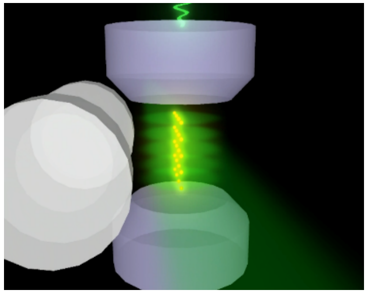
2017 Introduction to Our Research Programs

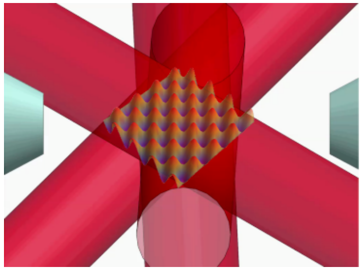
Quantum-Field Laser Laboratory

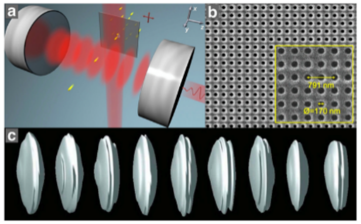
KW An's Group

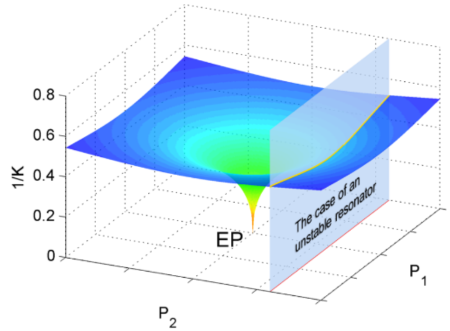
Physics of atom-field interaction

- Quantum information
  - Ideal single-photon sources
  - Ideal single-photon detectors
- Nonclassical light generation
  - Highly sub-Poisson intense light
  - Single-atom superradiance
  - Thresholdless lasing
- Manipulation of vacuum fluctuation
  - 3D imaging of vacuum fields
  - Enhanced emission near an exceptional point

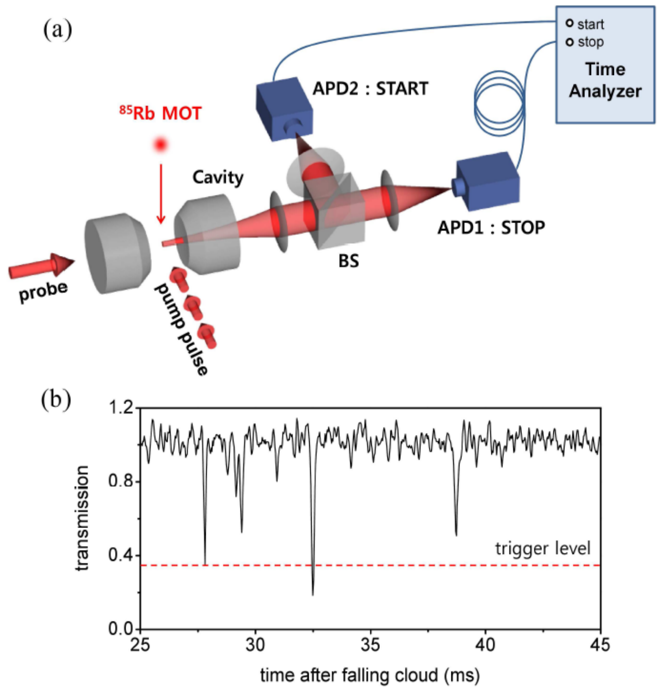


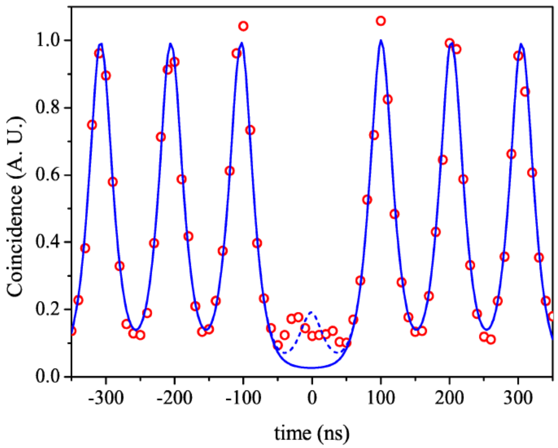






Single-photon generation on demand (2011)

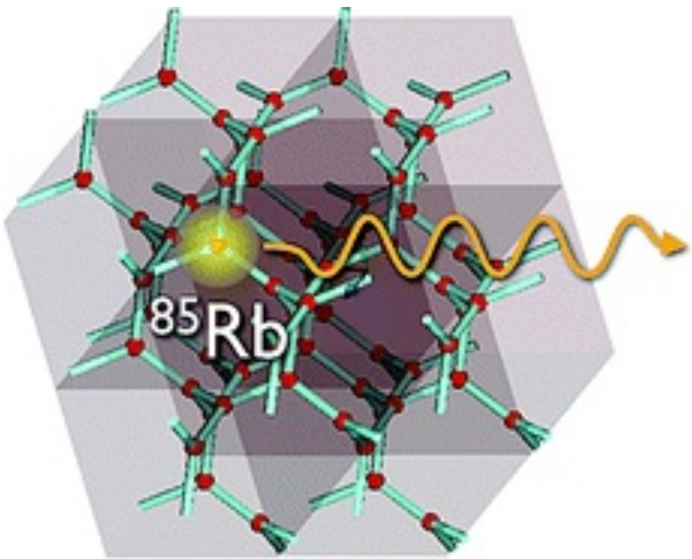


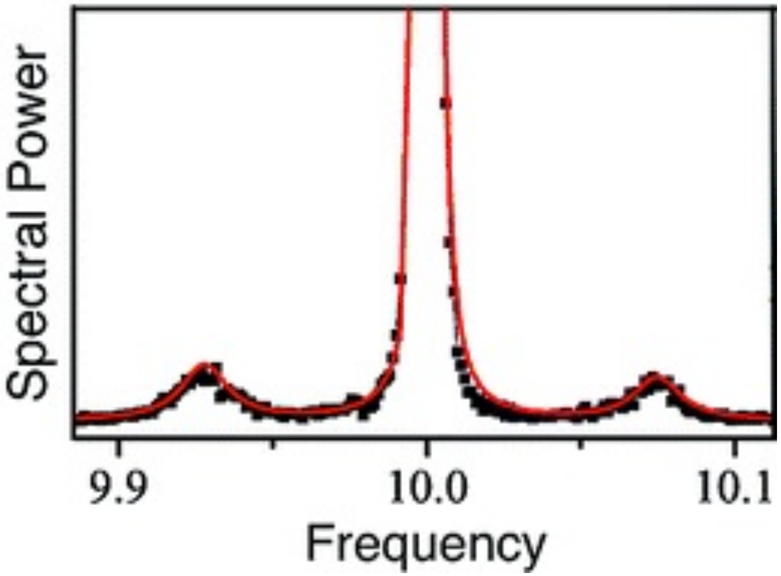


Sungsam Kang *et al.*, "Controlled generation of single photons in a coupled atom-cavity system at a fast repetition-rate", Optics Express **19**, 2440(2011)

- One atom trapped in a cavity
- A pi-pulse excitation induces single-photon emission.
- 10 MHz operation with 15% overall efficiency

Single atom spectrum in an optical lattice (2011)



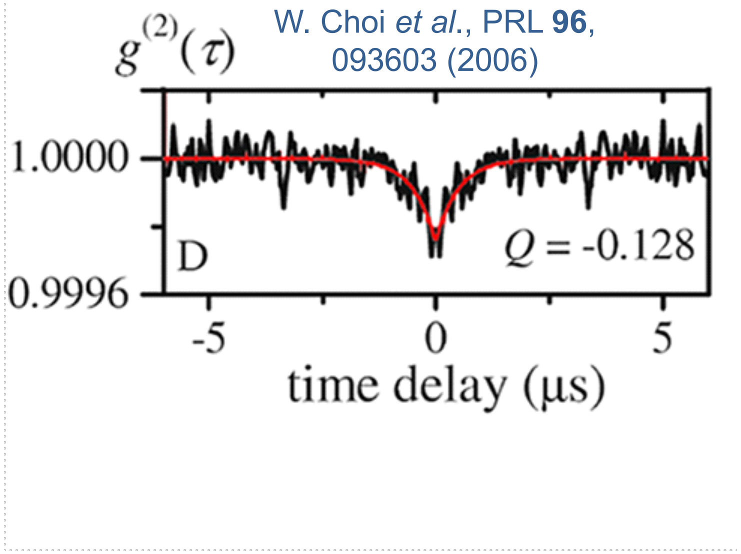


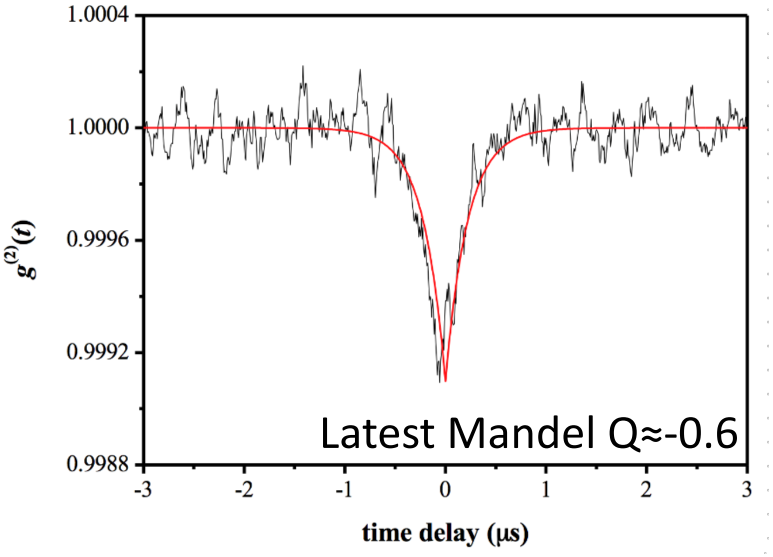
W. Kim *et al.*, Nano Letters **11**, 729 (2011)

- Single rubidium atom trapped in an optical lattice
- Lamb-Dicke regime, exhibiting three-peak spectrum
- Line broadening due to matter-wave tunneling among potential minima

Highly nonclassical intense light (2015)

- Photon number stabilization in the microlaser leads to nonclassical radiation.
- Theoretical prediction, Mandel Q≈-0.7 (-1.0 for a Fock state)
  - variance $\langle \Delta n^2 \rangle = 0.3\langle n \rangle$, only 30% of the shot-noise variance.



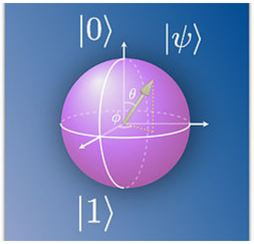


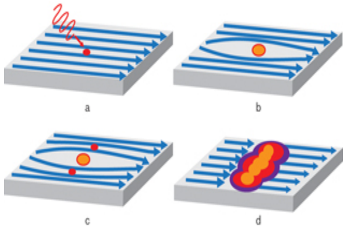
Quantum Information

I. Ideal Single-Photon Detector

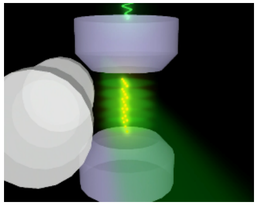
Why ideal single-photon detectors?

- Needs
  - photon-qubit-based quantum information processing
  - Detection of axion dark matter
- Current technology
  - Superconducting nanowire detectors at 2K
  - Avalanche photodiodes
- Our goal:
  - to realize an ideal optical/μ-wave single-photon detector at room temperature (low cost) based on
    - quantum dipole material
    - cavity-QED principle

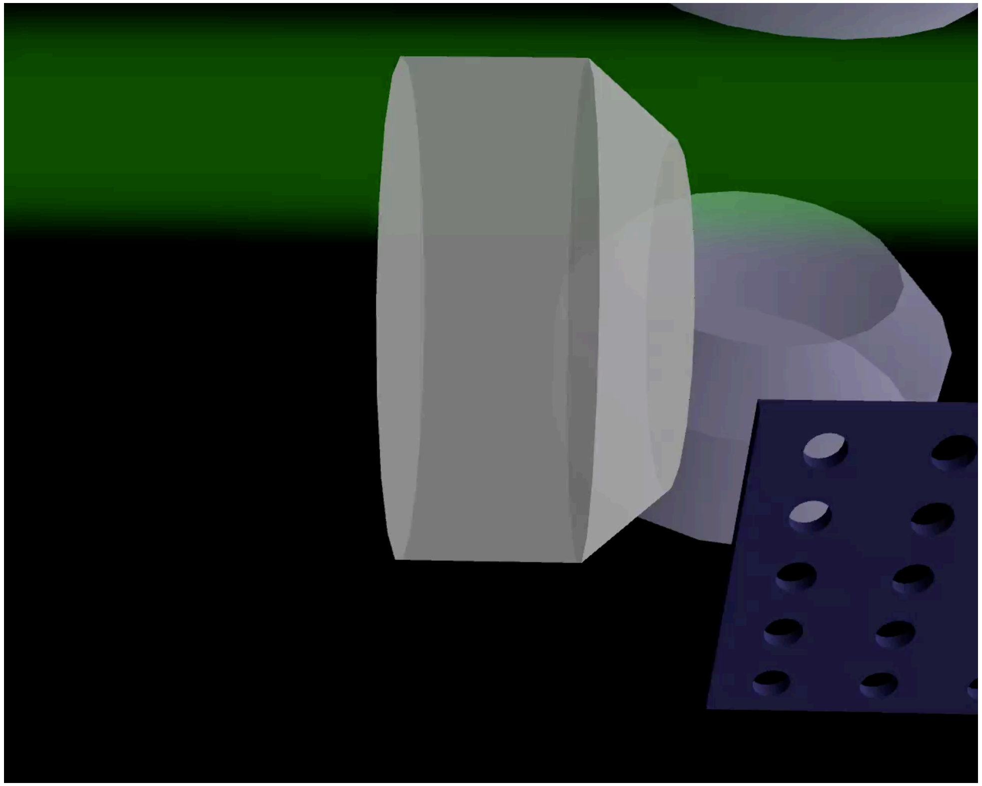


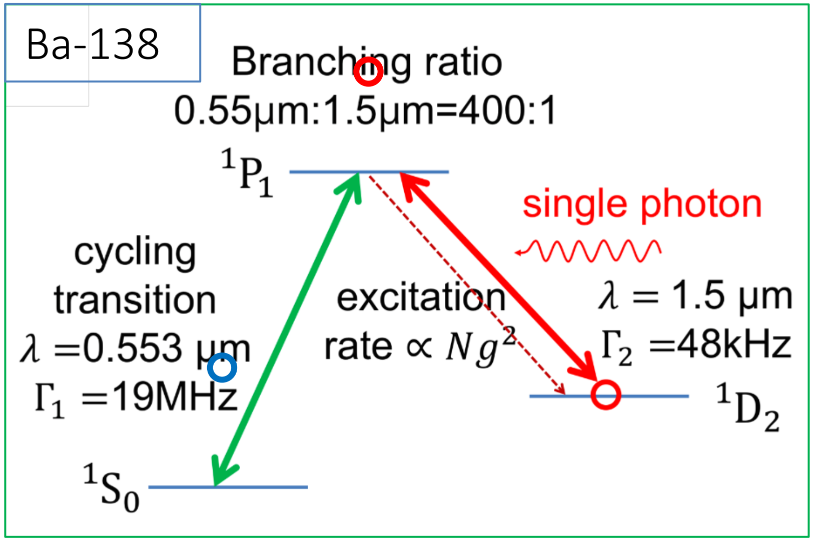


RLE@MIT



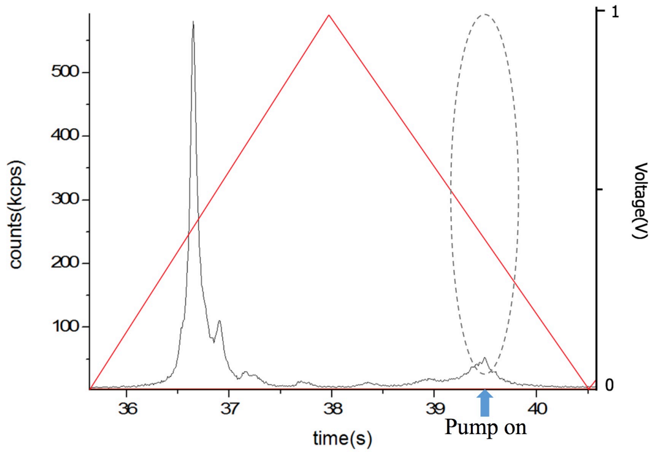
Optical single-photon detector

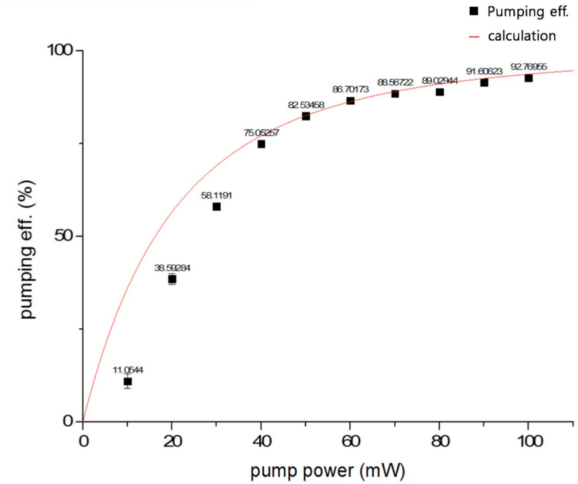


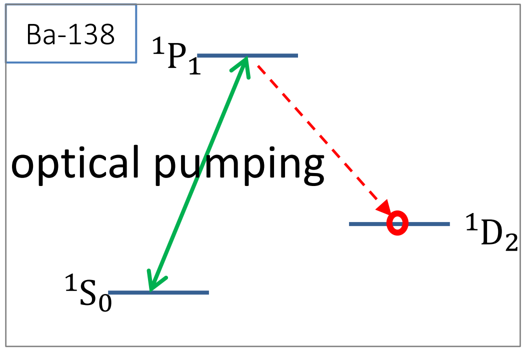


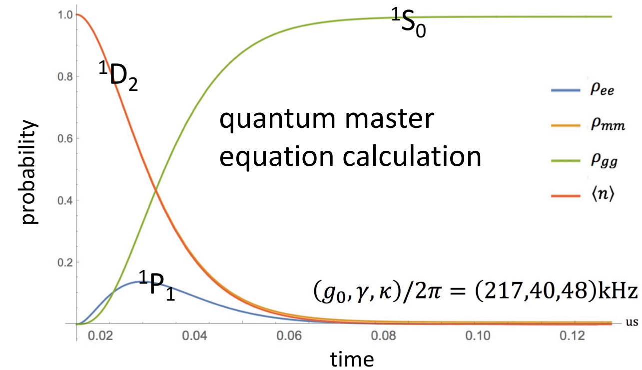
- Barium atoms in a beam localized by a nanohole array
- 1 input photon will generate about 400 output photons (gain=400) → photon amplifier
- Near-100% single-photon detection efficiency can be achieved.

Progress for the single-photon detector









- Preparing Ba atoms in $^1D_2$ state by optical pumping
- 1 red photon will induce one atom to go to $^1S_0$ ground state with 99% probability.
- A probe will drive the atom, generating 300 green photons → The event is detected with 100% probability.

Nonclassical light generation

II. Single-Atom Superradiance

Dicke's Superradiance

- In 1954, Robert H. Dicke predicted collective emission of densely packed emitters.

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

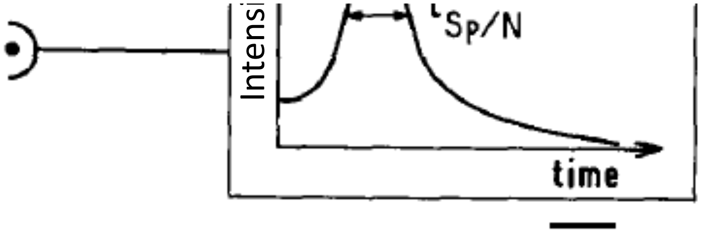
Coherence in Spontaneous Radiation Processes

R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

By considering a radiating gas as a single quantum-mechanical system, energy levels corresponding to certain correlations between individual molecules are described. Spontaneous emission of radiation in a transition between two such levels leads to the emission of coherent radiation. The discussion is limited first to a gas of dimension small compared with a wavelength. Spontaneous radiation rates and natural line breadths are calculated. For a gas of large extent the effect of photon recoil momentum on coherence is calculated. The effect of a radiation pulse in exciting "super-radiant" states is discussed. The angular correlation between successive photons spontaneously emitted by a gas initially in thermal equilibrium is calculated.

superradiance

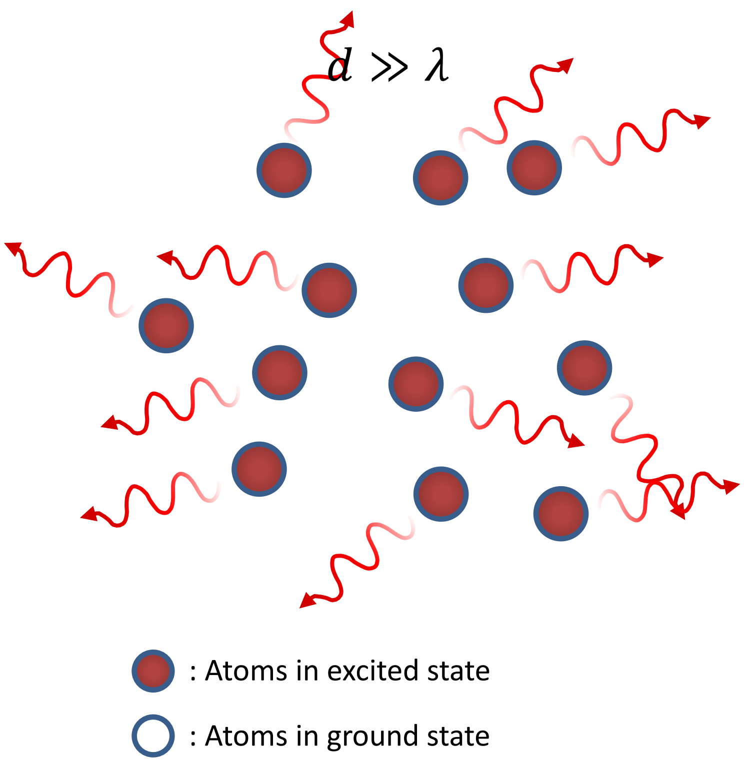
$d \ll \lambda$

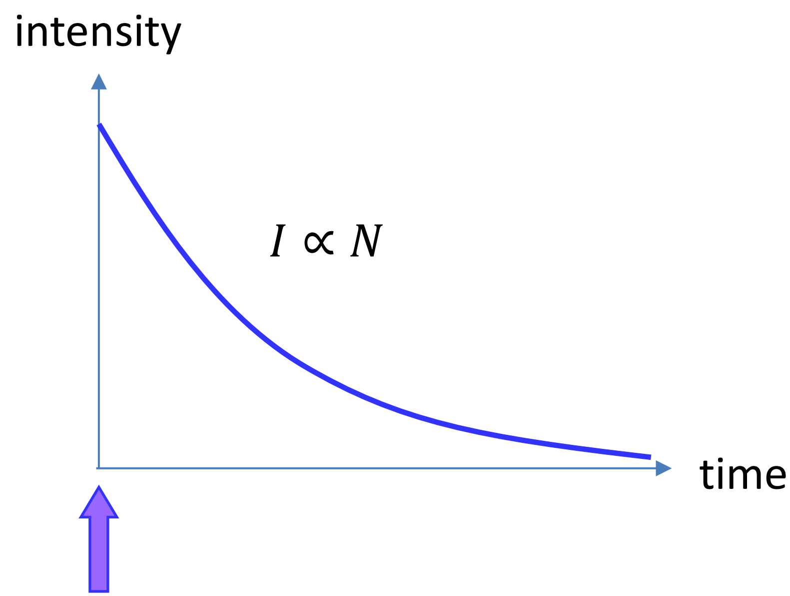


Review by M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982).

Ordinary emission

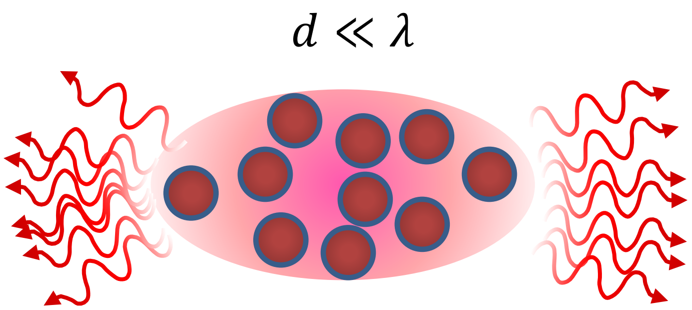
- Atoms emit photons individually.
- (Emission power) ∝ (number of excited atoms)



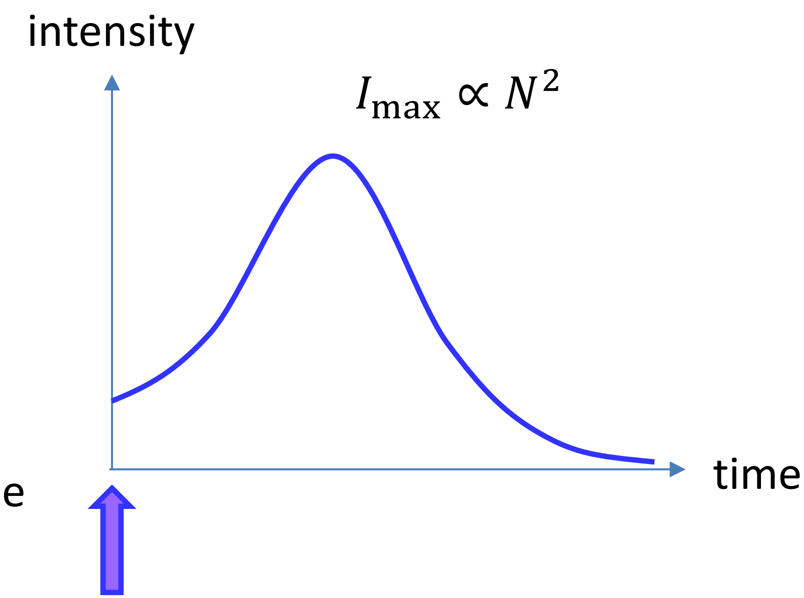


Superradiance

- Densely packed, impossible to distinguish which atom emits.
  → Phase correlation emerging → Collective decay of atoms



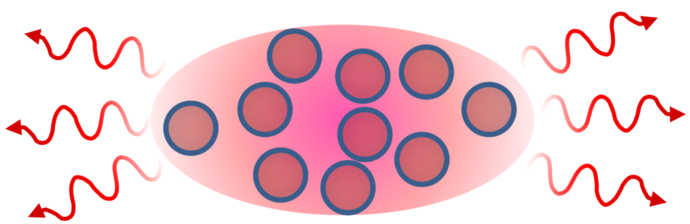
$\langle \sigma_i^+ \sigma_j \rangle > 0$: atoms have the same phase



Superradiance

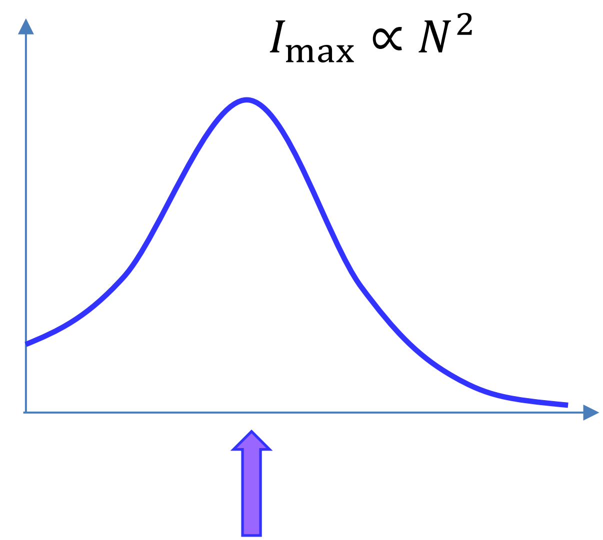
- Densely packed, impossible to distinguish which atom emits.
  → Phase correlation emerging → Collective decay of atoms
- Emission power ∝ (number of excited atoms)^2
- Enhanced matter-light interaction
  - Applicable to quantum information & photonics

$d \ll \lambda$



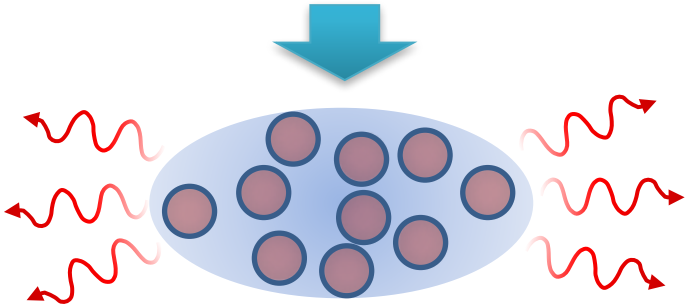
$\langle \sigma_i^+ \sigma_j \rangle > 0$: atoms have the same phase

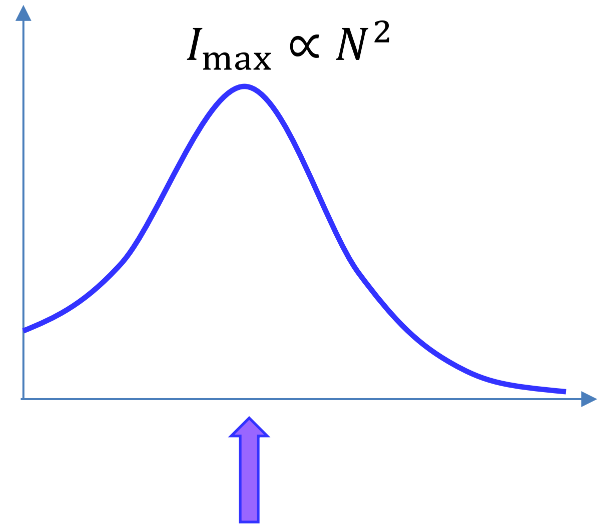
atom-atom correlation



Superradiance by phase-controlled atoms

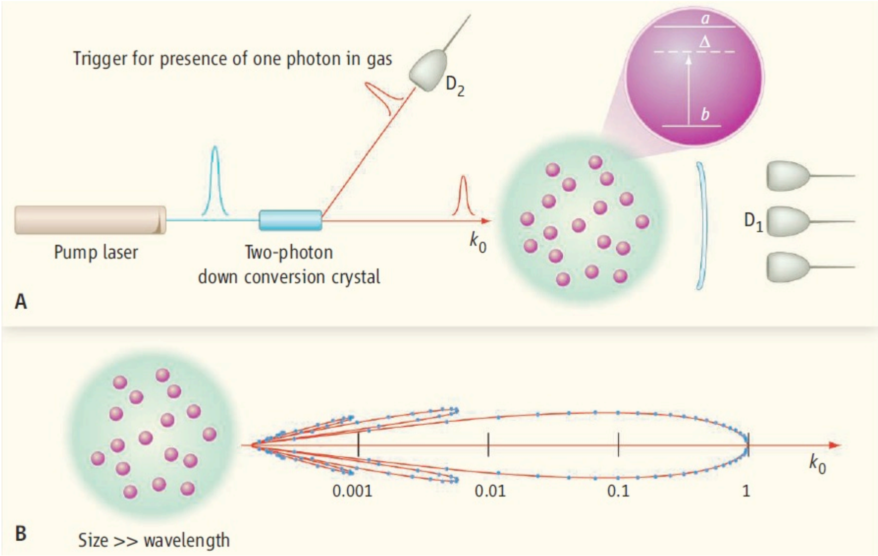
- Superradiance can be initiated by imposing atomic phase correlation with a pump field.
- Immediate strong radiation
- Tunable between superradiance and subradiance





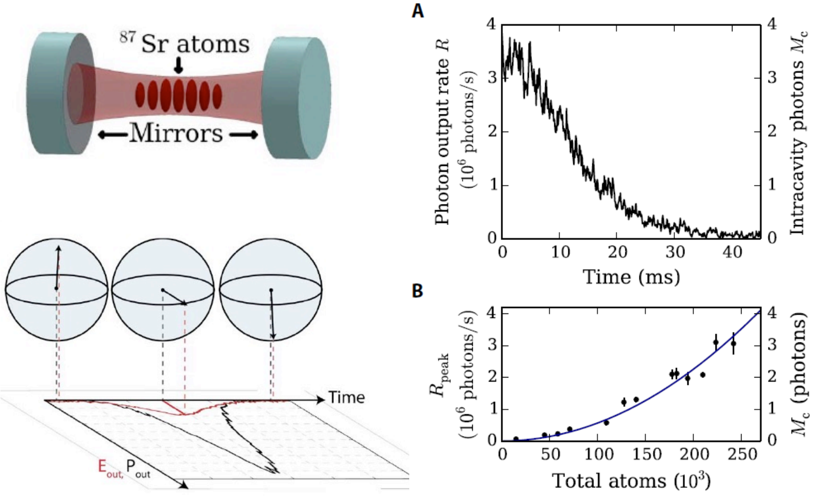
Superradiance of phase-controlled atomic ensemble (top down)

Single-photon superradiance



M. O. Scully and A. A. Svidzinsky, Science **325**, 1510 (2009).

Seeded superradiance

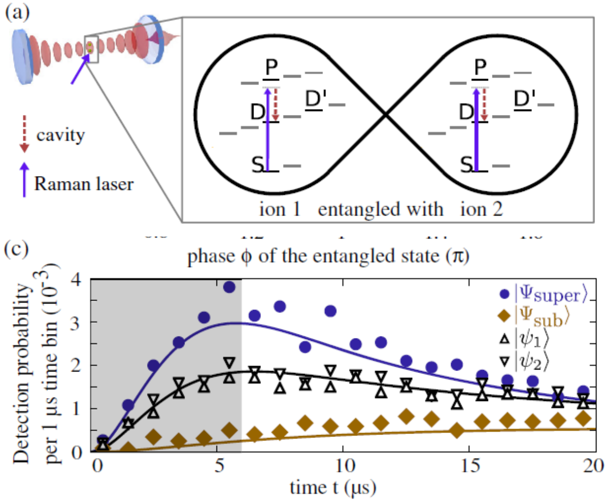


J. K. Thompson's group, Sci. Adv. **2**, e1601231 (2016).

- Phase imprinting by a coherent laser pulse (even a single-photon pulse)
- Spatial modes overlap between input and output fields
- Accessible in the pulse regime

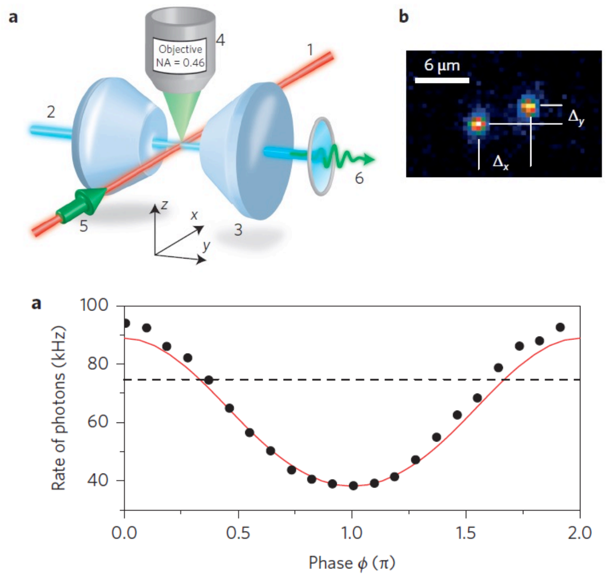
Superradiance of phase-controlled few atoms (bottom up)

Ions



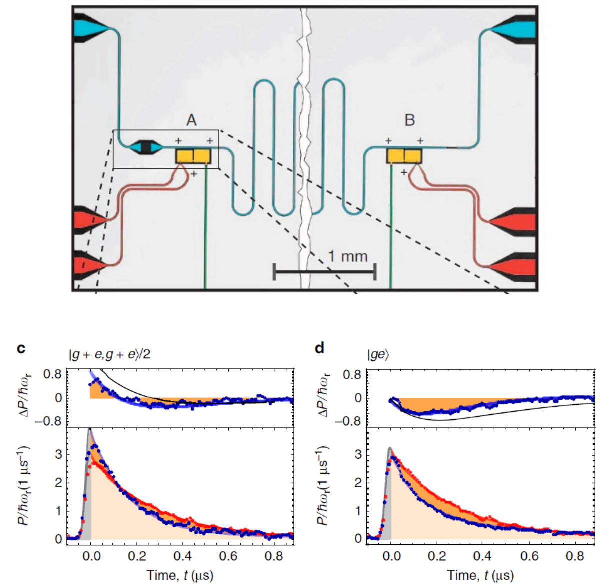
R. Blatt's group, PRL **114**, 023602 (2015)

Neutral atoms



G. Rempe's group, Nat. Photonics **10**, 303 (2016).

Artificial atoms



A. Wallraff's group, Nat. Commun. **5**, 5186 (2015)

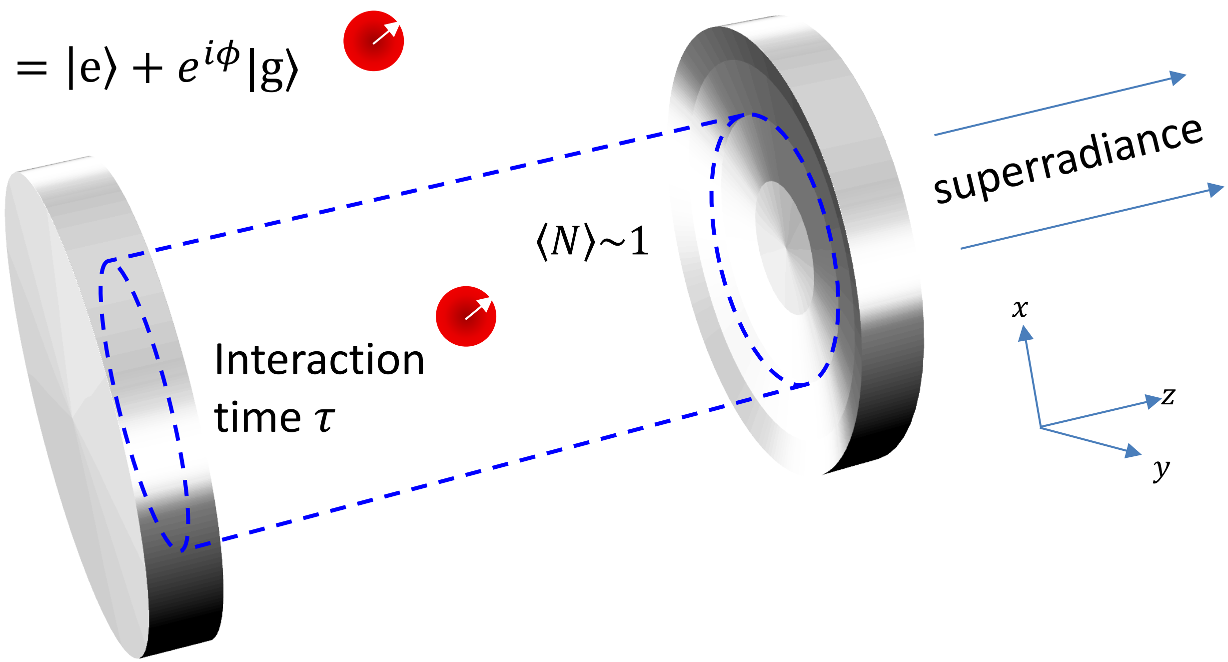
- Direct control of trapped atoms in a cavity
- Only up to two emitters

Single-atom superradiance

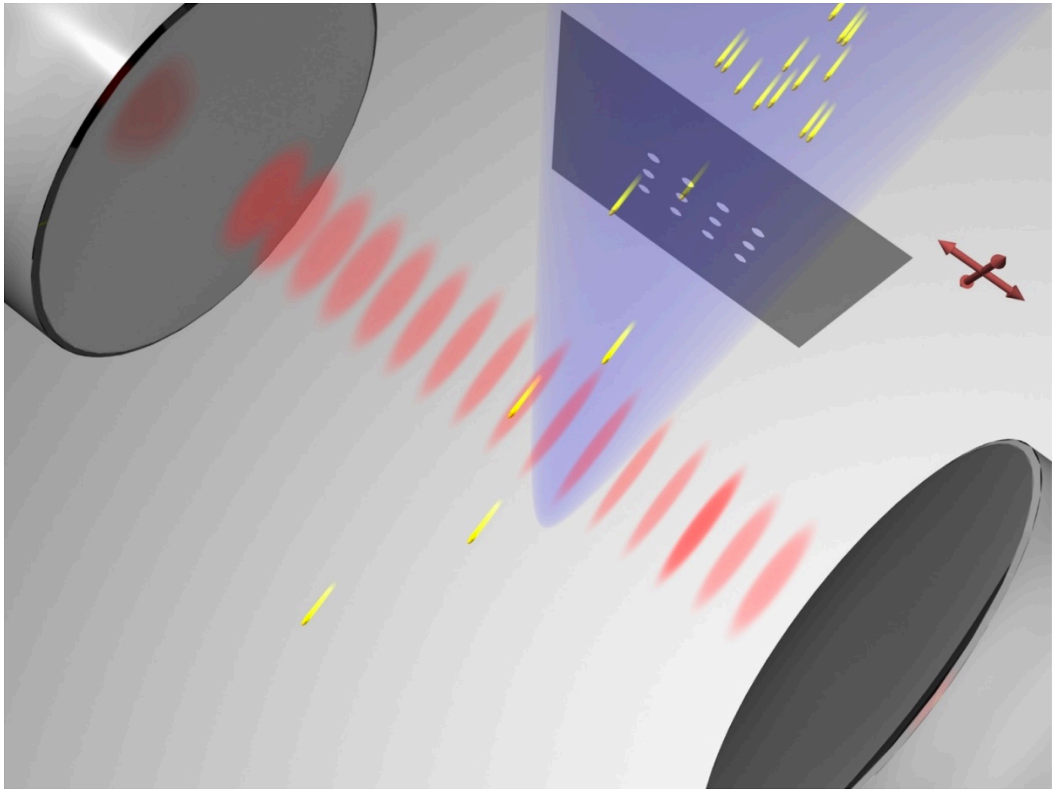
- Inject single atoms in the same superposition state into a cavity.
- Single atoms emit photons collectively with the atoms that have already gone through the cavity.

  → collective behavior among time-separated atoms induced by the long-lived cavity field.

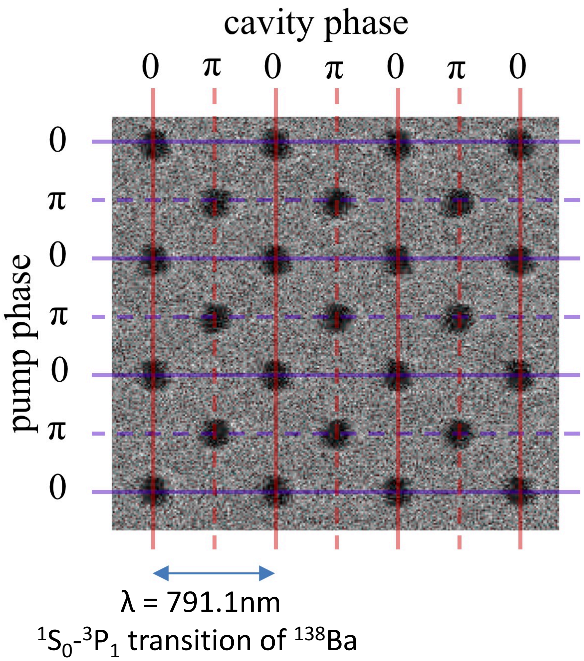
$$|\psi_{\mathrm{atom}}\rangle = |\mathrm{e}\rangle + e^{i\phi}|\mathrm{g}\rangle$$



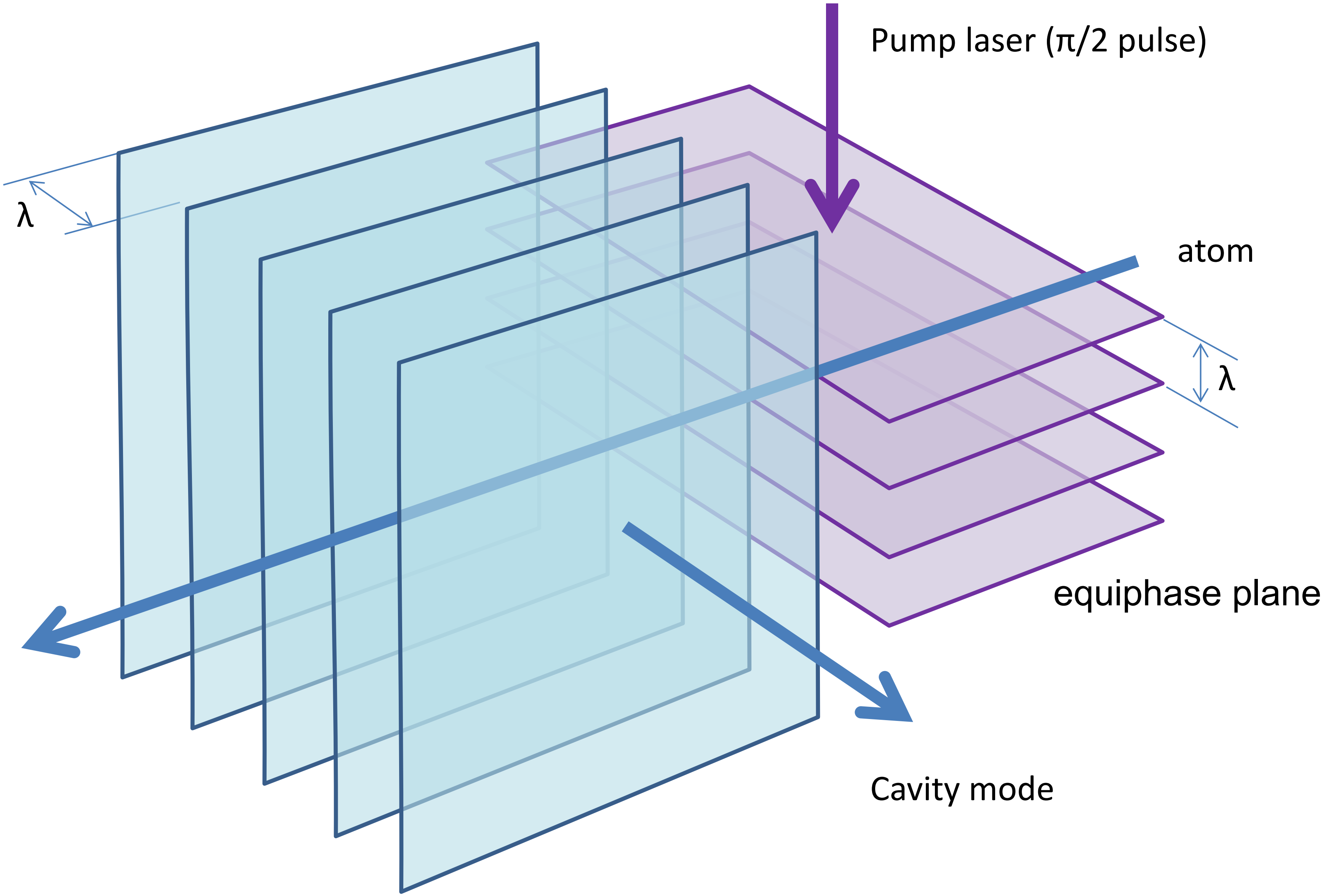
Experimental schematic



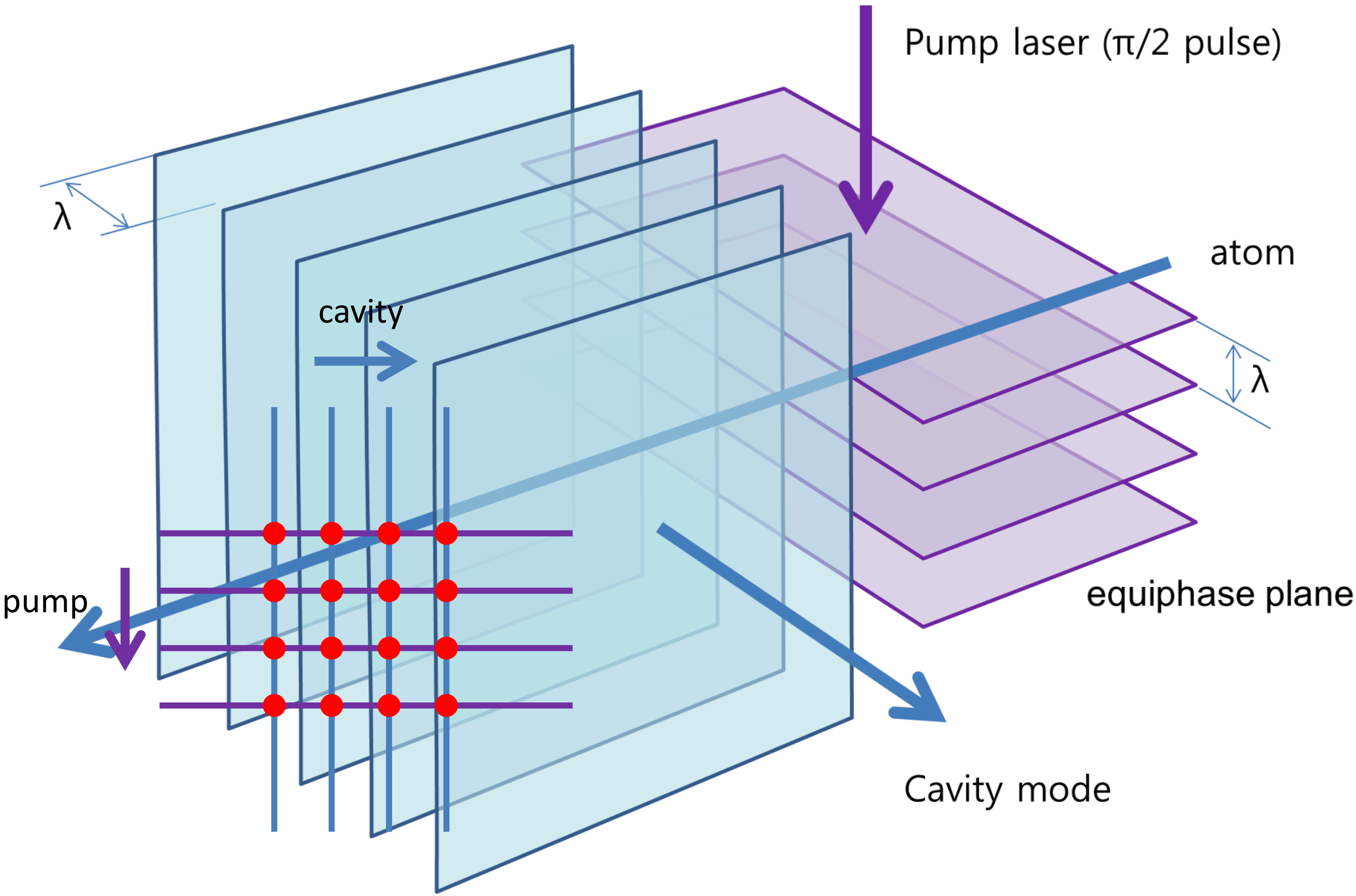
A nanohole array aperture made of Si_3Ni_4 membrane (Focused ion beam image)



How to realize the same phase

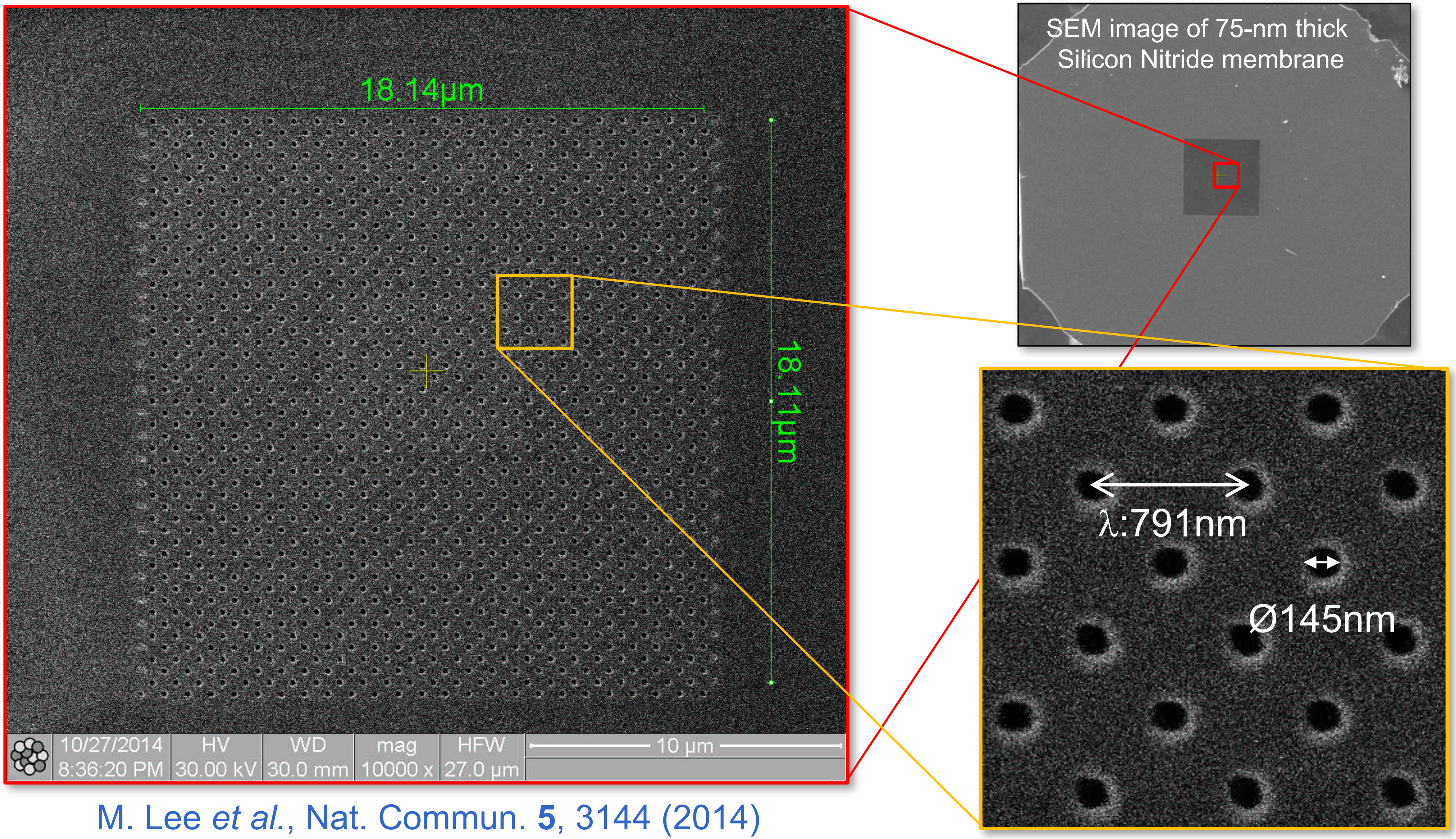


How to realize the same phase



Nanohole array

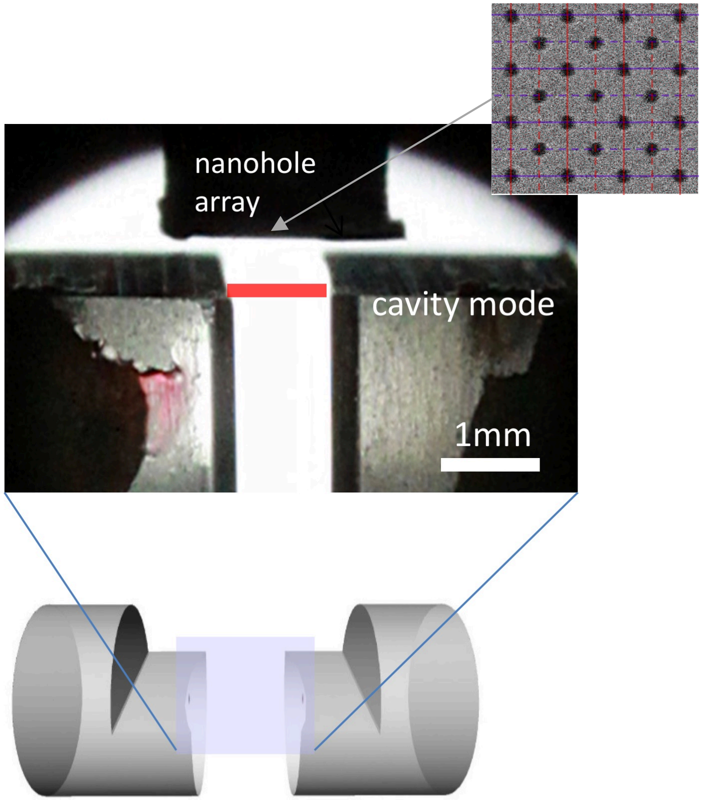
- Machined by focused ion beam (FIB)

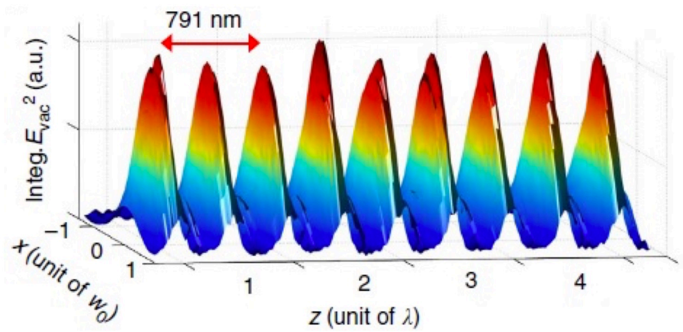


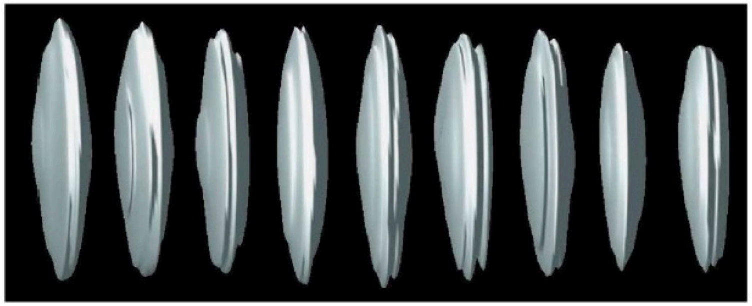
M. Lee *et al.*, Nat. Commun. **5**, 3144 (2014)

3D imaging of vacuum fluctuations

- Excited ^{138}Ba atoms (λ=791 nm, $^1S_0$-$^3P_1$ transition) traverse a high Q cavity one by one.
- Vacuum fluctuation in the cavity triggers the atom to emit a photon.







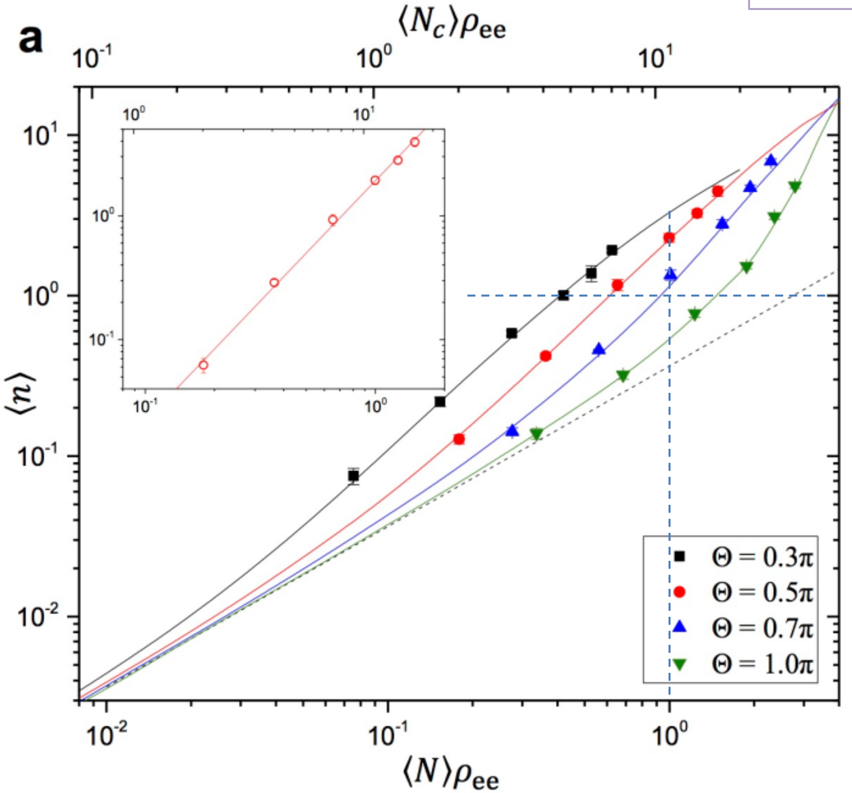
M. Lee *et al.*, Nat. Commun. **5**, 3441 (2014).

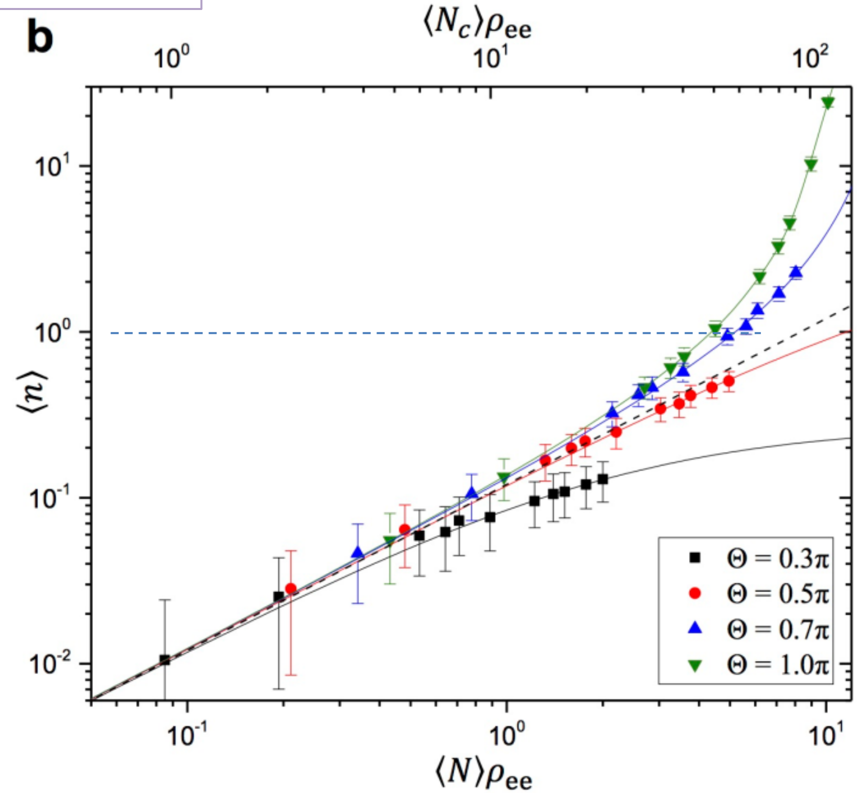
Result – single atom superradiance

Aligned atomic phase

Symbols : Exp. Data
Solid lines : Simulation

Random atomic phase

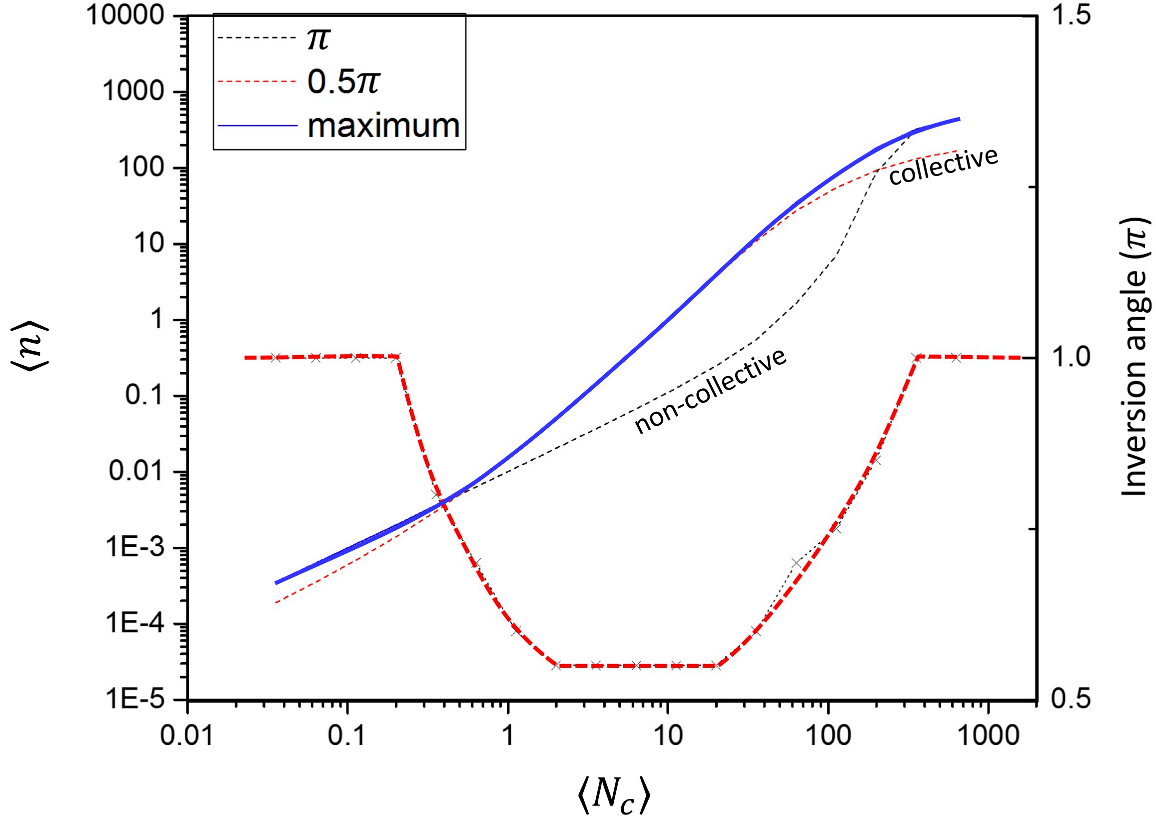




- Log-log slope ($\Theta = 0.5\pi$) = 1.67±0.01 → $\langle n \rangle \propto \langle N \rangle^{1.67}$
  - Without non-collective effect : $\langle n_{SR} \rangle \propto \langle N \rangle^{1.94}$ → the single-atom superradiance
- Slope remains almost constant → thresholdless lasing

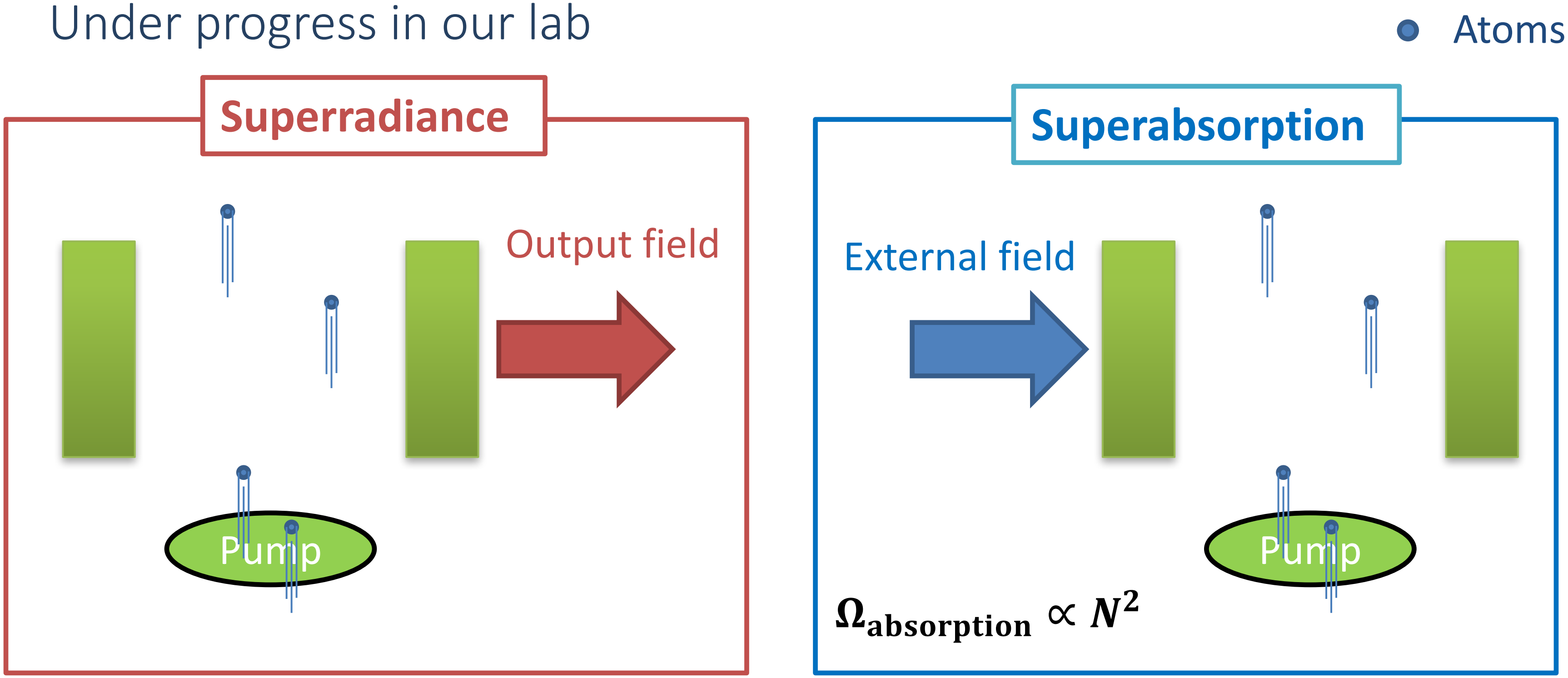
Prospects – the most efficient lasing

- By adjusting inversion angle between 0.5π and π, we can maximize the output while eliminating lasing threshold.



Prospects – superabsorption

- Superabsorption
  - Time reversal process of superradiance
- Efficient light-energy harvesting
- Under progress in our lab

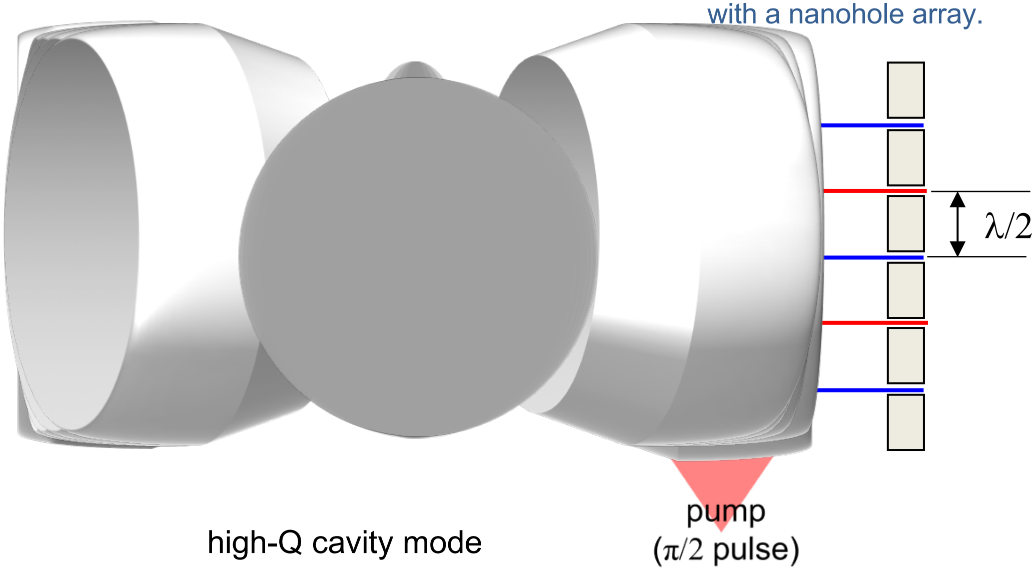


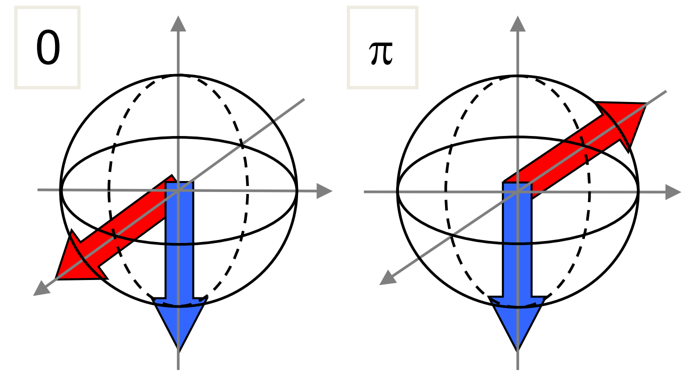
No input → Large Output

Large input → No Output

Prospects – cat state generation

The same phase is ensured with a nanohole array.

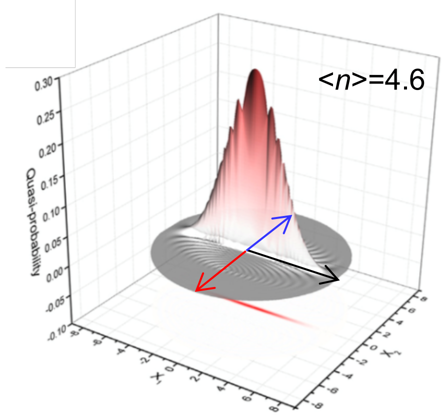




$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle - i|g\rangle\right) \qquad |\psi\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle + i|g\rangle\right)$$

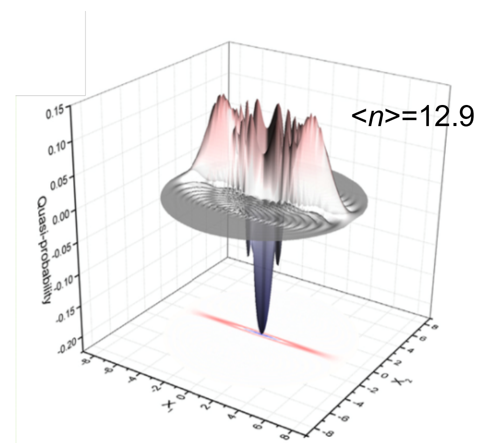
Bloch Sphere

Wigner function of the cavity field



Squeezed vacuum

single-photon decay
(herald)



Schrödinger's-cat-like state

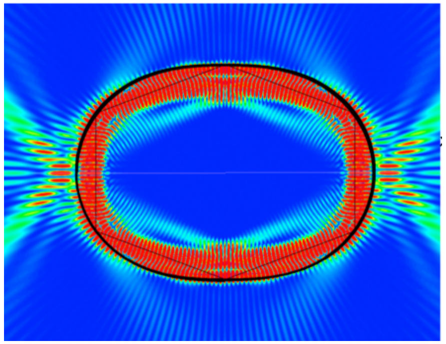
D. Yang *et al.*, PRA **94**, 023826 (2016).

III. Enhanced emission near an exceptional point

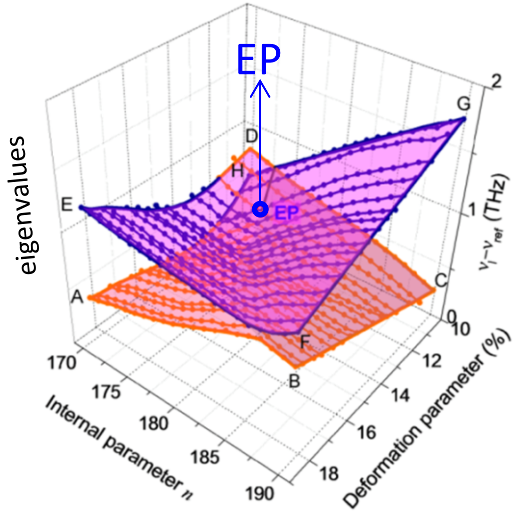
Exceptional point in a non-Hermitian system

- 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)

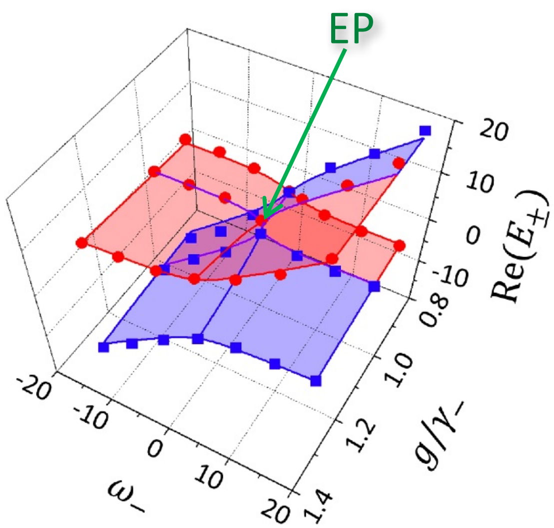
$$H = \begin{bmatrix} \omega - i\gamma_1 & g \\ g & \omega - i\gamma_2 \end{bmatrix}, E_\pm = \omega - i\gamma_+ \pm \sqrt{g^2 - \gamma_-^2}, \text{ where } \gamma_\pm = |\gamma_1 - \gamma_2|/2$$



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 atomic emission is enhanced at an EP?

- 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)

$$0 = \langle \varphi_m|H - H|u_n\rangle$$

$= (E_m - E_n)\langle \phi_m|u_n\rangle$ using $\langle \varphi_m|H = E_m\langle \varphi_m|$, adjoint (left eigenstate)

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

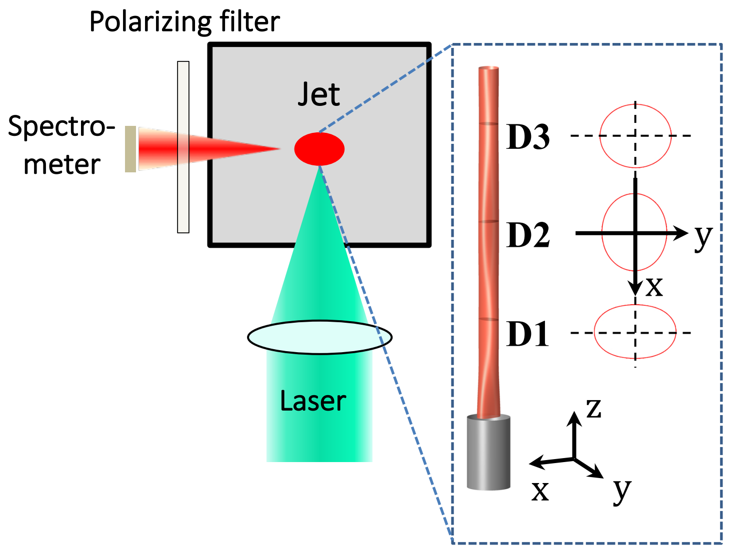
The mode at an EP becomes non-orthogonal to all cavity modes, and therefore, its vacuum fluctuations should be greatly enhanced.

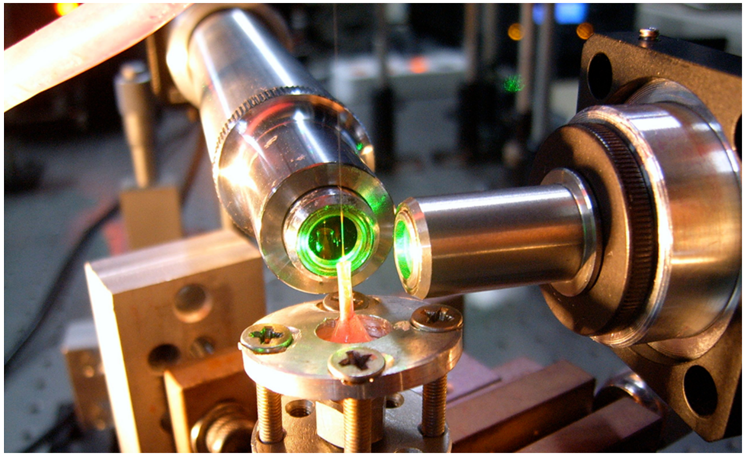
↓

[Hypothesis] Atomic emission will be greatly enhanced when interacting with the mode at an EP → Let's test it experimentally.

Experimental setup

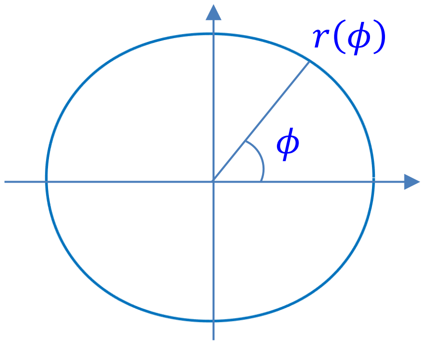
- Cavity deformation η is controlled by ejection pressure. ➔ coupling
- Refractive index can be adjusted by temperature of the jet. ➔ detuning, loss

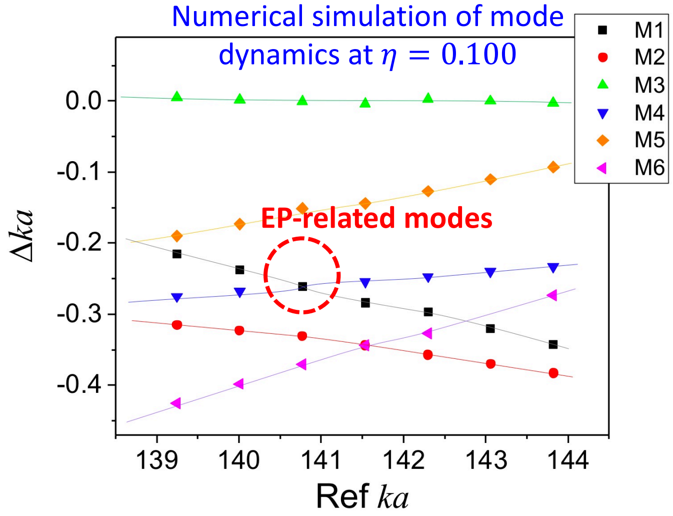




Cavity shape: $r(\phi) = a(1 + \eta \cos 2\phi + 0.42\eta^2 \cos 4\phi)$

Songky Moon et al., Scientific Reports **6**, 19805 (2016).



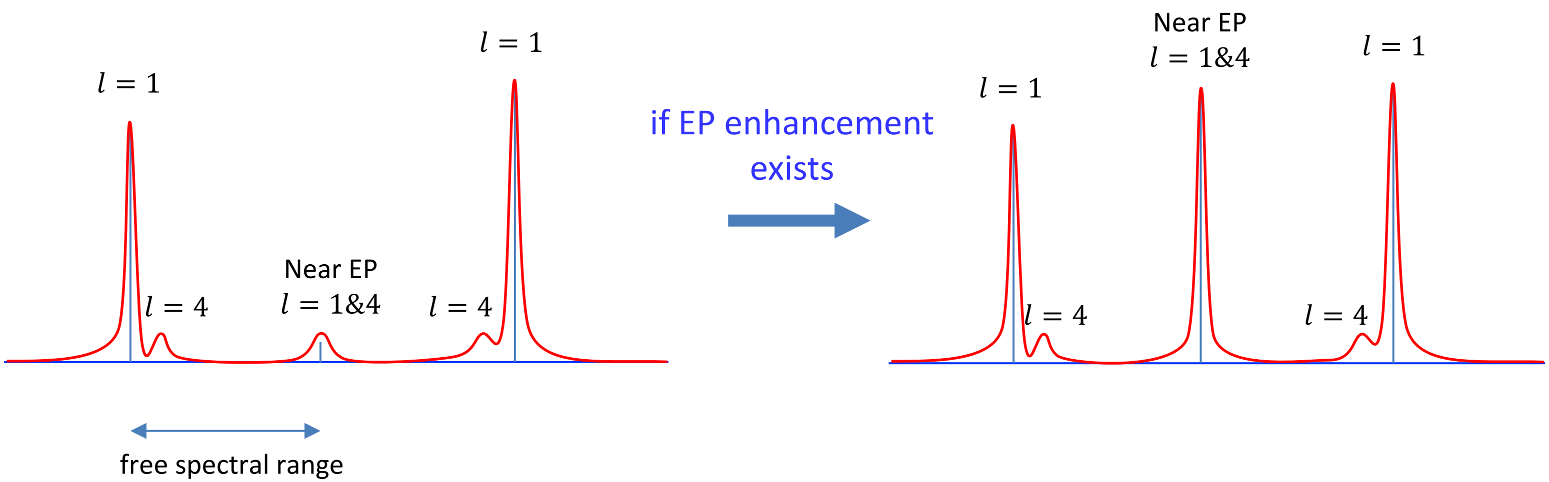


Experimental protocol

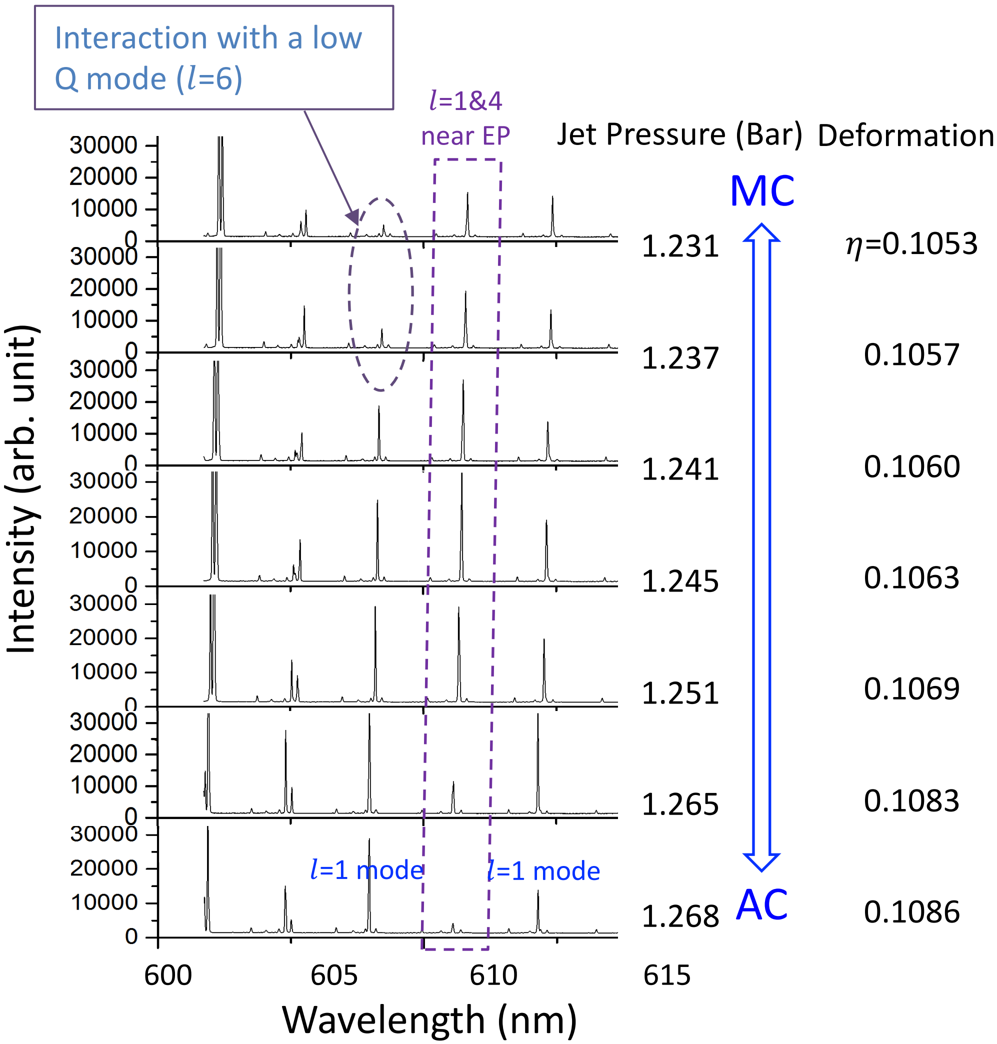
- Choose an EP between $l = 1$ $(Q \gg 10^6)$ and $l = 4$ $(Q \sim 10^6)$ modes.
- When they are near an EP, their decay rates are averaged $(\bar{Q} \sim 10^6)$.
- *With a fixed pump power*, vary the cavity deformation over a small range around the EP.

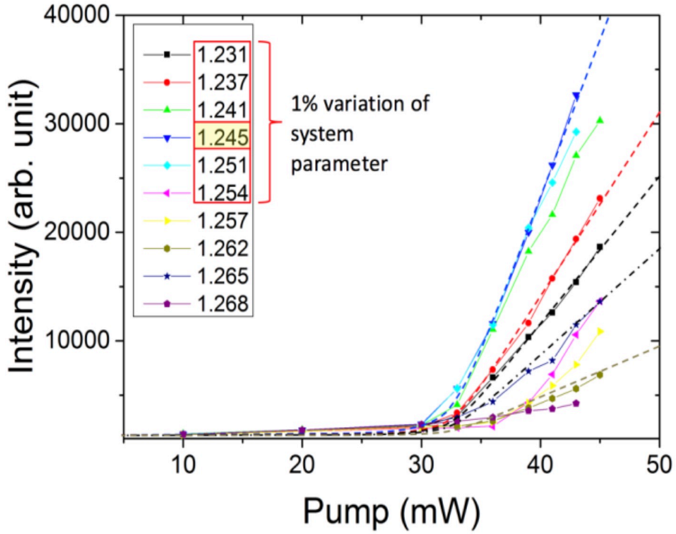
Lasing peaks
at other deformations

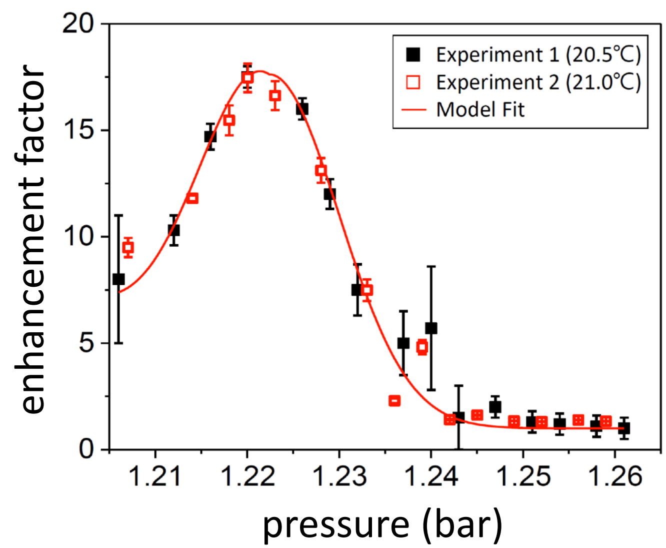
Lasing peaks
at a particular deformation



First observation of enhanced emission near an EP







(fixed pumping power, varied deformation)

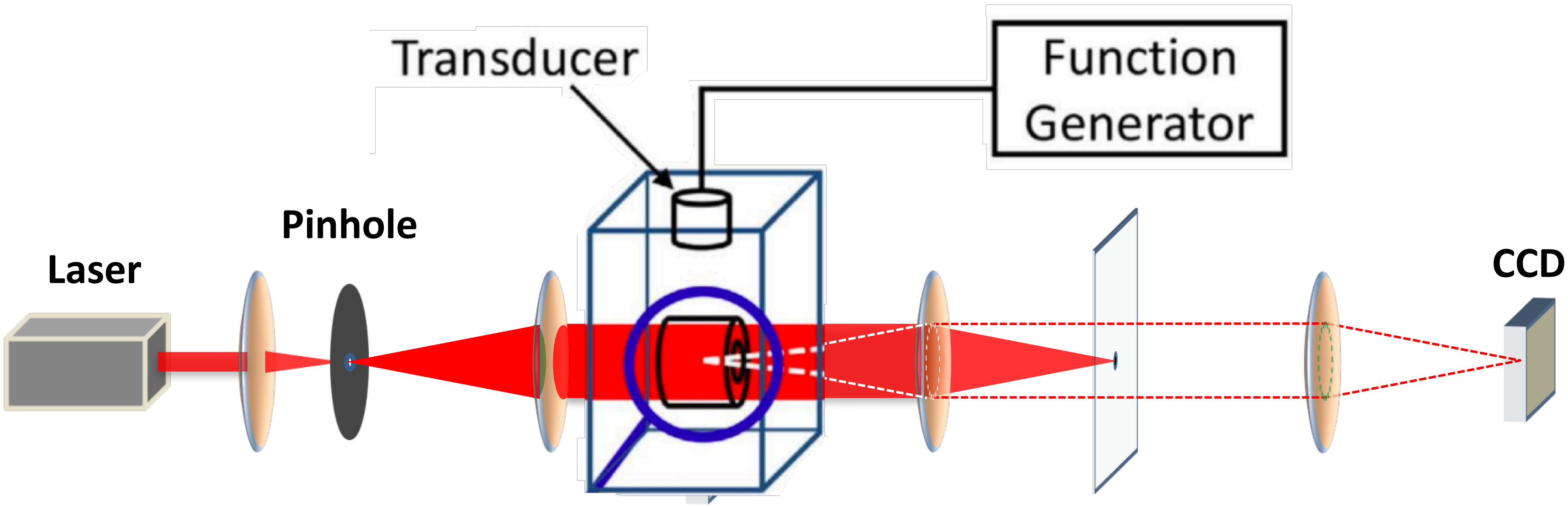
번외 편:

allowing to visualize topological phase changes

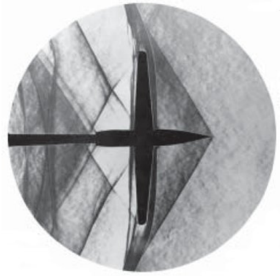
Acoustic mode Field imaging

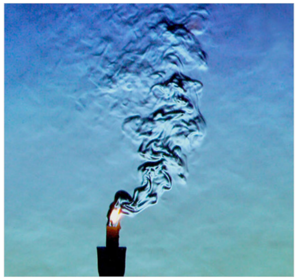
Schlieren imaging of density modulation

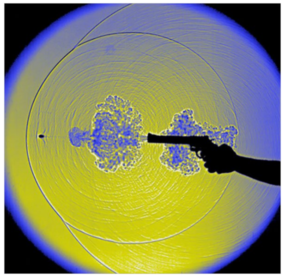
- Visualize fluidic density variation around an object such as bullet bow shockwave and thermal flume from a thermal source.
- Also can be used to visualize the sound pressure field in a circular cavity.

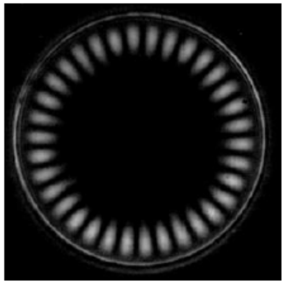


Examples:

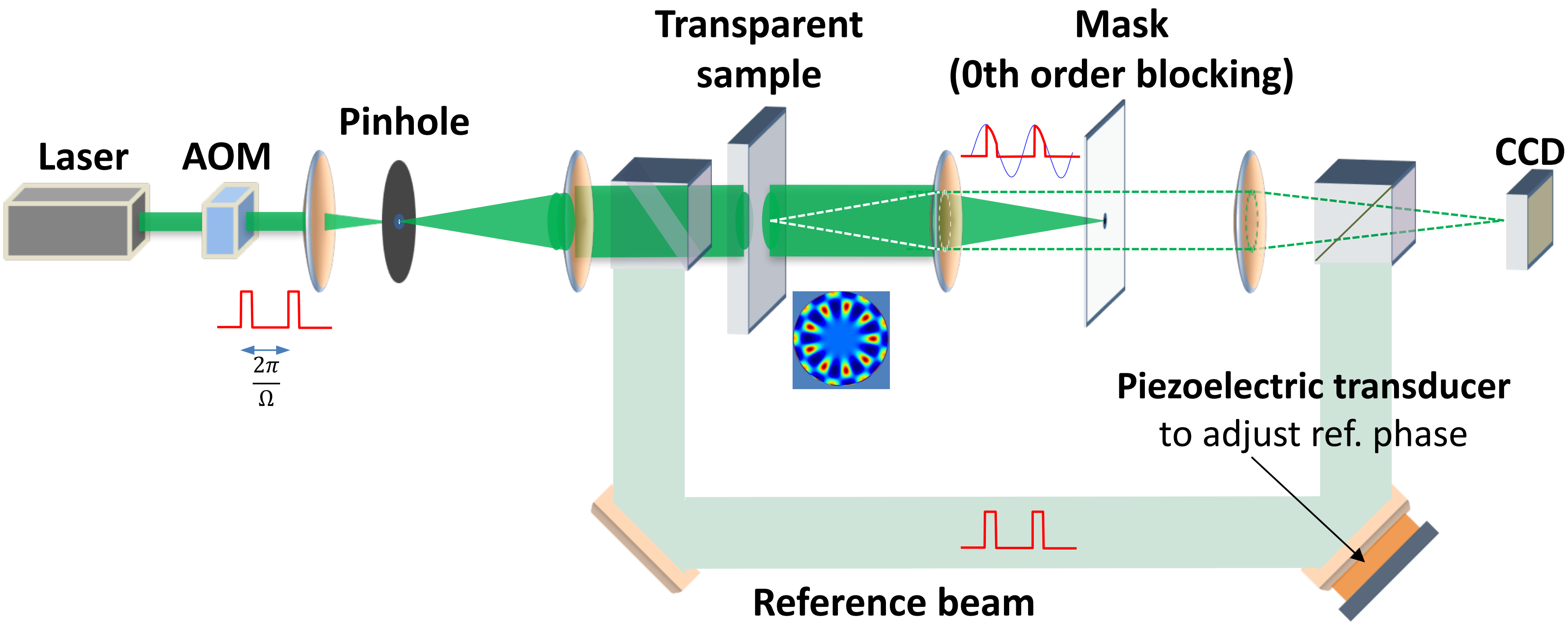








Principle of phase measurement



$\phi(x,y,t) = \phi(x,y)\cos\Omega t$, Ω : angular frequency of acoustic wave

$\phi(x,y) \propto \Delta n(x,y) \propto P(x,y)$

$E(x,y,t) = E_0 \exp[i\phi(x,y)\cos\Omega t] \simeq E_0[1 + i\phi(x,y)\cos\Omega t]$

$\rightarrow E_0[i\phi(x,y)\cos\Omega t] \rightarrow E_0\left[i\phi(x,y)\cos\Omega t + \eta e^{i\psi}\right] \rightarrow E_0\left[i\phi(x,y) + \eta e^{i\psi}\right]$

black spot

reference

stroboscopic

$$\boxed{I(x,y) \simeq I_0\left|\phi(x,y) + \eta e^{i\psi}\right|^2}$$

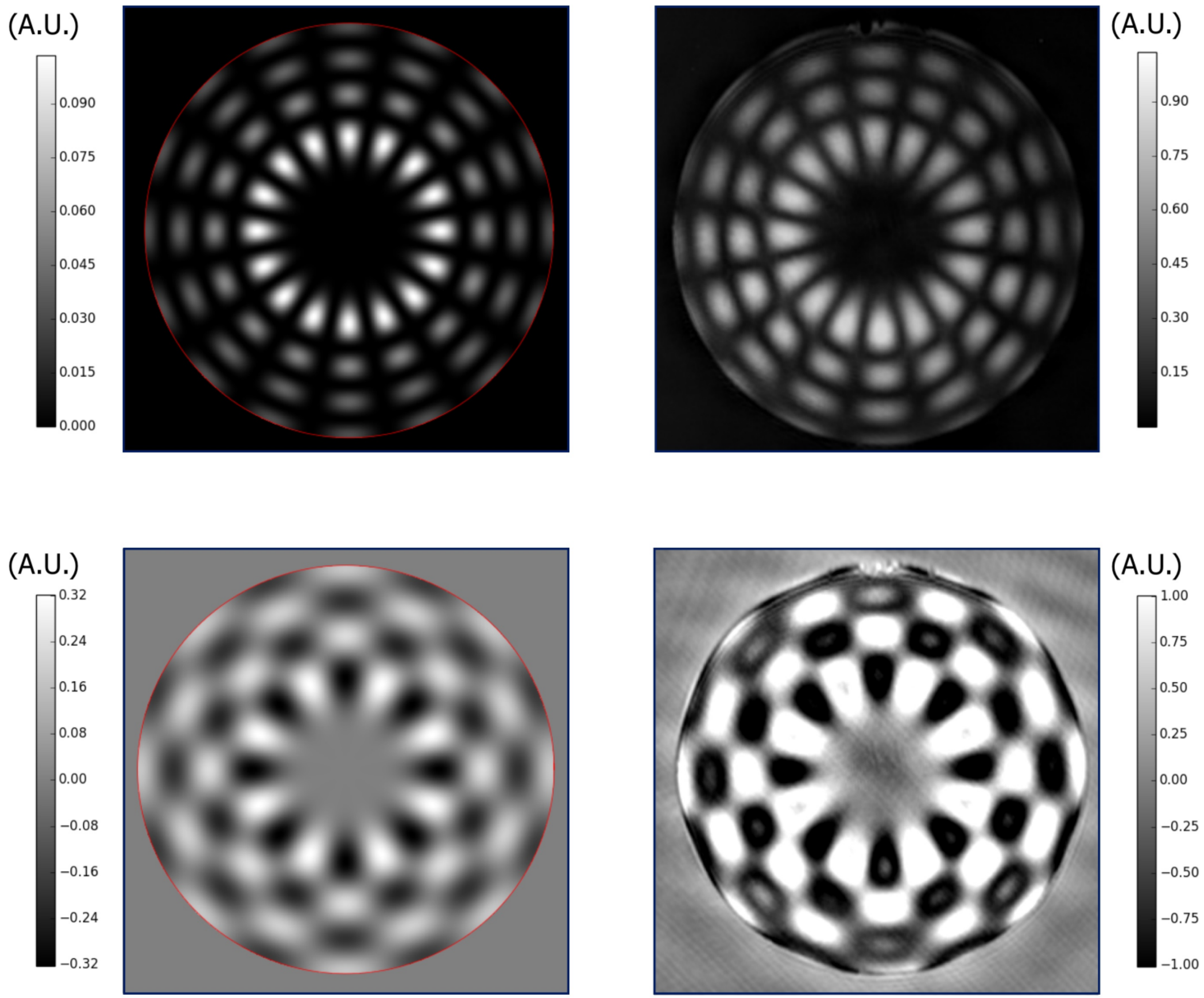
Intensity vs. field imaging

Theory

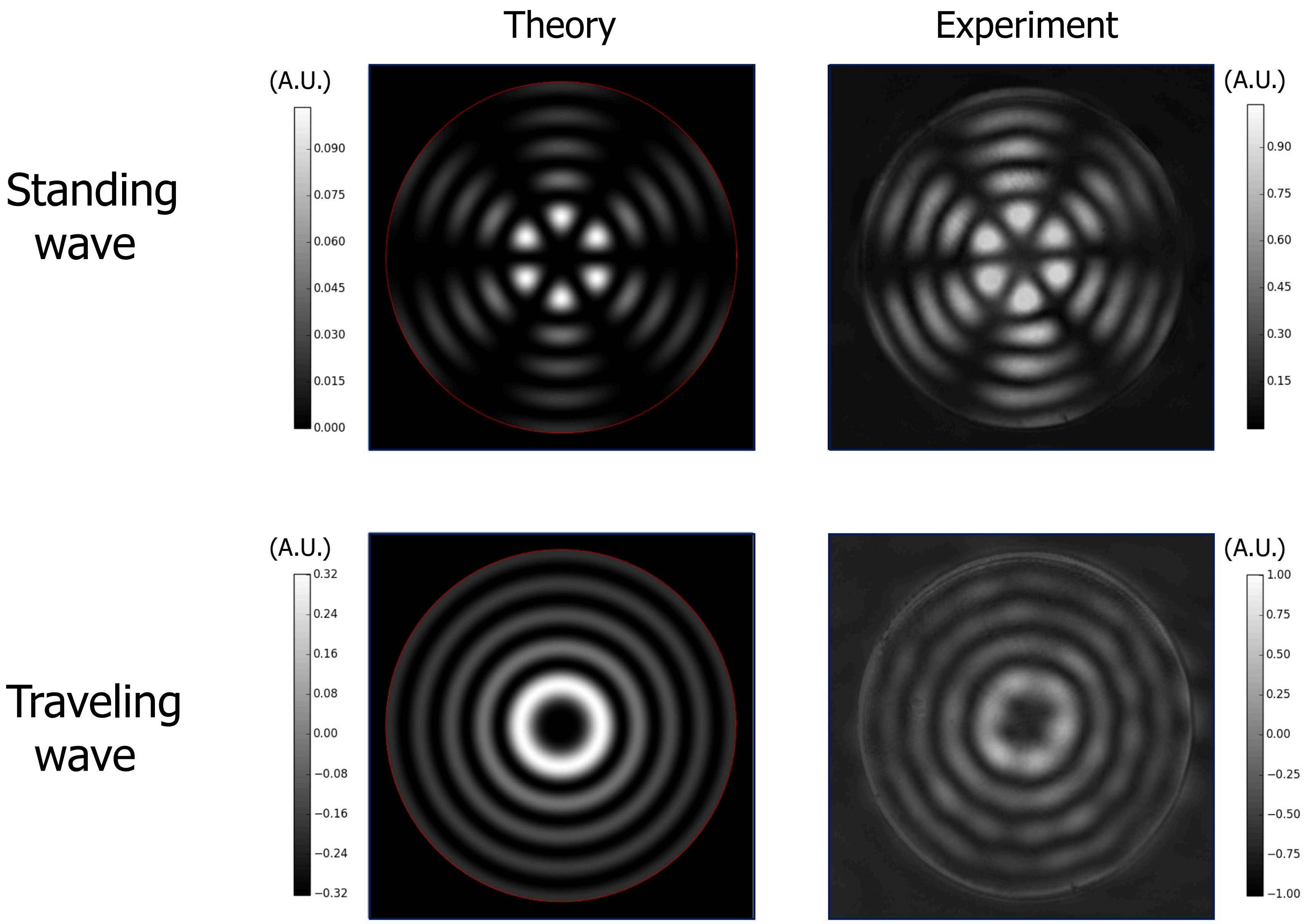
Experiment

Schlieren image (intensity)

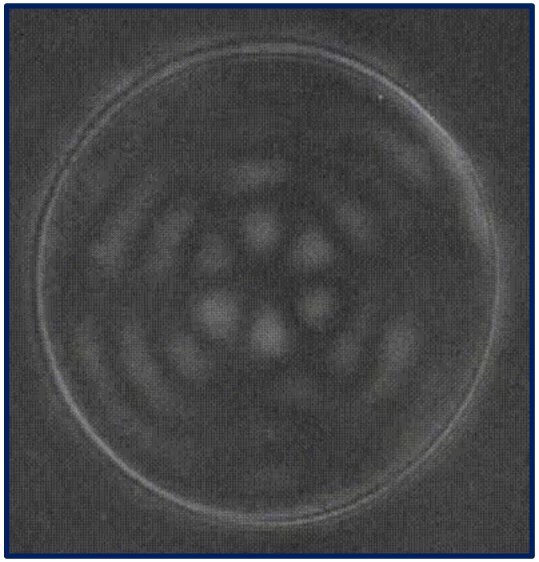
Eigenmode (field)



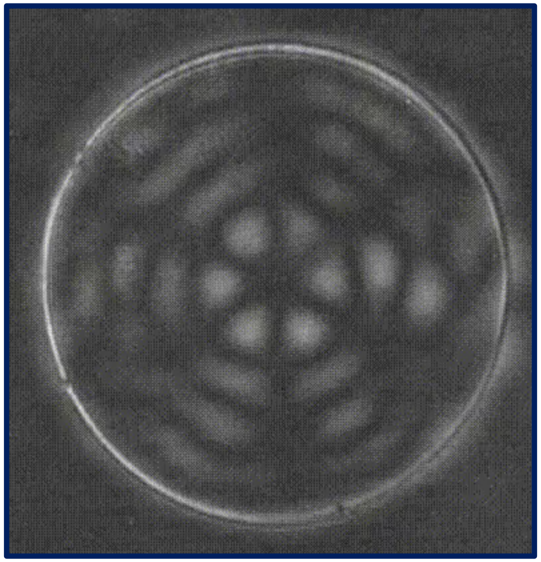
Time-averaged intensities



Time evolution of fields



Standing wave



Traveling wave

- Topological phase can be measured (Berry’s phase, etc)
- Phase imaging is more sensitive than intensity imaging.
- Practical applications? (biomedical, ultrasound,…)

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