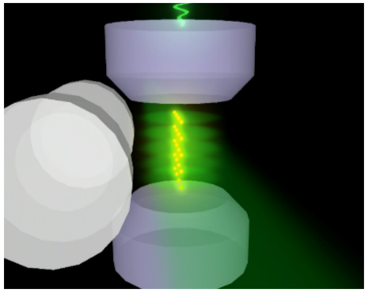
2016 Introduction to Our Research Programs

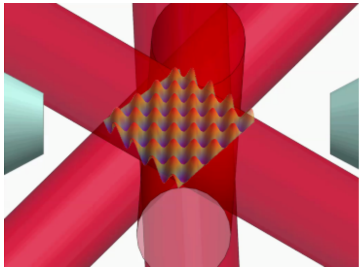
Quantum-Field Laser Laboratory

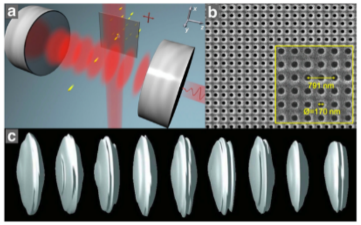
KW An's Group

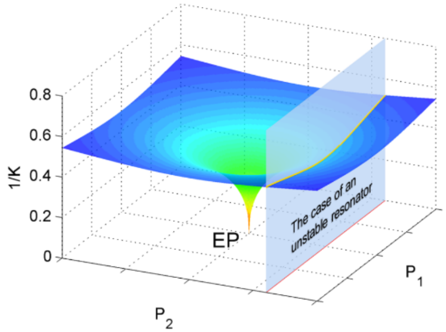
Physics of atom-field interaction

- Quantum information
  - Ideal single-photon sources
  - Ideal single-photon detectors
- Nonclassical light generation
  - Highly sub-Poisson intense light
  - Quantum-dipole lasing
- Manipulation of vacuum fluctuation
  - 3D imaging of vacuum fields
  - Diverging spontaneous emission in a non-Hermitian system
  - Thresholdless lasing



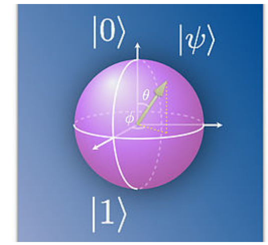




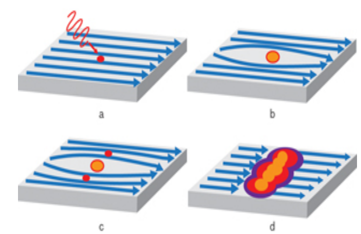


I. Ideal single-photon detectors

- Needs
  - A near ideal single-photon detection efficiency is needed in many photon-qubit-based quantum information processing schemes.
  - Detection of axion dark matter requires a high-efficient microwave photon detector.



- Current technology
  - Superconducting Josephson-junction-based detectors have very high efficiency but do not have single-photon resolution (∵large dark counts).
  - Avalanche photodiode detectors in the optical region have single-photon resolution but have only about 50% single-photon detection efficiency.



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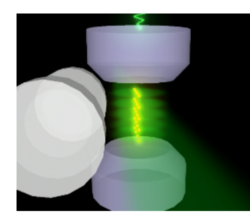
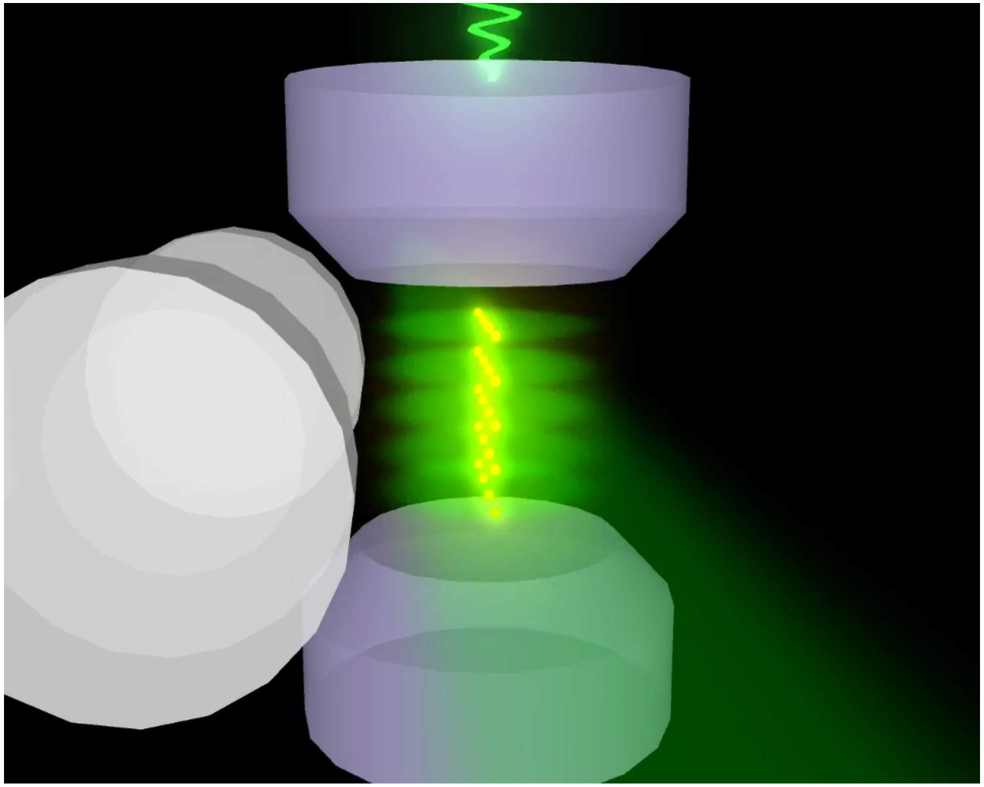
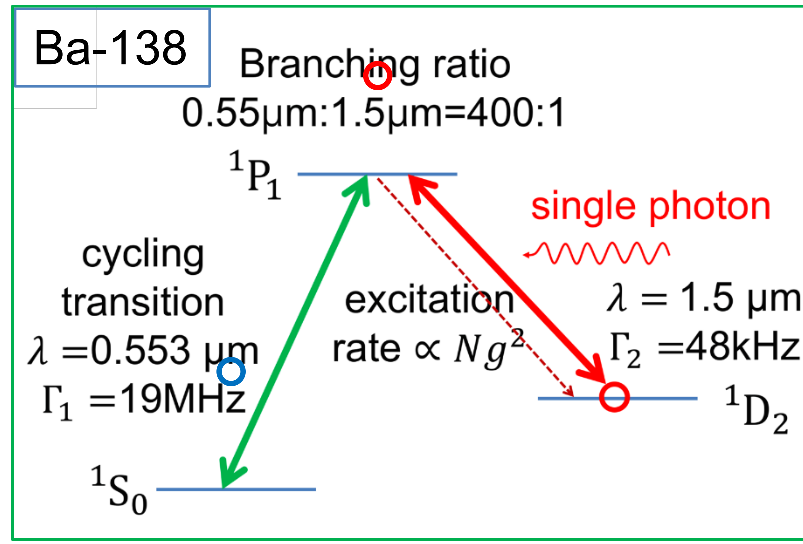
- Our goal:
  - to realize an ideal optical/μ-wave single-photon detector by using
    - quantum dipole material
    - cavity-QED principle



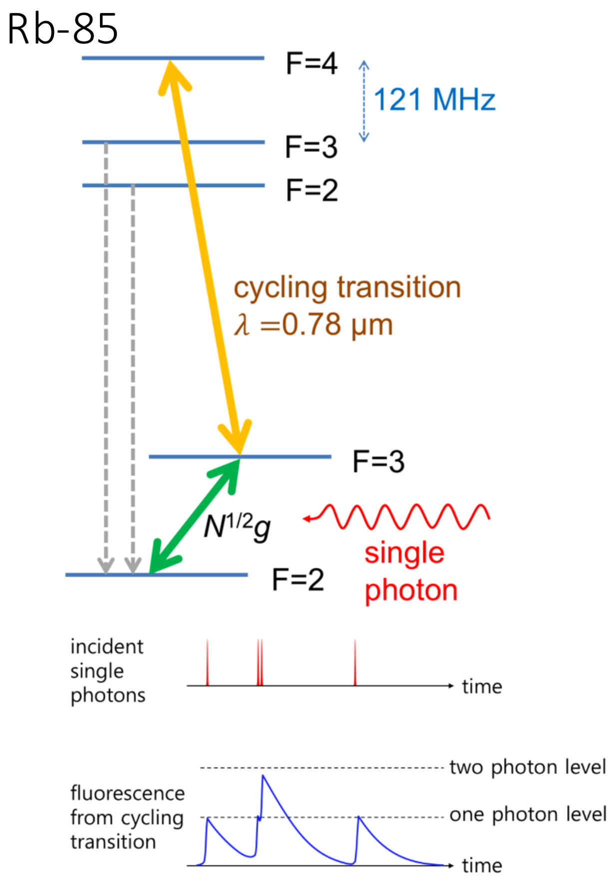
Optical single-photon detector

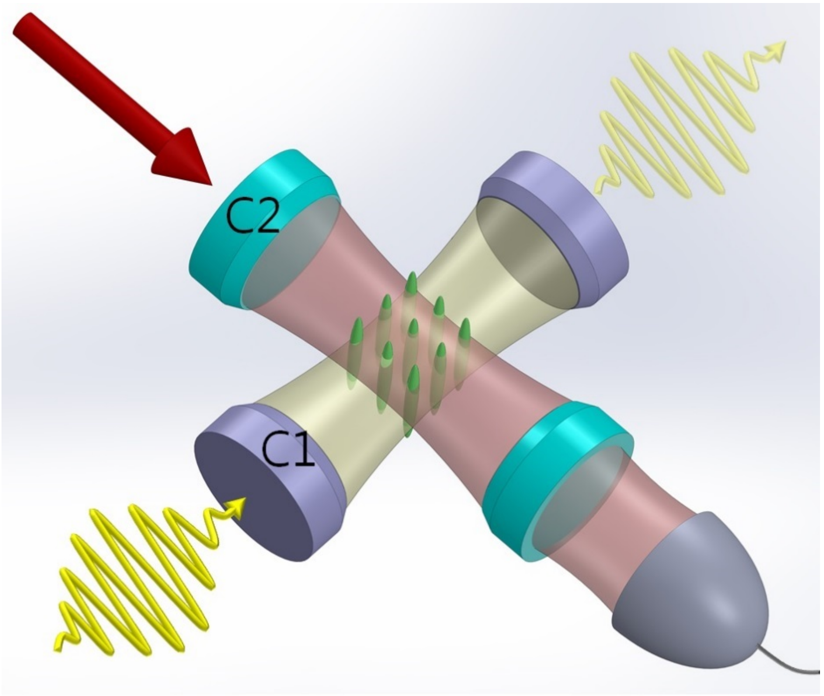




- Barium atoms in a beam localized by a nanohole array
- 1 input photon will generate about 400 output photons (gain=400).
- With a conventional detector, a near 100% single-photon detection efficiency can be achieved.

Microwave single-photon detector

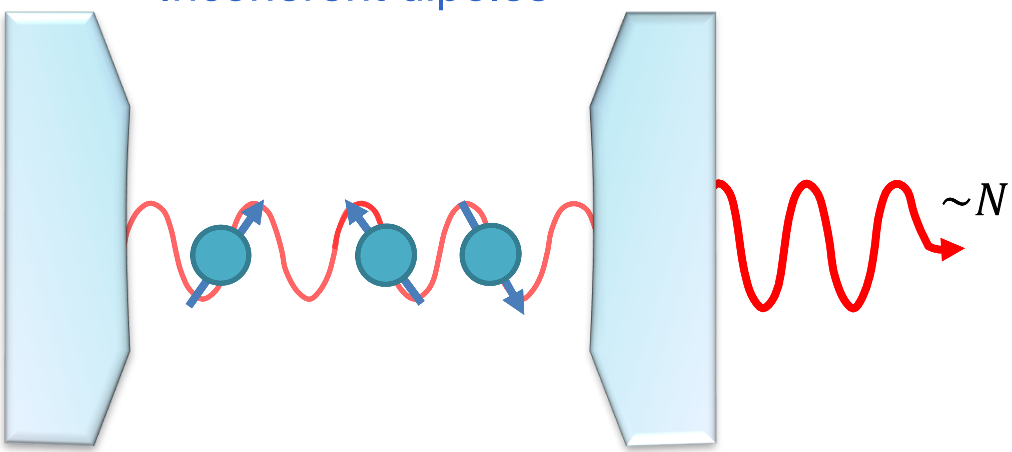




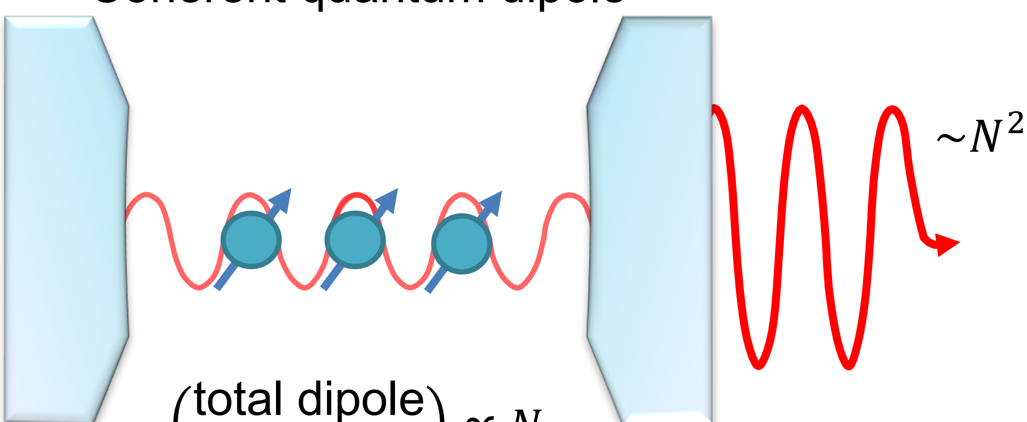
- Rubidium atoms localized in an optical lattice
- 1 microwave input photon will generate more than 1000 optical photons (gain>1000).

II. Quantum-dipole laser

Incoherent dipoles



Coherent quantum dipole

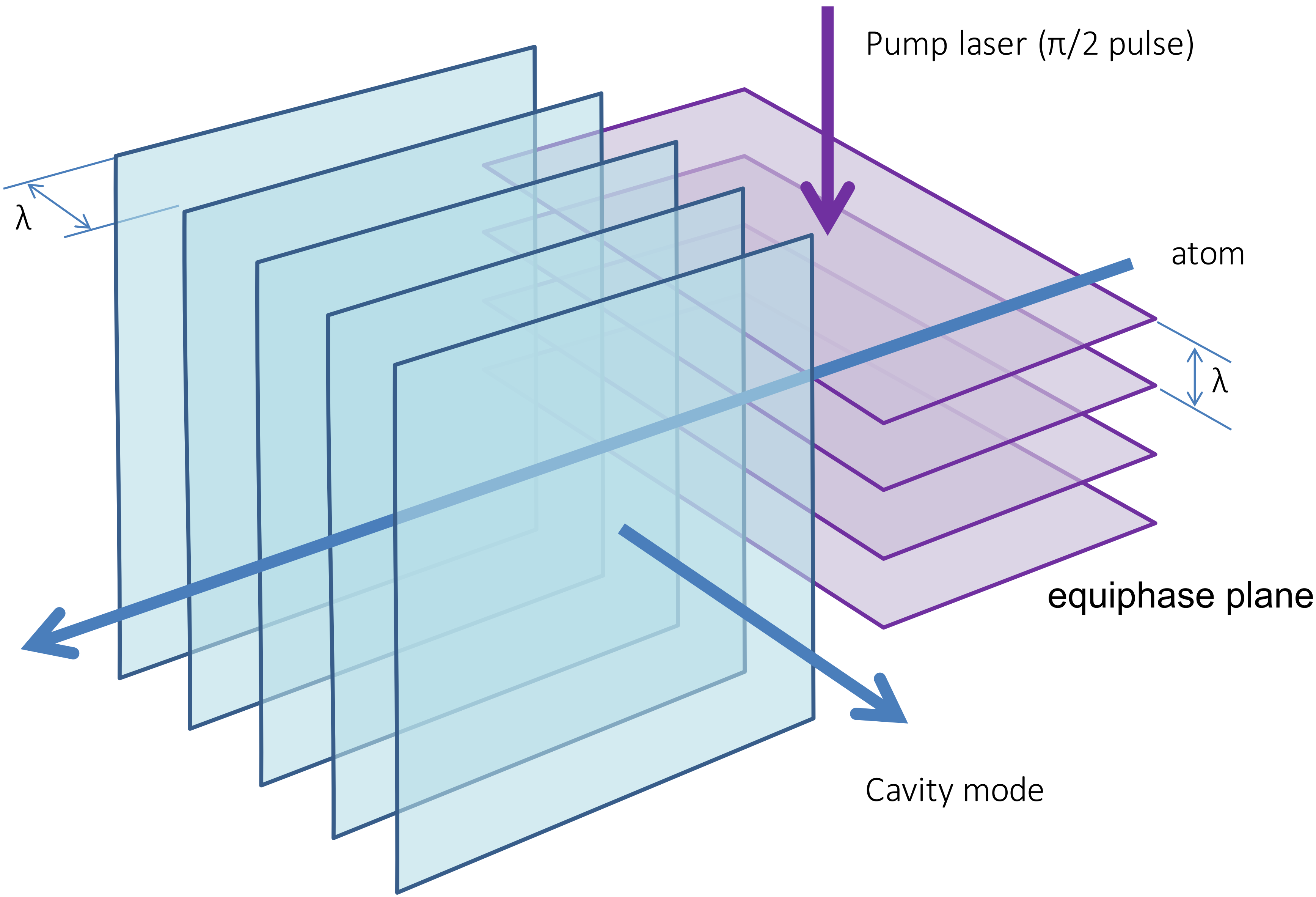


$\begin{pmatrix}\text{total dipole}\\ \text{moment}\end{pmatrix} \propto N$

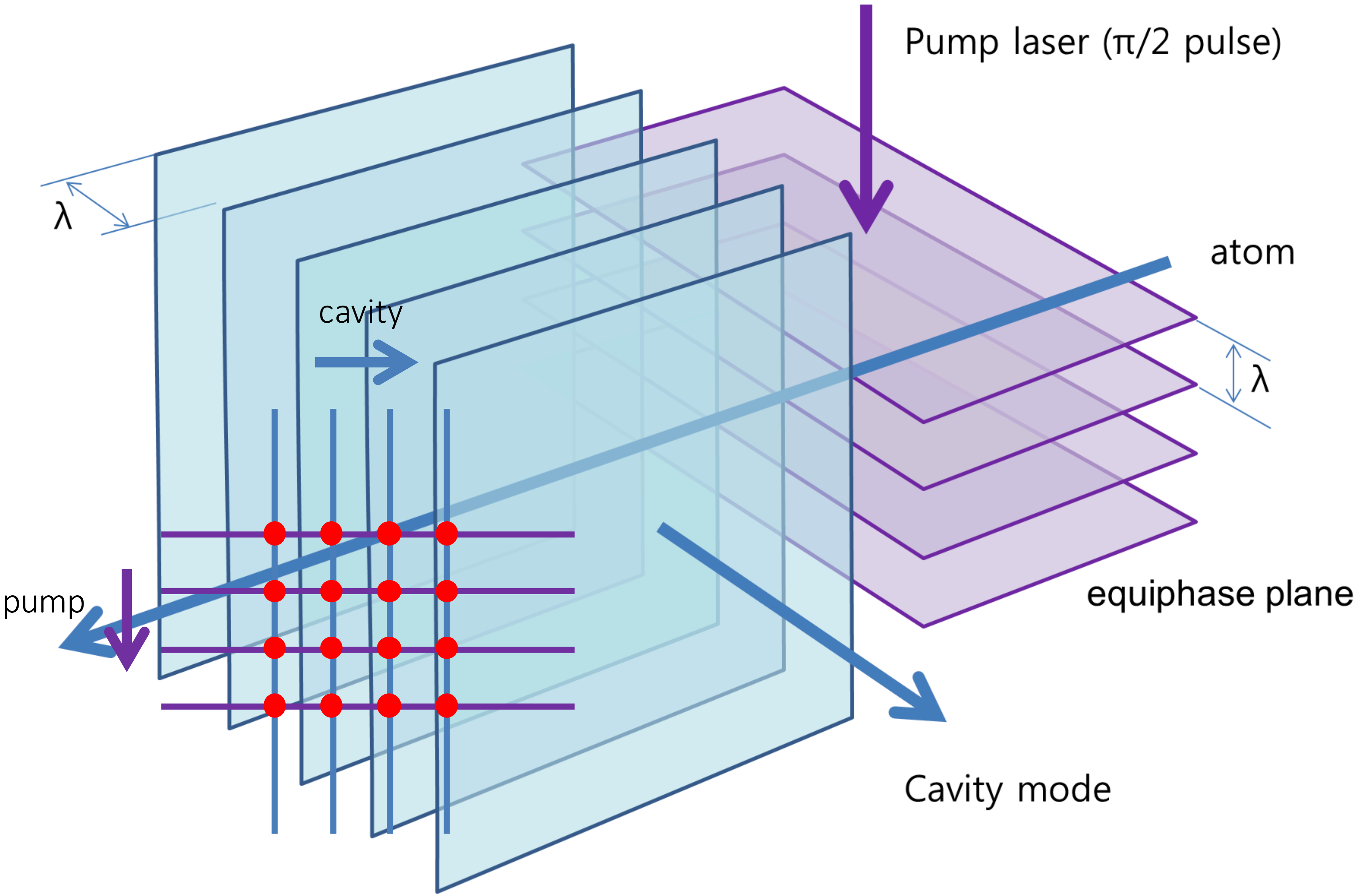
- What is the quantum-dipole material?
  - A collection of identical quantum dipoles* prepared periodically in space with the same phase

*Quantum dipoles: atoms in the same superposition of ground and excited states with the same phase

How to realize the same phase

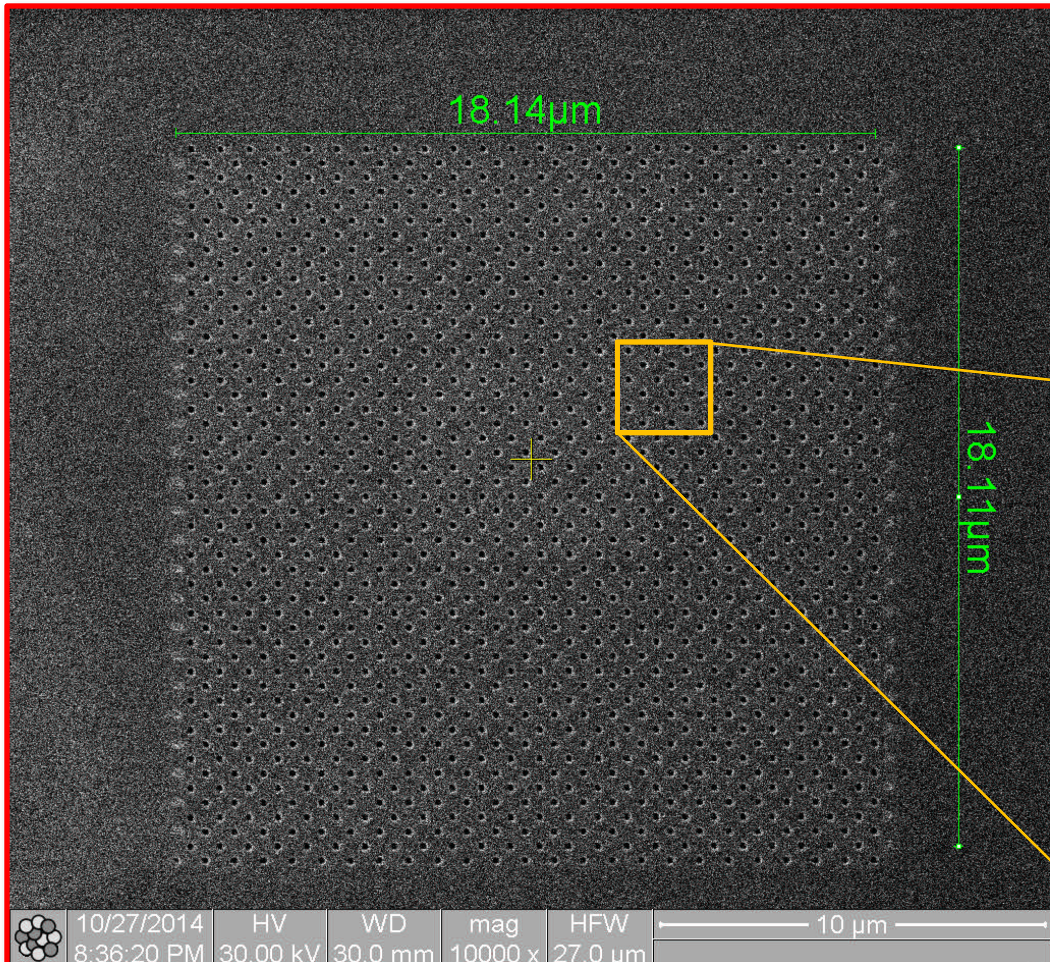


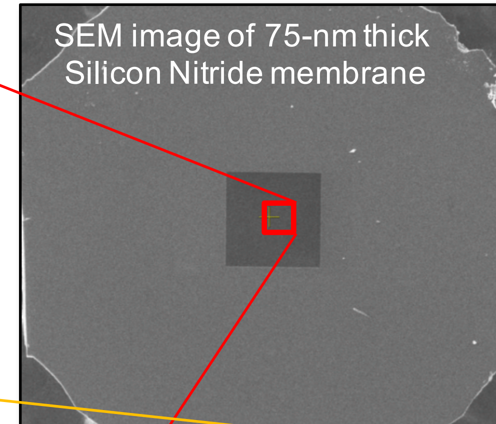
How to realize the same phase

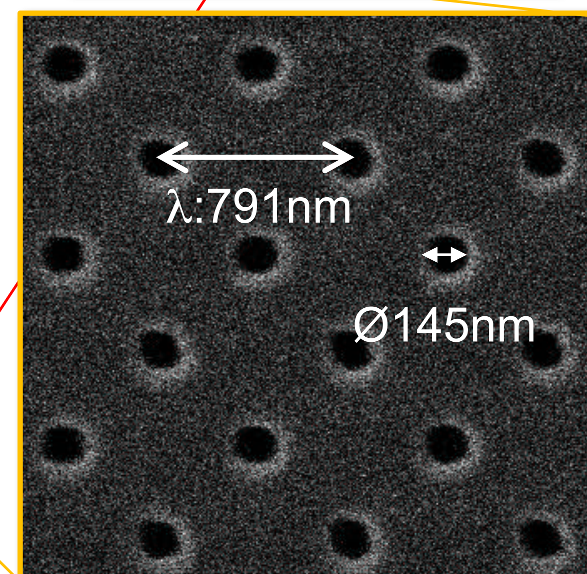


Nanohole array

- Machined by focused ion beam (FIB)

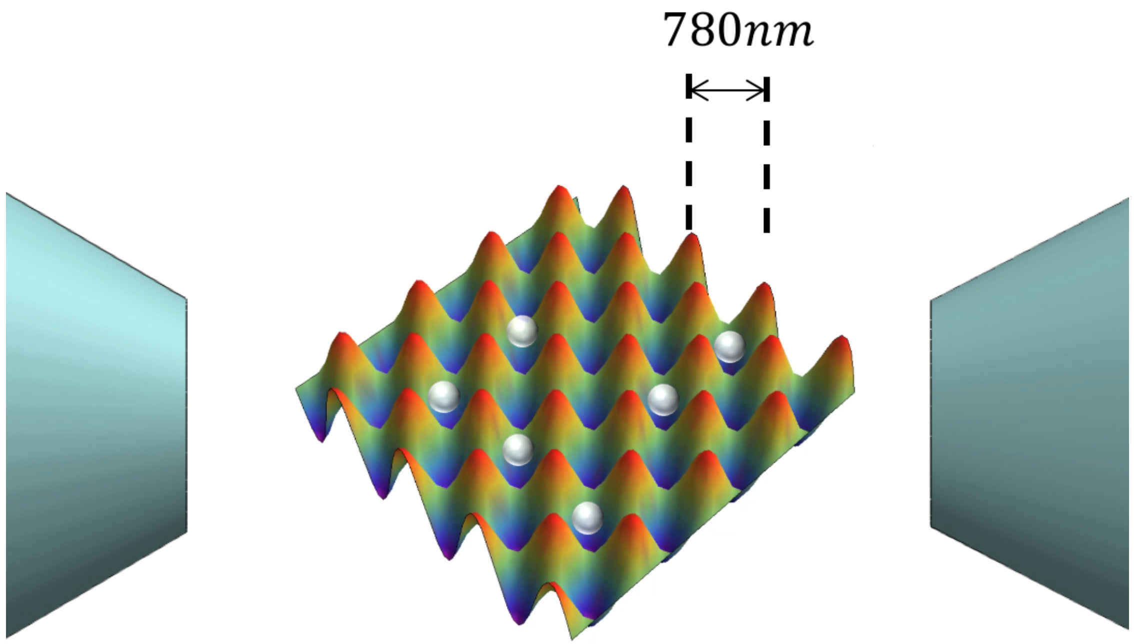






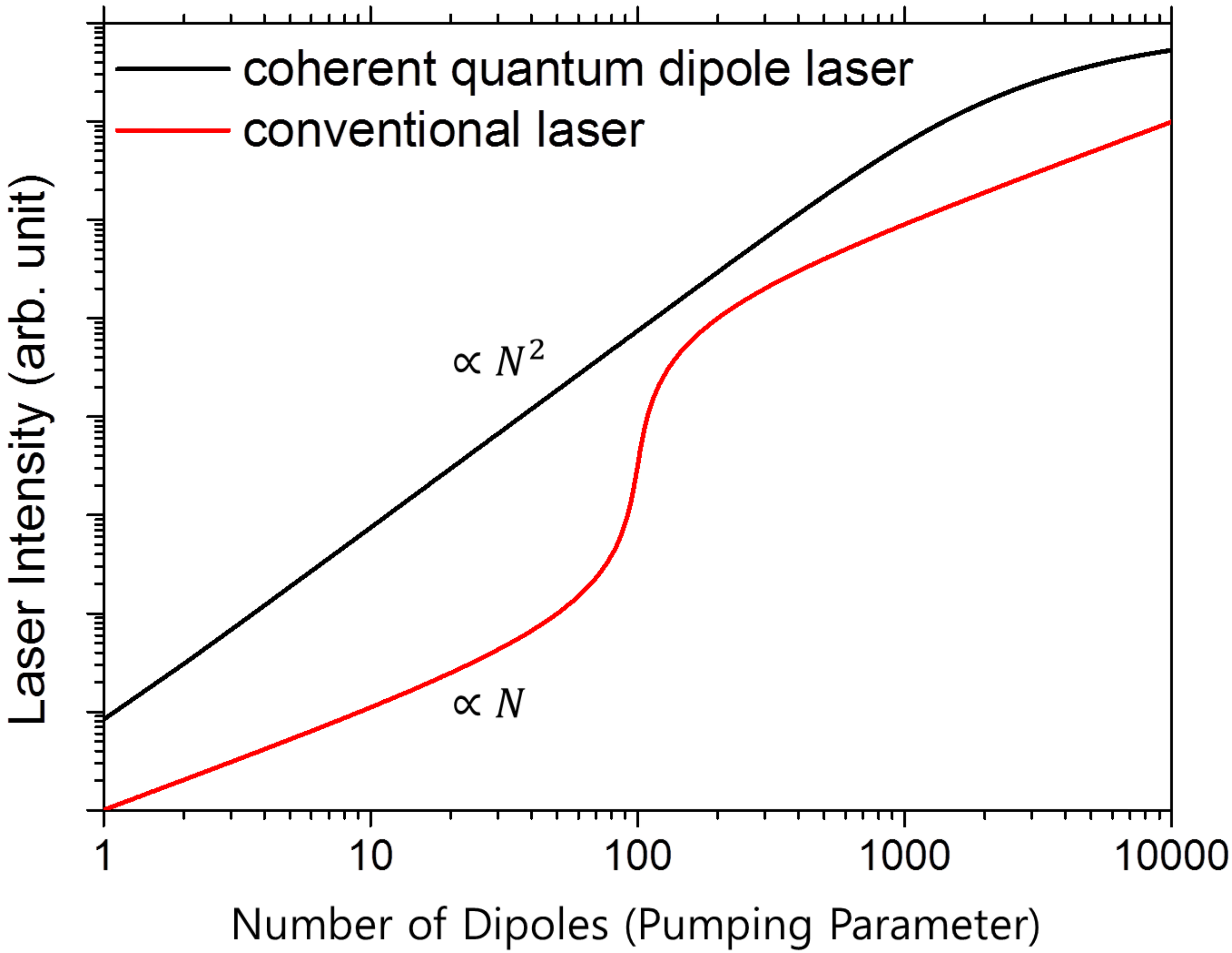
M. Lee *et al.*, Nat. Commun. **5**, 3144 (2014)

Stationary quantum dipole materials

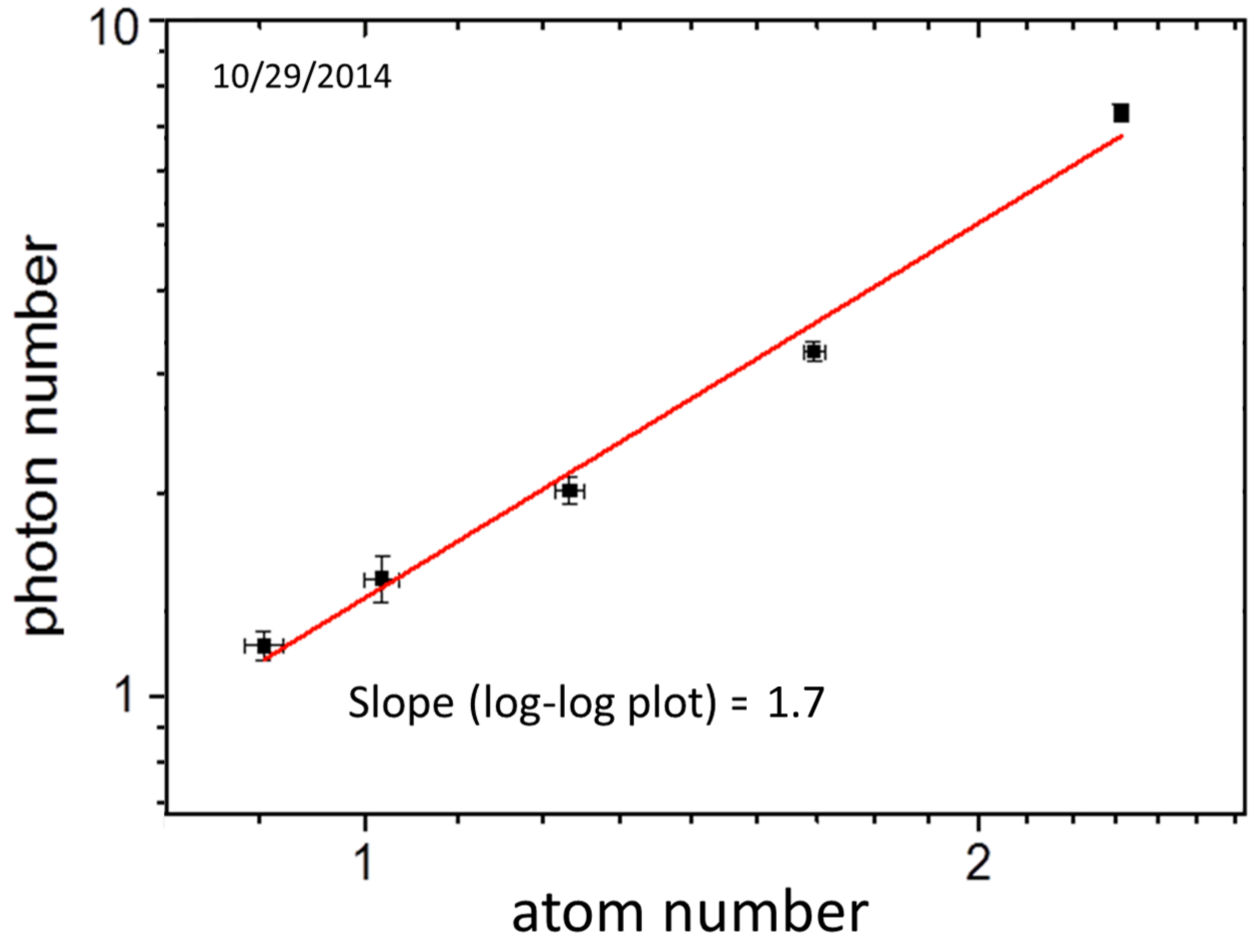


- ^{85}Rb Atoms are confined in a 2D optical lattice (pump in one direction). Along the cavity axis, the lattice spacing equals the Rb wavelength (equiphase to the cavity mode).
- To be used in the microwave single photon detector experiment.

Thresholdless lasing with QDM



Preliminary data of N^2 emission



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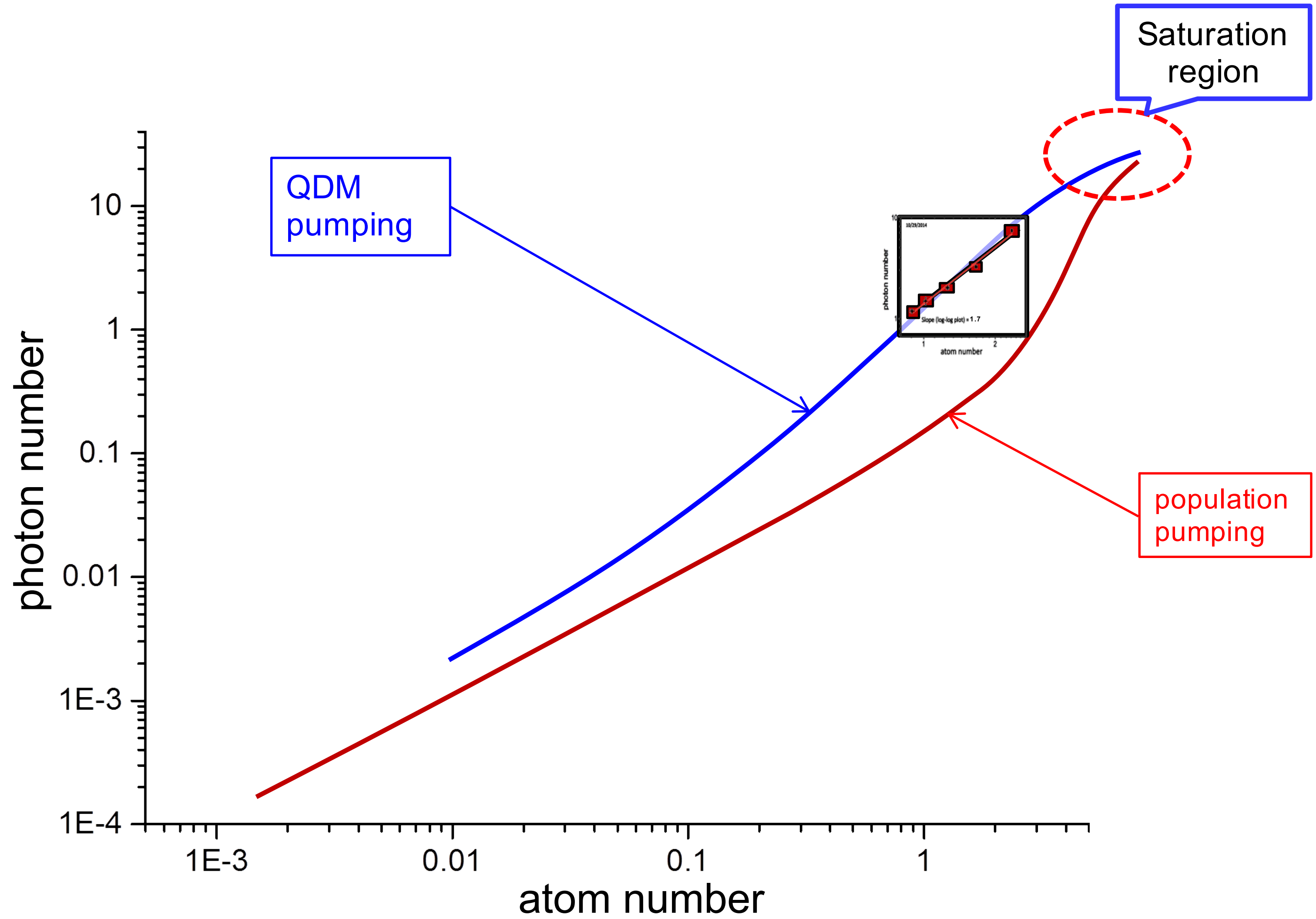


III. Diverging spontaneous emission

- According to our theoretical study, atomic spontaneous emission can *diverge* in a *non-Hermitian* optical system.
- Hermitian Hamiltonian, $H^{+} = H$

$$0 = \langle u_m|H - H|u_n\rangle = \langle u_m|H^{+} - H|u_n\rangle$$
$$= (E_m - E_n)\langle u_m|u_n\rangle \text{ using } \langle u_m|H^{+} = E_m\langle u_m|$$

→ $\langle u_m|u_n\rangle = 0\ (m \neq n)$, orthogonality, E_n=real.

- non-Hermitian, $H^{+} \neq H$ (e.g. Energy decays)

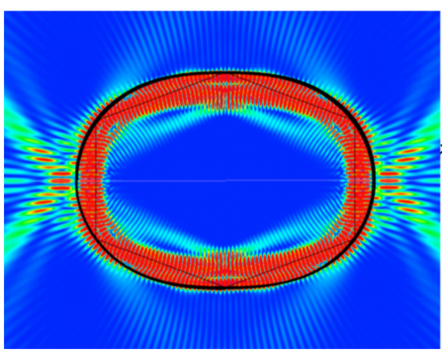
$$0 = \langle \varphi_m|H - H|u_n\rangle$$
$$= (E_m - E_n)\langle \phi_m|u_n\rangle \text{ using } \langle \varphi_m|H = E_m\langle \varphi_m| \text{ adjoint}$$

→ $\langle \varphi_m|u_n\rangle = 0\ (m \neq n)$, $\boxed{\text{bi-orthogonality}}$, E_n=complex.

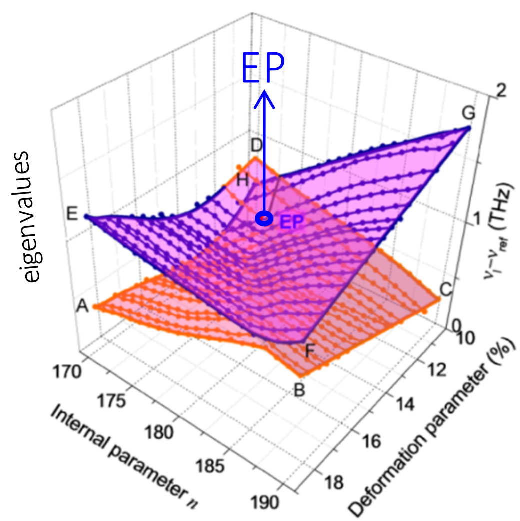
Exceptional Point (EP)

- In a non-Hermitian system (e.g. deformed microcavity), two eigenmodes *coalesce* to a single eigenmode when the intermode coupling equals their differential decay rate $(2g = \gamma_1 - \gamma_2)$
  → exceptional point (EP)

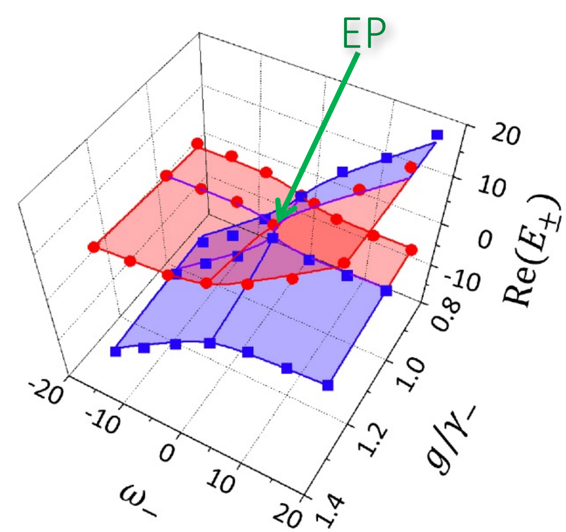
$$H = \begin{bmatrix} \omega - i\gamma_1 & g \\ g & \omega - i\gamma_2 \end{bmatrix}, E_\pm = \omega - i\gamma_+ \pm \sqrt{g^2 - \gamma_-^2}, \text{ where } \gamma_\pm = |\gamma_1 - \gamma_2|/2$$



Deformed microcavity
S.-B. Lee *et al*., PRL **88**, 033903 (2002)



Experimental observation of an EP in a deformed microcavity
S.-B. Lee *et al*., PRL **103**, 134101 (2009)



EP in an atom-cavity quantum composite
Y. Choi et al., PRL **104**, 153601 (2010)

Why Petermann factor diverge at EP

Petermann factor is defined as

u_n, φ_n normalized

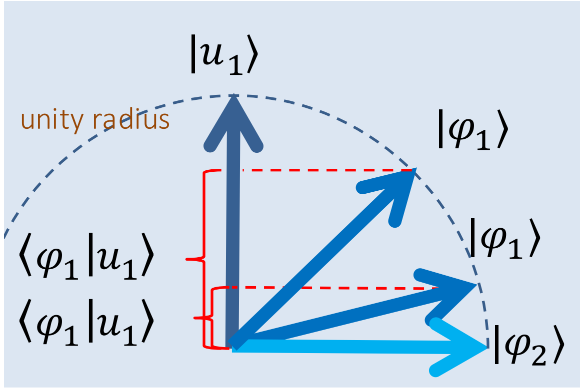
$$K_{nn} \equiv \frac{\langle\varphi_n|\varphi_n\rangle\langle u_n|u_n\rangle}{|\langle\varphi_n|u_n\rangle|^2} = \frac{1}{|\langle\varphi_n|u_n\rangle|^2}$$

Assume two interacting modes $|u_1\rangle$ and $|u_2\rangle$ coalesce into a single mode $|u_{EP}\rangle$ (at EP):

$$0 = \langle\varphi_1|u_2\rangle \to \langle\varphi_{EP}|u_{EP}\rangle = 0$$

$$\therefore K_{11} = \frac{1}{|\langle\varphi_1|u_1\rangle|^2} \to \frac{1}{|\langle\varphi_{EP}|u_{EP}\rangle|^2} \to \infty,$$

$$K_{22} = \frac{1}{|\langle\varphi_2|u_2\rangle|^2} \to \frac{1}{|\langle\varphi_{EP}|u_{EP}\rangle|^2} \to \infty$$



Sum rule of zero-point energy

- Total field energy (with rotating wave approximation)

$$\hat{H} = \int dx \left(\frac{1}{2} \epsilon_0 \hat{E}^2 \times 2 \right)_{\substack{\text{time} \\ \text{average}}} \simeq \sum_{m,n} \hbar \sqrt{\omega_m \omega_n} \left[\hat{a}_m^{+} \hat{a}_n A_{mn} + \underbrace{\frac{1}{2} K_{nm} A_{mn}}_{\text{zero-point energy}} \right]$$

where $A_{nm} \equiv \langle u_n | u_m \rangle, K_{nm} \equiv e^{i(\theta_m - \theta_n)} \sqrt{K_{nn} K_{mm}} A_{mn}$ and

$\theta_n = \mathrm{Arg}\left[\int u_n^2(x) dx \right]$.

- Zero-point energy is enhanced for diagonal terms, $K_{nn} > 1$

→ can enhance spontaneous emission into nth mode.

- Sum rule $\sum_{n,m} K_{nm} A_{mn} = p$, where p is the total number of cavity modes.

→ total zero point energy is conserved

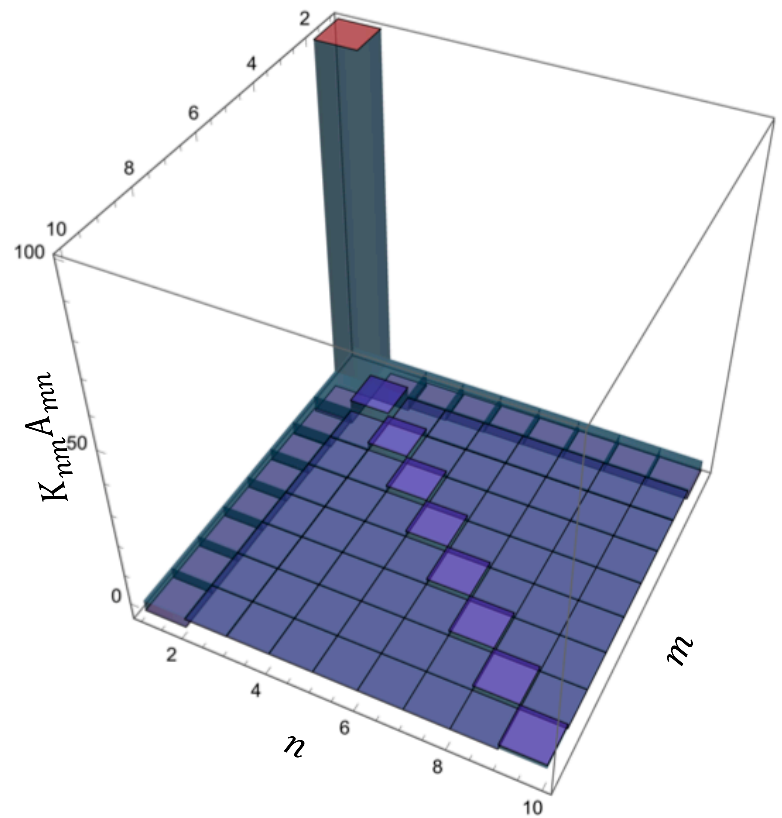
$$\frac{1}{2} \sum_{m,n} \hbar \sqrt{\omega_m \omega_n} K_{nm} A_{mn} \simeq \frac{1}{2} \sum_{n} \hbar \omega_n$$

→ total spontaneous emission is unchanged.

Simulation

Sum rule: $$\sum_{n,m} K_{nm}A_{mn} = p = 10$$

$K_{11} \simeq 100, K_{22} \simeq 3, K_{33} \simeq 2, K_{44} \simeq 2.67, \dots, K_{12}A_{21} \simeq -5.35, K_{13}A_{31} \simeq -0.47$, etc



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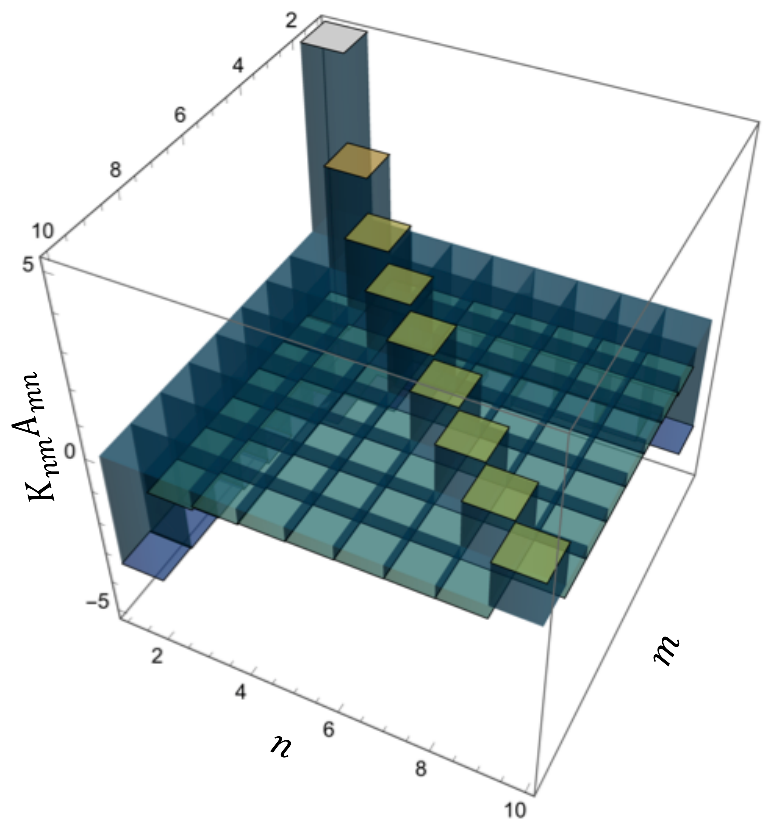
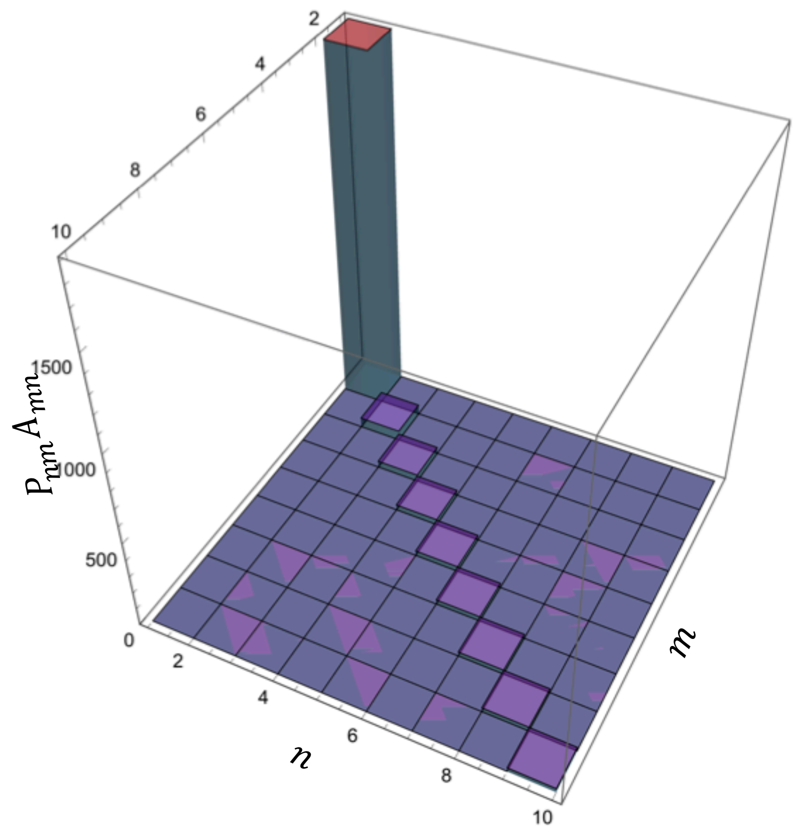
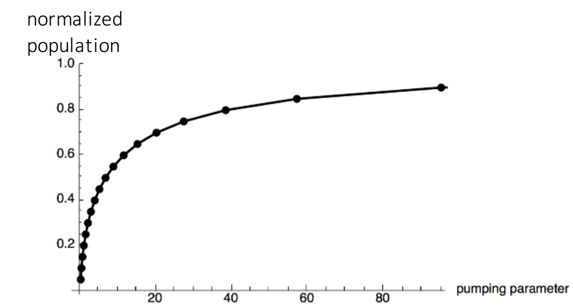
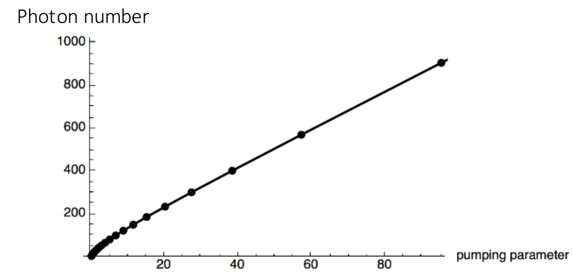


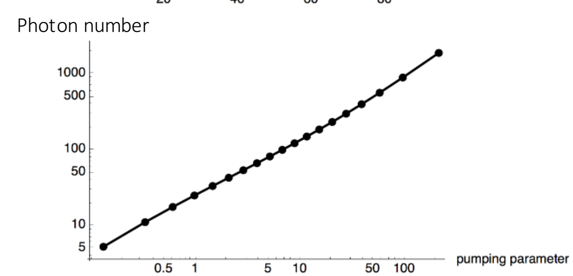
Simulation, near EP lasing

- $P_{11} \simeq 1400$ is the strongest. $P_{12} \simeq -0.5$ because of the large detuning.
- Thresholdless lasing
- Upperbound of $K_{nn} \sim 10^{13}$ (breakdown of dipole approximation)









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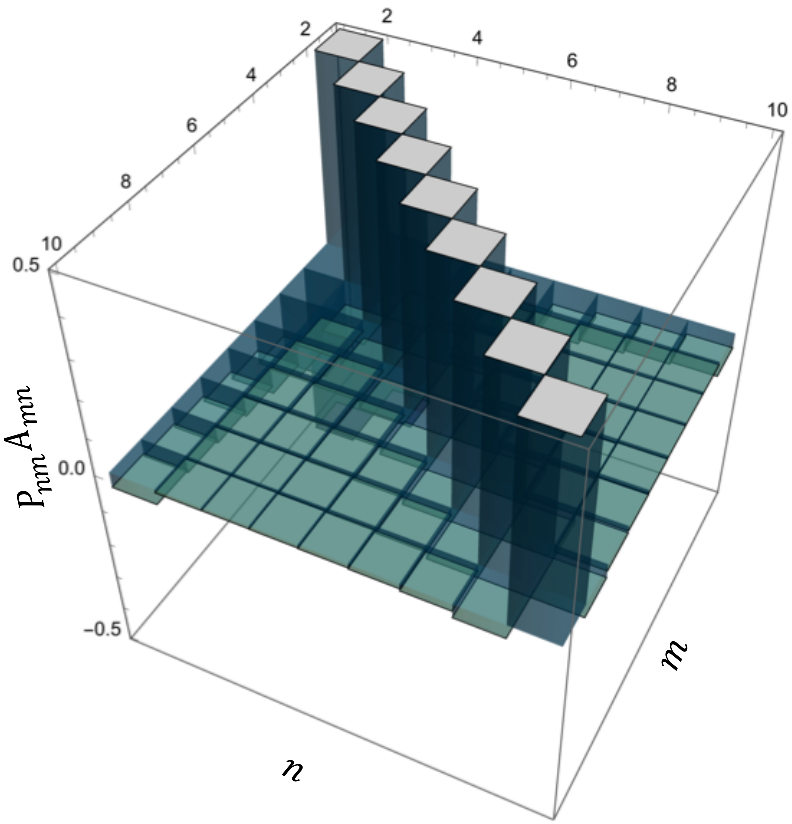
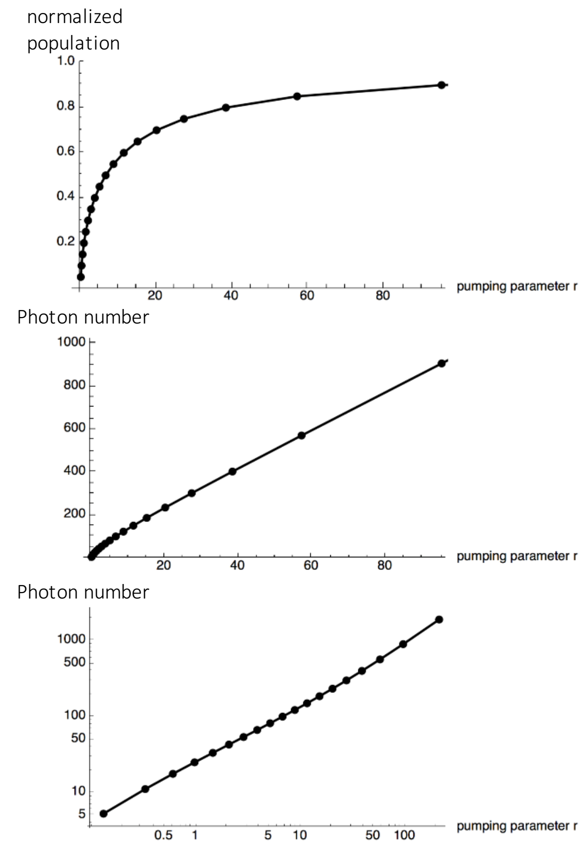
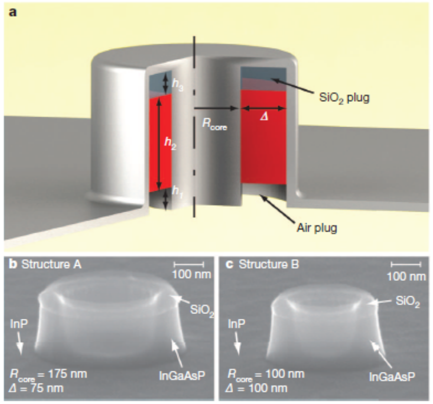
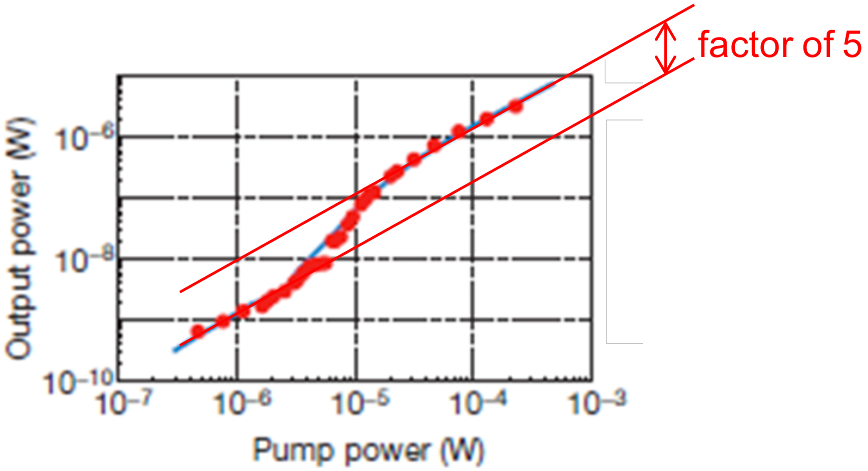




Conventional approach

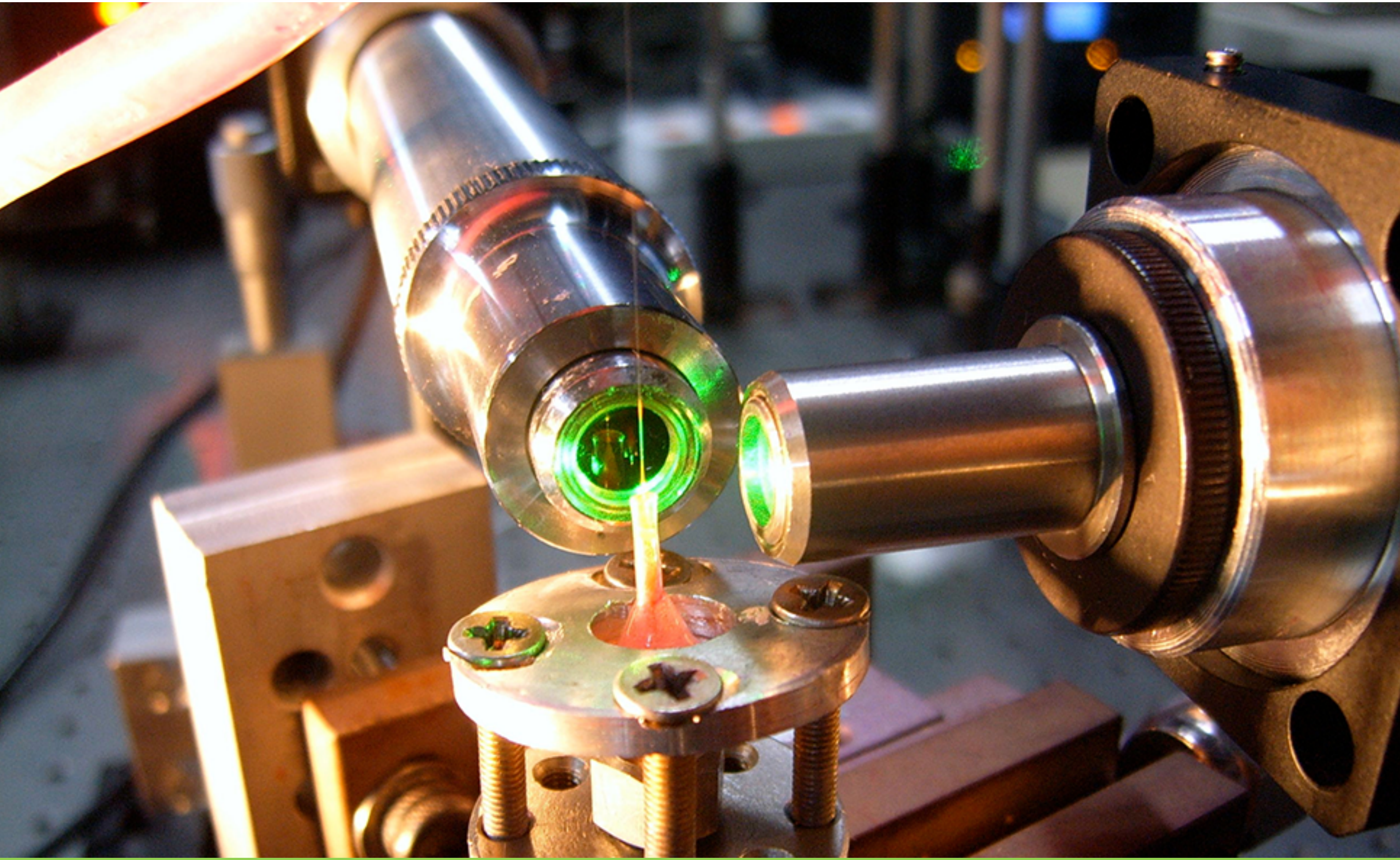
- All thresholdless lasers are based on the Purcell factor: spontaneous emission enhancement due to a small mode volume and a high Q
- To achieve thresholdless lasing, the mode volume → λ^3
- Relatively low Q → high pump density → heat dissipation problems, short life time, low temp operation





M. Khajavikhan *et al.*, Nature **482**, 204 (2012)

Preliminary experiment



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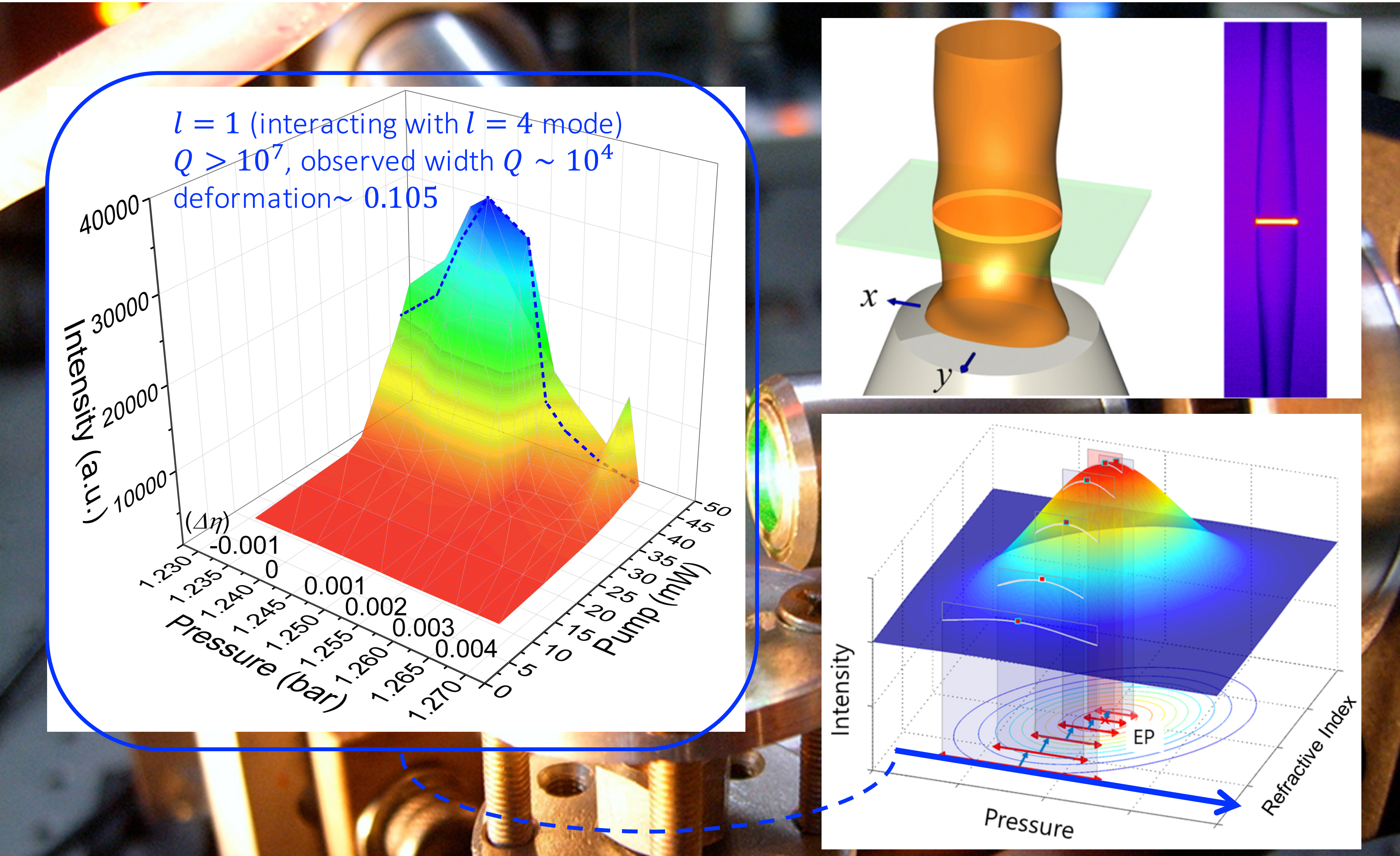


Further information

- Visit our homepage, http://sal.snu.ac.kr.
- Send e-mail inquiry to kwan@phya.snu.ac.kr or call 8286.
- Drop by my office at 56-324.

Quantum Field Laser Laboratory

NRF National Research Foundation of Korea

The second stage of BK21

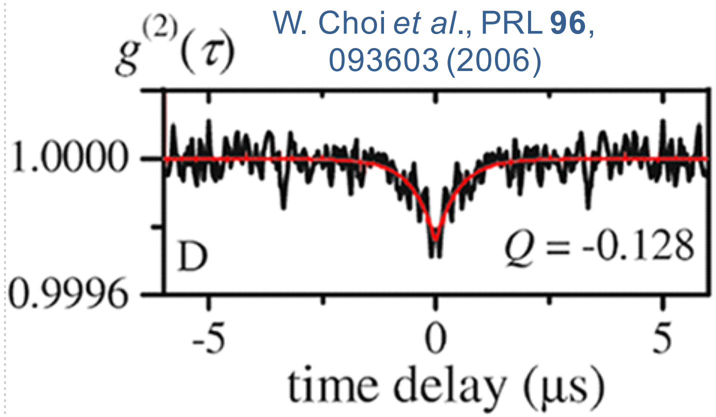
SAMSUNG 삼성미래기술육성재단 Samsung Science and Technology Foundation

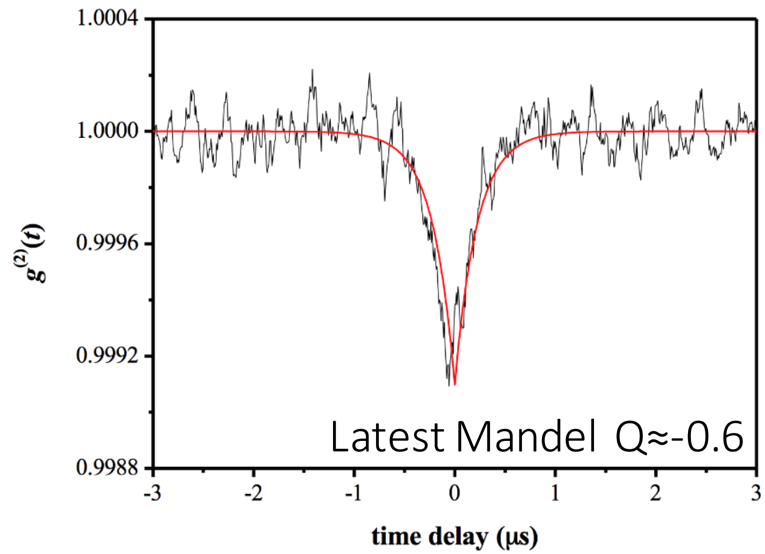
SUPPLEMENTARY MATERIALS

Highly sub-Poisson intense light

- Photon number stabilization occurs in the saturation region.
- Theoretical prediction, Mandel Q≈-0.7
  - variance $(\Delta n^2) = 0.3\langle n\rangle$, only 30% of the shot-noise variance.

W. Choi *et al*., PRL **96**, 093603 (2006)





$$g^{(2)}(t) = 1 + \frac{Q}{\langle n\rangle} e^{-t/\tau}$$

The second order correlation function

$$Q = \frac{\langle n^2\rangle - \langle n\rangle^2}{\langle n\rangle} - 1$$

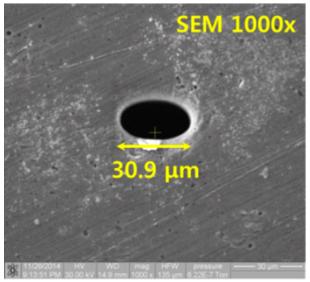
Mandel Q

$Q > 0$ super-Poisson
$Q = 0$ Poisson
$Q < 0$ sub-Poisson

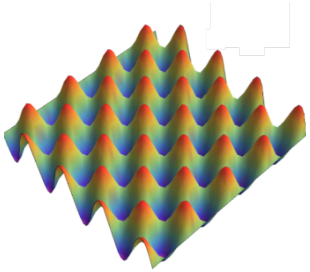
photon statistics

Extension to practical forms

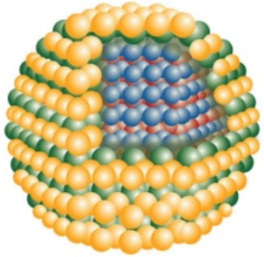
- Develop FIB technique for fabricating various microjet nozzles



- Simulate a stationary QDM by using an optical lattice in a cavity



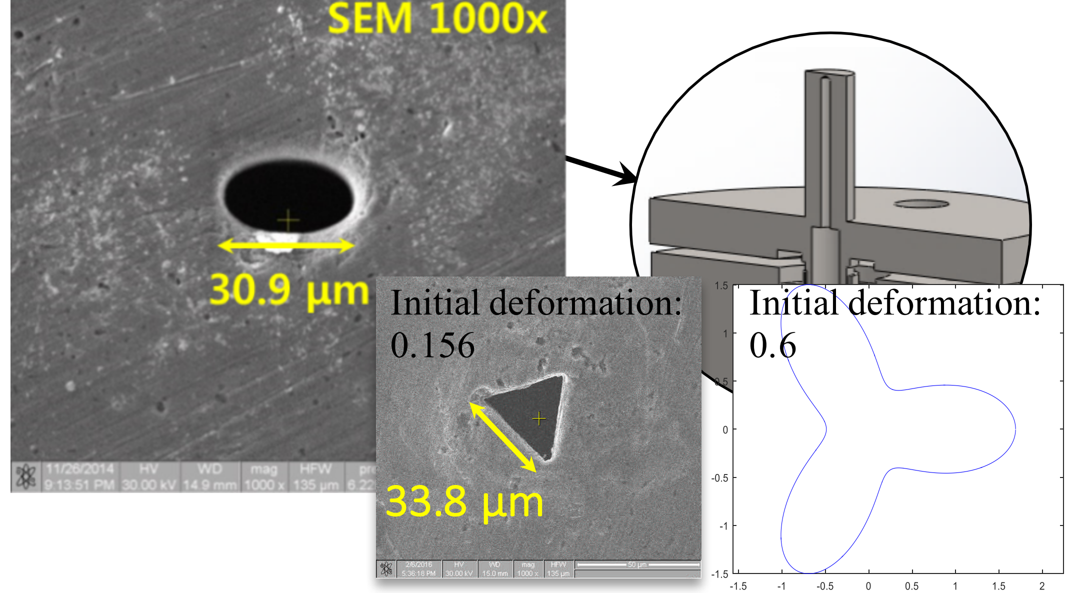
- Design a thresholdless quantum-field microlaser with artificial atoms (e.g., excitons, polaritons, surface plasmons, etc.)

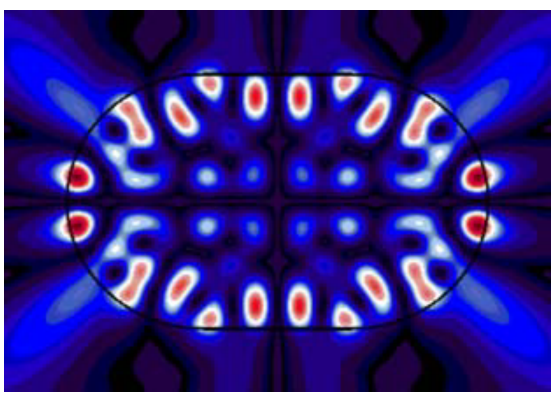


FIB technique for microjet nozzles

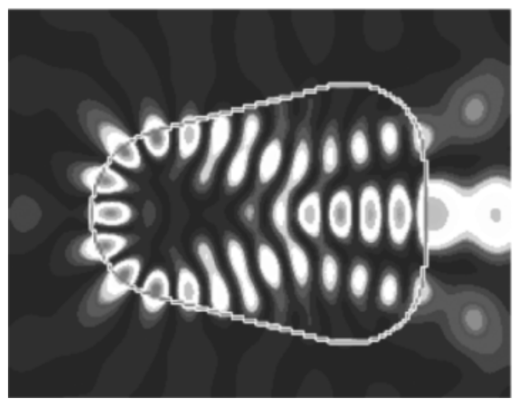
- FIB precision: 10nm
- Simulating various cavity shapes & array of cavities
- Compact optofluidic packaging possible

Sectional view

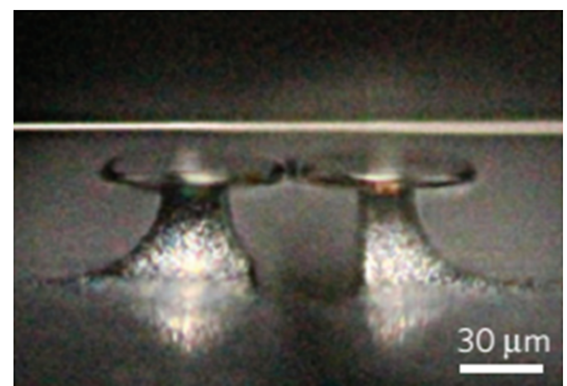




a stadium
Lee *et al.*, Phys. Rev. A **78**, 015805 (2008)



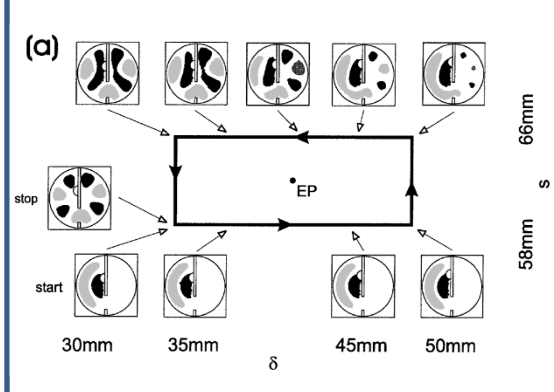
a rounded triangle
Kurdoglyan *et al.*, Opt. Lett. **29**, 2758 (2004)



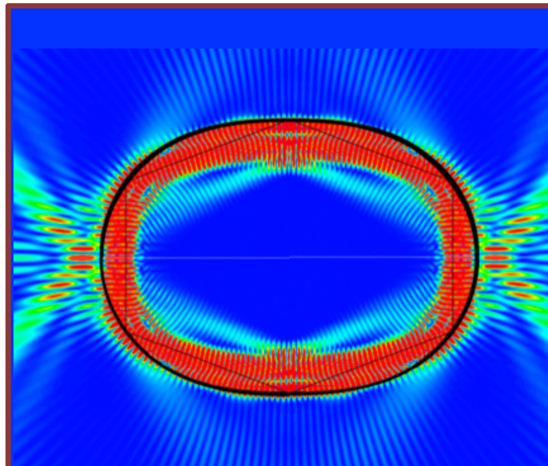
coupled disks
Peng *et al.*, Nat. Phys. **10**, 394 (2014)

EP in various physical systems

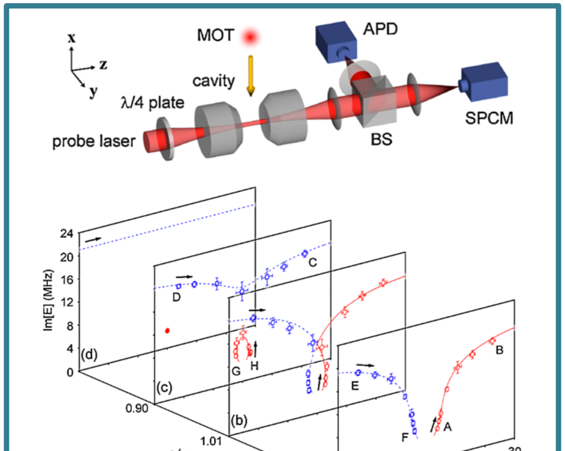
- Various examples of EP
  - Microwave cavity
  - Deformed microcavity
  - Atom-cavity quantum composite (atom-photon)
  - Coupled disk laser
  - Exciton-polariton in semiconductor



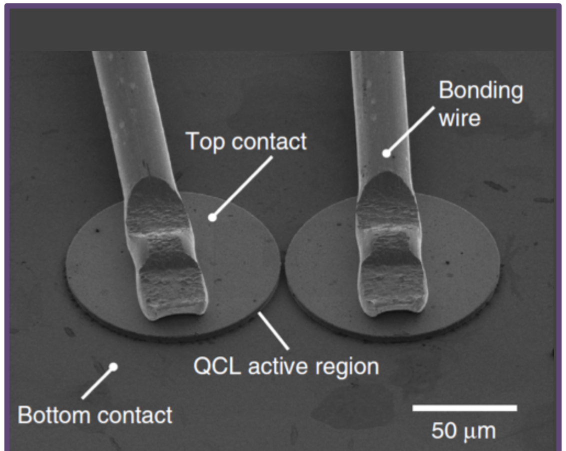
C. Dembowski et al., PRL **86**, 787 (2001)



S.-B. Lee *et al.*, PRL **103**, 134101 (2009)



Y. Choi et al., PRL **104**, 153601 (2010)



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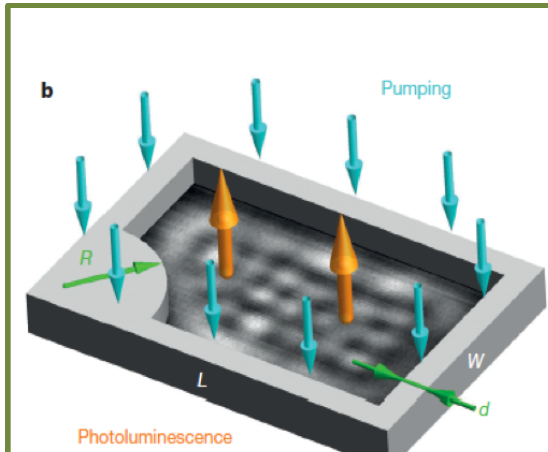

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