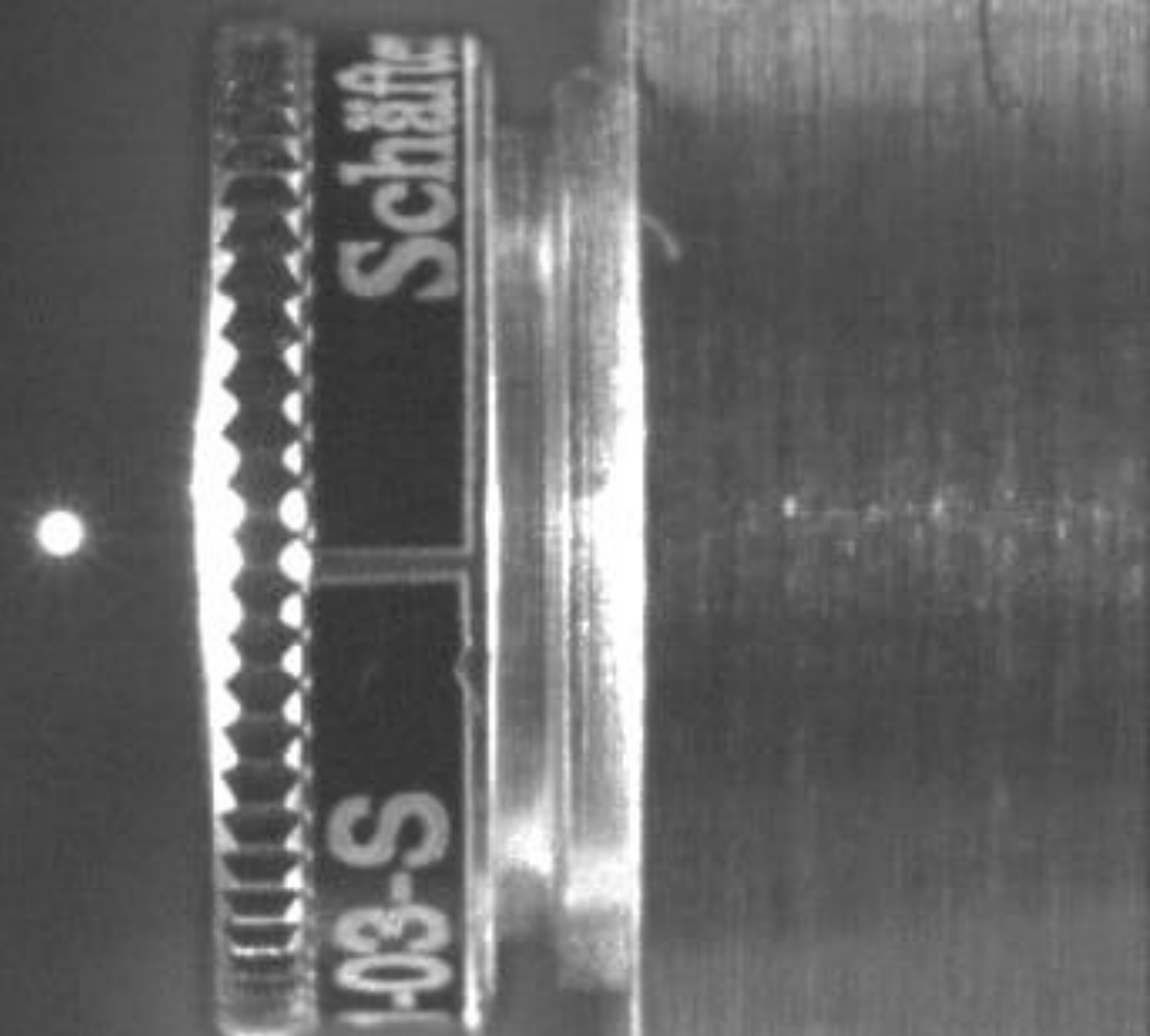
Two-dimensional quantum strong coupling with a levitated nanosphere



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QUANTERA
300K
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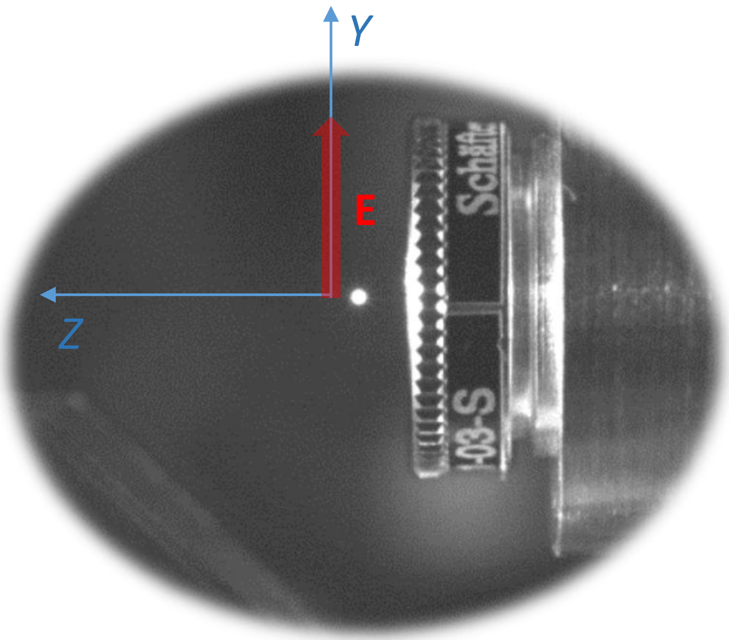
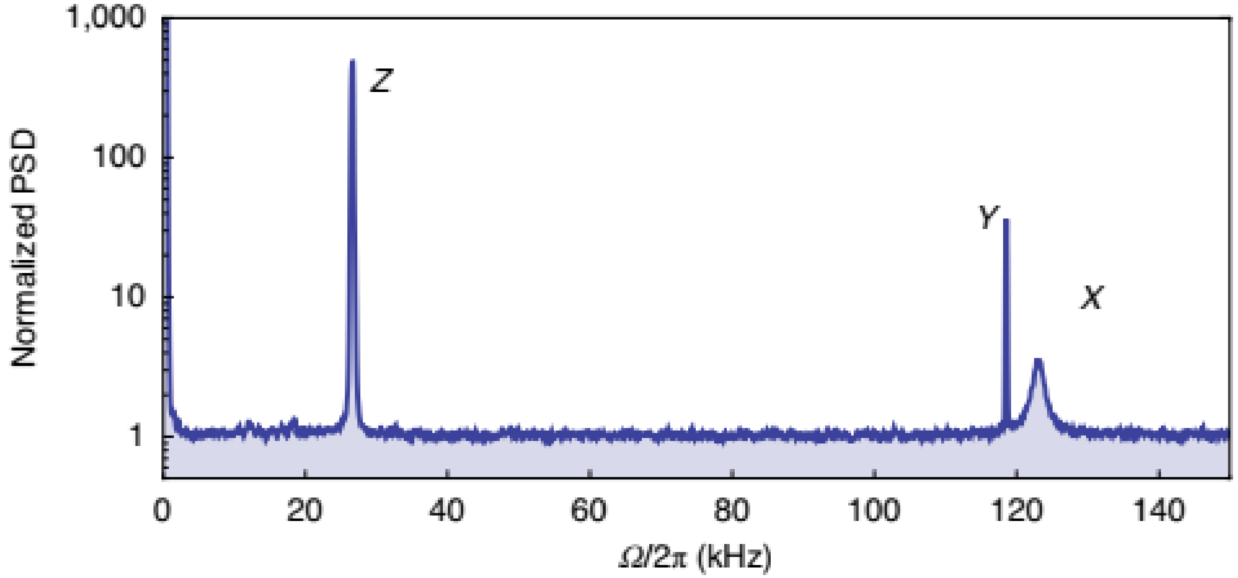
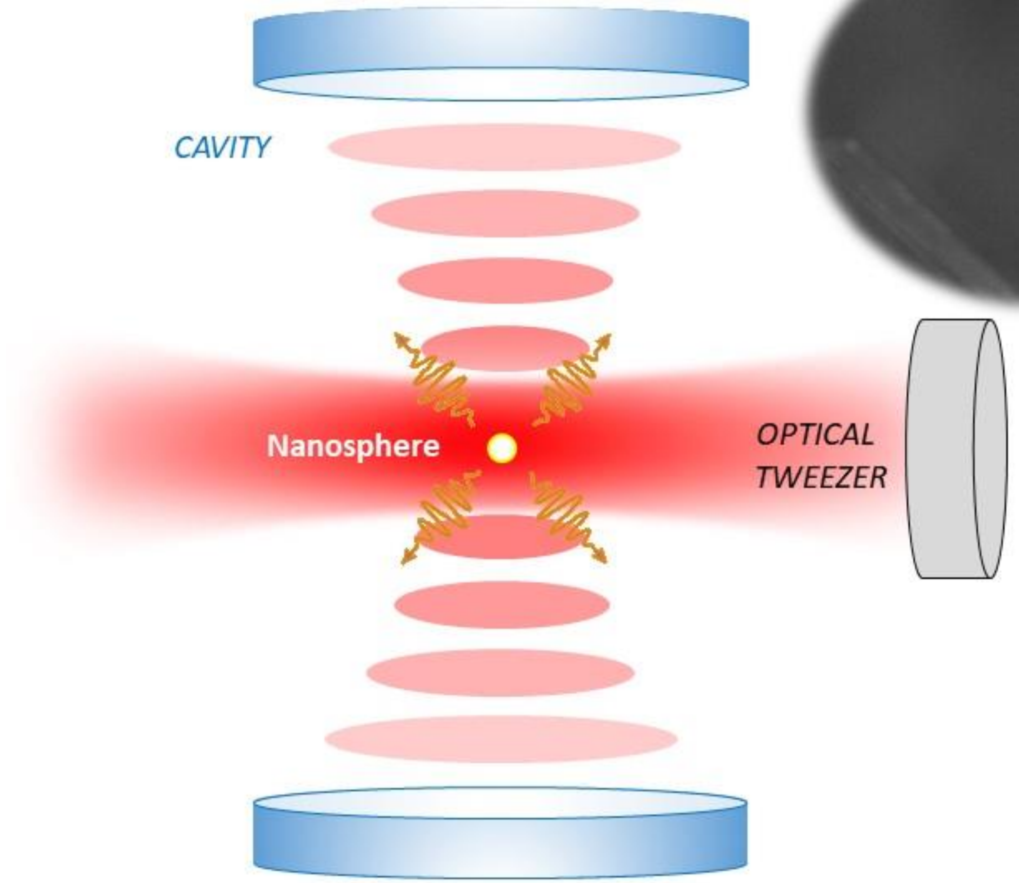
Levitated silica nanosphere

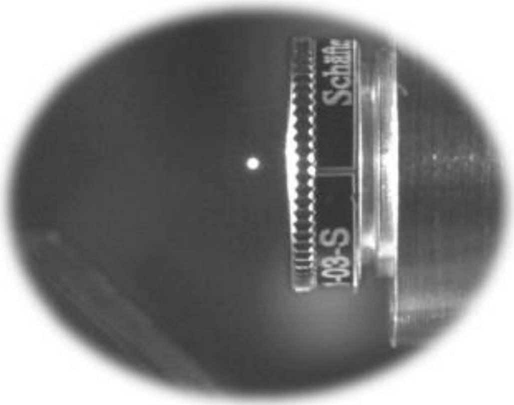




- diameter 125 nm
- $P_{tweezer}$ = 300 mW
- w_x = 0.9 μm
- w_y = 1.0 μm (// **E**)

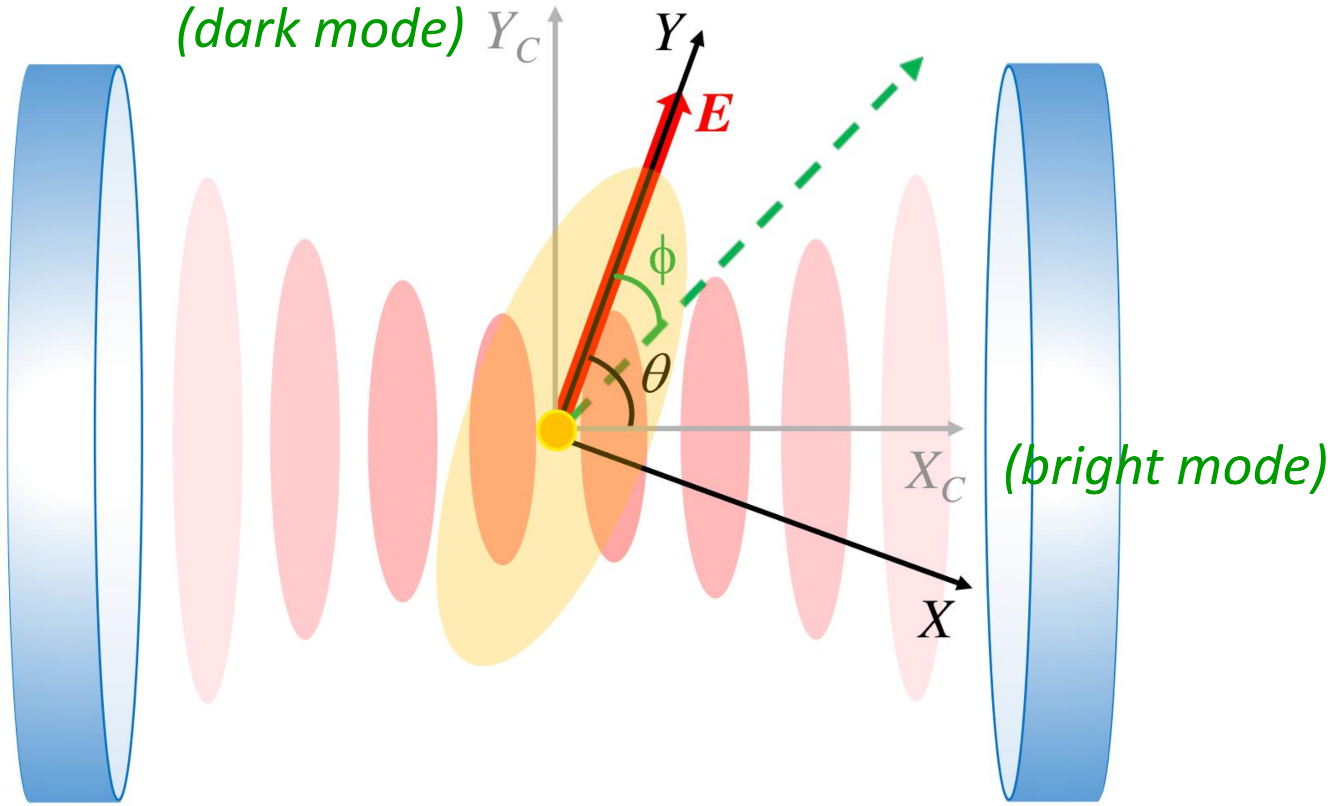
Coherent scattering





Delić, U. et al. Cavity cooling of a levitated nanosphere by coherent scattering. *Phys. Rev. Lett.* **122**, 123602 (2019).
Windey, D. et al. Cavity-based 3D cooling of a levitated nanoparticle via coherent scattering. *Phys. Rev. Lett.* **122**, 123601 (2019).
Gonzalez-Ballestero, C. et al. Theory for cavity cooling of levitated nanoparticles via coherent scattering: master equation approach. *Phys. Rev. A* **100**, 013805 (2019).

Coherent scattering



Hamiltonian

$$H = -\hbar\Delta a^\dagger a + \hbar\Omega_1 b_1^\dagger b_1 + \hbar\Omega_2 b_2^\dagger b_2 + \hbar g_1 (a^\dagger + a)(b_1^\dagger + b_1) + \hbar g_2 (a^\dagger + a)(b_2^\dagger + b_2)$$

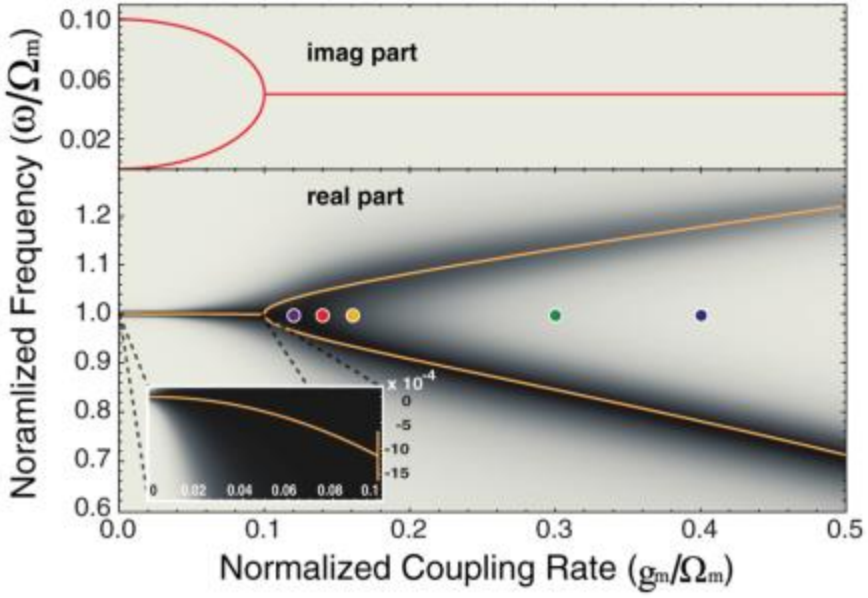
$g_1{}^2 + g_2{}^2 > k^2/16$ → STRONG COUPLING, HYBRID MODES

$2g > \Gamma_{dec}$ → QUANTUM COHERENT COUPLING, PHONON POLARITONS

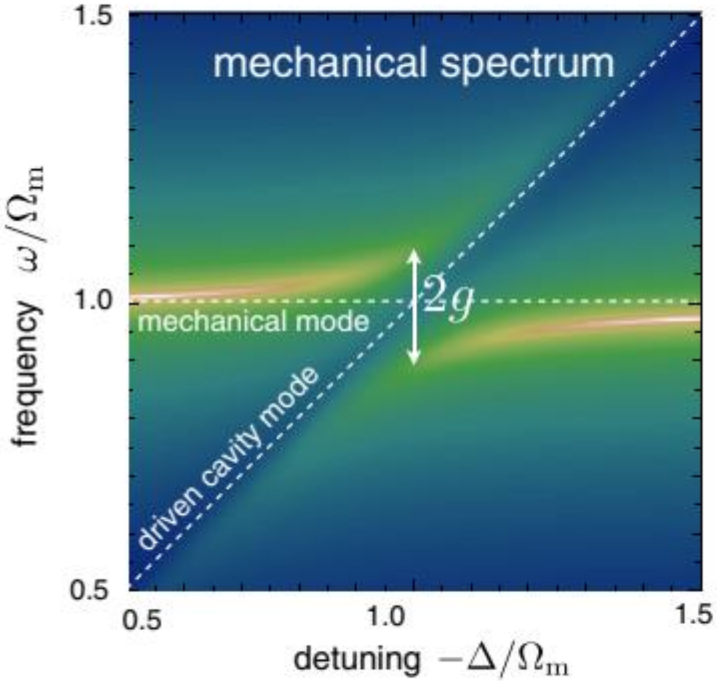
Strong coupling: single mechanical mode

$$\begin{pmatrix} \langle \delta \dot{\hat{a}} \rangle \\ \langle \dot{\hat{b}} \rangle \end{pmatrix} = -i \begin{pmatrix} -\Delta - i\frac{\kappa}{2} & -g \\ -g & \Omega_m - i\frac{\Gamma_m}{2} \end{pmatrix} \begin{pmatrix} \langle \delta \hat{a} \rangle \\ \langle \hat{b} \rangle \end{pmatrix}$$

$g > k/4$: avoided crossing



Dobrindt *et al.*, Phys. Rev. Lett. 101, 263602 (2008)



Aspelmeyer *et al.*, Rev. Mod. Phys. 86, 1391 (2014)

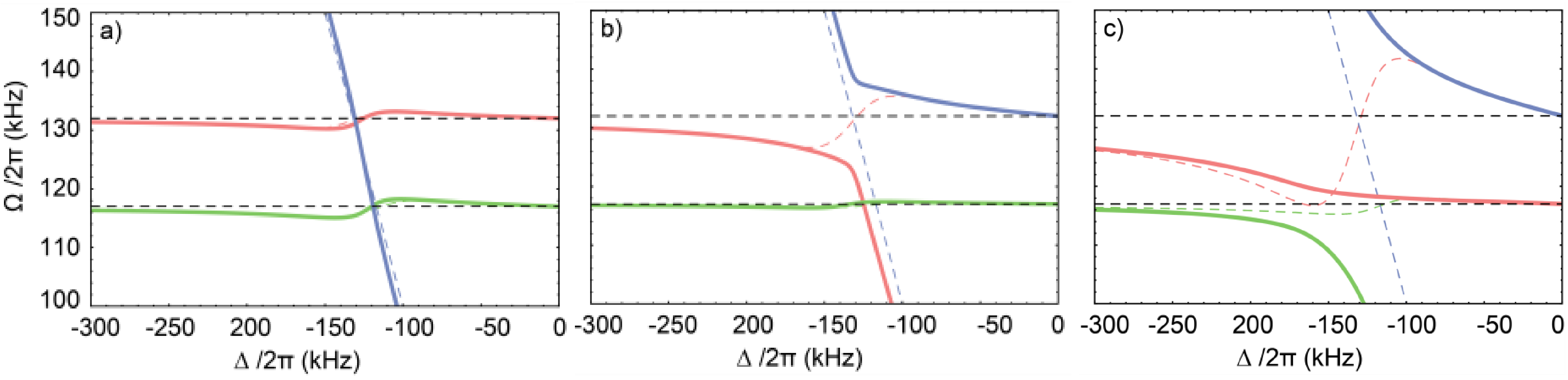
2D strong coupling

$$H = -\hbar\Delta a^{\dagger}a + \hbar\Omega_1 b_1^{\dagger}b_1 + \hbar\Omega_2 b_2^{\dagger}b_2 + \hbar g_1(a^{\dagger}+a)(b_1^{\dagger}+b_1) + \hbar g_2(a^{\dagger}+a)(b_2^{\dagger}+b_2)$$

$\kappa/2\pi = 57$ kHz $\quad \Omega_1^0/2\pi = 132$ kHz

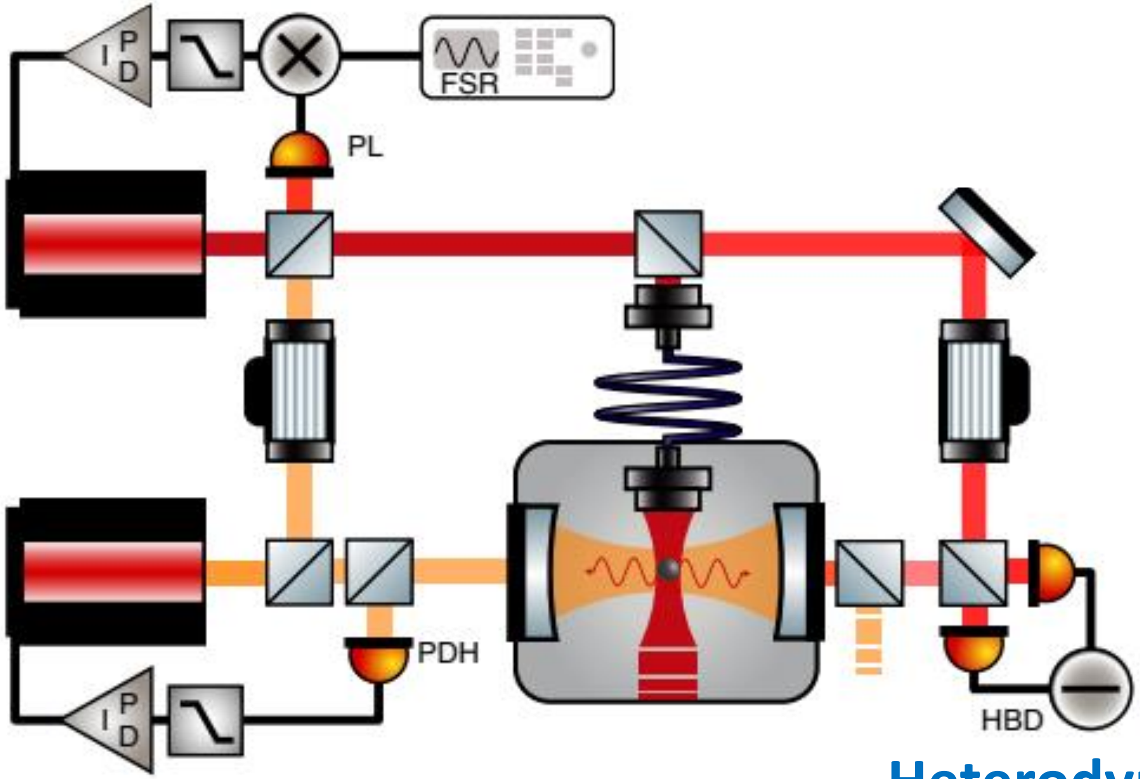
$\Omega_2^0/2\pi = 117$ kHz

$g_1 = g_2 = 2\pi$ x 9 kHz $\qquad g_1 = 2\pi$ x 16 kHz, $g_2 = 2\pi$ x 5 kHz $\qquad g_1 = 2\pi$ x 29 kHz, $g_2 = 2\pi$ x 9 kHz



Setup

Phase locking at +1FSR+detuning

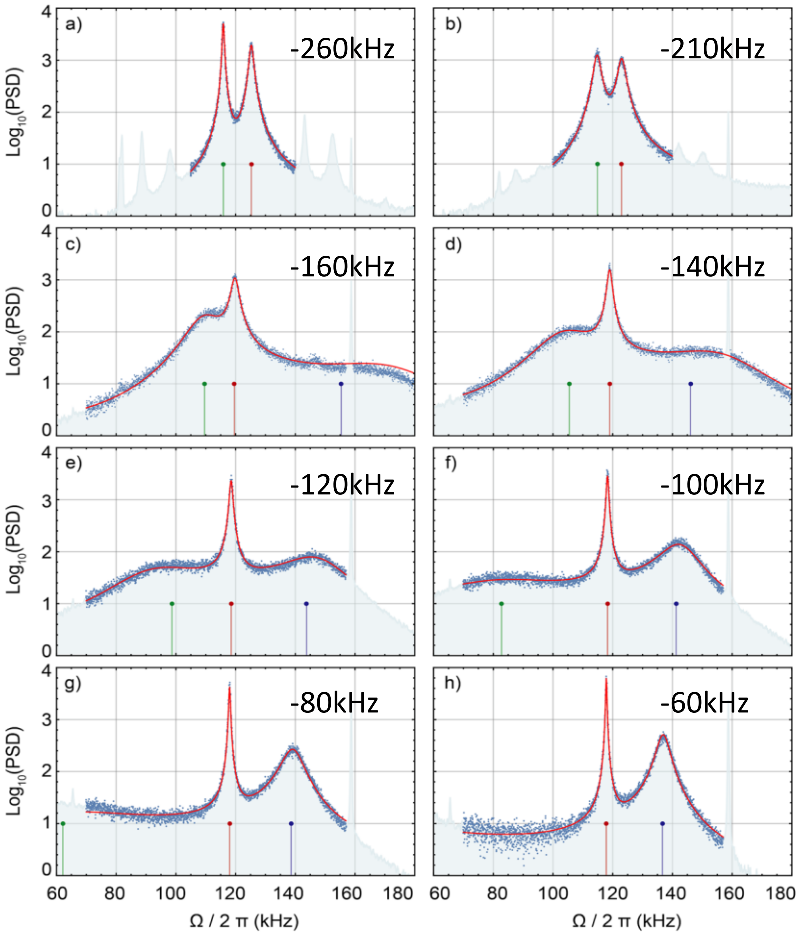


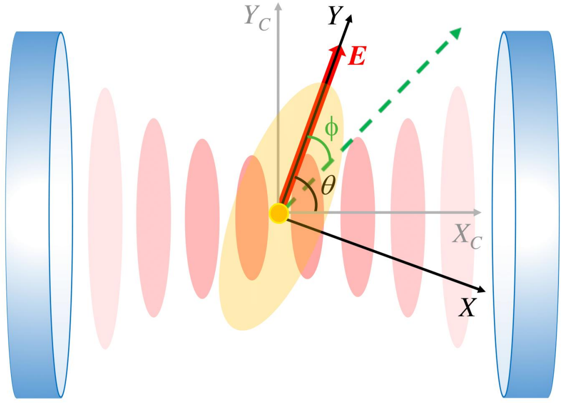
Heterodyne detection

Cavity locking

Vectorial polaritons

Spectra of the transmitted field





$\theta = 72^o$

$g_x = 2\pi \times 26.7$ kHz

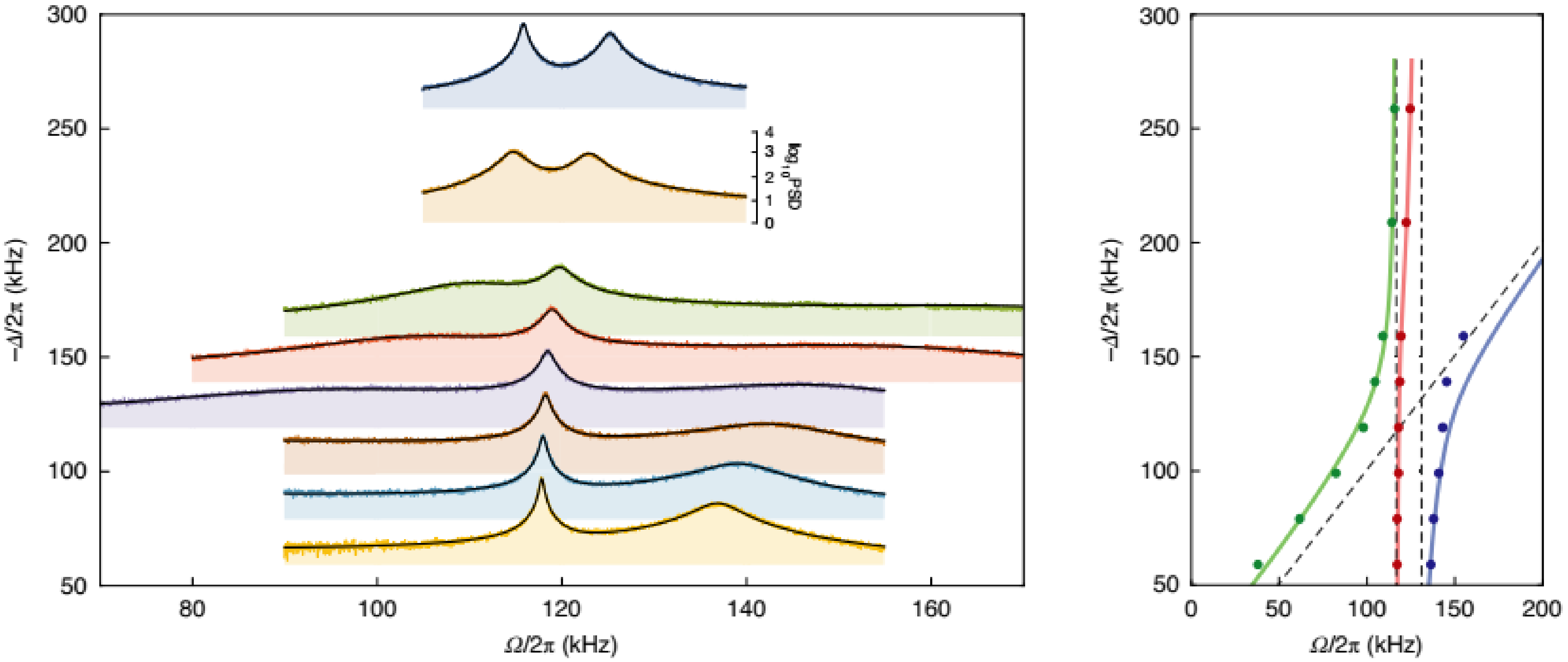
$g_y = 2\pi \times 9.4$ kHz

LETTERS
https://doi.org/10.1038/s41567-021-01307-y
nature physics
Check for updates

Vectorial polaritons in the quantum motion of a levitated nanosphere

A. Ranfagni[1,2], P. Vezio[1,2], M. Calamai[2], A. Chowdhury[3,5], F. Marino[2,3] and F. Marin[1,2,3,4]

Dispersion relations



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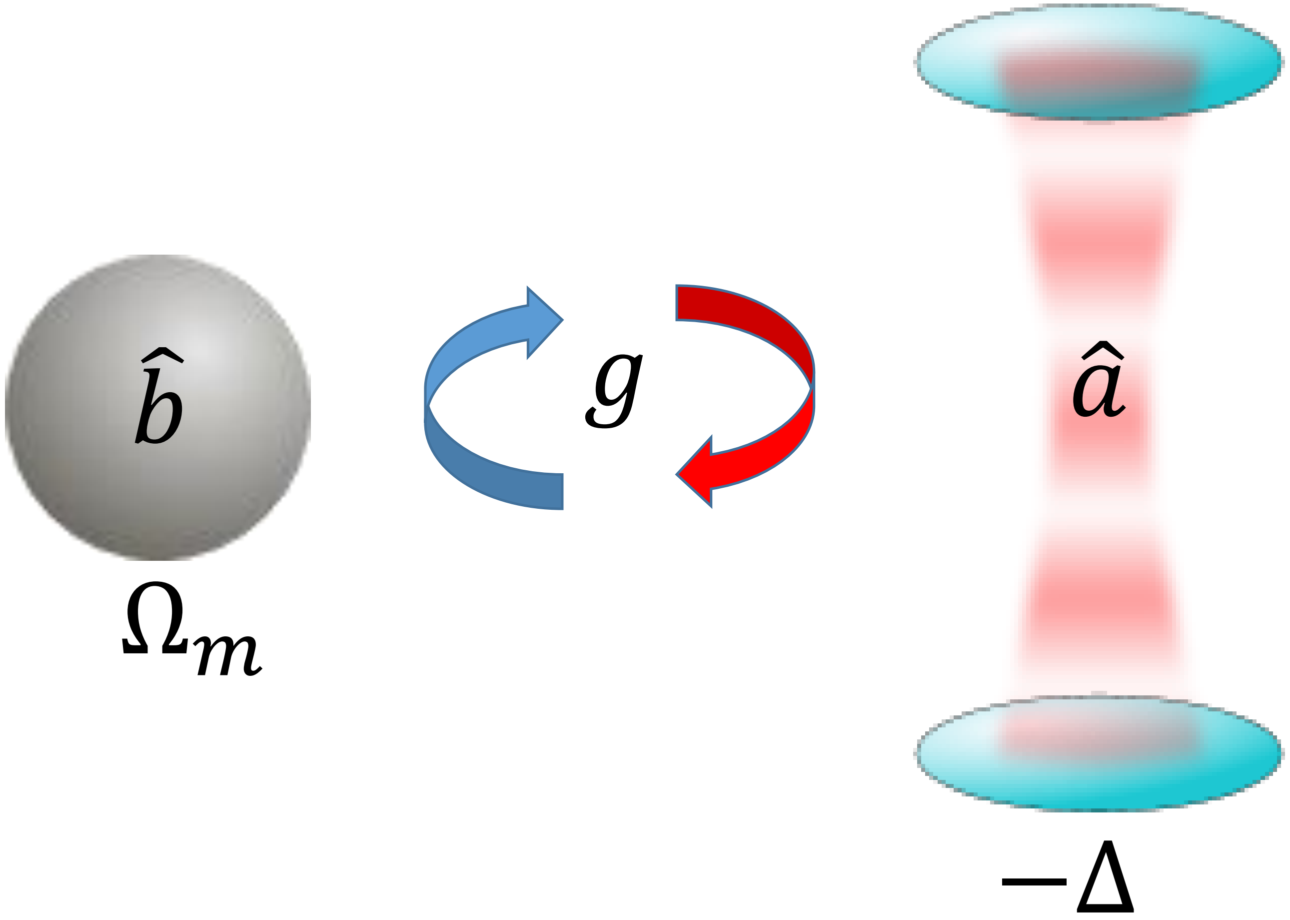
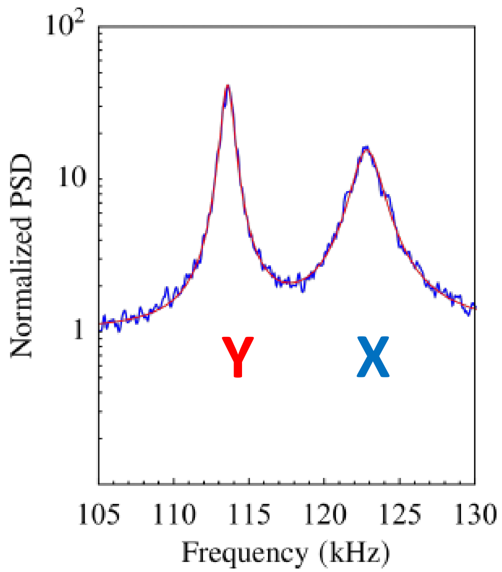
$g_1{}^2 + g_2{}^2 > k^2/16$ ⟹ STRONG COUPLING, HYBRID MODES

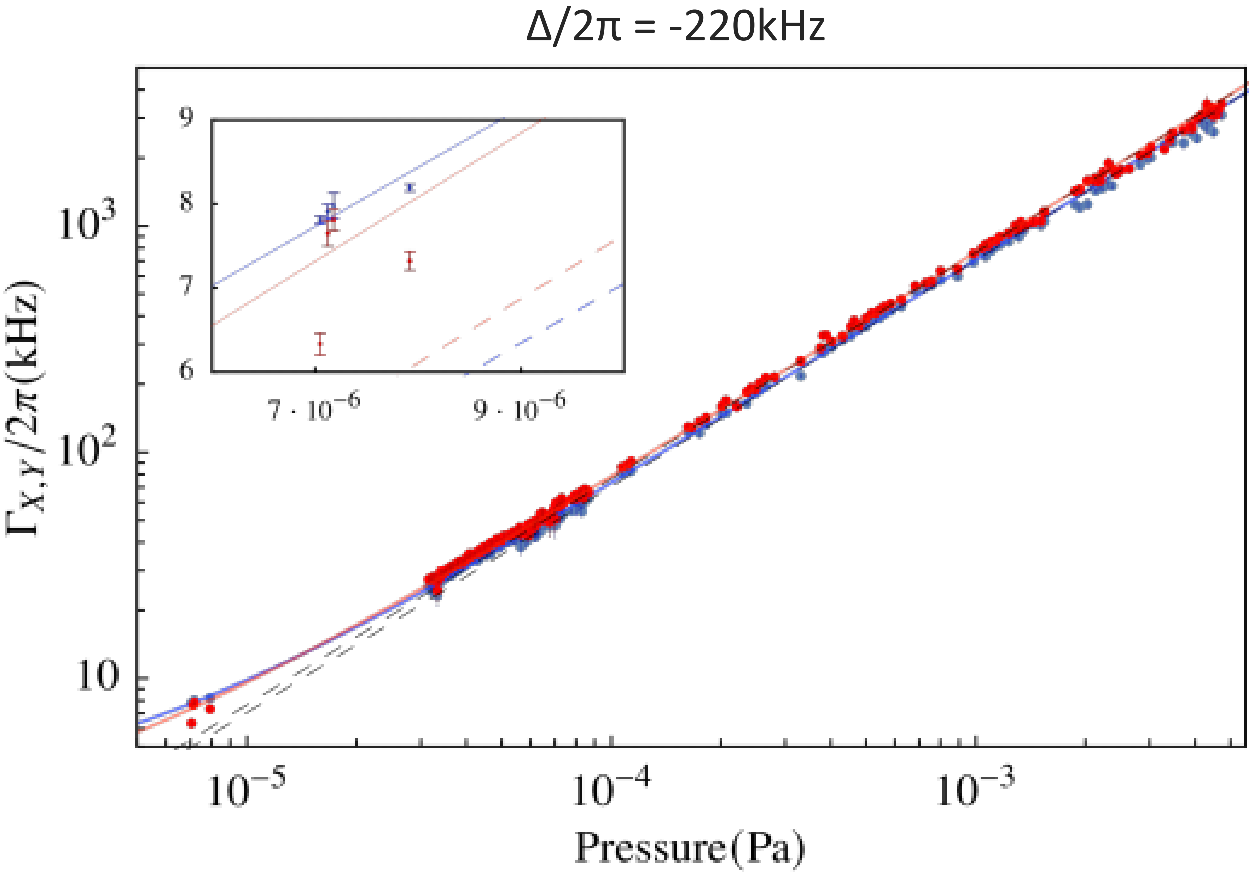
$2g > \Gamma_{dec}$ ⟹ QUANTUM COHERENT COUPLING, PHONON POLARITONS

Vectorial polaritons are observed when the decoherence time is longer than the swap time



Decoherence rate





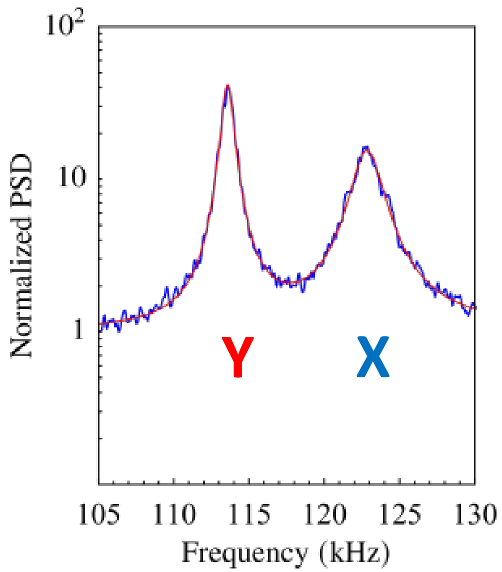
Decoherence rate: $\Gamma_{dec} = n_{th}\,\Gamma_m + \Gamma_{sc}$

Gas damping ∝ pressure

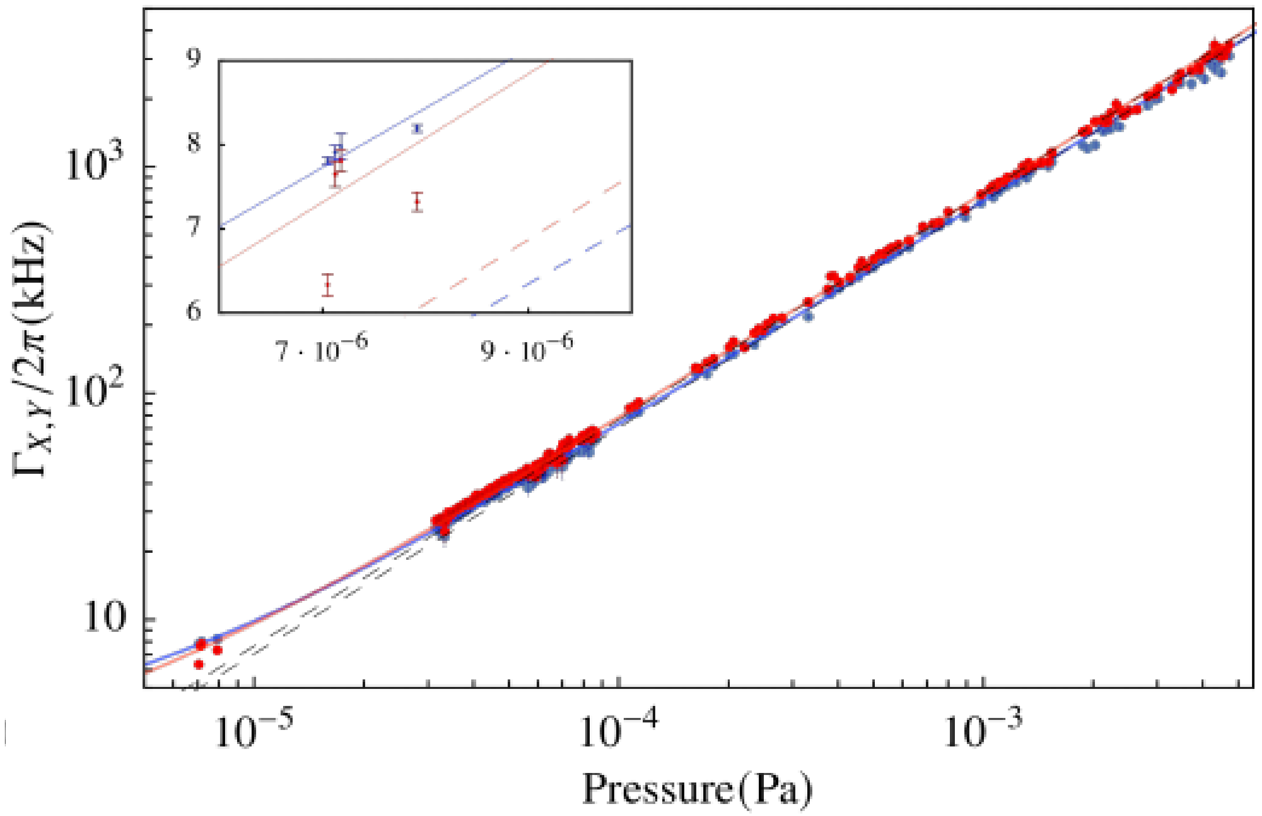
Shot noise in the dipole scattering

A. Ranfagni *et al.*, Phys. Rev. Res. **4**, 033051 (2022)

Decoherence rate



Δ/2π = -220kHz



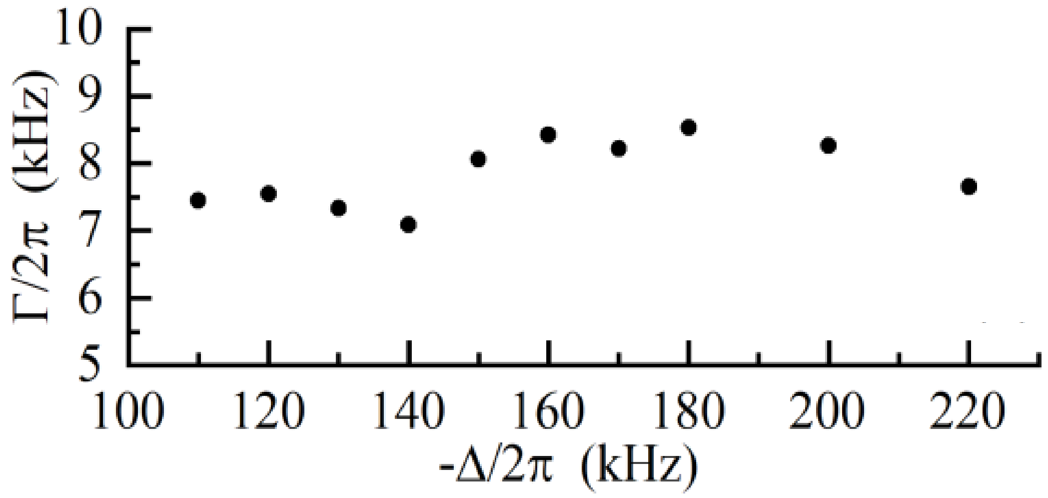
Decoherence rate: $\Gamma_{dec} = n_{th}\,\Gamma_m + \Gamma_{sc}$

$2g_X = 2\pi \times 50$ kHz $> \Gamma_{dec} = 2\pi \times 8$ kHz → **Quantum coherent strong coupling**

$C_Q = 4g^2/k\,\Gamma_{dec} = 5.5$

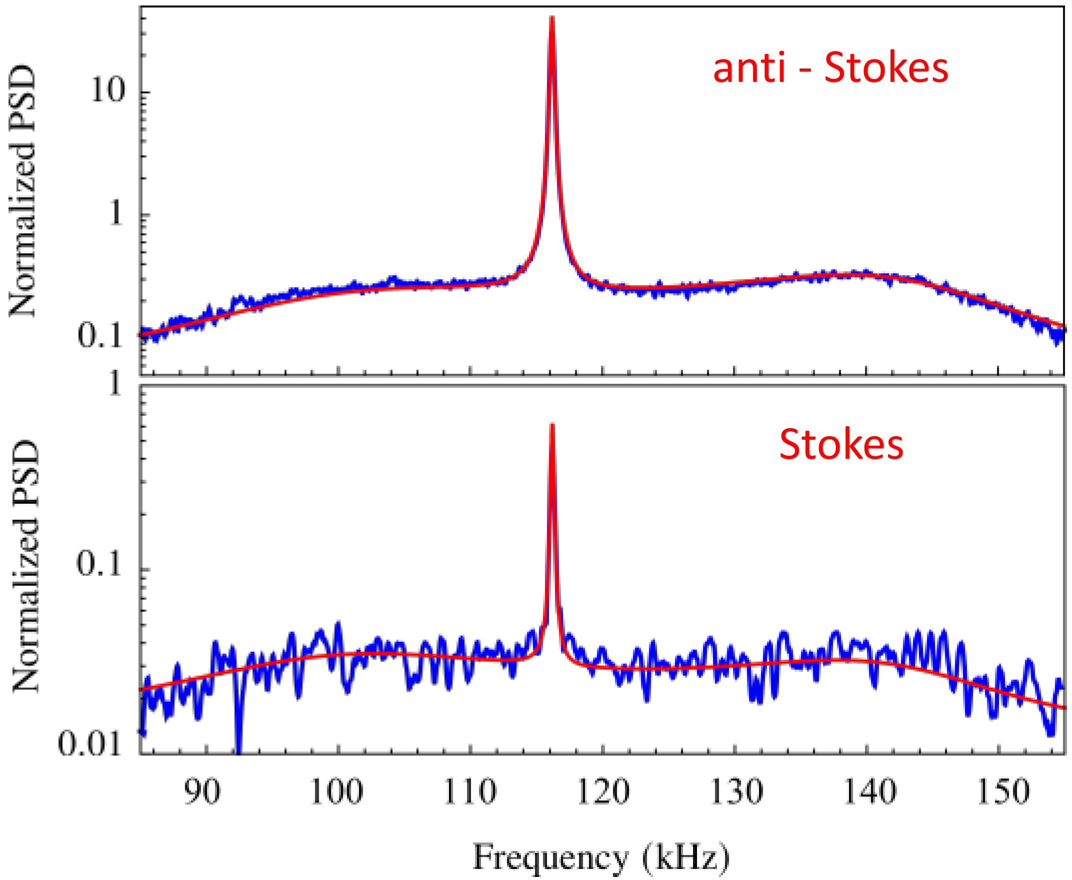
Quantum polaritons

Decoherence rate vs detuning



Heterodyne Spectra of the transmitted field

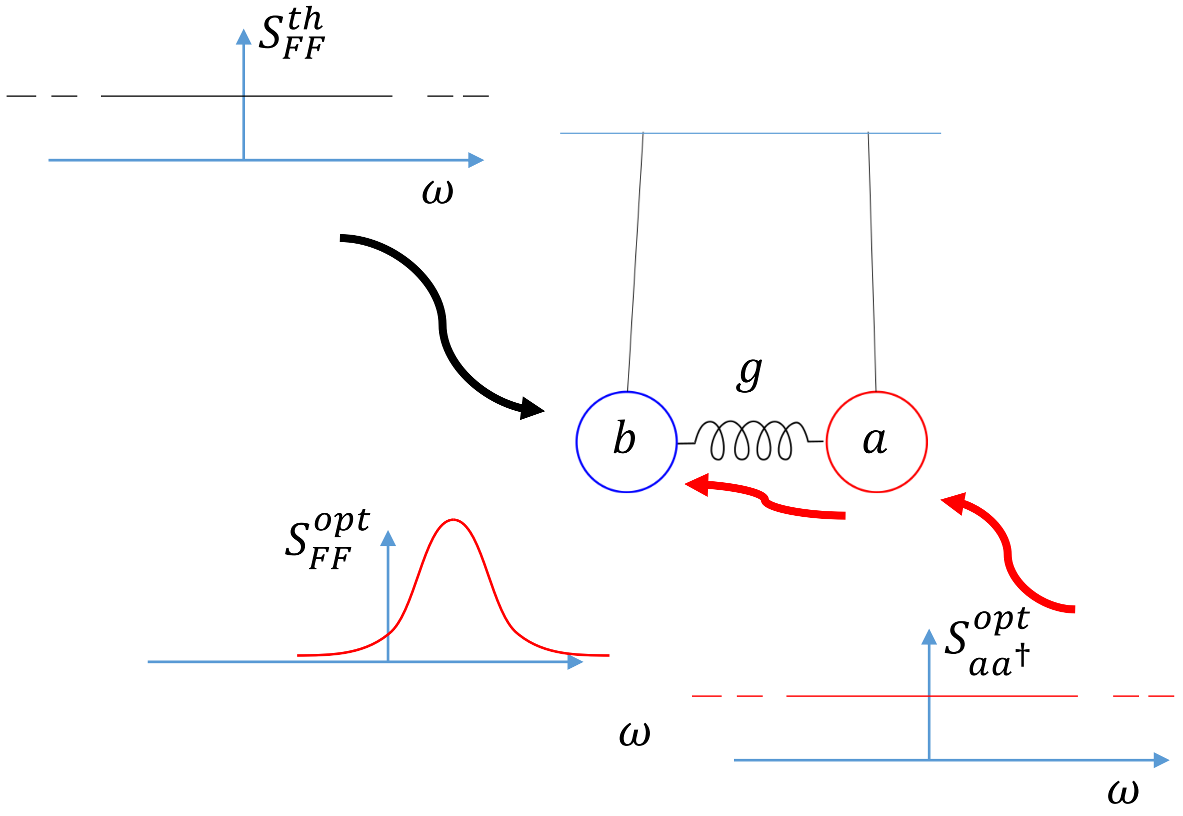
Δ/2π = -120kHz



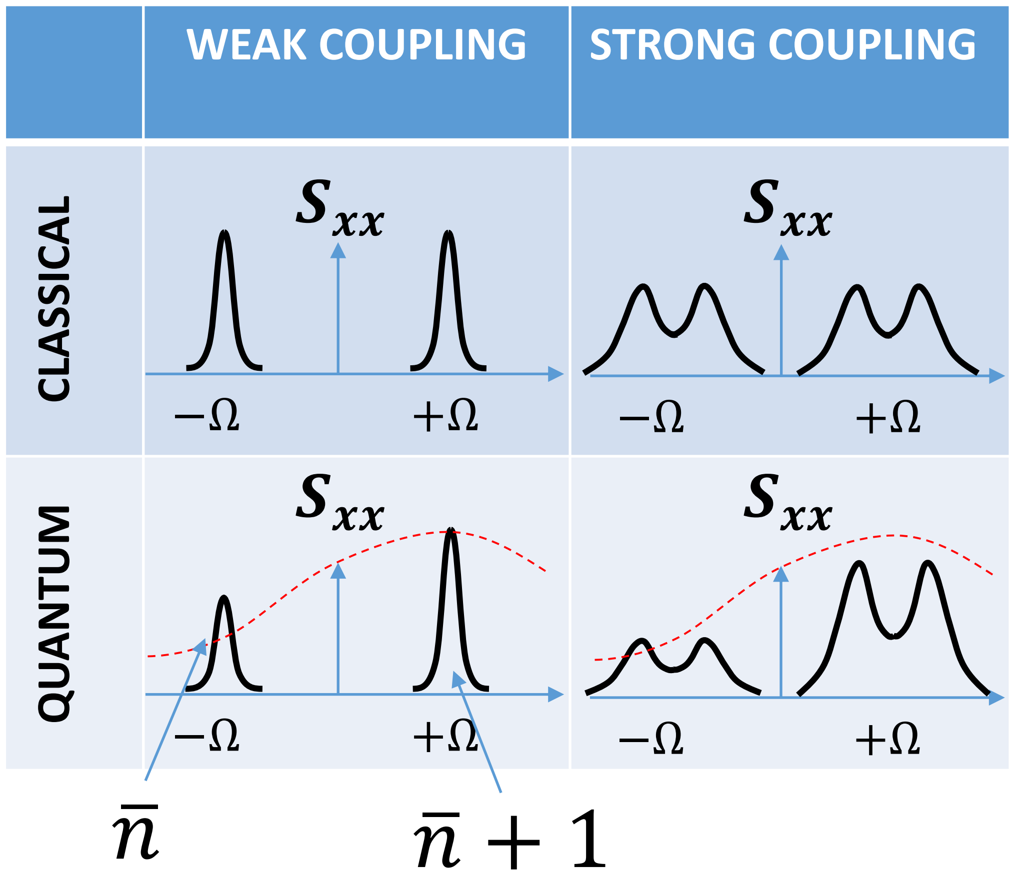
A. Ranfagni *et al.*, Phys. Rev. Res. **4**, 033051 (2022)

Which are the quantum features?

Sidebands asymmetry



$$S_{xx} = |\chi_m|^2 S_{FF}^{tot}$$



Florian Marquardt, Joe P. Chen, A. A. Clerk, and S. M. Girvin
Phys. Rev. Lett. 99, 093902 (2007)

Sidebands asymmetry

anti – Stokes sideband

$$S_{\text{out}}(\Omega_{\text{LO}} + \Omega) = 1 + \eta \frac{g^2}{\left(\frac{k}{2}\right)^2 + (\Delta + \Omega)^2} \frac{\Gamma_{dec}}{\left(\frac{\Gamma_{eff}}{2}\right)^2 + (\Omega - \Omega_{eff})^2}$$

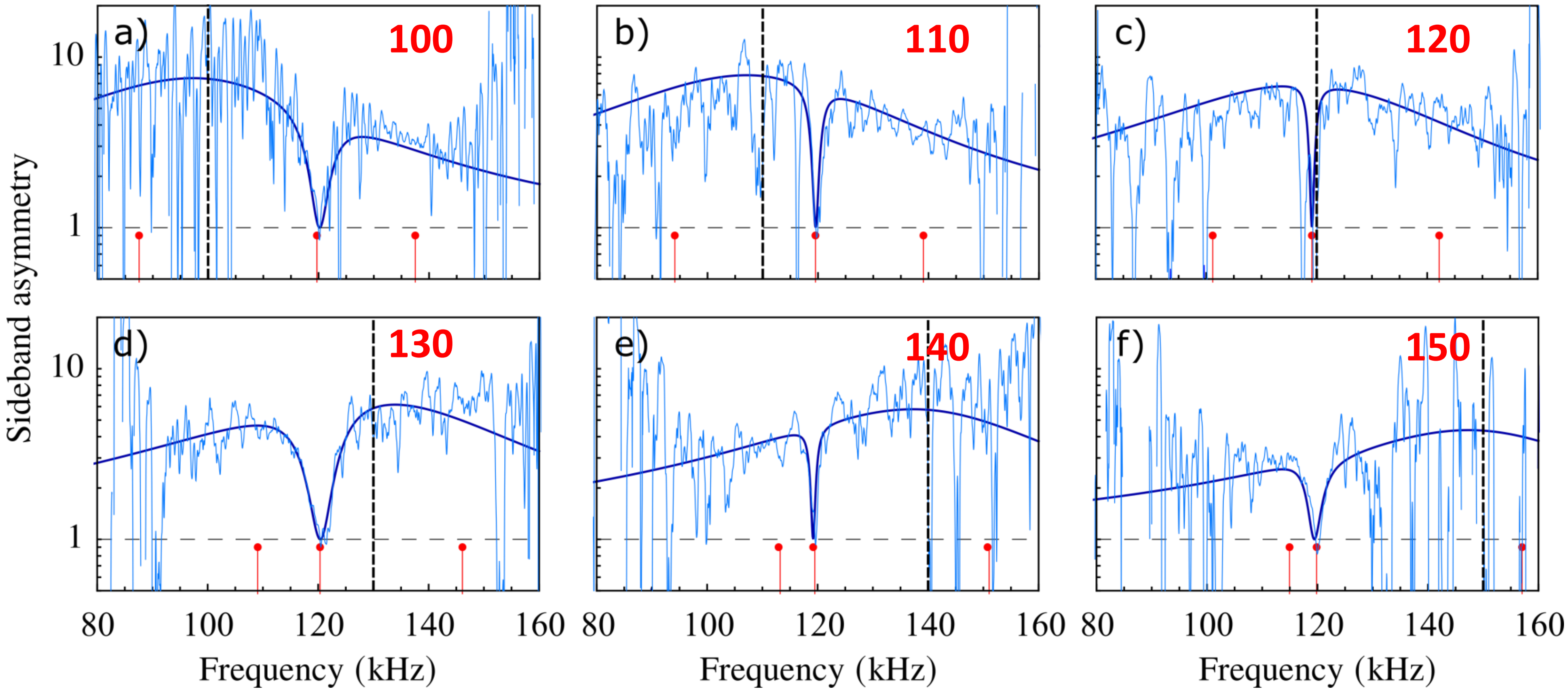
Stokes sideband

$$S_{\text{out}}(\Omega_{\text{LO}} - \Omega) = 1 + \eta \frac{g^2}{\left(\frac{k}{2}\right)^2 + (\Delta - \Omega)^2} \frac{\Gamma_{dec} + \Gamma_{eff}}{\left(\frac{\Gamma_{eff}}{2}\right)^2 + (\Omega - \Omega_{eff})^2}$$

Single mode, weak coupling

$$A(\Omega) = \frac{S_{\text{out}}(\Omega_{\text{LO}} - \Omega) - 1}{S_{\text{out}}(\Omega_{\text{LO}} + \Omega) - 1} \frac{(\Omega - \Delta)^2 + (\kappa/2)^2}{(\Omega + \Delta)^2 + (\kappa/2)^2} = \frac{\Gamma_{dec} + \Gamma_{eff}}{\Gamma_{dec}} = \frac{n+1}{n}$$

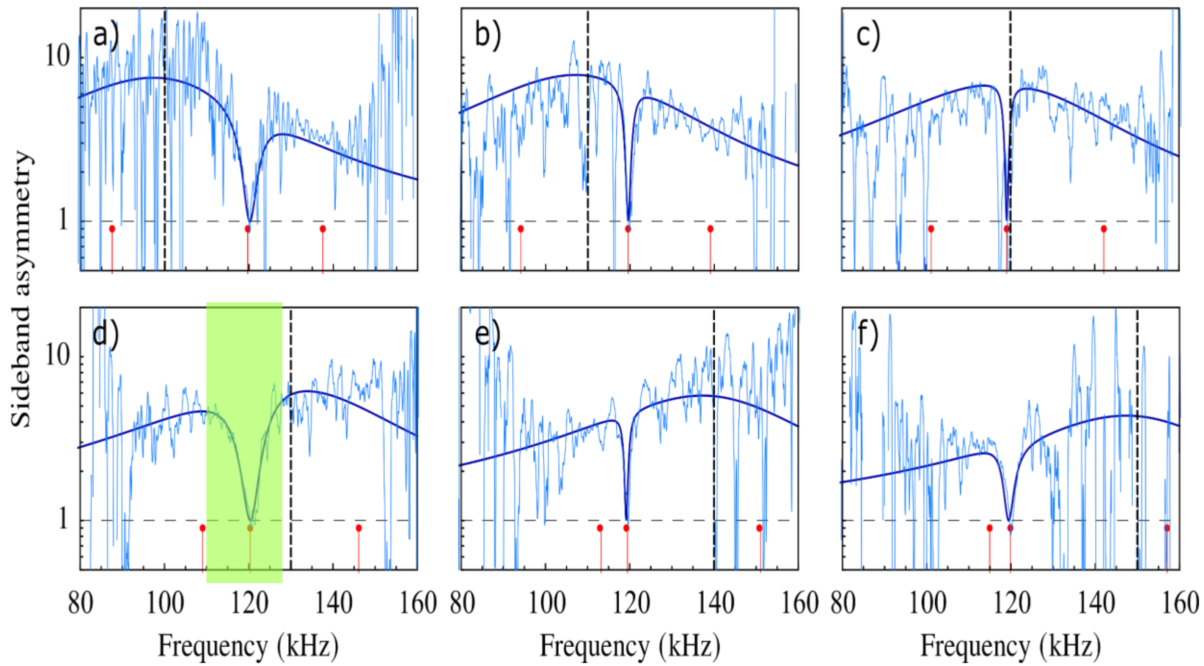
Quantum asymmetry in the strong coupling regime: the spectral shape of the field quantum noise

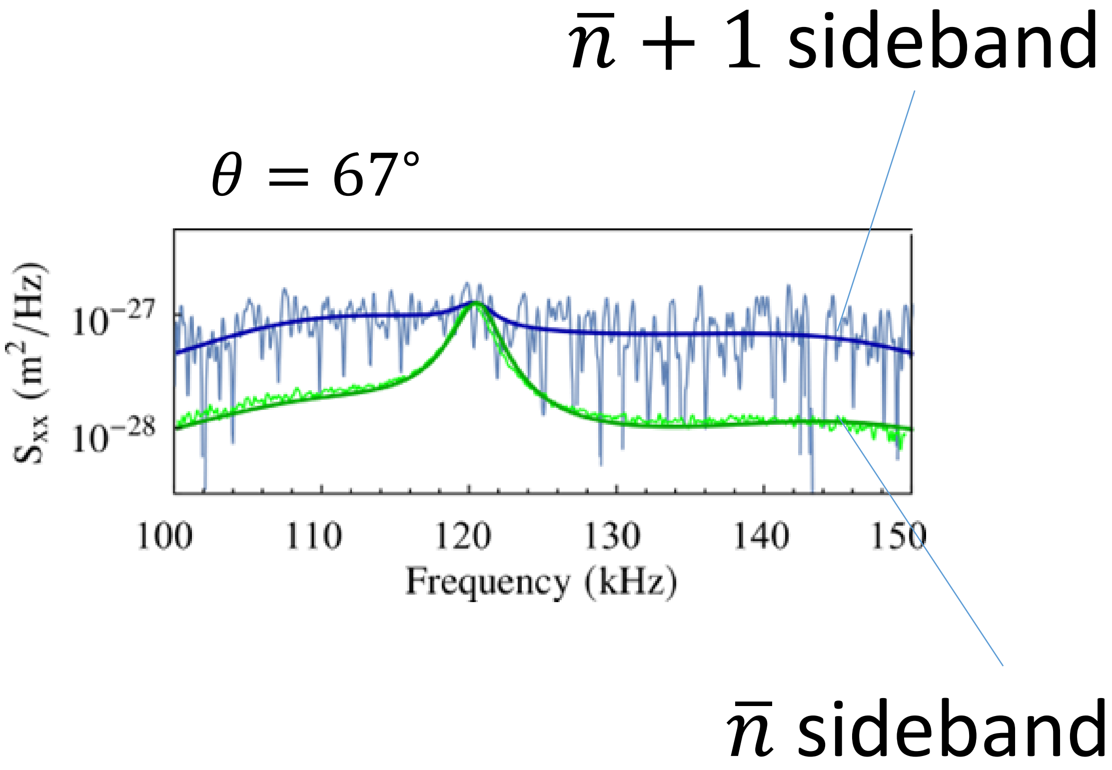


Spectral Analysis of Quantum Field Fluctuations in a Strongly Coupled Optomechanical System

A. Ranfagni, F. Marino, and F. Marin. Phys. Rev. Lett. **130**, 193601(2023)

2D strong coupling regime: Quantum backaction cancellation





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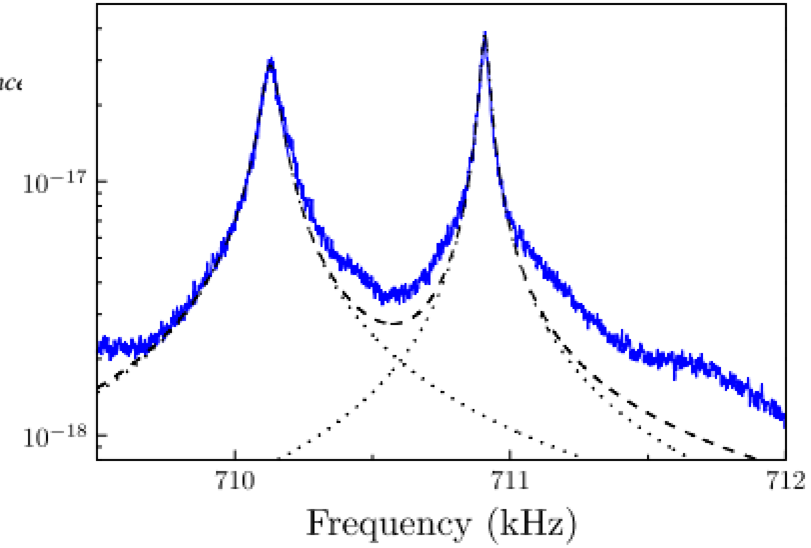
PRL 99, 110801 (2007) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2007

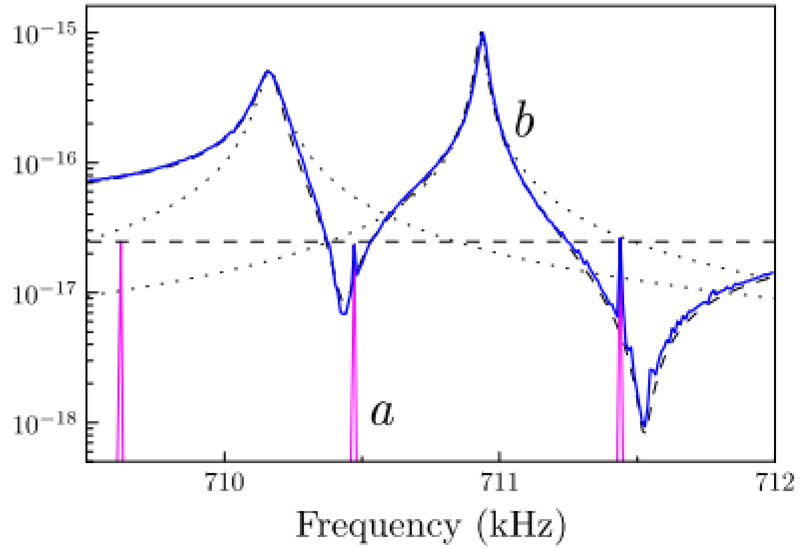
Observation of Back-Action Noise Cancellation in Interferometric and Weak Force Measurements

T. Caniard, P. Verlot, T. Briant, P.-F. Cohadon, and A. Heidmann
Laboratoire Kastler Brossel, ENS, UPMC, CNRS; case 74, 4 place Jussieu, 75005 Paris, France
(Received 13 June 2007; published 12 September 2007)

Classical experiment
(with strong laser amplitude noise)



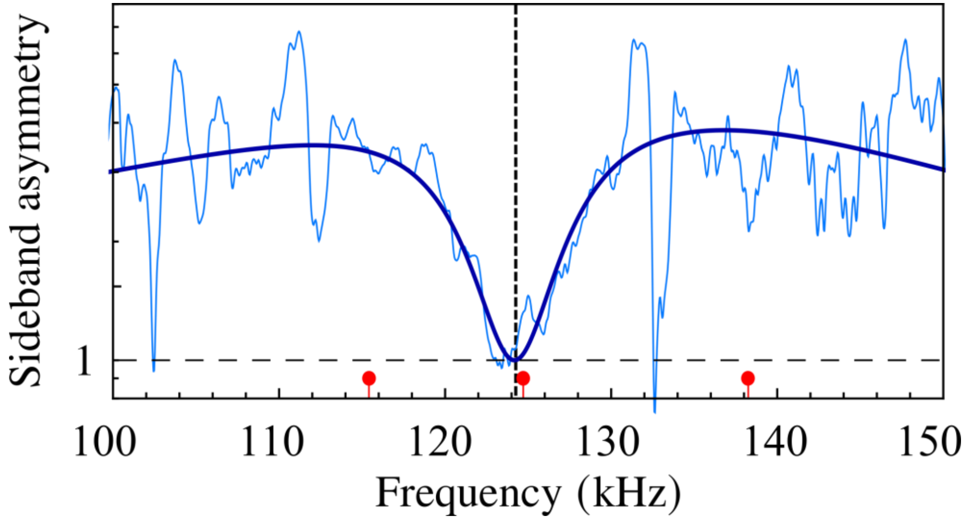
Thermal noise



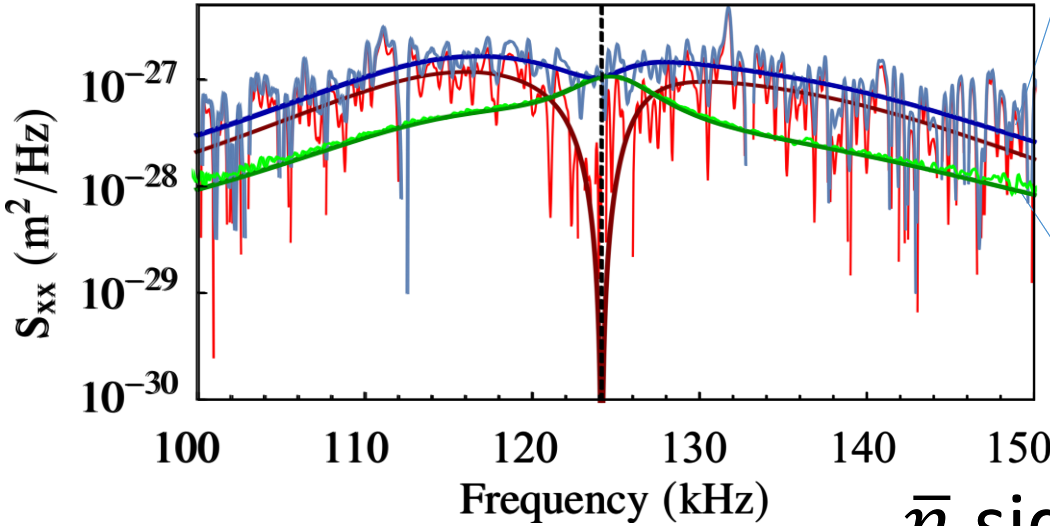
Radiation pressure noise

2D strong coupling regime: Quantum backaction cancellation

$\theta = 52°$



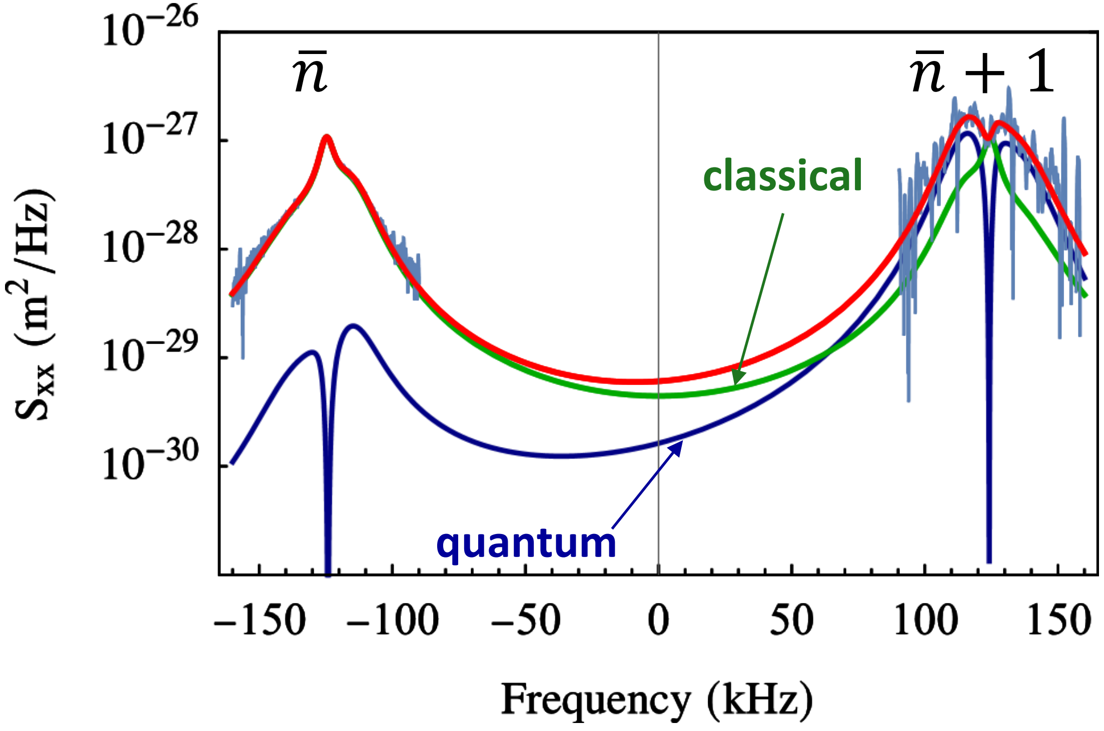
$\bar{n} + 1$ sideband



$\bar{n}$ sideband

A. Ranfagni *et al.*, Phys. Rev. Lett. **130**, 193601 (2023)

Direct evidence of quantum back action cancellation



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How much «quantum» is the oscillator?

Phononic occupation number

«Usual» opto-mechanical definition of phononic occupation number: $2\bar{n} + 1 = \frac{\langle x^2 \rangle}{x_{\mathrm{zpf}}^2} = \frac{1}{x_{\mathrm{zpf}}^2} \int S_{xx} \frac{\mathrm{d}\Omega}{2\pi}$.

- How far is it correct to use the bare oscillator number basis?
- How to get n in case of strong coupling? How we can use the spectral asymmetry in the polaritonic peaks? Which frequency should be used in x_{zpf}? Is it a thermal state?
- For a 2D oscillator, how far we can consider it as a product state of two 1D oscillators? Can we consider the motion along any direction as a 1D oscillator and define its occupation number?

2D motion

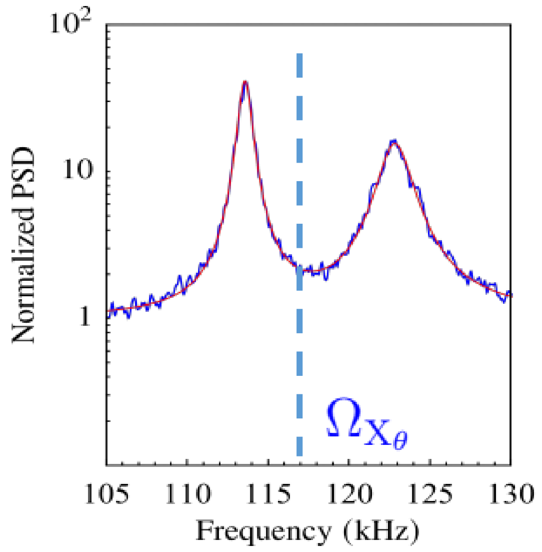
2D Hamiltonian: $$H = \frac{m}{2}\left(\Omega_X^2\, x^2 + \Omega_Y^2\, y^2\right) + \frac{1}{2m}\left(p_x^2 + p_y^2\right)$$

Framework rotation: $$\mathbf{x}_\theta = \mathbf{R}(\theta)\,\mathbf{x}$$

$$\Omega_{X_\theta}^2 = \Omega_X^2 \cos^2(\theta) + \Omega_Y^2 \sin^2(\theta)$$

$$H = \frac{m}{2}\left(\Omega_{X_\theta}^2\, x_\theta^2 + \Omega_{Y_\theta}^2\, y_\theta^2\right) + \frac{1}{2m}\left(p_{x_\theta}^2 + p_{y_\theta}^2\right) + G x_\theta y_\theta$$

$$m^2 \Omega_{X_\theta}^2 \langle x^2 \rangle \neq \langle p^2 \rangle$$



State purity

$$\mu = \mathrm{Tr}(\hat{\rho}^2)$$

For a 1D thermal oscillator: $\mu = \dfrac{1}{2\bar{n}+1}$

For an oscillator in a Gaussian state, there is a number basis where the oscillator is in a thermal state

$$\mu^{-1} = 2\bar{n}+1 = \frac{1}{\hbar}\sqrt{4\langle\Delta\hat{x}^2\rangle\langle\Delta\hat{p}^2\rangle - \langle\{\Delta\hat{x},\,\Delta\hat{p}\}\rangle^2}$$

For any state, this is also an indicator of how far we are from a minimal uncertainty state

$$x_{\mathrm{ZPF}}^2 = \frac{\hbar\langle\Delta\hat{x}^2\rangle}{\sqrt{4\langle\Delta\hat{x}^2\rangle\langle\Delta\hat{p}^2\rangle - \langle\{\Delta\hat{x},\,\Delta\hat{p}\}\rangle^2}}$$

K. Børkje and F. Marin, Phys. Rev. A **107**, 013502 (2023)

2D oscillator

Product state of two thermal oscillators:
$$\mu_{2D} = \frac{1}{(2\bar{m}+1)(2\bar{n}+1)}$$

For a 2D oscillator in a Gaussian state:
$$\mu_{2D} = \frac{(\hbar/2)^2}{\sqrt{A_{xx}A_{pp} - A_{xp}B_{xp} + B_{xp}^2}}$$

$$A_{xx} = \langle \Delta\hat{x}^2\rangle\langle \Delta\hat{y}^2\rangle - \langle \Delta\hat{x}\Delta\hat{y}\rangle^2$$

$$A_{pp} = \langle \Delta\hat{p}_x^2\rangle\langle \Delta\hat{p}_y^2\rangle - \langle \Delta\hat{p}_x\Delta\hat{p}_y\rangle^2$$

$$A_{xp} = \langle \Delta\hat{x}^2\rangle\langle \Delta\hat{p}_y^2\rangle + \langle \Delta\hat{y}^2\rangle\langle \Delta\hat{p}_x^2\rangle - 2\langle \Delta\hat{x}\Delta\hat{y}\rangle\langle \Delta\hat{p}_x\Delta\hat{p}_y\rangle$$

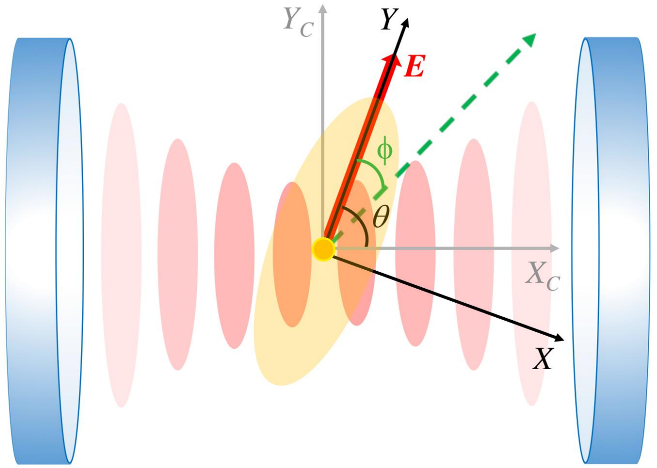
$$B_{xp} = \langle \Delta\hat{x}\Delta\hat{p}_y\rangle^2$$

K. Børkje and F. Marin, Phys. Rev. A **107**, 013502 (2023)

Phononic occupation number: 1D

«Usual» opto-mechanical definition of phononic occupation number: $2\bar{n}+1 = \frac{\langle x^2\rangle}{x_{\mathrm{zpf}}^2} = \frac{1}{x_{\mathrm{zpf}}^2}\int S_{xx}\frac{\mathrm{d}\Omega}{2\pi}.$

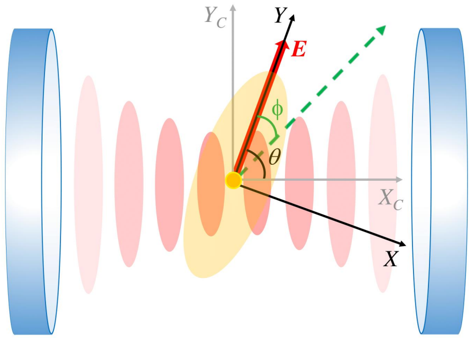
$$n_{\mathrm{eff}}(\phi) = \frac{1}{2}\left(\frac{2}{\hbar}\sqrt{\langle x_\phi^2\rangle\langle p_\phi^2\rangle}-1\right)$$

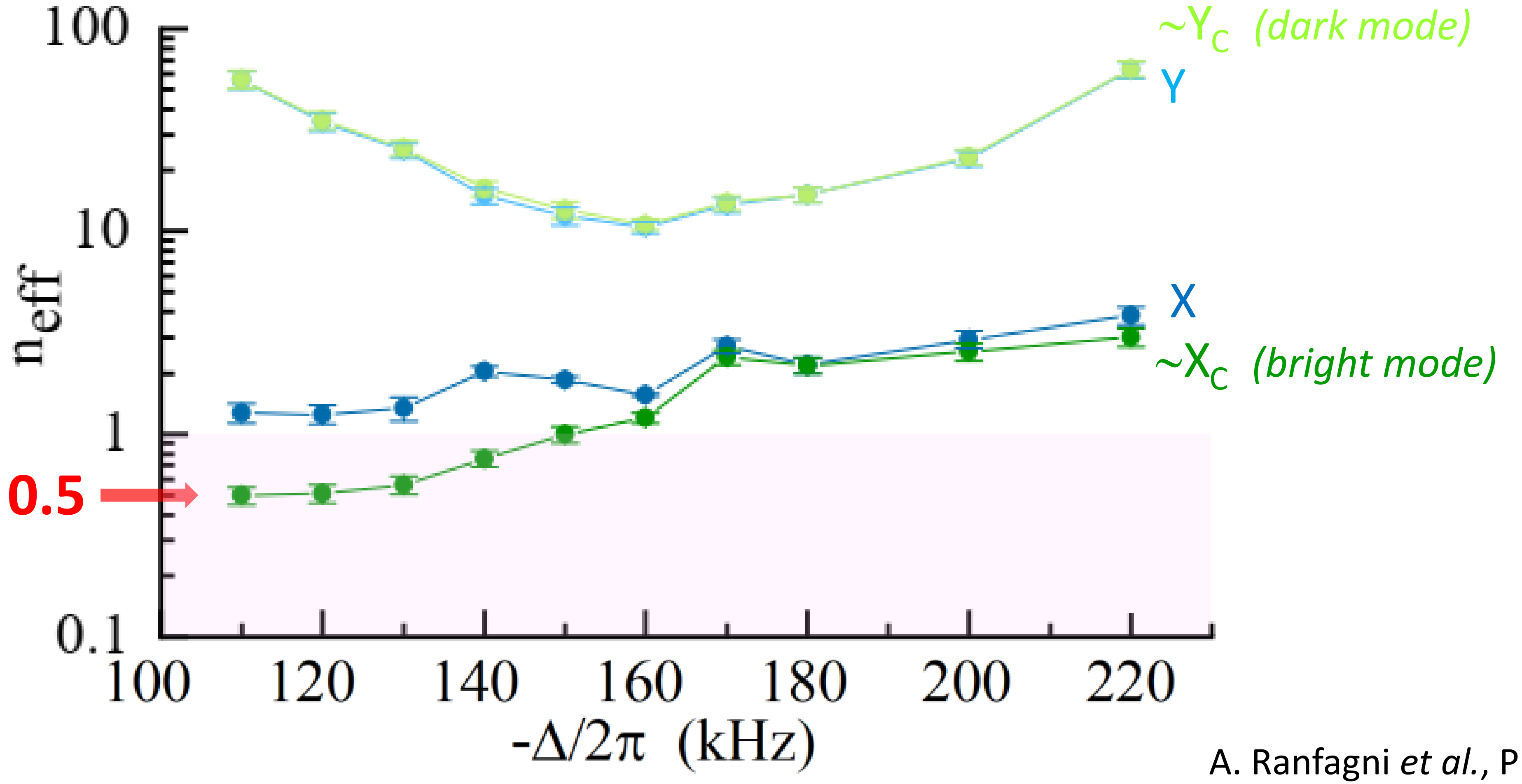


With the above definition: $\frac{\langle x^2\rangle}{x_{\mathrm{zpf}}^2} \rightarrow \sqrt{\frac{\langle x^2\rangle}{x_{\mathrm{zpf}}^2}\frac{\langle p^2\rangle}{p_{\mathrm{zpf}}^2}}$

Phononic occupation number: 1D

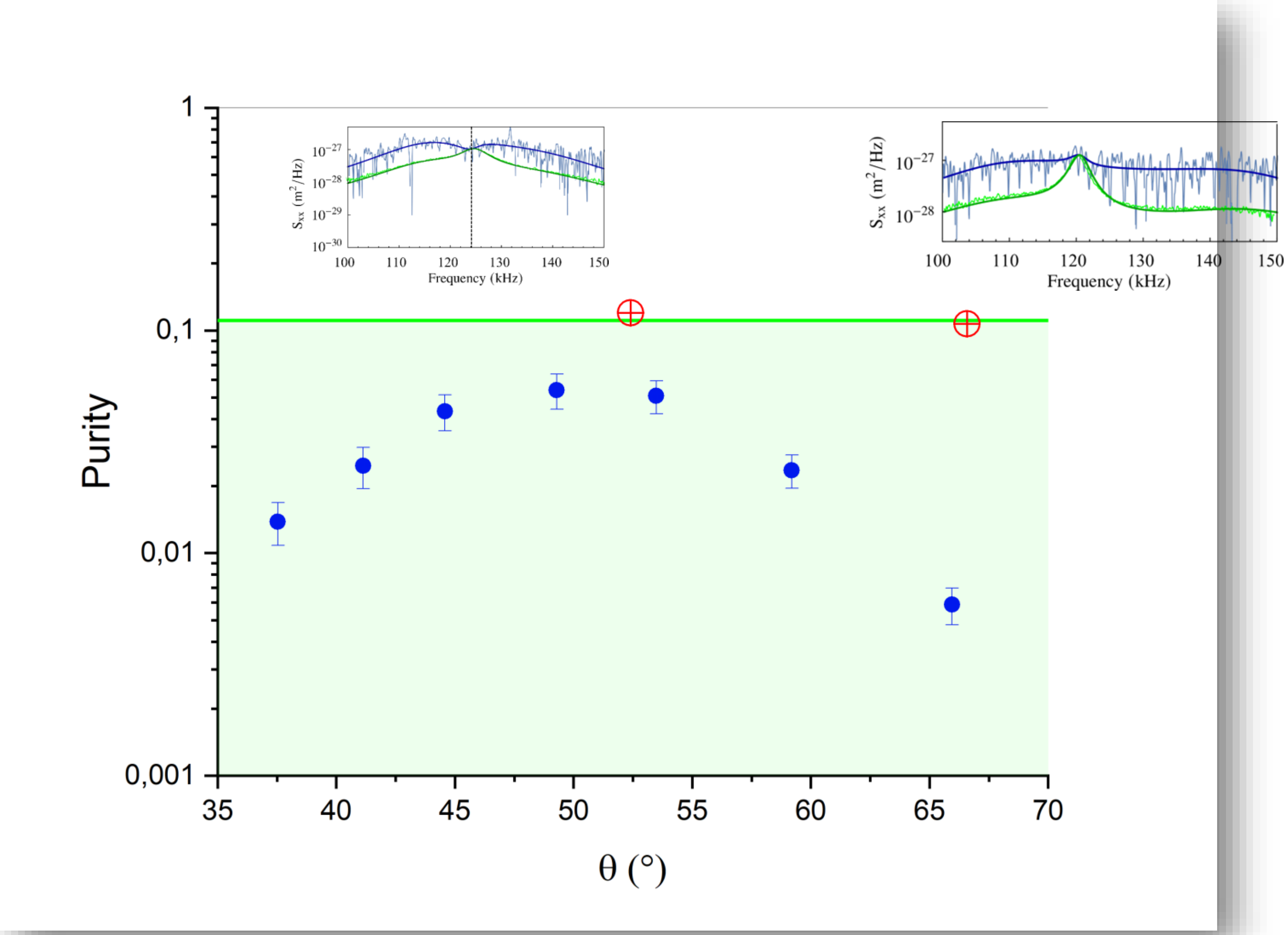
$$n_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{2}{\hbar}\sqrt{\langle x_\phi^2\rangle\langle p_\phi^2\rangle} - 1\right)$$

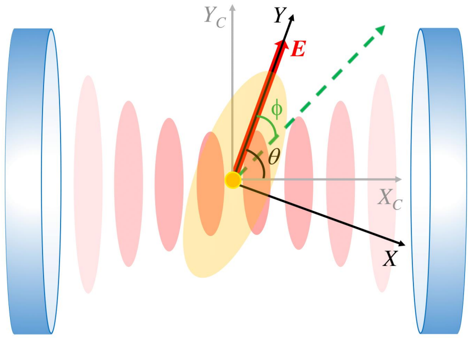




A. Ranfagni *et al.*, Phys. Rev. Res. **4**, 033051 (2022)

State purity: 2D





A. Ranfagni *et al.*, Phys. Rev. Res. **4**, 033051 (2022)

A. Ranfagni *et al.*, Phys. Rev. Lett. **130**, 193601 (2023)

CONCLUSIONS

- 2D polaritonic states
- Quantum coherent strong coupling
- Mechanical oscillator as quantum spectral analyzer
- 2D: Backaction cancellation
- 1D and 2D «ground state cooling»

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Università degli Studi Firenze

INFN

CNR-INO Istituto Nazionale di Ottica Consiglio Nazionale delle Ricerche

QUANTERA

300K QuaSeRT