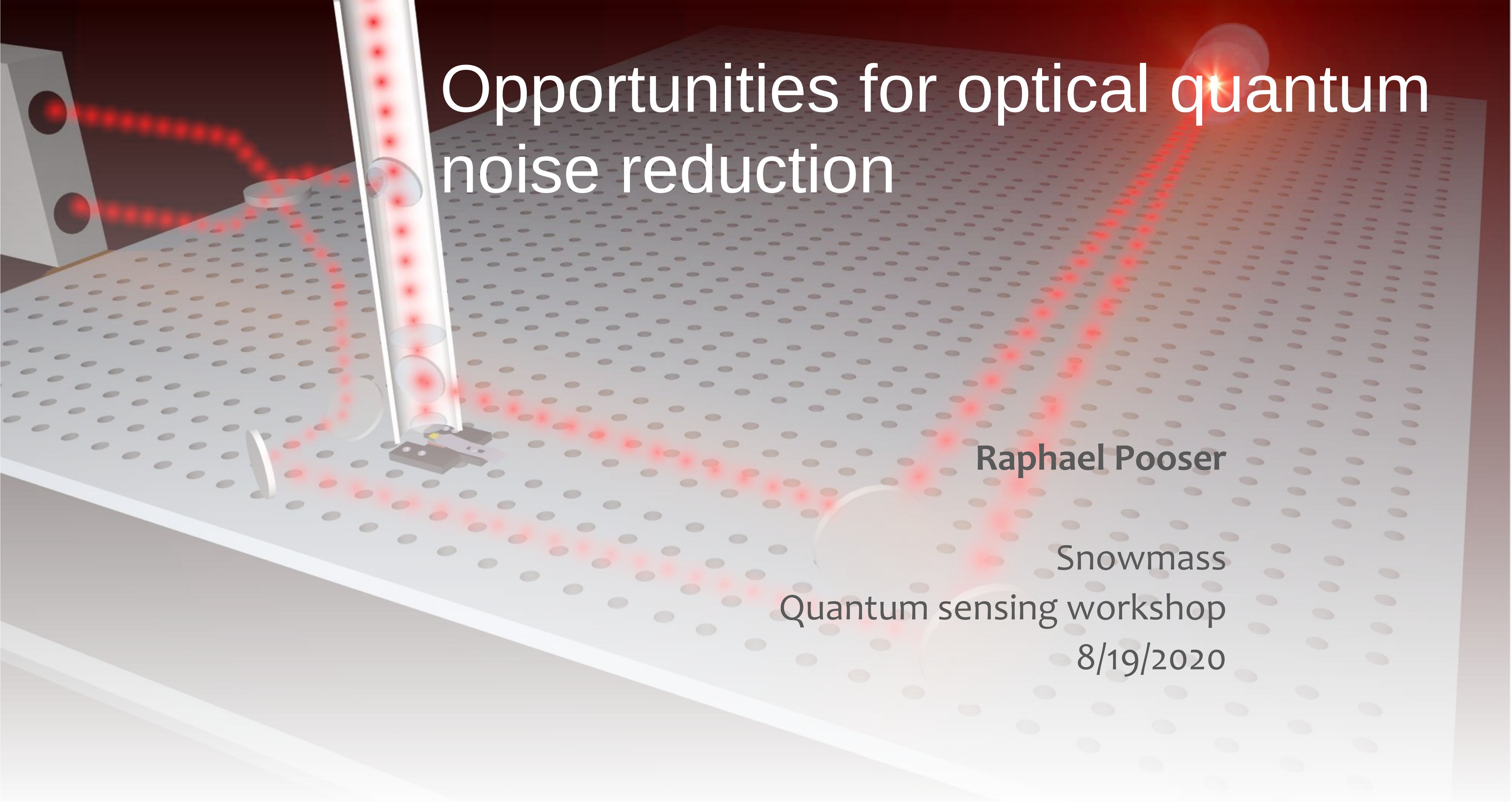


Opportunities for optical quantum noise reduction

Raphael Pooser

Snowmass

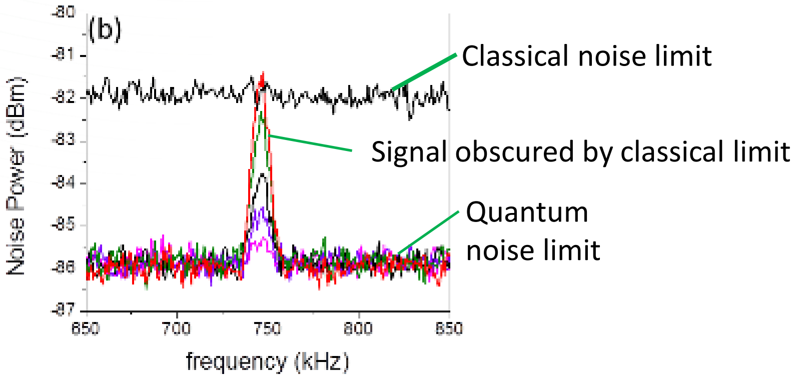
Quantum sensing workshop

8/19/2020

Quantum Sensing and Quantum Computing Across Quantum Networks

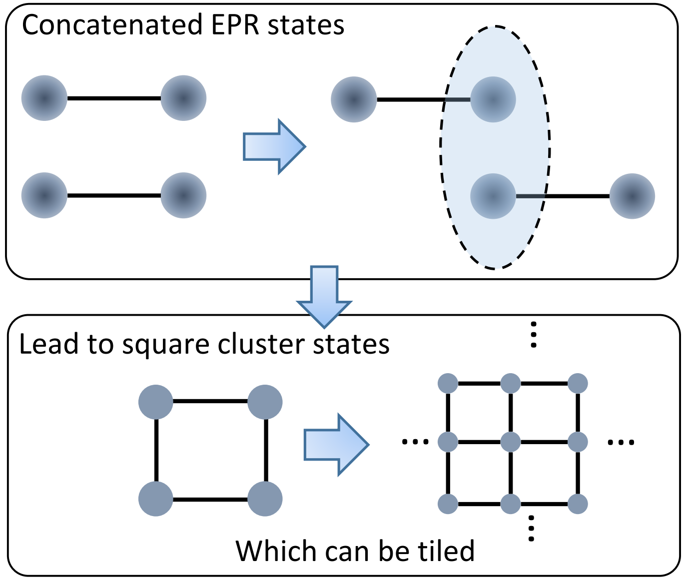
OAK RIDGE National Laboratory

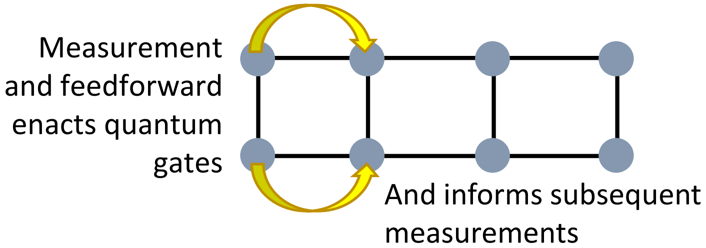
- Quantum networks are collections of qubits (nodes) connected by interactions, or quantum gates (edges)
- Simplest quantum network is the two qubit EPR state or Bell state, *which is a workhorse in quantum sensing*
  - The quantum correlations in EPR quantum networks can be used to *reduce the noise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

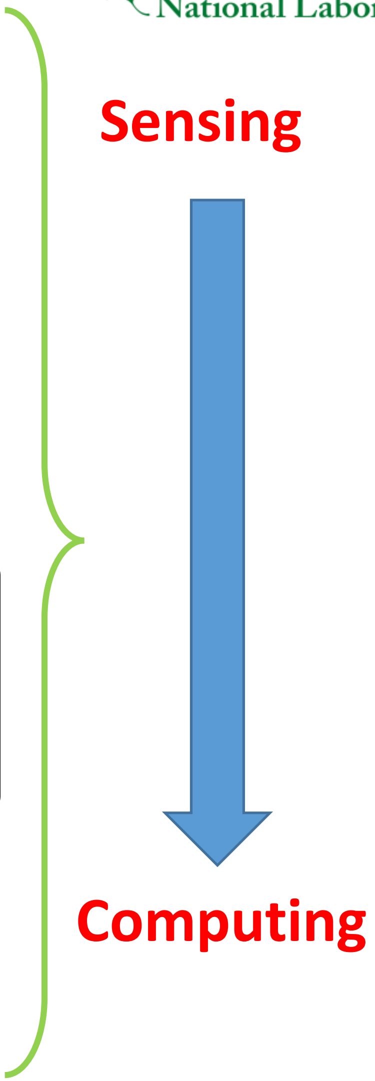


- Indefinitely large quantum networks can be built by concatenating EPR states – *the same network is a resource for measurement-based quantum computing and distributed quantum sensors*

$$|EPR\rangle = \int_{-\infty}^{\infty} |x\rangle_a \otimes |x\rangle_b dx$$

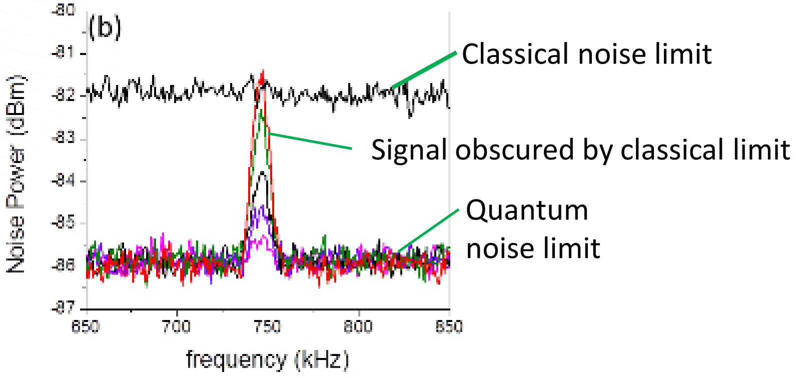






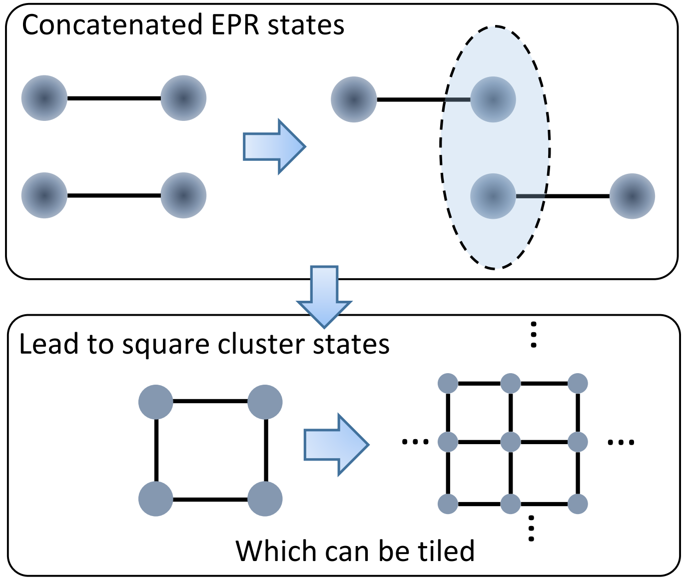
Quantum Sensing and Quantum Computing Across Quantum Networks

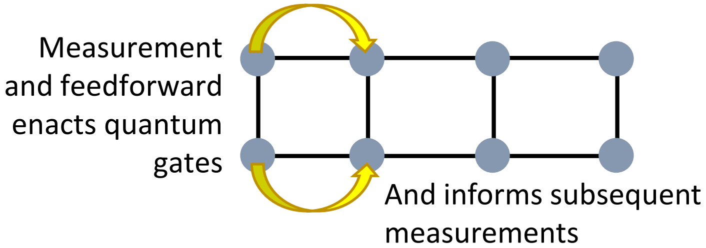
- Quantum networks are collections of qubits (nodes) connected by interactions, or quantum gates (edges)
- Simplest quantum network is the two qubit EPR state or Bell state, *which is a workhorse in quantum sensing*
  - The quantum correlations in EPR quantum networks can be used to *reduce the noise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

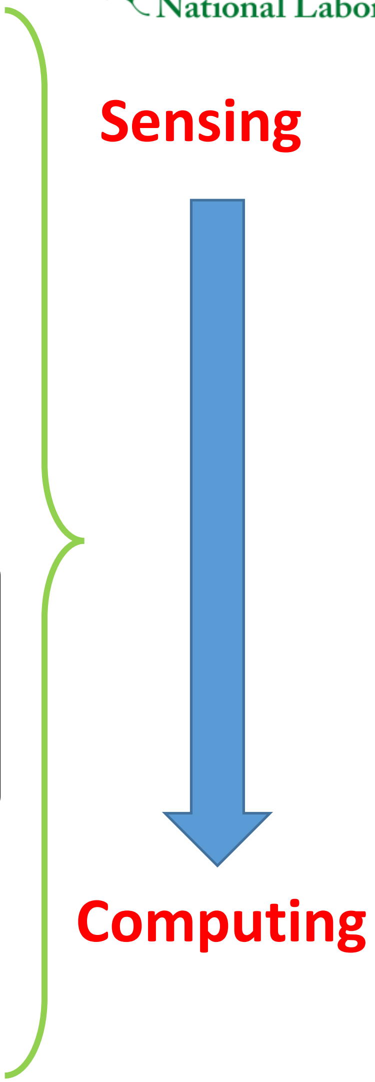


- Indefinitely large quantum networks can be built by concatenating EPR states – *the same network is a resource for measurement-based quantum computing and distributed quantum sensors*

$$|EPR\rangle = \int_{-\infty}^{\infty} |x\rangle_a \otimes |x\rangle_b dx$$







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.

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

$$|EPR\rangle = \int_{-\infty}^{\infty} |x\rangle_a \otimes |x\rangle_b dx$$

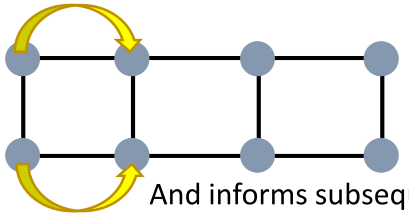
Sensing

Motivation:
- Build quantum networks of sensors with entangled states
- Construct, e.g., stabilizer code and perform joint measurements to detect syndromes on the network
- Quantum noise reduction (QNR) is a signature of this type of entanglement
- Harness QNR and networks to obtain Heisenberg scaling across large geo-distributed networks for HEP experiments

Also see Dan Carney and Juehang Qin's talks for more motivation

frequency (kHz)

- 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*



Computing

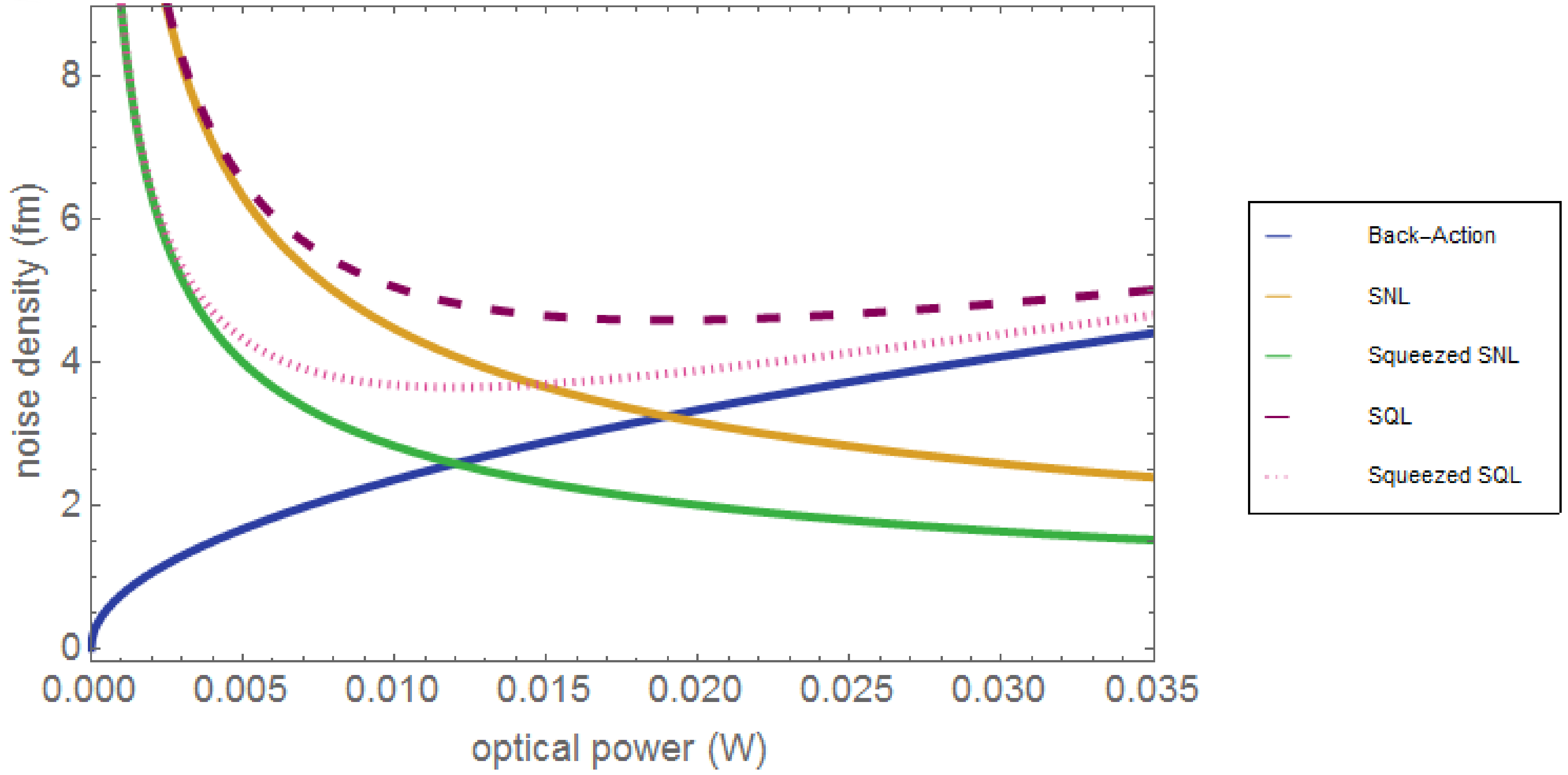
Optomechanics (MEMS) Noise

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.

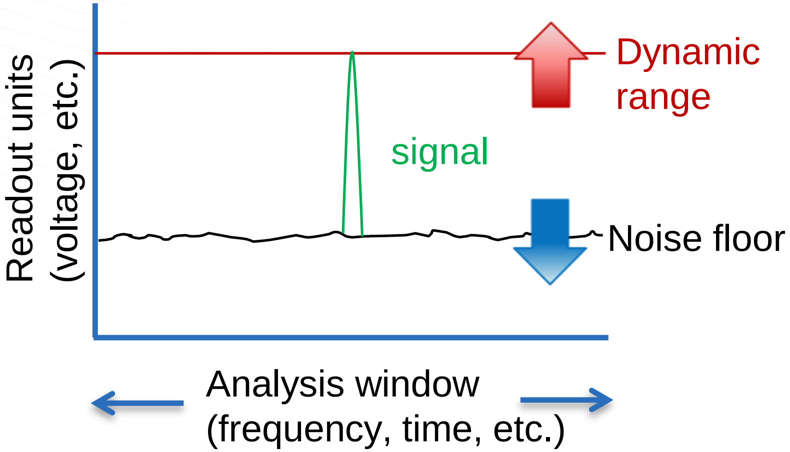
Off-resonance,

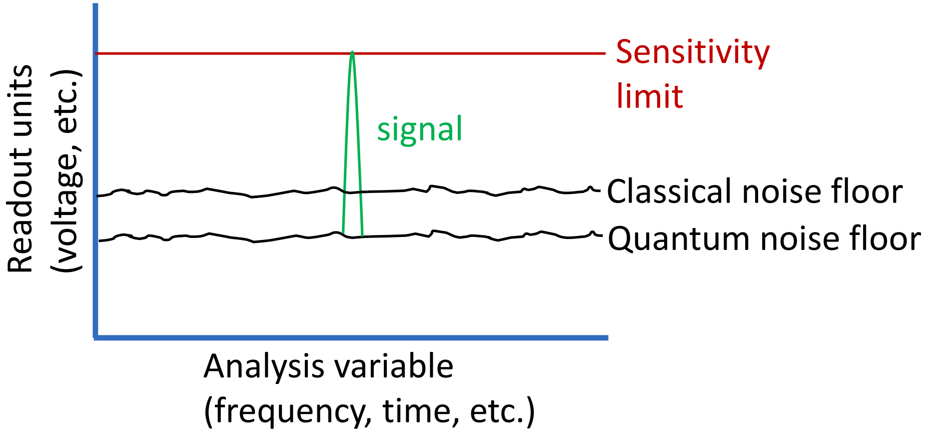
$$\langle(\Delta x)^2\rangle_{th} = \frac{2k_B T\Delta f}{k\pi f_0 Q},\ \left\langle(\Delta x)^2\right\rangle_{shot} = \frac{hc\lambda\Delta f}{8\pi^2 P},\ \text{and}\ \left\langle(\Delta x)^2\right\rangle_{back} = \frac{8Ph\Delta f}{c\lambda k^2}$$



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

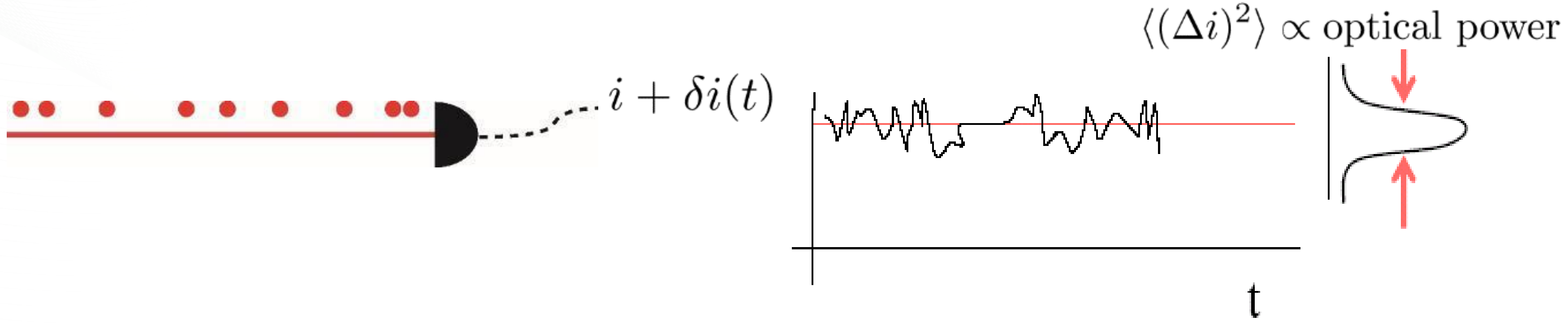




- Our approach increases the signal to noise (SNR) by decreasing the noise floor using **quantum noise reduction (QNR)** and increasing dynamic range using quantum signal modulation

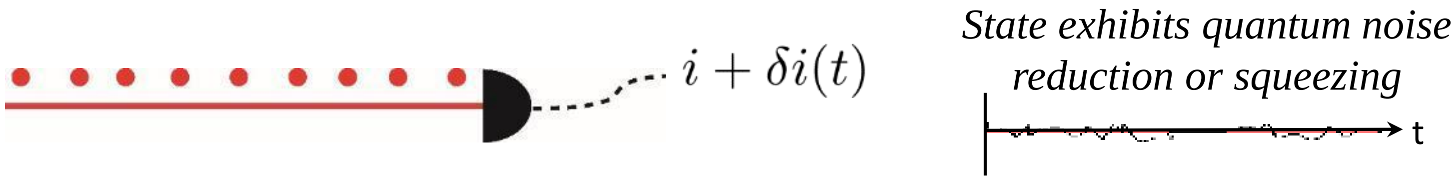
Quantum Noise Reduction

- 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.

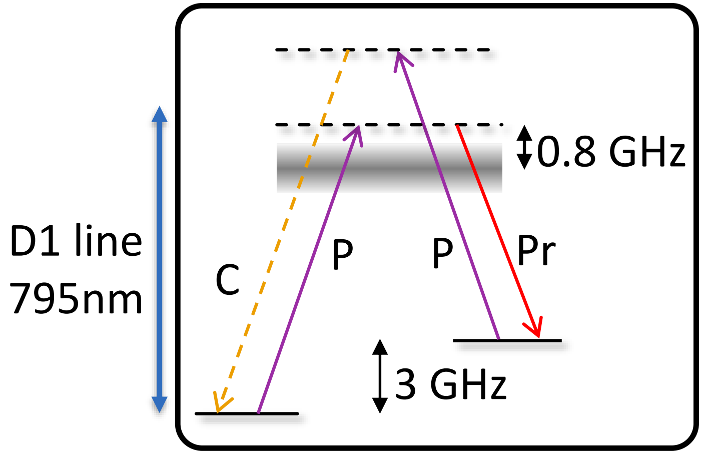


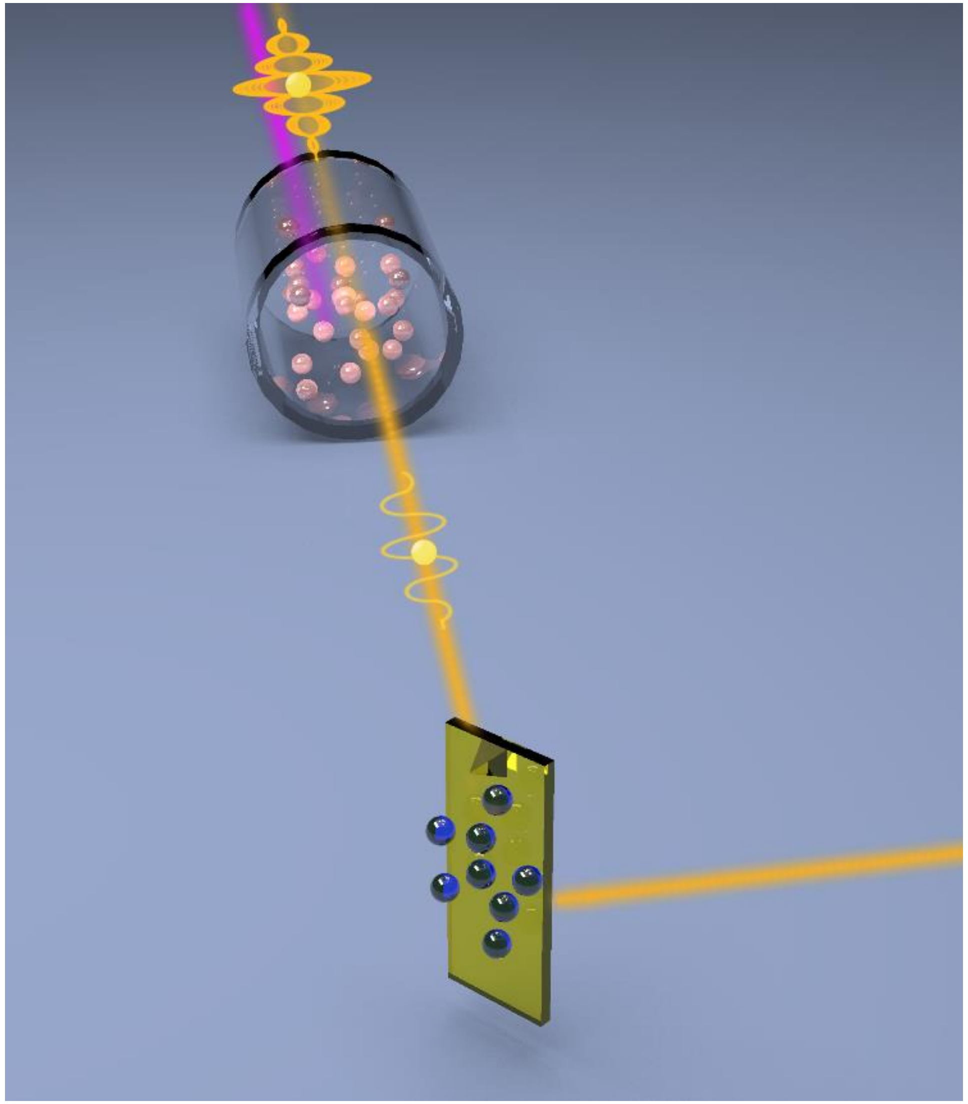
- Amount of quantum noise reduction increases with strength of nonlinearity.

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. *Joint detection allows quantum noise reduction*.





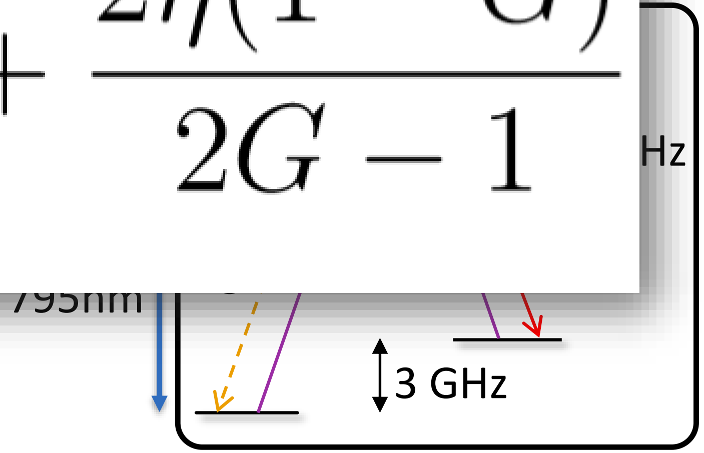
Science **321**, 544-547 (2008) *Nature* **457**, 859-862 (2009)

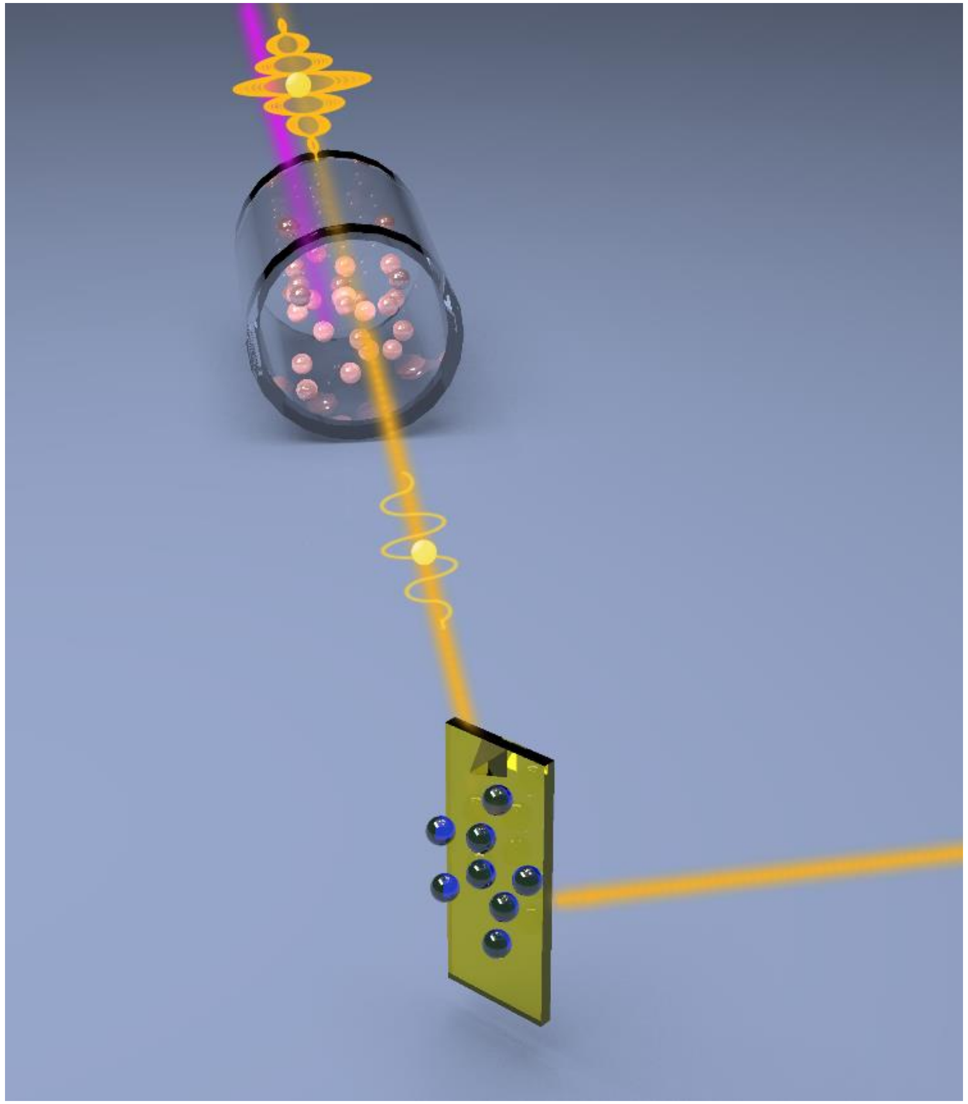
Four wave mixing for CV quantum optics

Generate quantum noise reduction via nonlinear interactions:

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

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





Science **321**, 544-547 (2008)   *Nature* **457**, 859-862 (2009)

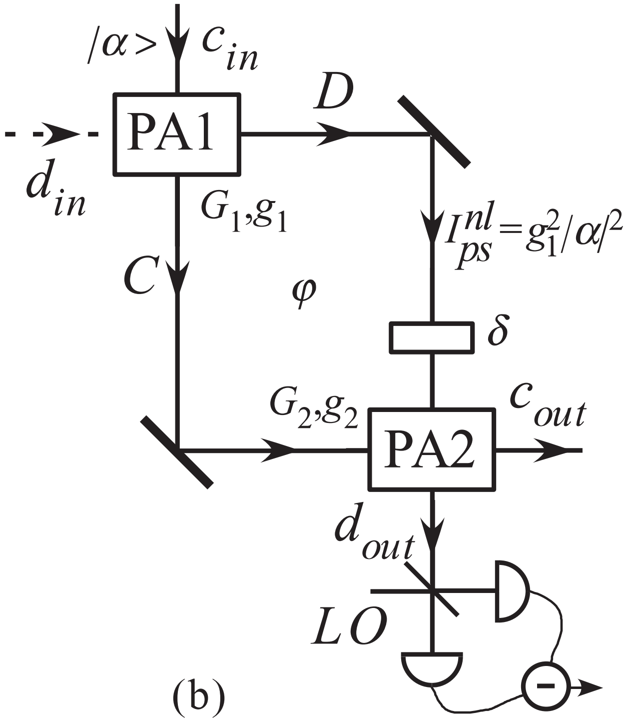
Recent Theoretical Innovation for Phase Estimation

- 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:

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

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

$$\text{SNR}_{\text{NLI}}/\text{SNR}_{\text{LI}} \approx 2\,G^2$$



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

Homodyne detection

- Phase sum and amplitude difference show noise reduction for misaligned modes
- For *pure* phase, noise equivalent to two-mode-squeezed source

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

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

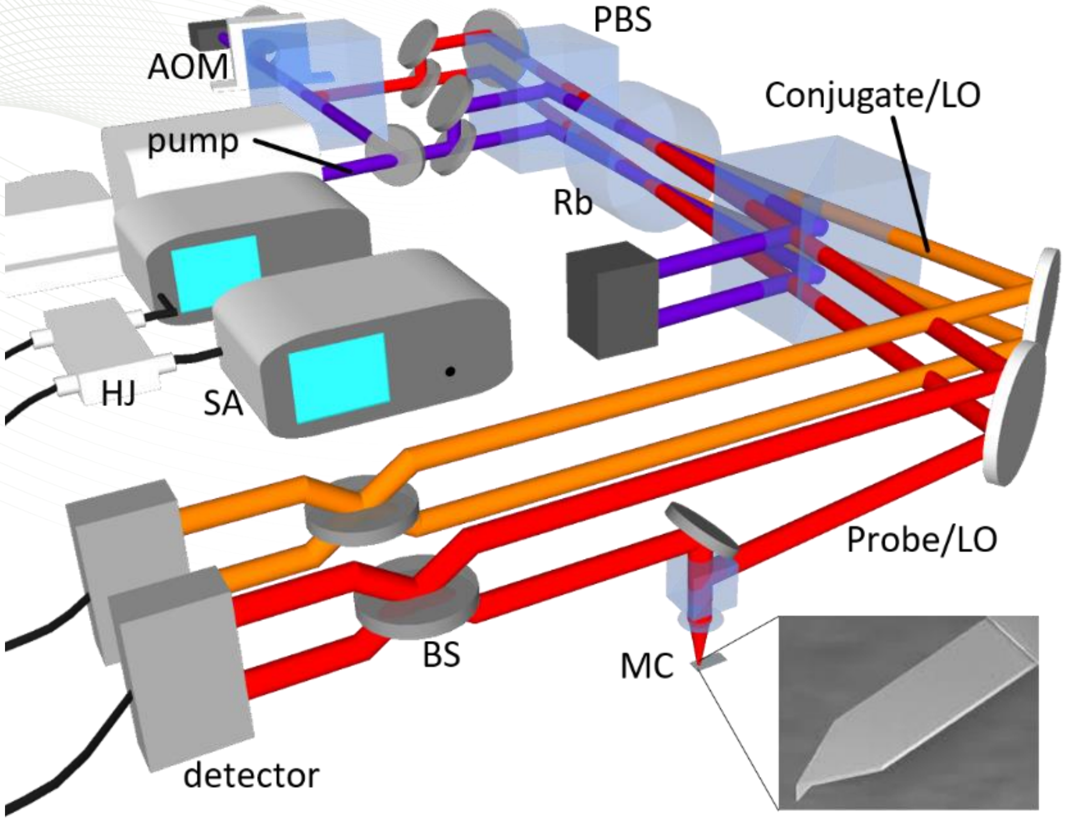
$$+ \sum_{i=1}^{N} \frac{(P_{\text{tot}} - P_0 - P_i)}{P_{\text{tot}}}[1 + 2\eta_i(G-1)]$$

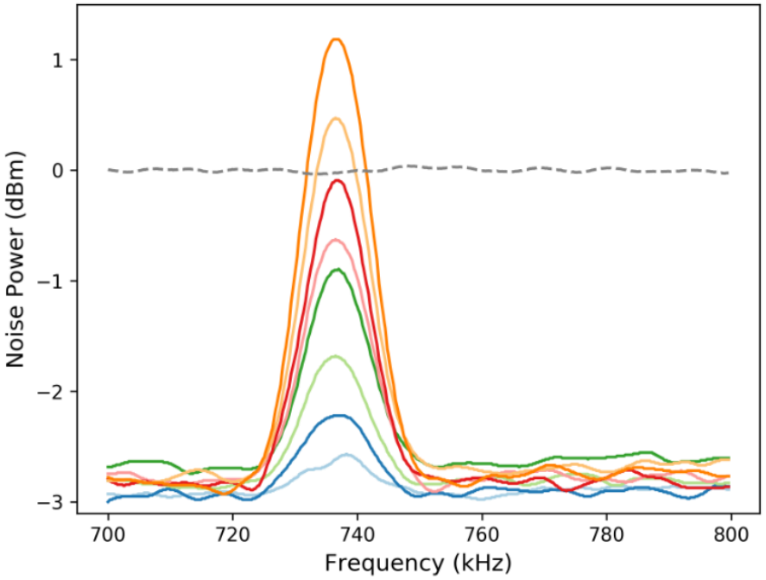
$$\Delta p_+^2 = 1 + 2\eta[G - 1 - \sqrt{G(G-1)}]$$

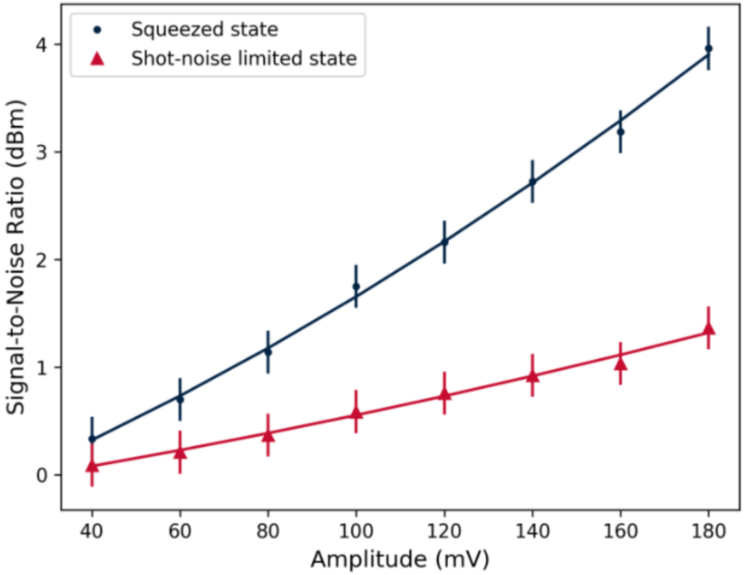
$$p_+ = p_i + p_j + \Delta\varphi$$

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

Nonlinear Interferometric AFM imaging



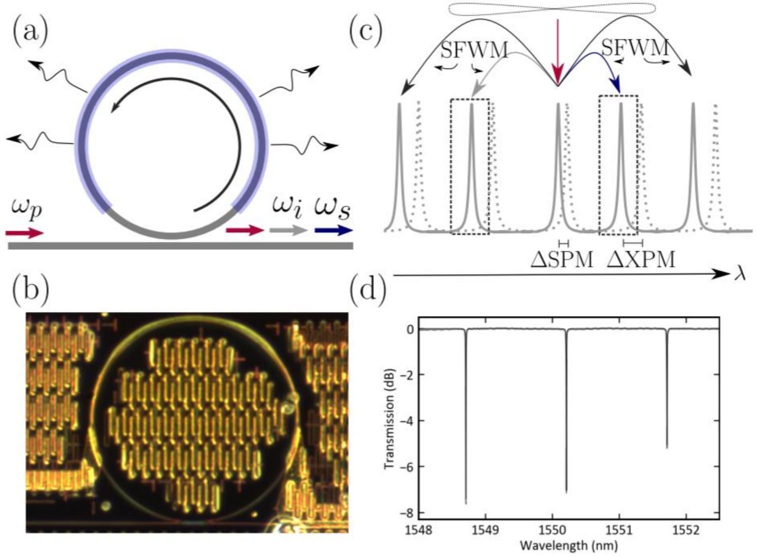




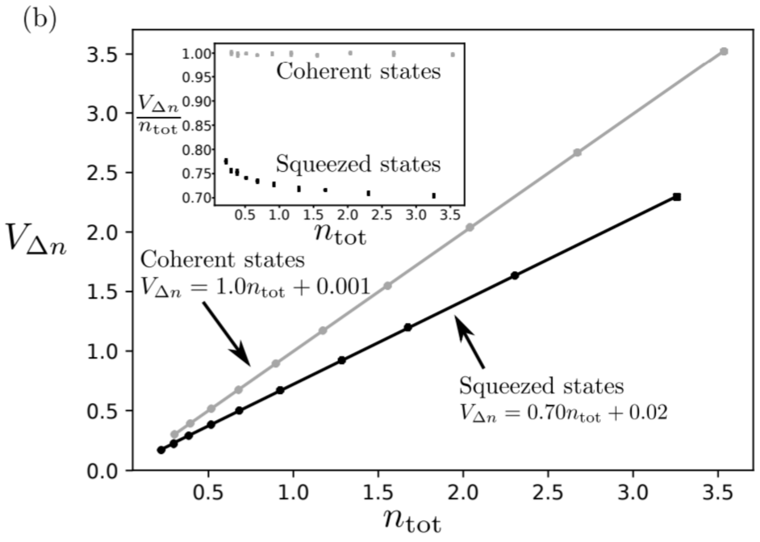
Truncated Nonlinear Interferometry for Quantum-Enhanced Atomic Force Microscopy, RC Pooser, N Savino, E Batson, JL Beckey, J Garcia, BJ Lawrie
Physical Review Letters **124** (23), 230504 (2020)

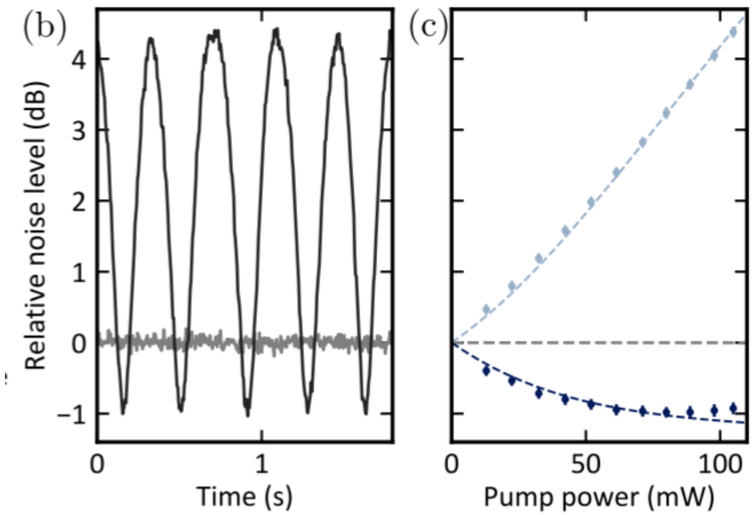
But probably should go integrated

- See Dan Carney and Jeuhang Qin's talks
- Much less squeezing on chip, but
- Will be crucial for limiting losses in signal transduction outlined by others here
- Will allow for longer range quantum networks



arXiv:1904.07833v3





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