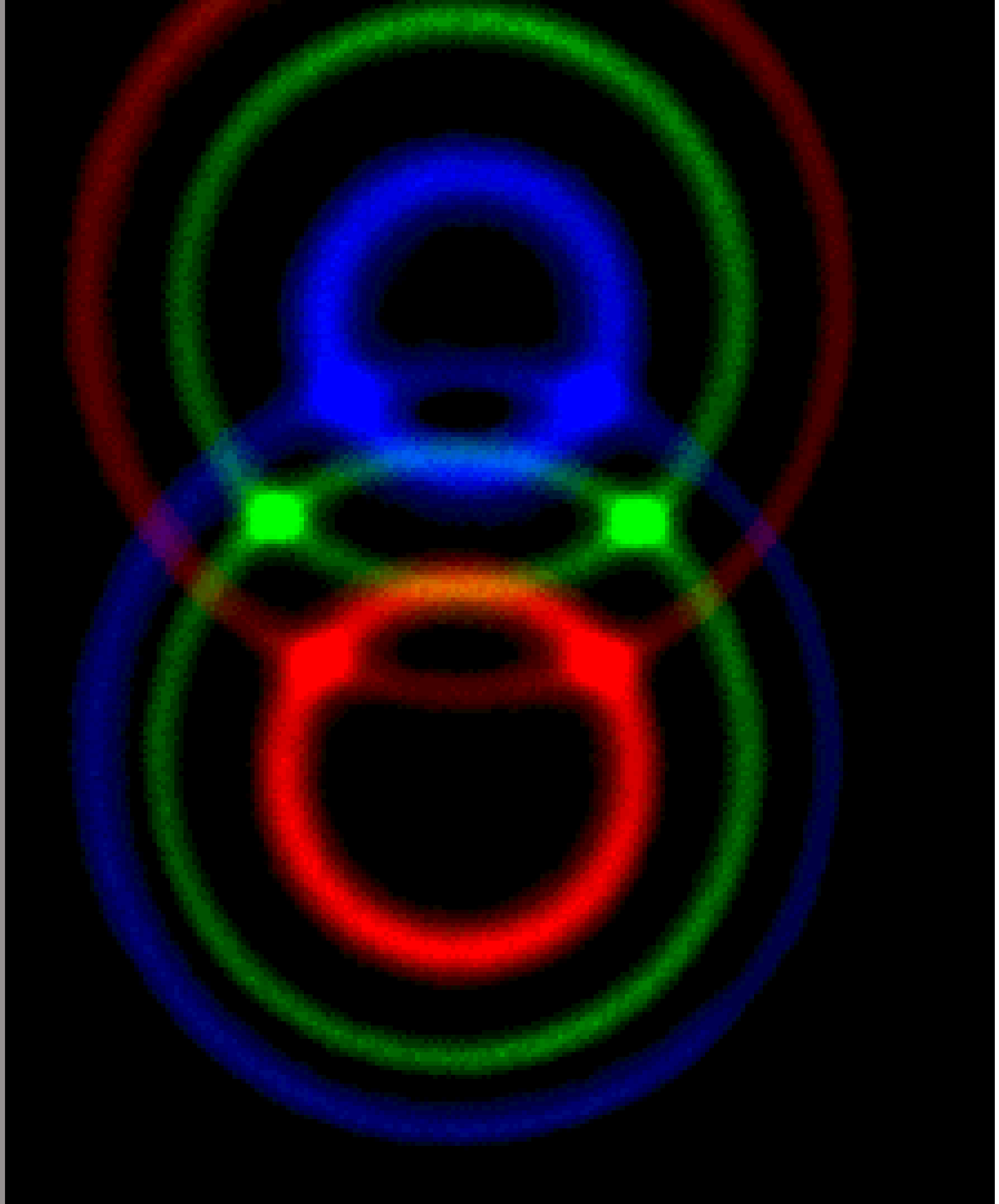
Indistinguishable Single Photons from Coupled Nano-Cavities

Carlos Sevilla, Abhi Saxena, Arka Majumdar (AM Lab)



Outline

- 1. Why we care
- 2. Cavity QED
- 3. Method
- 4. Results
- 5.Experimental Design

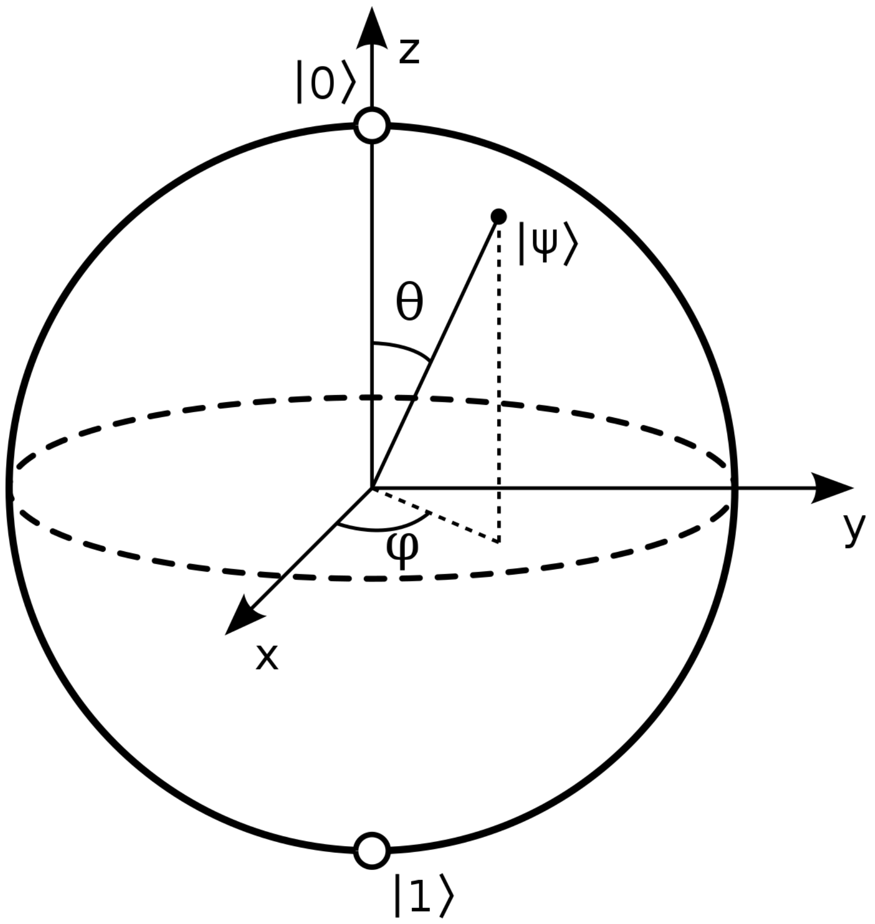
Applications

- Stepping stone towards Quantum technology, specifically Quantum Computing.
- Development of an emitter of indistinguishable Photons
- Photon Entanglement:

$$|00\rangle = |0\rangle \otimes |0\rangle$$

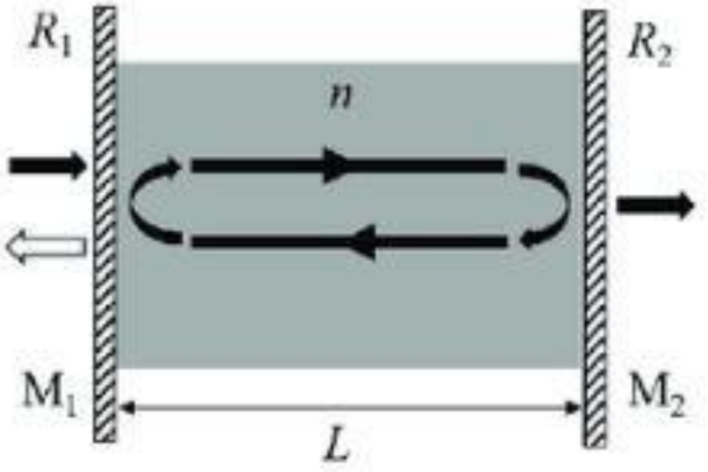
$$|\varphi\rangle_{AB} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

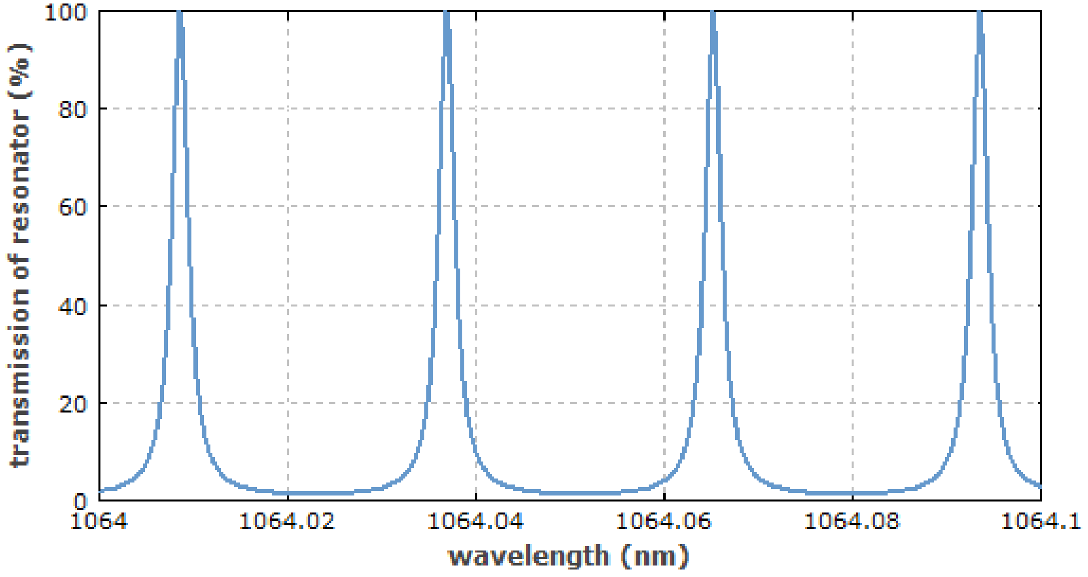
(Schmidt Decomposition)



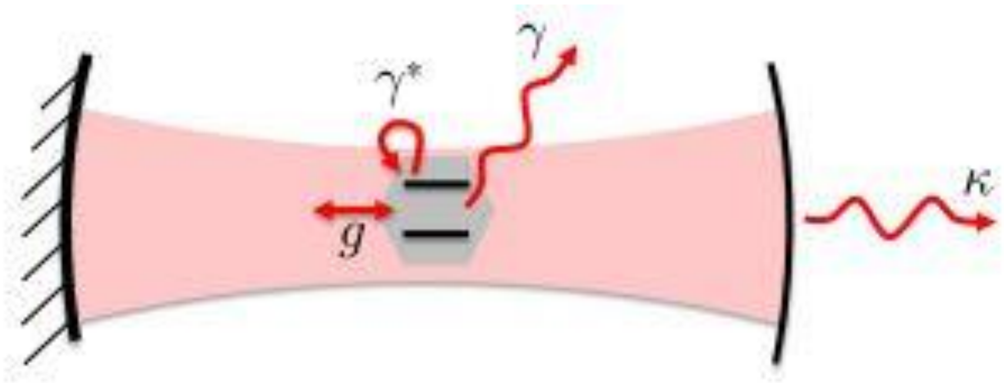
Elements of Cavity-QED

- Fabry-Perot, the simplest model of a cavity
- Intensity peaks at cavity resonance modes





Two-State within a Cavity

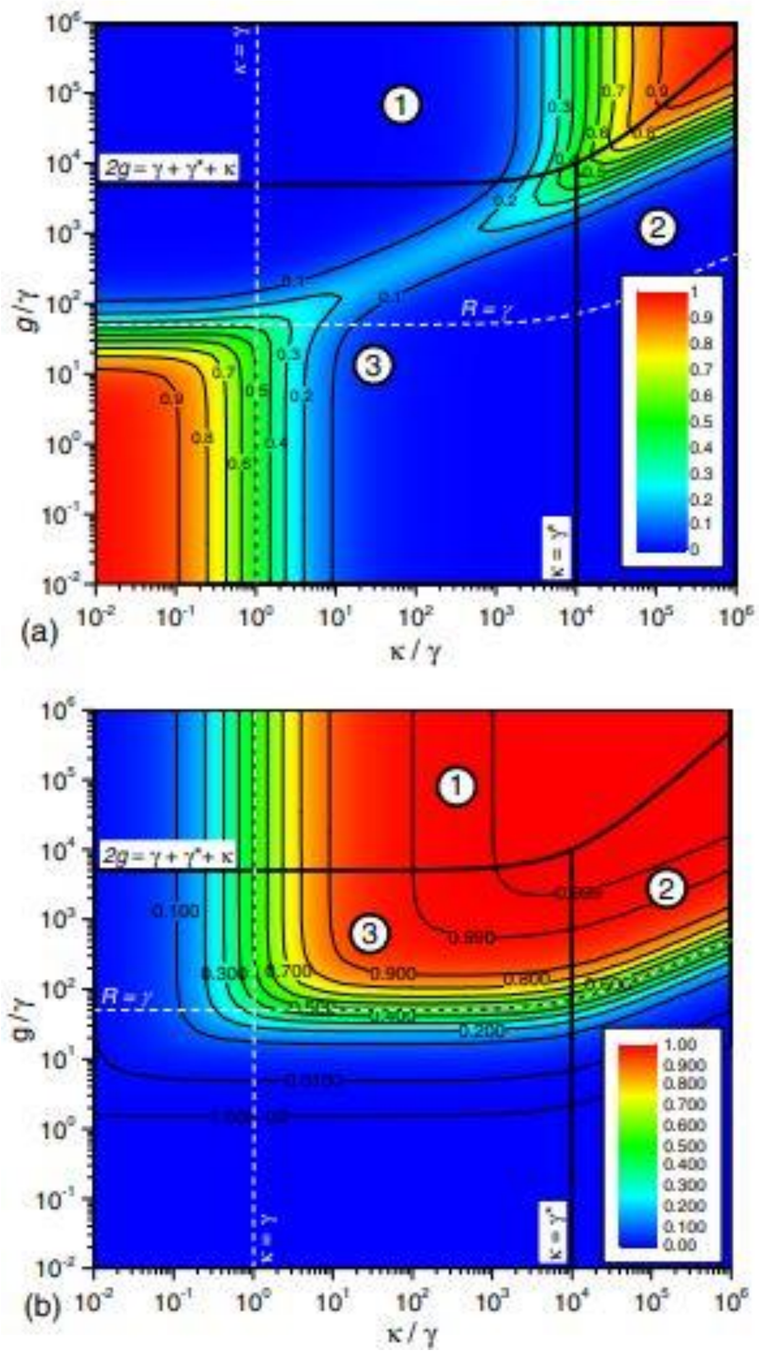


- For a two state system within a cavity our parameters are:

- $\Delta\omega$ ~ Lindewidth (FWHM)
- Q ~ Quality factor $= \frac{\omega}{\Delta\omega}$
- K ~ Photon Decay Rate $= \frac{w}{Q}$
- γ ~ Non-Resonant Decay
- γ^*~ Pure Dephasing
- g ~ Coupling coefficient
- V_{eff}~ Cavity Mode Volume

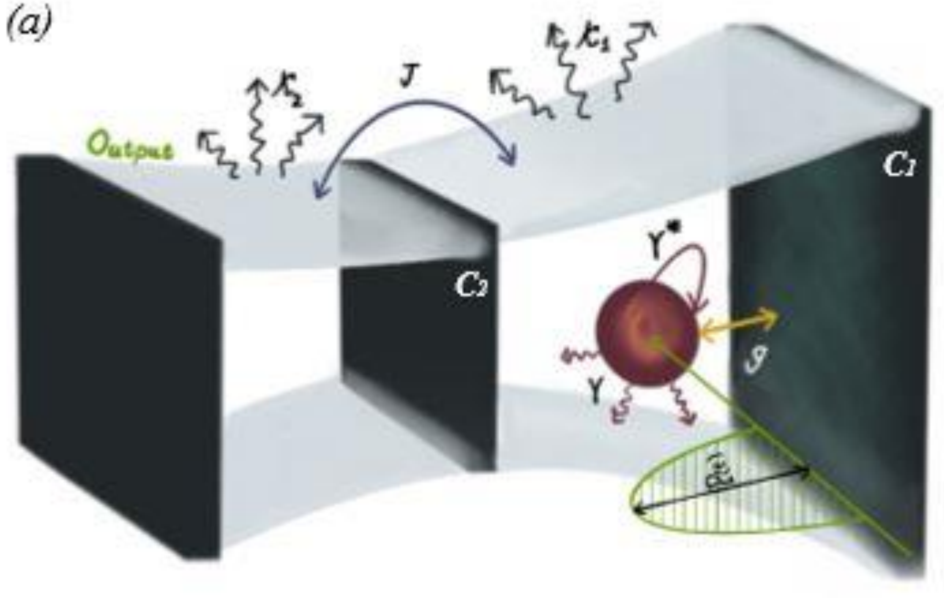
Indistinguishable Particles from Cavities

- Bare Quantum Emitters:
$$I = \frac{\gamma}{\gamma + \gamma^*}$$
- Increased indistinguishability and efficiency as compared to spectral filtering.
- Promising performance at room temperature
- Increased Performance with coupled cavities



Theory of Coupled Cavities

- Two Coupled cavities increase indistinguishability
- Increased degrees of freedom to optimize
- Given e, c_1, c_2 creation and annihilation operators
- g, J , coupling coefficients



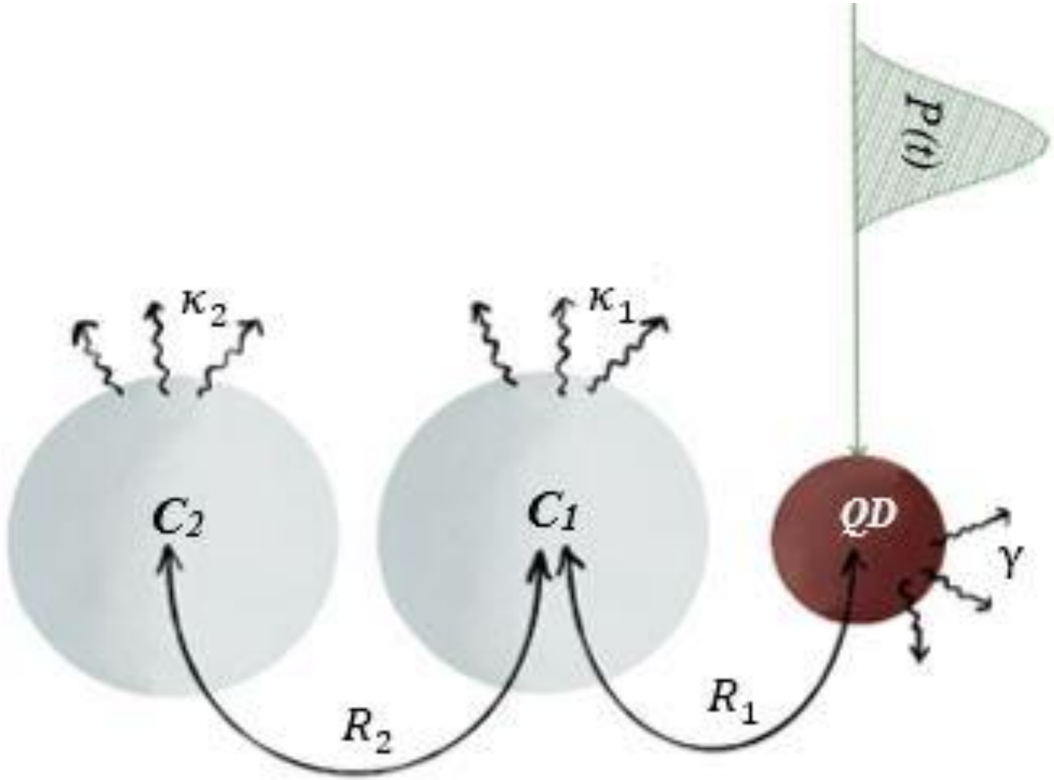
$$H = \omega_e e^\dagger e + \omega_{c_1} c_1^\dagger c_1 + \omega_{c_2} c_2^\dagger c_2 + g\left(e^\dagger c_1 + e c_1^\dagger\right) + J\left(c_1^\dagger c_2 + c_1 c_2^\dagger\right)$$

Degrees of Freedom

- Our cavities are designed with Q(k), and V_{eff}
- need the largest possible coupling since

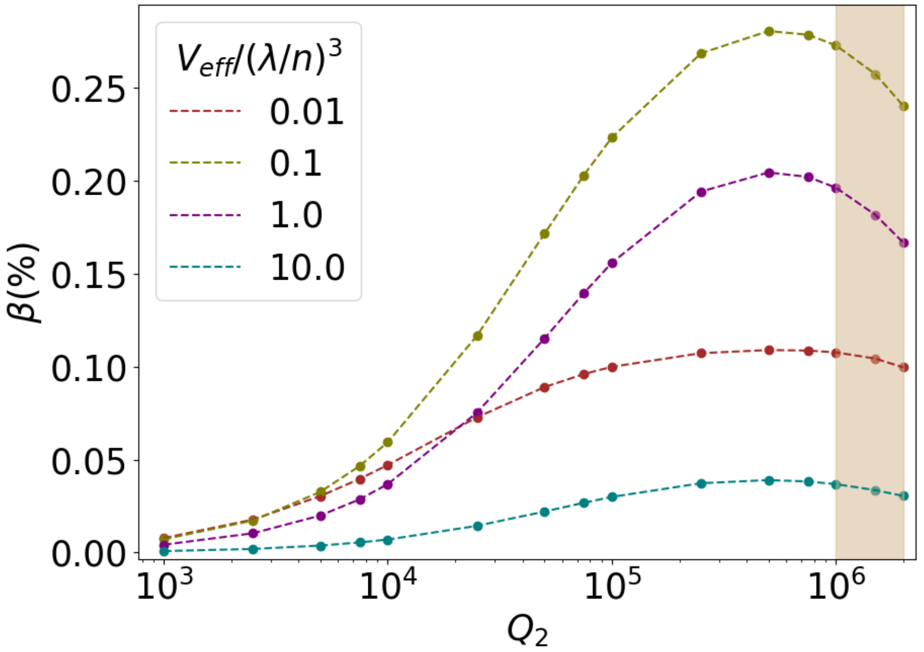
$$g \propto \frac{1}{\sqrt{V_{eff}}}$$

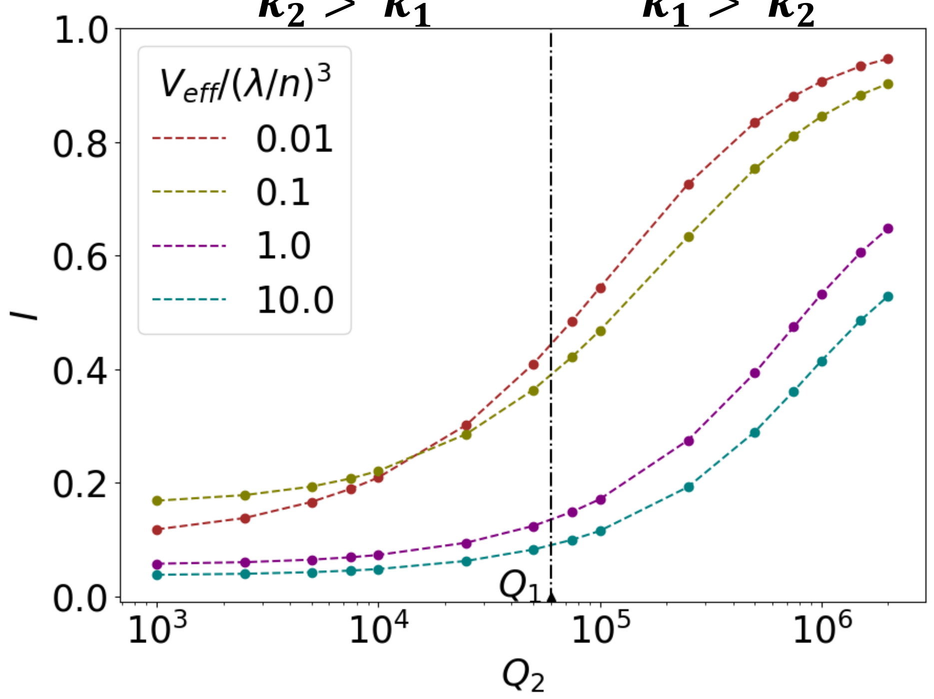
- V_{eff} of our first cavity is designed as small as possible.
- Our only degrees of Freedom are, Q_2 (k_2) and J.
- General improvement of I and B as we increase R_1.



$$R_1 = \frac{4g^2}{\gamma + \gamma^* + \kappa_1}, R_2 = \frac{4J^2}{R_1 + \kappa_1 + \kappa_2}$$

Simulated Results (Q_2)



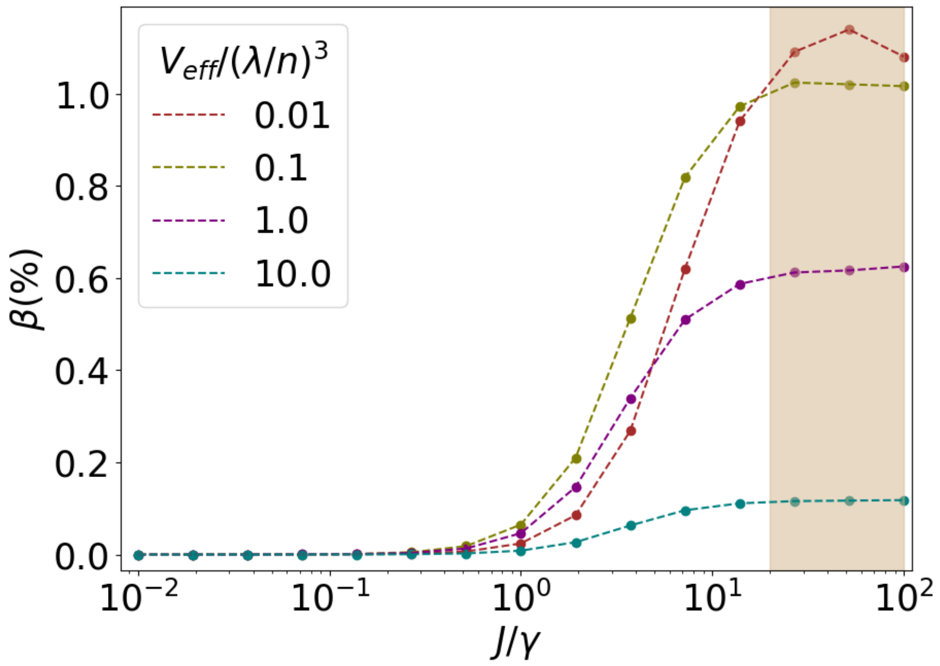


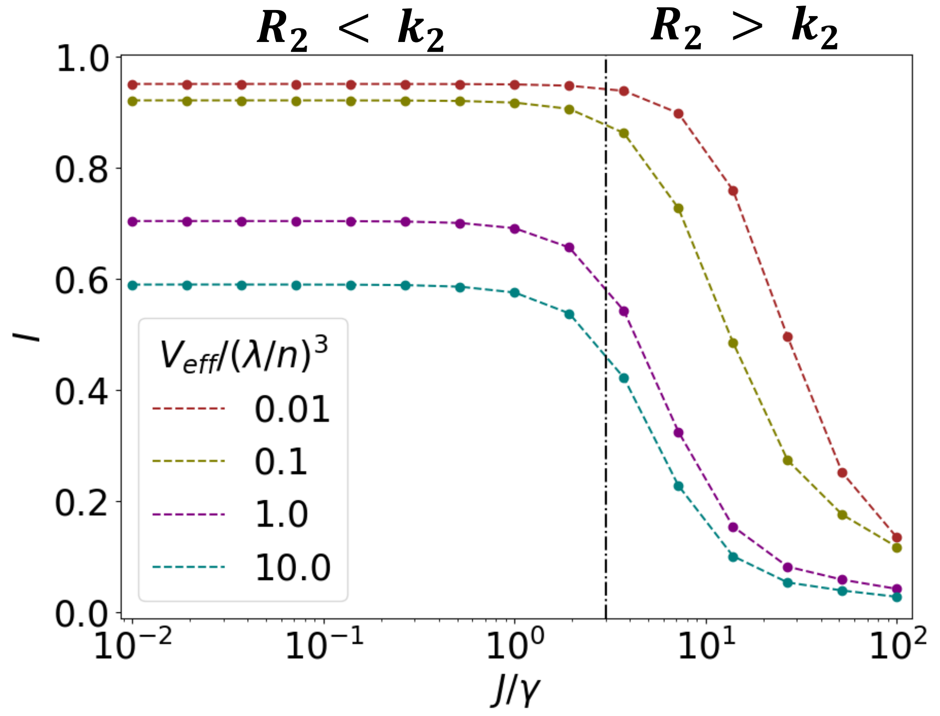
$Q_1 = 6 \, x \, 10^4, J = 2.1\gamma$

$$R_1 = \frac{4g^2}{\gamma + \gamma^* + \kappa_1}, R_2 = \frac{4J^2}{R_1 + \kappa_1 + \kappa_2}$$

- Limit for unidirectional flow as
  $R_2 \leq K_2$, $R_1 \leq k_1 + R_2$
- Because $R_2 \propto \frac{1}{R_1}$, Efficiency depends non-monotomically on V_{eff}, unlike 1 cavity

Simulated Results (J)





$Q_1 = 6 \, x \, 10^4, \; Q_2 = 2 \, x \, 10^6$

$$R_1 = \frac{4g^2}{\gamma + \gamma^* + \kappa_1}, R_2 = \frac{4J^2}{R_1 + \kappa_1 + \kappa_2}$$

- In region 1, $\boldsymbol{R_2 < k_2}$, indistinguishability unaffected by J, acting as Region 1 in previous plot.
- In region 2, **I** drops as photons go back and forth between cavities

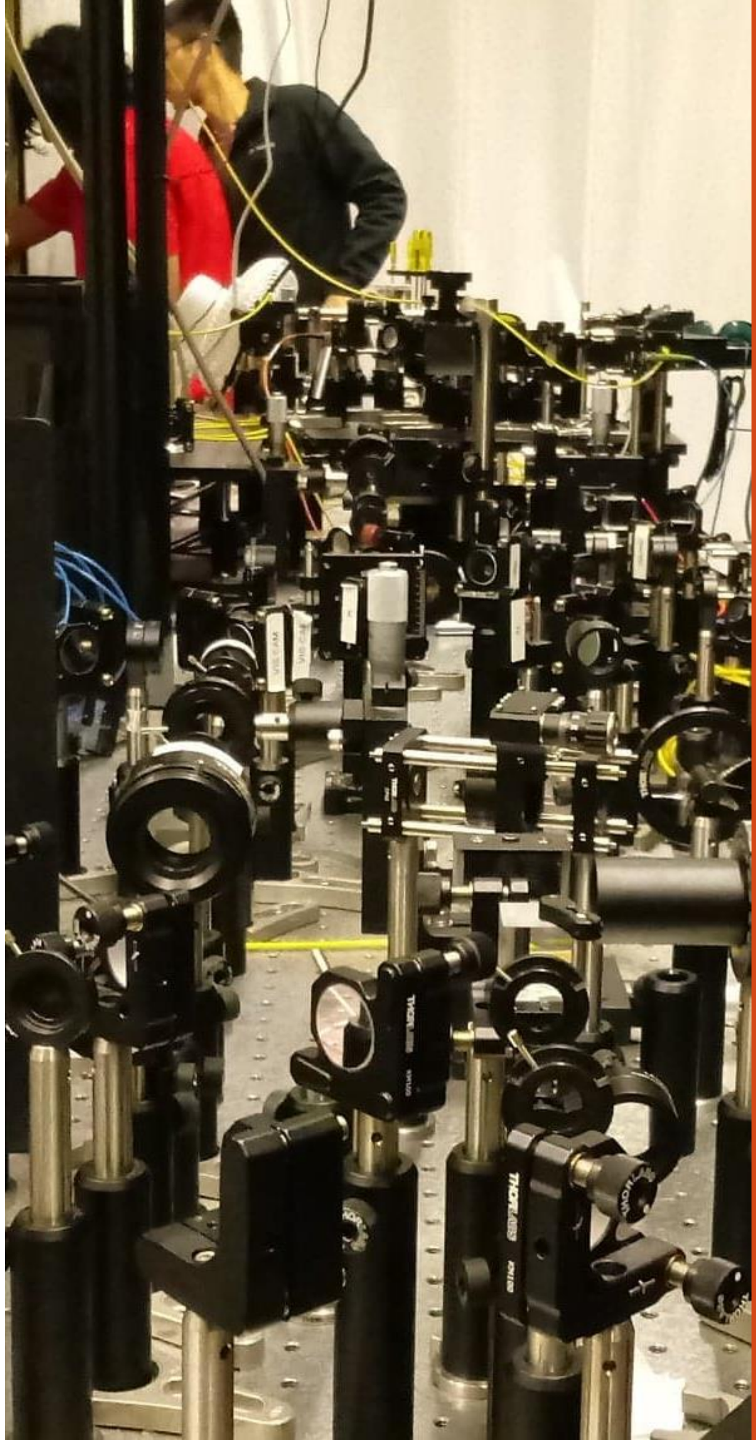
- Efficiency increases with R_2, limited by R_1,
- No longer affected by V_{eff}

Optimization

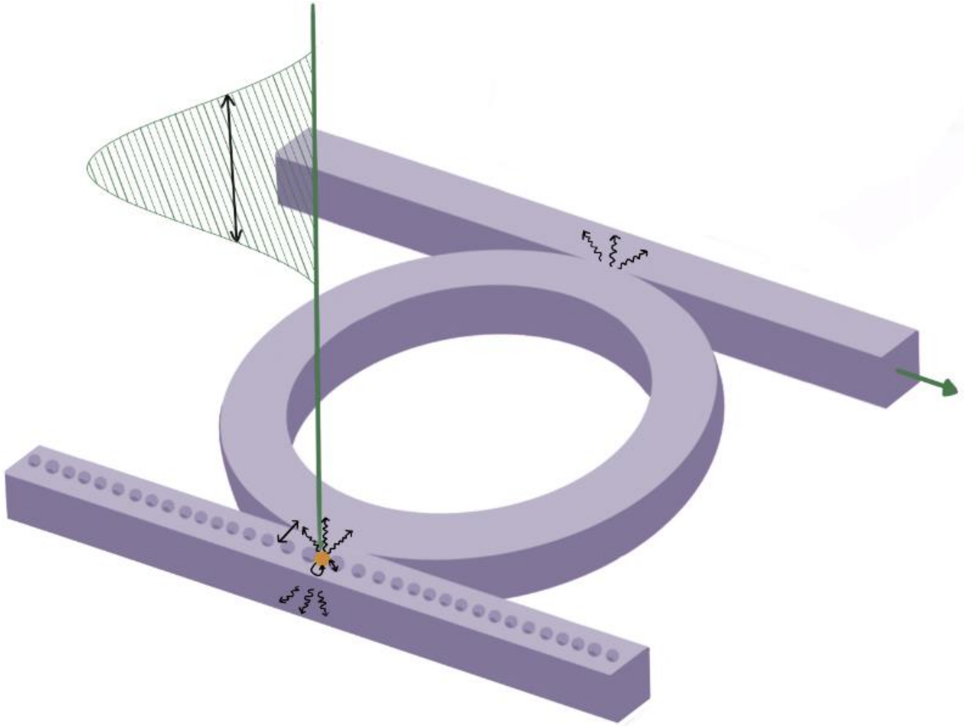
- System optimized for β *and* I with high Q_2,
- moderate J just above γ.

- Additionally optical mode volume:

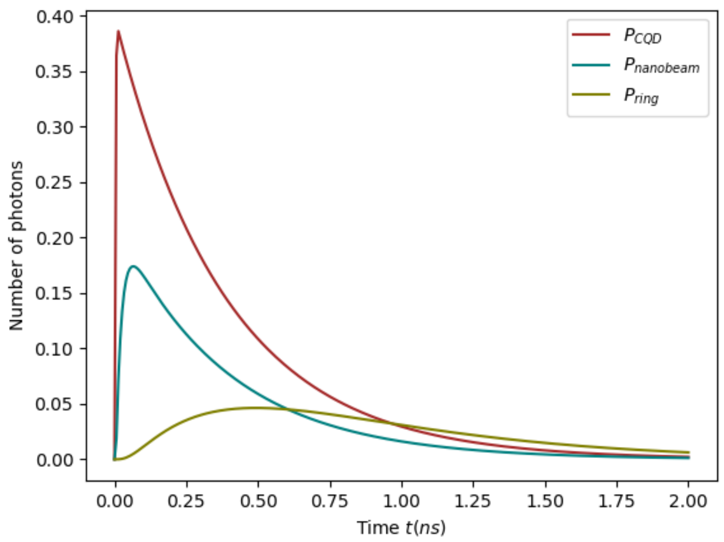
$$0.1\left(\frac{\lambda}{n}\right)^2 \leq V_{eff} \leq 1\left(\frac{\lambda}{n}\right)^2$$

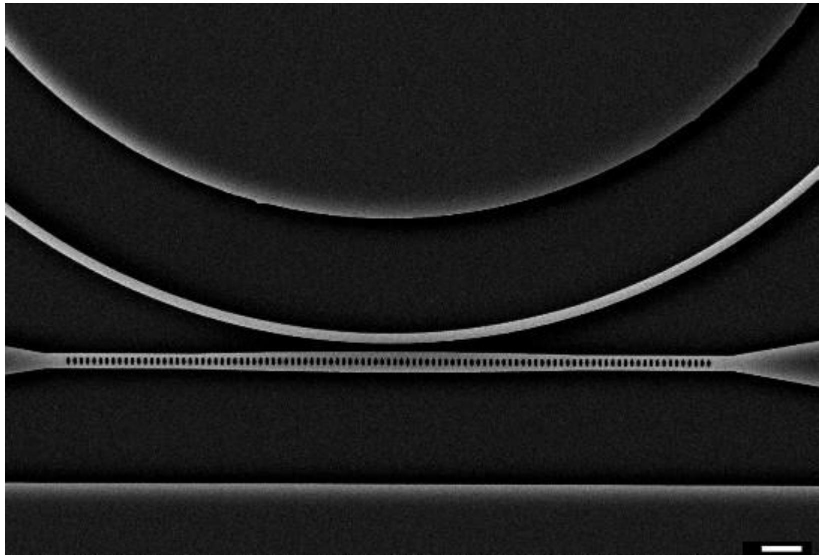


Experimental Design



- Proposal of a feasible experimental design using Colloidal Quantum Dots (CdS).
- We use a SiN nanobeam cavity to achieve a high Q_1 and small enough V_{eff}.
- Our second cavity has no limitations of V_{eff}, so we use a ring resonator
- J controlled by distance between cavities





Parameters

- For our Colloidal QDs our emission are:

$$\lambda = 630nm,$$

- And our SiN nanobeam gives us:

$$Q_1 = 6\,x10^4,\ V_{eff} \sim 1.2\,(\frac{\lambda}{n})^3$$

- And Likewise:

$J = 2.1\gamma$

$Q_2 = 2\,x\,10^6$

Category	Self-assembled QD in a single cavity[13,26]	SiV center in coupled cavities[11]	Colloidal QD in coupled cavities (optimal)	Colloidal QD in coupled cavities (experimental)
γ^*/γ	117	2500	83000	83000
Q_1 & Q_2	~5×10^4	7×10^3 & 5×10^5 / 3.6×10^3 & 5×10^4	6×10^4& 2×10^6	6×10^4& 2×10^6
$V_{effective}$	~$(\lambda/n)^3$	$0.007(\lambda/n)^3$	$0.1(\lambda/n)^3$	$1.2(\lambda/n)^3$
Indistinguishability	~0.6	0.94/0.78	0.9	0.63
Efficiency	12.1%	0.26%/0.99%	0.24%	0.15%

Comparison

References

Bogdanov, S.; Shalaginov, M. Y.; Boltasseva, A.; Shalaev, V. M. Material Platforms for Integrated Quantum Photonics. *Opt. Mater. Express* **2017**, *7* (1), 111. https://doi.org/10.1364/OME.7.000111.

Takeda, S.; Furusawa, A. Toward Large-Scale Fault-Tolerant Universal Photonic Quantum Computing. *APL Photonics* **2019**, *4* (6), 060902. https://doi.org/10.1063/1.5100160.

Gondarenko, A.; Levy, J. S.; Lipson, M. High Confinement Micron-Scale Silicon Nitride High Q Ring Resonator. *Opt. Express* **2009**, *17* (14), 11366. https://doi.org/10.1364/OE.17.011366.

Grange, T.; Hornecker, G.; Hunger, D.; Poizat, J.-P.; Gérard, J.-M.; Senellart, P.; Auffèves, A. Cavity-Funneled Generation of Indistinguishable Single Photons from Strongly Dissipative Quantum Emitters. *Phys. Rev. Lett.* **2015**, *114* (19), 193601. https://doi.org/10.1103/PhysRevLett.114.193601.

Choi, H.; Zhu, D.; Yoon, Y.; Englund, D. Cascaded Cavities Boost the Indistinguishability of Imperfect Quantum Emitters. *Phys. Rev. Lett.* **2019**, *122* (18), 183602. https://doi.org/10.1103/PhysRevLett.122.183602.

Acknowledgments

- Abhi Saxena, Arka Majumdar, James Whitehed, Christtopher Munley, David Rosser
- Subhadeep Gupta, Gray Rybka, Cheryl McDaniel, Linda Vilett
- And a special thanks to other participants in the University of Washington REU program