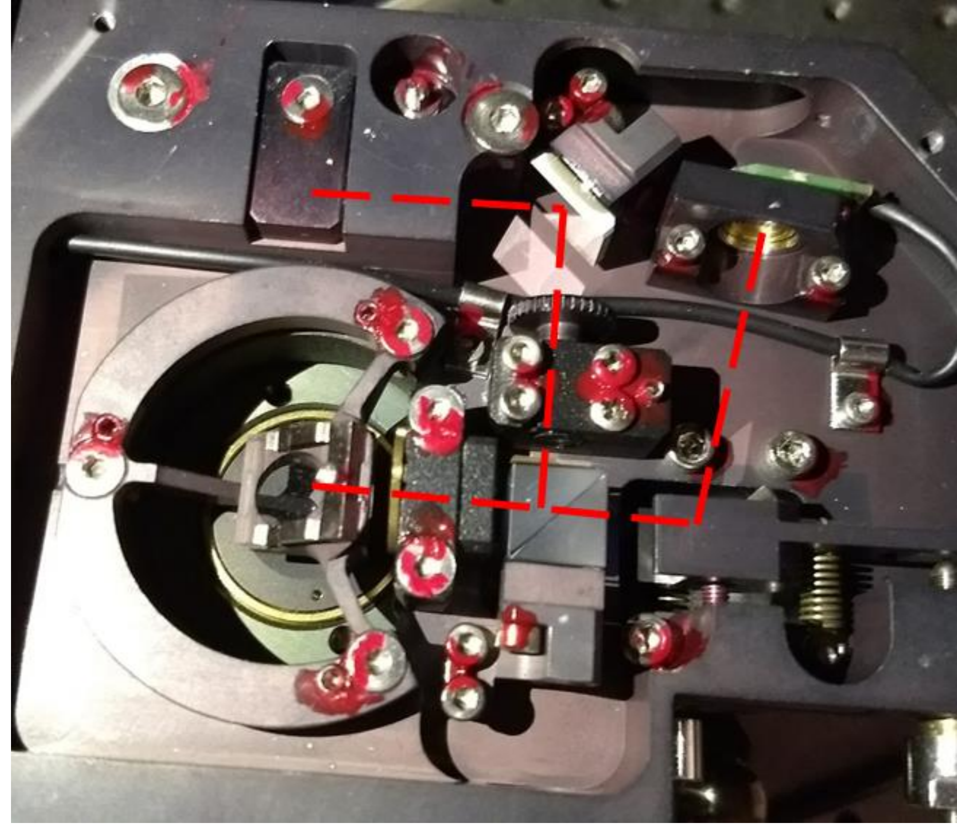
All fiber implementation



Joseph M. Lukens, Raphael C. Pooser, and Nicholas A. Peters, Appl. Phys. Lett. 113, 091103 (2018)

Squeezing in an AFM

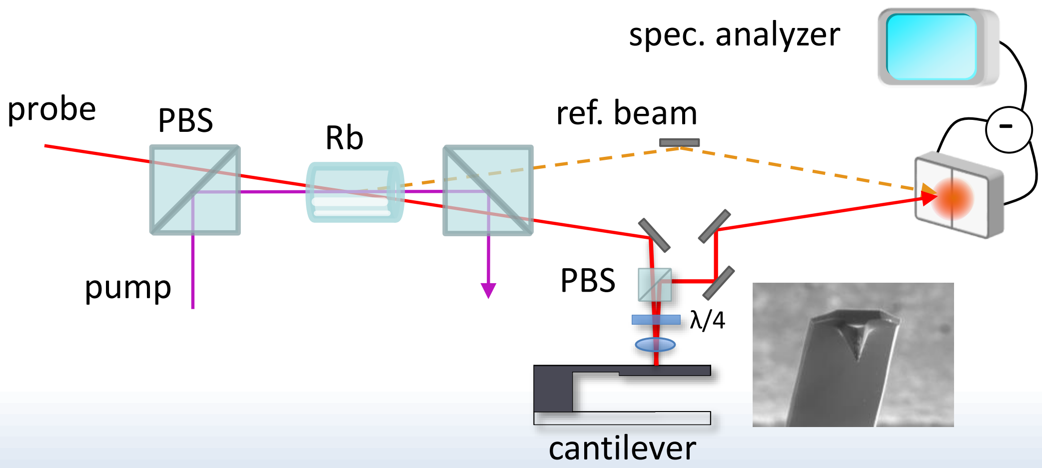
- Free-space optical access enables straightforward replacement of diode source with squeezed source.
- But integrated optics introduce significant losses for combined probe and conjugate field collection on quadrant photodiodes.



Ultra Sensitive MEMS displacement

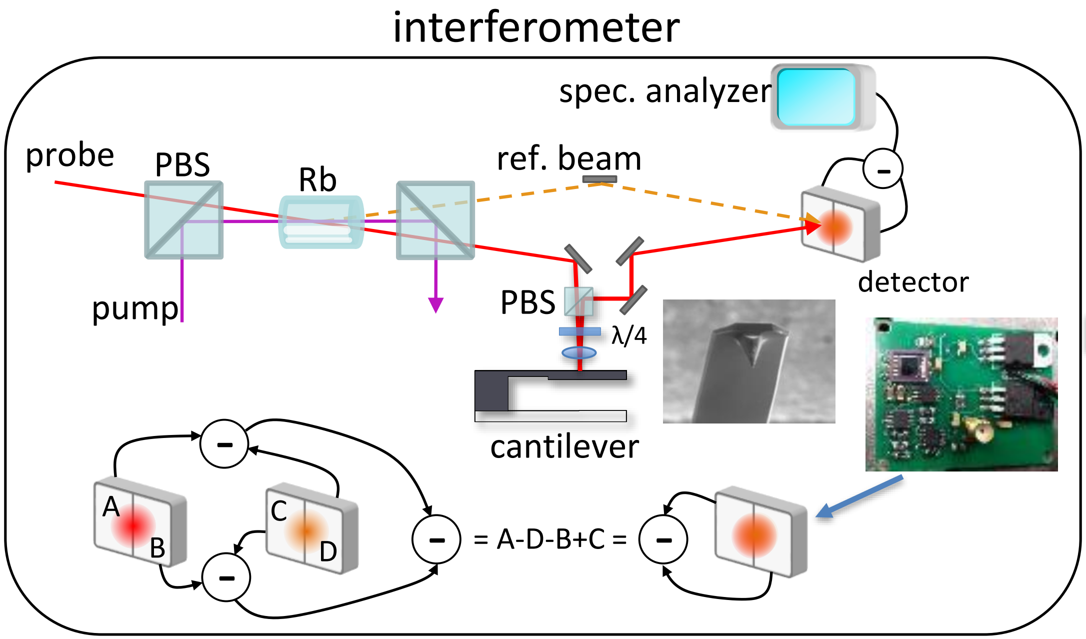
Optical readout noise in microcantilever devices, **such as accelerometers**, can reach the shot noise limit, which determines the absolute noise floor. Measurements below this floor require quantum noise reduction.

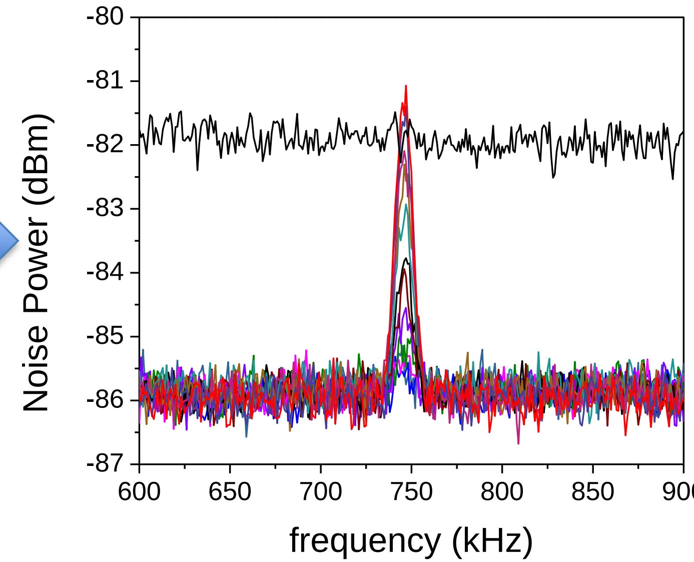
We use twin light beams that exhibit **QNR** when aligned on a spatially resolving detector. This technique reveals MEMS displacement signals previously buried in noise. *Improves off the shelf devices.*



Ultra Sensitive MEMS displacement

Noise floor reduced to less than 40% of the shot noise limit



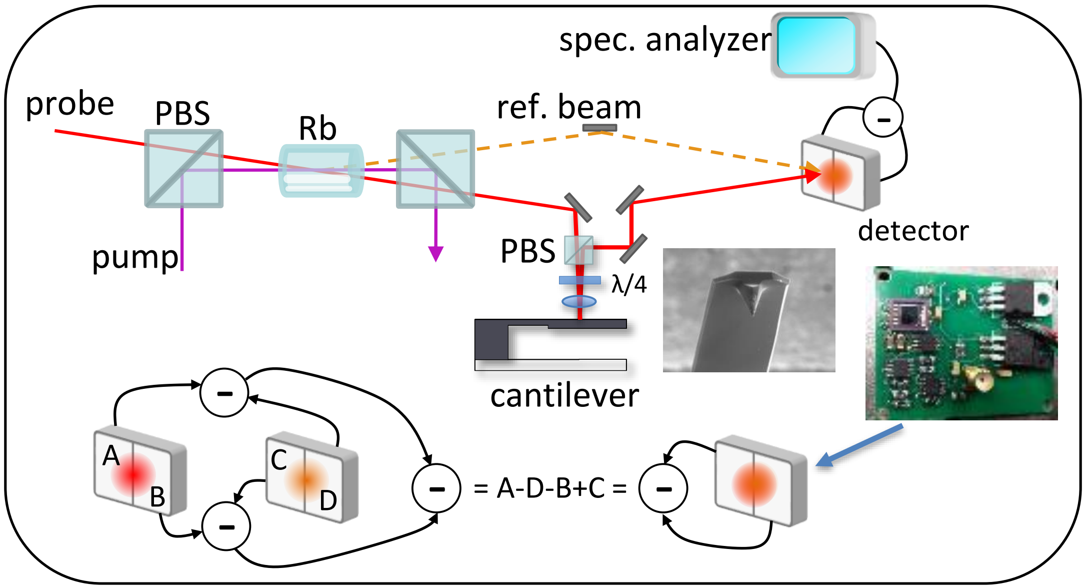


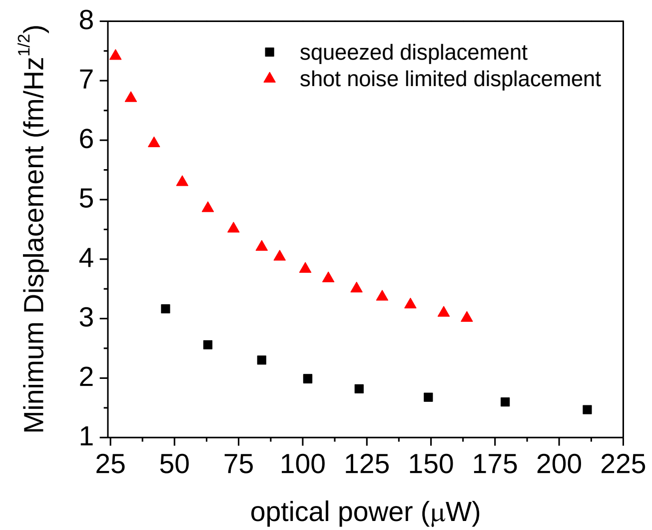
1.35 fm/$\sqrt{\mathrm{Hz}}$ sensitivity

R. C. Pooser, B. Lawrie, Optica 2(5) 393-399 (2015)

Ultra Sensitive MEMS displacement

Enables detection of displacement magnitudes that were previously hidden below the shot noise



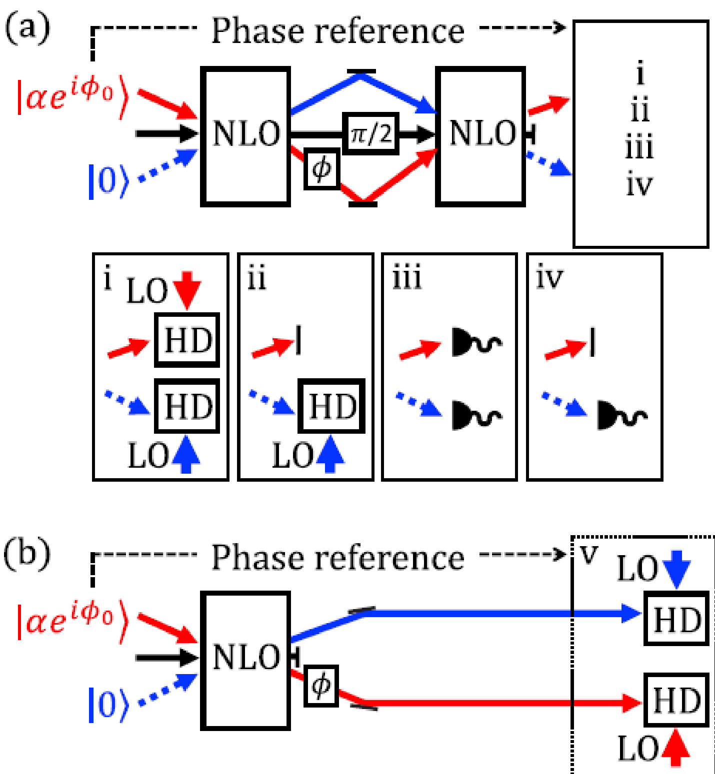


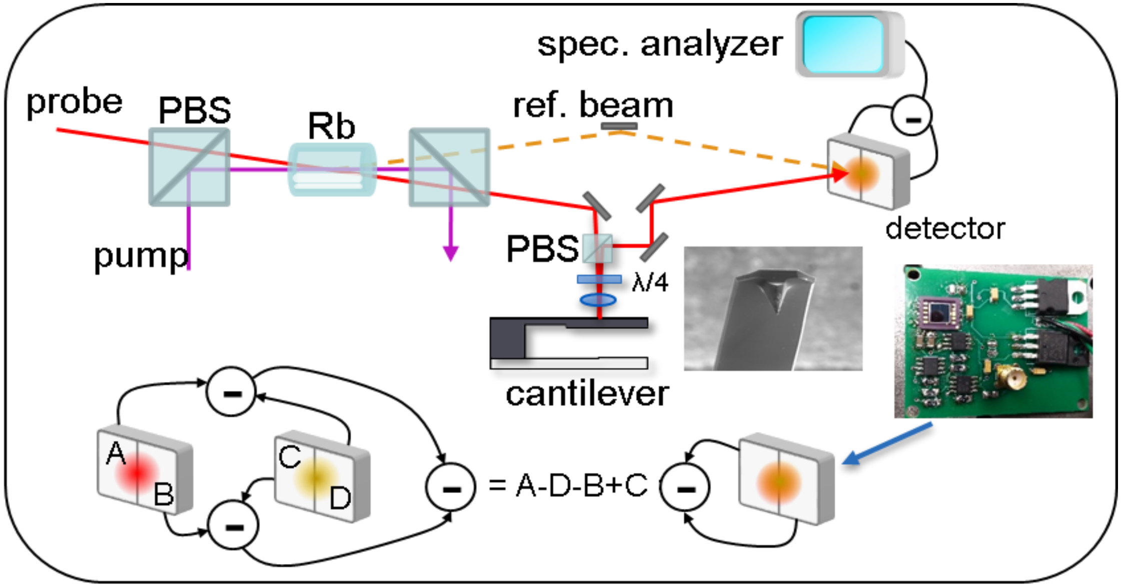
Directly measured SNR for 3.2-3.5 dB squeezing

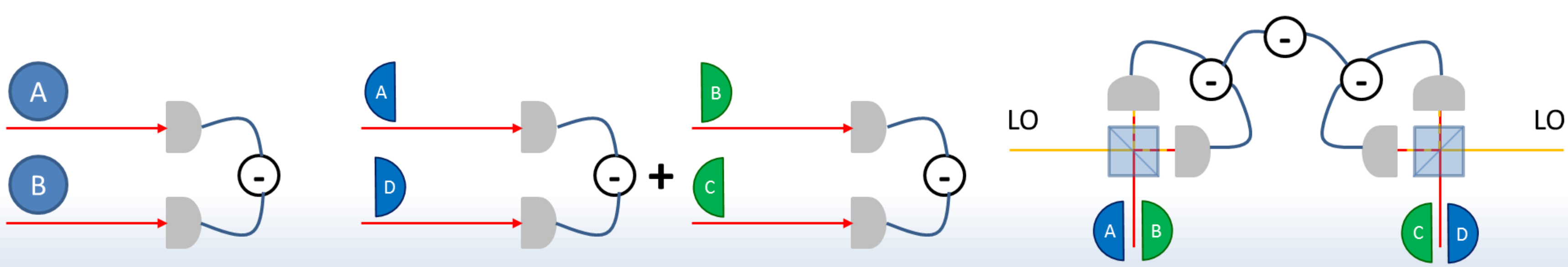
For a given confidence level, detected displacement is well below the classical limit
Alternatively, lower acquisition time by an order of magnitude time for same SNR

R. C. Pooser, B. Lawrie, Optica 2(5) 393-399 (2015)

Nonlinear Interferometers







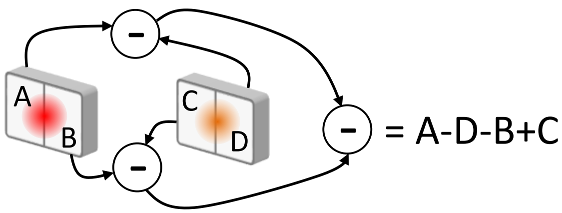
Normal whole beam difference detection

Difference detection of correlated beam portions

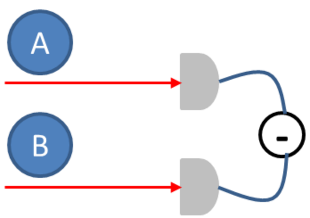
Dual balanced homodyne detection

Beam displacement with multi-spatial-mode squeezing

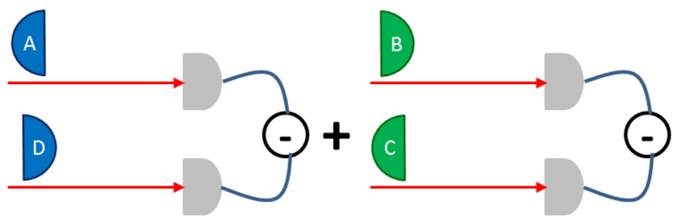
$$\langle \Delta N^2\rangle = \frac{1}{P_0}\left[\underbrace{\frac{P_s n_s}{(2G-1)}}_{\text{Noise in single mode case}} + \underbrace{\left(\sum_{i=1}^{M}\frac{P_i(x)n_i'(x)}{\eta_d(2G-1)}\right)}_{\text{Noise for multiple modes}}\right]$$



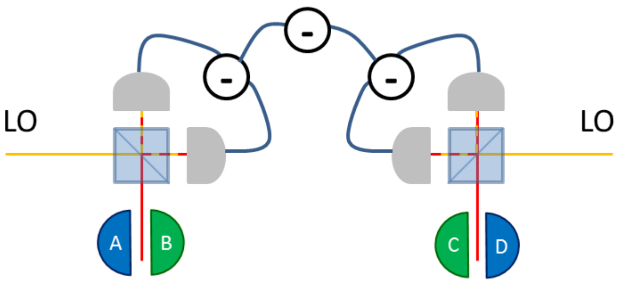
But split detection is equivalent to dual homodyne detection



Normal whole beam difference detection



Difference detection of correlated beam portions



Dual balanced homodyne detection

Single beam displacement equivalent to single beam homodyne detection (Barnett, Fabre, Maitre, Eur. Phys. J. D **22**, 513-519 (2003).

Homodyne detection

- Phase sum and amplitude difference show noise reduction for misaligned modes

$$\Delta p_+^2 = \frac{P_0}{P_{\text{tot}}}[1 + 2\eta_d(G - 1 - \sqrt{G(G-1)}]$$

$$+ \sum_{i=1}^{N} \frac{P_i}{P_{\text{tot}}}[1 + 2\eta_i(G - 1 - \sqrt{G(G-1)}]$$

$$+ \sum_{i=1}^{N} \frac{(P_{\text{tot}} - P_0 - P_i)}{P_{\text{tot}}}[1 + 2\eta_i(G - 1)]$$

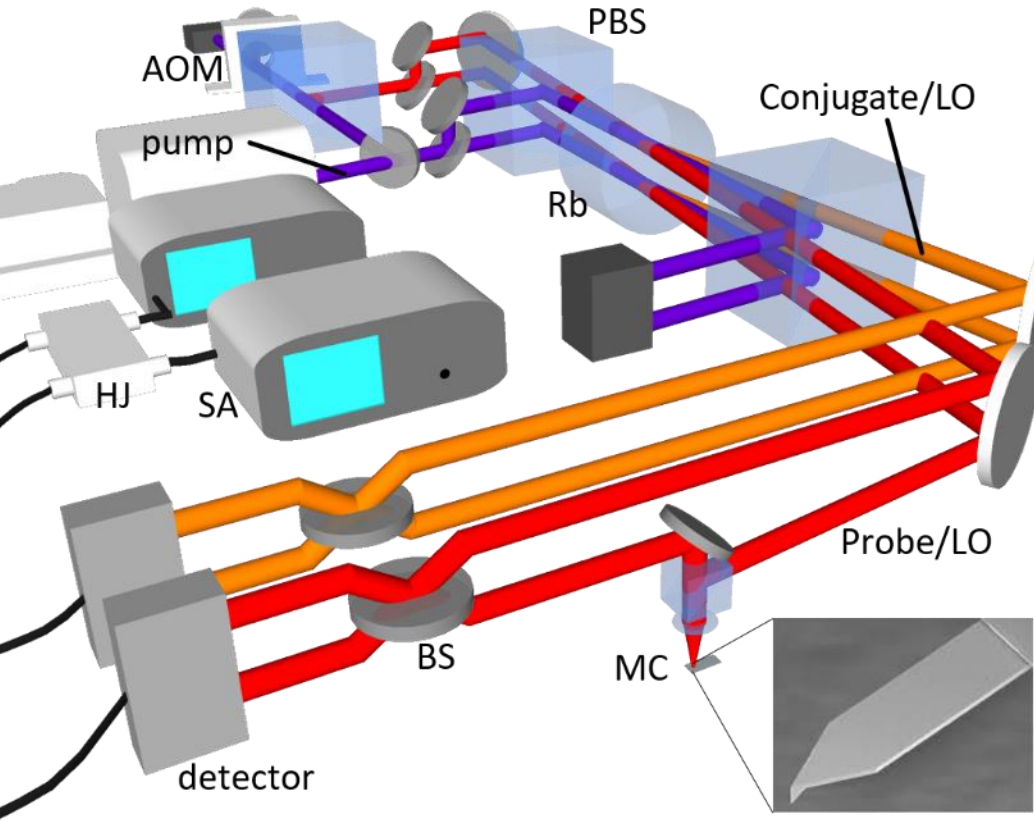
- For *pure* phase, noise equivalent to two-mode-squeezed source

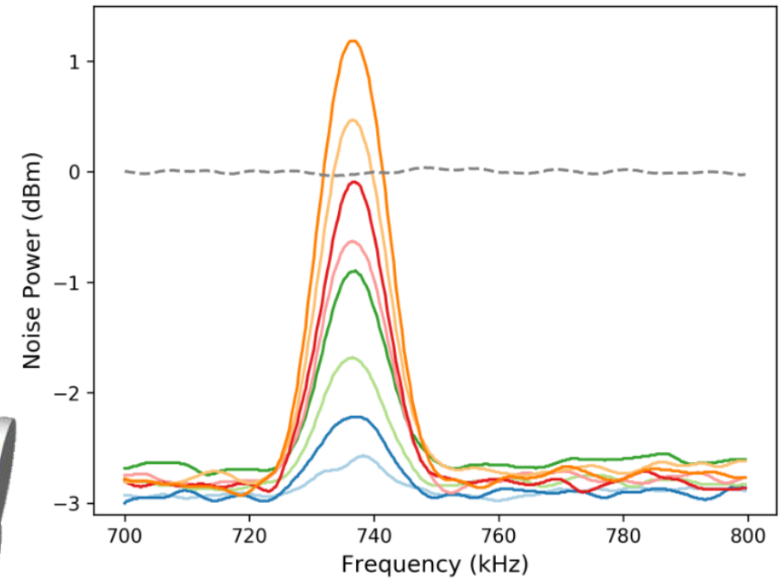
$$\Delta p_+^2 = 1 + 2\eta[G - 1 - \sqrt{G(G-1)}]$$

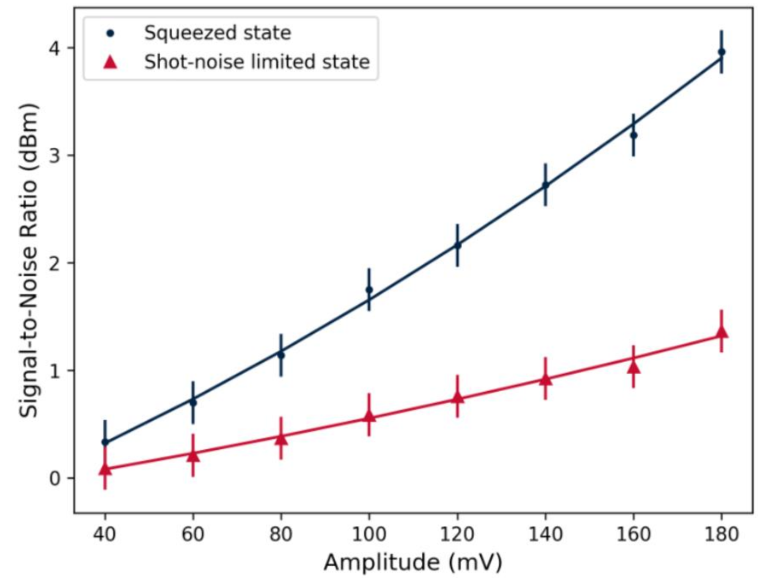
$$p_+ = p_i + p_j + \Delta\varphi$$

$$\Delta\varphi = n\Delta d$$

Nonlinear Interferometric AFM imaging







Conclusion

- Quantum-enhanced readout from MEMS devices
  - Direct detection
  - Interferometric readout
- Augment commercial AFMs
  - Replace diode laser with squeezed light source
- Need to control losses to be practical

Thanks!

- W. M. Keck foundation
- DOE BES
- ORNL LDRD program
- SULI program
- Intelligence community postdoc program
- ORNL CNMS
- Office of Naval Research

Collaborators

- Ben Lawrie (ORNL)
- Stephen Jesse (ORNL)
- Jeff Garcia (intern)
- Nick Peters
- Joe Lukens
- Nick Savino
- Emma Batson
- Nick Black
- Miller Eaton