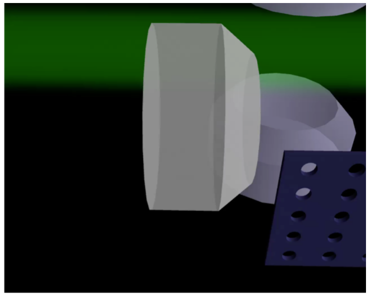
2019 Introduction to Research Programs at KW An's Group

Quantum-Field Laser Laboratory
Kyungwon An

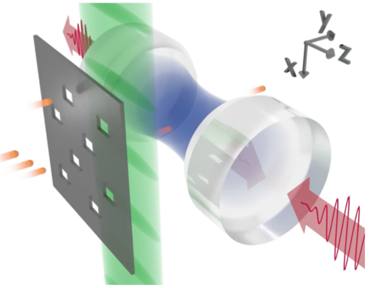
National Research Foundation of Korea
QC|AI⟩ KAIST ITRC
SAMSUNG 삼성미래기술육성재단 Samsung Science and Technology Foundation

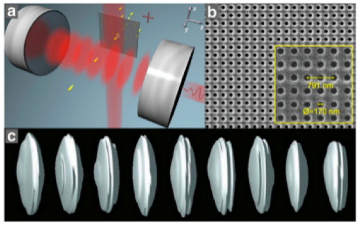
Physics of atom-field interaction

- Quantum information
  - Ideal single-photon sources (flying qubits)
  - Ideal single-photon detectors

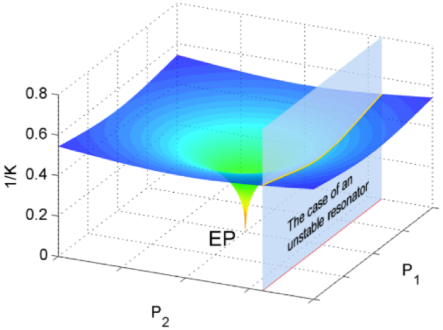


- Phase-controlled atom-field interaction
  - Single-atom superradiance
  - Theresholdless lasing
  - Superabsorption





- Manipulation of vacuum fluctuation
  - 3D imaging of vacuum fields
  - Enhanced emission near an exceptional point



Nonclassical light generation

I. Single-Atom Superradiance

Dicke's Superradiance

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

Robert H. Dicke

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

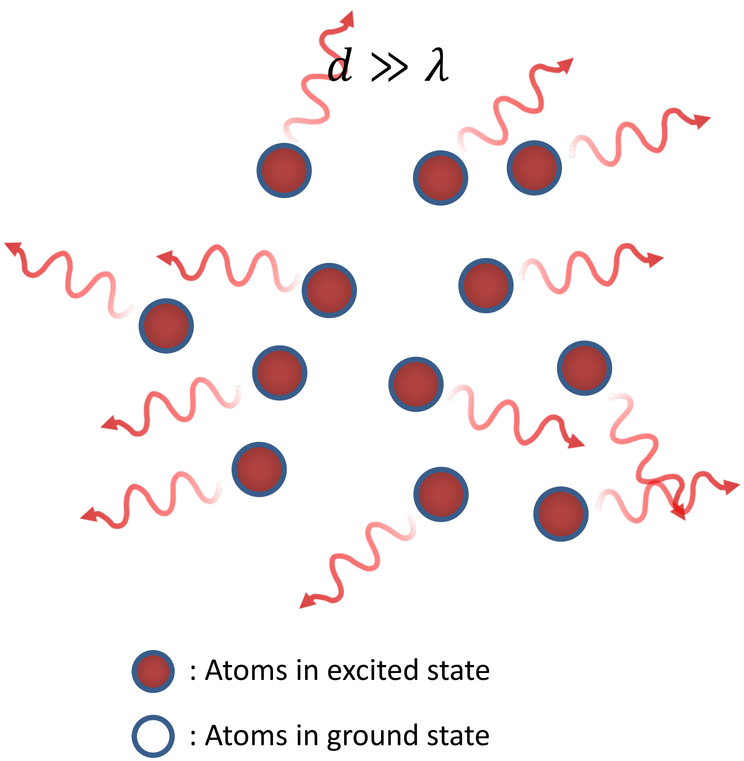
(Received August 25, 1953)

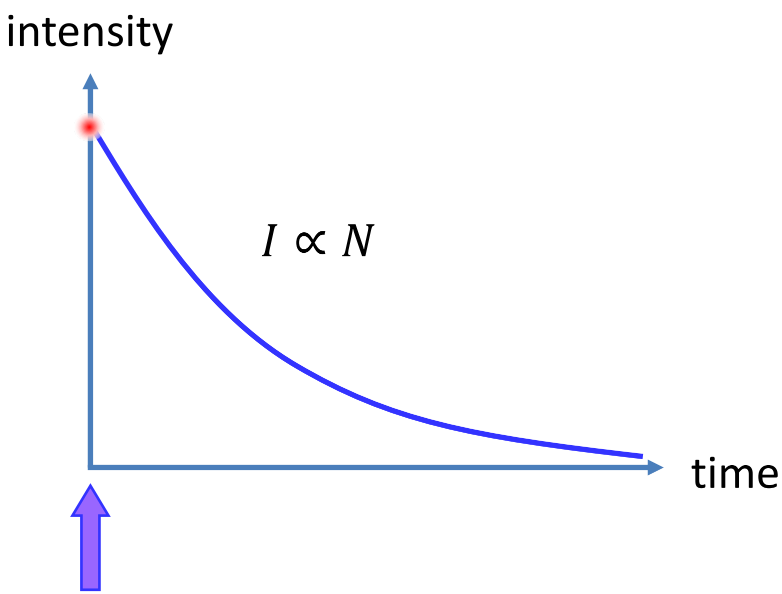
By considering a radiating gas as a single quantum-mechanical system, energy levels corresponding to certain correlations between individual molecules are described. Spontaneous emission of radiation in a transition between two such levels leads to the emission of coherent radiation. The discussion is 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.

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

Ordinary emission

- Atoms are well separated
- They emit photons individually.
- (Emission power) ∝ (number of excited atoms)

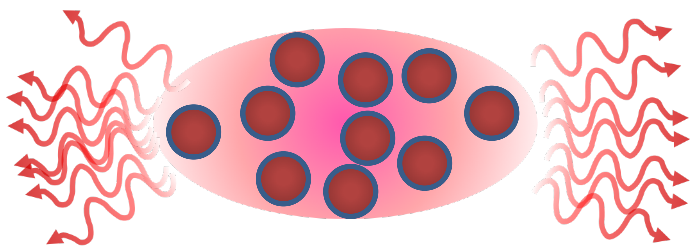




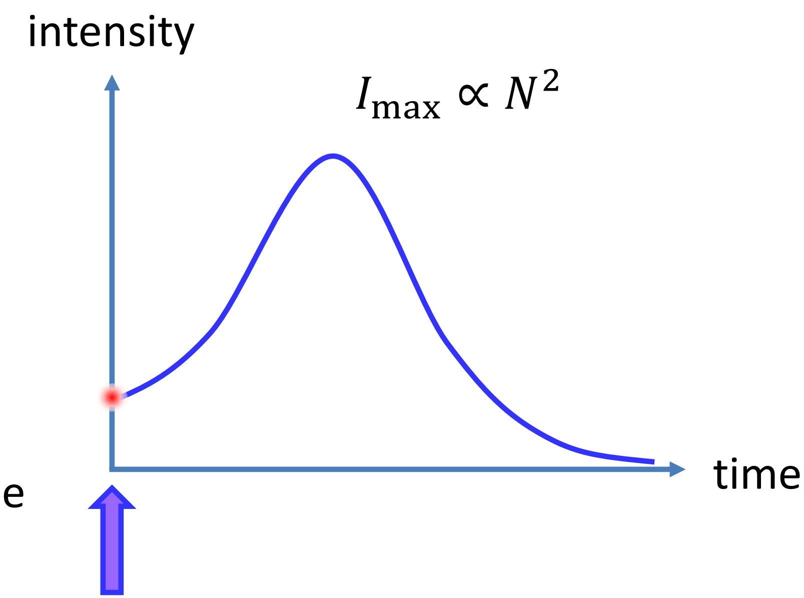
Superradiance

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

$d \ll \lambda$



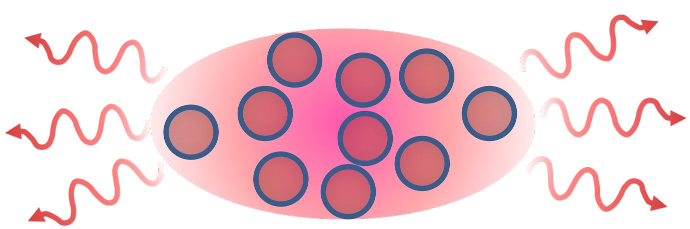
$\langle \sigma_i^+ \sigma_j \rangle > 0$: atoms have the same phase



Superradiance

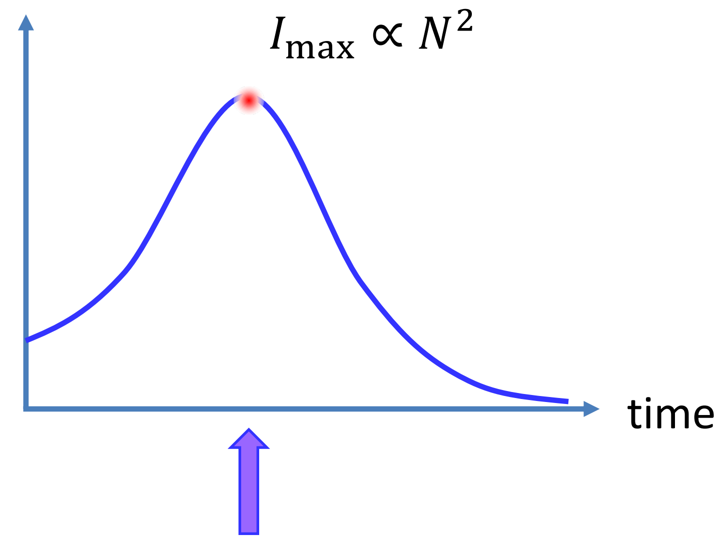
- Densely packed, impossible to distinguish which atom emits.
  → Phase correlation emerging → Collective decay of atoms
- Emission power ∝ (number of excited atoms)^2
- Enhanced matter-light interaction
  - Applicable to quantum information & advanced photonics

$d \ll \lambda$



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

atom-atom correlation

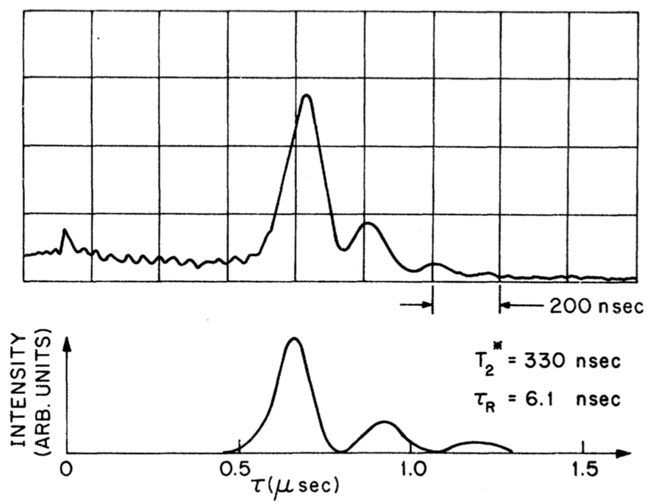


Old superradiance experiments

VOLUME 30, NUMBER 8 PHYSICAL REVIEW LETTERS 19 FEBRUARY 1973

Observation of Dicke Superradiance in Optically Pumped HF Gas*

N. Skribanowitz, I. P. Herman,† J. C. MacGillivray, and M. S. Feld
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 30 October 1972)

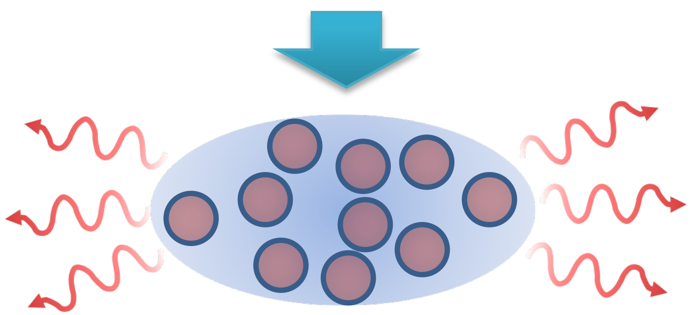


Michael S. Feld

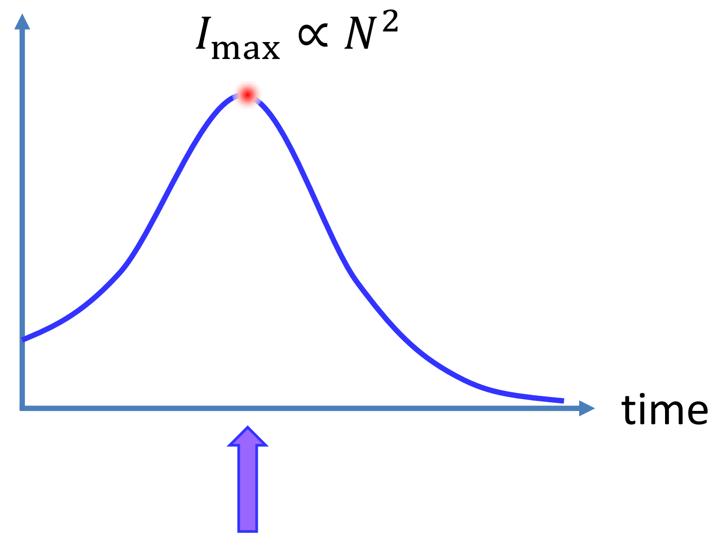
- The first optical observation, OD>>1, a HF-gas sample initially inverted
- Pulse output after μs deley
- Decay time ∝ 1/N (number of atoms)

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



$d \gg \lambda$

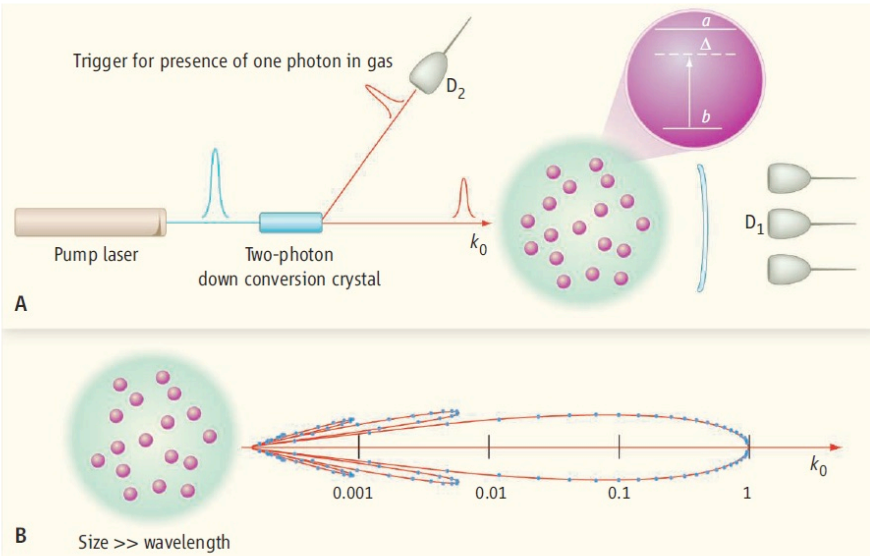


super-radiant states may be excited by irradiating the gas with radiation until states in the vicinity of $m=0$ are excited. R. Dicke (1954)

bright state

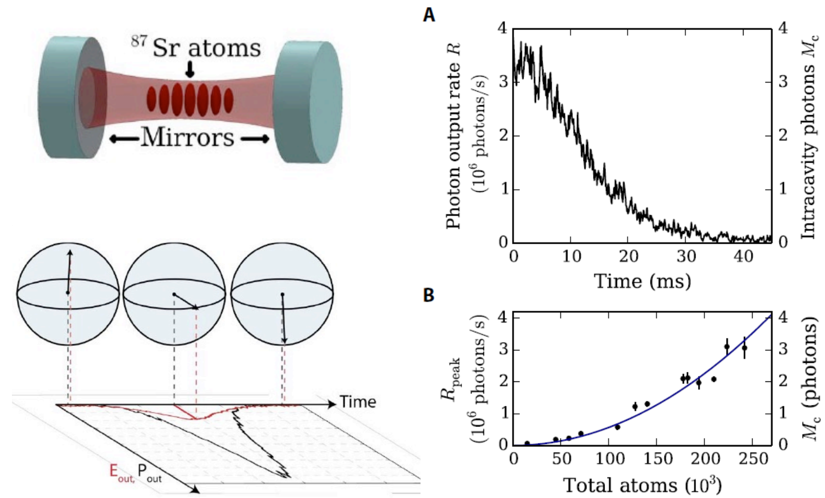
Superradiance of phase-controlled atomic ensemble (top down)

Single-photon superradiance



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

Seeded superradiance

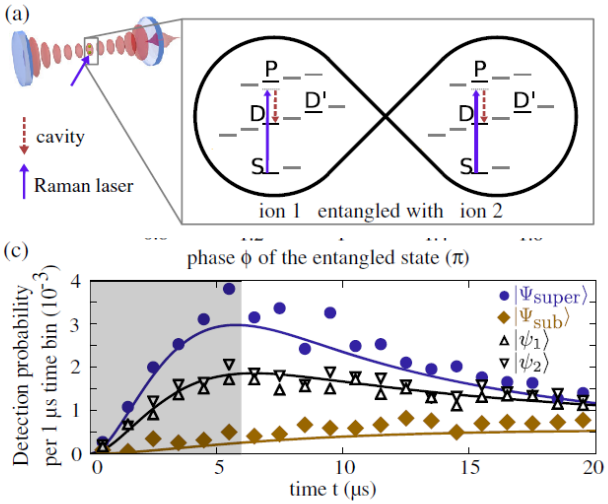


J. K. Thompson's group, Sci. Adv. **2**, e1601231 (2016).

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

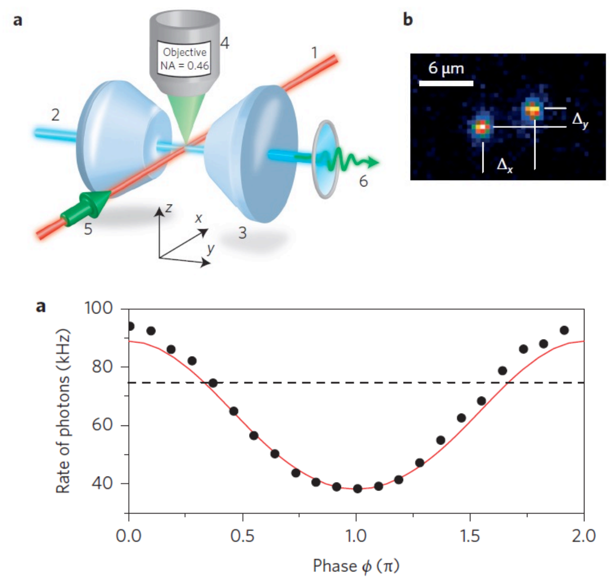
Superradiance of phase-controlled few atoms (bottom up)

Ions



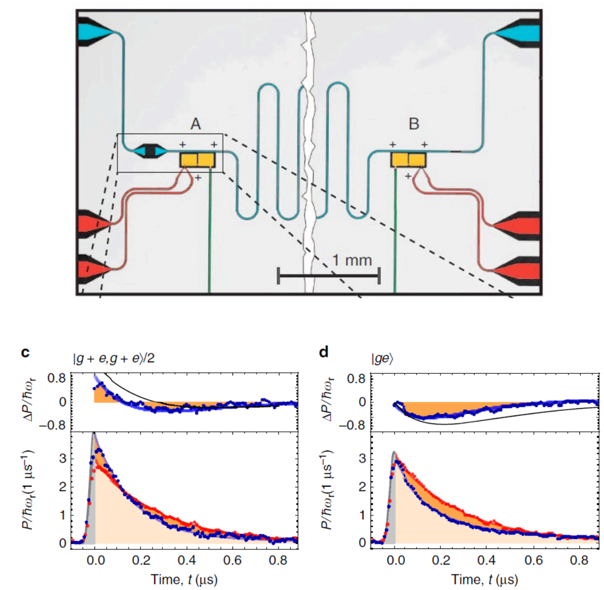
R. Blatt's group, PRL **114**, 023602 (2015)

Neutral atoms



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

Artificial atoms



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

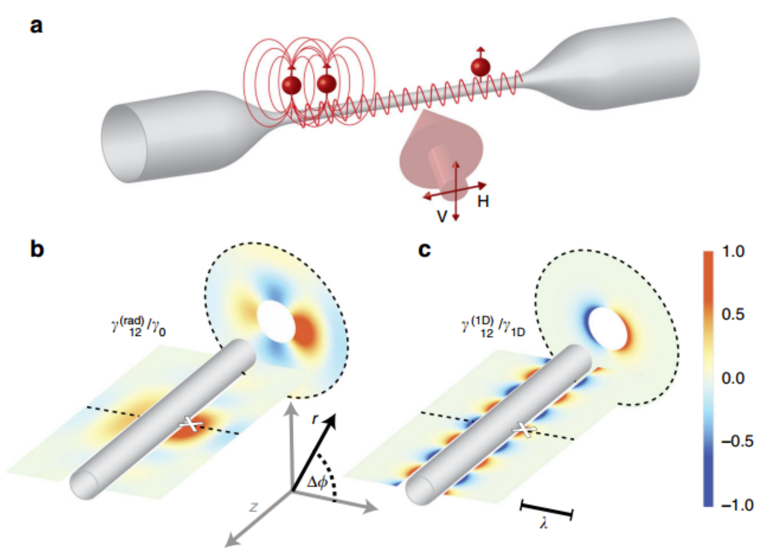
- Direct control of trapped atoms in a cavity, wavelength-scale separation
- Superradiance as well as subradiance
- Only up to two emitters work together for superradiance

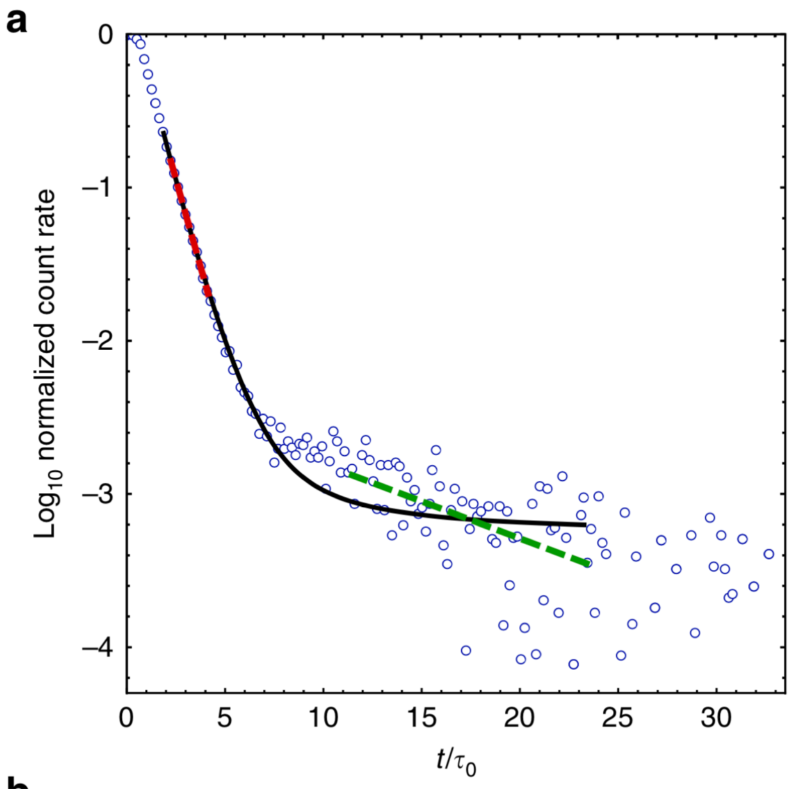
Super- and sub-radiance with atoms around a nanofiber

Pablo Barberis-Blostein
Universidad Nacional Autonoma de Mexico, Mexico

Weak pulse excitation from the side
Regime of single-photon superradiance

Rubidium87

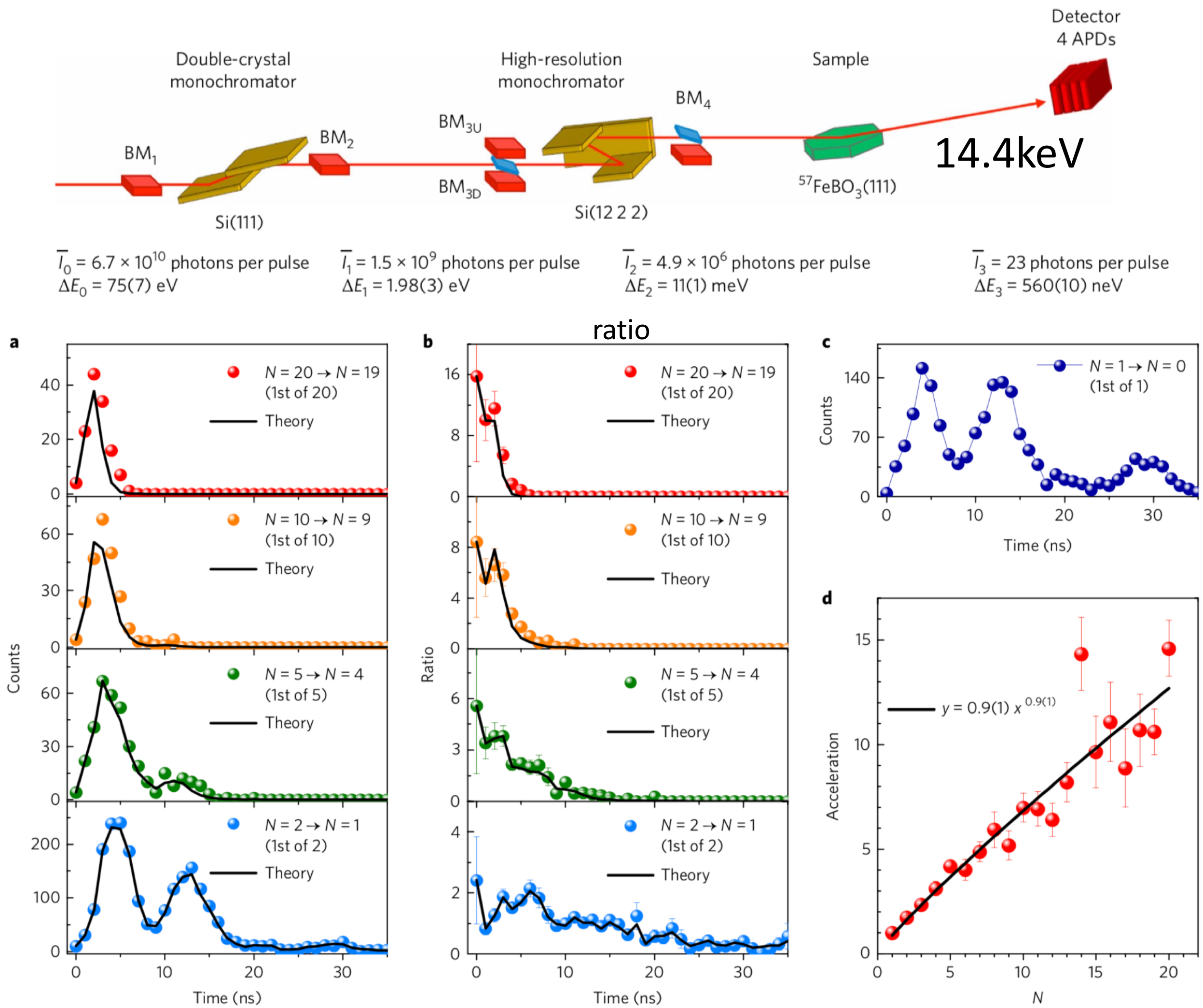




P. Solano *et al.*, Nat. Commun. **8**, 1857 (2017)

Superradiant $1.10 \pm 0.02\ \gamma_0$
Subradiant $0.13 \pm 0.01\ \gamma_0$

Superradiance of an ensemble of nuclei excited by a free electron laser

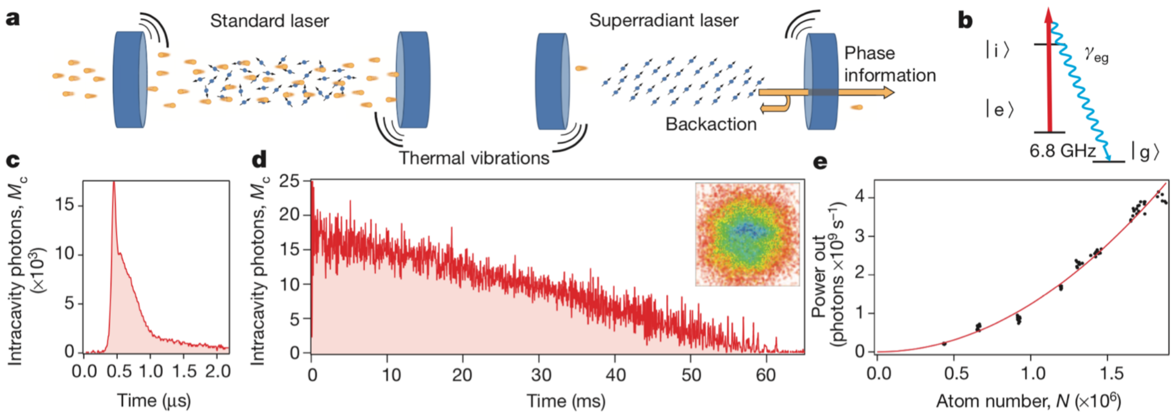


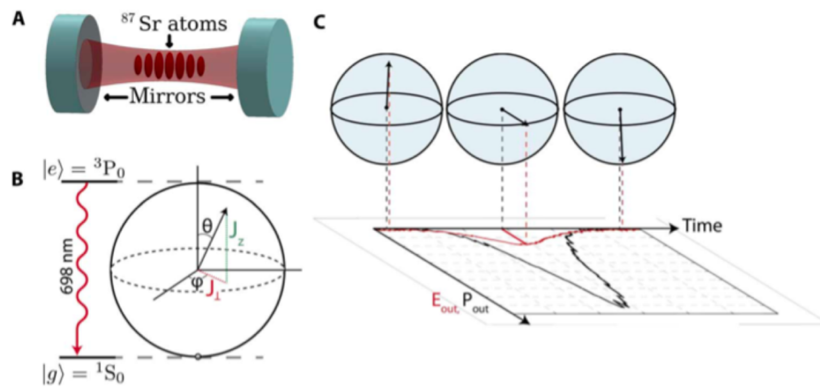
A. I. Chmakov *et al.*, Nat. Phys. **14**, 261 (2018)

Twists, gaps and superradiant emission on a mHz linewidth transition

James K. Thompson

JILA, NIST, and Dep. of Physics, Univ. of Colorado, USA

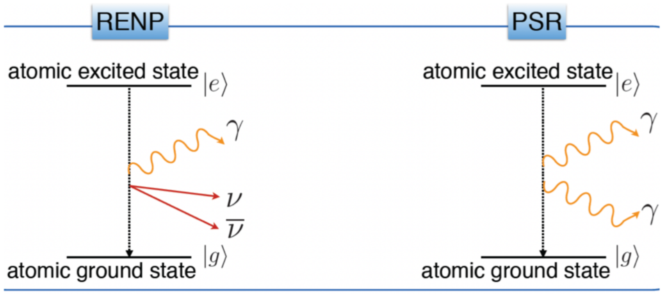




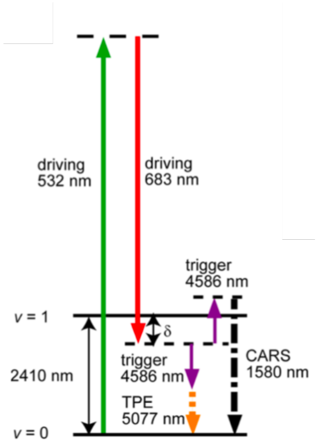
J. G. Bohnet *et al.*, Nature **484**, 78 (2012); M. A. Norcia *et al.*, Sci. Adv. **2**, e1601231 (2016); M. A. Norcia et al., Science **361**, 259 (2018)

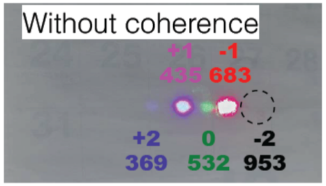
Coherence amplification of two-photon emission toward neutrino absolute mass measurement

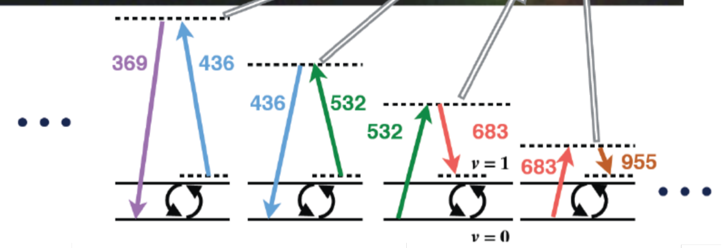
Noboru Sasao, Motohiko Yoshimura *et al.*,
RIIS, Okayama University, Japan



RENP(Radiative Emission of Neutrino Pair)
PSR (Paired Super Radiance)
Experiment of solid para hydrogen

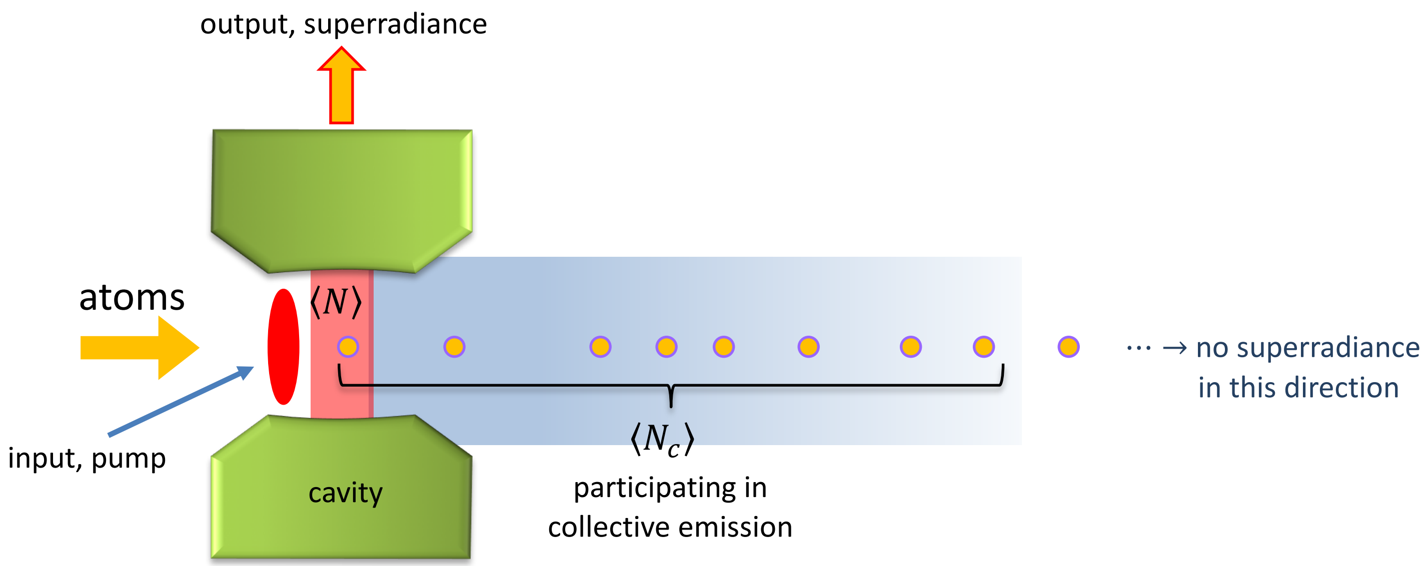






Our approach: coherently pumped microlaser

- Use the cavity-QED microlaser platform
- Direct control of individual atomic states
- Up to 30 atoms participate in superradiance now, but it can be easily scaled up.
- Output field is well separated from the input field.
- However, only one atom in the cavity, others outside
- We call this new type of superradiance the single-atom superradiance



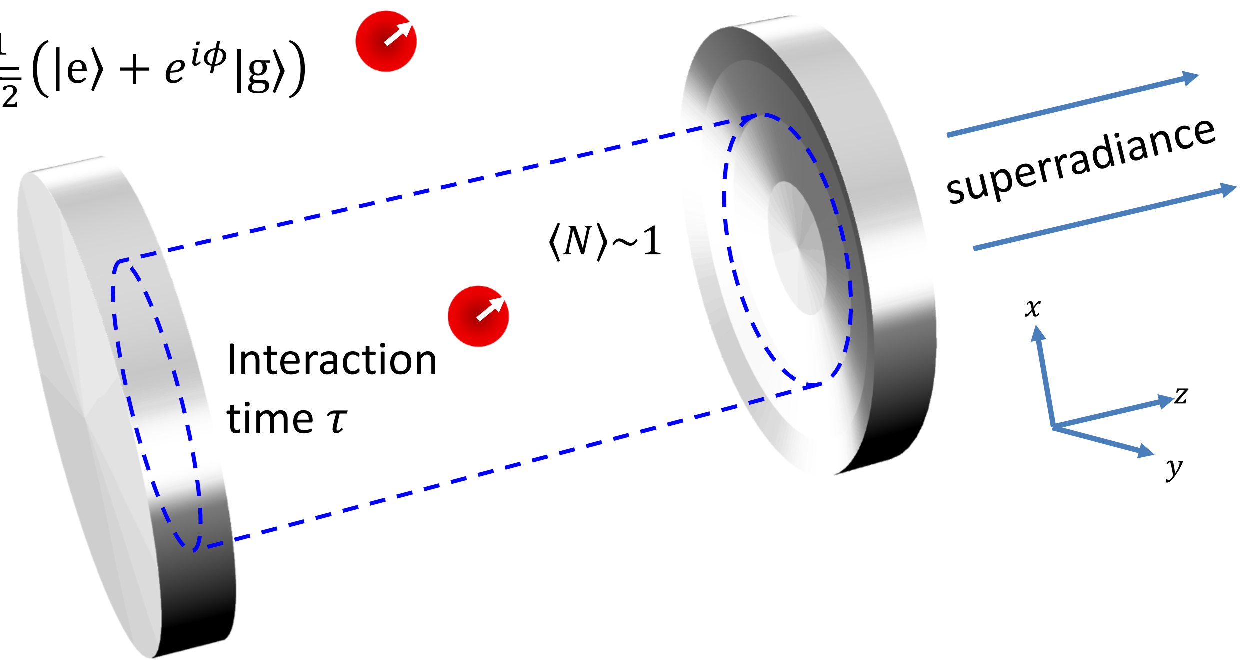
Junki Kim *et al.*, *Science* **359**, 662 (2018)

Superradiance by time-separated atoms

- 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.

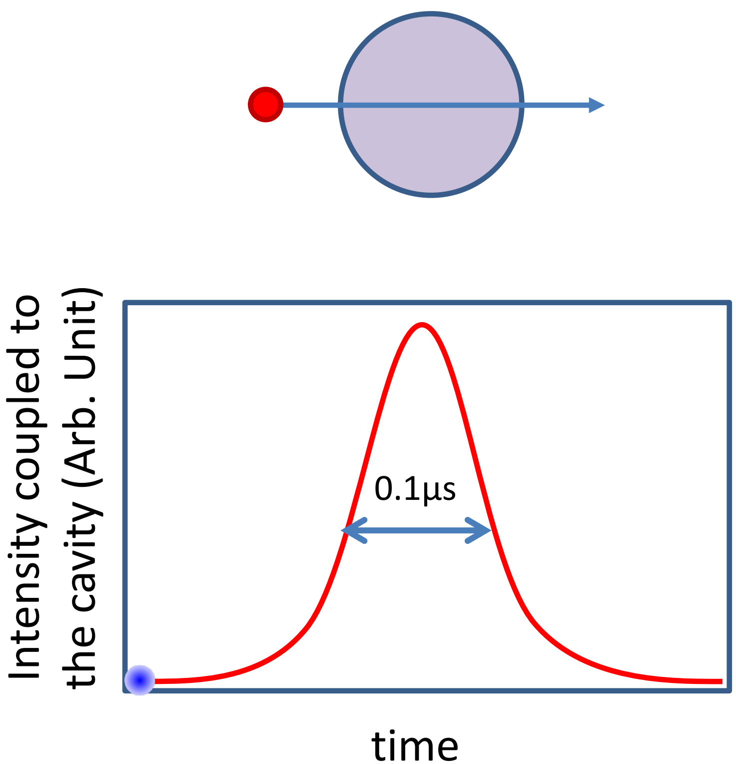
→ collective behavior among time-separated atoms induced by the long-lived cavity field.

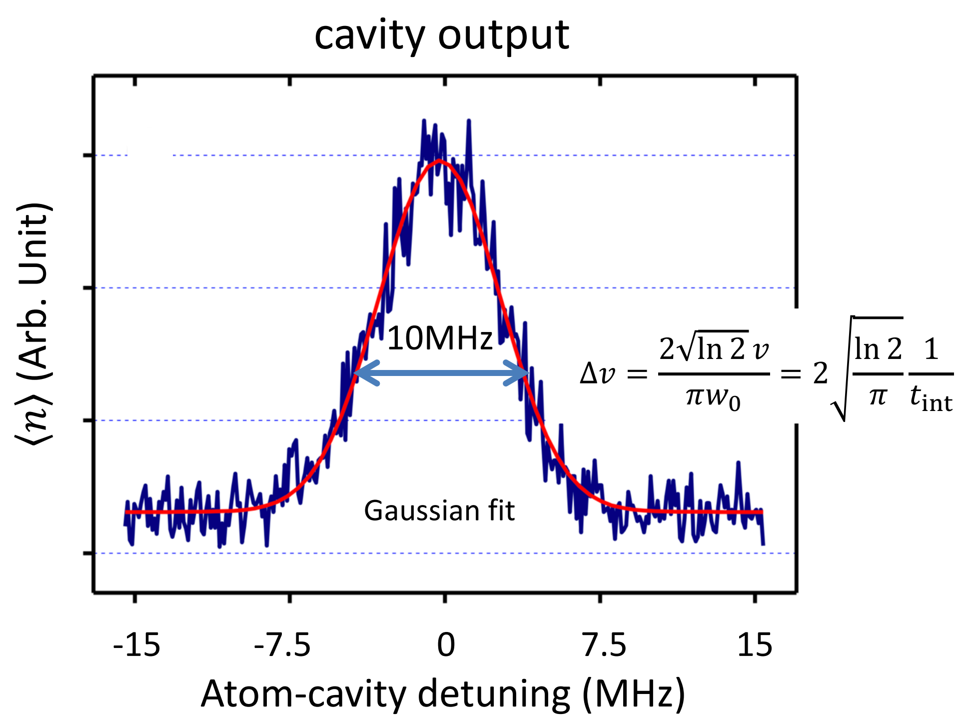
$$|\psi_{\mathrm{atom}}\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{e}\rangle + e^{i\phi}|\mathrm{g}\rangle\right)$$



Transit time broadening of uncorrelated atoms

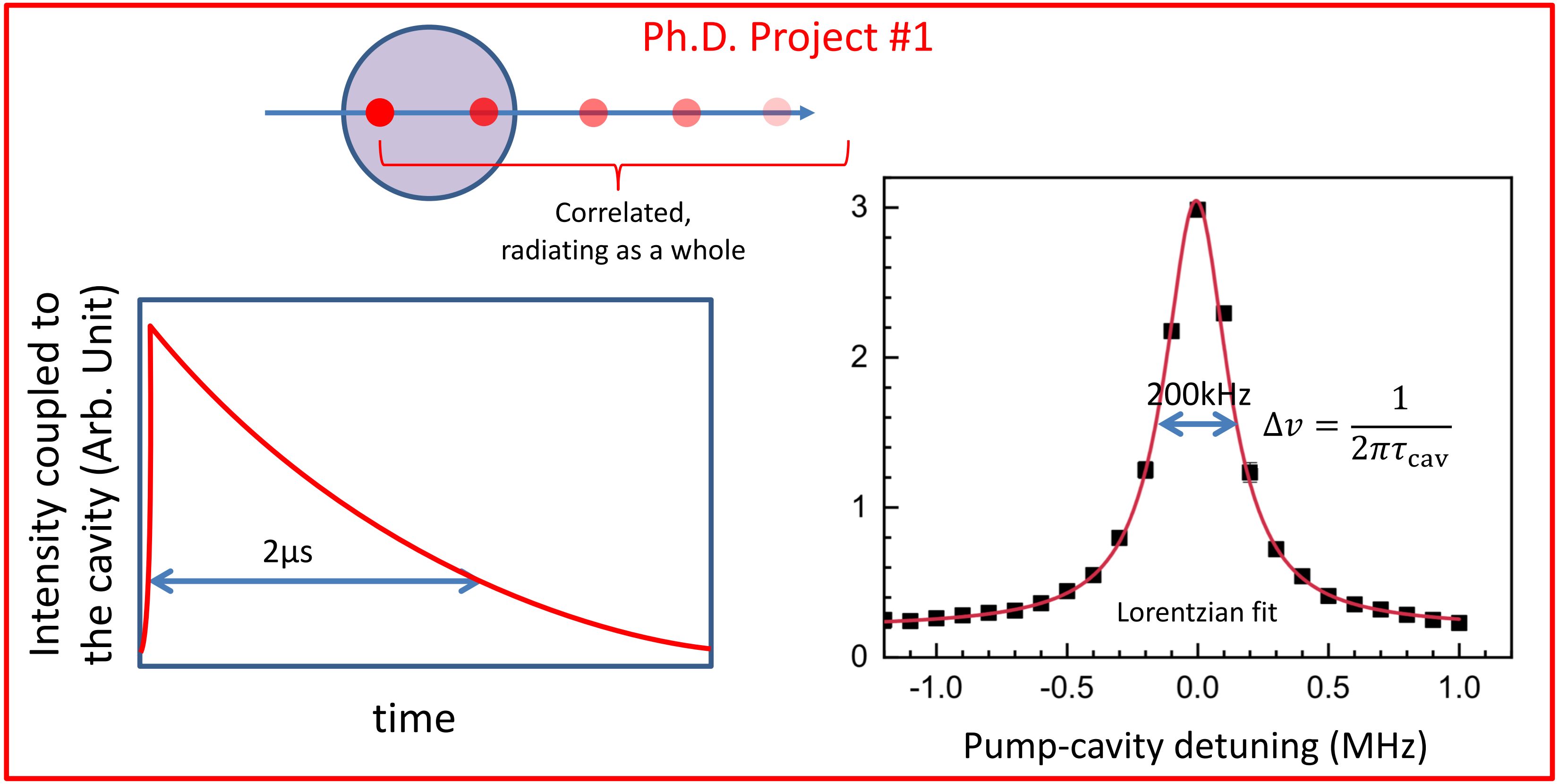
- When uncorrelated atoms go through a cavity mode, the cavity emission exhibits transit time broadening due to the short atom-cavity interaction time (~0.1μs→10MHz broadening).





Absence of transit time broadening by correlated atoms

- In the coherent single-atom superradiance, the atoms are correlated and emit photons collectively within the cavity-field decay time (~2μs), resulting in disappearance of the transit time broadening.



Mean photon number in the cavity

- The steady-state field from the master equation

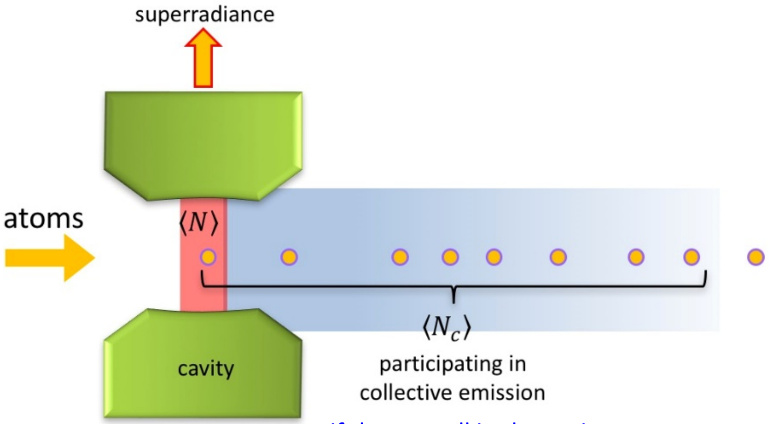
$$\boxed{|\psi_{\text{field}}\rangle \simeq |\alpha\rangle, \alpha = -i\rho_{\text{eg}}\langle N_c\rangle g\tau}$$

Enhancement by the superradiance

$$\langle n\rangle \simeq \langle n\rangle_{NC} + \langle n\rangle_{C} = \frac{\frac{1}{2}\rho_{\text{ee}}\langle N_c\rangle(g\tau)^2}{1-(\rho_{\text{ee}}-1/2)\langle N_c\rangle(g\tau)^2} + \left(|\rho_{\text{eg}}|\langle N_c\rangle g\tau\right)^2$$

By non-collective emission of atoms $\propto\langle N_c\rangle$

By collective emission of atoms $\propto\langle N_c\rangle^2$



as if they are all in the cavity at the same time for time τ, repeatedly.

$\rho_{\text{ee}}, \rho_{\text{eg}}$: density matrix elements of atoms
g, τ : atom-field coupling constant and interaction time

$\langle N\rangle$: Number of atoms in the cavity
$\langle N_c\rangle$: Number of atoms going through the cavity during the cavity-*field* decay time
$\beta = (g\tau)^2$<<1, the beta factor (the fraction directed to the cavity mode out of one energy quantum injected into the cavity)

Bright state of two-level atoms

- Ensemble of N two-level atoms (spin ½) in terms of eigenstates $|J = N/2\,, M\rangle$ of total angular momentum (↑: excited state, ↓: ground state)

  e.g. $N = 2$, $|1,1\rangle = |\uparrow\uparrow\rangle$, $\underbrace{\boxed{|1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)}}_{}$, $|1,-1\rangle = |\downarrow\downarrow\rangle$

  bright state

- Emission rate of $|J, M\rangle$ state

$$\Gamma_a\langle\sigma_\Sigma^+\sigma_\Sigma\rangle = \Gamma_a\left(\frac{N}{2}+M\right)\left(\frac{N}{2}-M+1\right)$$

$$\xrightarrow[M=0]{} \frac{1}{4}\Gamma_a N(N+2) \sim \frac{\Gamma_a}{4}N^2$$

bright state

- Ensemble of N two-level atoms *in the same superposition state*

$$|\Psi_{\text{atom}}\rangle = \prod_i (C_e|e_i\rangle + C_g|g_i\rangle)$$

- Its emission rate

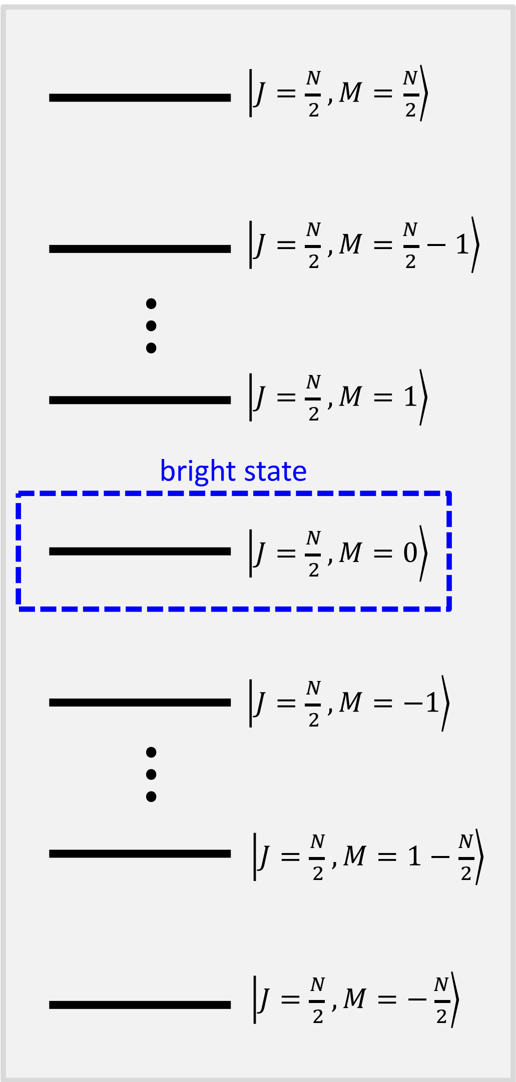
$$N\Gamma_a\rho_{\text{ee}} + N(N-1)\Gamma_a|\rho_{\text{eg}}|^2 \xrightarrow[\rho_{\text{eg}}=\rho_{\text{ee}}=1/2]{} \frac{1}{4}\Gamma_a N(N+1) \sim \frac{\Gamma_a}{4}N^2$$

  Equally strong as the bright state!

- In our case, emission into a cavity mode

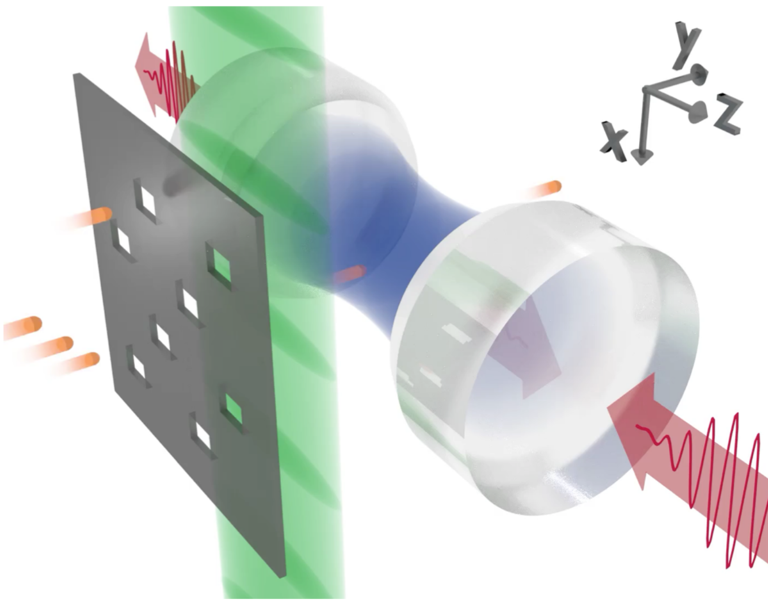
$$\Gamma_a \to g^2\tau \text{ and } N \to \langle N_c\rangle, \text{ so } |\rho_{\text{eg}}|^2\langle N_c\rangle^2 g^2\tau$$

Dicke Ladder

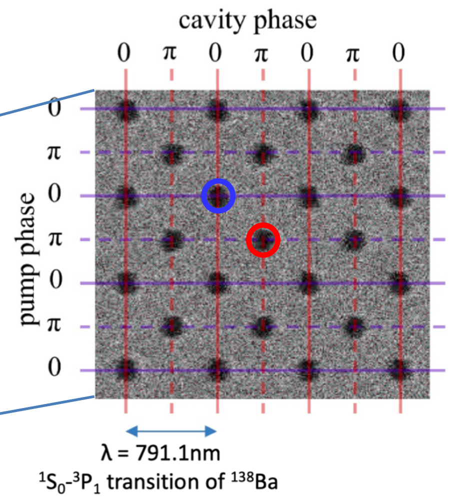


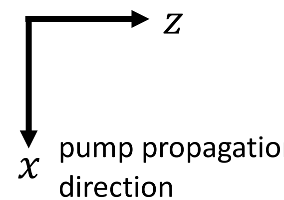
The same phase for every atom

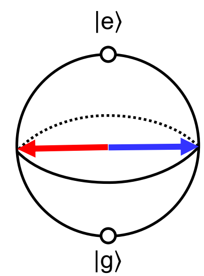
- A nanohole array aperture localizes atomic position.
- Atom-cavity relative phases are aligned.

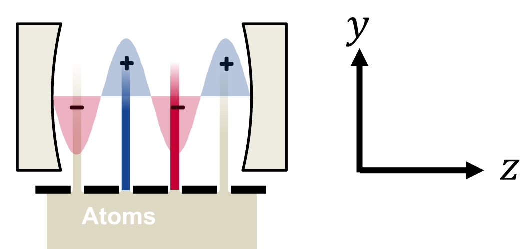


A nanohole array aperture made of Si_3Ni_4 membrane of 30nm thickness (Focused ion beam image)



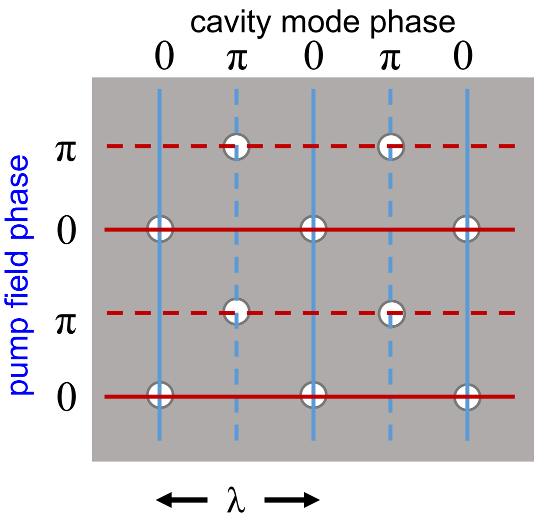






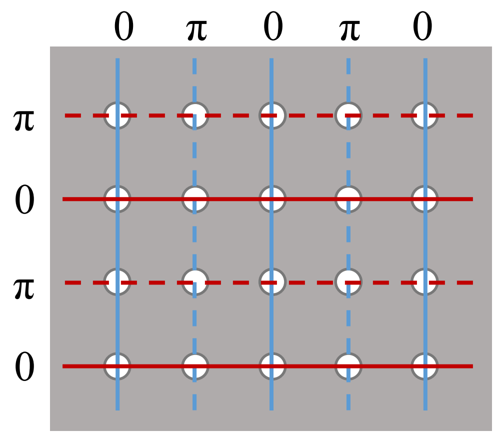
Phase control, multi-phase imprinting

- Various atom-cavity relative phases can be encoded by different nanohole array structures (by displacing the patter along the pump phase direction)



all the same phase

Single-atom superradiance, superabsorption

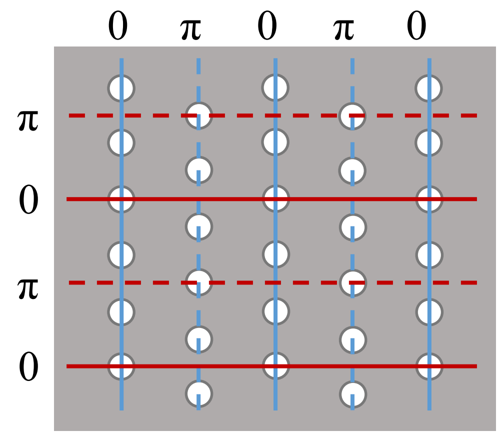


white : 0, black : π

two phases

Squeezed vacuum & cat state generation

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



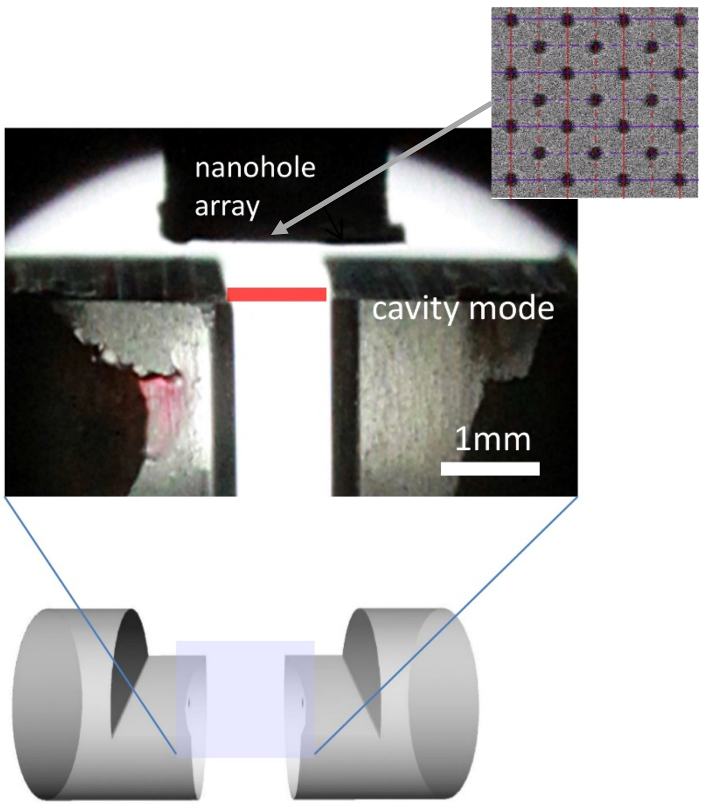
white : 0, blue : 2π/3, green : 4π/3

three phases

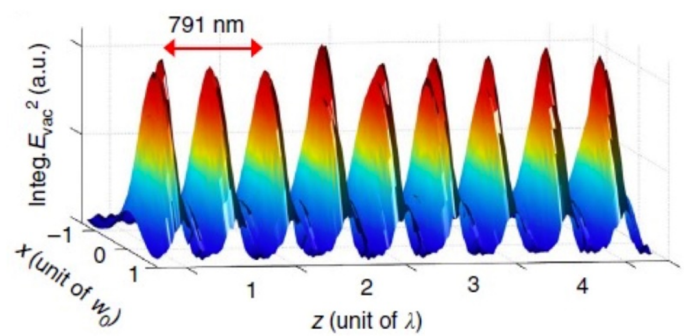
Exotic quantum states

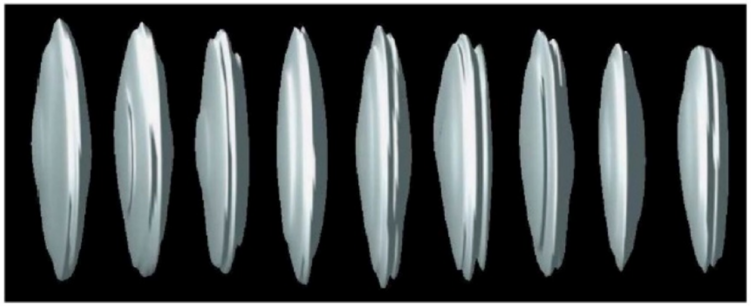
Atom & cavity parameters

- Use ^{138}Ba atoms (λ=791 nm, $^1S_0$-$^3P_1$ transition) and a high Q cavity of 1 million finesse.
- Strong coupling regime, $(g, \gamma_a, \gamma_c) = 2\pi\times(290{,}25{,}69)\mathrm{kHz}$, cooperativity $C \simeq 20$



3D imaging of vacuum fluctuation in a cavity

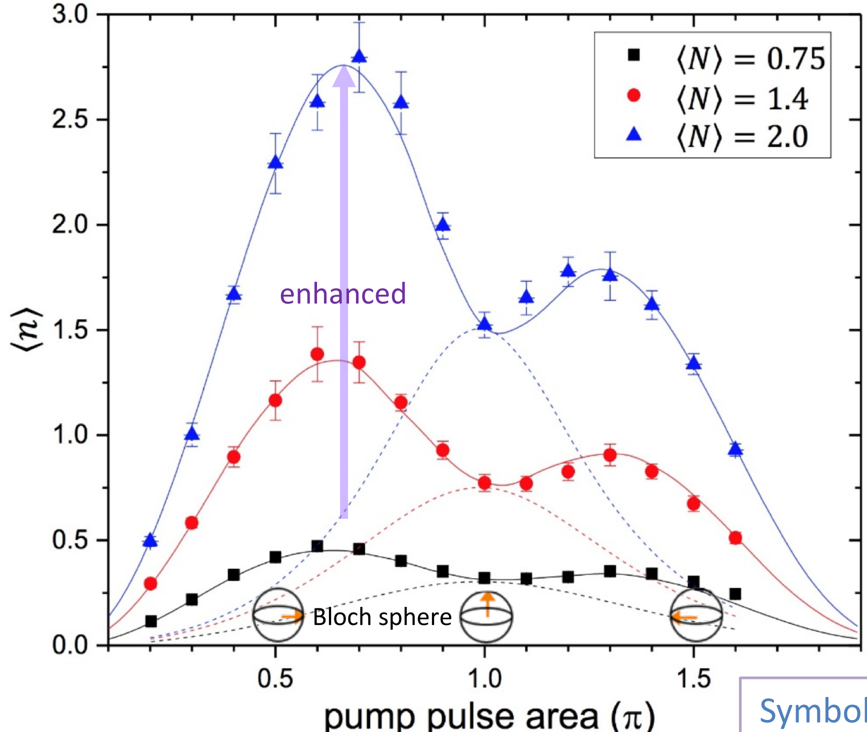




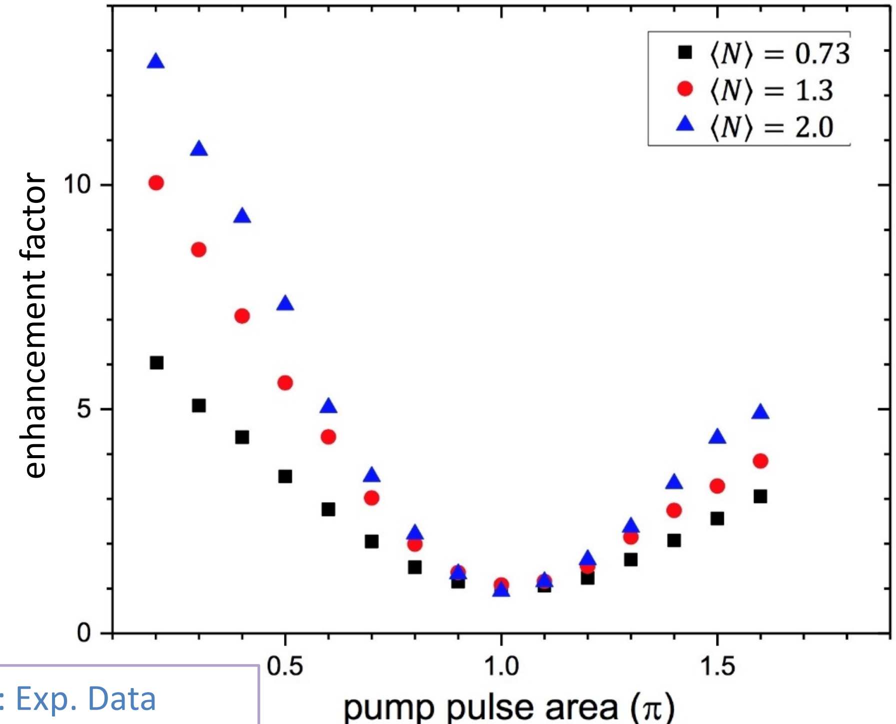
M. Lee *et al.*, Nat. Commun. **5**, 3441 (2014)

Result – atomic state dependence

Aligned atomic phase ($g\tau = 0.18$)



Photon number ratio, $\langle n \rangle / \langle n_{NC} \rangle$



Symbols : Exp. Data
Solid Curves : Simulation

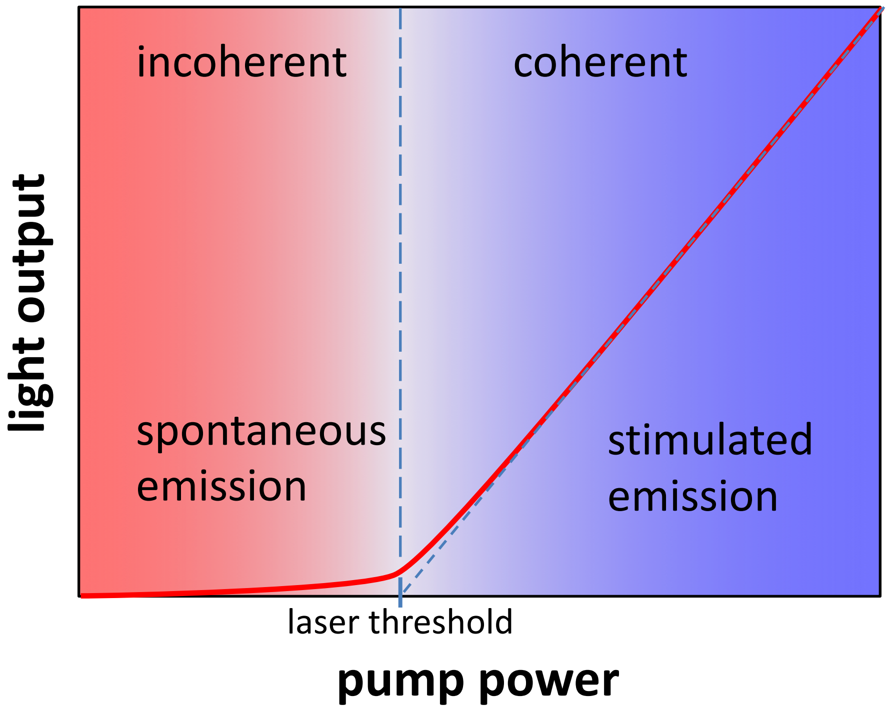
$|\psi_{\mathrm{atom}}\rangle = \sin\left(\frac{\Theta}{2}\right)|\mathrm{e}\rangle + \cos\left(\frac{\Theta}{2}\right)e^{i\phi}|\mathrm{g}\rangle$, Θ is pump pulse area

- Strong enhancement (>1000%) was observed.
- Enhancement is strong even with the mean atom number less than one.

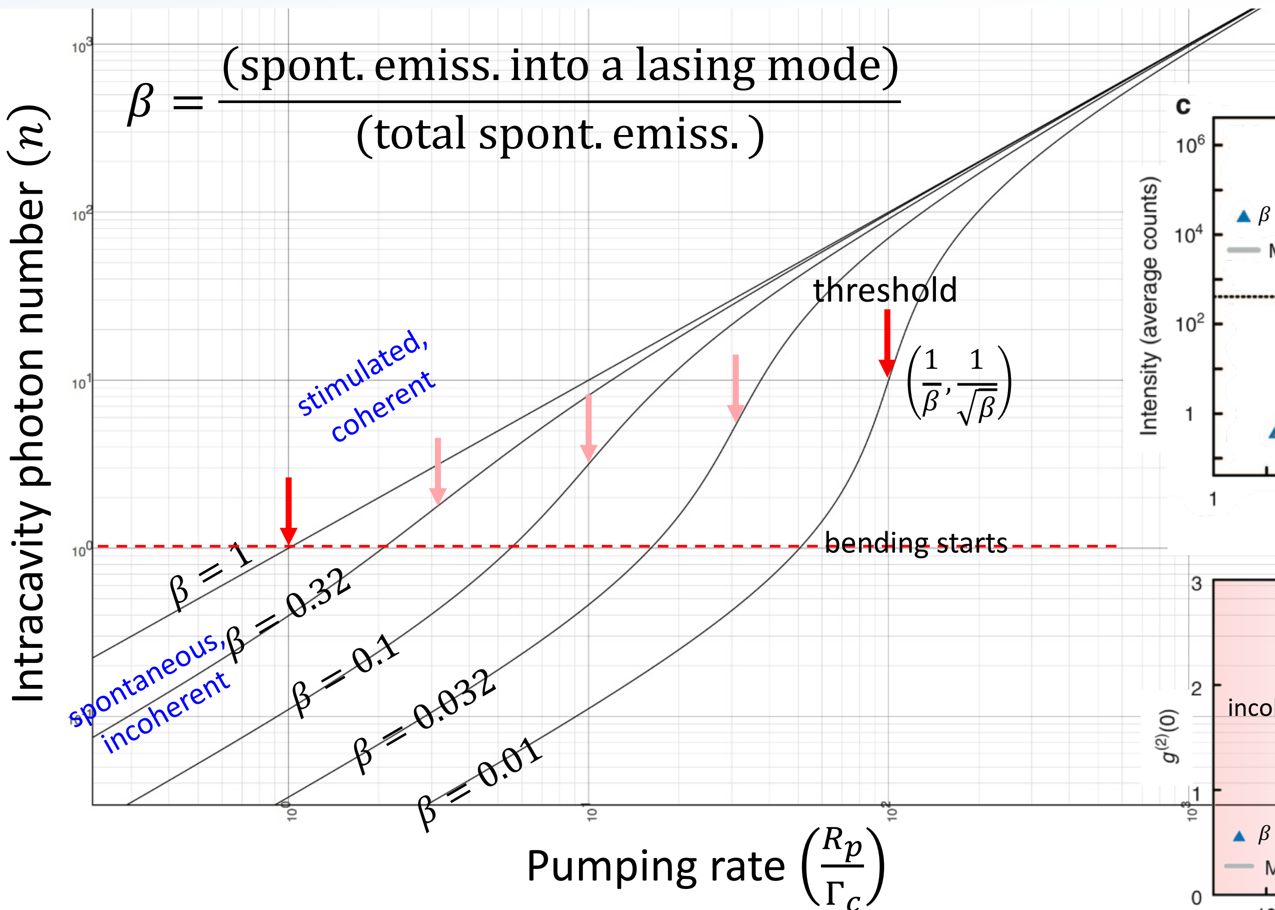
J. Kim *et al.*, *Science* **359**, 662 (2018)

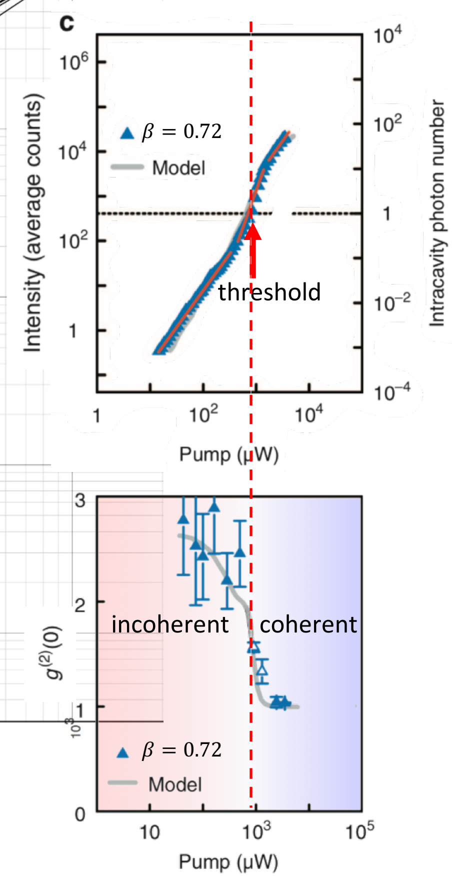
Laser threshold

- A laser requires a certain pump power in order to produce coherent light.
- Below threshold, the light is generated by spontaneous emission and thus it is incoherent.
- Above threshold, stimulated emission dominates and the field state approaches a coherent state.



Disappearing laser threshold





S. Kreinberg et al., Light: Science & Applications 6, e17030 (2017).

- Threshold occurs when $\frac{R_p}{\Gamma_c} = \frac{1}{\beta}$.
- Threshold disappears when $\beta = 1$.
- However, photon statistics still differ: incoherent vs. coherent

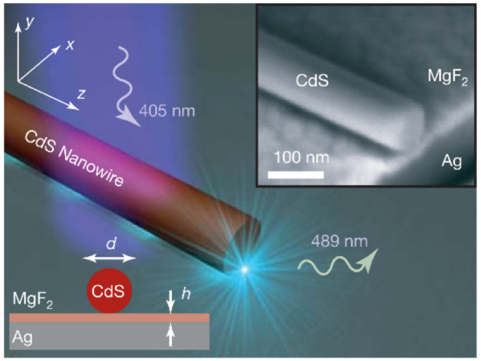
Some near-thresholdless lasers

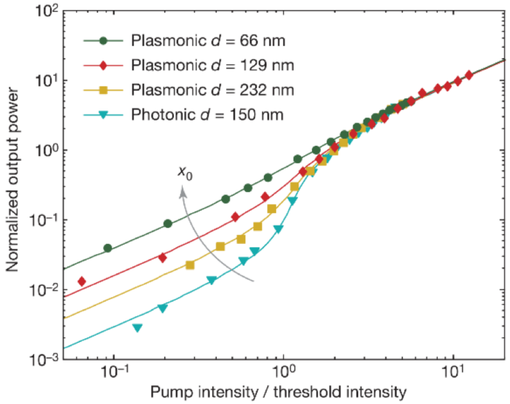
conventional approach

- Non-collective emission
- Clever cavity design & Purcell effect, mode volume $\sim \lambda^3 \rightarrow \beta \simeq 1$

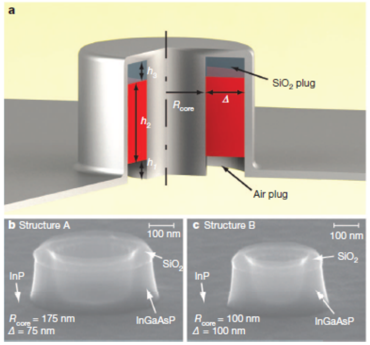
Purcell factor, $F_P = \dfrac{3Q}{4\pi^2}\dfrac{(\lambda_0/n)^3}{V}$

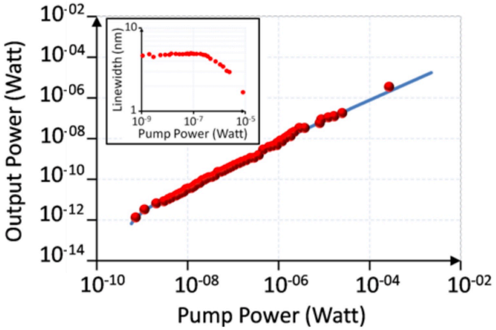
Plasmon lasers at deep subwavelength scale: R. F. Oulton *et al.*, Nature **461**, 08364 (2009)



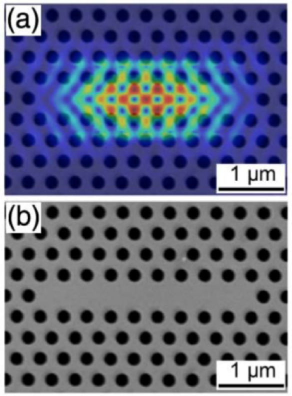


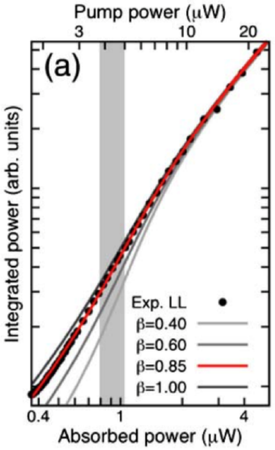
Thresholdless nanoscale coaxial lasers: M. Khajavikhan *et al.*, Nature **482**, 204 (2012)





Near thresholdless laser operation at room temperature: I. PRIETO *et al.*, Optica **2**, 2334 (2015)





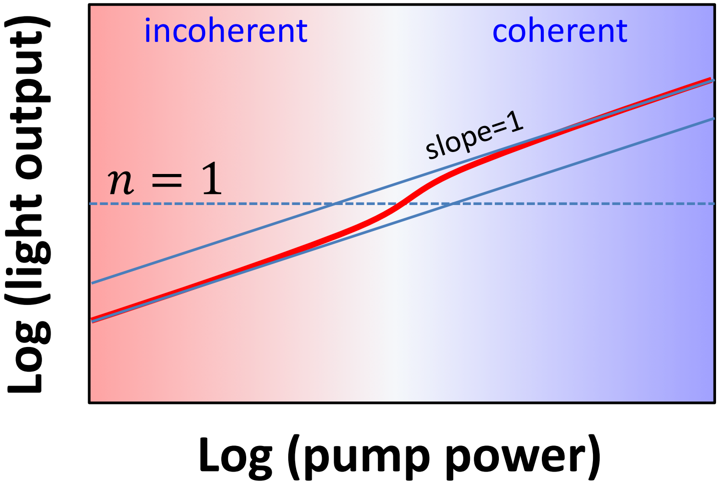
All coherent thresholdless lasing?

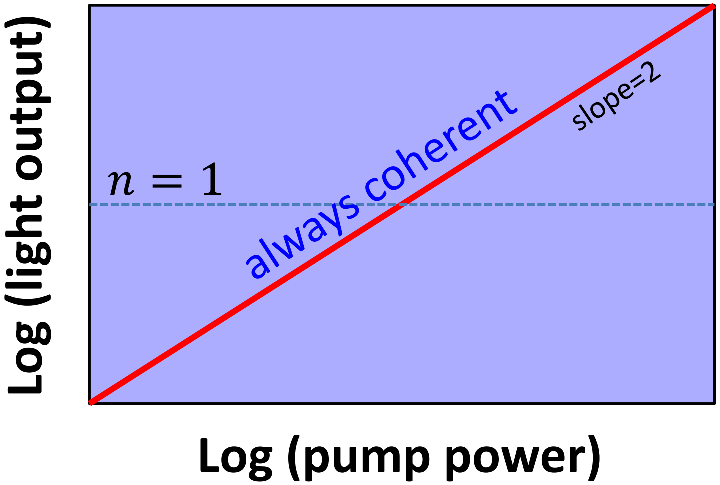
conventional approach

- Non-collective emission
  - spontaneous vs. stimulated emissions
  - incoherent vs. coherent
- Clever cavity design & Purcell effect, mode volume $\sim \lambda^3$ ➔ $\beta \simeq 1$
  - Small output, thermally weak

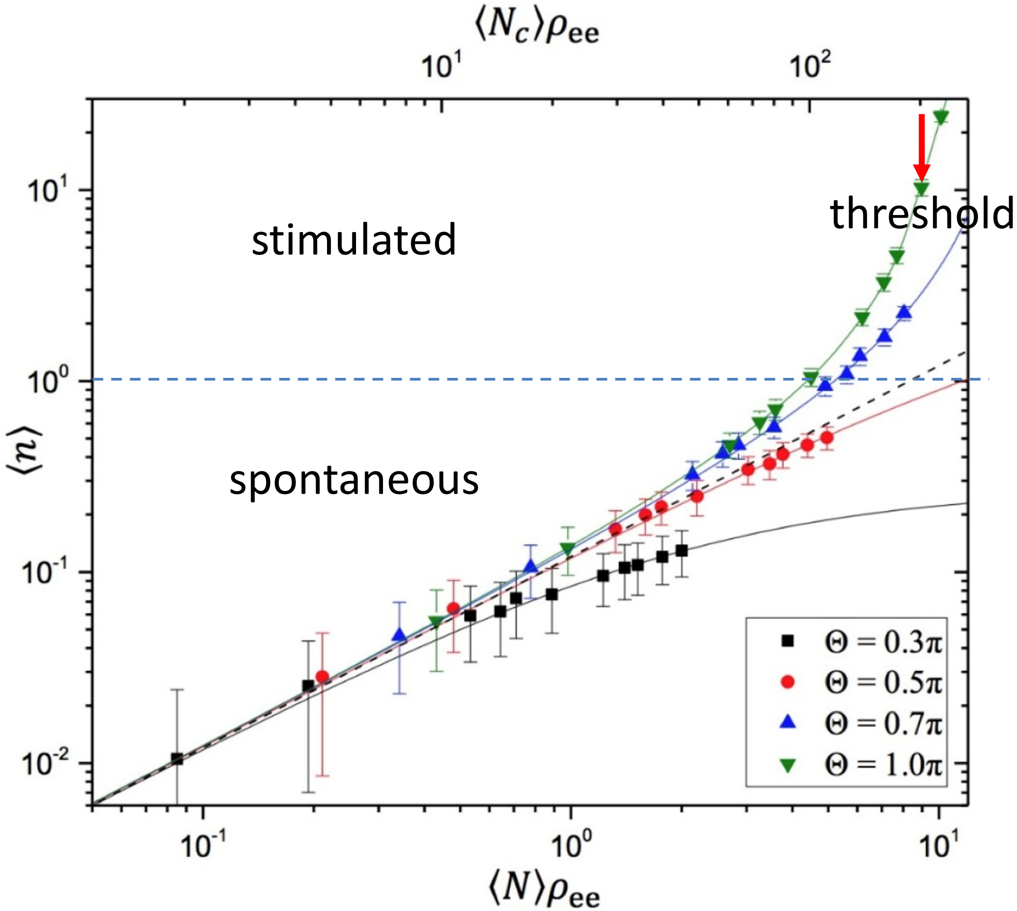
our approach

- Collective emission (superradiance)
  - no distinction between spontaneous and stimulated emissions
  - no threshold
  - always coherent
- Large cavity (mode volume $\gg \lambda^3$) & $\beta \ll 1$ possible
  - Large output, thermally strong





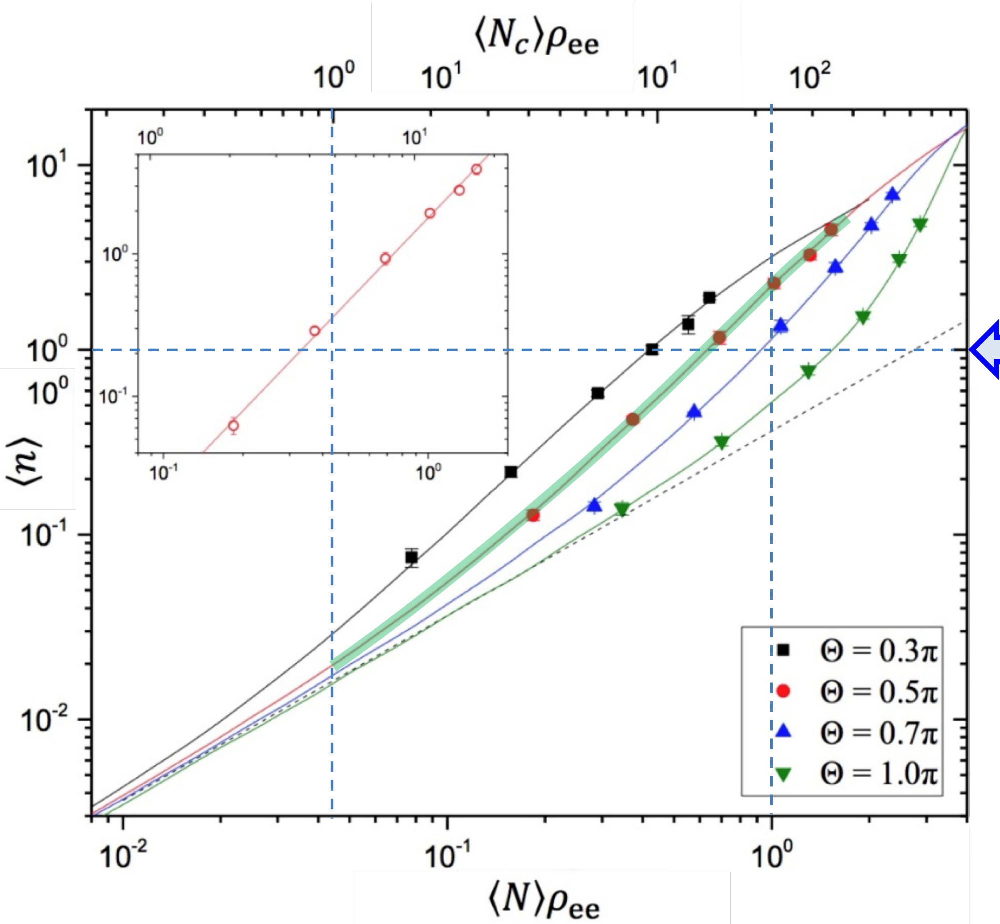
Lasing threshold – noncollective case



- Clear threshold for $\Theta = \pi$ (fully inverted)
- Threshold occurs at $\frac{\langle N\rangle}{\Gamma_c\tau} = \frac{1}{\beta}$ or $\langle N\rangle = \frac{\Gamma_c}{g^2\tau} \simeq 8$
- $\beta \simeq (g\tau)^2$=0.032

J. Kim *et al.*, *Science* **359**, 662 (2018)

Thresholdless lasing – collective case



No distinction between stimulated and spontaneous emission for $\Theta = \frac{\pi}{2}$

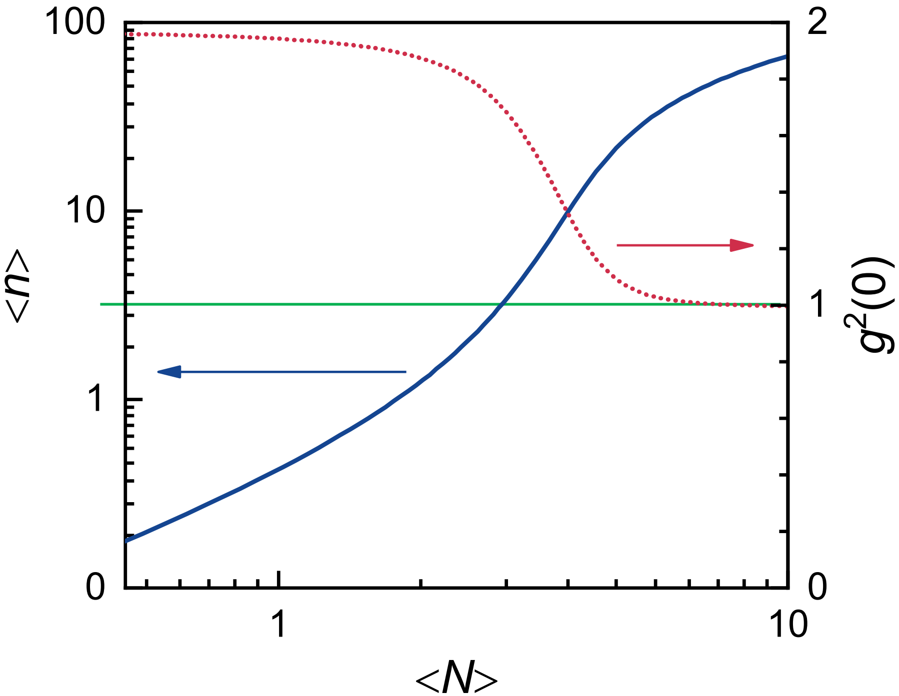
- Log-log slope ($\Theta = 0.5\pi$) = 1.67±0.01 → $\langle n \rangle \propto \langle N \rangle^{1.67}$
  - Without non-collective effect : $\langle n_{SR} \rangle \propto \langle N \rangle^{1.94}$ → the single-atom superradiance
- No slope change when $\langle n \rangle = 1$ → thresholdless lasing [note $\beta \simeq (g\tau)^2$=0.032]

J. Kim *et al.*, *Science* **359**, 662 (2018)

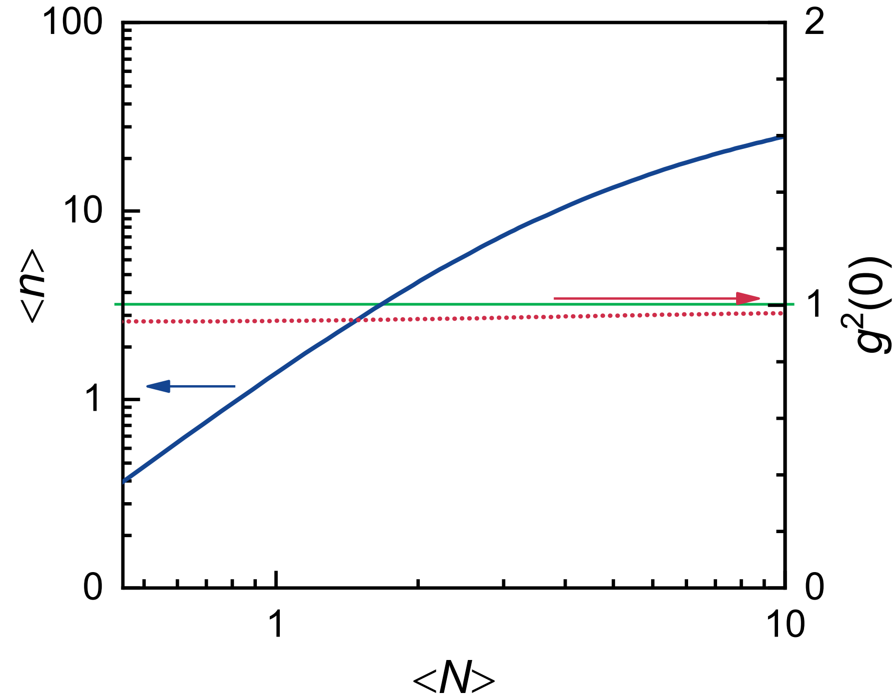
Thresholdless lasing – collective case

Ph.D. Project #2

Non-collective emission case



All coherent thresholdless lasing (slightly sub-Poisson)



- Log-log slope ($\Theta = 0.5\pi$) = 1.67±0.01 → $\langle n \rangle \propto \langle N \rangle^{1.67}$
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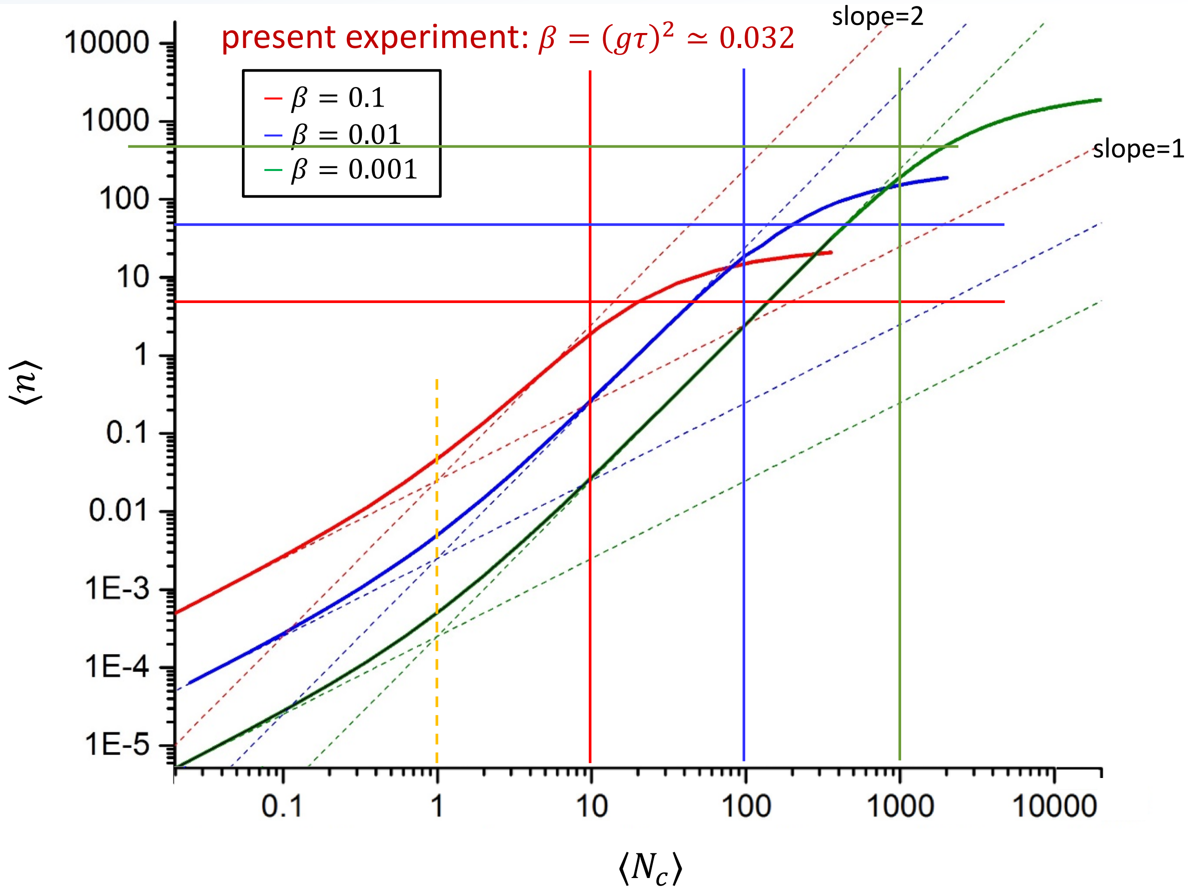
- No slope change when $\langle n \rangle = 1$ → thresholdless lasing [note $\beta \simeq (g\tau)^2$=0.032]

J. Kim *et al.*, *Science* **359**, 662 (2018)

Scalability: smaller beta factor is better



- Collective emission, $|\psi_{\text{field}}\rangle \simeq |\alpha\rangle$, where $\alpha = -i\rho_{eg}\langle N_c\rangle g\tau$, for $\boxed{1 < \langle N_c\rangle < 1/\beta}$

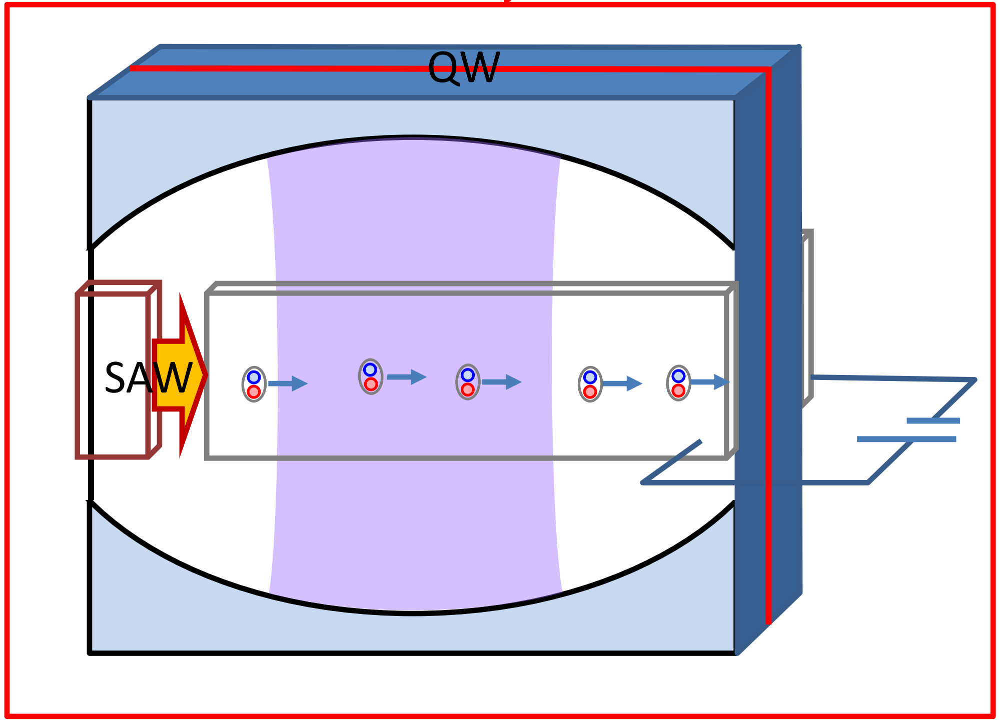
  Intracavity photon number $\langle n\rangle = |\alpha|^2 \simeq |\rho_{eg}|^2 \langle N_c\rangle^2 \beta < \frac{1}{4\beta}$

- By choosing a smaller beta factor, we can enlarge the quadratic region more and increase the maximum photon number more.

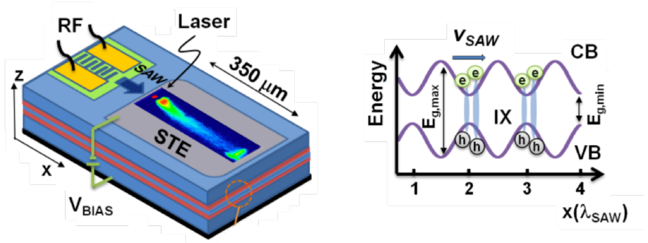
Application to solid state microlasers?

- Replace atoms with *excitions* or *plasmons* in solid-state microlasers
- *Coherent superposition* of upper and lower levels (dipoles)
- *Transporting* coherent dipoles across the cavity mode enables time-separated interactions

Ph.D. Project #3



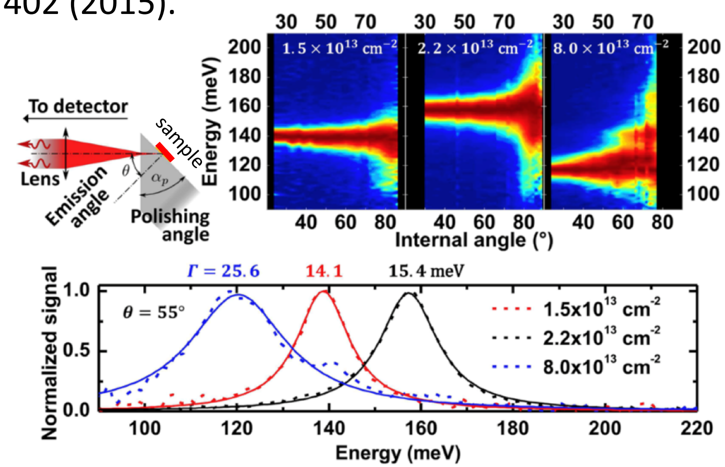
Exciton transport by surface acoustic wave



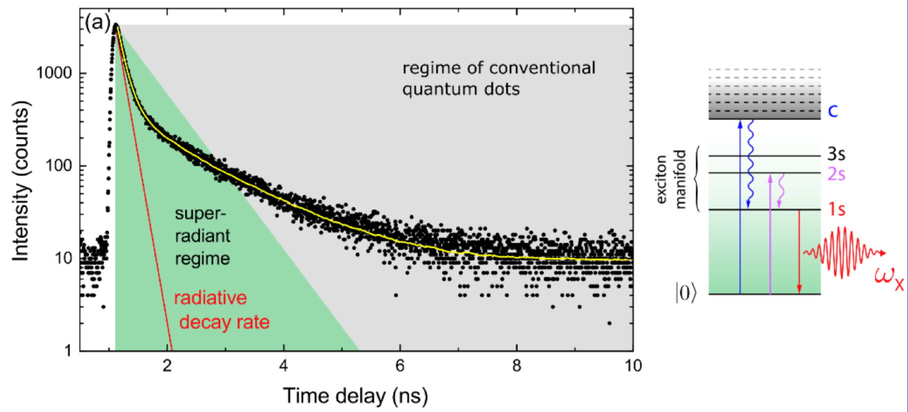
A Violante *et al*, New J. Phys. **16**, 033035 (**2014**)

Possible candidates - superradiance in solid

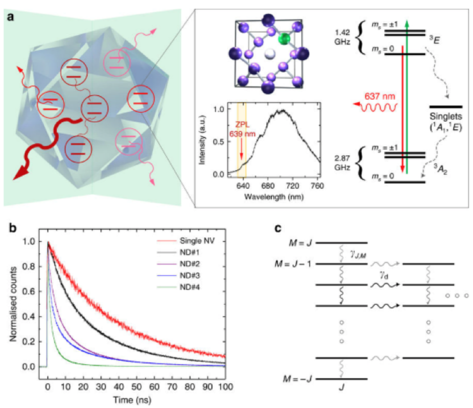
Superradiant emission from a collective excitation in a semiconductor (plasmon): T. Laurent *et al.*, PRL **115**, 187402 (2015).



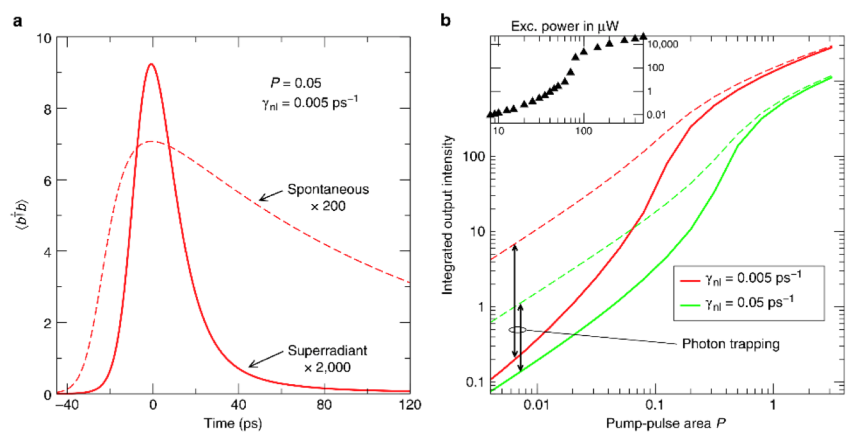
Single-photon superradiance from a quantum dot: P. Tighineanu *et al.*, PRL **116**, 163604 (2016)



Room-temperature spontaneous superradiance from single diamond nanocrystals: C Bradac *et al.*, Nat. Comm. **8**, 1205 (2017)



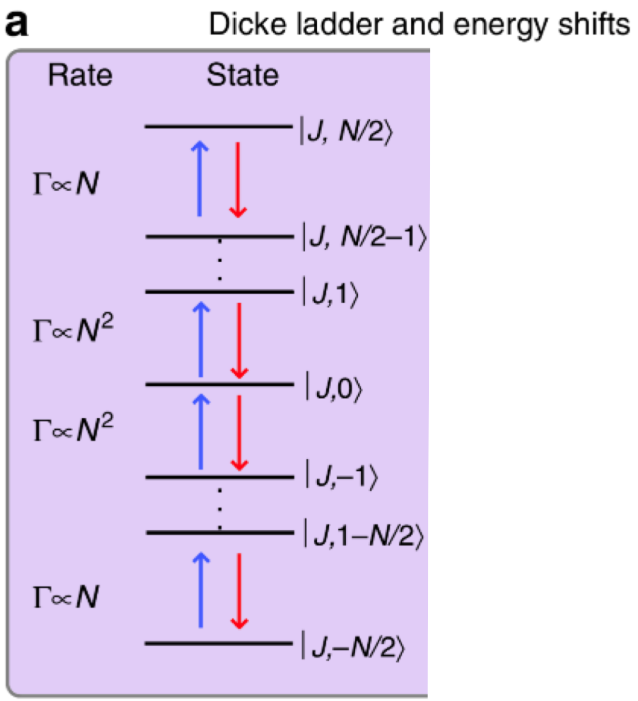
Superradiant …in quantum-dot nanolasers: F. Jahnke *et al.*, Nat. Comm. **7**, 11540 (2016)



New way of light-energy harvesting

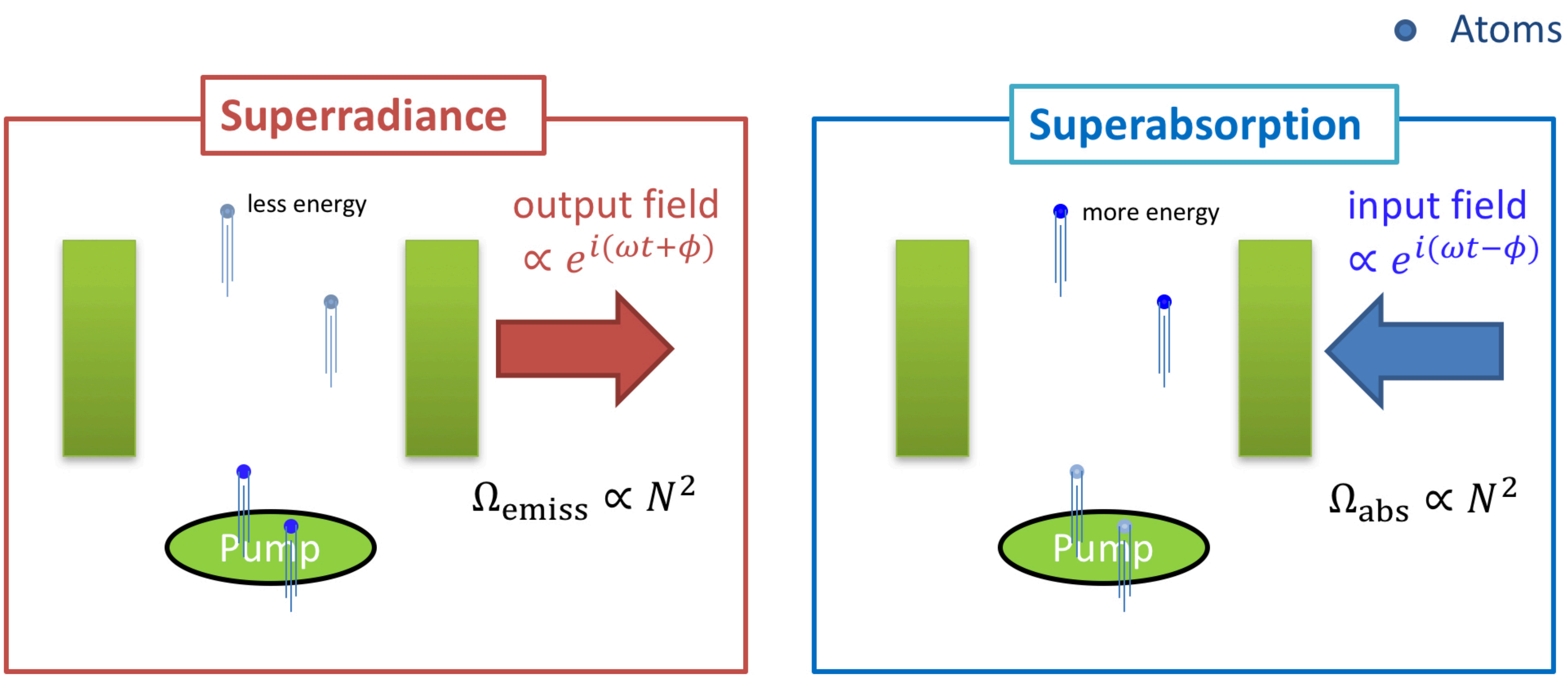
II. Superabsorption

Absorption by correlated atoms - superabsorption



Superabsorption – our scheme

- Superabsorption - time reversal process of superradiance



No input → Large Output

No Output ← Large input

Superabsorption – our scheme

- Superabsorption - time reversal process of superradiance

Jaynes-Tavis Hamiltonian

$$\hat{H} = \hbar g \sum_{i}^{N} (\hat{a}^{+}\hat{\sigma}_i + \hat{\sigma}_i^{+}\hat{a})$$

Time-evolution operator

$$\hat{U}(t) = e^{-\frac{i\hat{H}t}{\hbar}}$$

π-rotation in photonic phase space

$$\hat{R} = e^{-i\pi\hat{a}^{+}\hat{a}}$$

Then

$$\hat{R}^{+}\hat{a}\hat{R} = -\hat{a}, \hat{R}^{+}\hat{a}^{+}\hat{R} = -\hat{a}^{+}$$

$$\therefore \hat{R}^{+}\hat{U}(t)\hat{R} = \hat{U}(-t)$$

Consider a superradiance process

$$\hat{U}(t)|\Psi\rangle_a|0\rangle_p = |\Psi'\rangle_a|\alpha\rangle_p$$

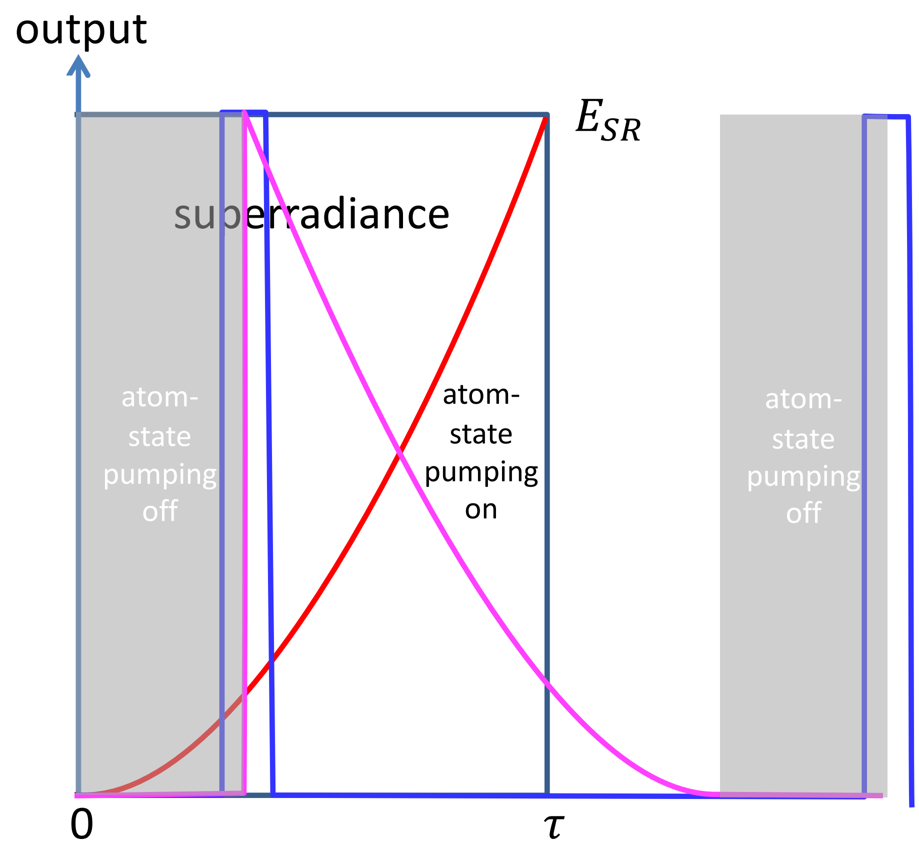
Then

$$\hat{U}(t)|\Psi'\rangle_a|-\alpha\rangle_p = \hat{U}(t)\hat{R}^{+}\hat{R}|\Psi'\rangle_a|-\alpha\rangle_p = \hat{U}(t)\hat{R}^{+}|\Psi'\rangle_a|\alpha\rangle_p$$

$$= \hat{R}^{+}\hat{U}(-t)|\Psi'\rangle_a|\alpha\rangle_p = \hat{R}^{+}|\Psi\rangle_a|0\rangle_p = |\Psi\rangle_a|0\rangle_p$$

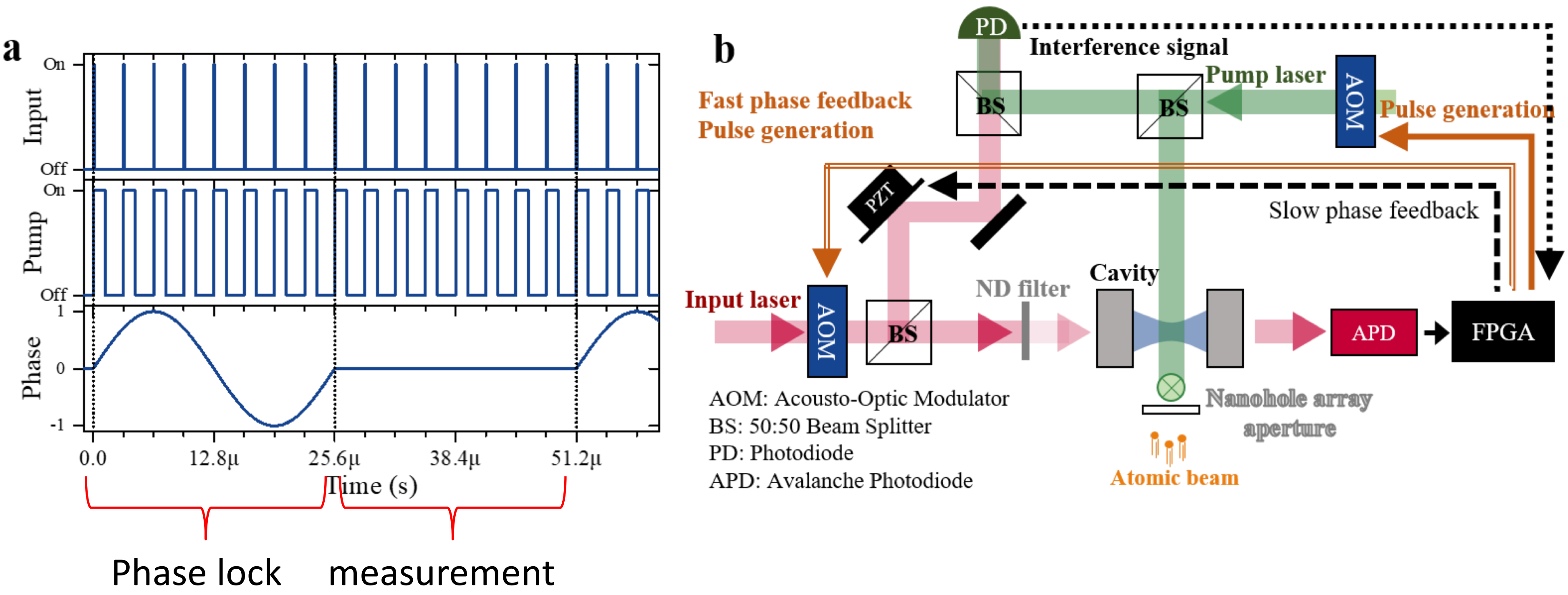
Superabsorption – our scheme

- Superabsorption - time reversal process of superradiance
- Our scheme works for arbitrary pulsed inputs.
- Applicable to light-energy harvesting (light energy transferred to atoms)



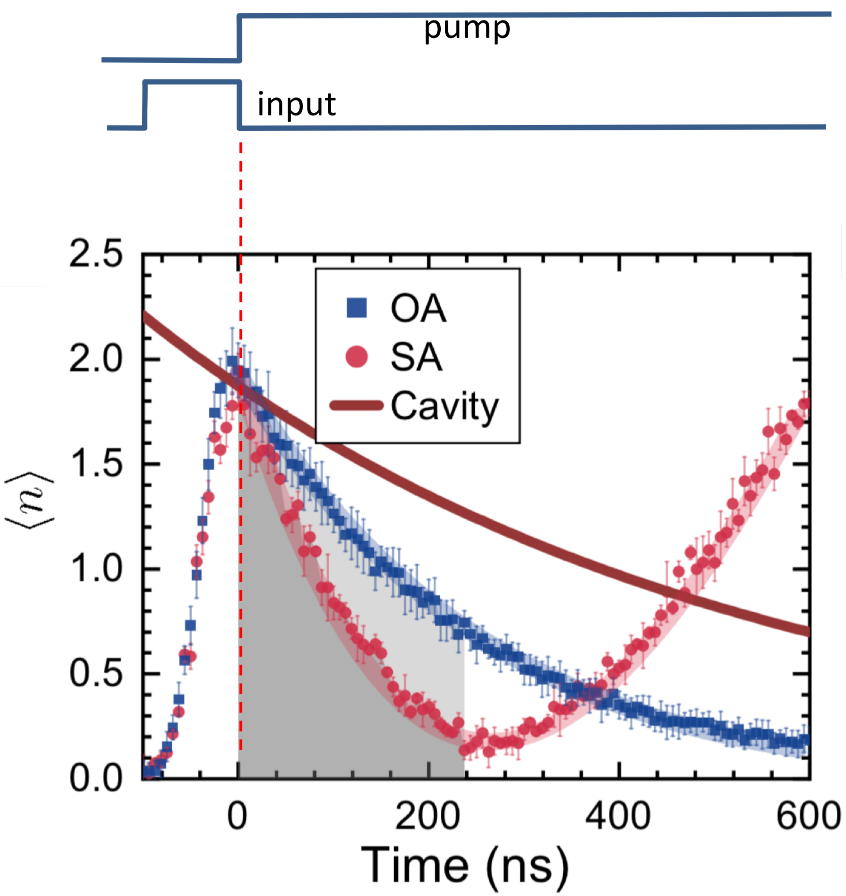
Phase locking setup

- The phase of the input laser is locked to that of the pump laser (preparing superposition state) with an offset, which is adjusted to induce superabsorption.

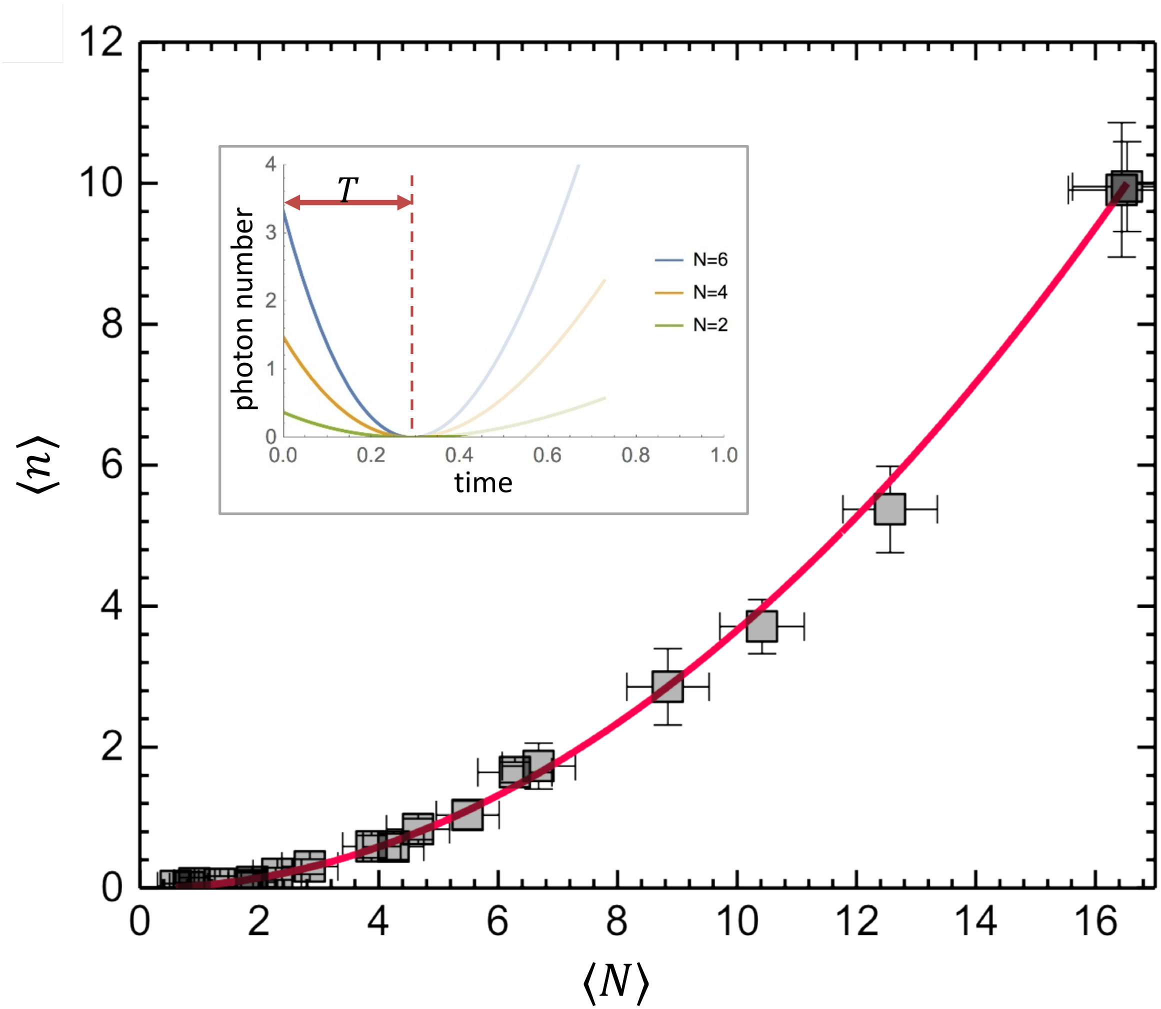


Experimental results

OA: ordinary absorption
SA: superabsorption



N^2 dependence of superabsorption

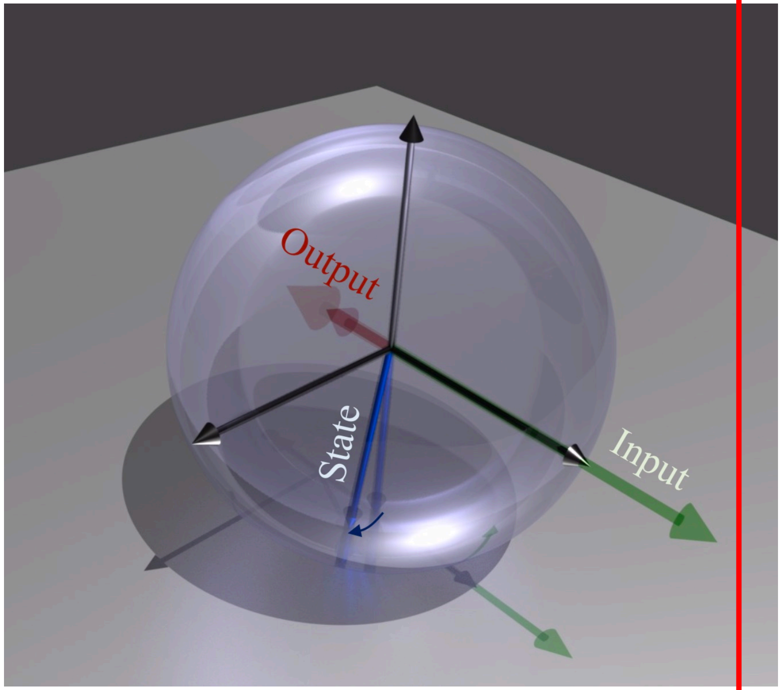


- Number of photons completely absorbed during a time interval T is proportional to N^2 in the cavity (N: number of atoms in the cavity).

Superabsorption as intereference

- Ordinary absorption as interference between the input field and the emitted field of an excited dipole.
- The superradiant state emits a stronger output, which destructively interfere with the input field, resulting in superabsorption.
- This interpretation does not require a cavity, suggesting a possibility of free-space superabsorption.

Ph.D. Project #4



Further information

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- Drop by my office at 56-324.