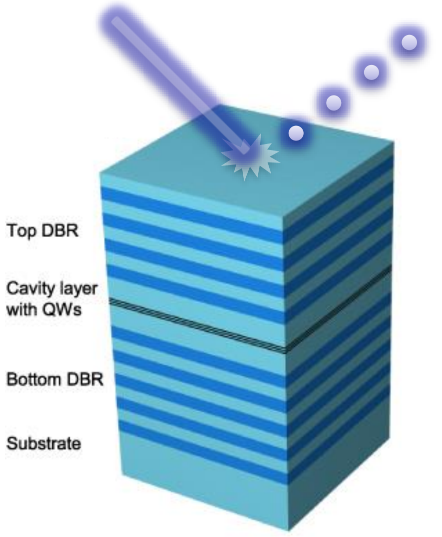
Nonclassical statistics in Semiconductor Microcavities

H. Flayac and V. Savona



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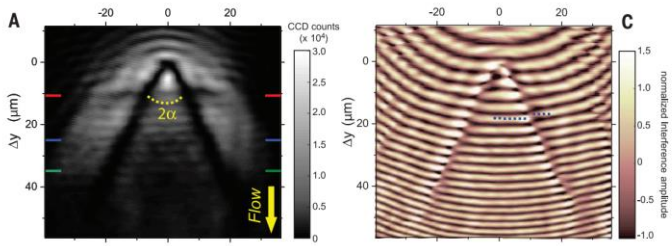
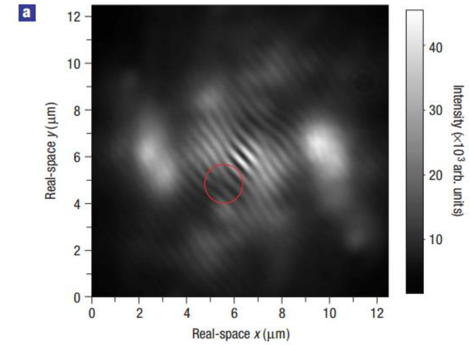
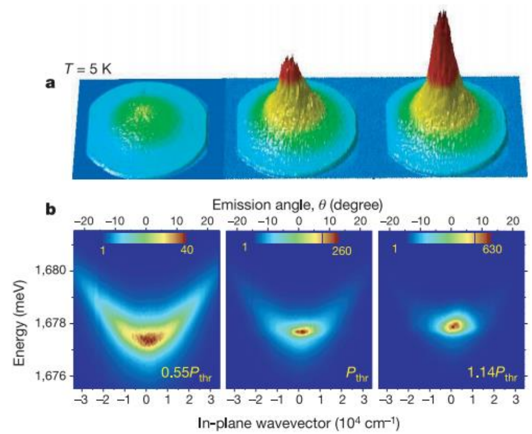
Classical experiments with polaritons



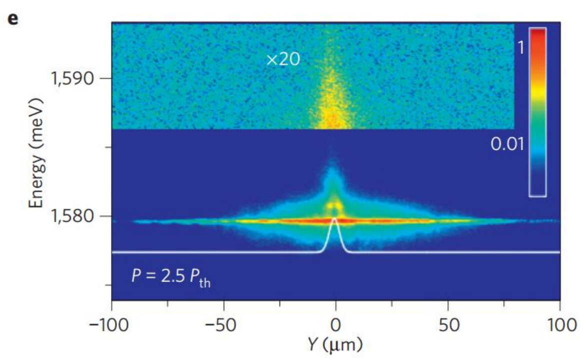
A. Amo et al., Science (2011)



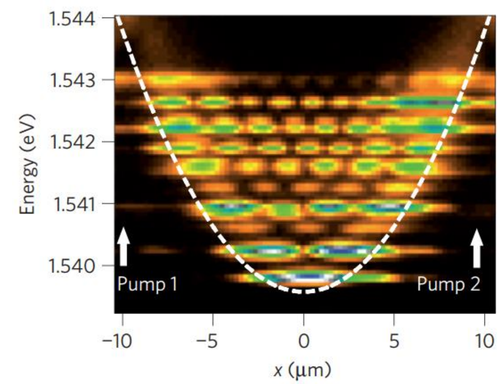
K. G. Lagoudakis et al., Nature Physics (2008)



J. Kasprzak et al., Nature (2006)



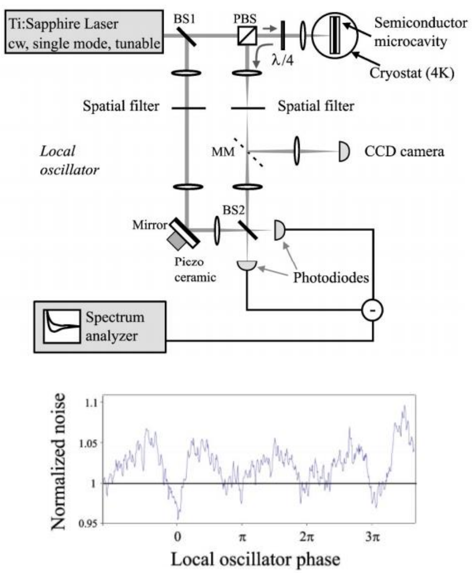
E. Wertz et al., Nature Physics (2010)



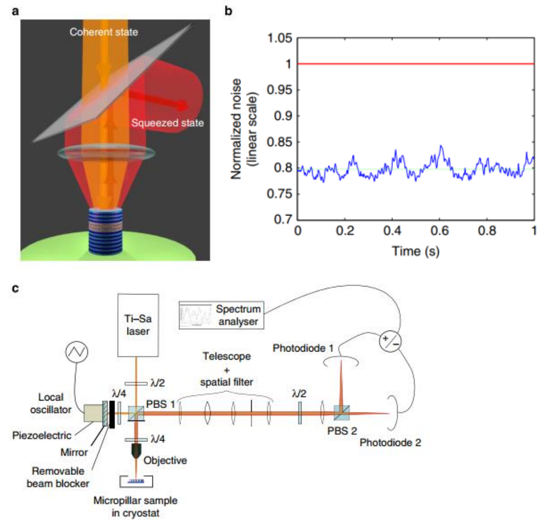
G. Tosi, Nature Physics (2012)

Quantum Experiment with polaritons

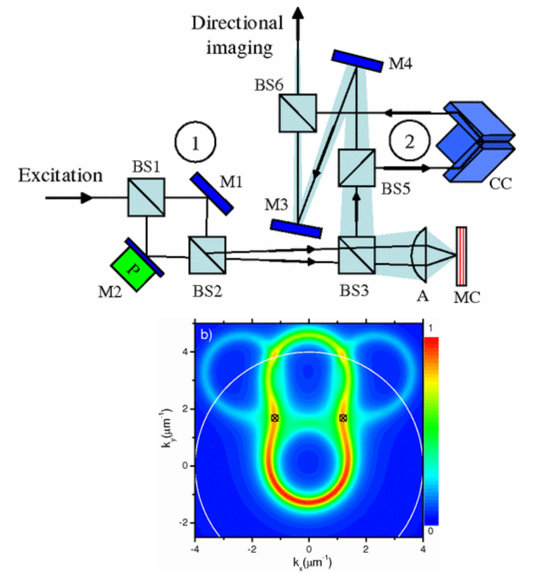
J. Ph. Karr et al., Phys. Rev. A (2004)



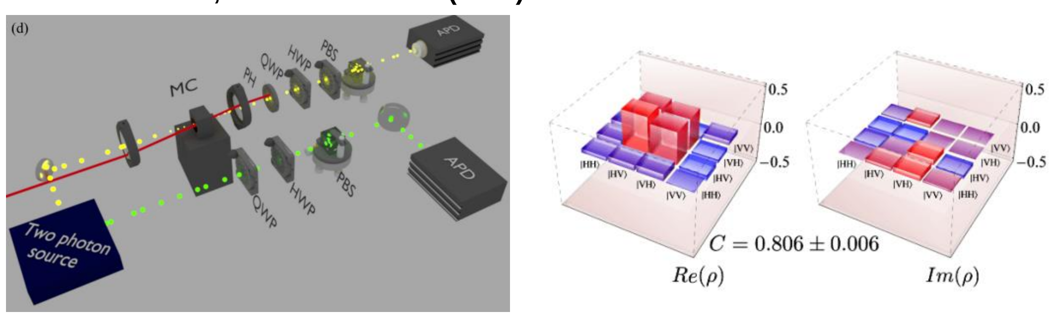
T. Boulier et al. Nat. Comm. (2014)



S. Savasta et al., Phys. Rev. Lett. (2005)



A. Cuevas et al., arXiv:1609.01244 (2016)



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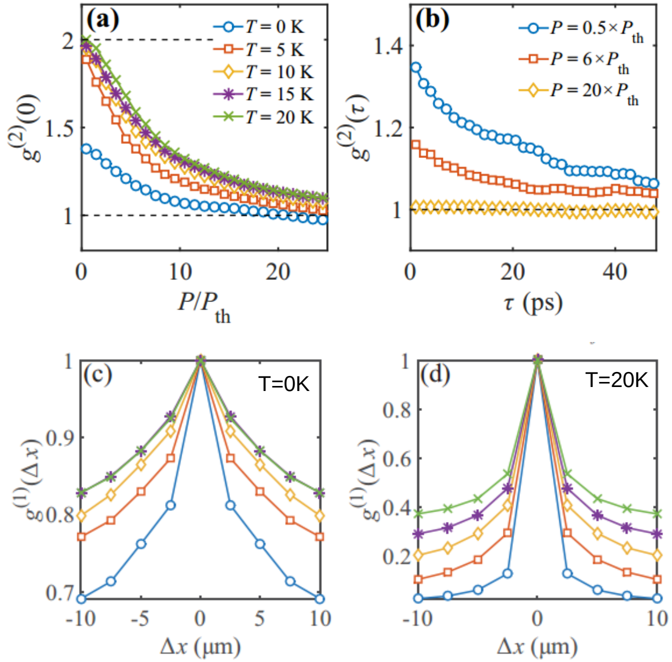
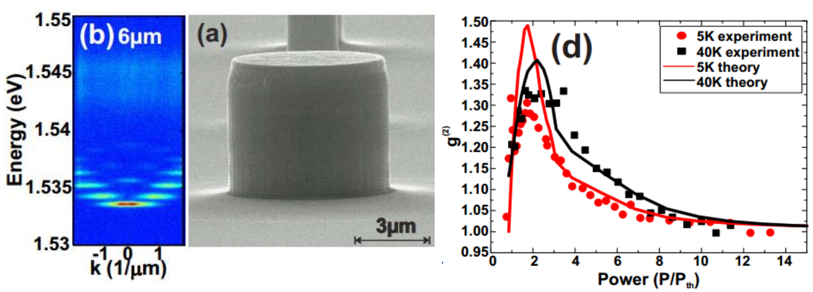
Quantum correlations in semiconductor microcavities

Quantum model for confined polariton BEC
H. Flayac et al., Phys. Rev. B **92**, 115117 (2015)

Aalto University

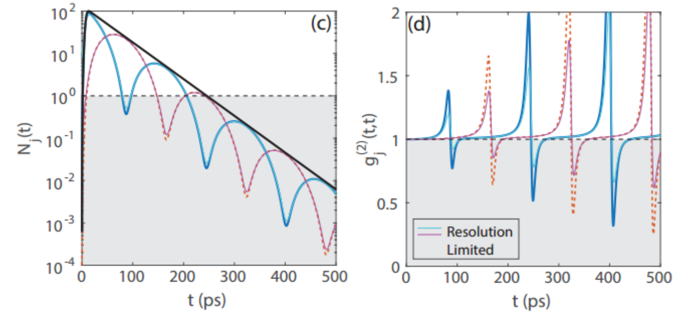




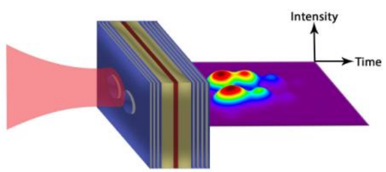
M. Amthor, H. Flayac et al. *arXiv*:1511.00878 (2017)
Micropillar emission statistics

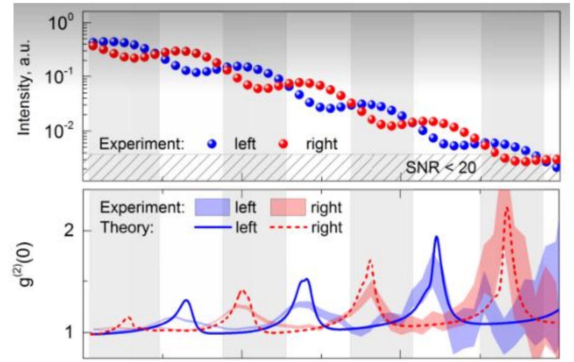
Julius-Maximilians-
UNIVERSITÄT WÜRZBURG

Nonclassical stats from a polaritonic Josephson junction
H. Flayac and V. Savona, PRA (2017)



Periodic Squeezing in a polaritonic Josephson junction
A. F. Adiyatullin, M. D. Anderson, H. Flayac et al., *arXiv*:1612.06906 (2016)





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Nonclassical Statistics
in
Semiconductor Microcavities

Hugo Flayac – Daejeon – May 16th 2017

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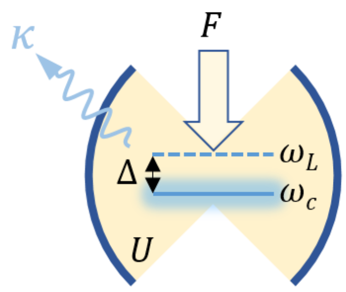
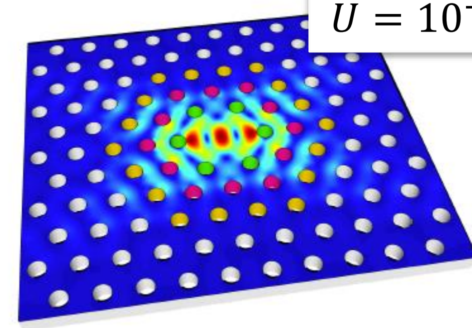
Weakly nonlinear open quantum systems



$U \ll \kappa$

$U = 10^{-3}\kappa$

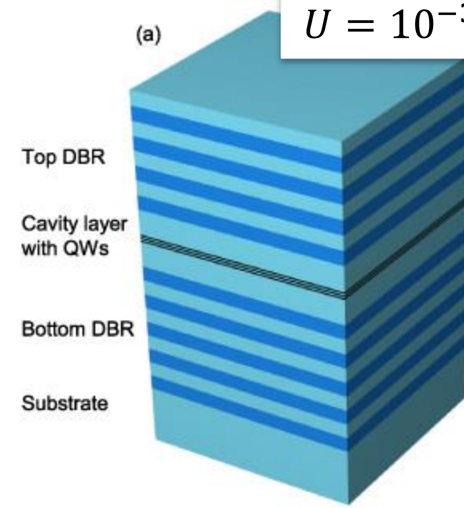


Photonic crystal cavity

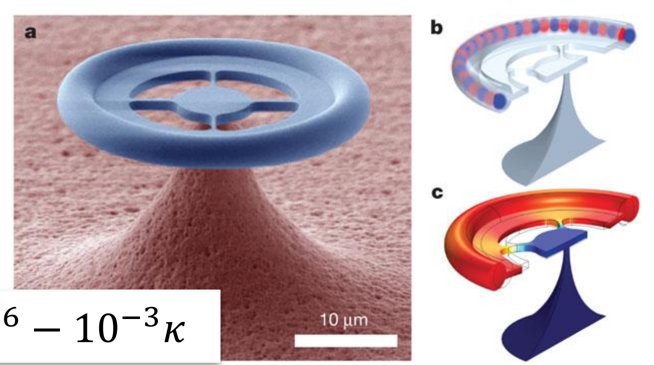
Kerr Nonlinearity

$$\hat{H}_K = U\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

$U = 10^{-3} - 10^{-2}\kappa$



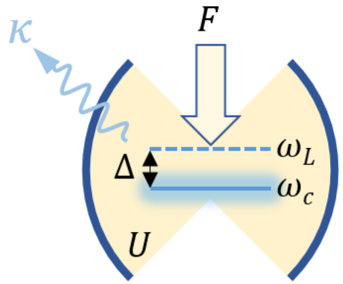
Semiconductor Microcavity



$U = 10^{-6} - 10^{-3}\kappa$

Optomechanical Resonator

Second order correlation function



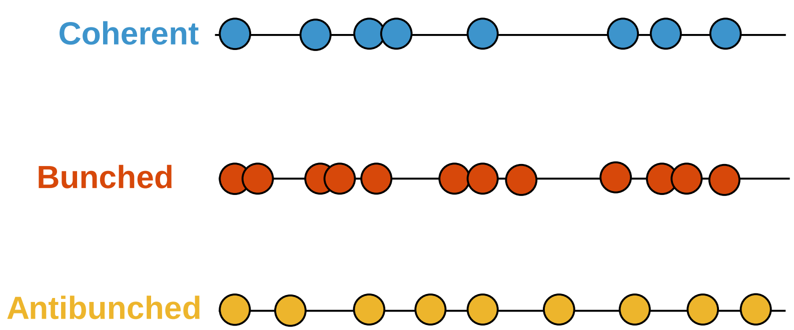
$$g^{(2)}(0) = \frac{\langle \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2}$$

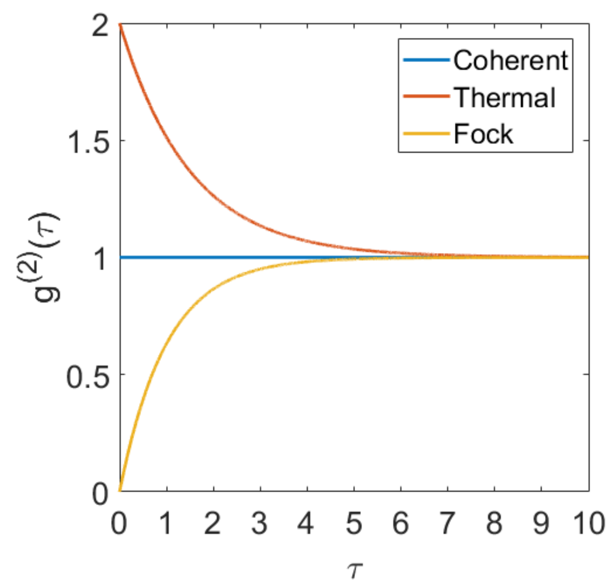
Normalized equal time N>2 photon probability

Characterizes the field statistics:

- $g^{(2)}(0) = 1$: Poissonian – e.g. **Laser**
- $g^{(2)}(0) > 1$: Super-Poissonian – e.g. **Thermal light**
- $g^{(2)}(0) < 1$: Sub-Poissonian – e.g. **Fock State**

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(0) \hat{a}^\dagger(\tau) \hat{a}(\tau) \hat{a}(0) \rangle}{\langle \hat{a}^\dagger(0) \hat{a}(0) \rangle^2}$$





Optimal squeezing of a coherent state

Squeezed coherent state: $|\alpha,\xi\rangle$

$$\begin{cases} \alpha = \bar{\alpha} e^{i\varphi} \\ \xi = r e^{i\theta} \end{cases}$$

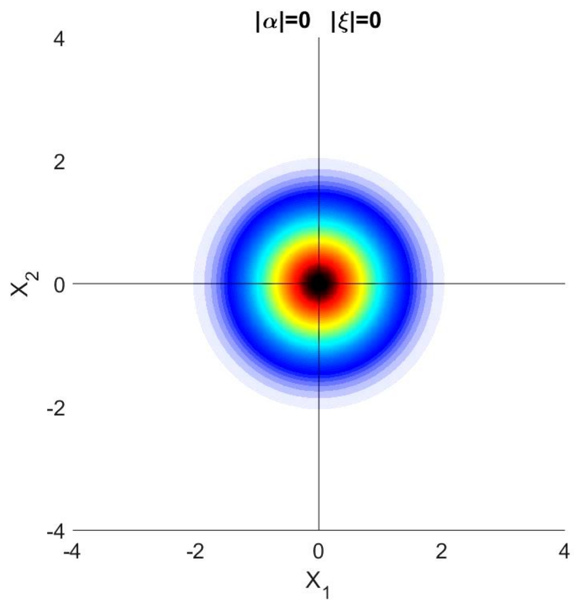
Second order correlation for $\theta = 2\varphi = 0$

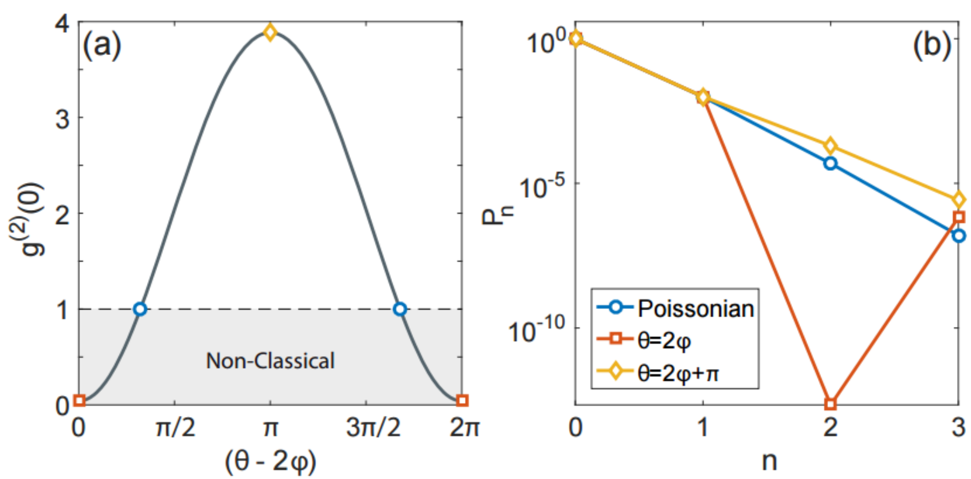
$$g^{(2)}(0) = 1 + \frac{\cosh 2r}{\bar{\alpha}^2 + \sinh^2(r)} - \frac{\bar{\alpha}^2 (1 + \sinh 2r)}{(\bar{\alpha}^2 + \sinh^2 r)^2}$$

In the limit $\bar{\alpha} \to 0$

$$r_{\text{opt}} \approx \bar{\alpha}^2$$

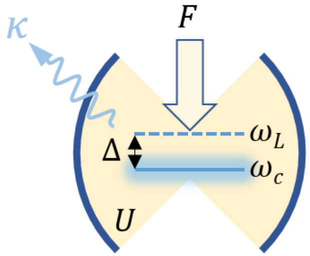
$$g^{(2)}(0)|_{\min} \approx 4\bar{\alpha}^2$$





M. A. Lemonde, **N. Didier**, and A. A. Clerk, *Phys. Rev. A* **90**, 063824 (2014).

The Kerr oscillator

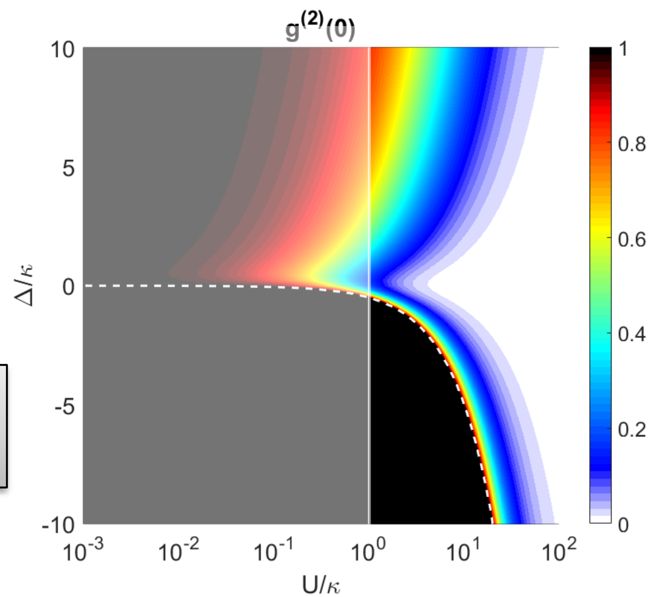


Driven-dissipative Kerr Oscillator

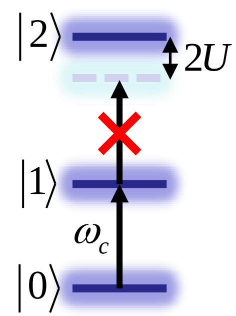
$$\hat{H} = \Delta \hat{a}^\dagger \hat{a} + U \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} + F\left(\hat{a}^\dagger + \hat{a}\right)$$

$U < \kappa$
Squeezing
(Gaussian)

Laser → Displacement α
Kerr → Squeezing $\xi \approx U\alpha^2$

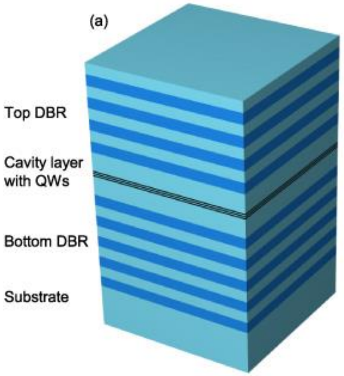


$U \gtrsim \kappa$
Blockade
(non-Gaussian)



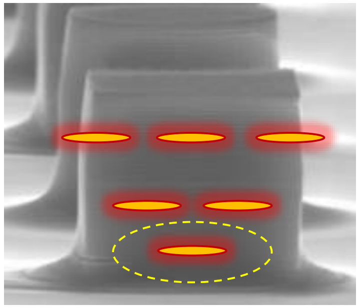
No Optimal Squeezing!

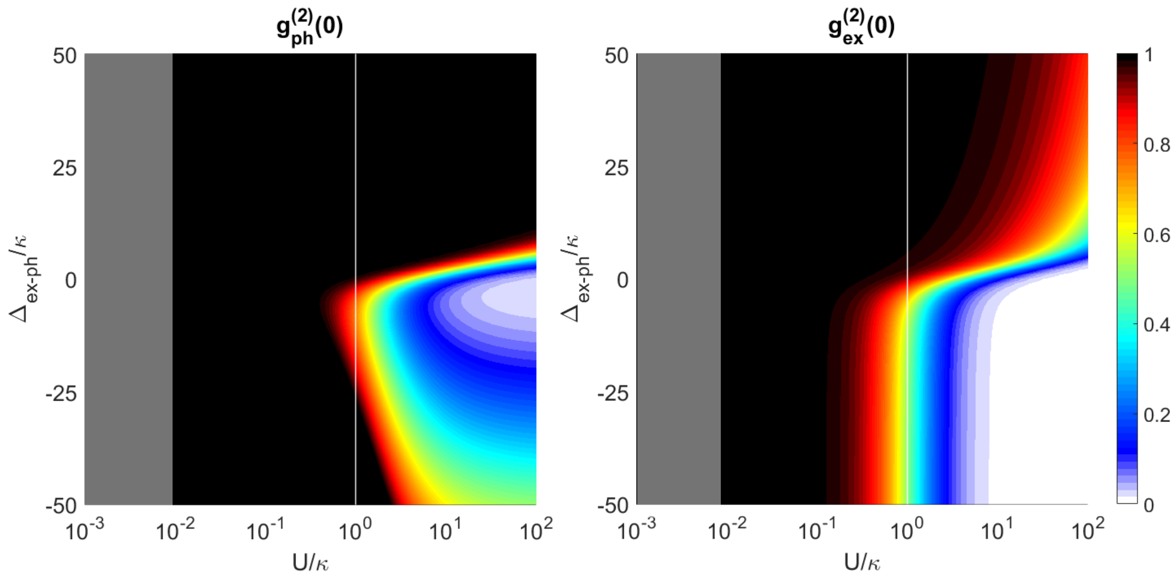
The polariton blockade



Two coupled oscillators: exciton-photons

$$\hat{H} = \Delta_{ph}\hat{a}^\dagger\hat{a} + \Delta_{ex}\hat{b}^\dagger\hat{b} + U\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b} + J\left(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a}\right) + F\left(\hat{a}^\dagger + \hat{a}\right)$$





Requires $U \gtrsim \kappa$

But typically $\boldsymbol{U/\kappa = 10^{-3} - 10^{-2}}$

A. Verger, C. Ciuti and I. Carusotto, *Phys. Rev. B* **73**, 193306 (2006).

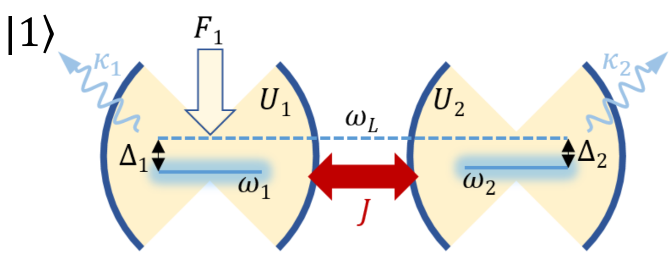
UPB in a weakly nonlinear 2 mode system

Coupled Kerr oscillators:

$$\hat{H} = \sum_j \Delta_j \hat{a}_j^\dagger \hat{a}_j + U_j \hat{a}_j^\dagger \hat{a}_j^\dagger \hat{a}_j \hat{a}_j + J\left(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1\right) + F_1\left(\hat{a}_1^\dagger + \hat{a}_1\right)$$

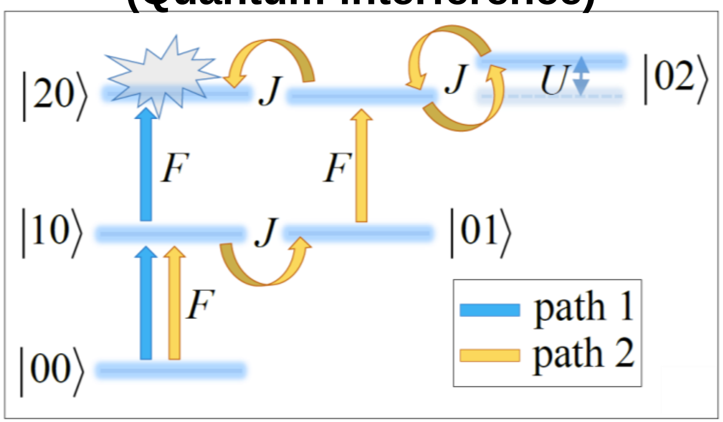
$$\Delta_{|\text{opt}} = \pm\frac{1}{2}\sqrt{\sqrt{9J^4 + 8\kappa^2 J^2} - \kappa^2 - 3J^2}$$

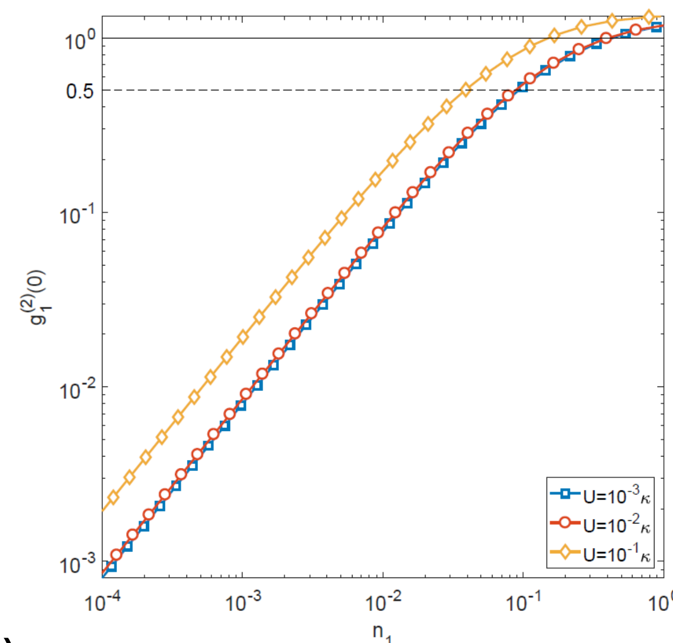
$$U_{|\text{opt}} = \frac{\Delta_{\text{opt}}\left(4\Delta_{\text{opt}}^2 + 5\kappa^2\right)}{2\left(2J^2 - \kappa^2\right)}$$



Strong Antibunching
$g_1^{(2)}(0) \ll 1$ despite $\boldsymbol{U} \ll \boldsymbol{\kappa}$

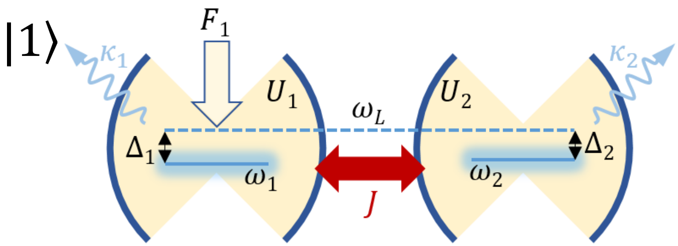
Unconventional Photon Blockade (Quantum interference)



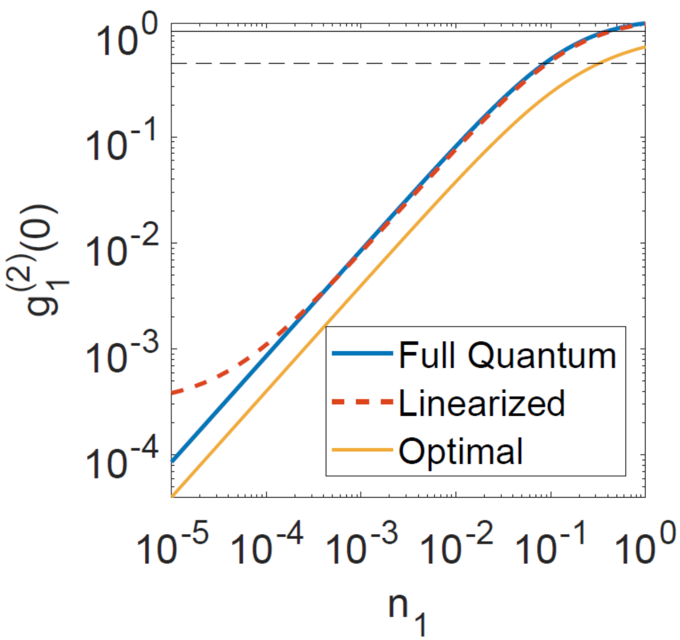


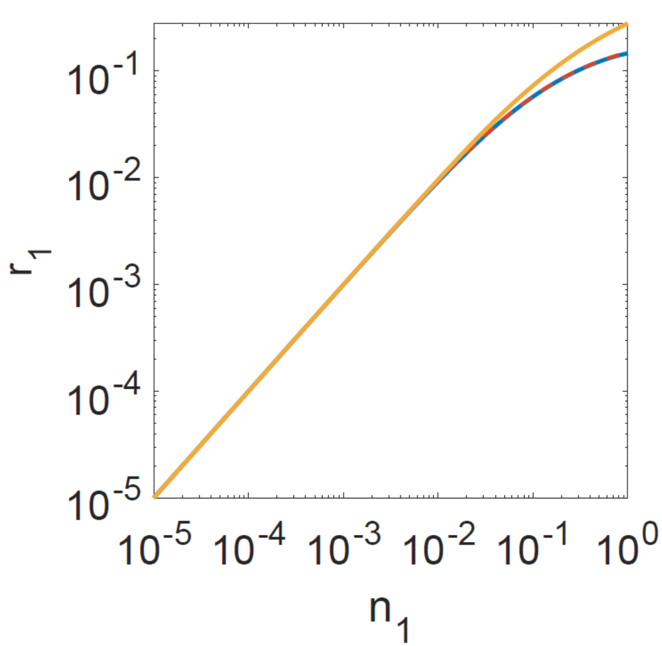
Liew and Savona, *Phys. Rev. Lett.* 104, 183601 (2011)
Bamba, Imamoğlu, Carusotto, and Ciuti, *Phys. Rev. A* 83, 021802(R) (2011)
Flayac and Savona, Phys. Rev. A 88, 033836 (2013)

UPB vs Optimally Squeezed State



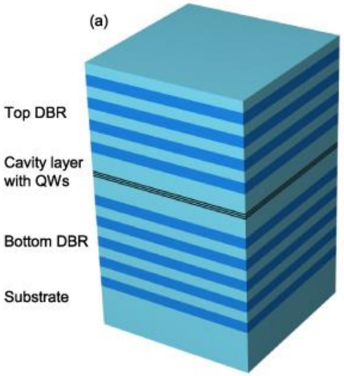
$$\xi_1 = U_1\alpha_1^2 + \frac{J^2}{\Delta^2+\kappa^2-U_2^2\left|\alpha_2\right|^4}U_2\alpha_2^2$$

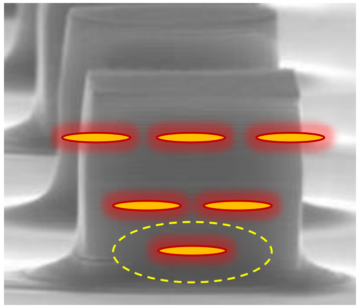




UPB allows reaching the optimal squeezing condition!

The unconventional polariton blockade?

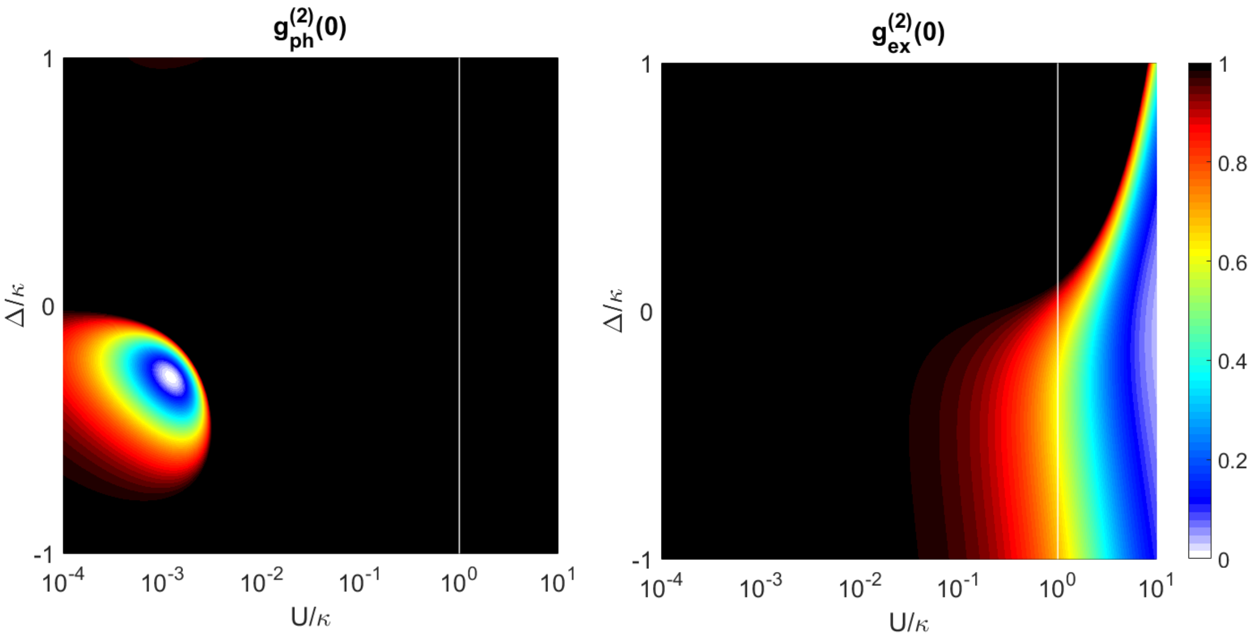




Two coupled oscillators: exciton-photons

$$\hat{H} = \Delta_{ph}\hat{a}^\dagger\hat{a} + \Delta_{ex}\hat{b}^\dagger\hat{b} + U\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b} + J\left(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a}\right) + F\left(\hat{a}^\dagger + \hat{a}\right)$$

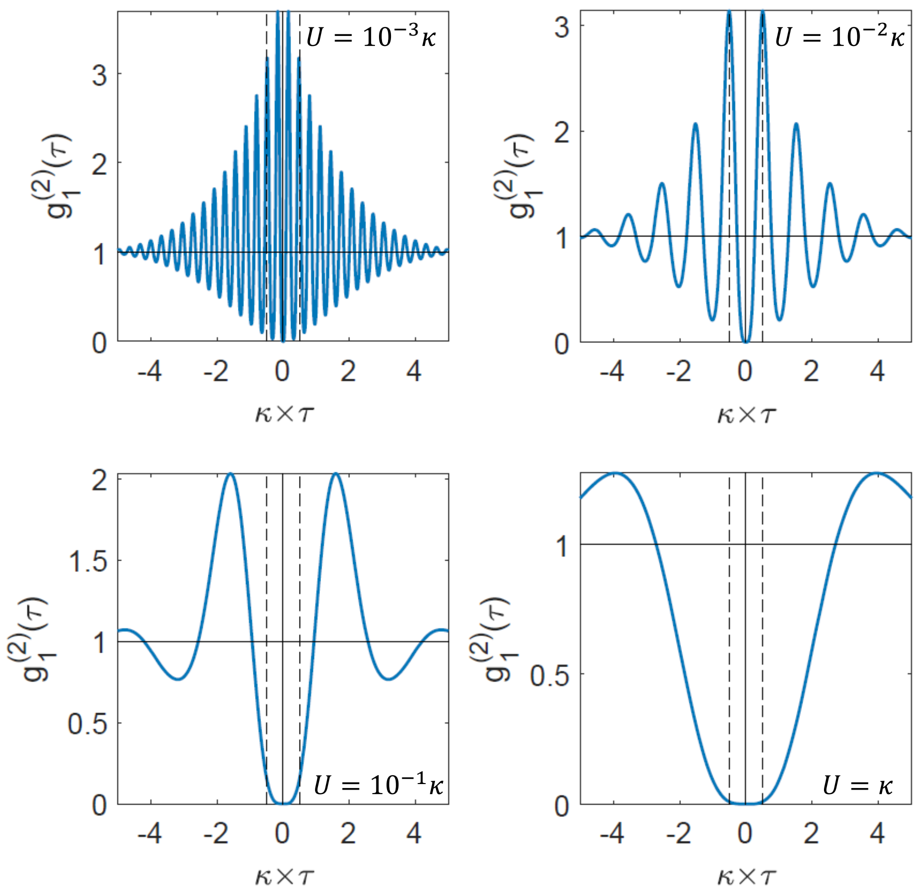
Assume $\begin{cases} \kappa = 0.1 \text{ meV} \\ J = 2 \text{ meV} \end{cases}$ $\begin{cases} \Delta_{ex} = \Delta_{ph} = \Delta_{|\mathbf{opt}} = 0.29\kappa \\ U = U_{|\mathbf{opt}} = 10^{-3}\kappa \end{cases}$

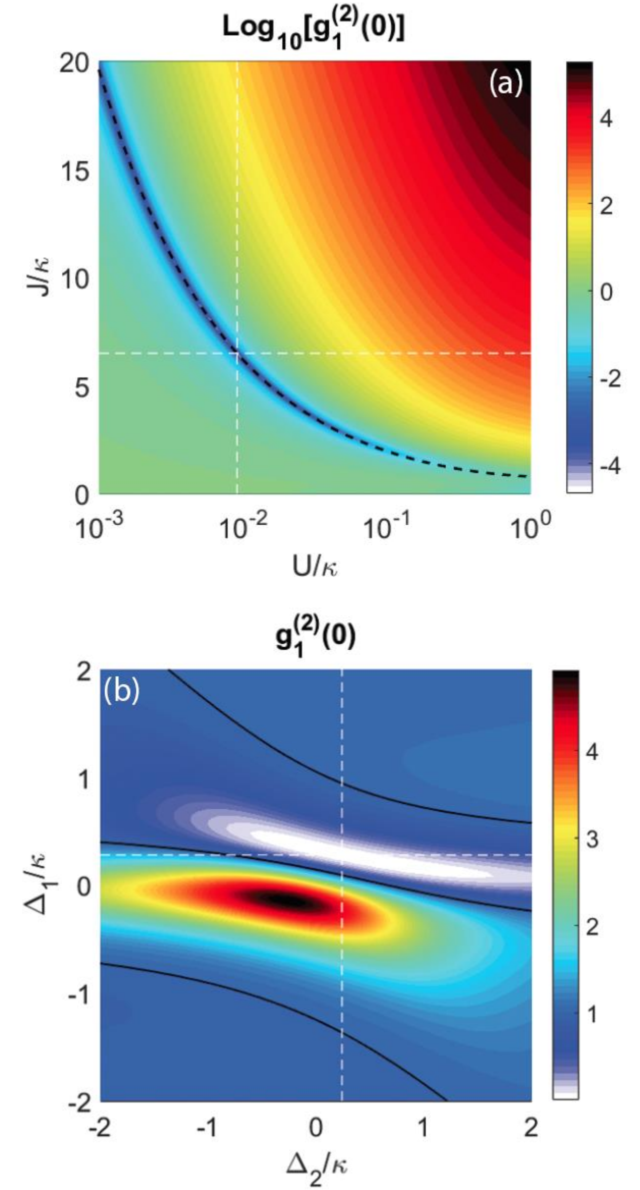


H. Flayac and V. Savona, in preparation (2017).

Measuring the antibunching

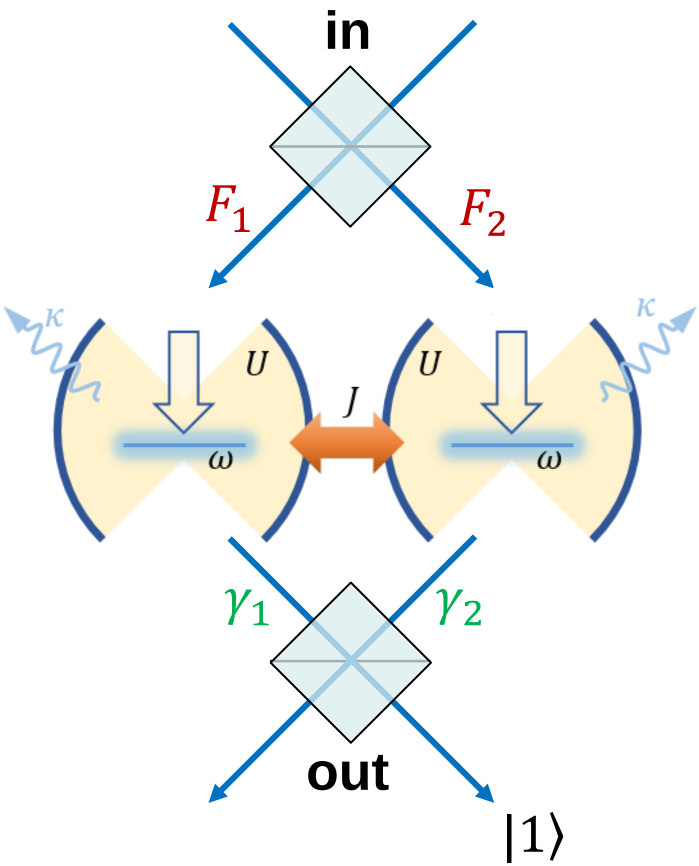
$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(0)\hat{a}^\dagger(\tau)\hat{a}(\tau)\hat{a}(0)\rangle}{\langle \hat{a}^\dagger(0)\hat{a}(0)\rangle^2}$$





Oscillations period: π/J

Input-output tuning



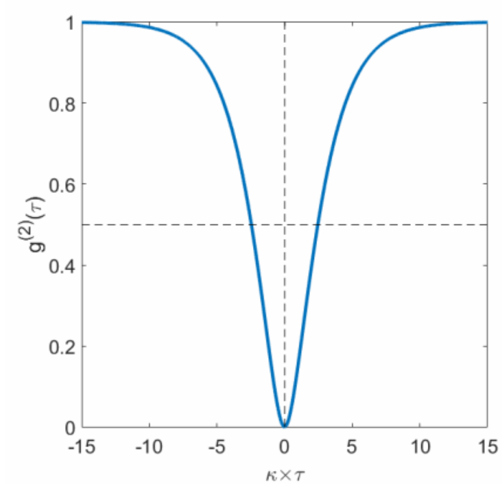
Tune the **input**

$$F_1 = F_2 \frac{2\tilde{\Delta}(\tilde{\Delta}+U)+\sqrt{U[2\tilde{\Delta}^2(U+\tilde{\Delta})-J^2(U+2\tilde{\Delta})]}}{J(2\tilde{\Delta}+U)}$$

or Tune the **output**: allows for $\boldsymbol{J} = \mathbf{0}$

$$\gamma_1 = \gamma_2 \frac{\sqrt{F_1^2F_2^2(2\tilde{\Delta}+U)U} \pm F_1F_2(\tilde{\Delta}+U)}{F_1^2\tilde{\Delta}}$$

To obtain a strong antibunching
for any intrinsic parameters



Unconventional polariton blockade with polarization

Circular polarization basis:

$$\hat{H} = \sum_{j=\pm}\left[\Delta_j \hat{a}_j^\dagger \hat{a}_j + U_1 \hat{a}_j^\dagger \hat{a}_j^\dagger \hat{a}_j \hat{a}_j + P_j \hat{a}_j^\dagger + P_j^* \hat{a}_j\right] + U_2 \hat{a}_+^\dagger \hat{a}_+ \hat{a}_-^\dagger \hat{a}_- + J\left[\hat{a}_+^\dagger \hat{a}_- + \hat{a}_+^\dagger \hat{a}_-\right]$$

$\hat{a}_j = LP$ operators

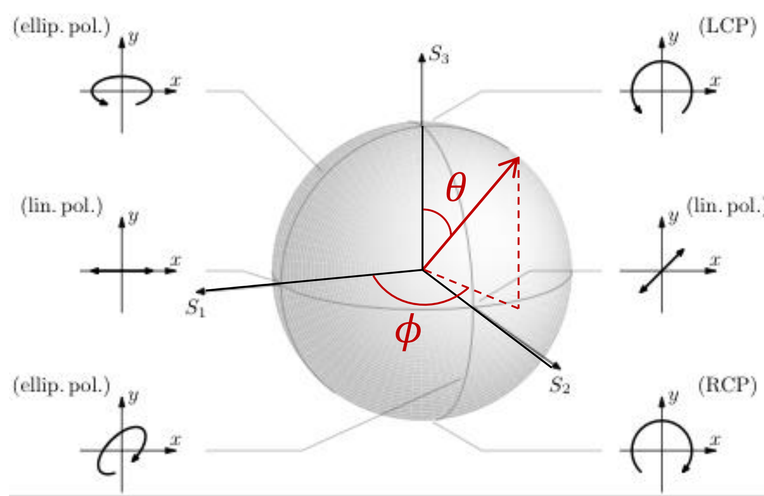
$P =$ Pump amplitude

$$\begin{cases} \Delta_j = \omega_{LP} - \omega_{pump} \\ 2J = \omega_{TE} - \omega_{TM} \end{cases} \quad \begin{cases} U_1 = \text{Same spin interaction} \\ U_2 = \text{Opposite spin interaction} \end{cases}$$

Input Polarization

$$P_+ = P_0 \cos\left(\theta_{in}/2\right)$$
$$P_- = P_0 \sin\left(\theta_{in}/2\right)\exp\left(i\phi_{in}\right)$$

$$\begin{cases} \theta = \text{Circular polarization} \\ \phi = \text{Linear polarization} \end{cases}$$



Bloch sphere

Output polarization

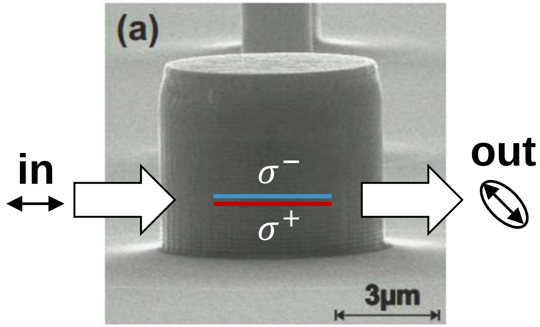
$$\hat{a}_{out} = \underbrace{\cos\left(\theta_{out}/2\right)}_{\gamma_+}\hat{a}_+ + \underbrace{\sin\left(\theta_{out}/2\right)\exp\left(i\phi_{out}\right)}_{\gamma_-}\hat{a}_-$$

Unconventional polariton blockade with polarization

$$P_+ = P_-$$

in

Single Micropillar

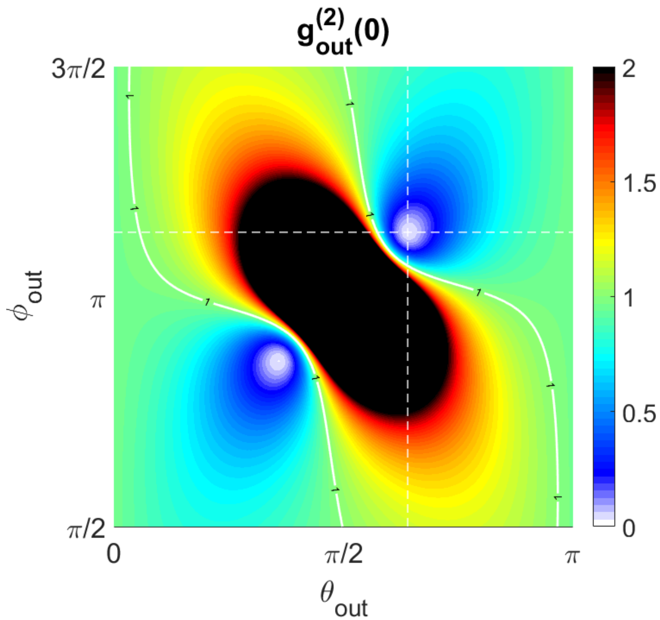


out

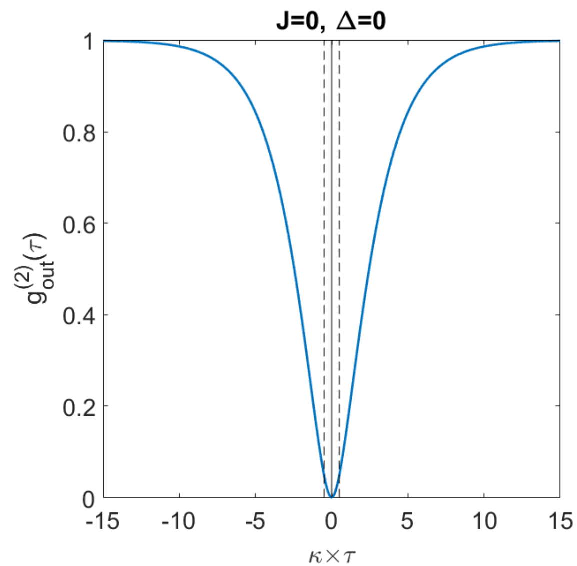
$$\gamma_+ = \gamma_- \frac{\sqrt{(2\tilde{\Delta} + U)U} \pm (\tilde{\Delta} + U)}{\tilde{\Delta}}$$

$$\gamma_+ = \cos(\theta_{out})$$

$$\gamma_- = \sin(\theta_{out}) e^{i\phi_{out}}$$



Vary output polarization

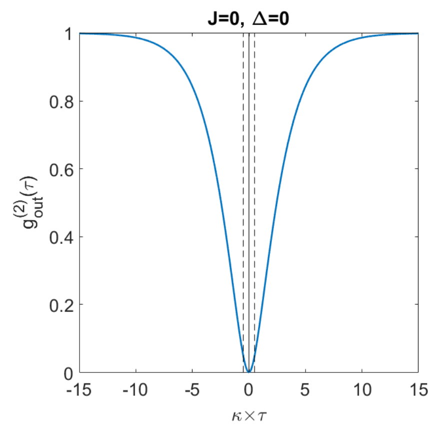


Long correlation time

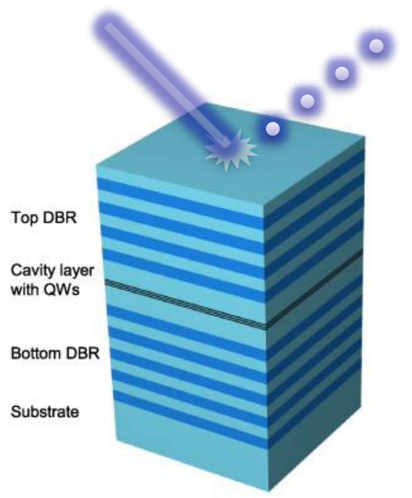
Take to the Lab Message

- **Nonclassical statistics accessible for $U \ll \kappa$**

- **Recipe**
  - 2 nonlinear modes *coupled* or *not*
  - Weak driving $\rightarrow n \lesssim 1$ occupancies
  - Properly mix the input/output fields



- **Recipe with Polaritons**
  - Confined system (pillar, mesa…)
  - CW driving (ideally at $\Delta = 0$)
  - **Linearly polarized** laser
  - Tune the output polarization
  - HBT setup
  - Single photon detector
    - ✓ $T_{res} \lesssim 5\tau_{pol} = 50 - 500$ ps (e.g. superconductor)
    - ✓ **High quantum efficiency** (not a streak camera)



Collaborators