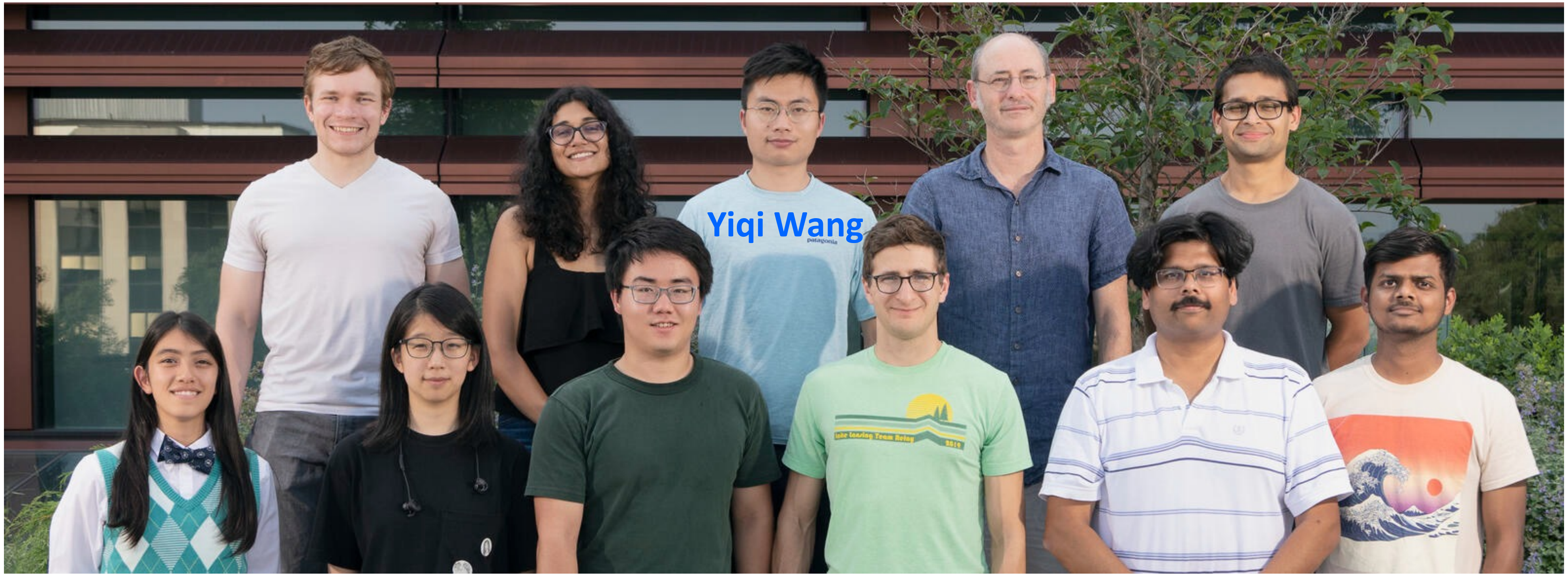
Measuring higher-order phonon statistics in a nanogram-scale superfluid optomechanical system

Jack Harris *Department of Physics, Department of Applied Physics, Yale Quantum Institute*

Optomechanics: an approach to macroscopic quantum phenomena
Superfluid helium: an excellent material for quantum optics & acoustics
Single-photon detectors: a source of nonlinearity
Measuring quantum signatures: high-order phonon correlations
Next steps: indistinguishable optomechanical devices, tests of Planck-scale physics

Jakob Reichel
(ENS Paris)



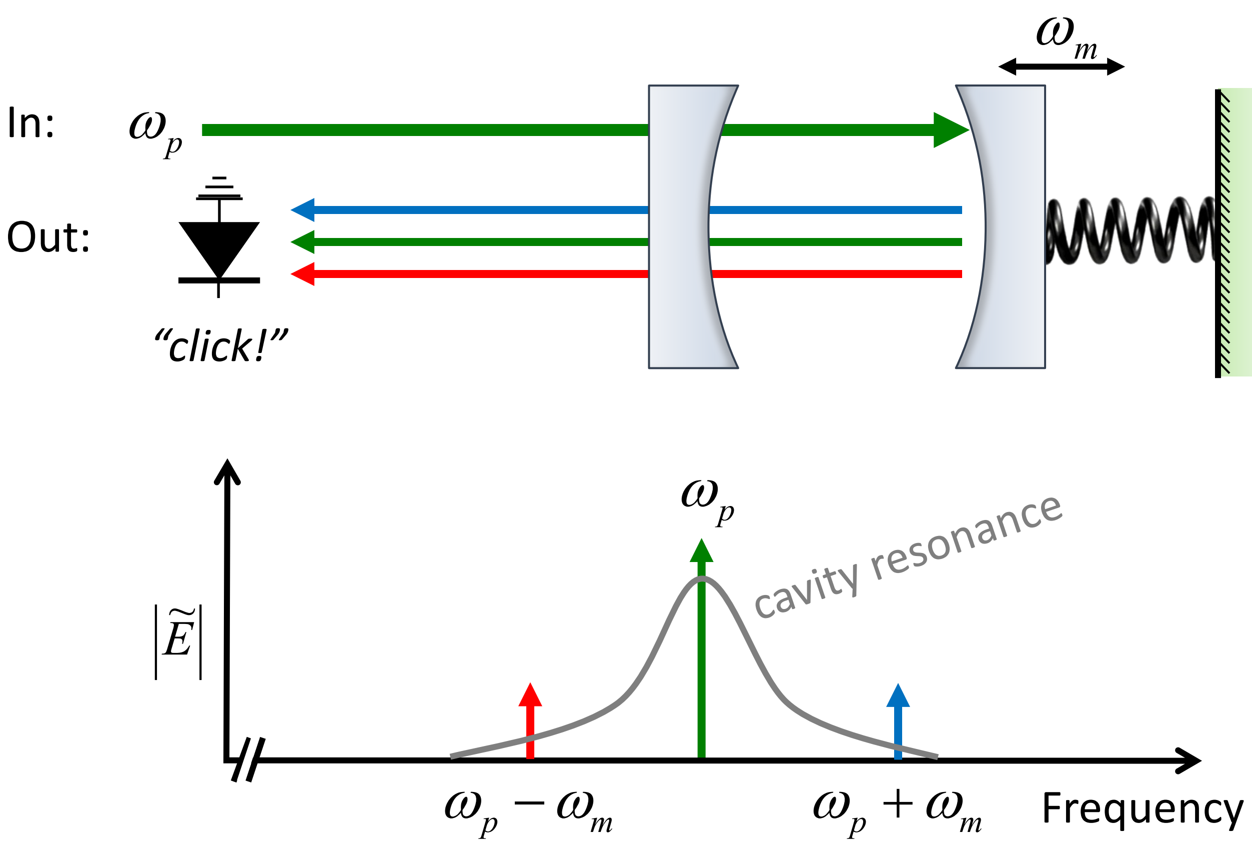
Lucy Yu

Yogesh Patil

postdoc positions available!!

Thanks to: Radim Filip, Kjetil Børkje, Florian Marquardt, Francesco Massel, Aash Clerk, Steve Girvin

Counting phonons *in any optomechanical system*



"Click" from an unshifted photon –
no information about mechanical oscillator.

"Click" from a red-shifted photon –
one phonon has been added to mechanical oscillator.

"Click" from a blue-shifted photon –
one phonon has been removed from mechanical oscillator.

These herald a single-phonon event…

…but only 1 photon in ~10^8

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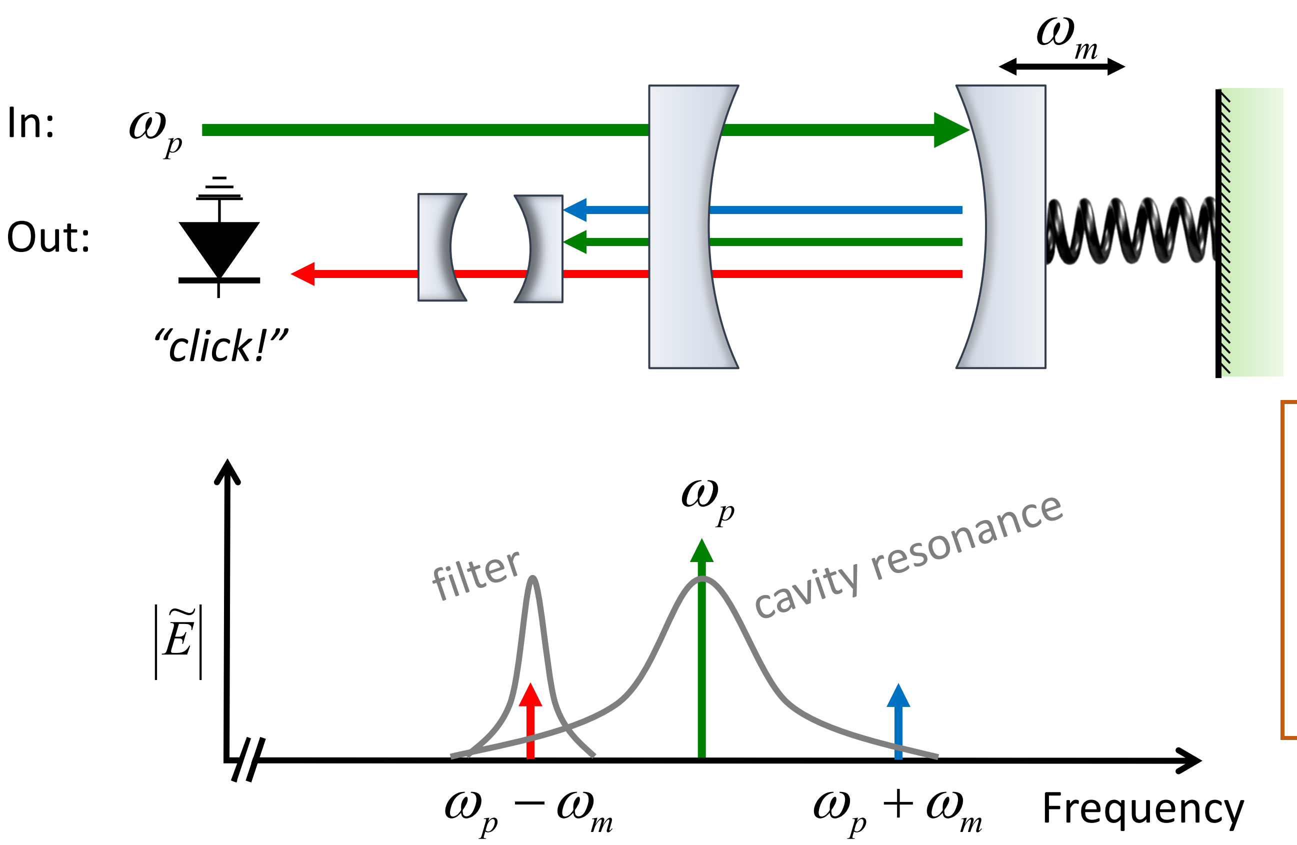

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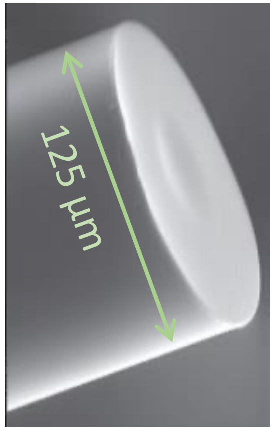
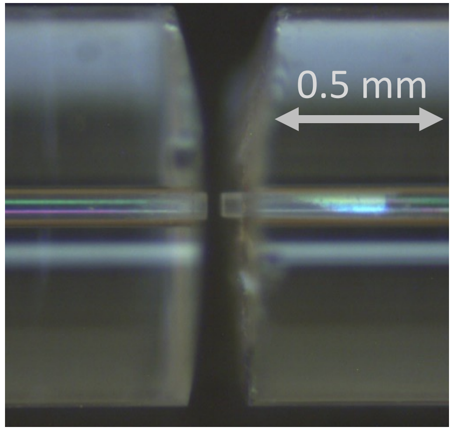
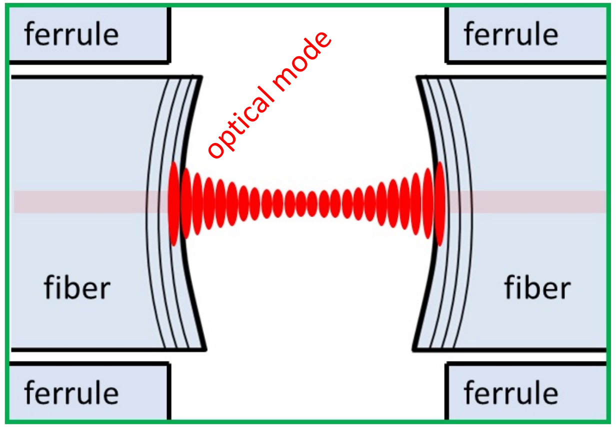
applying this idea to optomechanics:

Vanner, Aspelmeyer, Kim (2013)
Painter group (2015)
Gröblacher & Aspelmeyer groups (2017 et. seq.)
Polzik group (2020)
Vanner group (2021)
…

Counting phonons *in a nanogram-scale superfluid cavity*







Cavity mode volume: 100µm x 10µm x 10µm
(Jakob Reichel's group, ENS Paris)

Mirrors confine:
optical standing waves: λ = 1550 nm

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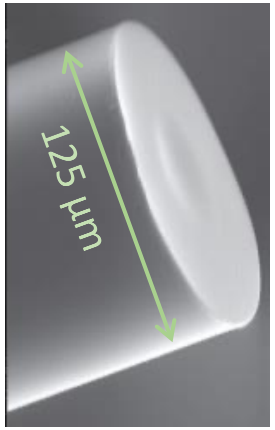

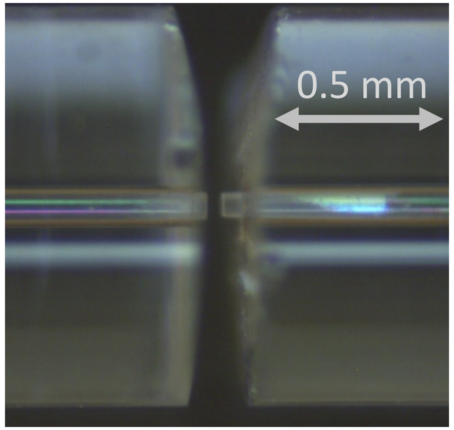

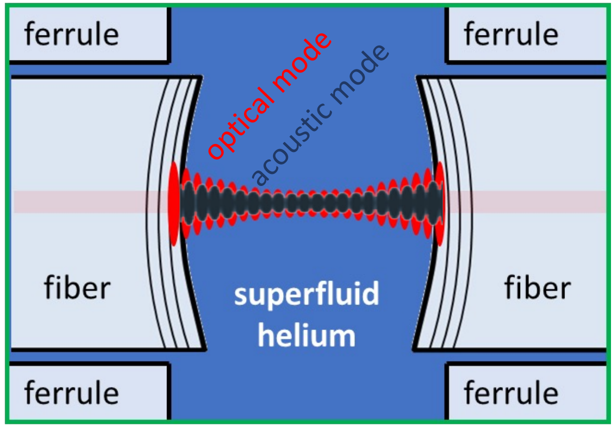

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Why superfluid He:

- 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
- Promising system for light DM searches

No optical absorption!
Very low mechanical loss!
Stays cold!
No AttoCubes!
Stay tuned
Stay tuned

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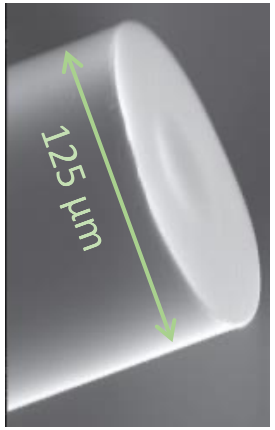

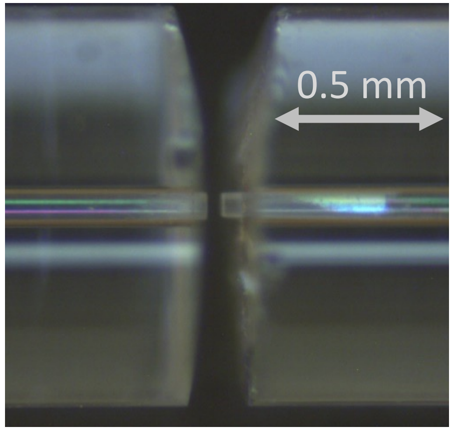

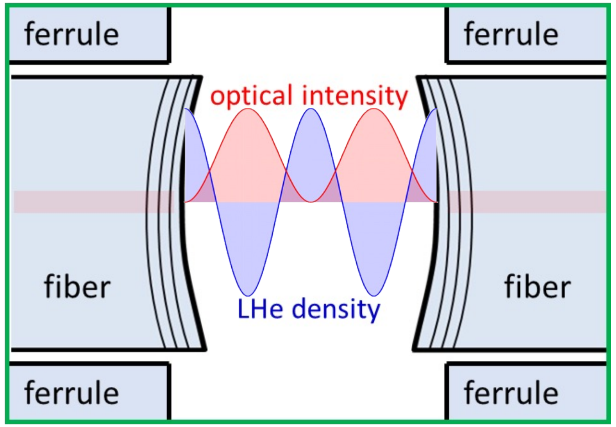

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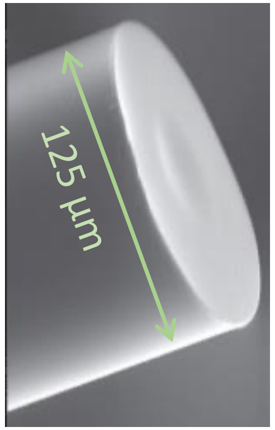

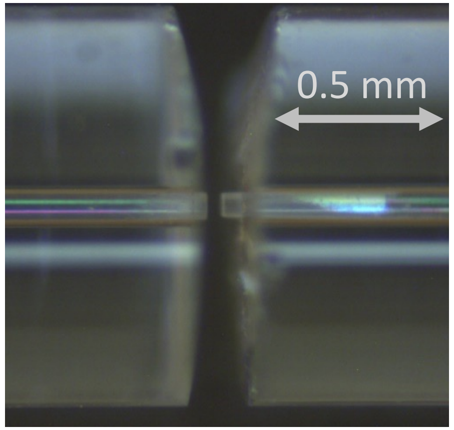

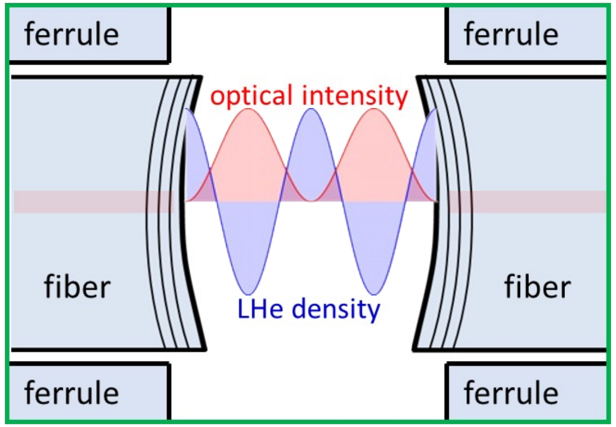

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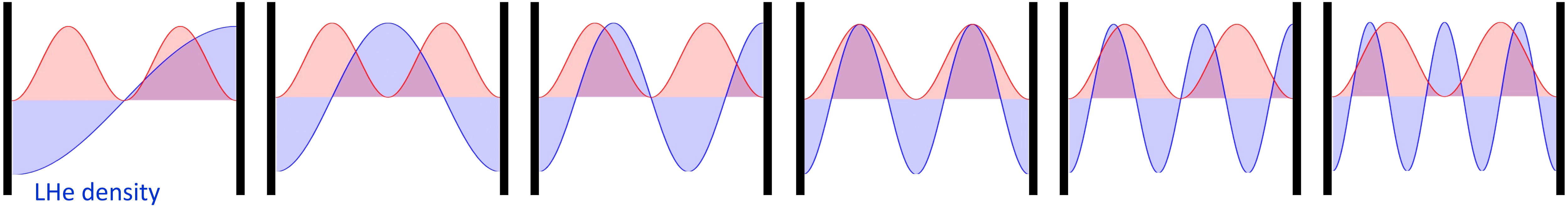
For the optical mode with $N_{opt} = 2$:



$N_{ac} = 1$, $g_0 = 0$

$N_{ac} = 2$, $g_0 = 0$

$N_{ac} = 3$, $g_0 = 0$

$\mathbf{N_{ac} = 4}$, $\mathbf{g_0 = 3\ kHz}$

$N_{ac} = 5$, $g_0 = 0$

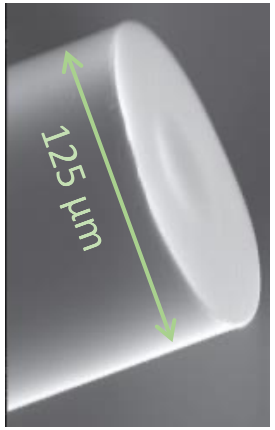
$N_{ac} = 6$, $g_0 = 0$

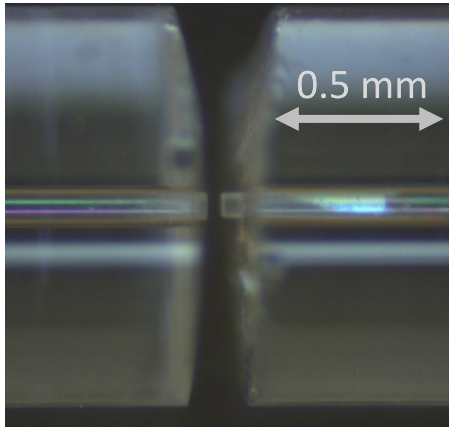
$\lambda_{ac} = \lambda_{opt}/2$

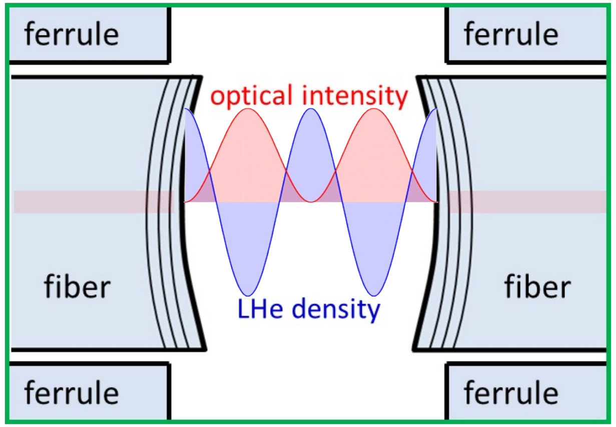
Truly single-mode optomechanical coupling

(similar story for transverse modes)

Counting phonons *in a nanogram-scale superfluid cavity*







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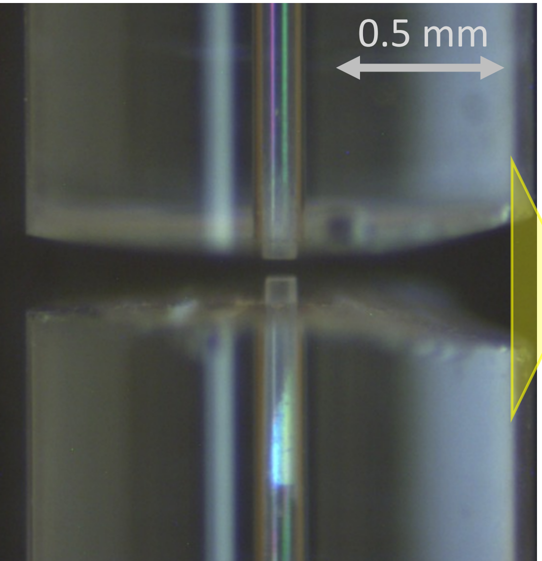
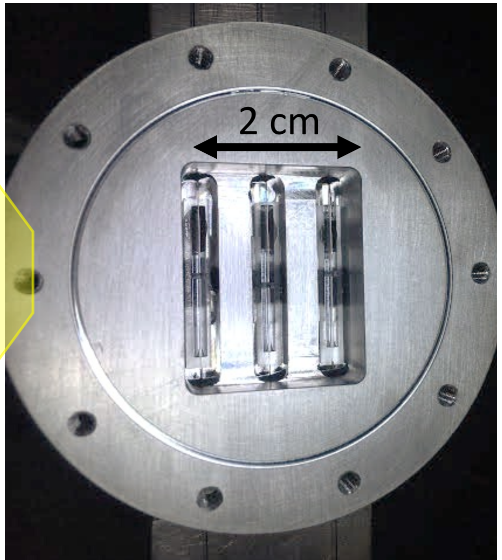
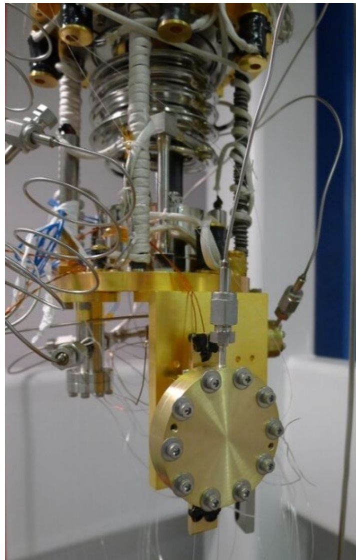
Mirrors confine:
optical standing waves: λ_{opt} = 1550 nm
couples only to λ_m = 775 nm (ω_m = 315 MHz)

No in situ alignment. Compact, robust to thermal cycling, fiber-coupled, monolithic, scalable, telecom wavelengths

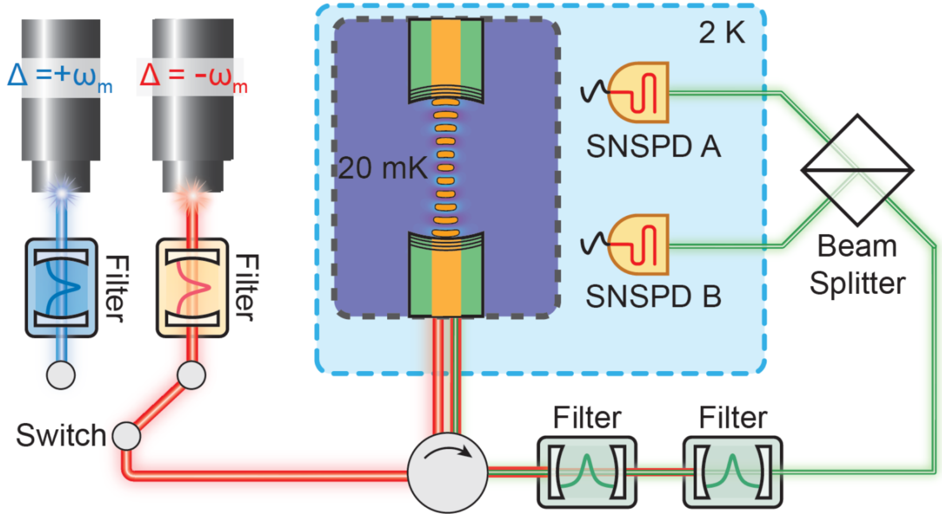




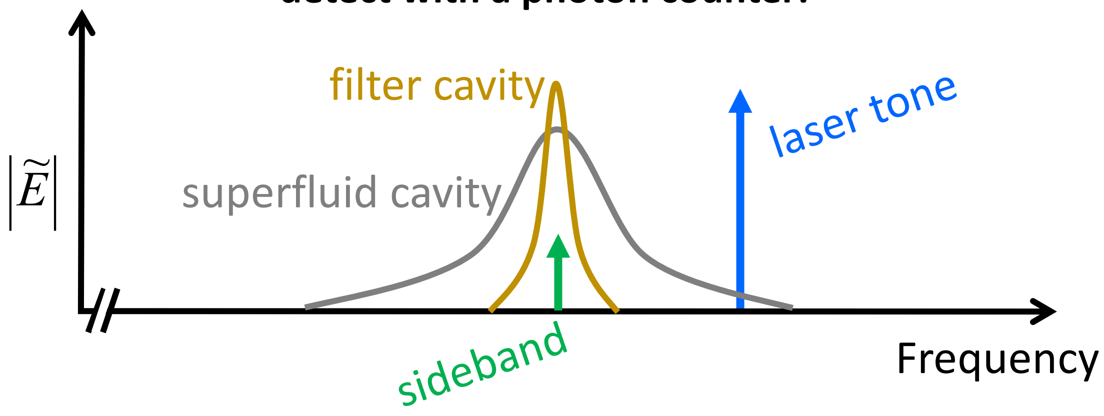


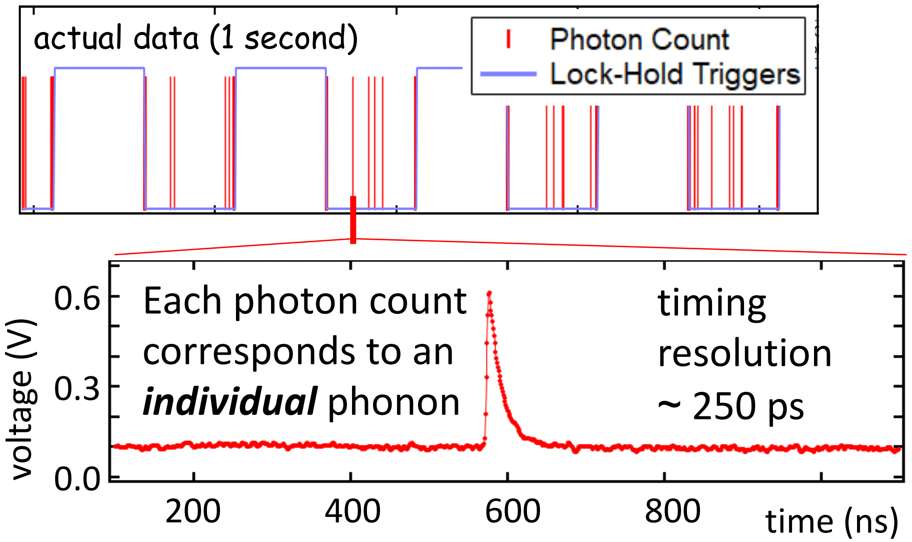
Experimental cell:
- one capillary fill line
- two fibers per device

Multiple devices
- no *in situ* alignment needed
- scalable to $10^2 – 10^3$ devices
- devices can be indistinguishable…

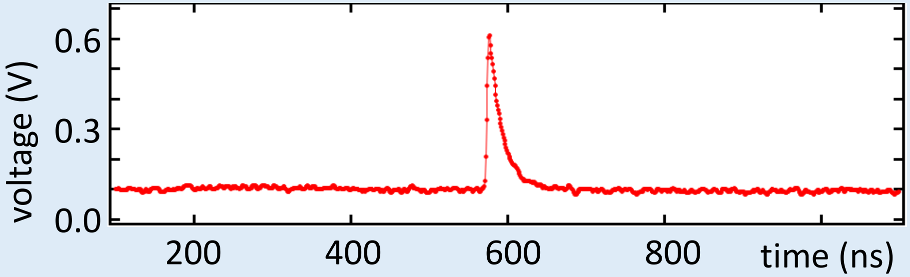


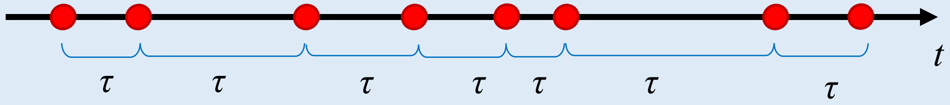
Collect only photons that created/annihilated a phonon, detect with a photon counter:





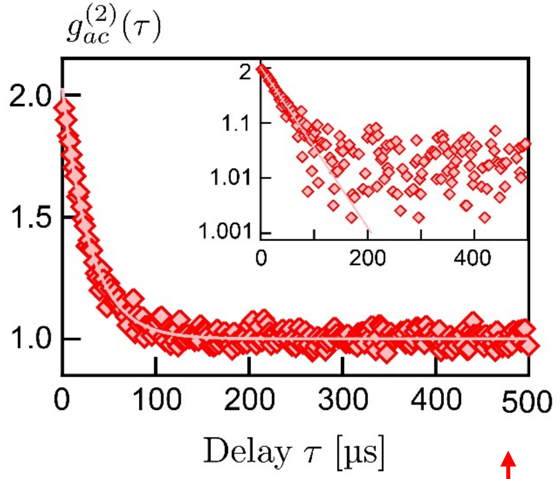
Use photon arrival times to characterize the acoustic mode's state:



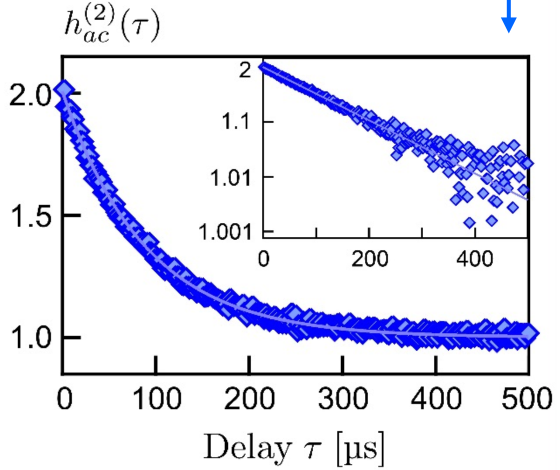


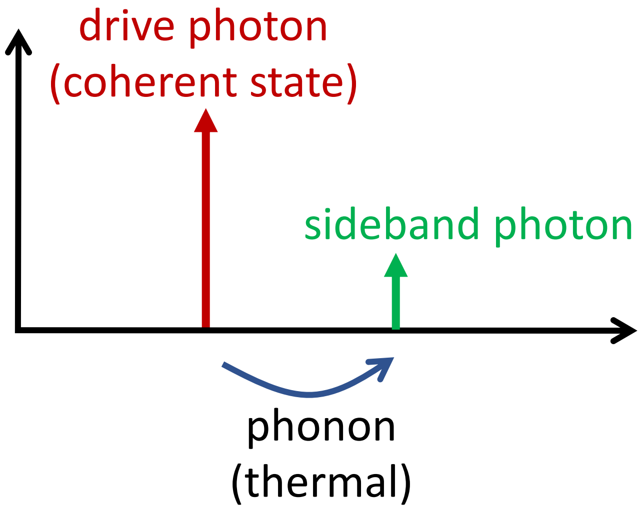
histogram of delays: $g^{(2)}(\tau)$ two-phonon correlation

two-phonon correlation:



Difference is due to optical damping





Red-detuned drive:
(beamsplitter interaction)

$$a^\dagger a \Rightarrow b^\dagger b$$

photon $g^{(n)} \rightarrow$ **phonon $g^{(n)}$**
(normally-ordered)

Blue-detuned drive:
(two-mode squeezing)

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photon $g^{(n)} \rightarrow$ **phonon $h^{(n)}$**
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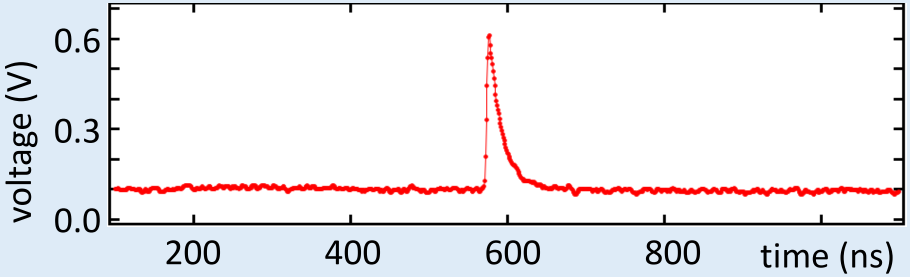

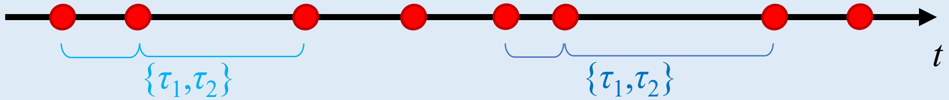

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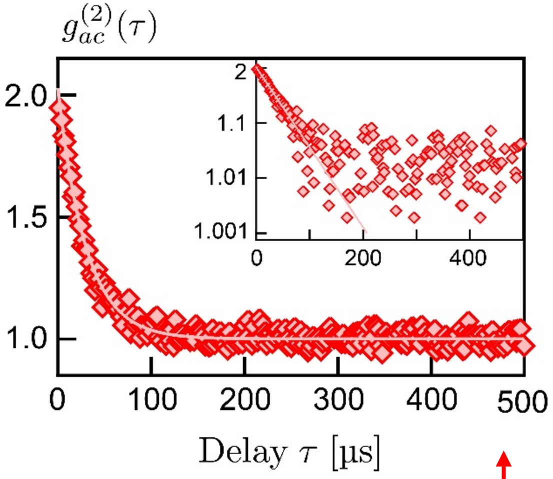

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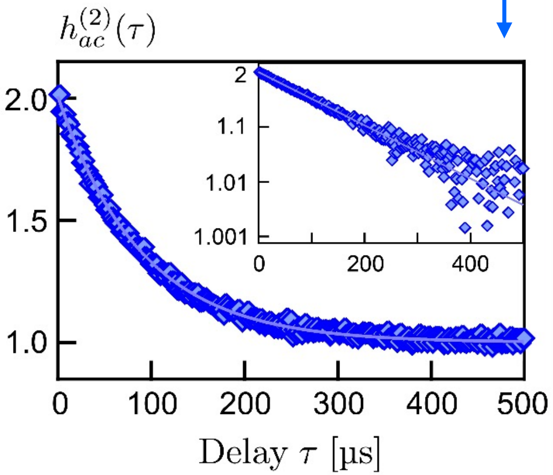

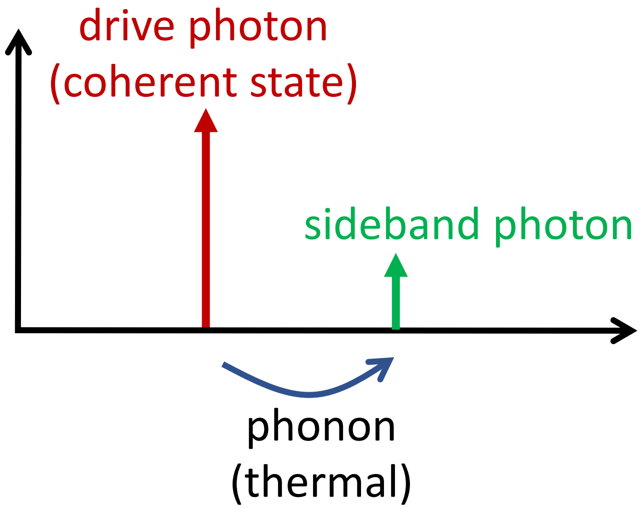

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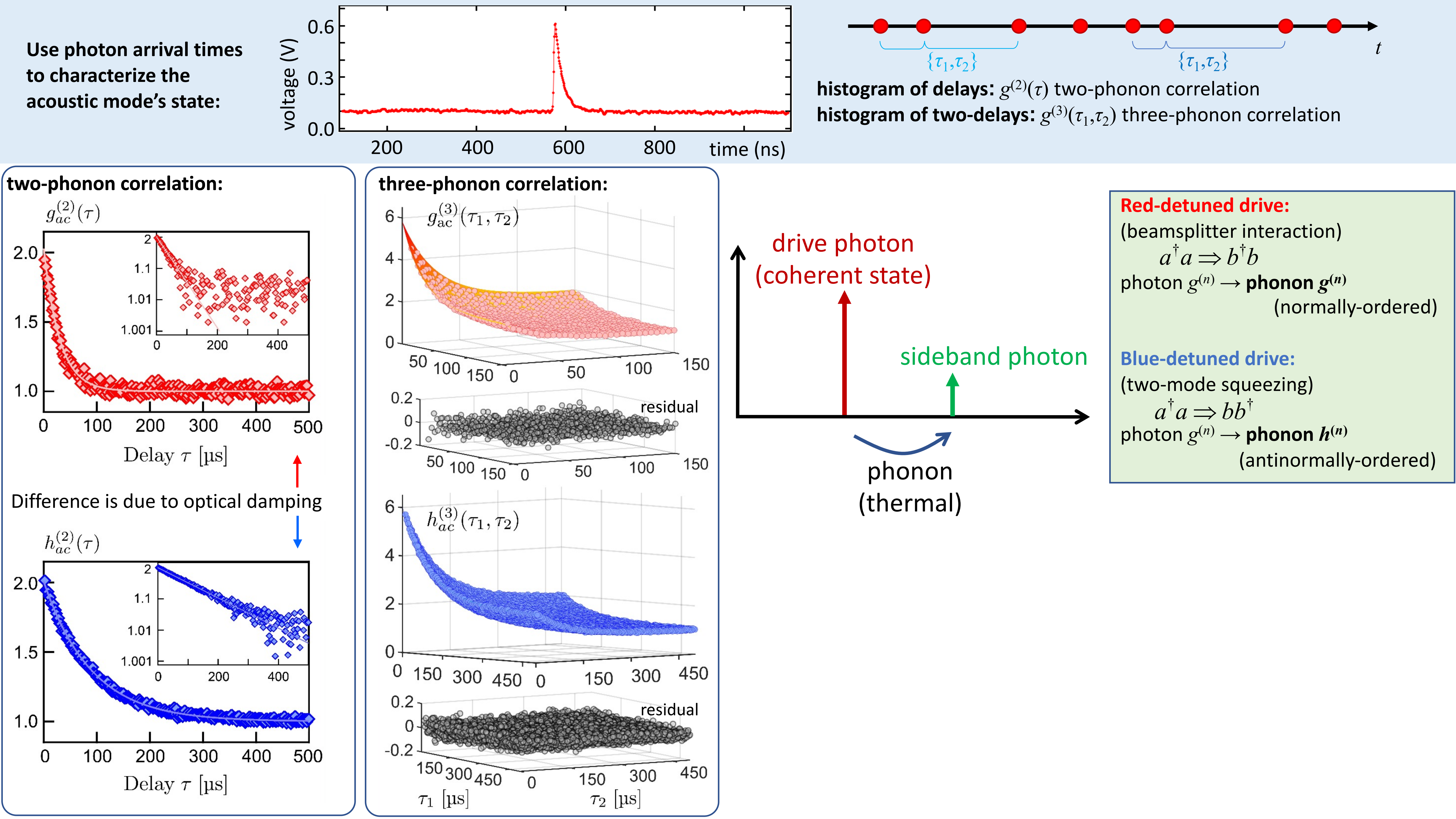

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time (ns)
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two-phonon correlation:
$g^{(2)}_{ac}(\tau)$
Delay τ [µs]
Difference is due to optical damping
$h^{(2)}_{ac}(\tau)$
Delay τ [µs]
three-phonon correlation:
$g^{(3)}_{\rm ac}(\tau_1,\tau_2)$
residual
$h^{(3)}_{ac}(\tau_1,\tau_2)$
residual
τ_1 [µs]
τ_2 [µs]
drive photon
(coherent state)
sideband photon
phonon
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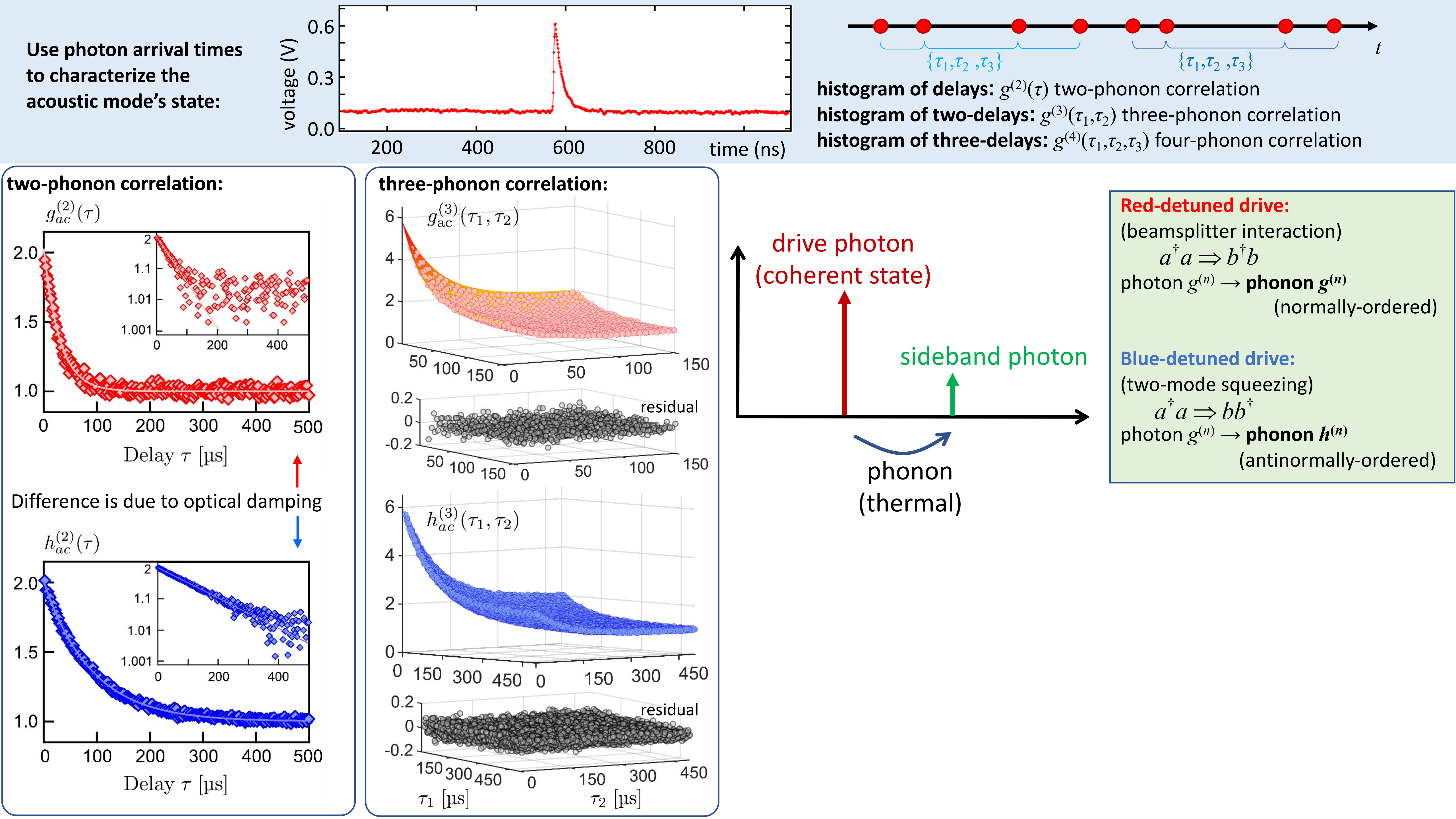

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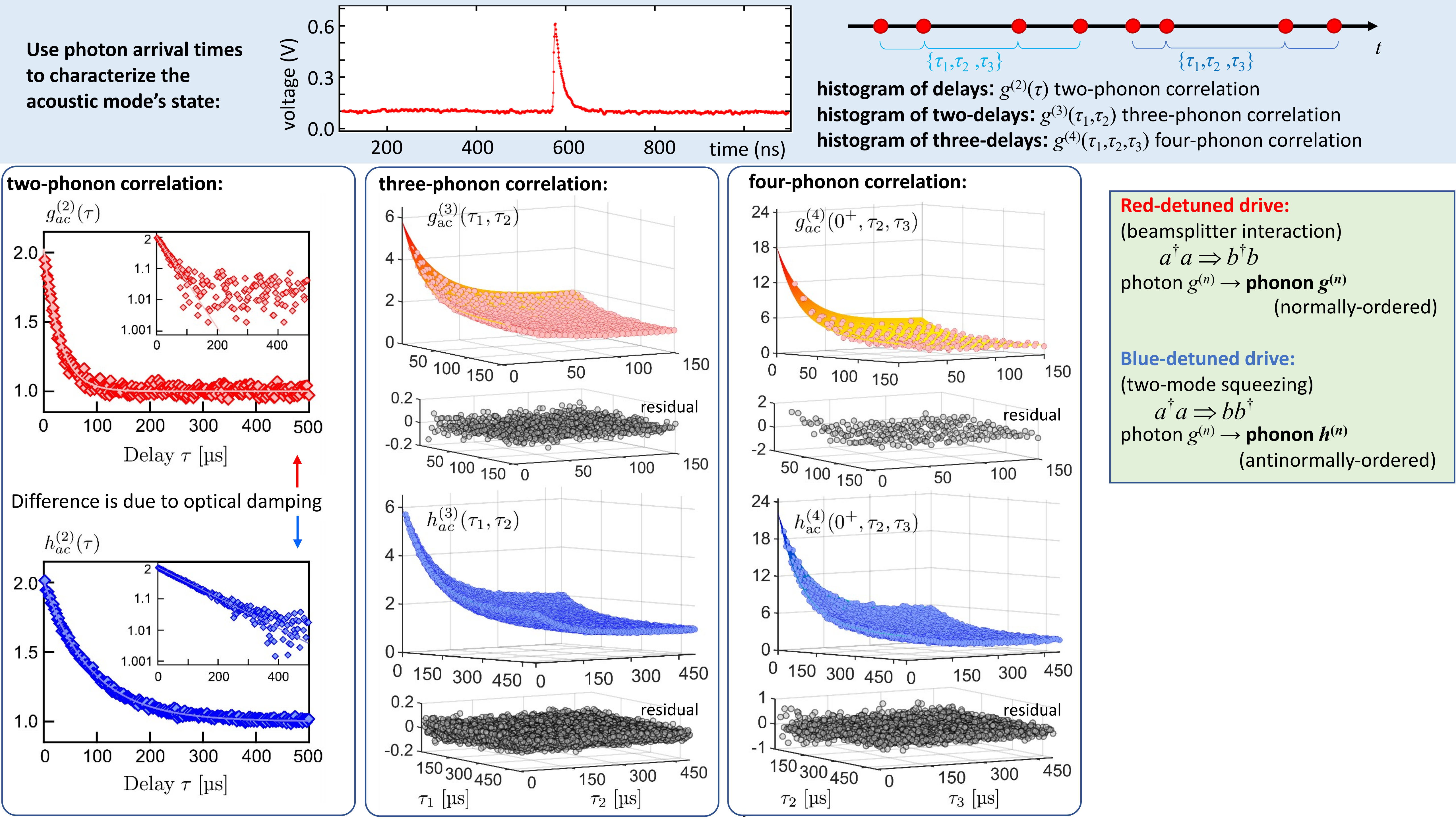

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residual
τ_1 [µs]
τ_2 [µs]
four-phonon correlation:
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τ_2 [µs]
τ_3 [µs]
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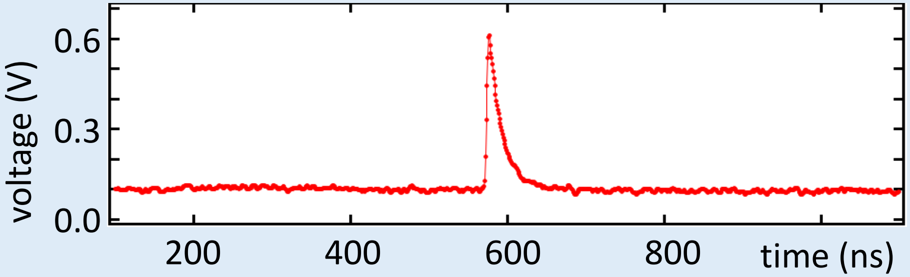

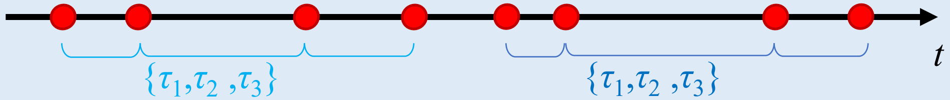

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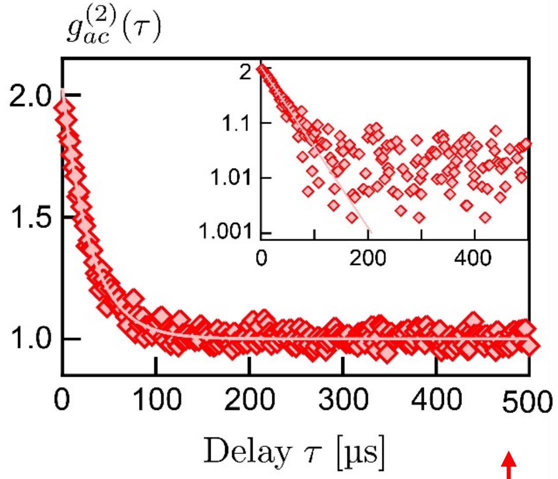
two-phonon correlation:



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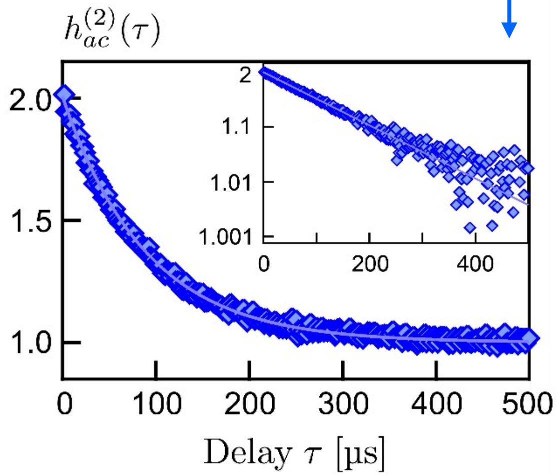

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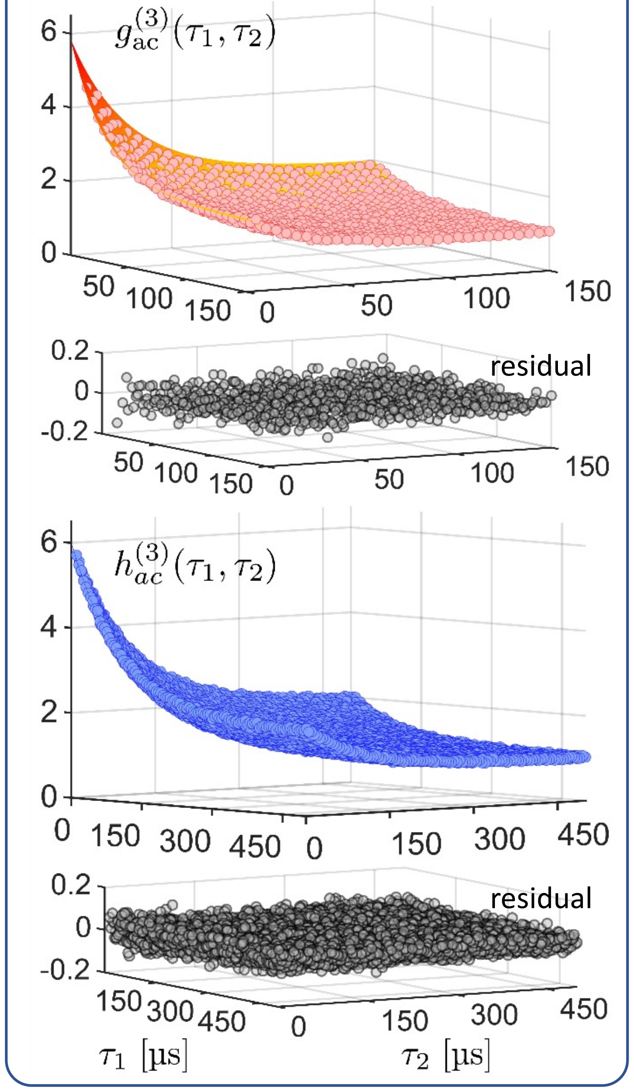

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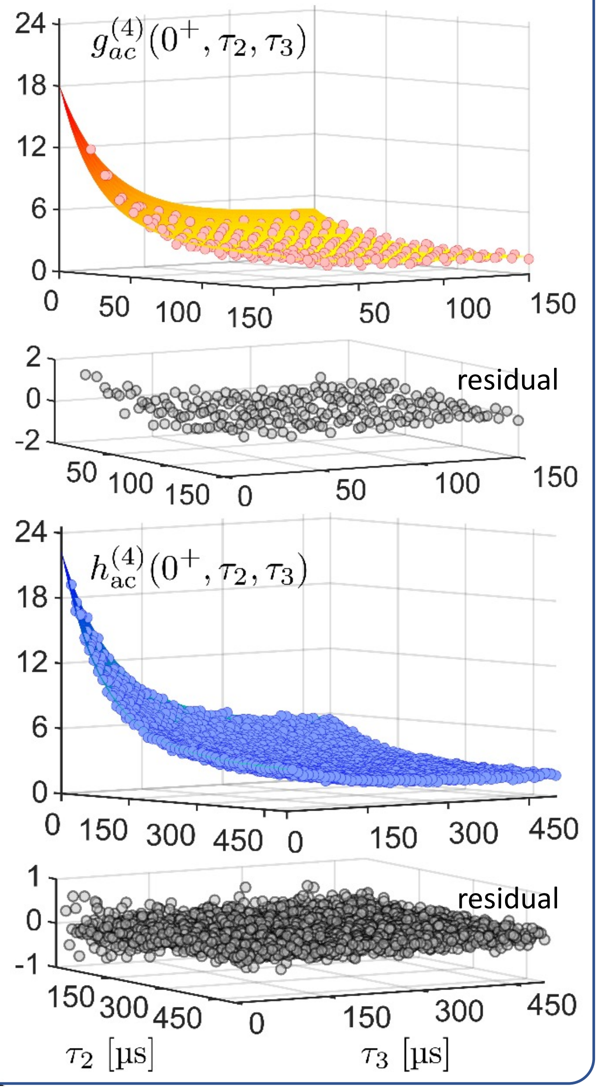

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(two-mode squeezing)
$a^\dagger a \Rightarrow b b^\dagger$
photon $g^{(n)} \to$ **phonon $h^{(n)}$**
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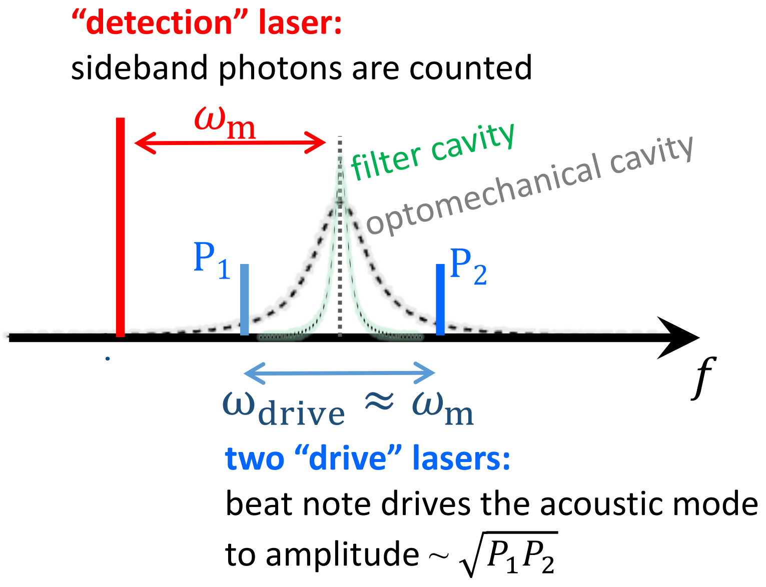
correlations for a thermal state

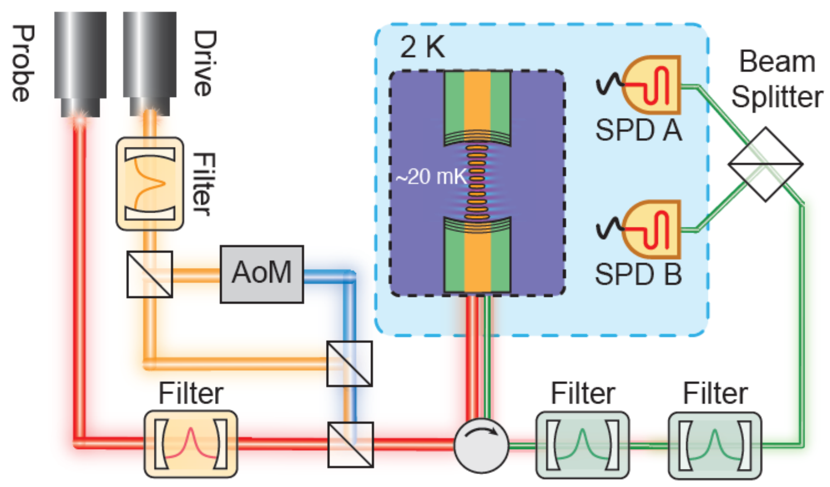
	exp.	thy.
$g^{(2)}(0)$	2.02(2)	2
$g^{(3)}(\mathbf{0})$	5.98(2)	6
$g^{(4)}(\mathbf{0})$	24.02(2)	24

acoustic mode's energy distribution is Gaussian to the 4th cumulant: ***very*** thermal!

Adding a linear drive to the acoustic mode: producing high-amplitude "coherent states"

- **Quantum-limited parameter estimation** (e.g.: ω_m)
- **Quantum-limited acoustic interferometry**
- **Tests of spacetime geometry**

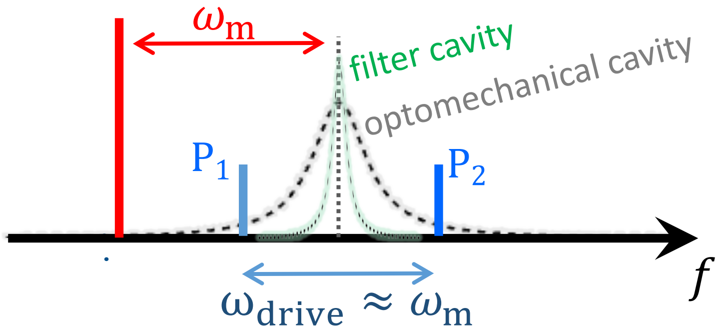




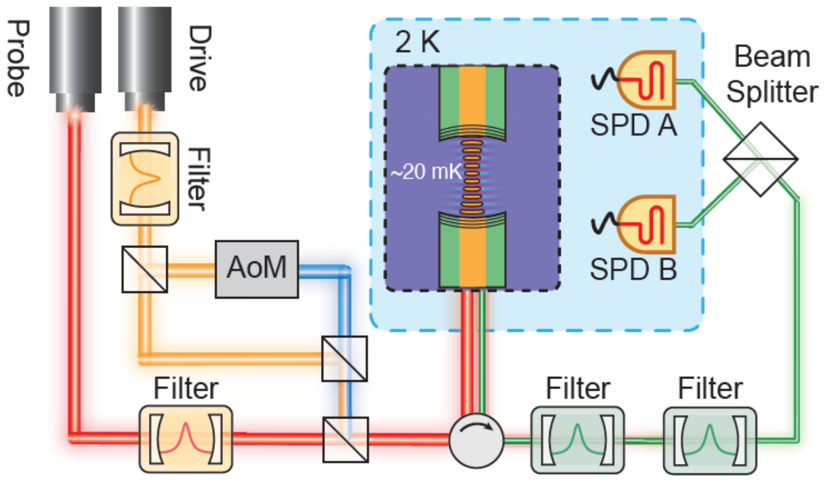
Adding a linear drive to the acoustic mode: producing high-amplitude "coherent states"

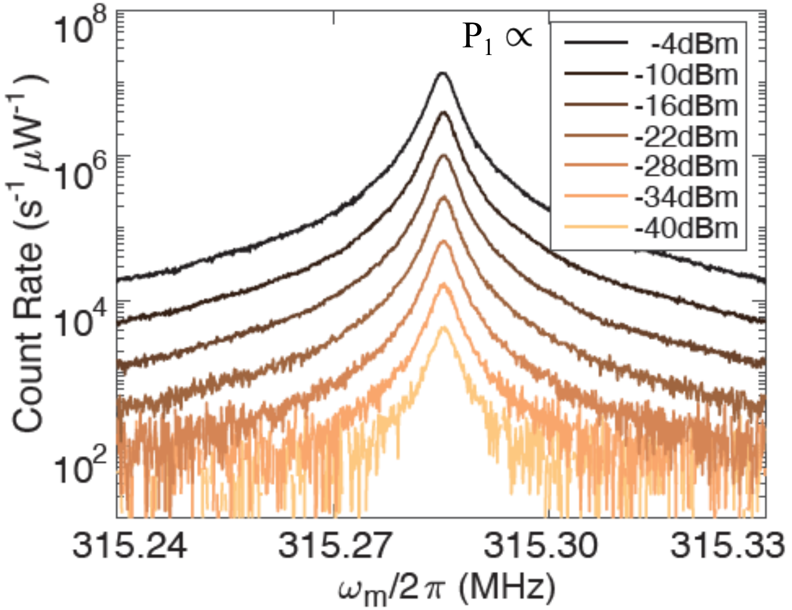
- **Quantum-limited parameter estimation** (e.g.: ω_m)
- **Quantum-limited acoustic interferometry**
- **Tests of spacetime geometry**

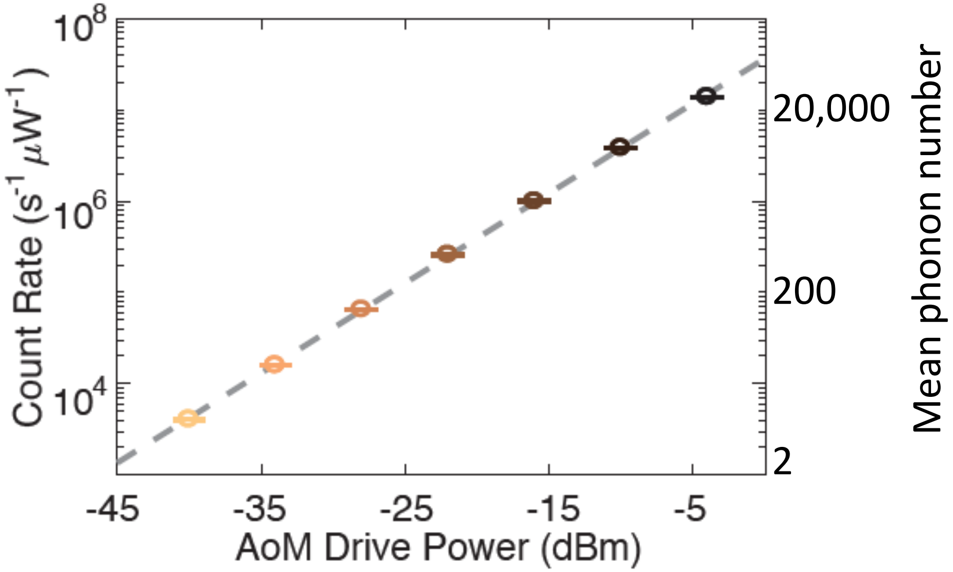
"detection" laser:
sideband photons are counted



two "drive" lasers:
beat note drives the acoustic mode
to amplitude ~ $\sqrt{P_1 P_2}$



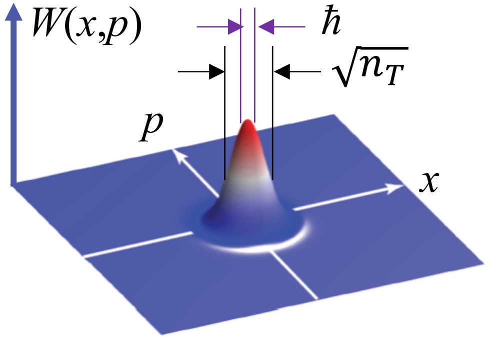




- **Lineshape is constant**
- **Mean phonon number is proportional to drive strength**
- **Acoustic mode is linear (to ≥ 40,000 phonons)**
- **Purity of the displaced state?**

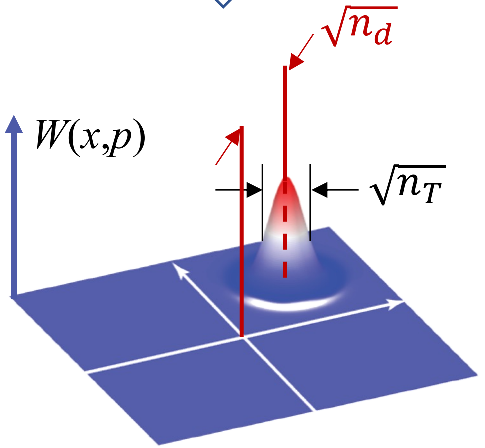
Adding a linear drive to the acoustic mode: producing high-amplitude "coherent states"

Acoustic mode is linear (to $\langle n_d \rangle \sim 40,000$). Purity of the state during driving?



Undriven state is thermal $n_T \sim 1.5$
confirmed by $g^{(2)}$, $g^{(3)}$, $g^{(4)}$, etc.

Drive ⇓ **?**



Best-case scenario for driven:
thermal state is displaced with
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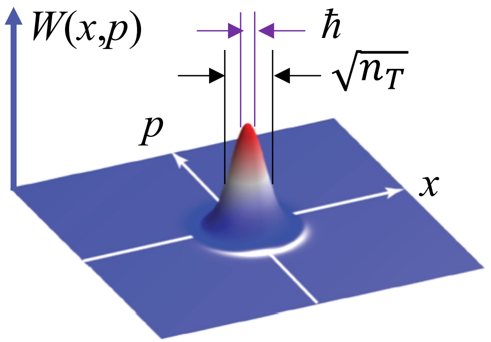

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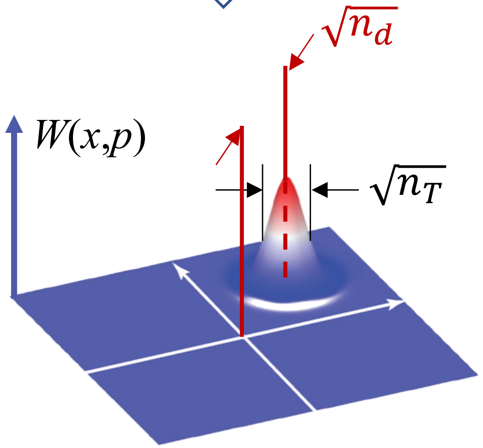

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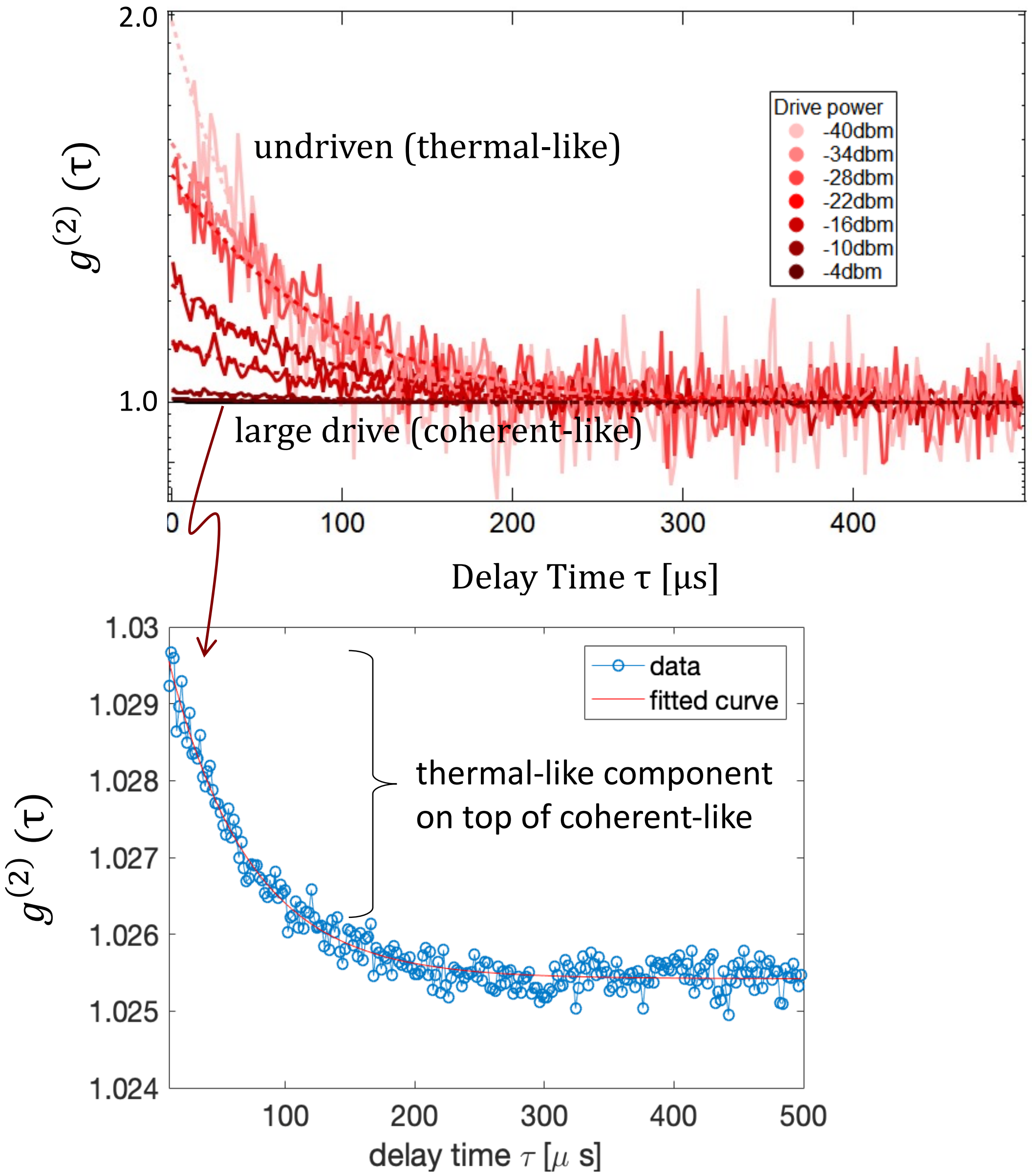

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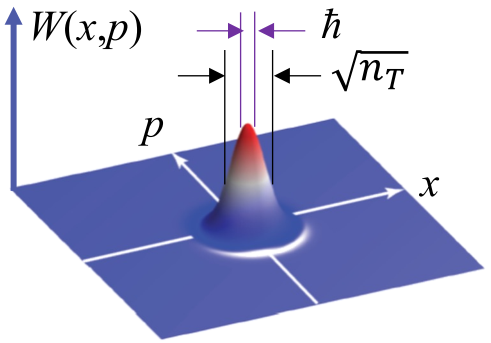

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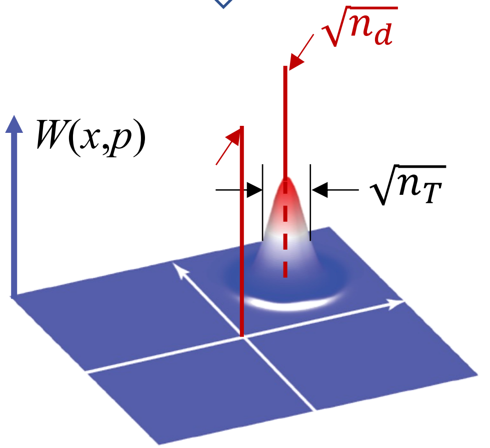

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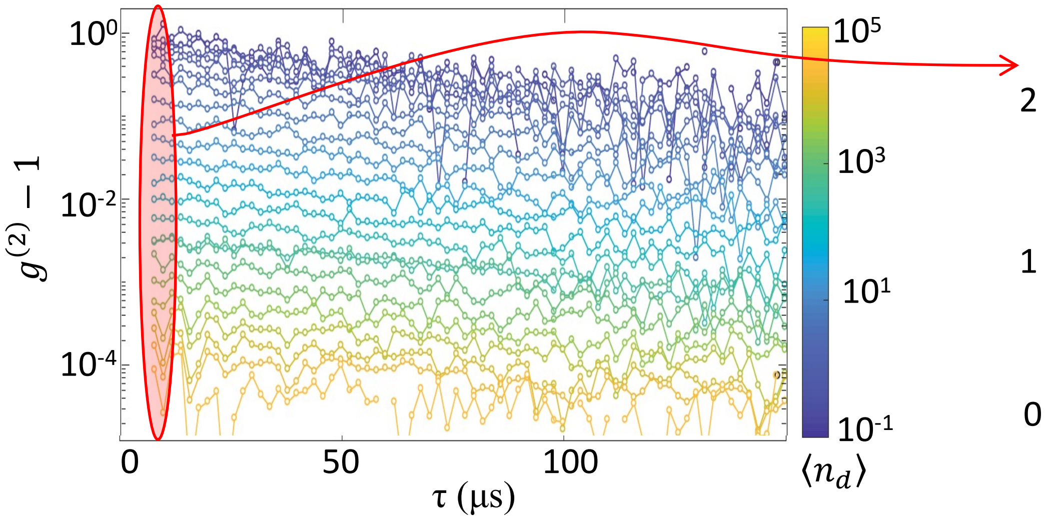

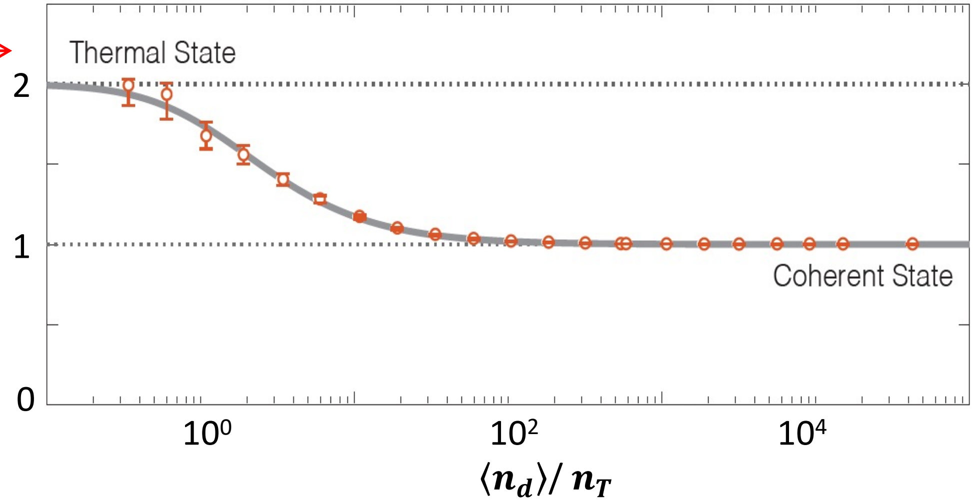

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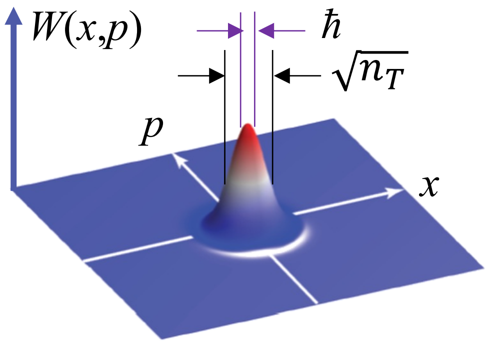

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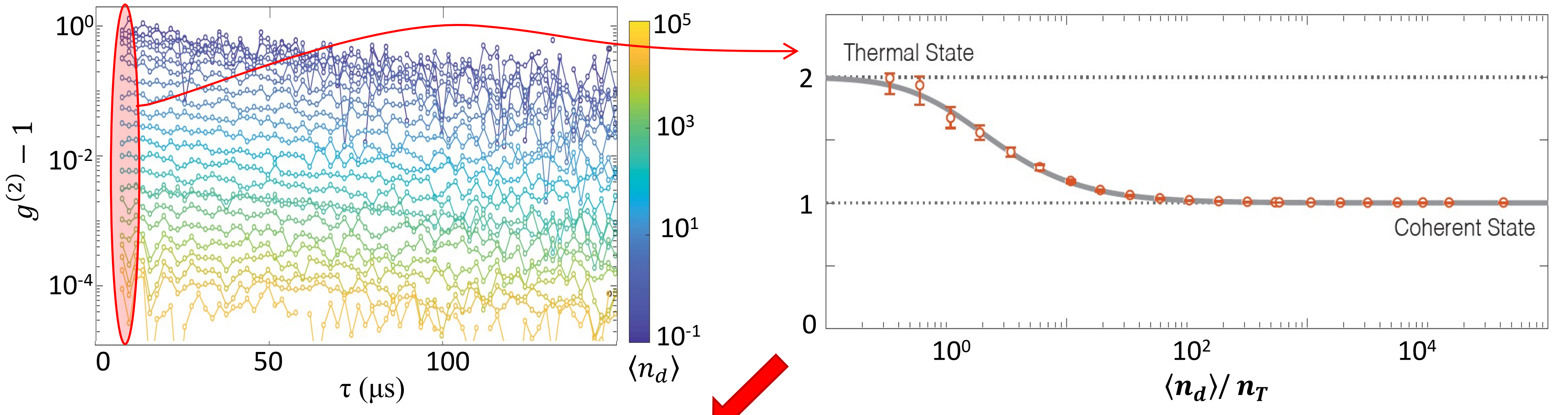

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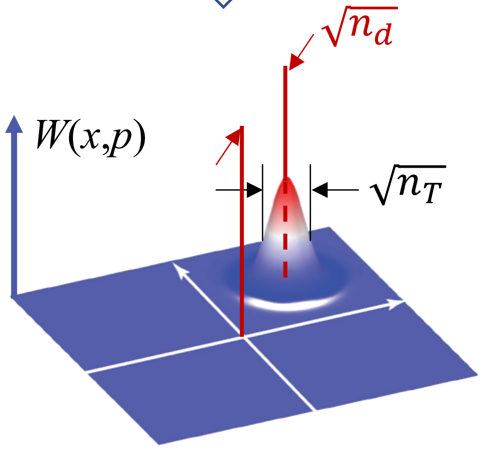

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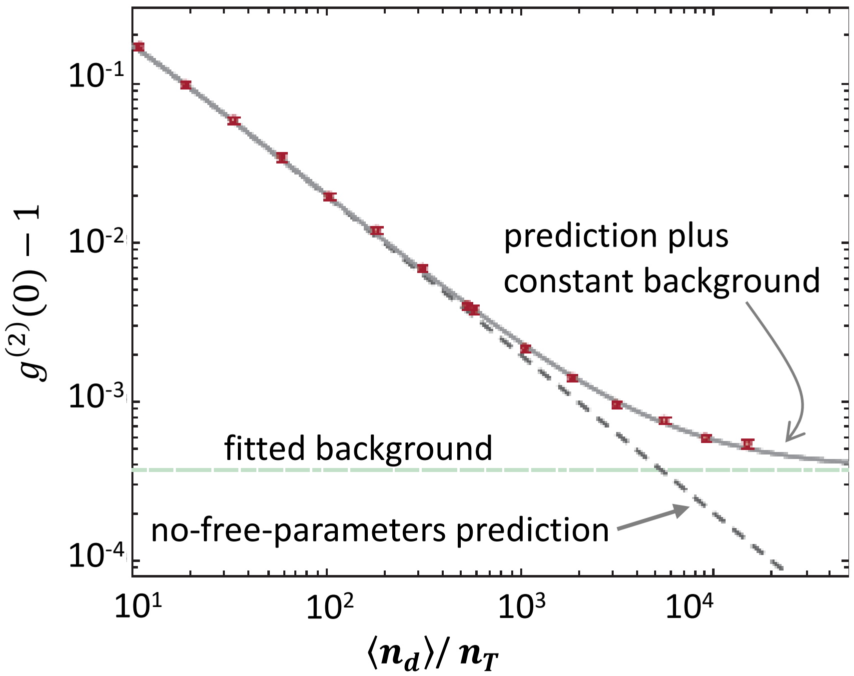

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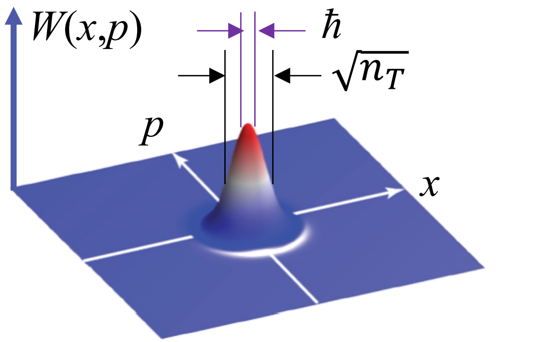

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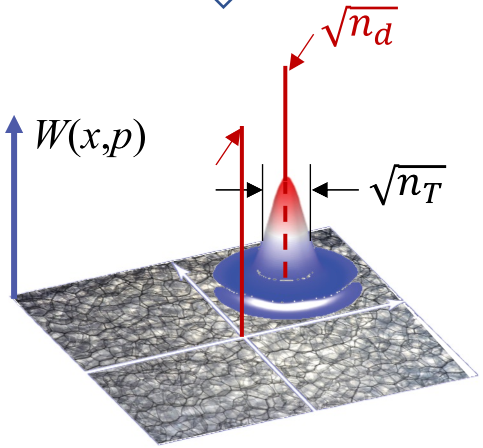

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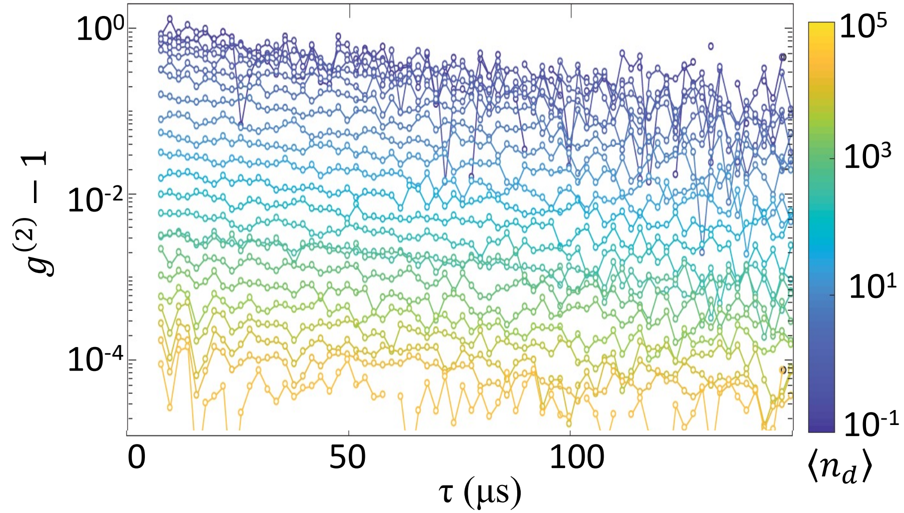
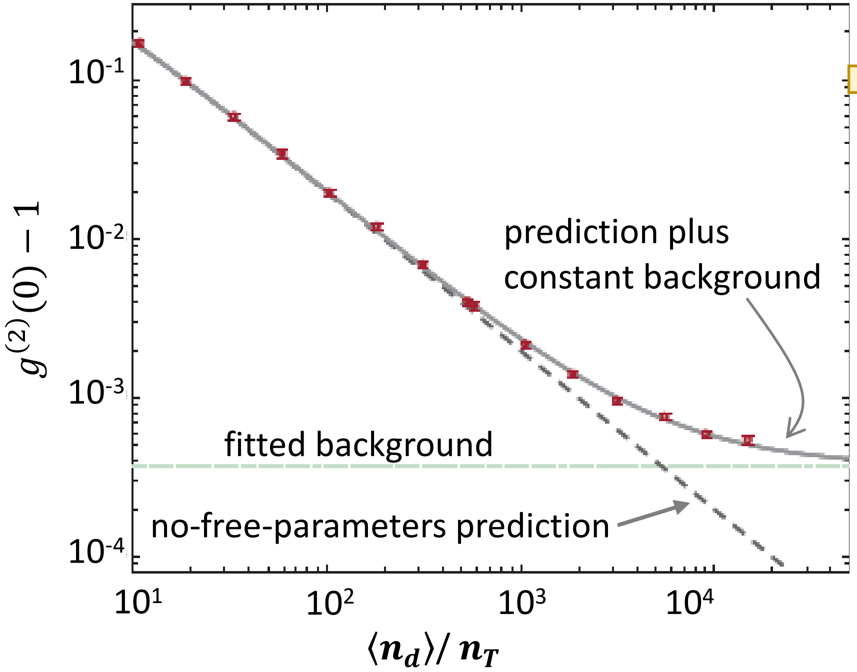
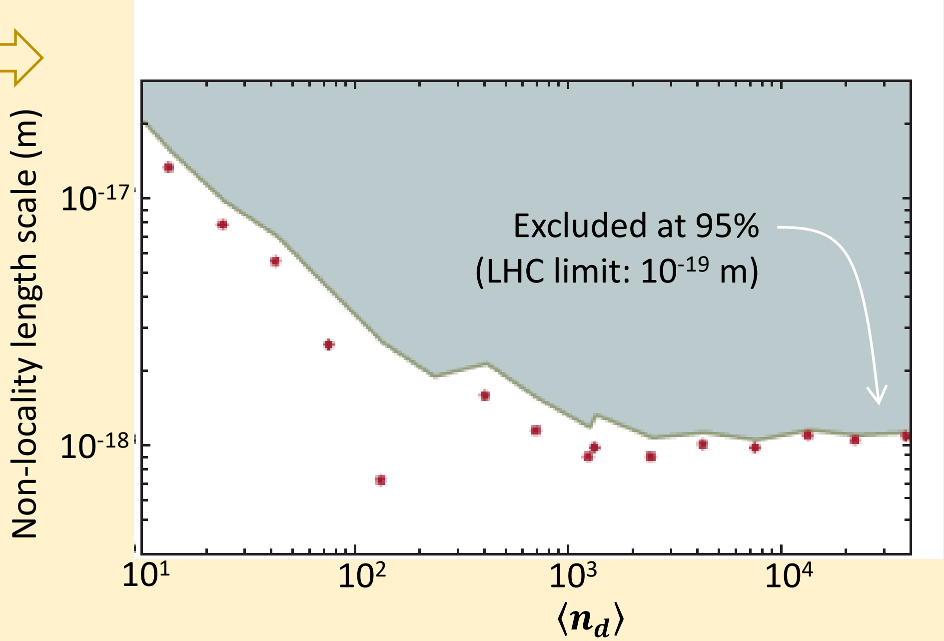




Beyond-Standard-Model physics via high-amplitude quantum-limited motion of a massive object:

- Hard to have a smallest length (ℓ_{Planck}) and Lorentz invariance.
- One solution: non-locality (causal set theory, string theory)
- ***Belenchia et al. PRL 2016:***
  - Non-locality has a length scale ($\neq \ell_{\text{Planck}}$) and modifies non-relativistic dynamics: a driven SHO becomes squeezed.
  - Qualitatively: oscillator probes lengths $\sim\sqrt{\hbar/2m\omega} \sim 10^{-15}$ m
  - Driving to large amplitude increases sensitivity by $\sim\sqrt{n_d}$
  - So, drive an oscillator and look for squeezing: $g^{(2)}(0) > 1$



Conclusions

Superfluid optomechanical devices:

truly single-mode coupling
efficient cooling
nanogram scale
can count single phonons

Confirmed Gaussian states (m ~ 1 ng, T ~ 20 mK, n ~ 1.5)

- to 4^{th} cumulant
- in post-selected phonon added/subtracted data
- with coherent drive to <n> ~ 40,000
- no sign of fundamental nonlocality at 10^{-18} m

Ongoing work:

Next generation of devices:

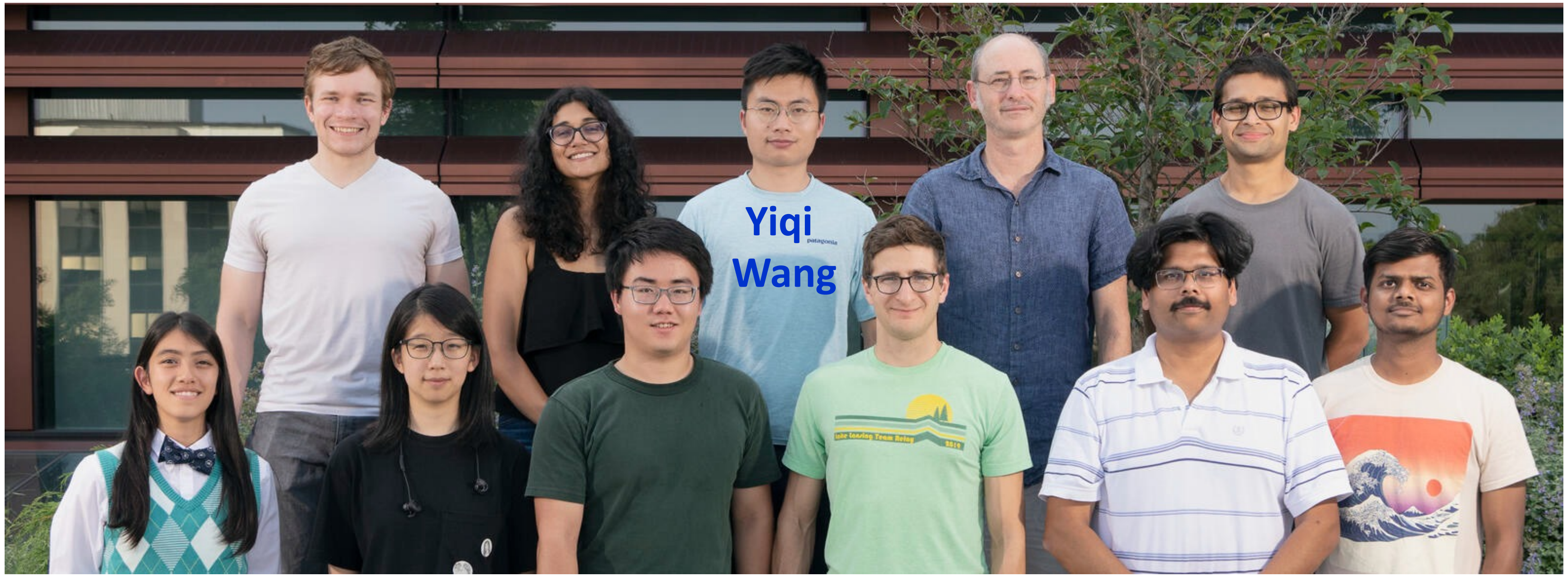
second-scale phonon lifetime
indistinguishable devices
microgram scale

Measure non-classical phonon statistics in nanogram-scale object

Improved devices for applications in:

entanglement distribution over km-scale fiber networks
quantum communication via DLCZ protocol
tests of discrete spacetime via high-amplitude coherent states
searches for dark matter
trapping electron bubbles (ultracoherent spins) in the fiber cavity

Jakob Reichel
(ENS Paris)



Lucy Yu

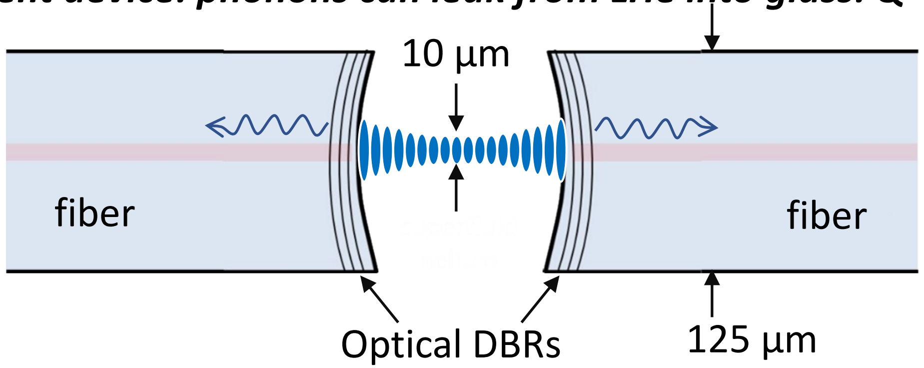
Yogesh Patil

postdoc
positions
available!!

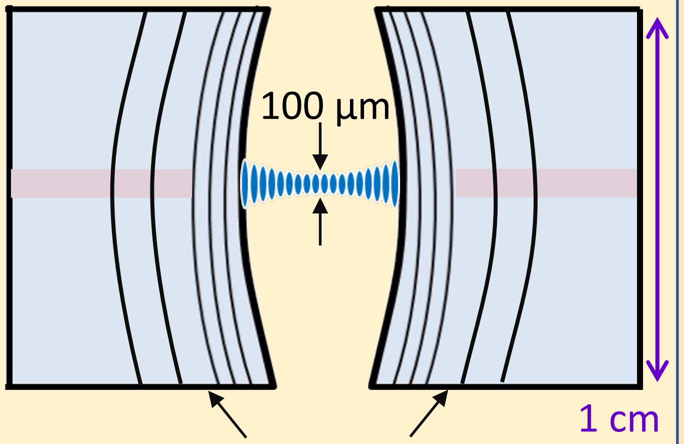
Next steps with new devices: non-Gaussian states & Bell tests

1. Improve acoustic Q: phonon lifetime >> heralding rate

Present device: phonons can leak from LHe into glass: $Q = 10^5$



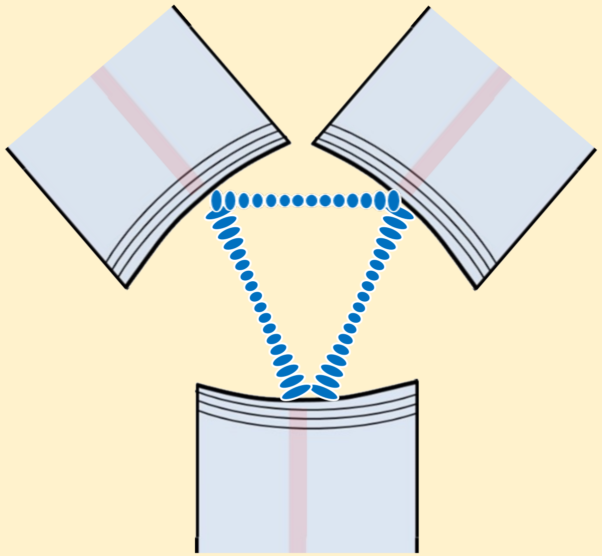
(A) Mirrors with acoustic DBRs



Optical and acoustic
dual-band DBRs

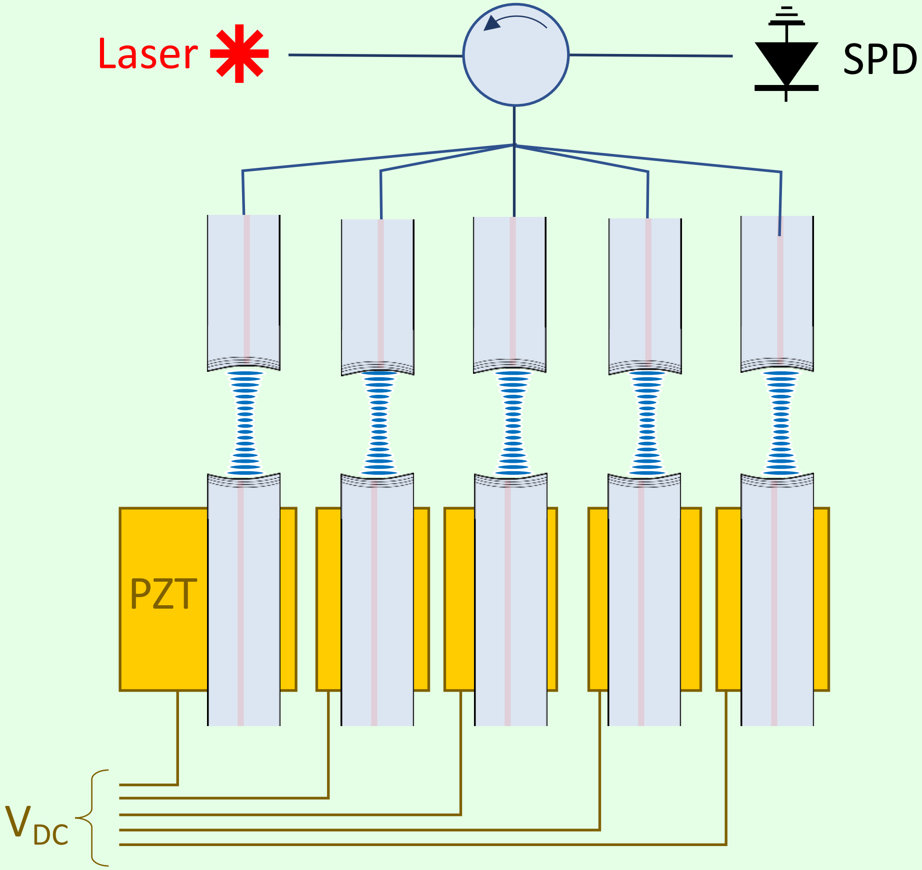
FEM predicted $Q = 10^7$

(B) Ring cavity



Acoustic mode confined by total internal reflection; $Q = 10^8$

2. Acoustic & optical indistinguishability for entanglement across arrays via DLCZ



One piezo per cavity to tune length;
detection on SPD heralds W-state

- **Entanglement distribution via 1550 nm photons**
- **Over fiber networks**
- **Long-lived quantum memory (~1 s) at nodes**