Single Photon Generation from Cavity Higgs Polaritons

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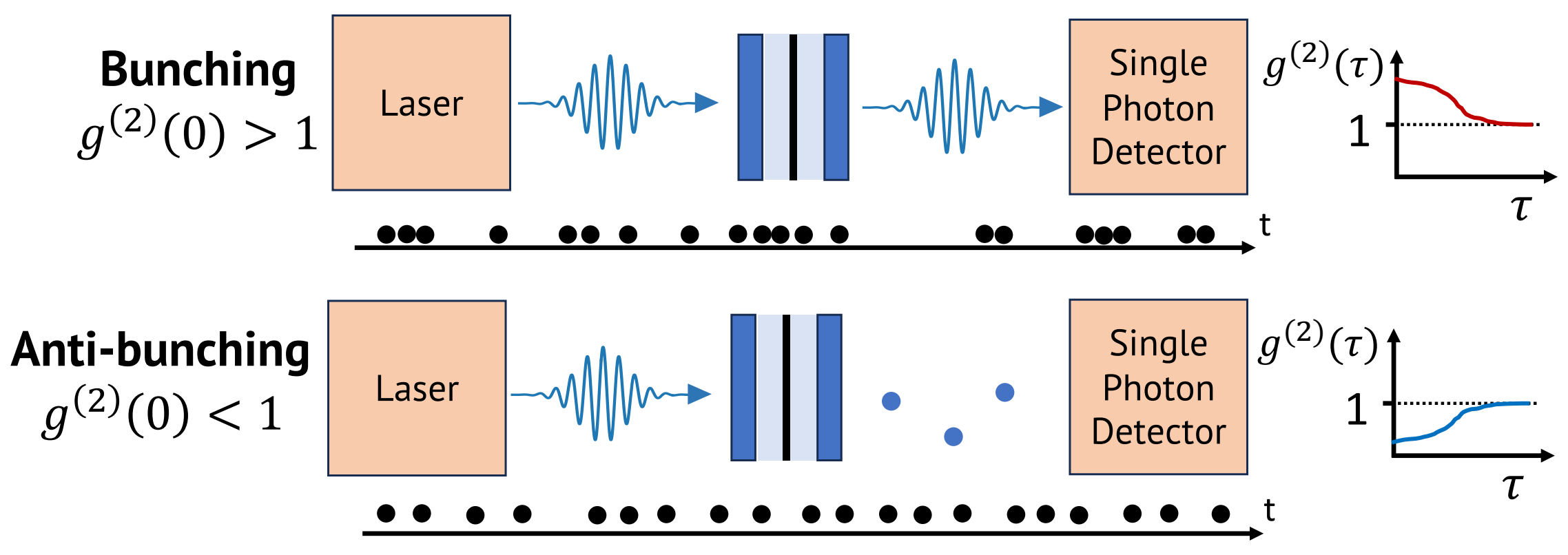
Abstract

Single photon generation is a key step in enabling optical quantum computing. Current single photon emitters are almost exclusively characterized by a geometry of localized quantum dots/atoms, where efficiency plummets when emitters couple to one another. In contrast to this conventional picture, we leverage quantum coherence of a collective order parameter to theoretically demonstrate high efficiency single photon emission by an extended material. The platform is a superconductor described by a Ginzburg-Landau order parameter embedded in a terahertz cavity coupled to light via minimal substitution. We rigorously compute the normalized two photon coherence function at coincidence and find that it can approach zero in high quality factor cavities corresponding to single photon emission.

Quantum Light

A key parameter for light is its intensity $\langle n\rangle$ and its fluctuations in intensity $\mathrm{var(n)} = \langle (a^+a)^2\rangle - \langle a^+a\rangle^2$. It turns out that classical electromagnetism can only represent light with $\mathrm{var(n)} \geq \langle n\rangle$ corresponding to "Poissonian" or "super-Poissonian" light [1]. An equivalent experimentally measurable version of this is to consider the bunching or anti-bunching of light [2]



where the $g^{(2)}$ functional corresponds to intensity fluctuations. At long times intensity fluctuations are uncorrelated ($g^{(2)}$ → 1), but at short times there can be "bunching" ($g^{(2)} > 1$) and "antibunching" of light ($g^{(2)} < 1$). When $g^{(2)}(0)$ → 0 this is perfect anti-bunching and photons arrive alone corresponding to single photon emission. The $g^{(2)}$ functional is given by

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

Input-Output Theory

Cavity input-output theory as formulated by Gardiner and Collett [3] relates output light modes to the input modes and the features of the cavity via the relation

$$\hat{b}_{\mathrm{out}}(t) = \hat{b}_{\mathrm{in}}(t) + \gamma\hat{a}(t)$$

where γ quantifies the quality factor of the cavity. This enables us to calculate the output from scattering-type experiments, including $g^{(2)}$ of light emitted from a cavity.

$g^{(2)}(0)$ for Single Mode States

Number State

Number state (a single emitter is $|n\rangle = |1\rangle$)

$$g^{(2)}(0) = \frac{\langle n|a^\dagger a^\dagger aa|n\rangle^2}{\langle n|a^\dagger a|n\rangle^2} = \frac{n(n-1)}{n^2} = 1 - \frac{1}{n}$$

Coherent State

Coherent state (like laser light)

$$g^{(2)}(0) = \frac{\langle \alpha|a^\dagger a^\dagger aa|\alpha\rangle^2}{\langle \alpha|a^\dagger a|\alpha\rangle^2} = \frac{\bar{\alpha}\bar{\alpha}\alpha\alpha}{(\bar{\alpha}\alpha)^2} = 1$$

Thermal State

Thermal state ($P_n = e^{-\beta n\hbar\omega}/(e^{\beta\hbar\omega} - 1)$, $\langle o\rangle = \mathrm{Tr}[o\rho]$)

$$\left.\begin{aligned} \rho &= \sum\nolimits_{n=0}^{\infty} P_n|n\rangle\langle n| \\ \langle a^\dagger a\rangle &= \sum\nolimits_{n=0}^{\infty} nP_n = \langle n\rangle \\ \langle a^\dagger a^\dagger aa\rangle &= \sum\nolimits_{n=0}^{\infty} n(n-1)P_n = 2\langle n\rangle^2 \end{aligned}\right\} g^{(2)}(0) = 2$$

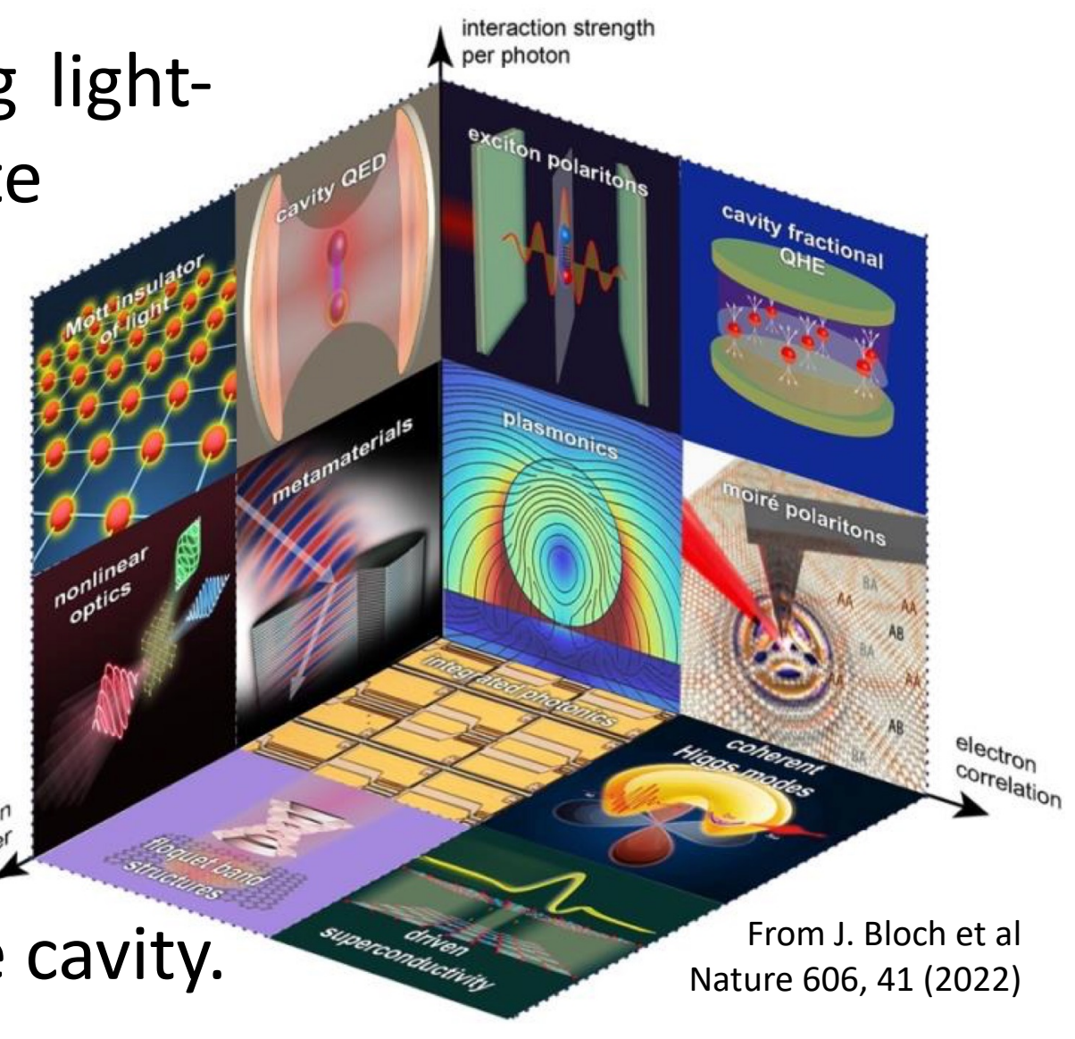
For all Temperatures!

Other States

One can consider $g^{(2)}$ for other photonic states and light-matter couplings. For N two-level-system emitters coupled to a single bosonic mode $g^{(2)} = 1 - 1/N$.

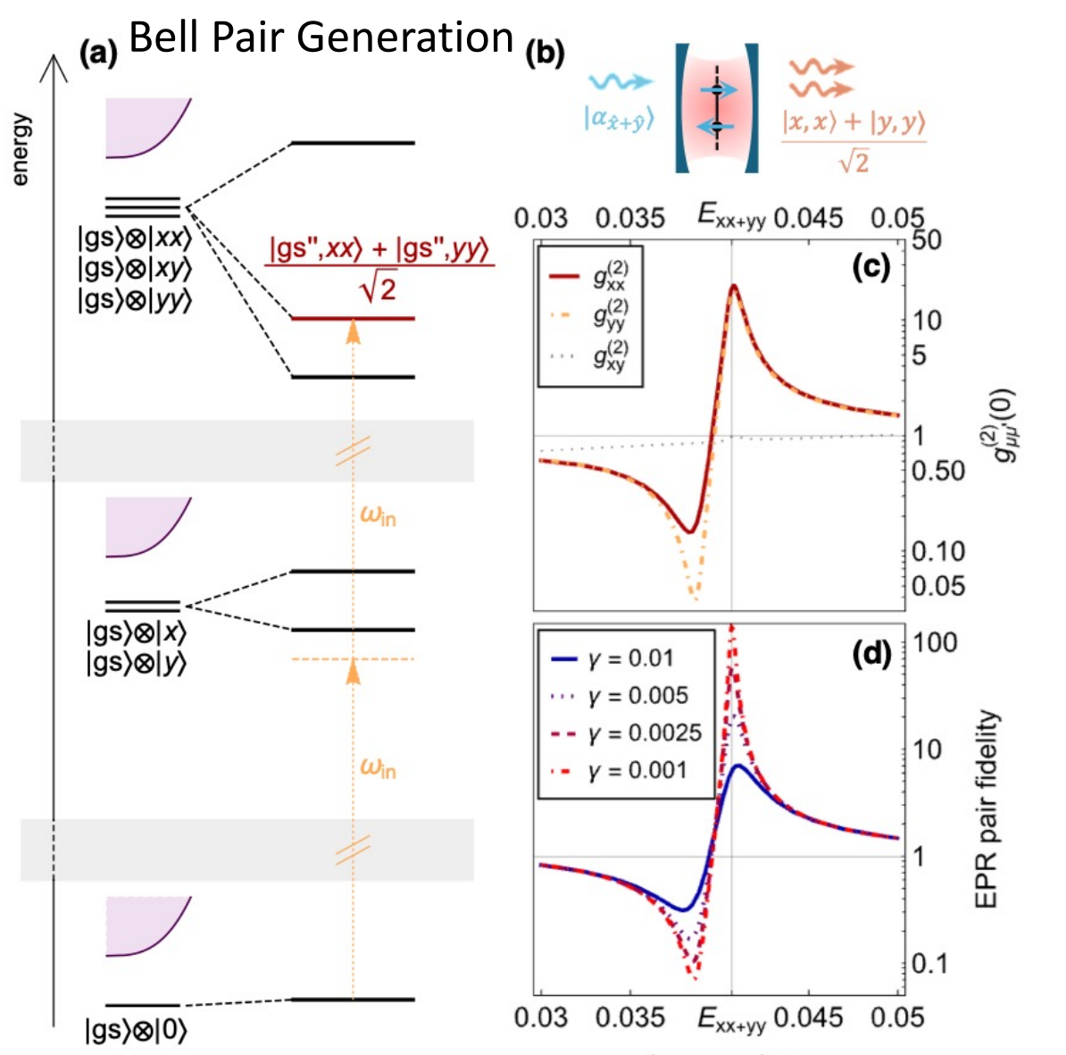
Cavity Quantum Materials

Cavities can enable strong light-matter coupling to generate hybrid light-matter states with distinct properties from the light or matter alone such as polariton physics, non-linear optics and superconductivity [4]. Input/output light is used to drive/dissipate the cavity.



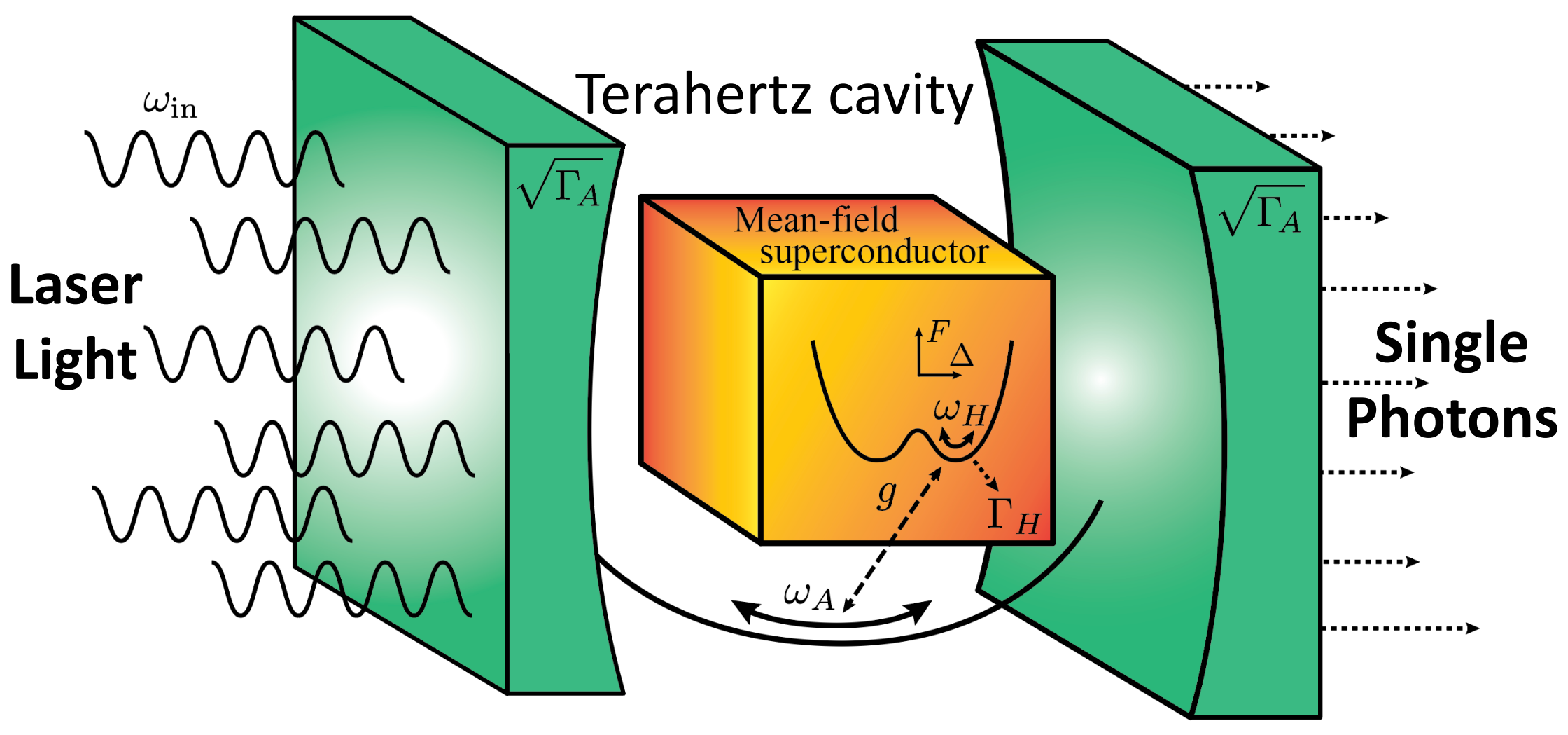
From J. Bloch et al Nature 606, 41 (2022)

Here we take a different approach by focusing on controlling the output state of light using a cavity-material system. In our previous work [5] we showed that optical Raman processes of a material near a critical point can emit single photons and Bell pairs.



From Kass et al, arXiv 2411.08964

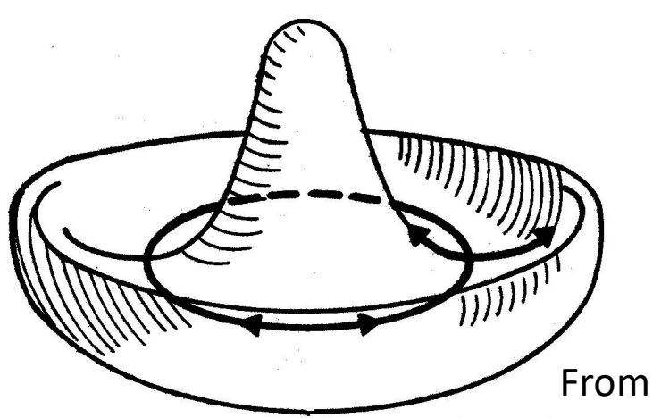
Collective Modes



Ginzburg Landau Theory

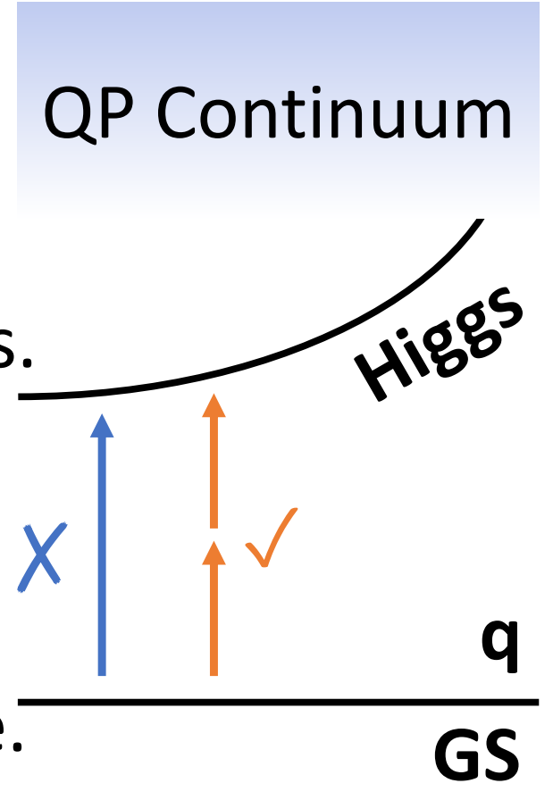
Consider a collective order parameter Δ describing a conventional superconductor [6].

$$\begin{aligned} F =&F_0 - \alpha|\Delta|^2 + \beta|\Delta|^4 \\ &+g^\mu|(i\nabla^\mu + eA^\mu)\Delta|^2 \\ &\boldsymbol{g} = (-P, g_0, g_0, g_0) \end{aligned}$$



From arXiv:0109.409

This can couple to light through spatial fluctuations via minimal substitution. Now, well below T_c, we can expand $\Delta = (\Delta_0 + h)e^{i\theta}$ in in amplitude (Higgs) and phase fluctuations. This leads to $F' = \omega_H hh + gA^2h$ with $\omega_H = \sqrt{2\alpha/P}$ and $g = 2\Delta_0 e^2 g_0$. Note there is no Ah term, so the Higgs only couples to light in non-linear response.



Non-Equilibrium Steady State

We can formulate the dynamics of this system as a master equation where $\partial_t\rho = (\mathcal{L}_{\mathrm{empty}} + \mathcal{L}_F)[\rho]$ and $A = a + a^+$, and we discard the counter-rotating terms

$$\begin{aligned} \mathcal{L}_{\mathrm{empty}}[\rho] =& -i[\omega_A a^\dagger a + \sqrt{\Gamma_A}(fa^\dagger + \bar{f}a), \rho] \\ &+ \Gamma_A(a^\dagger a\rho + \rho a^\dagger a - 2a\rho a^\dagger) \end{aligned}$$

$$\begin{aligned} \mathcal{L}_F[\rho] =& -i[\omega_H h^\dagger h + g(aah^\dagger + a^\dagger a^\dagger h), \rho] \\ &- \Gamma_H(h^\dagger h\rho + \rho h^\dagger h - 2h\rho h^\dagger) \end{aligned}$$

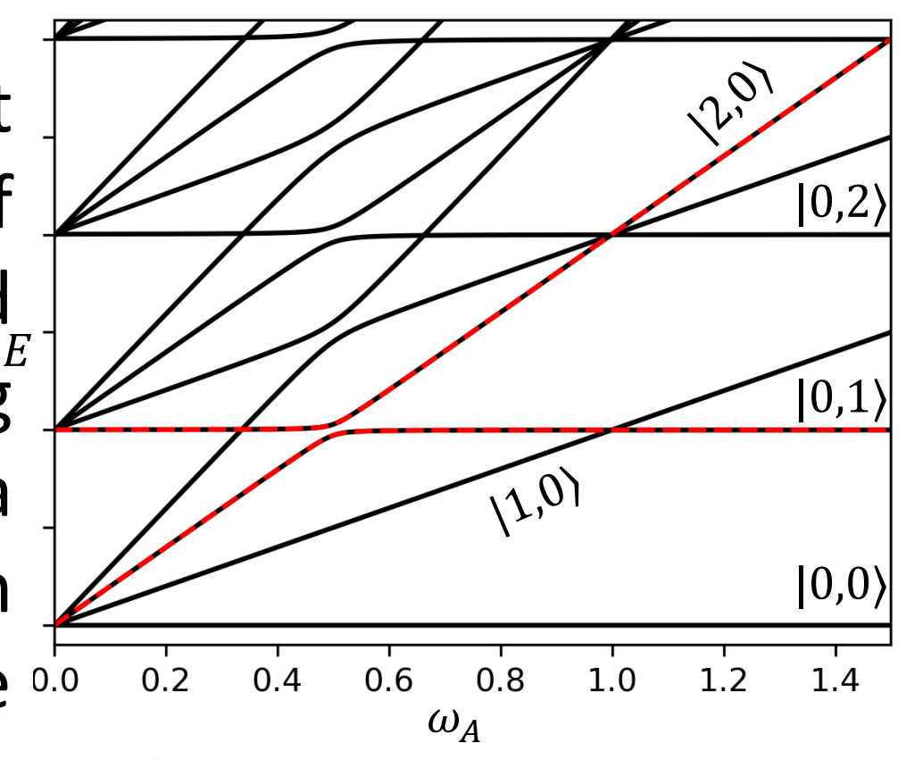
One can numerically evolve for fixed sizes of the a and h operators until a steady state is reached. Alternatively when $\Gamma_A \ll \Gamma_H$ we can find an exact solution by mapping to Fokker-Planck equation whose solution is known [7].

Our Previous Works

Dissipation in quantum systems is not invariably inimical: it can be a resource to engineer desirable steady states. Dissipation can be used to engineer band structures [PRB 106, L161109 (2022)], realize non-equilibrium steady states and probe their dynamic response properties [PRB 109, 235421 (2024), npj Quantum Materials 9, 104 (2024)], and to enable a photon blockade [2411.08964].

Cavity Higgs Polaritons

Coupling matter modes to light creates polaritonic mixtures of light and matter near avoided crossings. For superconducting modes coupled to photons in a cavity this is a Higgs polariton [8]. We can then consider the full structure of energy levels as a function of the cavity frequency ω_A and we see an anti-crossing at $\omega_A = \omega_H/2$. The splitting at the anti-crossing enables single photon generation: the one-photon resonance is not half the energy of the two-photon resonance and so there is a strong anti-bunching when $\omega_A/2$ is in the polaritonic gap. We can understand the physics further in a reduced space

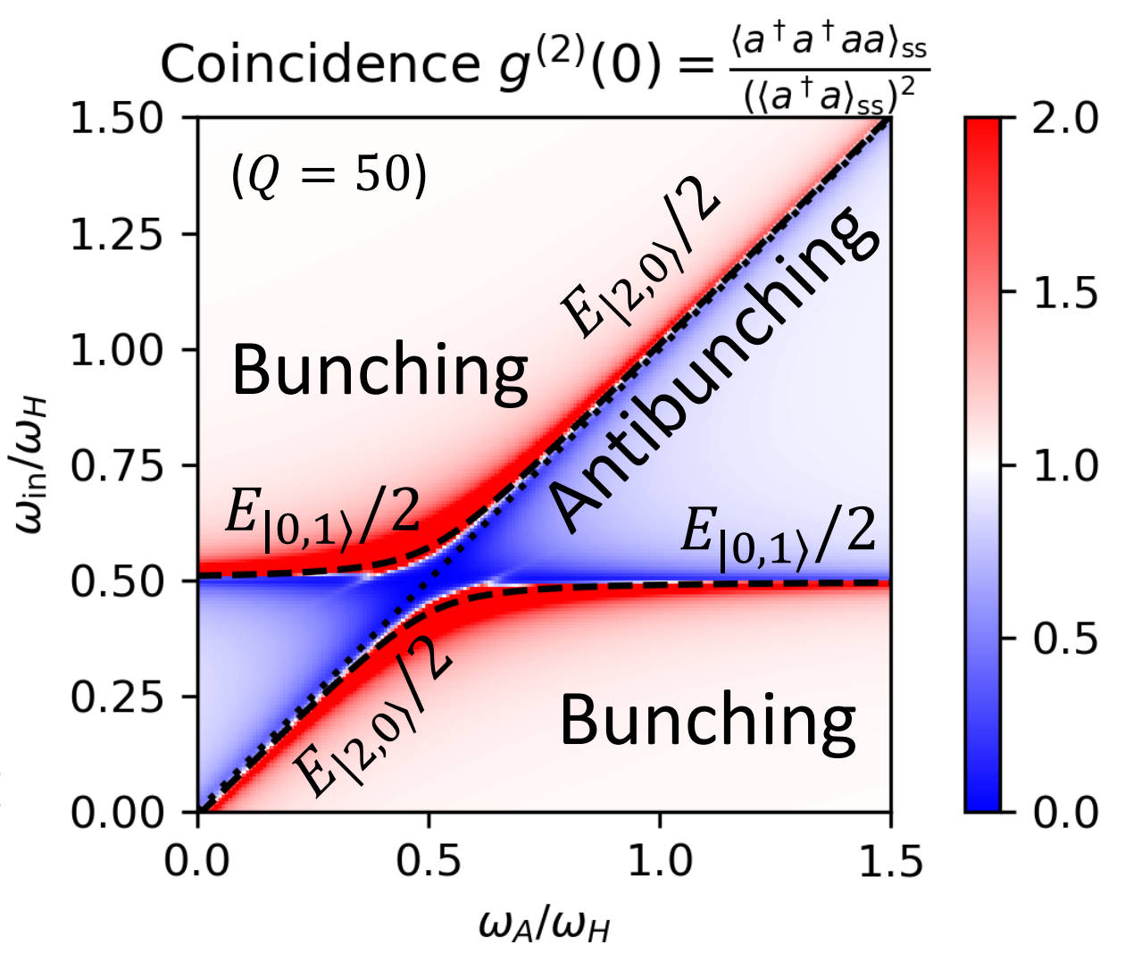


$$H_{\mathrm{red}} = \begin{pmatrix} \langle 2{,}0|H|2{,}0\rangle & \langle 2{,}0|H|0{,}1\rangle \\ \langle 0{,}1|H|2{,}0\rangle & \langle 0{,}1|H|0{,}1\rangle \end{pmatrix} = \begin{pmatrix} 2\omega_A & \sqrt{2}g \\ \sqrt{2}g & \omega_H \end{pmatrix}$$

Photon Blockade

Due to the coherence of the collective order parameter, the extended superconductor acts as a single emitter with antibunching $g^{(2)} << 1$.

The anti-bunching peaks when driving is resonant $\omega_{\mathrm{in}} = \omega_A$, $\omega_{\mathrm{A}} = \omega_H/2$.



In the limit of weak driving the analytic solution gives [9]

$$g^{(2)}(0) = \left|\frac{(\Gamma_A + i(\omega_A - \omega_{\mathrm{in}}))(\Gamma_H + i(\omega_H - 2\omega_{\mathrm{in}}))}{g^2 + (\Gamma_A + i(\omega_A - \omega_{\mathrm{in}}))(\Gamma_H + i(\omega_A - 2\omega_{\mathrm{in}}))}\right|^2$$

which is single photon emission $g^{(2)} = 0$ for a high-*Q* cavity.

Summary

Single photon generation has been limited to low total photon counts generated due to a limited cross-section of single-emitters: traditionally increased cross-section through increased number of emitters reduces the fidelity of the output as quantified by $g^{(2)}$. Here we show that large cross-section and high fidelity need not be inimical provided there are correlations among atoms. We consider an example of correlations captured by an amplitude (Higgs) mode in a collective Ginzburg-Landau order parameter. A polaritonic splitting between one and two photon states allows single photon generation.

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