University of South-Eastern Norway

QuaSeRT

Nonclassical photon statistics in two-tone continuously driven optomechanics

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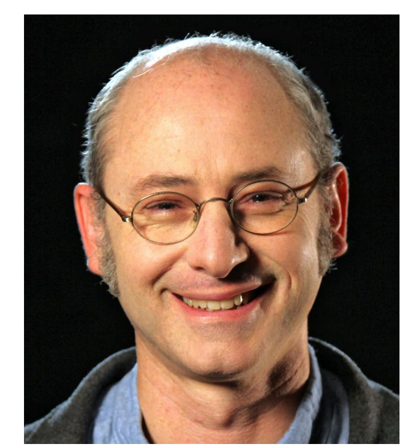
QuaSeRT online project meeting, 2021-12-09

arXiv:2108.10738, Phys. Rev. A (in press)

F. Massel, USN



J. Harris (Yale)

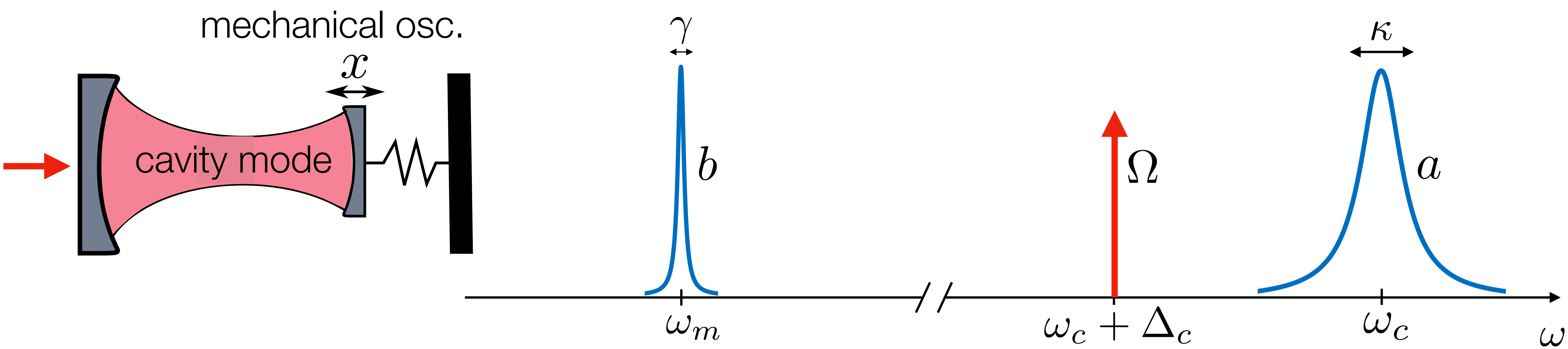
QUANTERA

The Research Council of Norway

Outline

- Introduction, motivation, earlier work
- Proposed experimental setup with two-tone driving
- Photon statistics, normalized second order coherence
- Model-independent nonclassicality
- Possible routes to implementation
- Conclusion

Linearized quantum optomechanics

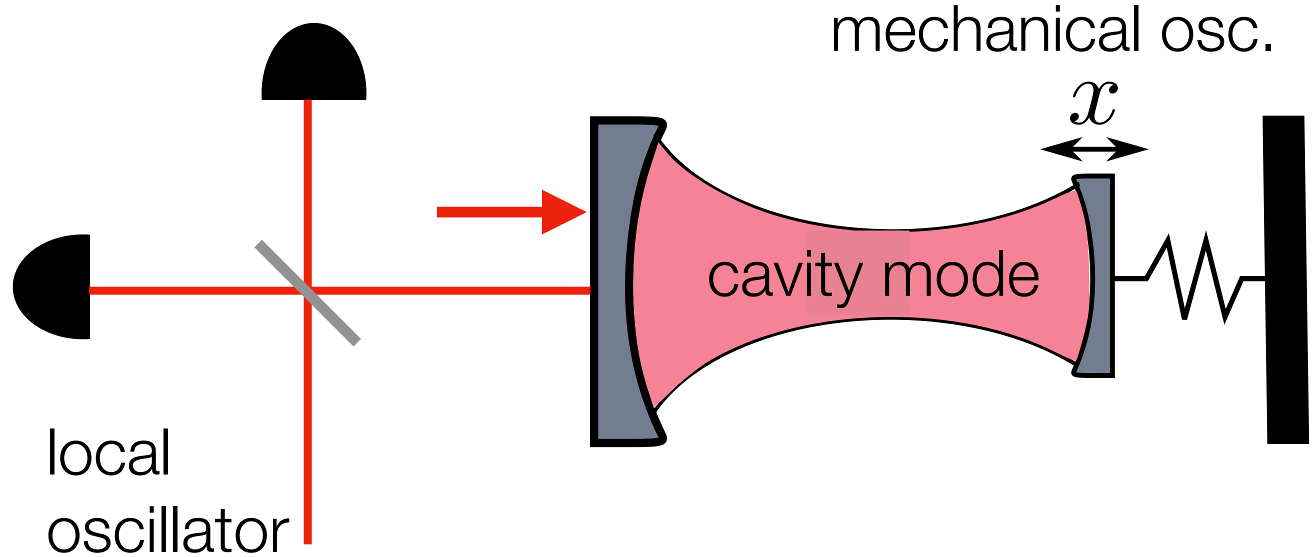


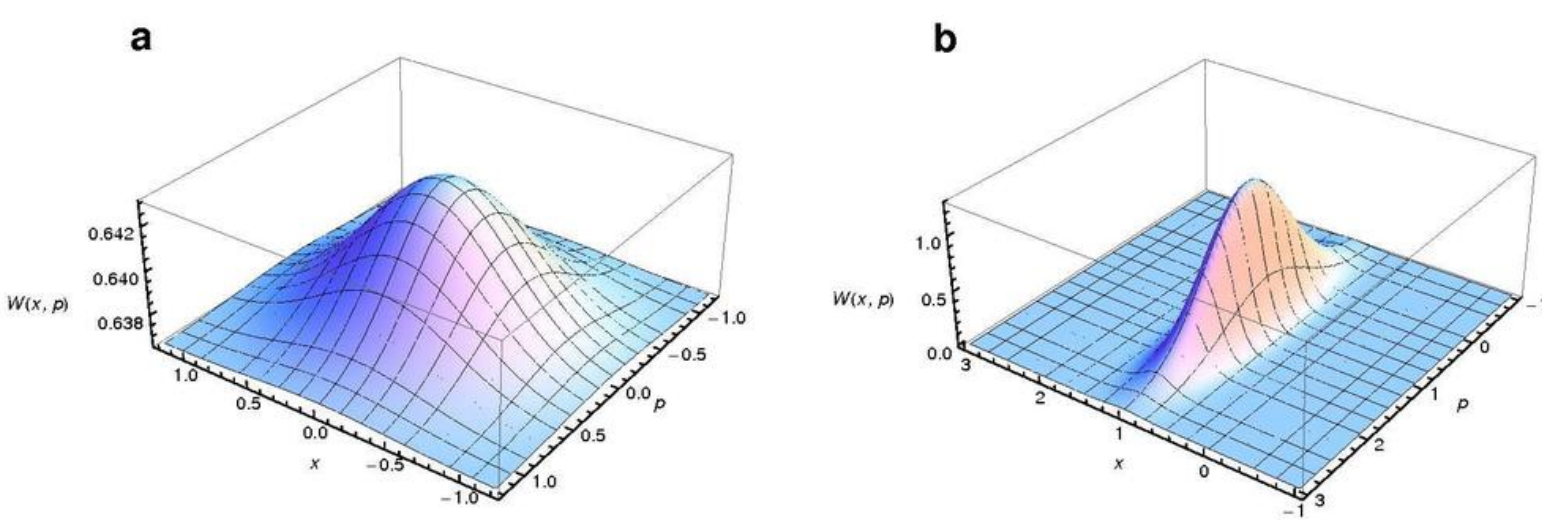
$$H = -\hbar\Delta_c a^\dagger a + \hbar\omega_m b^\dagger b + \overbrace{\underbrace{\overbrace{\hbar g_0 (b + b^\dagger) a^\dagger a}^{\text{interaction}} + \overbrace{\hbar\Omega\left(a + a^\dagger\right)}^{\text{cavity drive}}}}$$

$a \to \bar{a} + a\ , \quad g_0 \ll \kappa \qquad G = g_0 \bar{a}$

$$\hbar G (b + b^\dagger)(a + a^\dagger)$$

Gaussian states and linear measurements





Mechanical ground state cooling

Optical squeezing

Mechanical squeezing

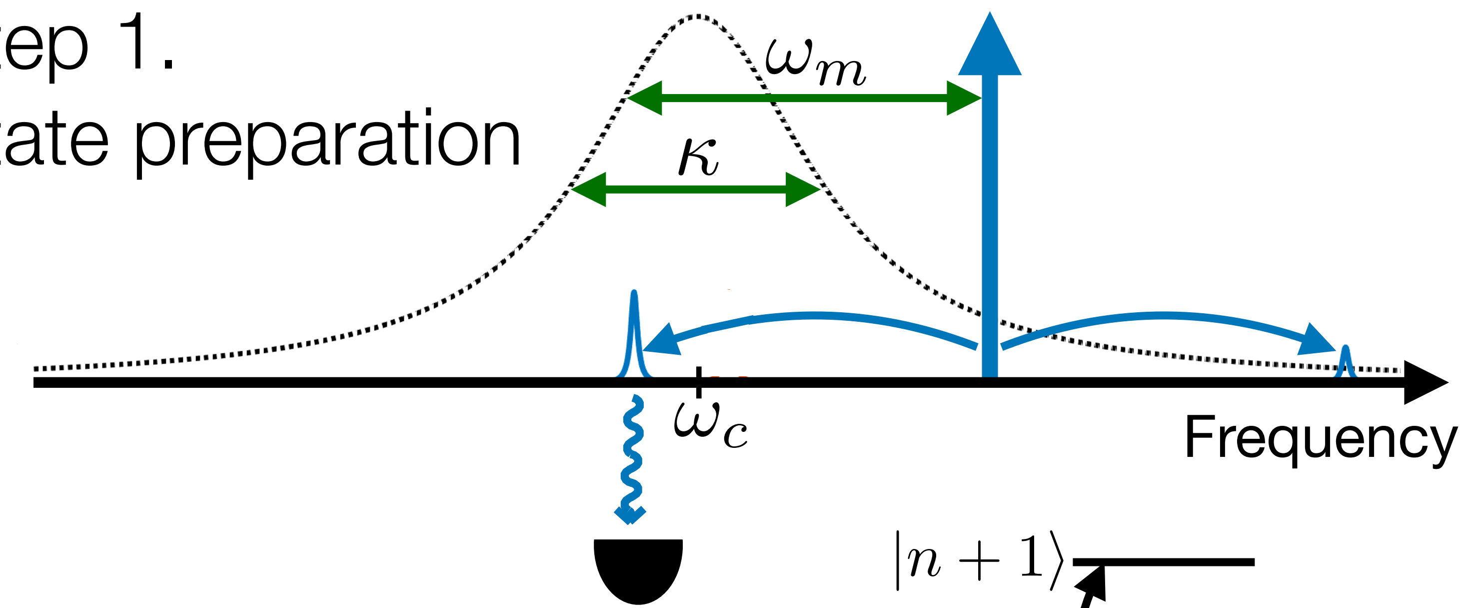
Opto-mech. entanglement

Mech-mech. entanglement

Additional checks necessary
to infer quantum features

Sideband single-photon detection

Step 1.
State preparation



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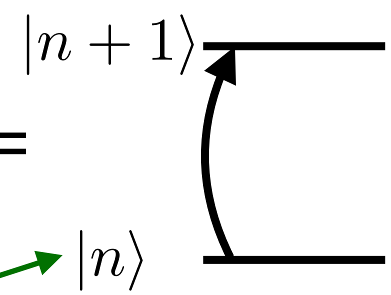


phonon Fock state

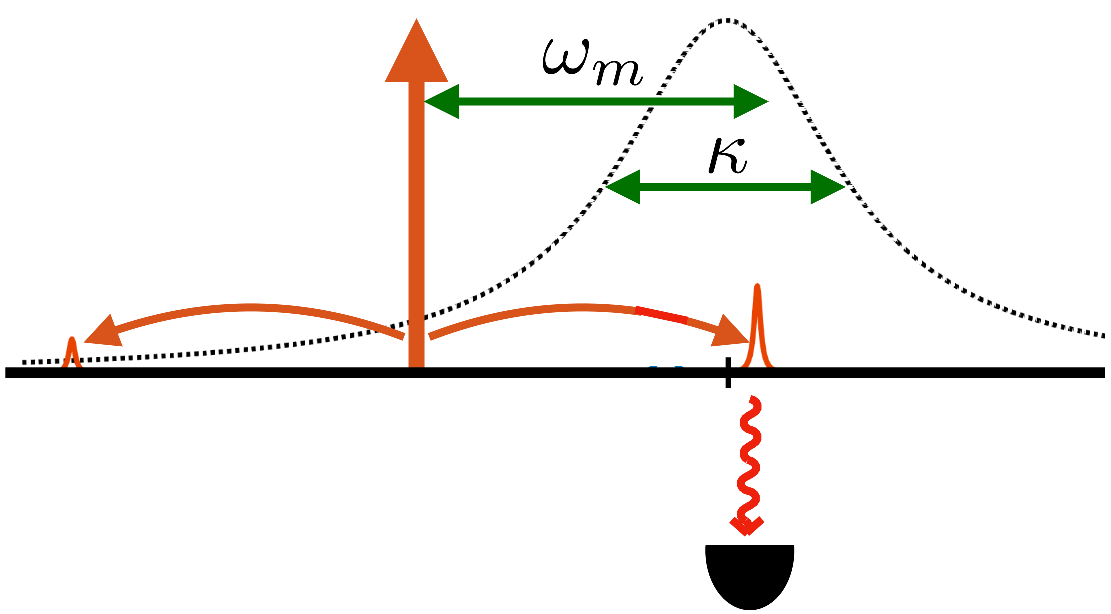
(non-Gaussian)

$$\rho_{\text{conditional}} \approx |1\rangle\langle 1|$$

$$\Uparrow$$

$$\rho_{\text{steady state}} \approx |0\rangle\langle 0|$$

Step 2.
Verification

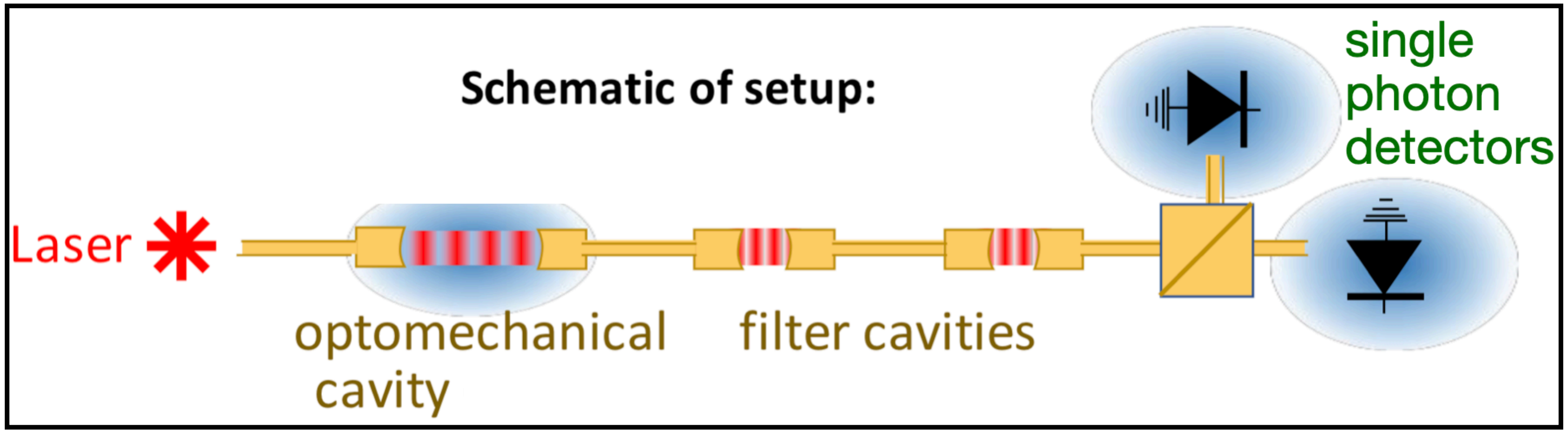


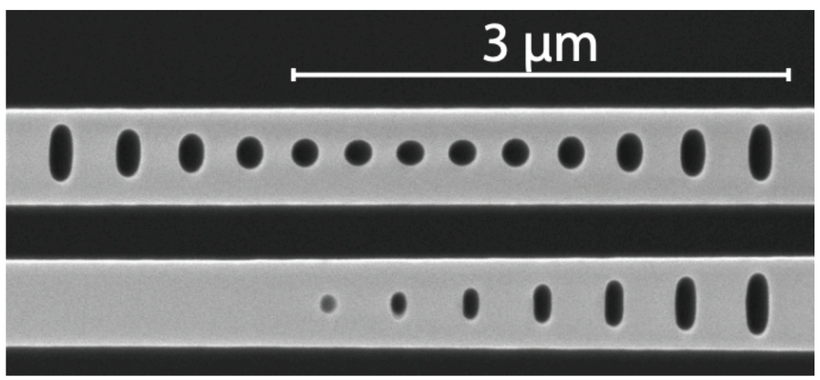
Non-classical photon-phonon correlations,
*Riedinger et al., Nature **530**, 313 (2016)*

Phonon antibunching,
*Hong et al., Science **358**, 203 (2017)*

Entanglement, teleportation,…

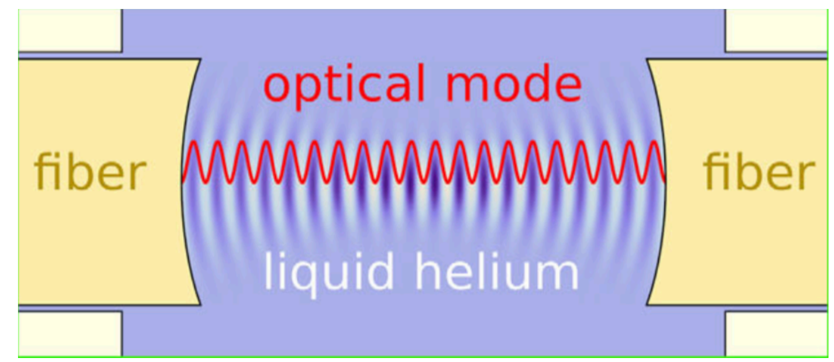
Implementation of sideband single-photon detection





suspended photonic crystals (Delft/Vienna/Caltech)

$$\omega_m \sim 5 \text{ GHz}$$

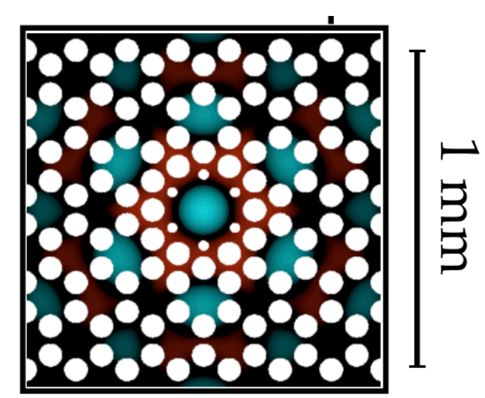


superfluid helium in fiber cavities (Yale)

$$\omega_m \sim 300 \text{ MHz}$$

whispering gallery microresonators (Imperial)

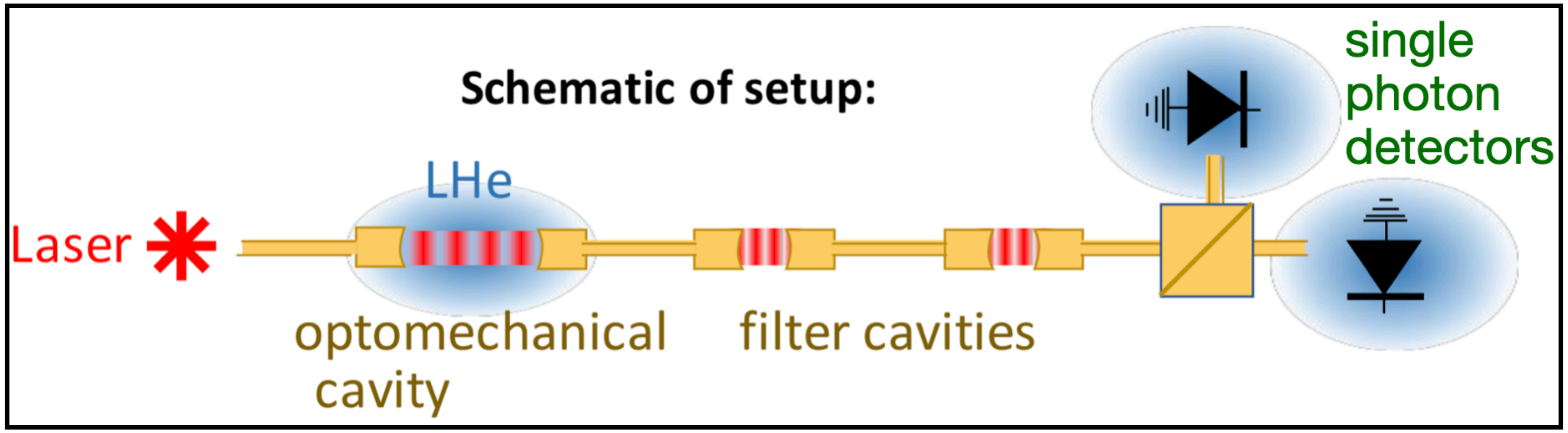
$$\omega_m \sim 8 \text{ GHz}$$



silicon-nitride membranes (NBI)

$$\omega_m \sim 1 \text{ MHz}$$

Motivation for this work

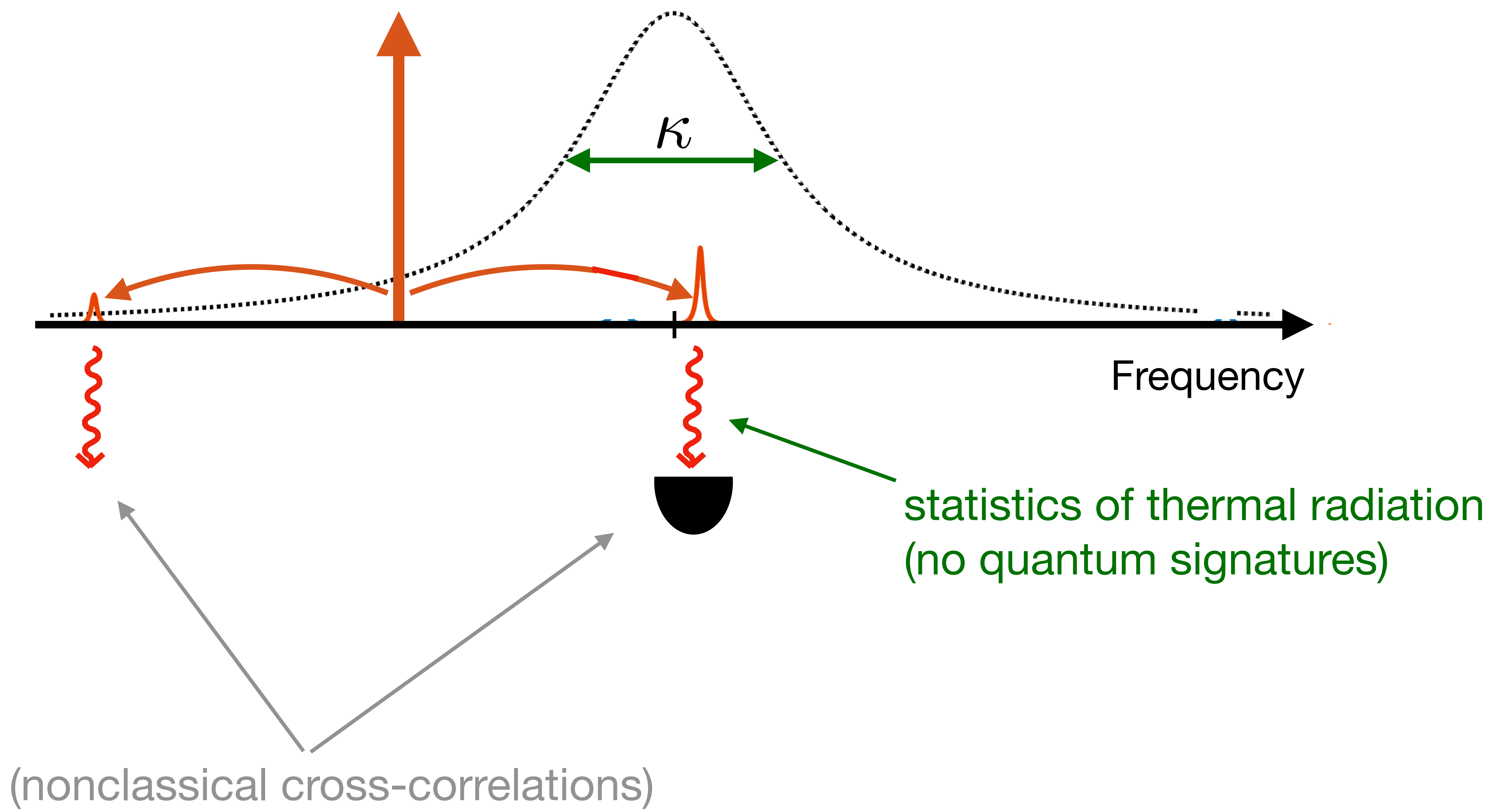


Sequential pulsed driving can be challenging,
continuous driving easy (for helium and membranes)

- Testing quantum mechanics:
  Quantum features in sideband photon statistics with continuous driving?

- Quantum resource for sensing:
  Steady stream of photons with nonclassical statistics?

One continuous drive tone



*Børkje et al., PRL **107**, 123601 (2011)*

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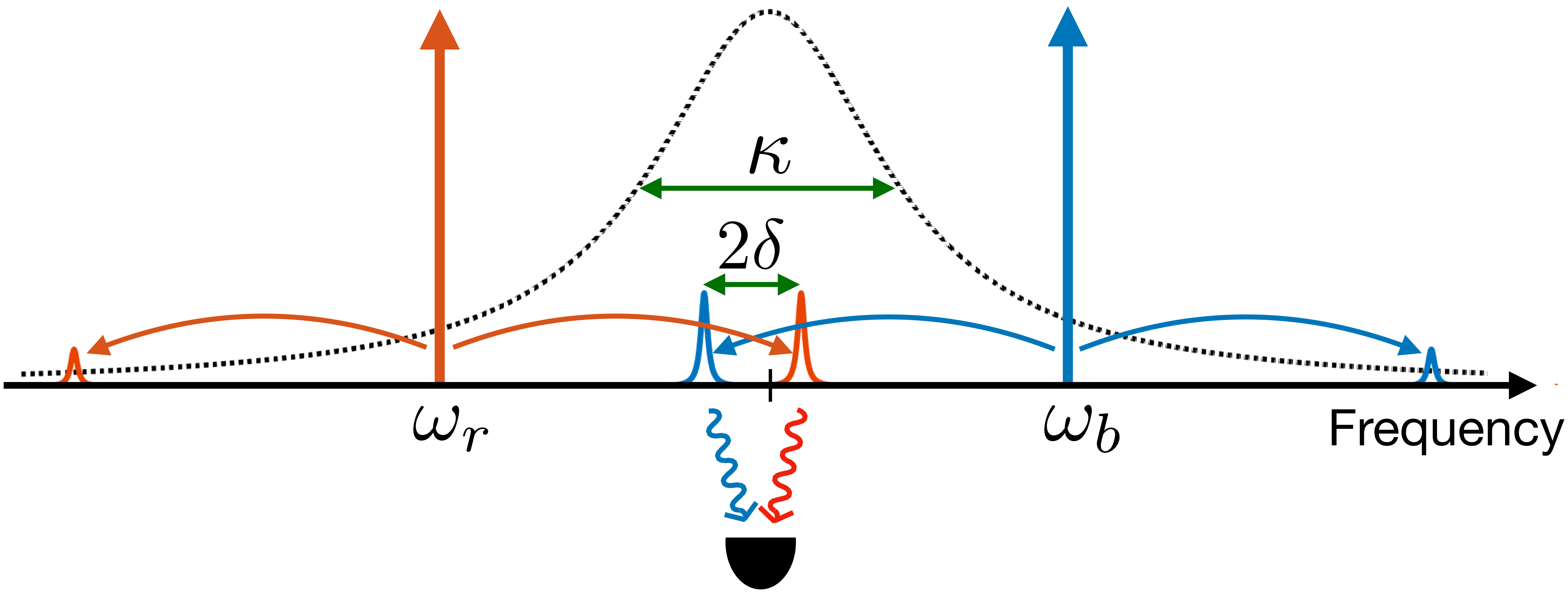
Setup and measurement scheme

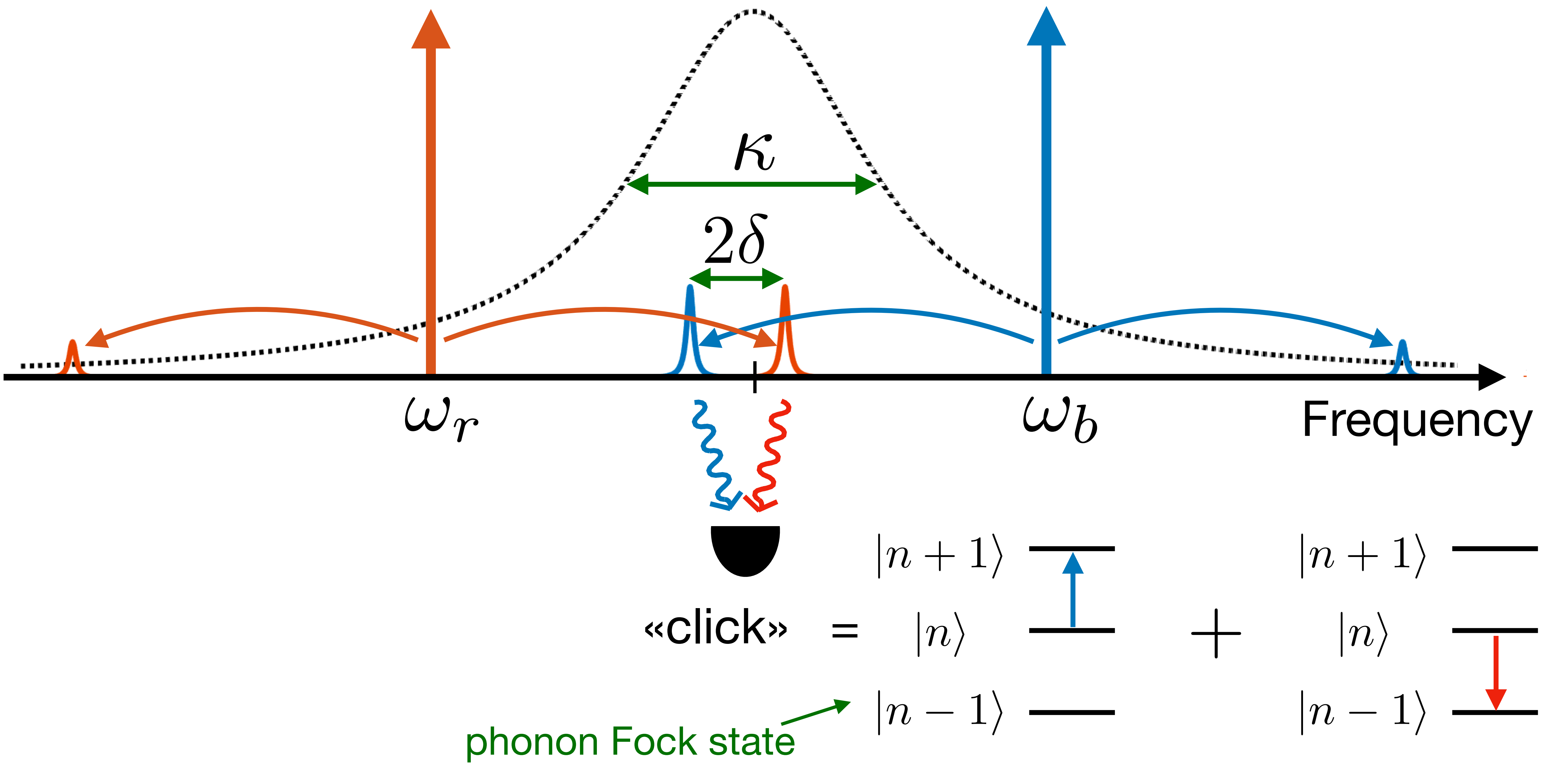


effective mech. linewidth → $\tilde{\gamma} \ll \delta \ll \kappa, \omega_m$

Two coupling rates:

$$G_r = g_0 \bar{a}_r \qquad G_b = g_0 \bar{a}_b \qquad \beta \equiv \left(\frac{G_b}{G_r}\right)^2 = \frac{P_b}{P_r}$$

Setup and measurement scheme



Assume mechanical state thermal since $\tilde{\gamma} \ll \delta$

Average phonon occupation number: $\langle b^\dagger b \rangle \equiv n_m$

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Normalized second order coherence

Photodetection gives

$$= \frac{\langle I(t) I(t+\tau) \rangle}{\langle I(t) \rangle^2}$$

classical

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t) a^\dagger(t+\tau) a(t+\tau) a(t) \rangle}{\langle a^\dagger(t) a(t) \rangle^2}$$

quantum

$$= \frac{P(\text{click at } t+\tau \mid \text{click at } t)}{P(\text{click at } t+\tau)}$$

Coherent radiation: $g^{(2)}(\tau) = 1$

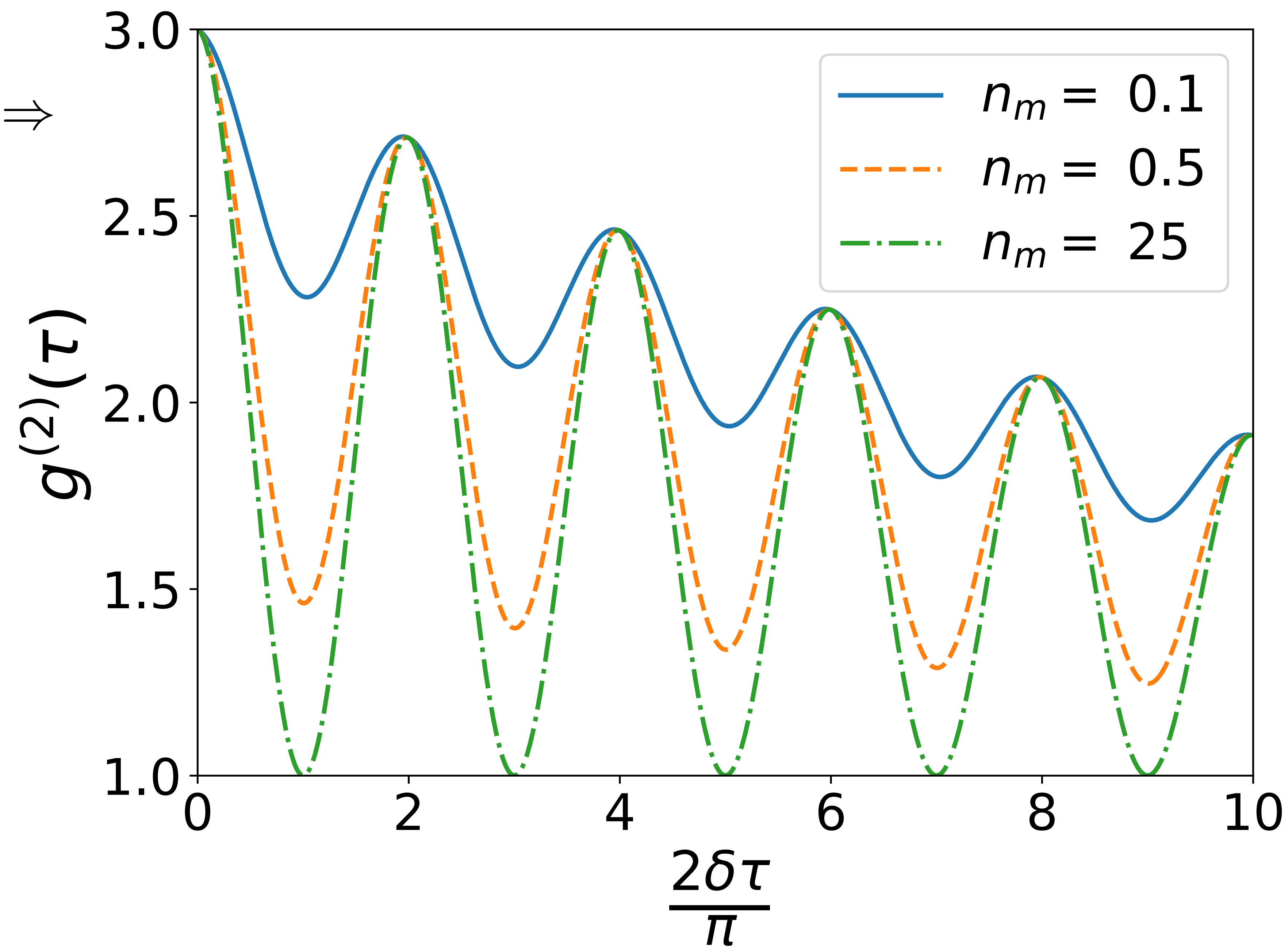
Thermal radiation: $g^{(2)}(\tau) = 1 + e^{-\tilde{\gamma}\tau}$

Antibunching (nonclassical radiation): $g^{(2)}(\tau) < 1$

Result and interpretation

$$g^{(2)}(\tau) = 1 + e^{-\tilde{\gamma}\tau}\left(1 + \frac{4\beta\left[1/4 + n_m(n_m+1)\cos(2\delta\tau)\right]}{\left[n_m + \beta(n_m+1)\right]^2}\right)$$

$$\beta = \left(\frac{G_b}{G_r}\right)^2 = 1 \Rightarrow$$



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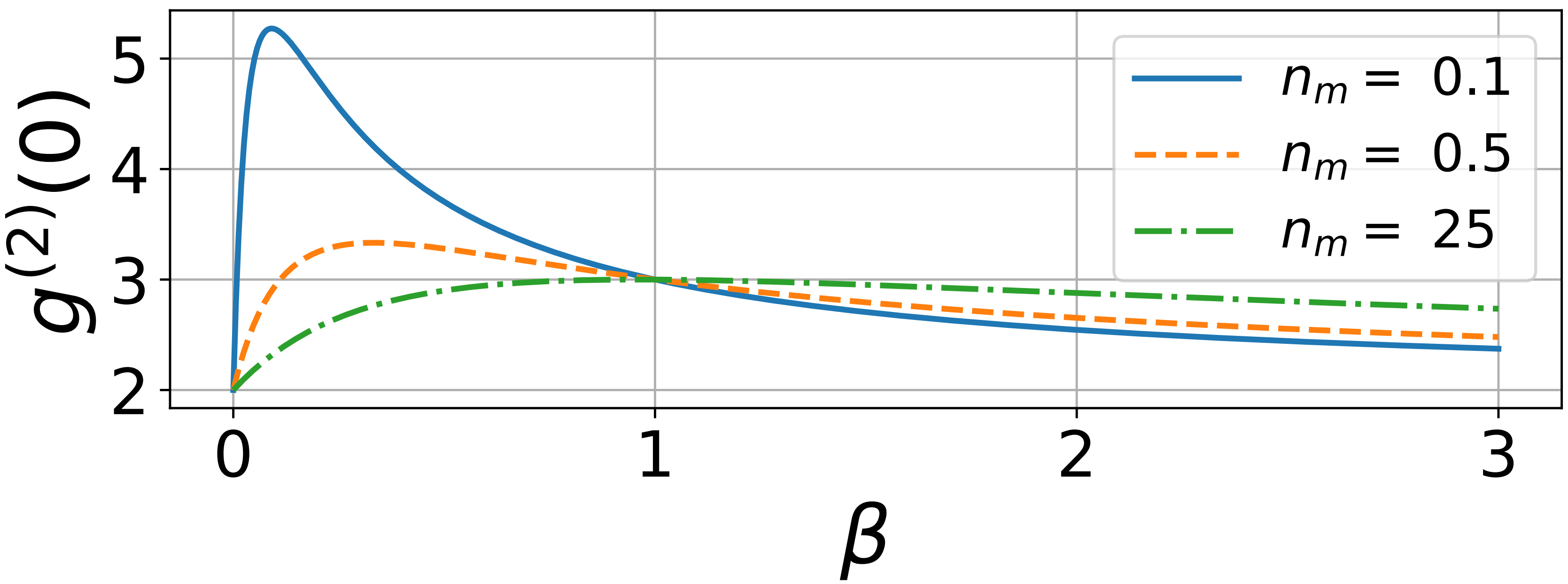
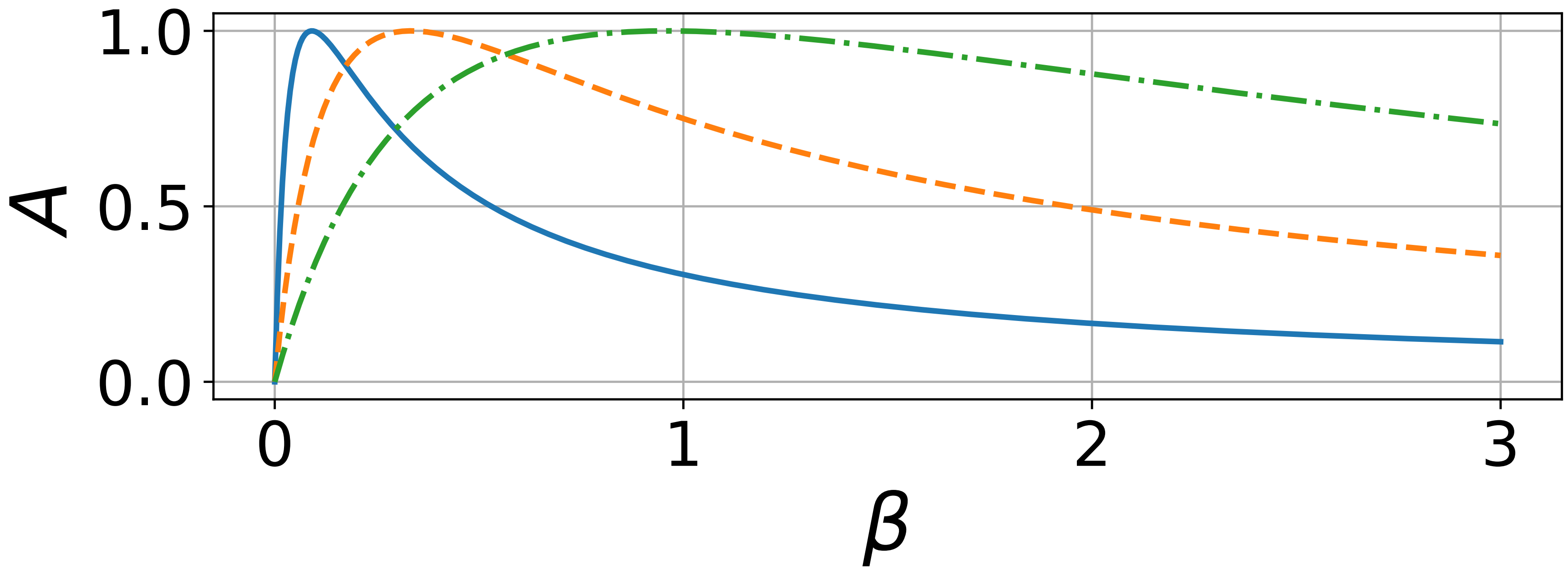
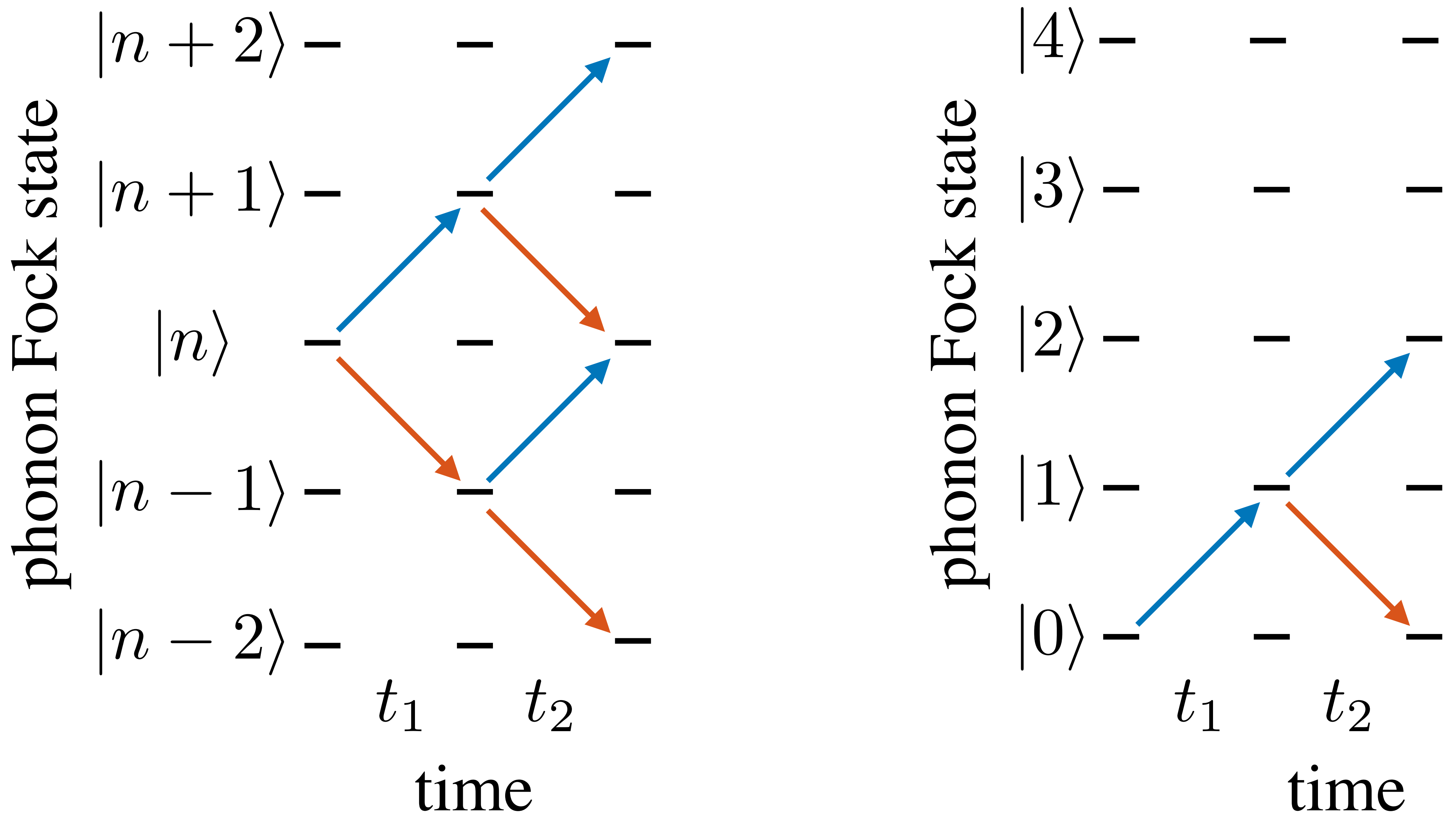
Zero time delay



Amplitude of oscillations



Interference vanishes at low temperatures



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Model-independent nonclassicality

$g^{(2)}(\tau)$: features due to quantum nature of mechanical oscillator

But is it foolproof?

- Correct model of the system?
- Thermal mechanical state?
- Technical laser noise?
- Detector noise?
- ???

Normalized third order coherence

two clicks at t ,
one at $t + \tau$

$$g^{(3)}(t,t,t+\tau) = \frac{\langle a^{\dagger\,2}(t) a^\dagger(t+\tau) a(t+\tau) a^2(t)\rangle}{\langle a^\dagger(t) a(t)\rangle^2 \langle a^\dagger(t+\tau) a(t+\tau)\rangle}$$

Thermal state $\Rightarrow$ also oscillating in τ with period π/δ

Define

$$K(t,t+\tau) = \frac{g^{(3)}(t,t,t+\tau)}{\left[g^{(2)}(t,t+\tau)\right]^2}$$

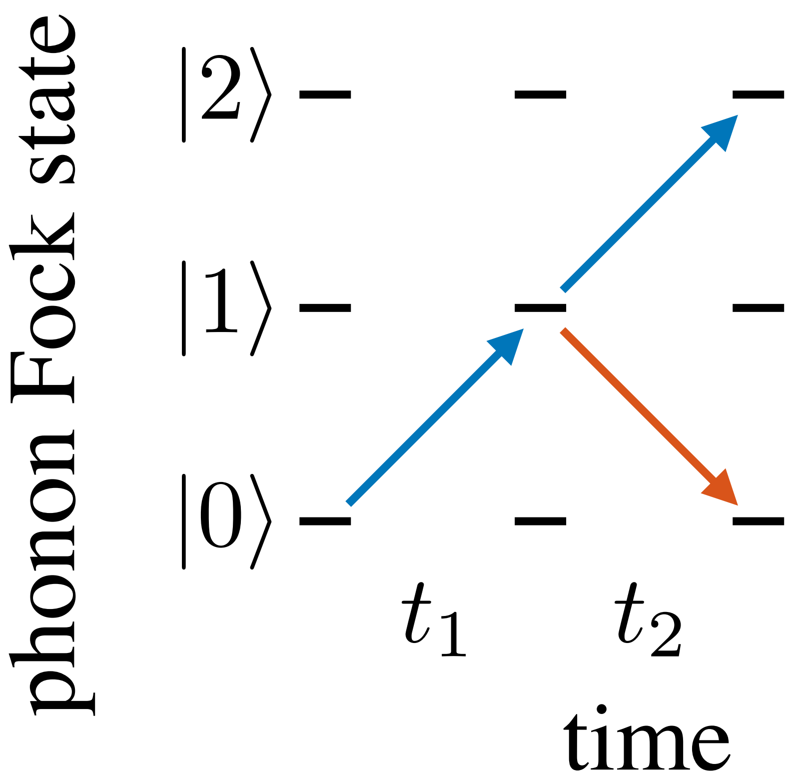
Classical inequality #1

If (filtered) cavity mode described by
positive-definite Glauber-Sudarshan distribution $P(\alpha)$:

$$K(t,t) \geq 1$$

Titulaer & Glauber, Phys. Rev. ***140****, B676 (1965)*

Note that $K(t,t) = g_c^{(2)}(0)$,
i.e., second order coherence **conditioned** on one photon detection



When

$n_m \ll 1 \qquad \beta \ll 1$

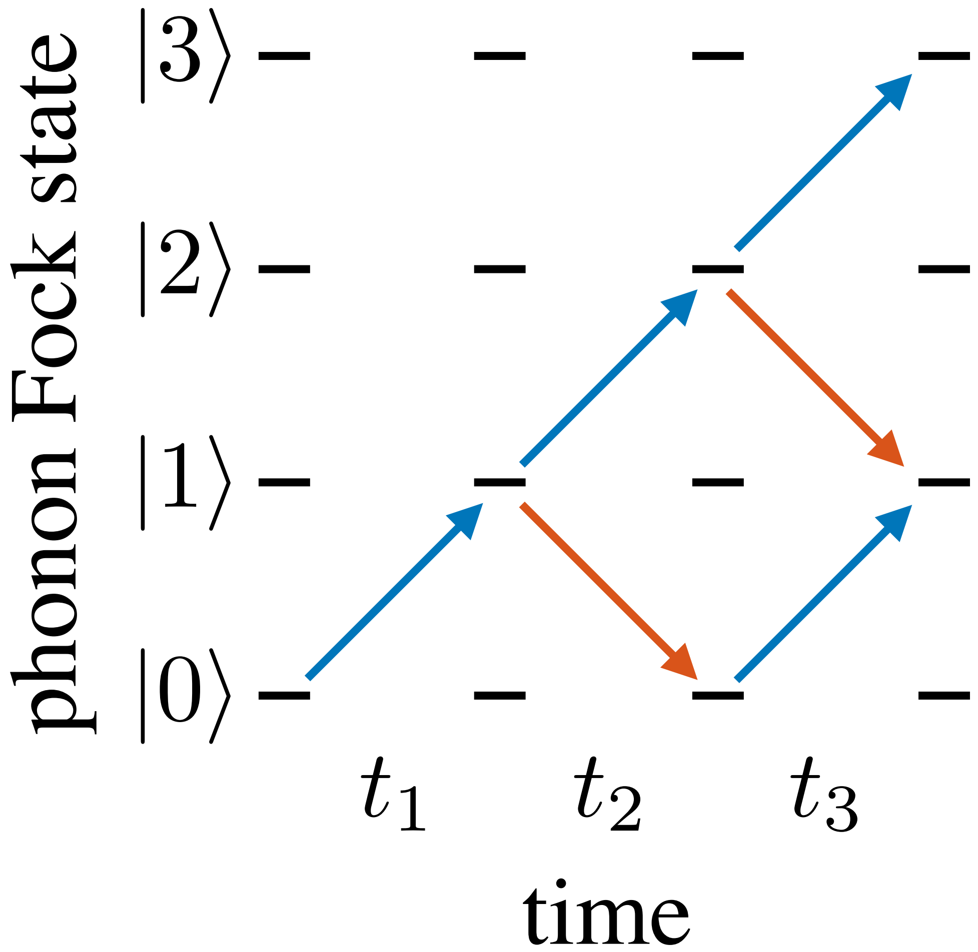
photons tend to come in well-separated pairs

Classical inequality #2

If (filtered) cavity mode at times t and $t+\tau$ described by joint positive-definite distribution $P(\alpha_1, \alpha_2)$:

$$K(t, t+\tau) \geq 1$$

Vogel, Phys. Rev. Lett. ***100****, 013605 (2008)*

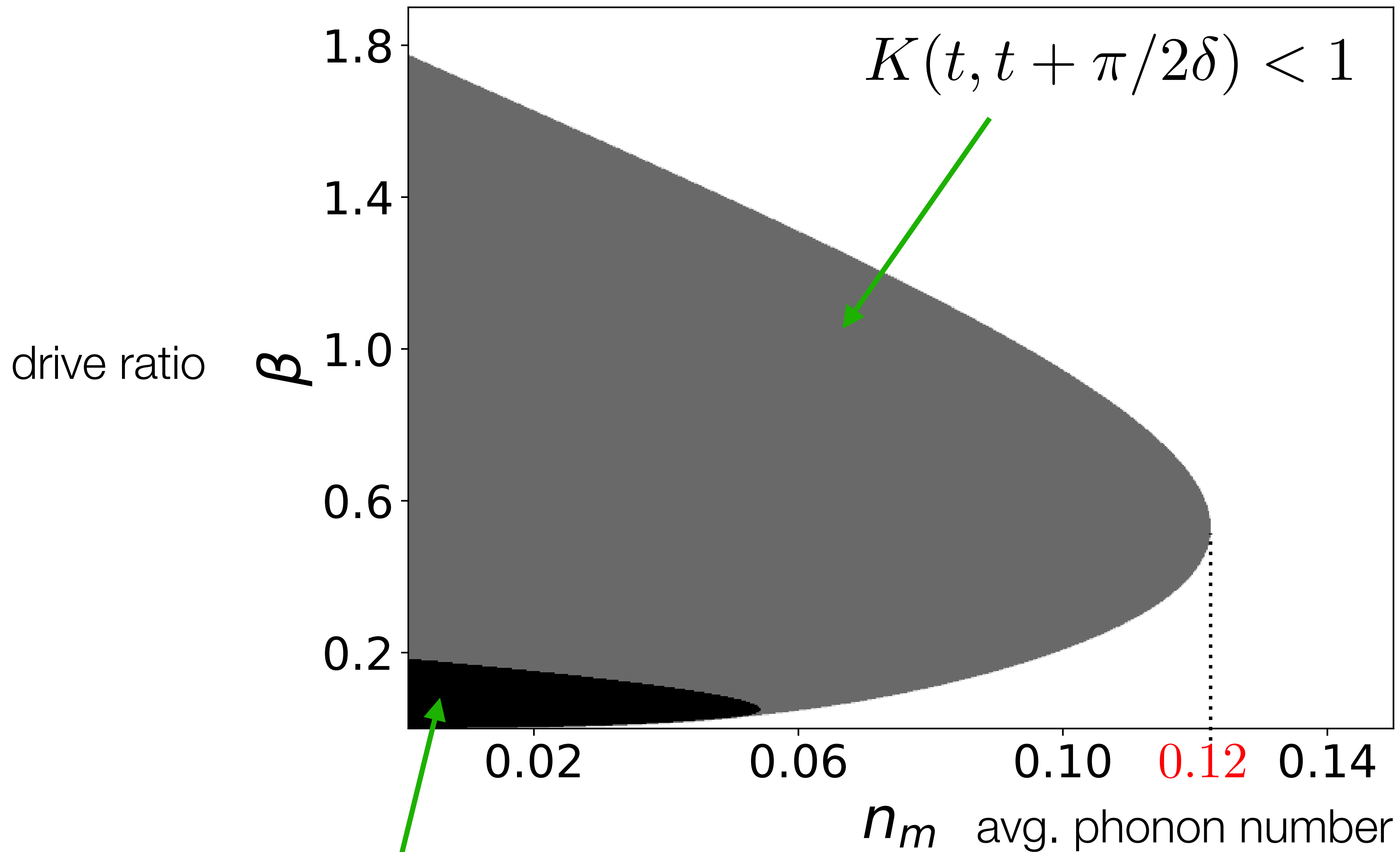


When

$n_m \ll 1$

destructive interference in three-photon detection amplitude, but not two-photon

Results, violation of classical inequalities



$K(t,t) < 1$ and $K(t, t + \pi/2\delta) < 1$

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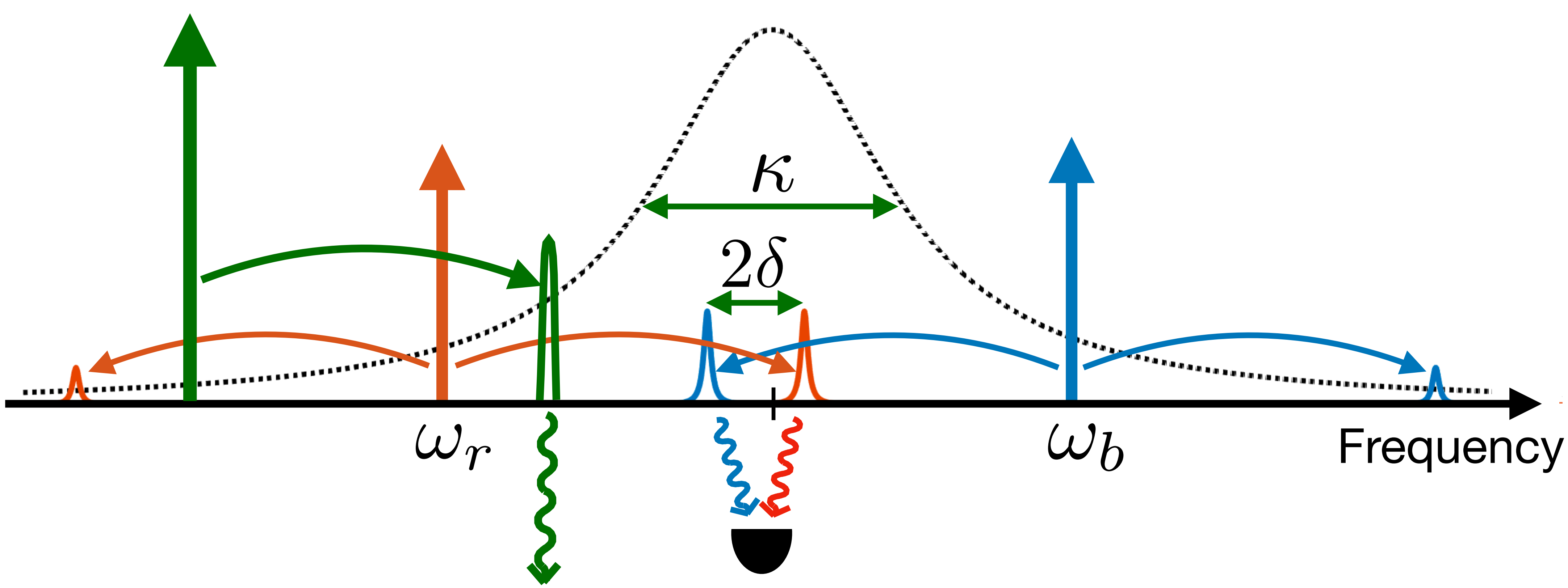
Cold reservoir: $k_B T_{\text{eff}} \ll \hbar\omega_m$

Small cooperativities $C_r = \dfrac{4G_r^2}{\kappa\gamma}$ $C_b = \dfrac{4G_b^2}{\kappa\gamma}$ < 1

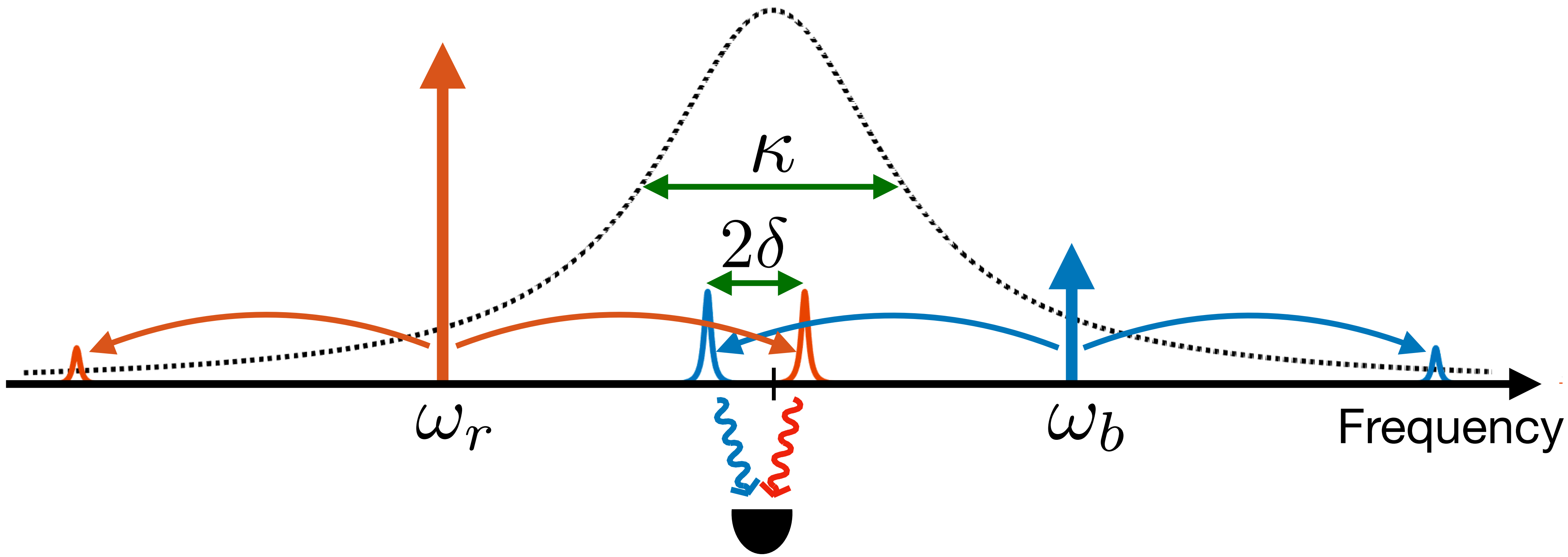
gives $n_m \approx n_{\text{th}} = \dfrac{1}{e^{\hbar\omega_m/k_B T_{\text{eff}}} - 1}$

Could be realized with sideband cooling if $\omega_m > \kappa$:



Hot reservoir: $k_B T_{\text{eff}} > \hbar\omega_m$

Exploit intrinsic sideband cooling: $\beta \ll 1$ $C_r \gg 1$



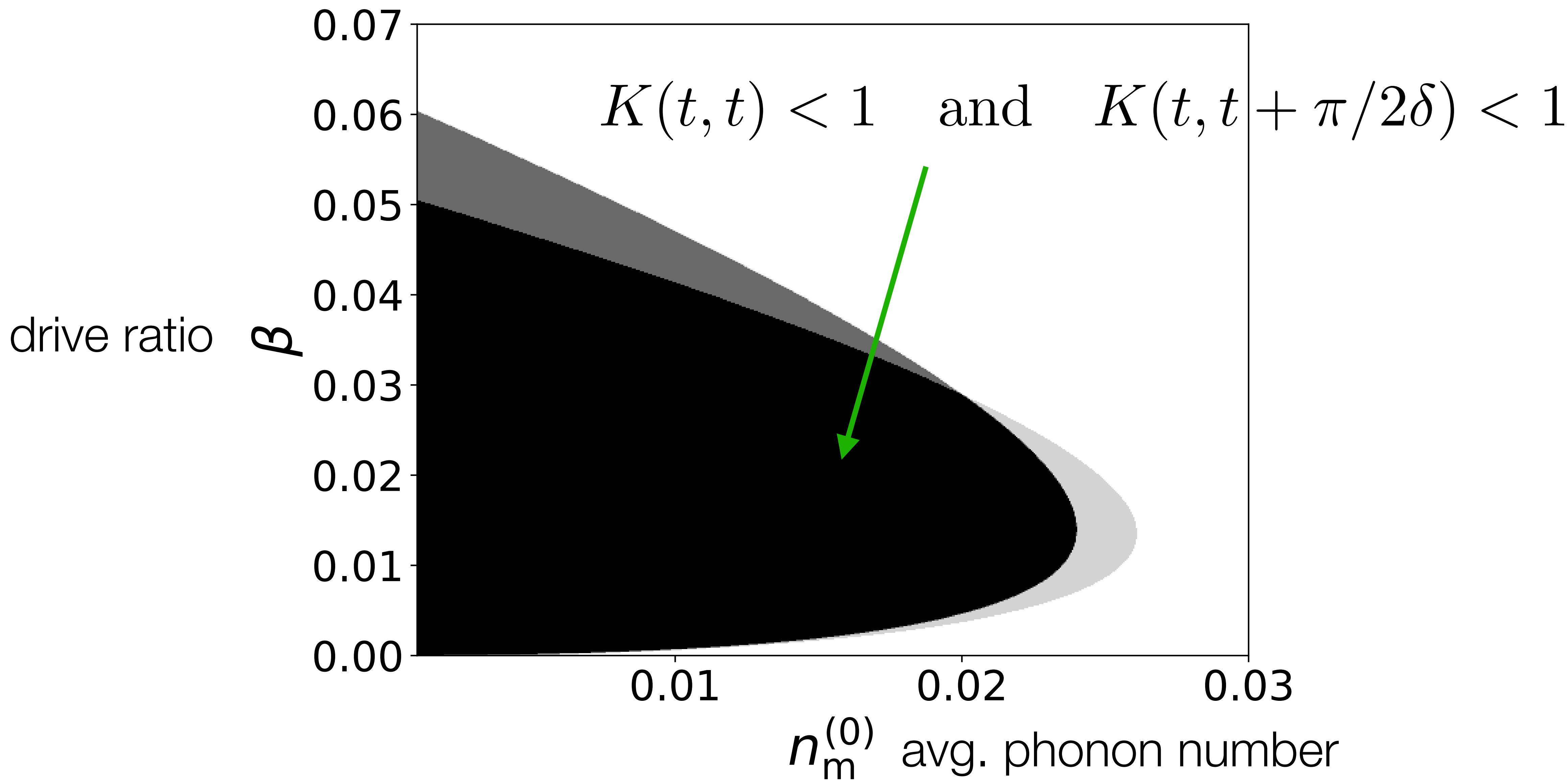
$$n_m = \frac{n_m^{(0)} + \beta}{1 - \beta}$$

avg. phonon number

$$n_m^{(0)} = \frac{n_{\text{th}}}{C_r} + \left(\frac{\kappa}{4\omega_m}\right)^2$$

for only red-detuned drive

Hot reservoir, intrinsic sideband cooling



$$n_m = \frac{n_m^{(0)} + \beta}{1 - \beta}$$

avg. phonon number

$$n_m^{(0)} = \frac{n_{\mathrm{th}}}{C_r} + \left(\frac{\kappa}{4\omega_m}\right)^2$$

for only red-detuned drive

Conclusion

- Richer photon statistics with two-tone driving than single-tone
- Model-independent nonclassicality possible when mechanical oscillator close to ground state
- Inequality #2: «nonclassicality in time» - reminiscent of Leggett-Garg inequalities
- Steady-state source of photons with nonclassical statistics

arXiv:2108.10738, Phys. Rev. A (in press)