Manipulating and Measuring States of an Optomechanical Resonator in the Quantum Regime

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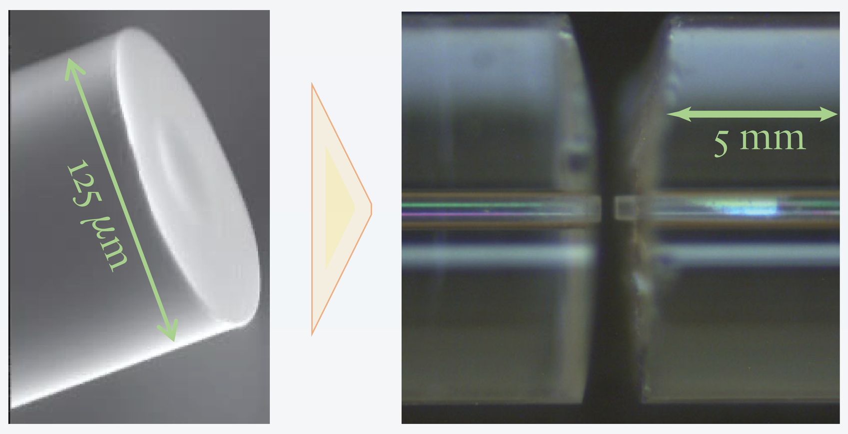
Motivation

Why Superfluid Helium:

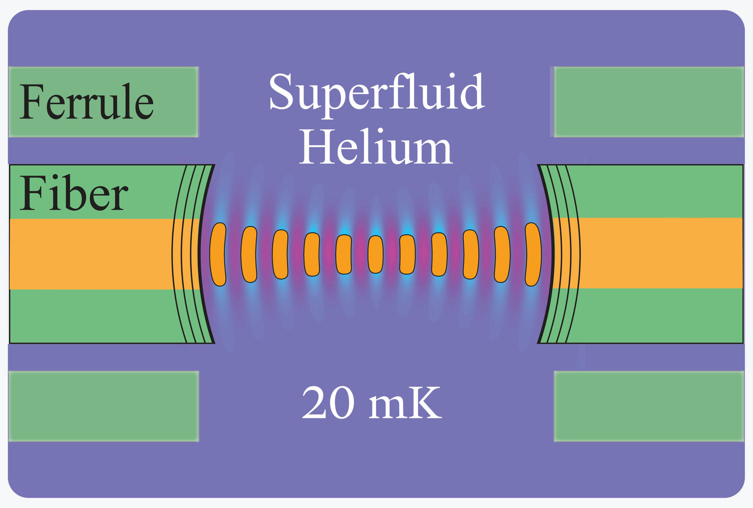
- 19 eV bandgap
- Zero chemical impurities
- Zero structural defects
- Zero viscosity
- High thermal conductivity
- Self-aligned optical & acoustic modes
- Can host new hybrid quantum systems



Cavity mode volume: $70\mu m \times 8\mu m \times 8\mu m$
(Jakob Reichel's group, ENS Paris)

Goal of the Experiment:

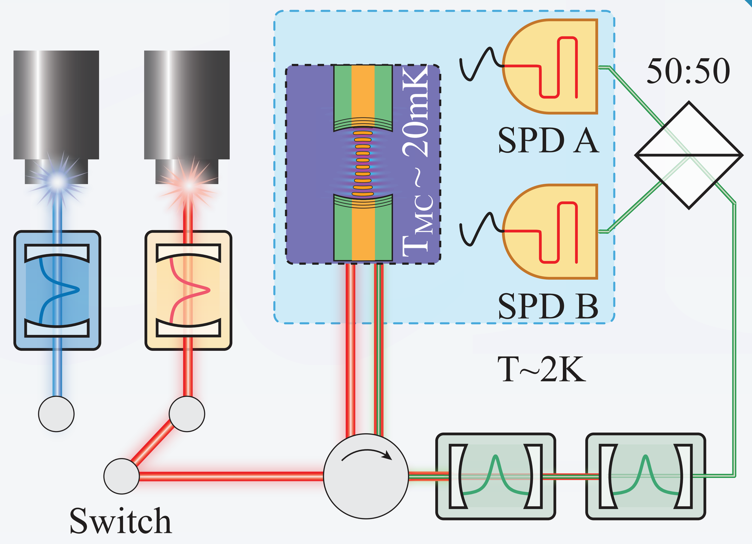
- Quantum optomechanics
- Macroscopic quantum phenomena
- Test quantum gravity effects
- Promising system for light DM searches
- Quantum sensing
- Quantum memory
- Superfluid dynamics
- … …



Experiment Setup

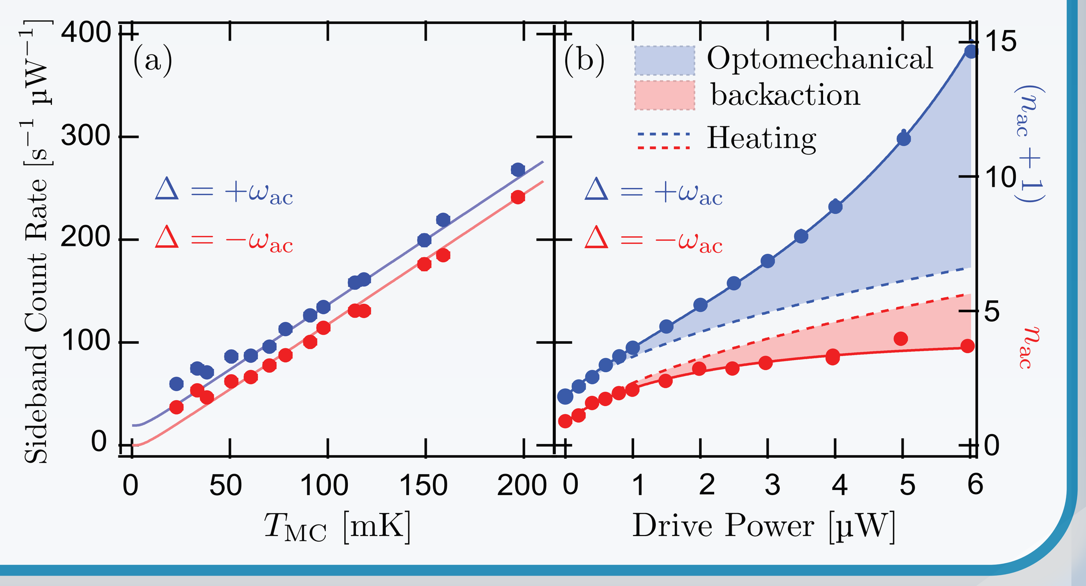
Photon Counting

- Nonlinearity induced by measurement projection
- Measure motional state by photon statistics
- Weak measurements
- 'Heralded' protocols to prepare **Nonclassical state**
  - ☞ *Phonon-phonon entanglement*
  - ☞ *Fock states*
  - ☞ *Entanglement of two mechanical oscillators*
  - ☞ … …

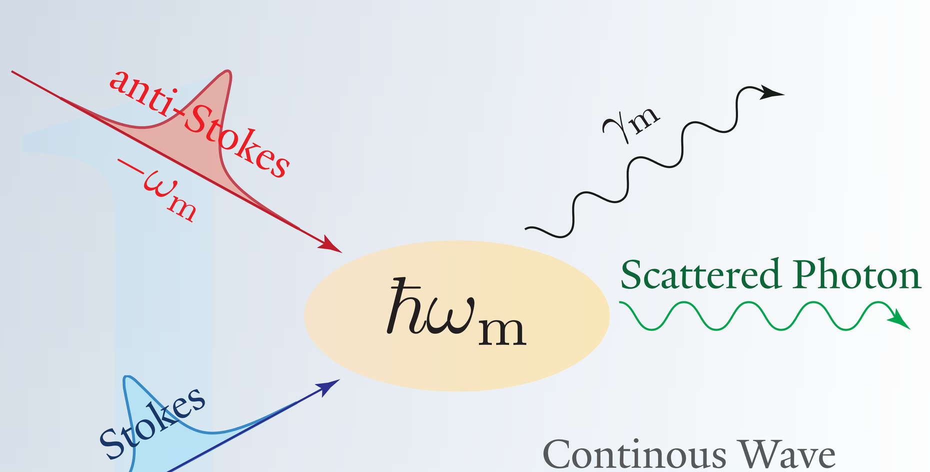


Quantum Optomechanics

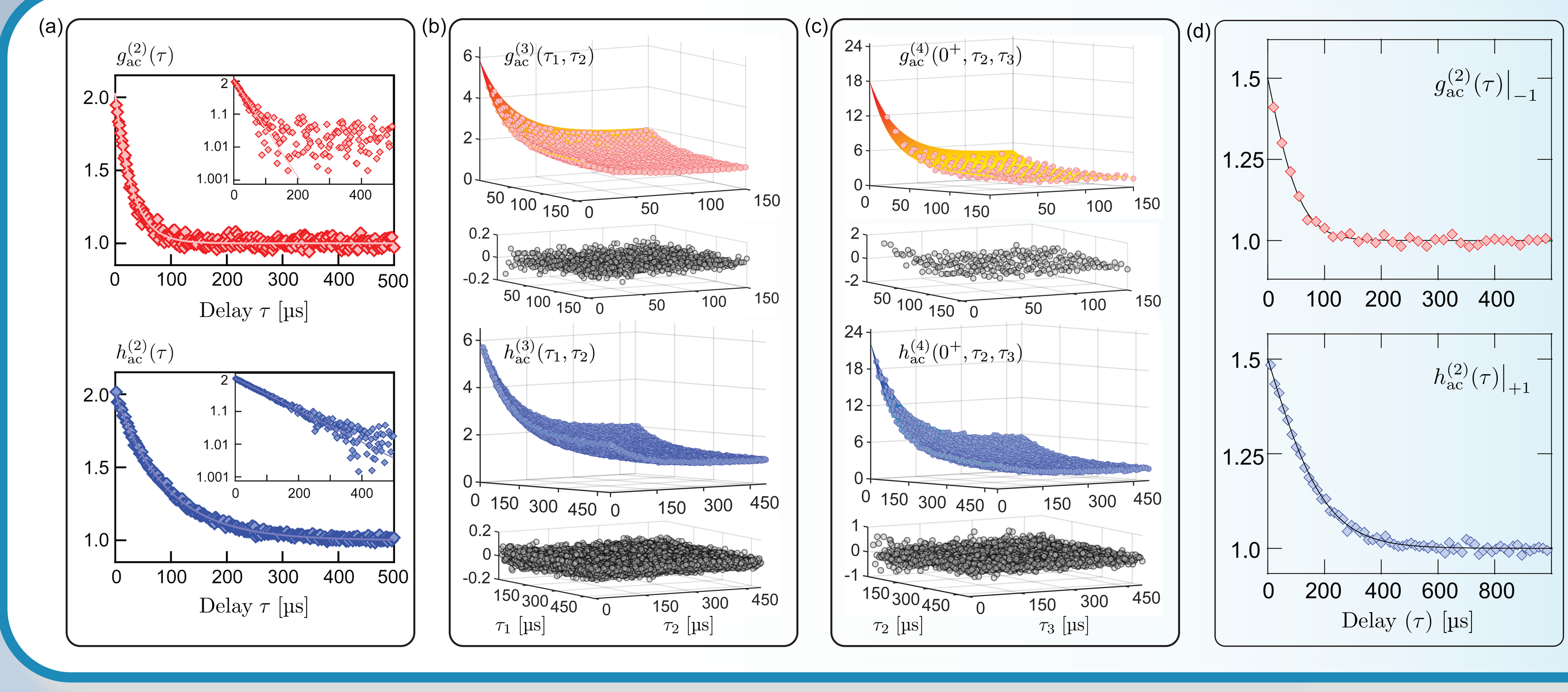
- Single-mode optomechanics
- Stokes/anti-Stokes scattering
- Quantum backaction
- Quantum sideband asymmetry
- Zero point fluctuation (ZPF)
- Photon correlations



Thermal State



- Continous Wave
- Thermal State
- Raman Scattering
- Photon Counting



High-order Phonon Correlations*

- Photon-phonon correspondance
- Phonon bunching effect
- Charaterize phonon statistics of a thermal state up to 4th order
- Less than 4 phonons
- Reconstruct Wigner function?

Phonon Added/Substracted States

- Heraled protocol
- Nonclassical states preparation
- … …

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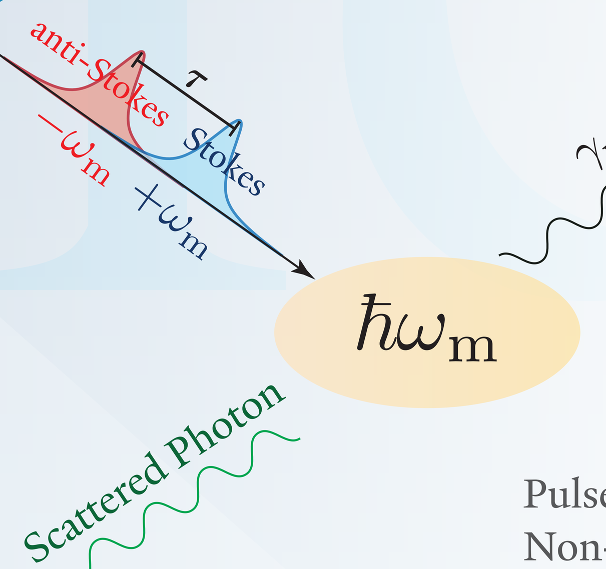
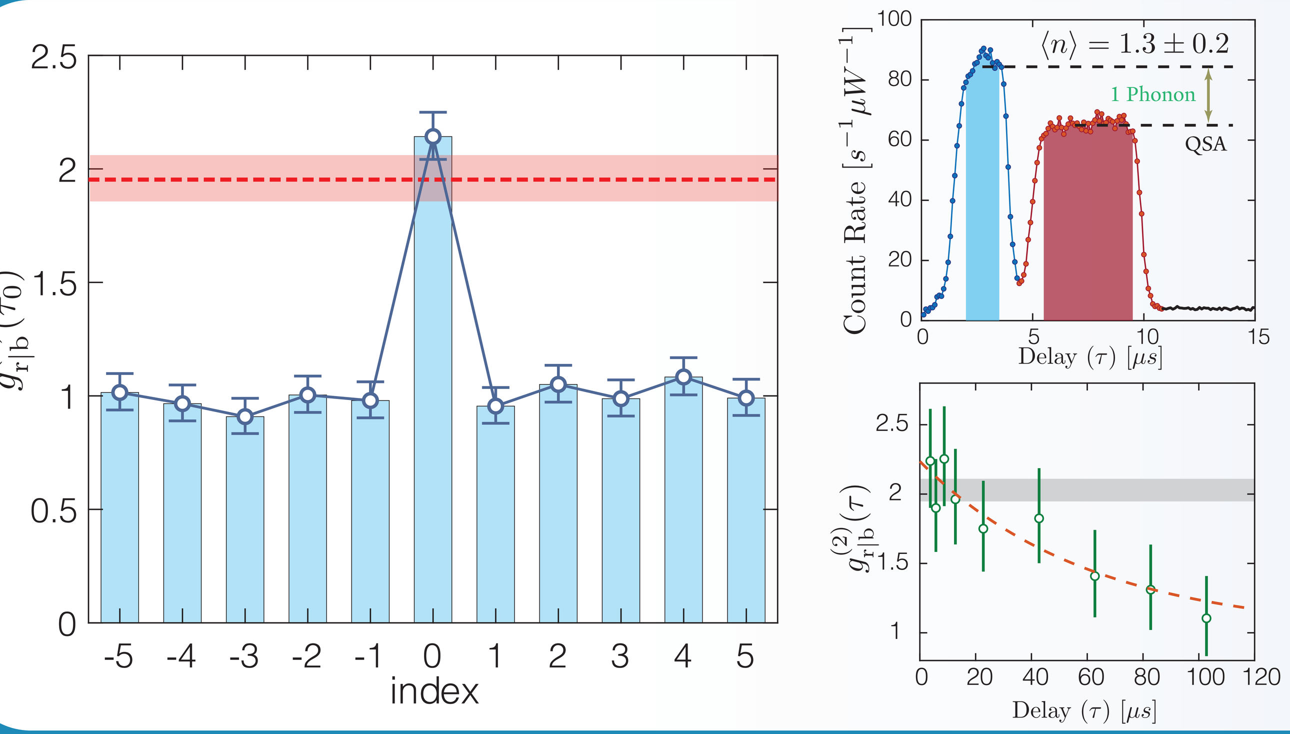
Entangled State



- Pulsed Pump
- Non-Classical State
- Cross-Correlation
- Statistic Violation



Photon-phonon Entanglement

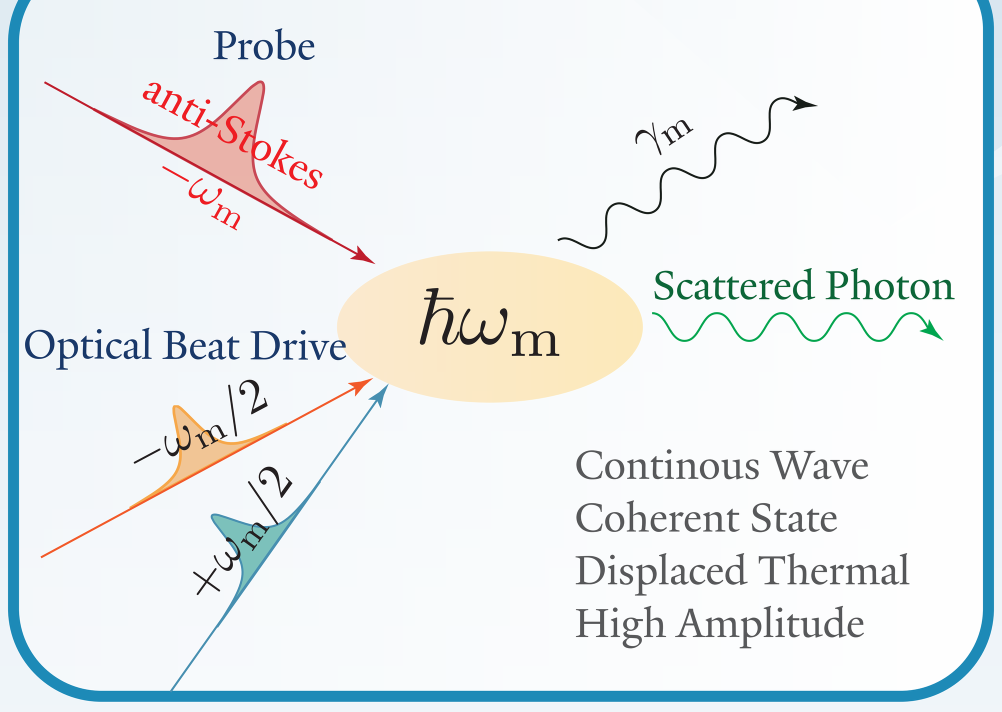
- Prepare the mechanical state
- Send a blue-detuned pulse (Two-mode Squeezing)
  - ☞ **Add one phonon** into the mechanical mode
- Send a red-detuned pulse (State Swap)
  - ☞ **Swap** the mechanical state into the optical mode
- Measure the correlation between photons

Cauchy-Schwarz Inequality

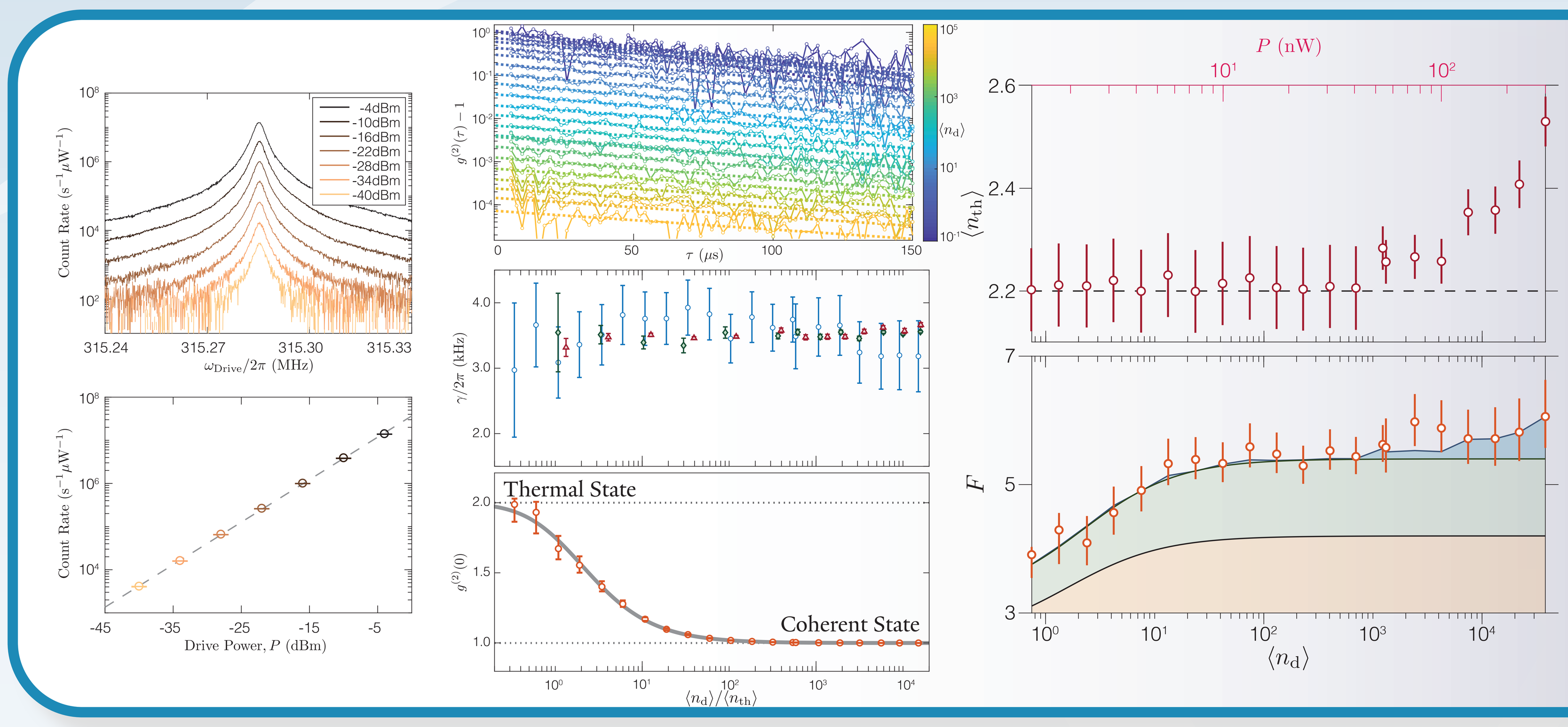
$$g^{(2)}_{r|b}(\tau_0) = 2.14^{+0.10}_{-0.10} \nleq g^{(2)}_{CL} \equiv \sqrt{g^{(2)}_{b|b}(0)g^{(2)}_{r|r}(0)} = 1.95^{+0.10}_{-0.10}$$

Negative Glauber-Sudarshan *P*-function with 99.5% Confidence on a **Macroscopic, Massive (~1 ng)** resonator

Coherent State



- Continous Wave
- Coherent State
- Displaced Thermal
- High Amplitude



Phonon Coherent State

- Nearly ZPF (<3 Phonon) in the motional state
- Realize nearly coherent states up to 10^4 phonons in **a massive mechanical oscillator(~1 ng)**
- Characterize displaced thermal states by measuring the first-order and the second-order coherence of the anti-Stokes photons

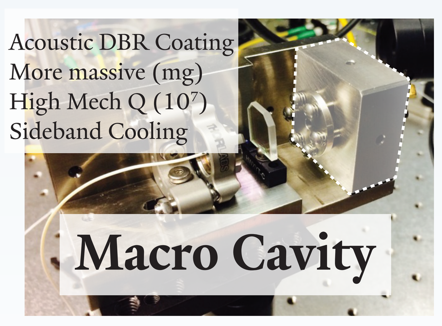
Applications

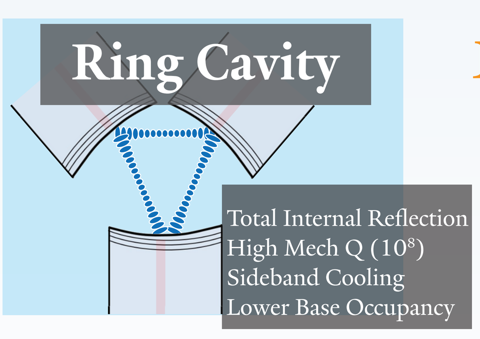
- Quantum Gravity Effect (Non-local dynamics)
- SQL in Acoustic Interferometer
- Macroscopic Quantum Mechanics
- … …

Outlook

Even More MACRO!

- Increased **Mass and Size**
- Longer **Coherence Time**
- "Cooler" New Devices
- … …





Even More QUANTUM!

- **Non-Classical** Motional State
- **Entangled** Multi Devices
- **Macroscopic** Quantum Effects
- … …

Acknowledgements

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