

Strong Coupling Cavity QED with Nitrogen Vacancy Centers and Silica Microspheres

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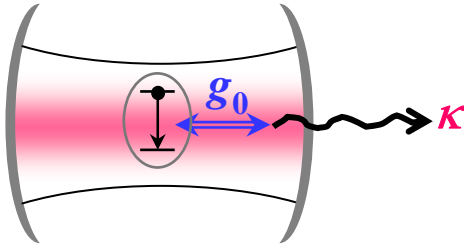
Yumin Shen

Scott Lacey (Franklin and Marshall Univ.)

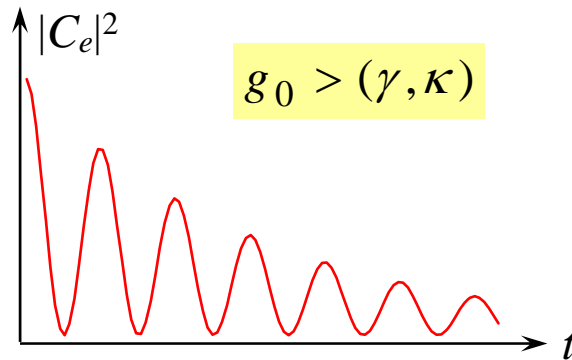


Supported by NSF and ARO

Strong-Coupling Cavity QED



κ : Decay rate of the cavity optical field
 γ : Decoherence rate of the 2-level system
 g_0 : Single photon Rabi frequency



- Reversible energy exchange between the 2-level system and a single photon in the cavity mode.

A single quantum can profoundly affect dynamics of the system.

For reviews, see for example, H.J. Kimble, Phys. Scr. T 76, 127 (1998); J. M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. 73, 565 (2001); H. Mabuchi and A.C. Doherty, Science 298, 1372 (2002).

Cavity QED

- **Model system for manipulating and controlling dynamical processes at the level of single photons:**

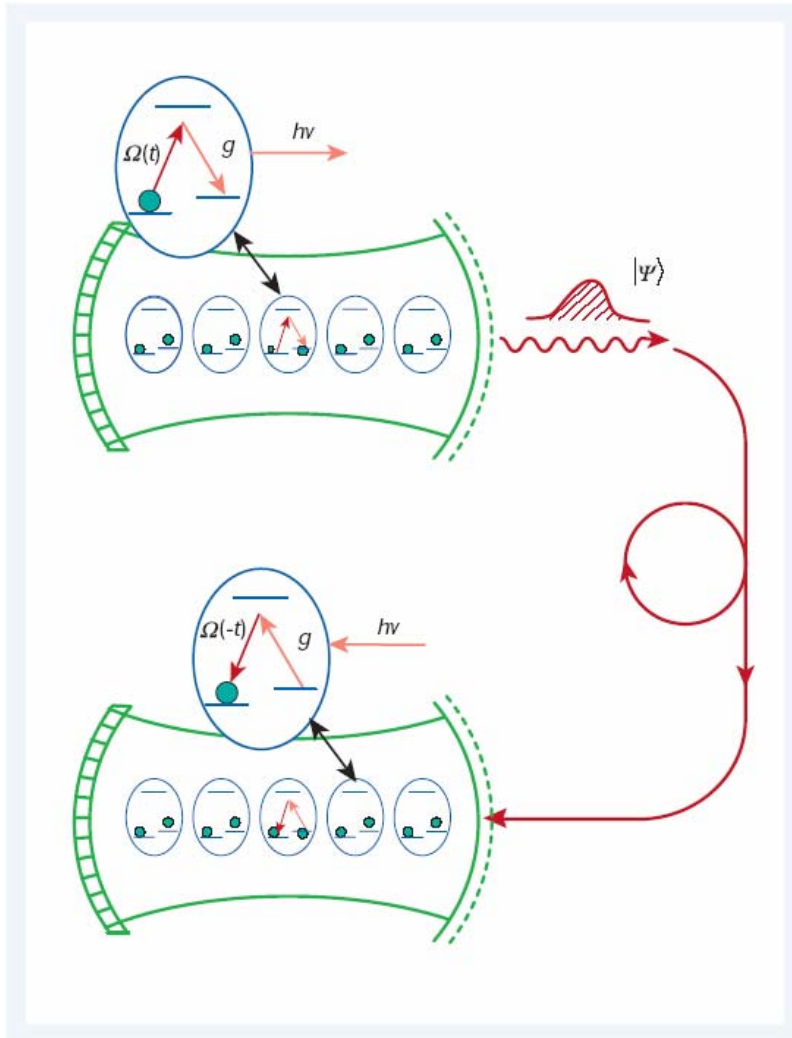
Quantum measurements

Controlled single-photon sources

Entanglement of atoms and/or photons

Distributed quantum network

Distributed Quantum Network



Cirac, Zoller, Kimble, Mabuchi,
Phys. Rev. Lett. 78, 3221 (1997).

Van Enk, Cirac, Zoller, Science 279,
205 (1998).

**Difficult to implement
with traditional atomic
cavity QED systems.**

Cavity QED with Artificial Atoms

- **Circumventing the complexities of trapping single atoms in an optical microresonator.**
- **Possibility of integration and scaling up to a quantum network.**
- **Artificial atoms:**
 - **Quantum dots, defect centers, Cooper pair boxes**

J.P. Reithmaier *et al.*, Nature 432, 197 (2004).

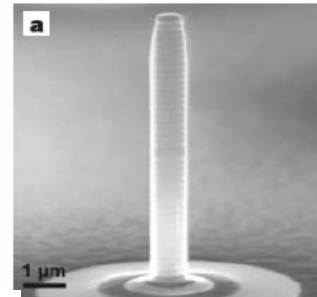
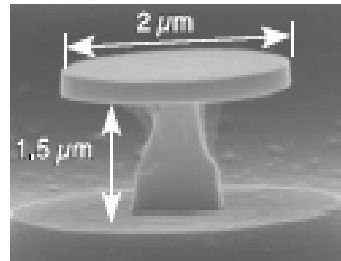
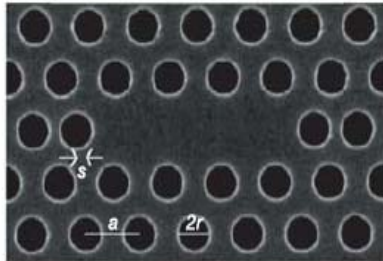
T. Yoshie *et al.*, Nature 432, 200 (2004).

E. Peter *et al.*, Phys. Rev. Lett. 95, 067401 (2005).

A. Wallraff *et al.*, Nature 431, 162 (2004).

Y. Park *et al.*, Nano Lett. 6, 2075 (2006).

Monolithic Semiconductor Microresonators



Geometry:

- Photonic crystals
- Microdisks
- Micro-pillar Fabry-Perot cavities

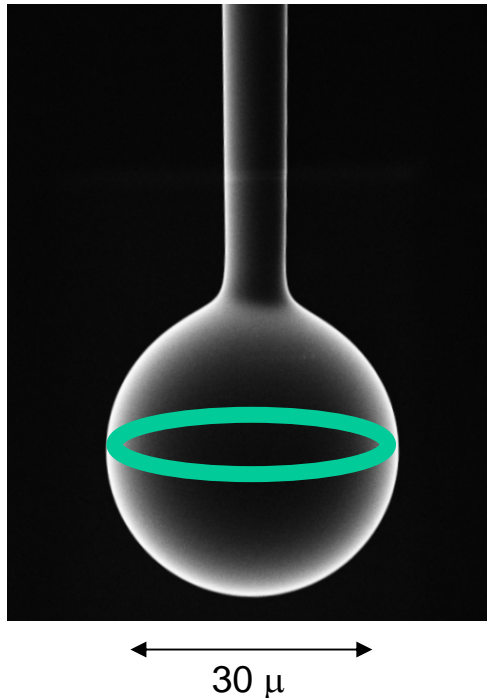
Advantages:

- Extremely small mode volume, leading to large g_0

Disadvantages:

- Relatively small Q-factors (short photon lifetime)

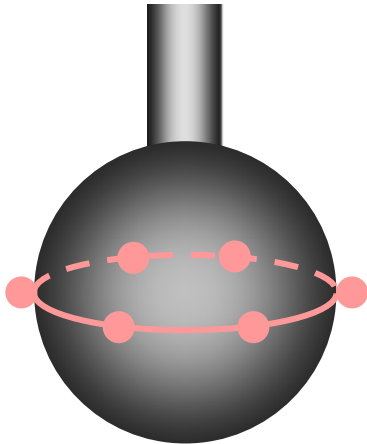
Silica Microsphere



Whispering gallery modes form via total internal reflections along equator.

- **Q-factors as high as 10^{10} can be achieved.**
Extremely small absorption and scattering loss in high purity silica
Nearly atomically smooth silica surface.
Braginsky *et al.*, Phys. Lett. 137, 393 (1989).
- **Best figure of merit for an optical resonator in terms of strong coupling cavity QED.**
Buck and Kimble, Phys. Rev. A 67, 033806 (2003).
Spillane *et al.*, Phys. Rev. A 71, 013817 (2005).

Composite Nanocrystal-Microsphere System



- **Artificial atoms: Nanocrystals**
- **Fabrication and selection of individual electronic and photonic components.**
- **Incorporate practically any type of nanocrystals.**

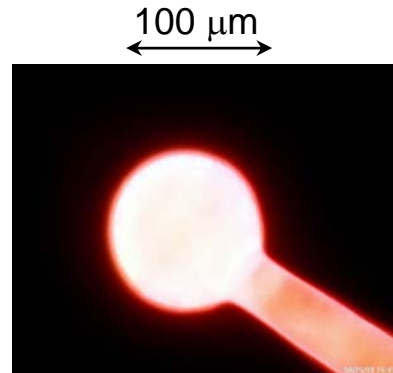
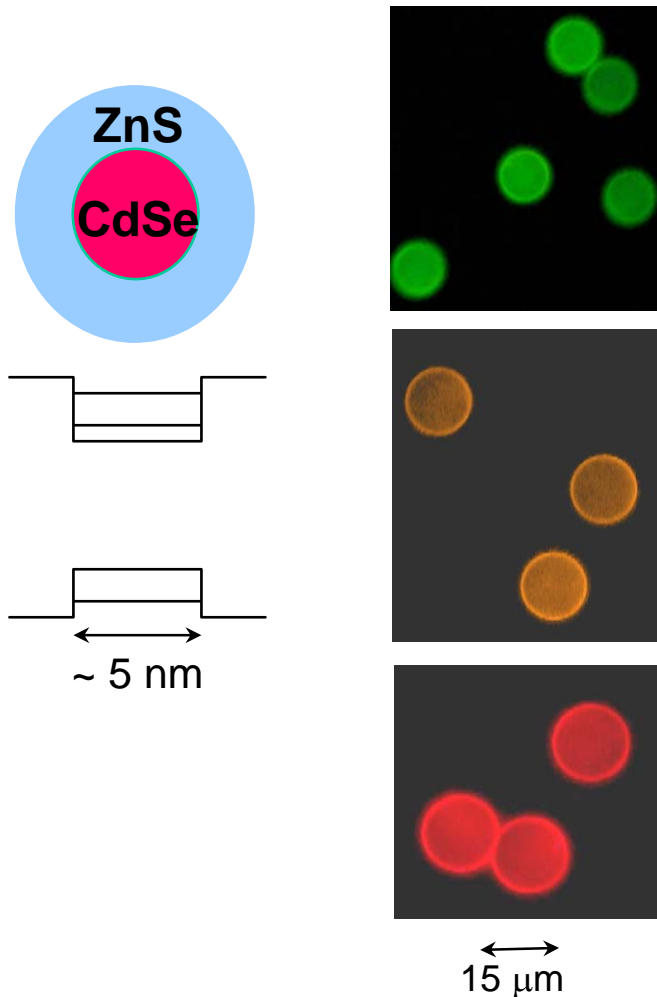
Semiconductor nanocrystals

Diamond nanocrystals

- **Crucial parameter for nanocrystals:**

Decoherence rate or homogeneous linewidth of the optical transition

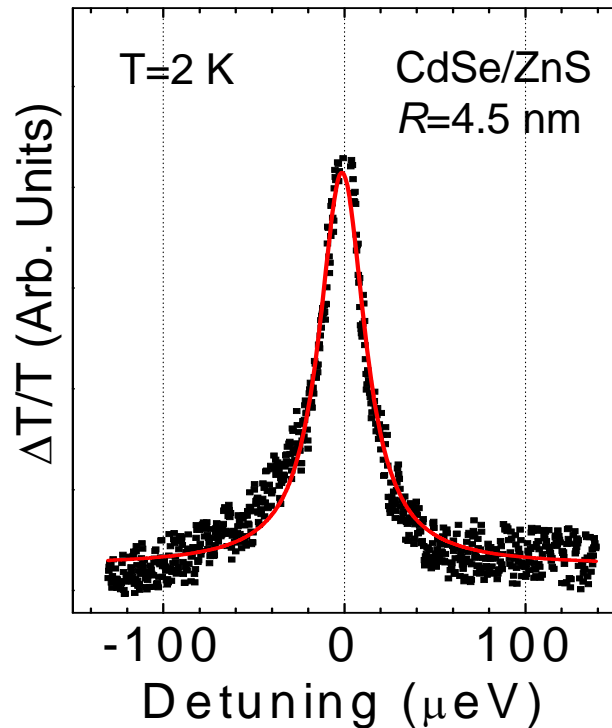
Cavity QED with Semiconductor Nanocrystals



Fan *et al.*, *Opt. Lett.* 25, 1600 (2001).
Fan *et al.*, *Phys. Rev. B* 64, 115310 (2001).
Le Thomas *et al.*, *Nano Lett.* 6, 557 (2006).

Homogeneous Linewidth in CdSe Nanocrystals

$\gamma \sim 3 \mu\text{eV}$ (0.75 GHz)

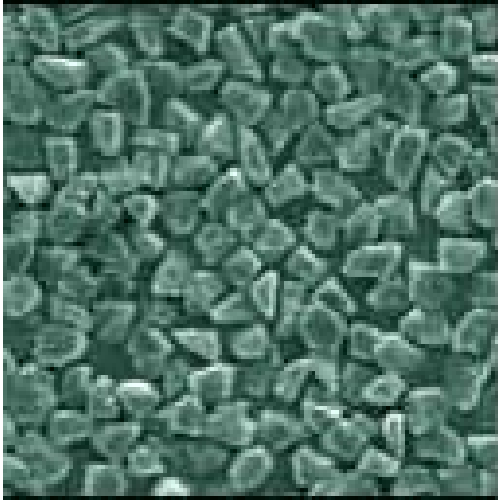


- High resolution spectral hole burning
- More than one order of magnitude smaller than those obtained by single nanocrystal PL measurement.
- The decoherence rate far exceeds the expected radiative decoherence rate (0.1 μeV).

Palinginis *et al*, Phys. Rev. B 67, R201307 (2003); Kruger *et al*, Nano Letters 6, 2154 (2006).

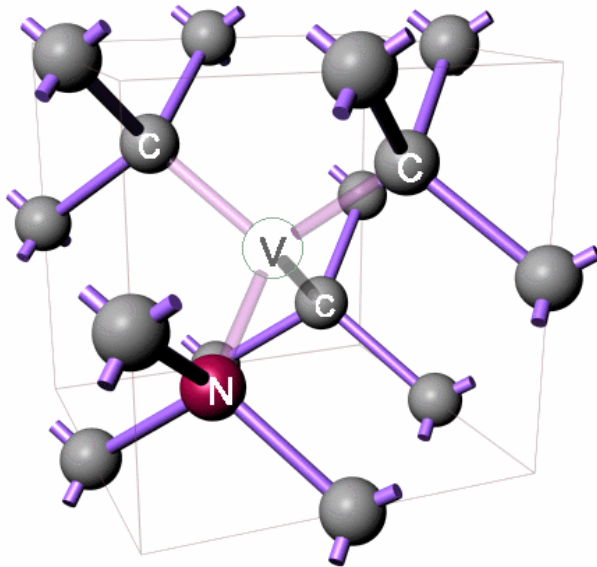
Decoherence is still too fast for strong coupling cavity QED.

Diamond Nanocrystals



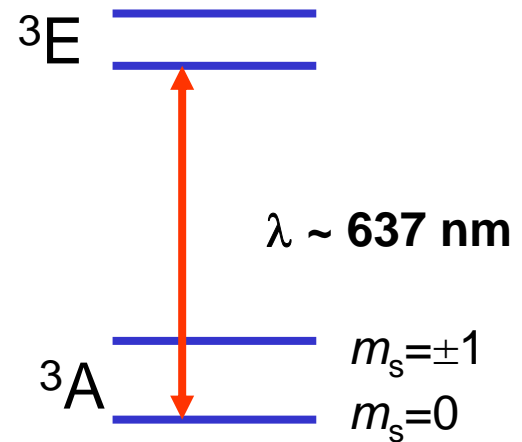
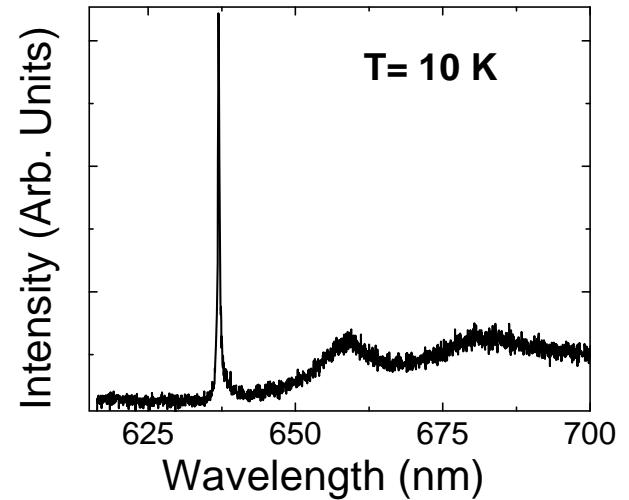
- Both synthetic and natural diamond nanocrystals are available.
- Size as small as 10 nm.
- Widely used in the semiconductor industry for applications such as polishing.
- **Optical transitions: Defect centers**

Nitrogen Vacancy Centers in Diamond

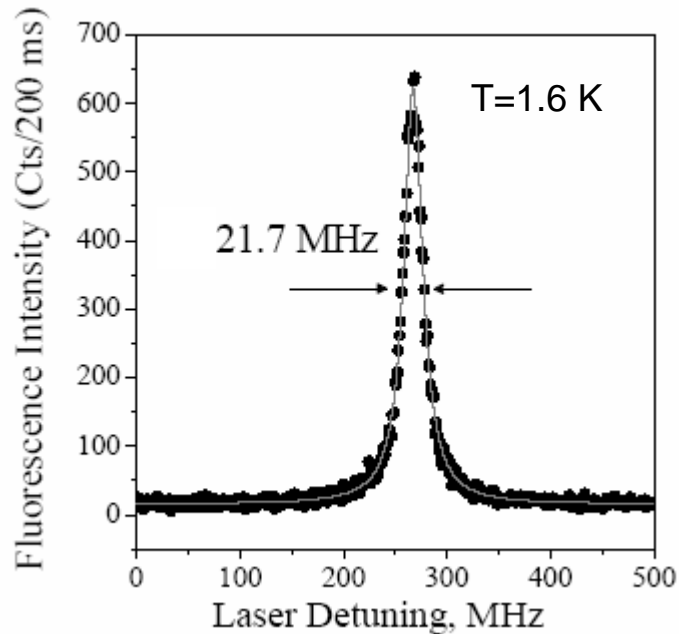


Generation of NV centers:

Electron irradiation creates vacancies.
Annealing at 900 K leads to migration of
vacancy to nitrogen, creating NV centers.



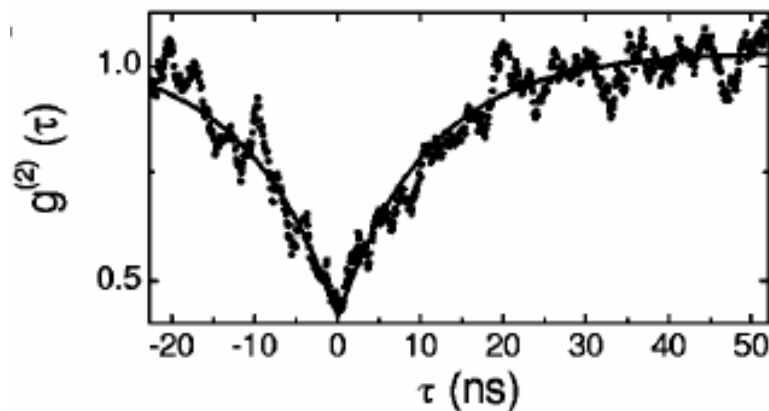
Optical Properties of Single NV Centers



Nearly radiative lifetime limited homogeneous linewidth.

Radiative lifetime: 12 ns

Tamarat *et al.*, Phys. Rev. Lett. 97, 093002 (2006); D. Redman *et al.*, J. Opt. Soc. Am. B 9, No. 5, (1992).



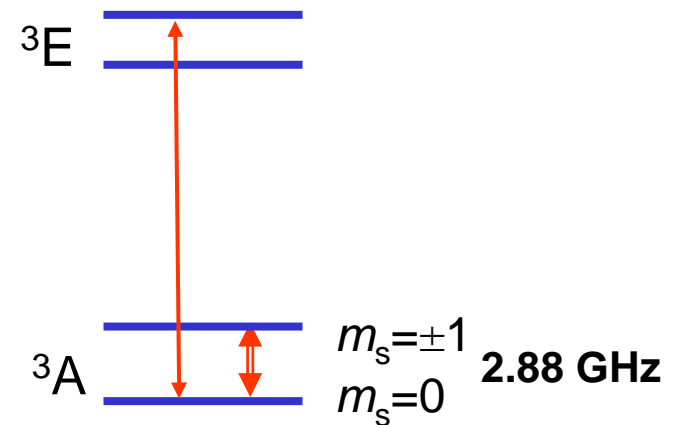
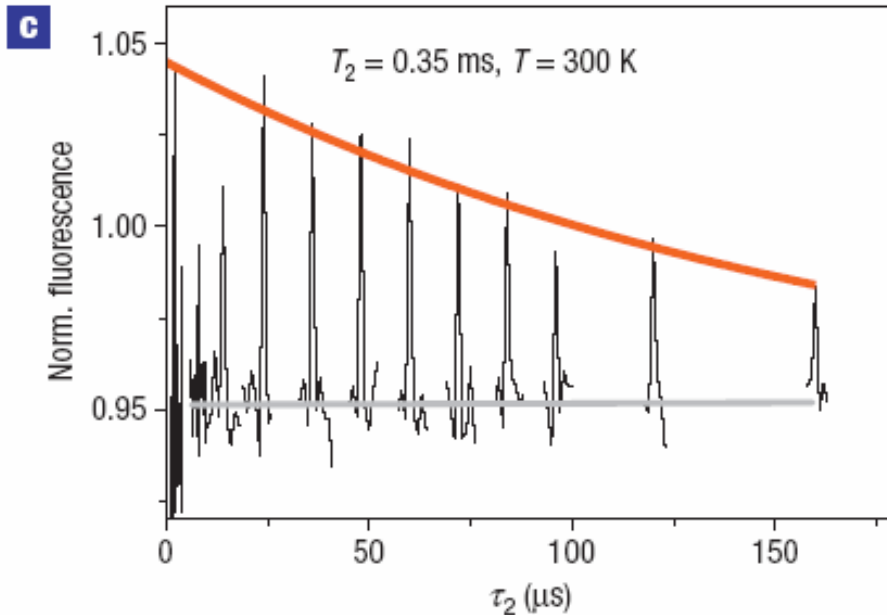
Photon correlation demonstrates single photon emission.

Beveratos *et al.*, Phys. Rev. A 64, 061802 (2001); Jelezko *et al.*, Phys. Rev. A **67**, 041802 (2003).

Robust Spin Coherence in NV Centers

T.A. Kennedy *et al.*, Appl. Phys. Lett. 83, 4190 (2003); Gaebel *et al.*, Nature Physics 2, 409 (2006).

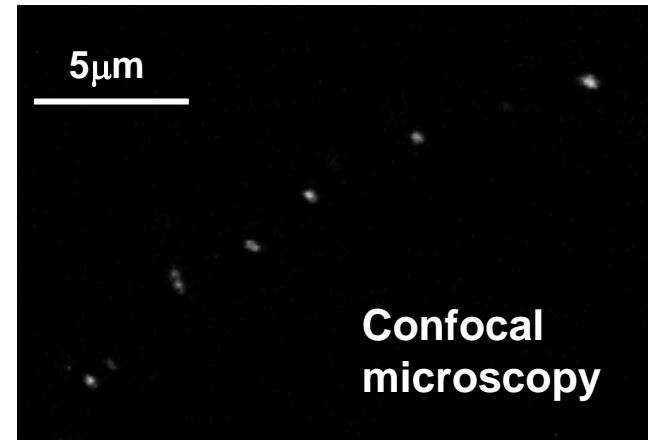
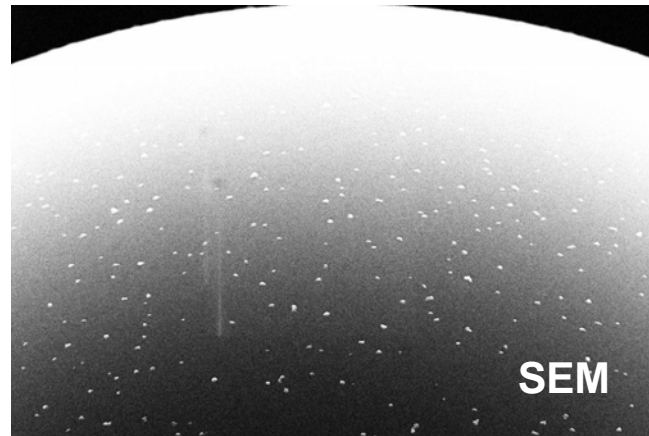
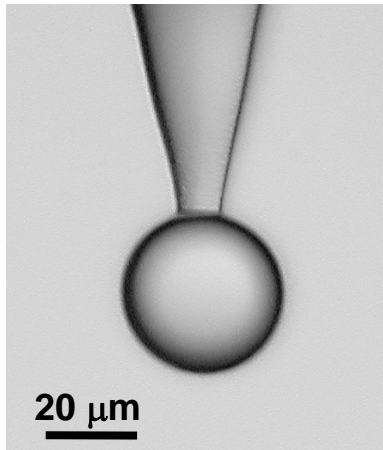
$T_2 \sim 0.35$ ms, $T=300$ K



NV centers feature robust triplet spin states as the ground states, which is ideal for using the spin as a qubit.

Composite Nanocrystal-Microsphere System

Diamond nanocrystals are dispersed on the surface of a silica microsphere through solution deposition.



Strong-coupling regime: $g_0 > (\kappa, \gamma)$

Decoherence rate:

$$\gamma/2\pi \sim 10 \text{ MHz}$$

Cavity decay rate:

$$\kappa/2\pi \sim 10 \text{ MHz}$$

Dipole coupling rate:

$$g_0/2\pi \sim 50 \text{ MHz}$$

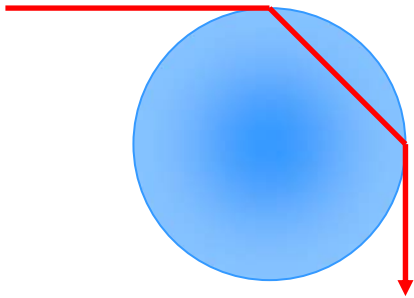
Experimental Obstacles

- **Launching WGMs in a microresonator.**
 - Experiments need to be carried out at low temperature.

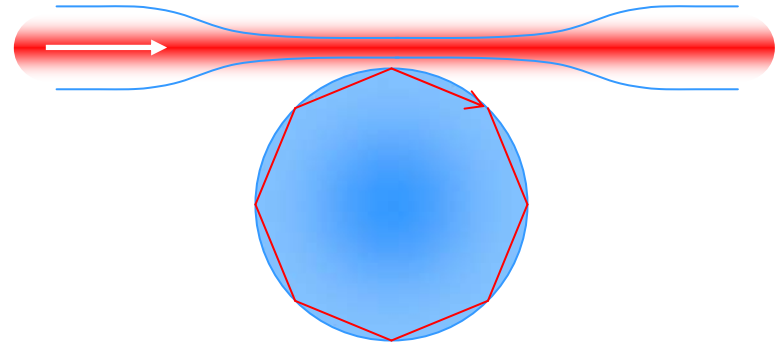
- **Matching the resonance of a WGM with the transition frequency of a NV center.**
 - Every artificial atom or NV center is different.
 - Very few NV centers are stable.

Launching WGMs via Evanescent Waves

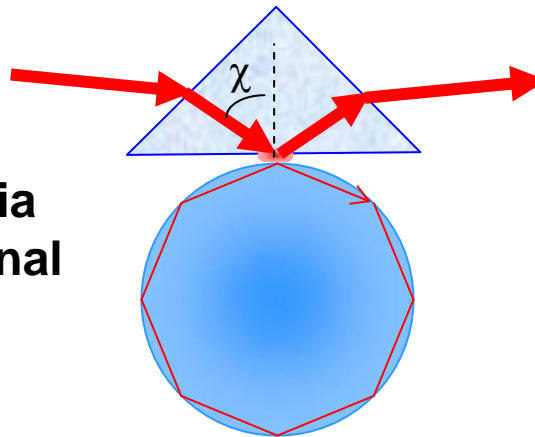
- Free space launching of WGMs is not effective.



- Excite WGMs with evanescent waves via a tapered fiber



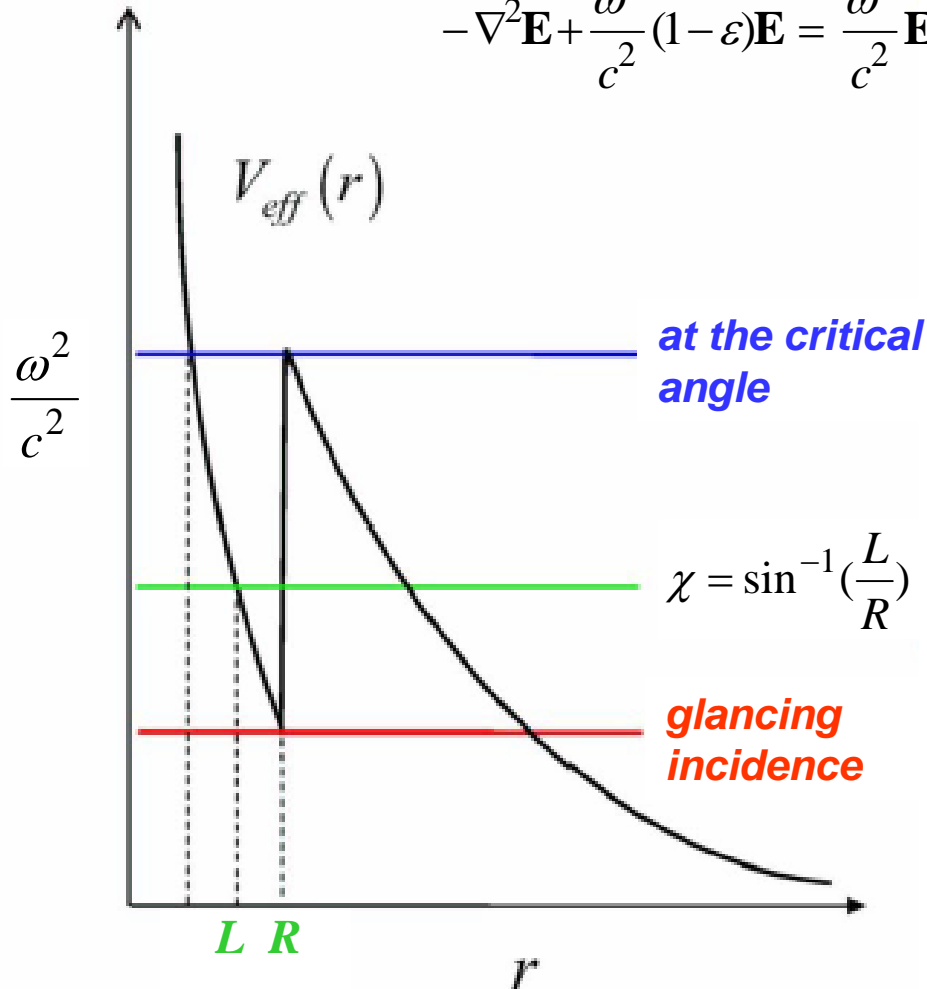
- Excite WGMs with evanescent waves via frustrated total internal reflection



Difficult to implement at cryogenic temperature

Evanescent Escape (Tunneling)

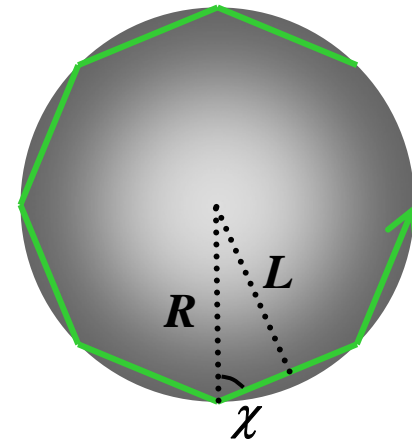
$$-\nabla^2 \mathbf{E} + \frac{\omega^2}{c^2} (1 - \varepsilon) \mathbf{E} = \frac{\omega^2}{c^2} \mathbf{E}$$



Classical turning points:

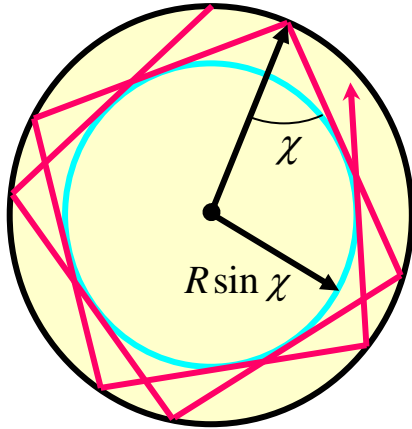
$$r = R$$

$$r = L = R \sin(\chi)$$



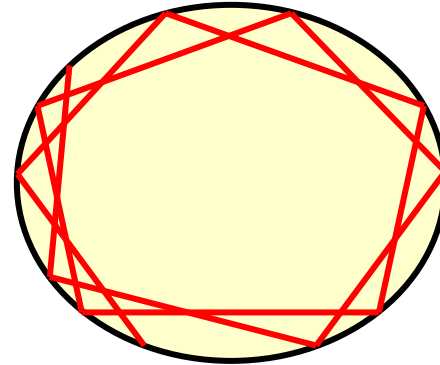
The tunneling rate increases exponentially as χ approaches the critical angle.

Effects of Deformation



The angle of incidence is conserved.

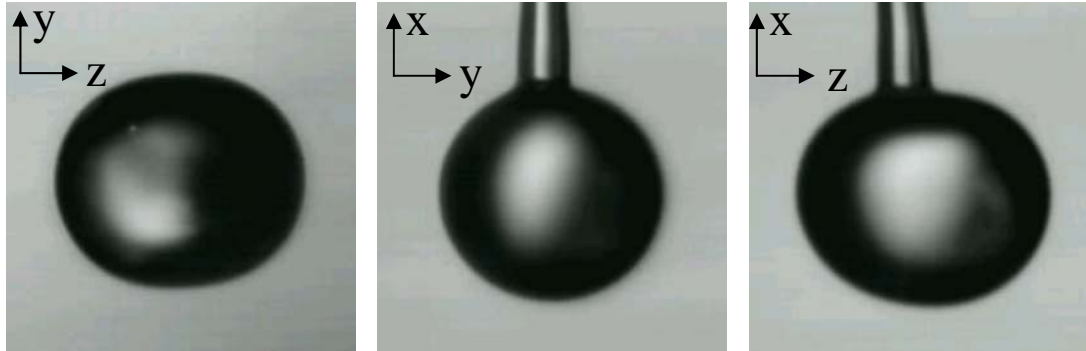
The orbit is periodic or quasi-periodic and fills an annulus between $R \sin \chi$ and R .



The angle of incidence is no longer conserved.

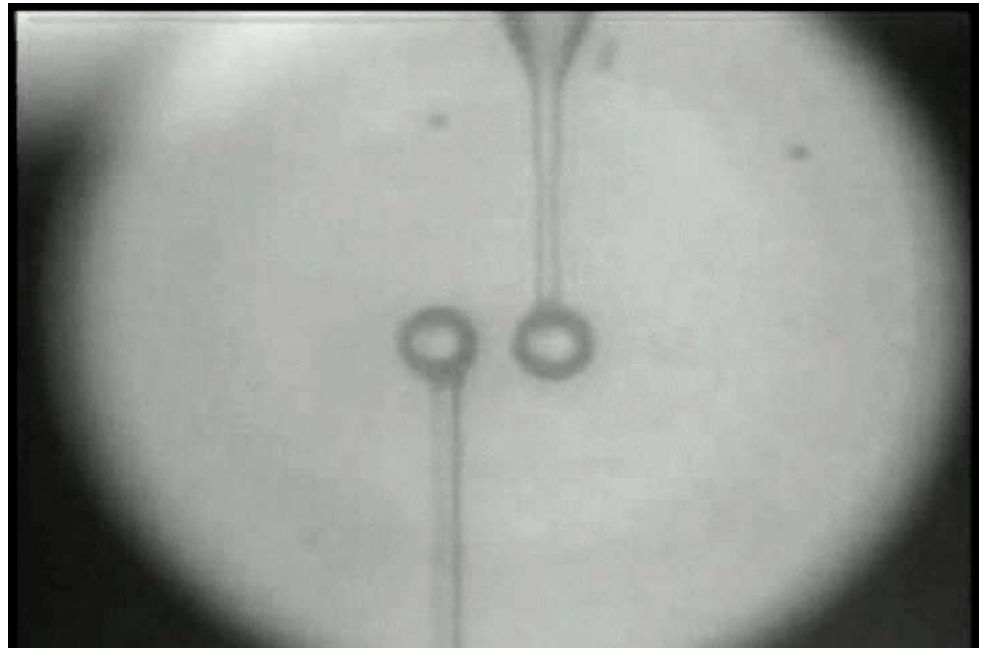
The tunneling rate varies as the light ray travels around the curved boundary, which can be exploited for the excitation of WGMs.

Deformed Silica Microsphere

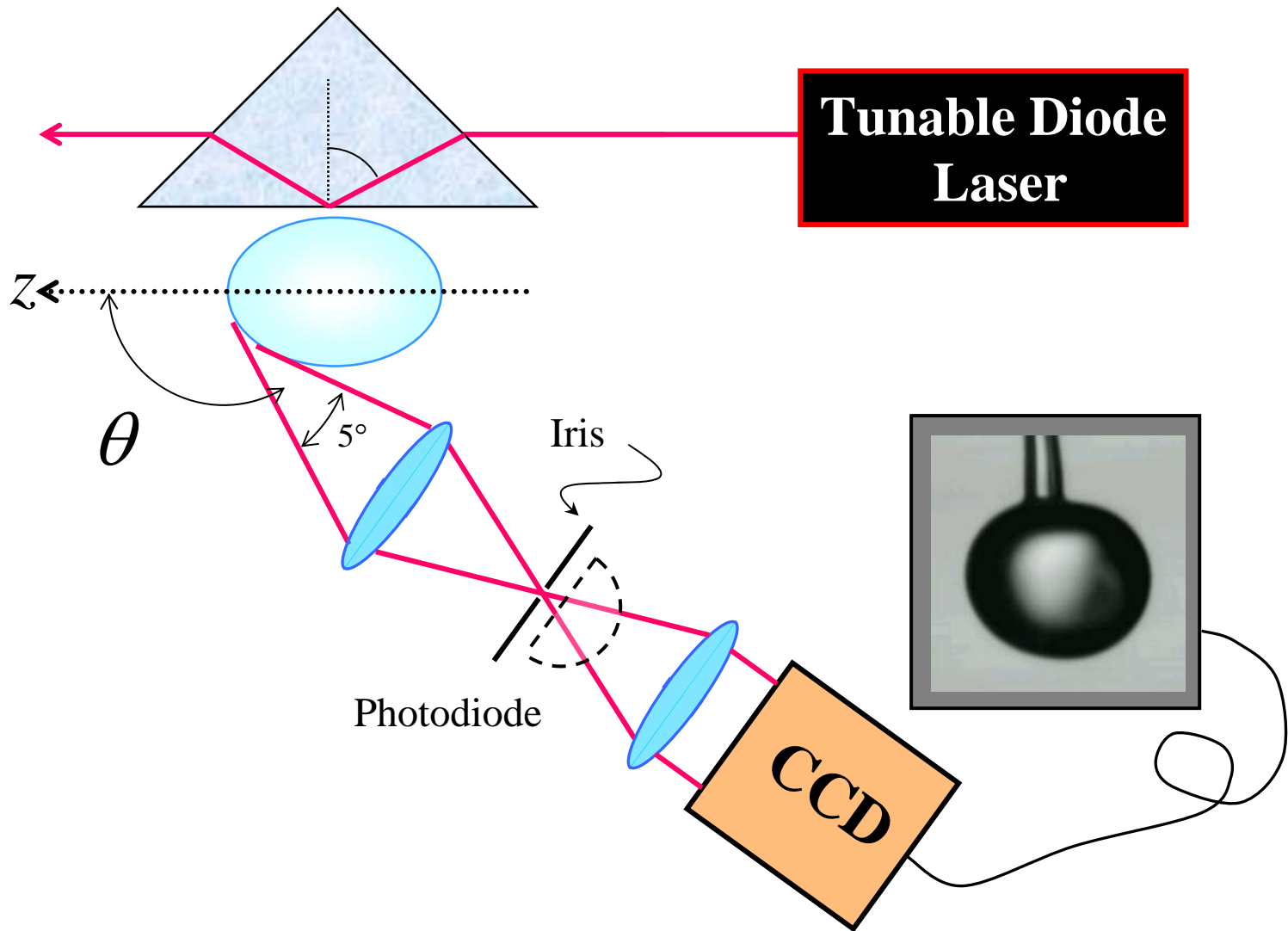


- **Formed by fusing together two spheres**

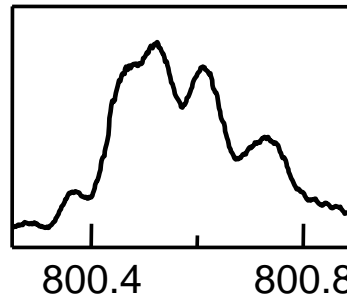
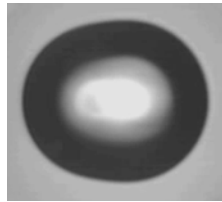
S. Lacey and H. Wang, *Opt. Lett.*
26, 1943 (2001).



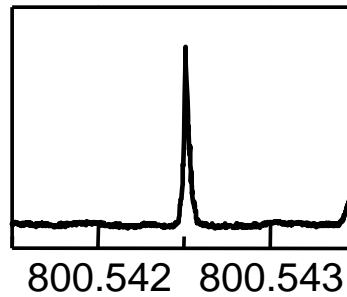
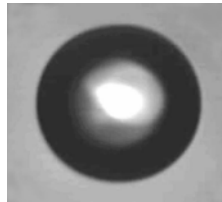
Experimental Setup



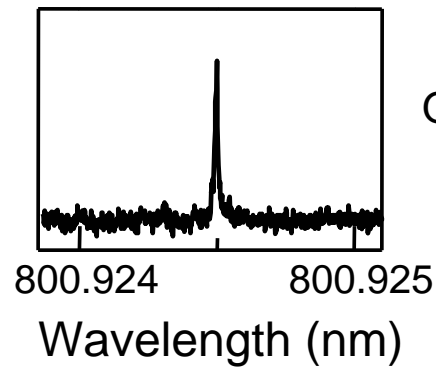
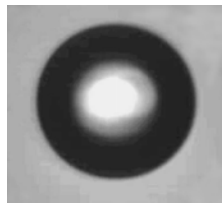
Q-Factor vs Deformation



$Q \sim 10^4$

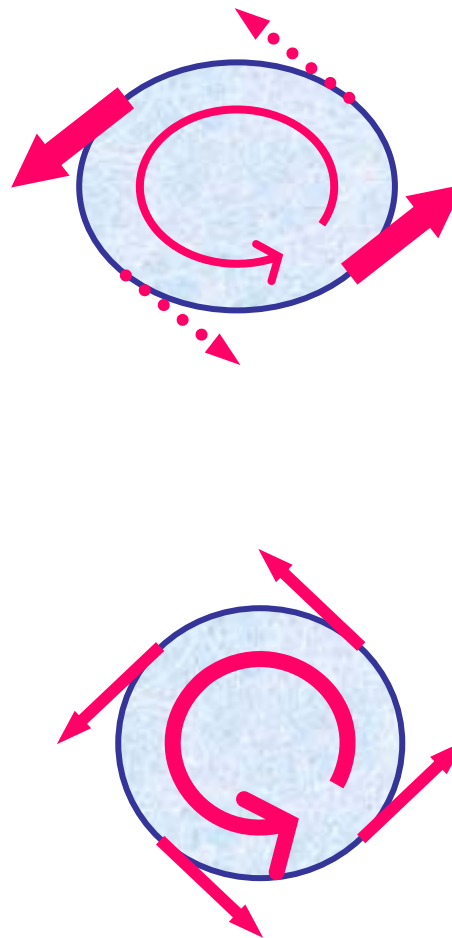
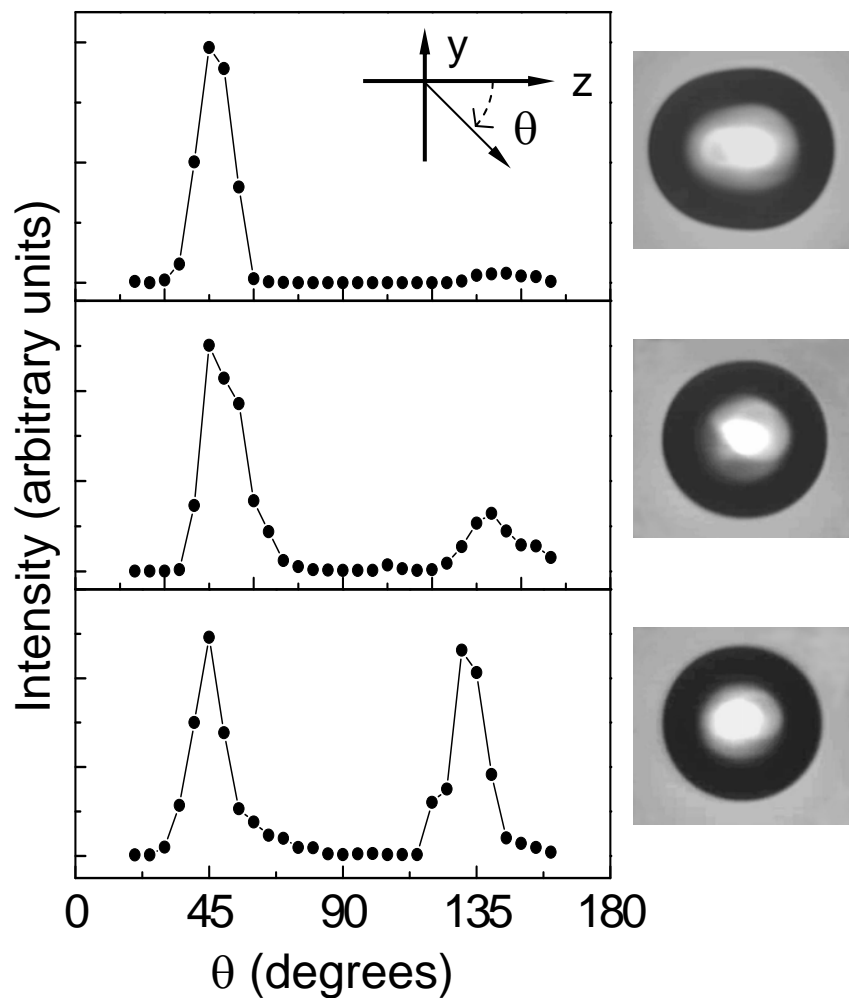


$Q \sim 3 \times 10^7$

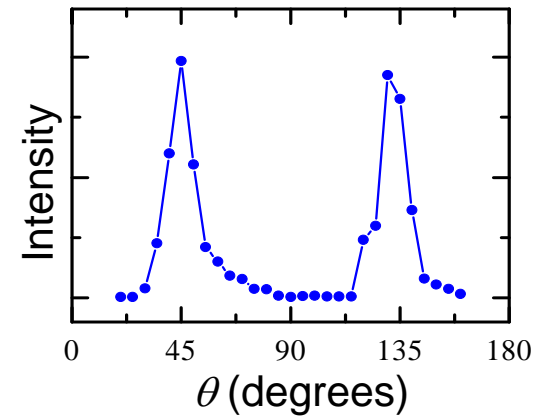
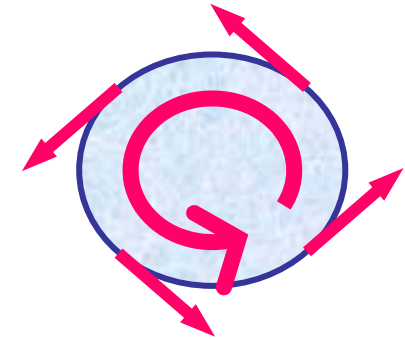
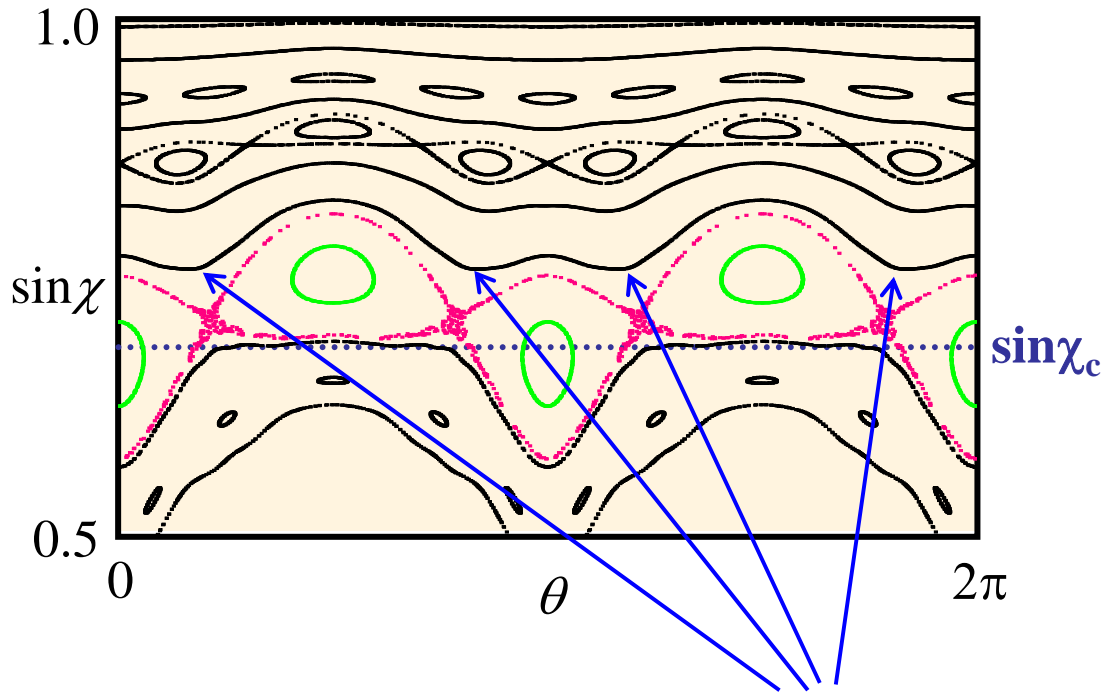


$Q \sim 7 \times 10^7$

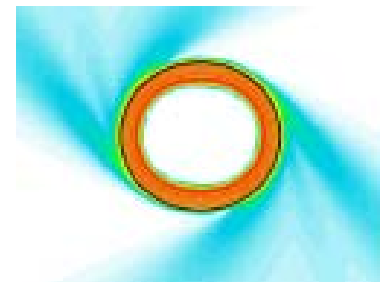
Directional Emission from Nearly Spherical Resonators



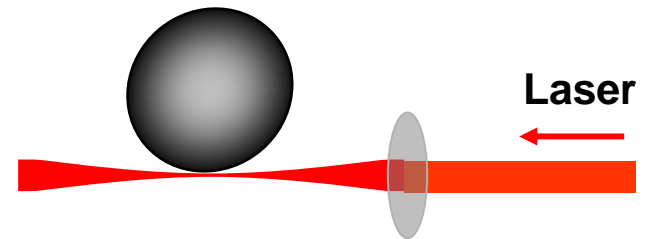
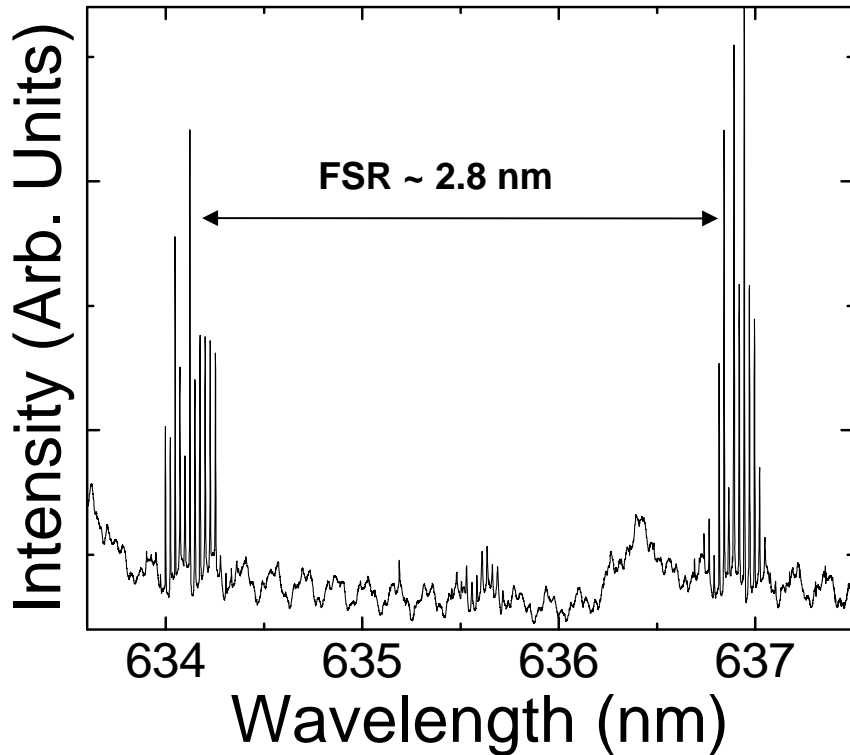
Directional Evanescent Escape



Evanescent escape occurs in regions where the angle of incident reaches a minimum.



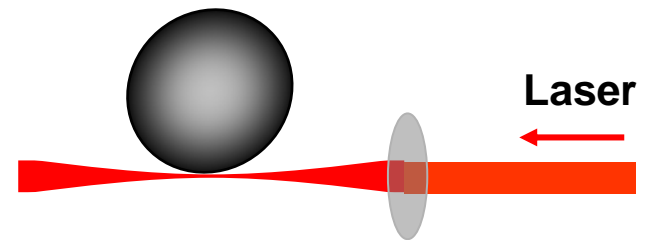
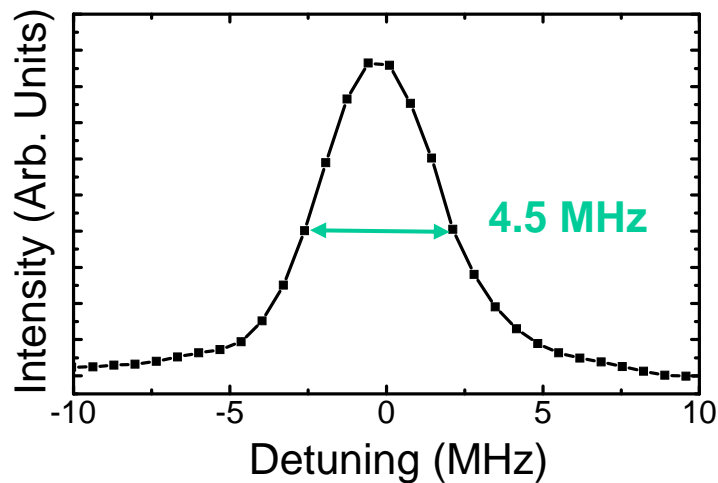
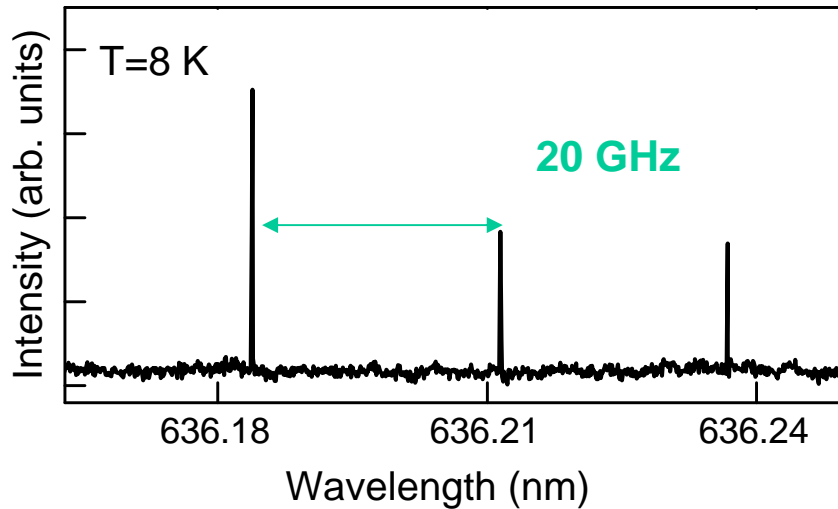
Free-Space Evanescent Excitation of WGMs



- Sphere size: 32μ
- Deformation $< 2\%$
- Free Spectral range: 2.8 nm
- Modes near the equator: $m \sim l$

Y. Park *et al.*, Nano. Lett. **6**, 2075 (2006).

Mode Spacing and Q-Factor



- Deformation removes the azimuthal degeneracy.
- Mode spacing: ~ 20 GHz
- Sphere size: 32μ
- **Ultrahigh Q-factor $\sim 10^8$**

Experimental Obstacles

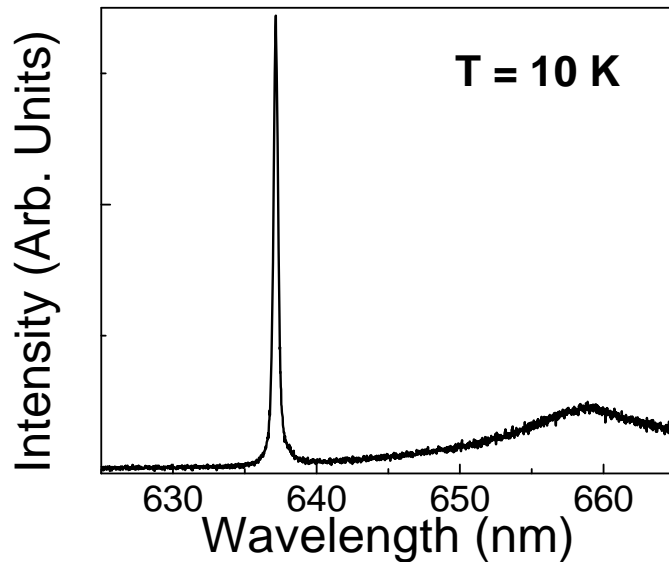
- **Launching WGMs in a microresonator.**
 - Experiments need to be carried out at low temperature.



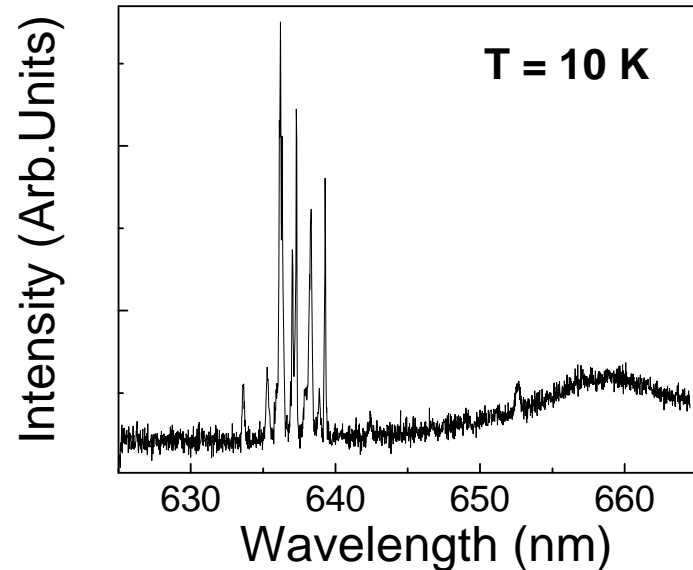
- **Matching the resonance of a WGM with the transition frequency of a NV center.**
 - Every artificial atom or NV center is different.
 - Very few NV centers are stable.

Photoluminescence Spectra of NVs

PL from a single microcrystal
with a diameter near $30\ \mu\text{m}$

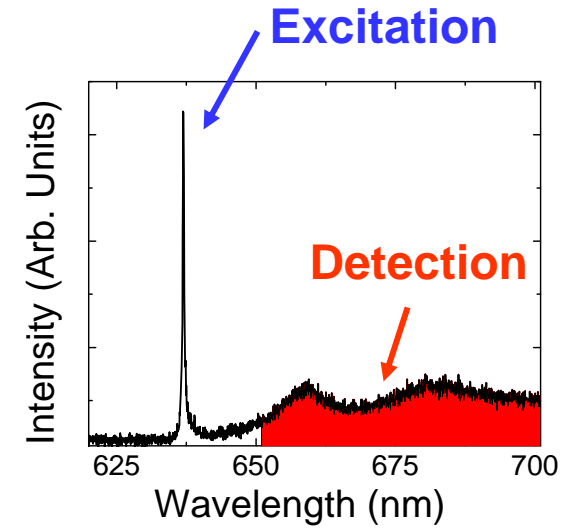
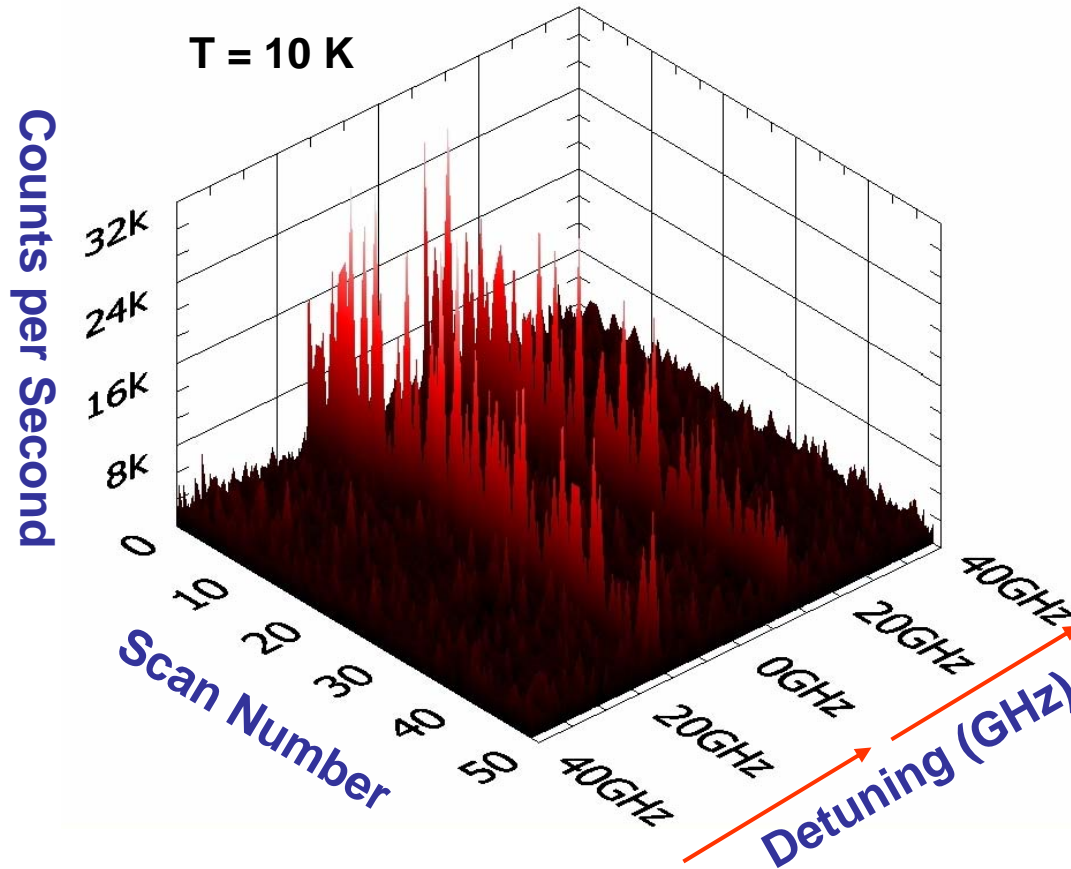


PL from nanocrystals formed
by **crushing the microcrystals**.



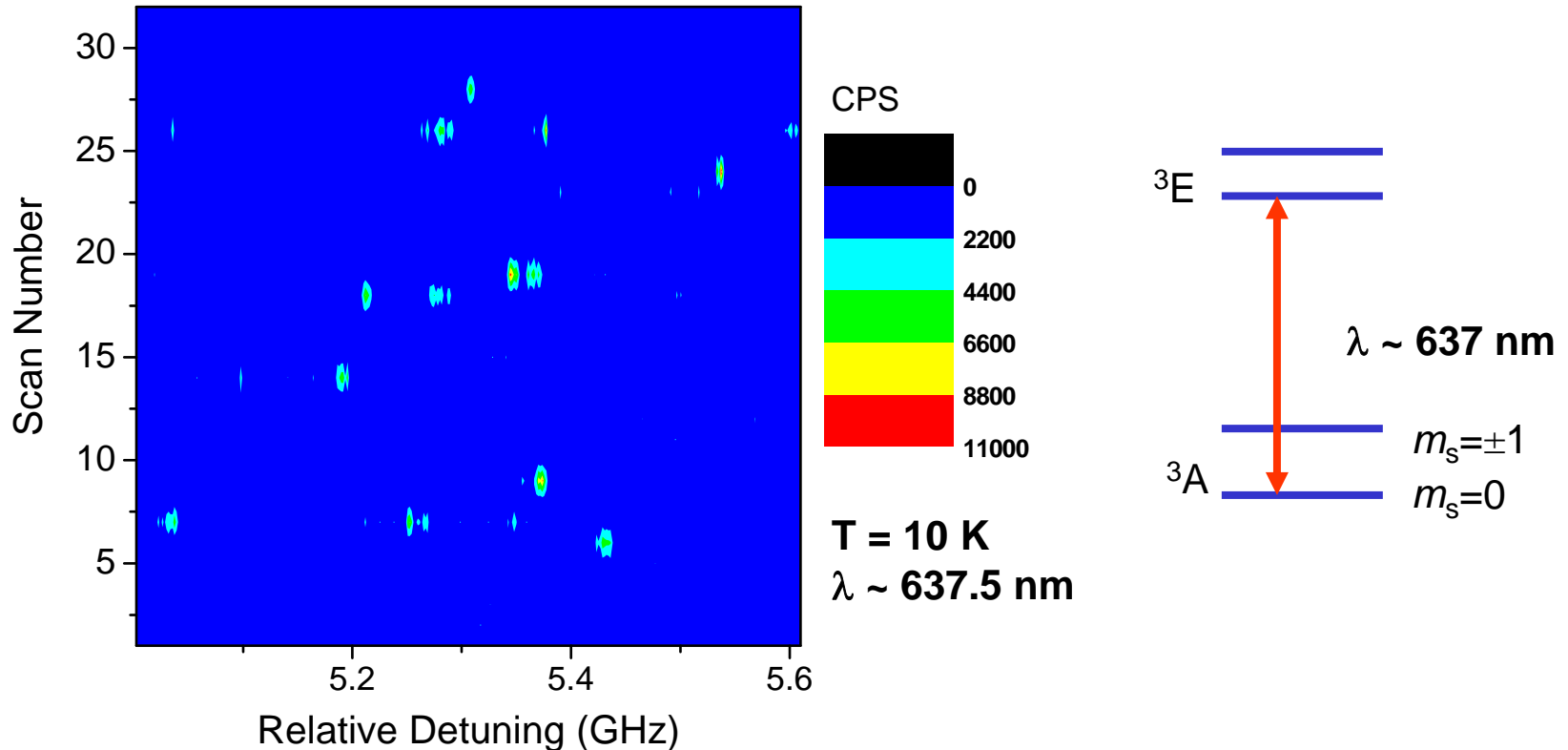
- Transition frequencies of NV centers depend strongly on local environment, such as local strain and local electric field.

Excitation Spectra of Single NVs



A very small number of NVs show stable emissions during hours of measurements.

Excitation Spectra of Single NVs



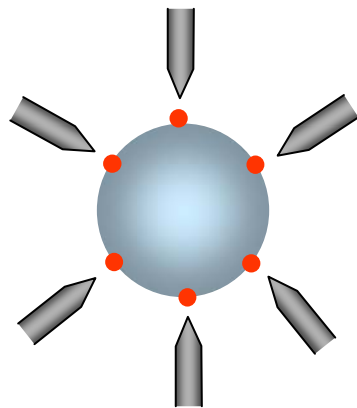
- Typical NVs spend significant amount of time in dark states.
- Transition frequency for most NVs also fluctuates.
- Linewidth of single NVs: ~ 20 to 40 MHz

Matching NV and WGM Resonances

- **Ideal solution:**

Select and deposit individual diamond nanocrystals that contain stable NV centers.

Tune the transition frequency of individual NV centers.

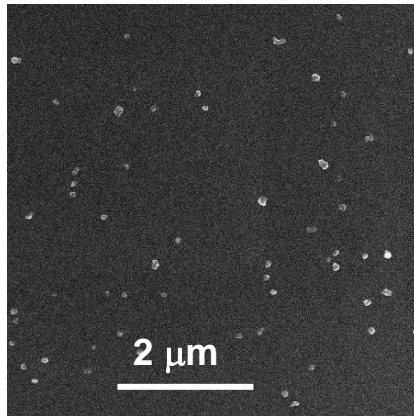


Frequency tuning with microelectrodes via Stark effects.

- **Near-term solution:**

Depositing a large number of NVs on the sphere surface.
Work with a large number of WGM modes.

Diamond Nanocrystals on a Sphere Surface



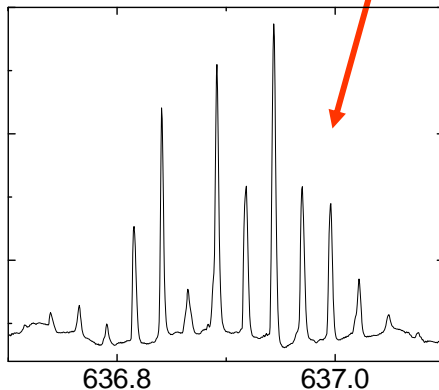
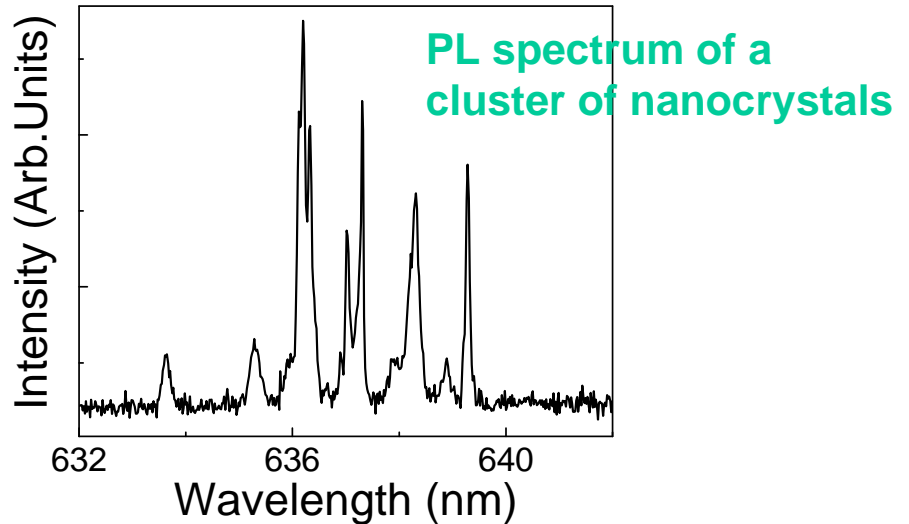
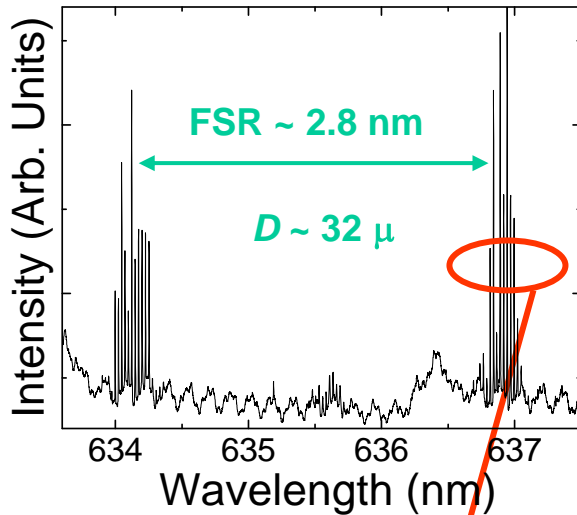
SEM of nanocrystals on a sphere surface.

Average Nanocrystal size: 75 nm

- 1 nanocrystal / μm^2
- 200 nanocrystals within a given mode area
- Cavity linewidth (FWHM): 100 MHz

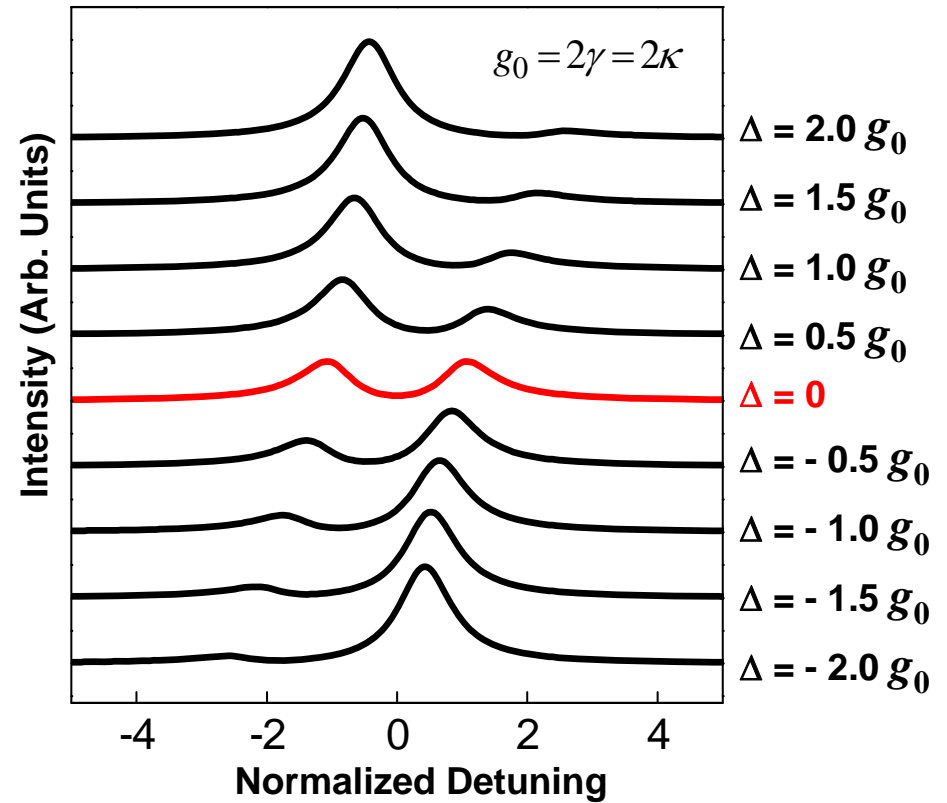
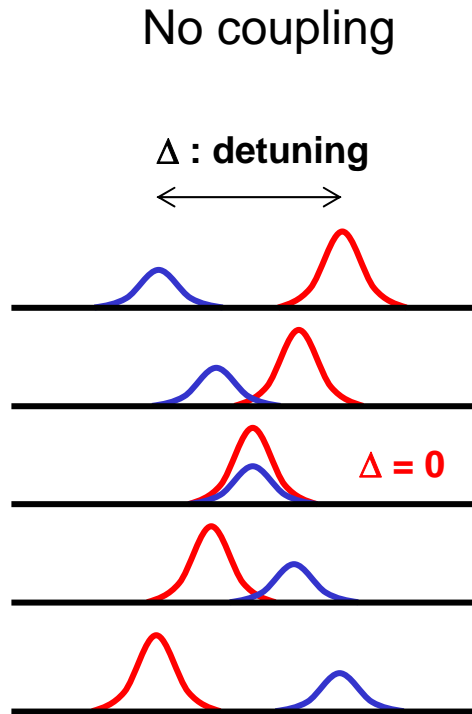
Deposition of a large number of nanocrystals leads to significant broadening of the WGMs.

Matching NV and WGM Resonances



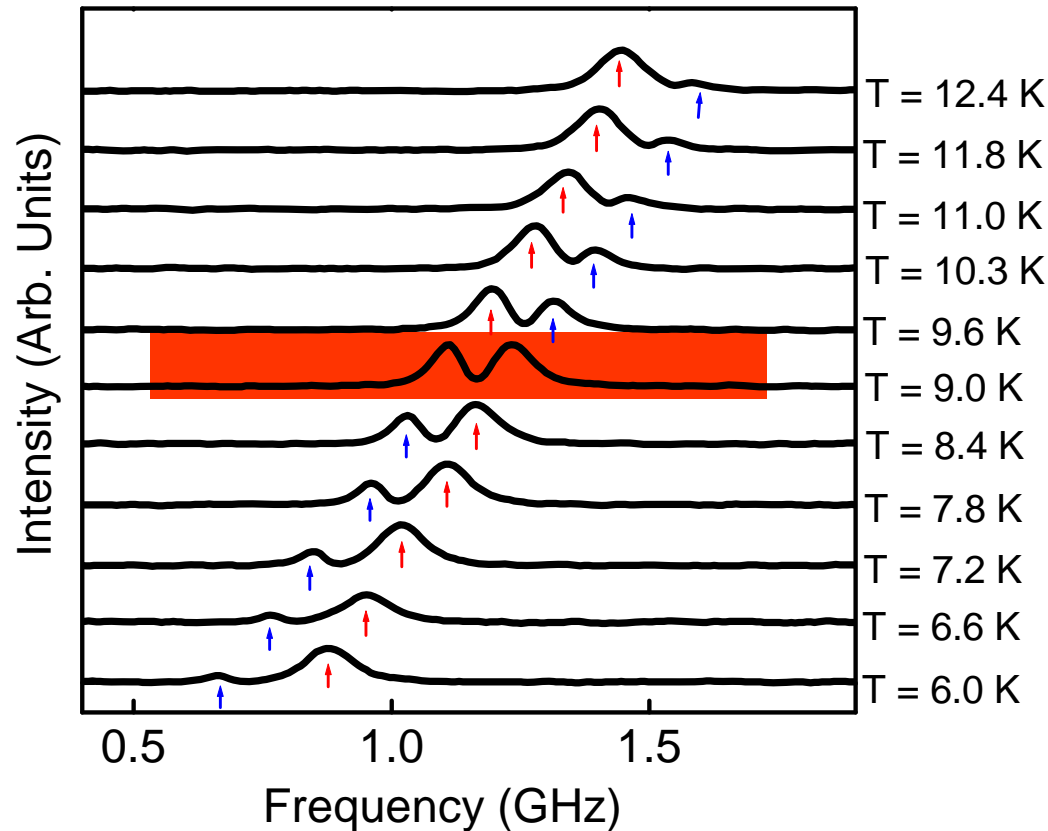
- **Within the frequency distribution of NV centers, we can work with one to three groups of WGMs.**
- **Each group of WGMs contain nearly 10 modes.**

Normal Mode Spectra: Theory



The cavity-like mode dominates the transmission spectrum away from zero-detuning.

Normal Mode Spectra: Experiment



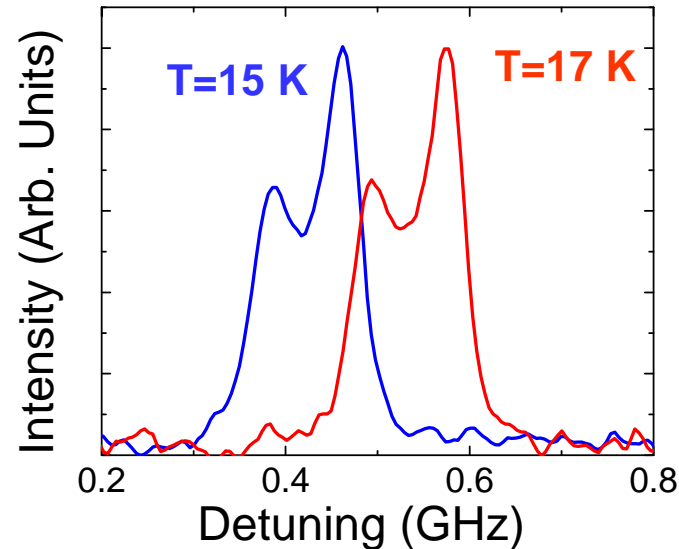
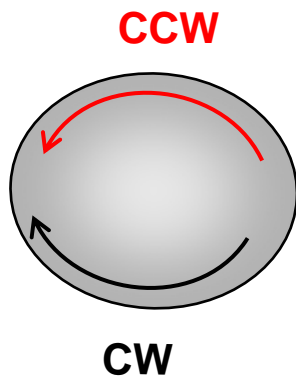
Matching the NV and WGM resonances using temperature tuning.

Resonance matching occurs at T=9 K.

Transmission spectra are dominated by the cavity-like mode (indicated by the red arrows).

Modal Coupling of Countering Propagating WGMs

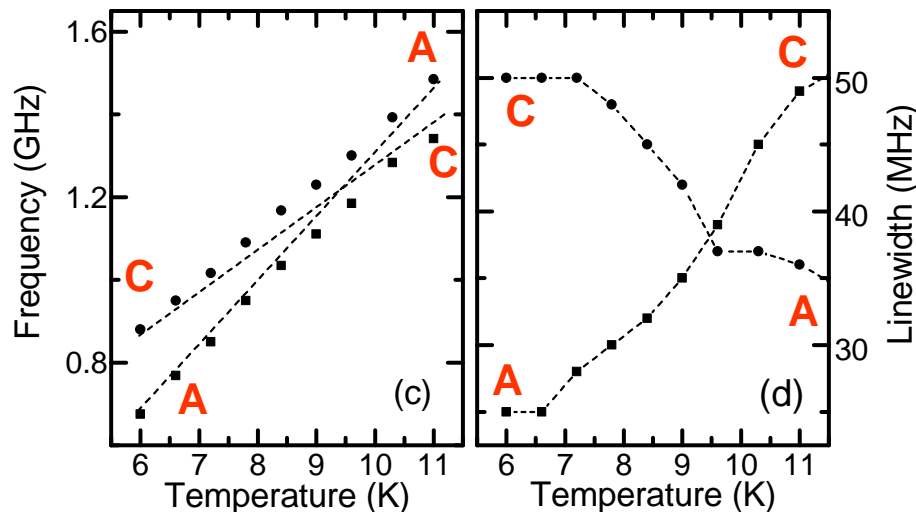
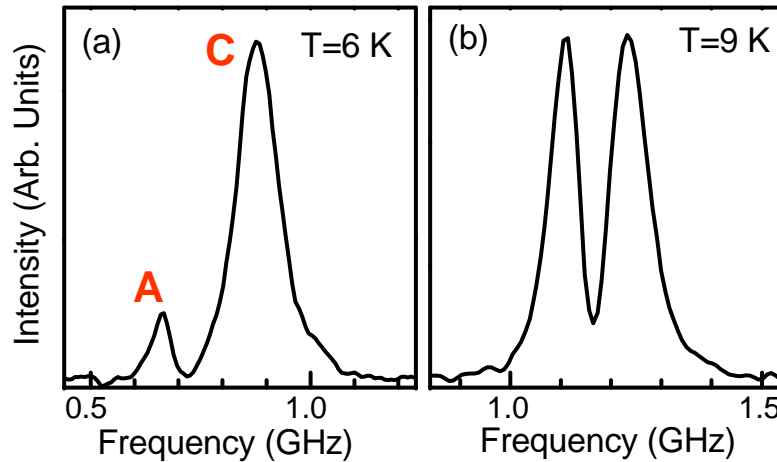
Coupling between clock-wise and counter clock-wise modes can lift the two-fold degeneracy and lead to splitting of the WGMs.



The splitting and relative amplitude are independent of temperature.

D. Weiss *et al.*, *Opt. Lett.* 20, 1835 (1995); M.L. Gorodetsky *et al.*, *JOSA B* 17, 1051 (2000); T.J. Kippenberg *et al.*, *Opt. Lett.* 27, 1669 (2002).

Normal Mode Coupling



- **Normal mode coupling:**
Anti-crossing in the spectral positions of the normal modes.

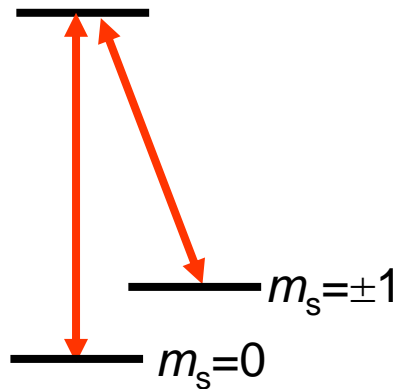
Switching of the normal mode linewidth across the anti-cross region.

C: Cavity-like mode
A: Atom-like mode

$$(\gamma, \kappa, g)$$

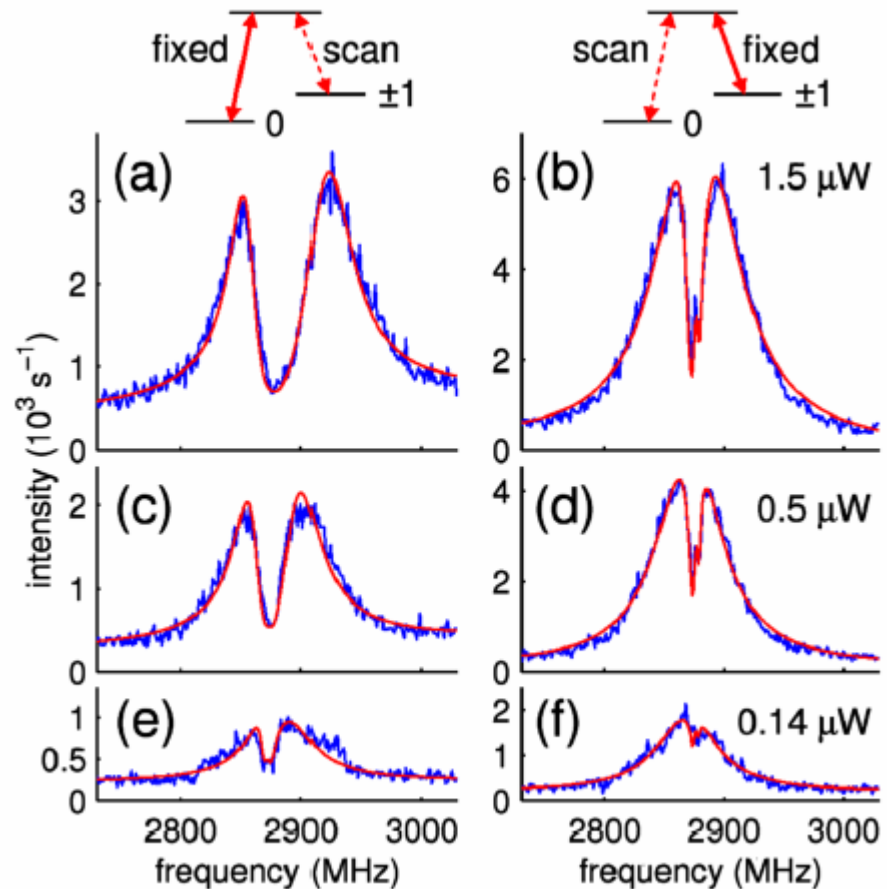
$$= 2\pi (25, 50, 55) \text{ MHz}$$

Optical Manipulation of Single Spins in NV Centers

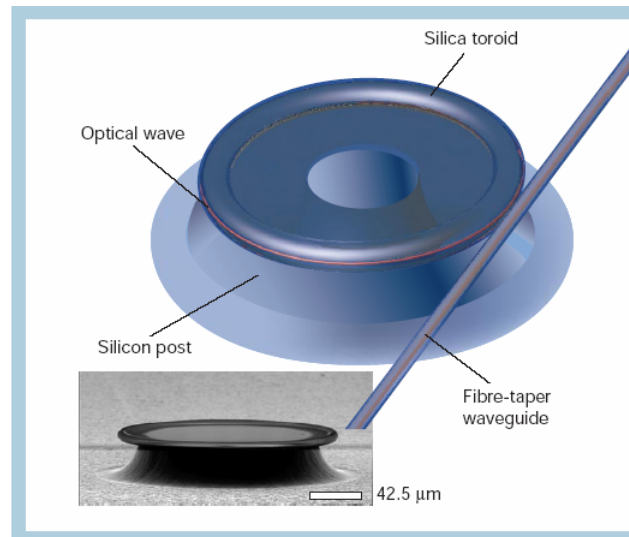
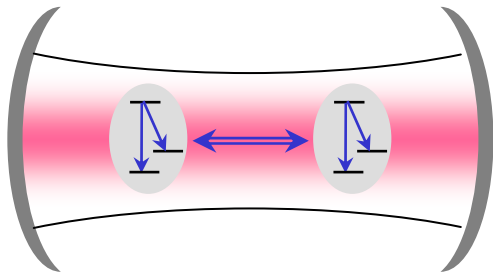


Santori *et al.*, Phys. Rev. Lett. **97**, 247401 (2006).

Coherent population trapping



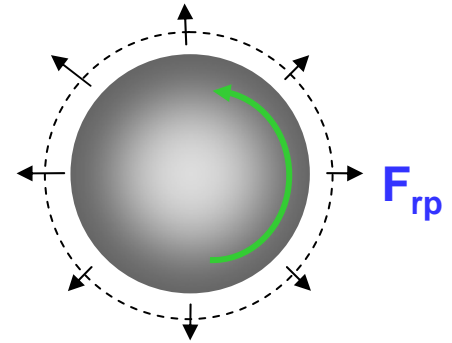
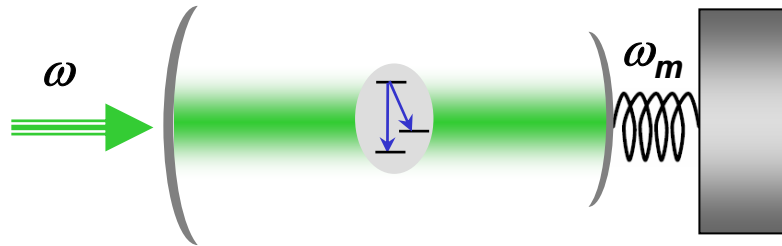
Future Work



**Vahala, Nature
424, 839 (2003)**

- Incorporate robust spins in a strong coupling cavity QED system.
- Spin entanglement via vacuum Rabi oscillation.
- Improving scalability by using chip-based toroidal microresonator.

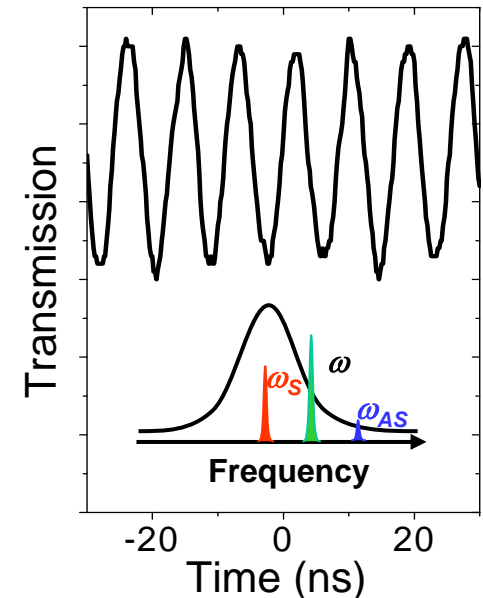
Coupling Spins to Mechanical Excitations



- **Silica microspheres can also be used as a mechanical resonator.**

Carmon *et al*, PRL 94, 223902 (2005); Schliesser *et al.*, PRL 97, 243905 (2006).

- **NV centers can be coupled to the mechanical oscillation via radiation pressure.**
- **Exploring quantum entanglement between a spin and a mechanical oscillator.**



Summary

- Achieved strong-coupling cavity QED by coupling NV centers in diamond nanocrystals to WGMs in a silica microsphere.
- Opportunity to incorporate robust electron spins in a solid state cavity QED system.
- Avenue to couple a macroscopic mechanical oscillator to a spin.

