서울대학교
SEOUL NATIONAL UNIVERSITY

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양자중첩상태의 위상제어를 통한 새로운 빛-물질 상호작용의 제어

서울대학교 물리천문학부
안경원

목차

- 양자 중첩상태를 이용한 초방사
  - 항상 결맞은 문턱 없는 레이징
- 초방사의 시간 역과정→ 초흡수
  - 자유공간 초흡수
- 초방사의 응용
  - 직접적 광학주파수 합성, Axion 암흑물질 검출기

금년 석박통합 opening 2명, 내년부터는 신입생을 받지 않음

Enhanced photoemission by correlated atoms

양자중첩상태를 이용한 초방사

초방사(superradiance)의 소개

- 초방사는 1954년에 미국의 물리학자 Robert Dicke가 처음 고려.
- 양자역학적으로 연관된(correlated) 원자들의 빛 방출 현상.
- 방사의 세기가 원자수 제곱에 비례, 방사시간은 원자수에 반비례.

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.

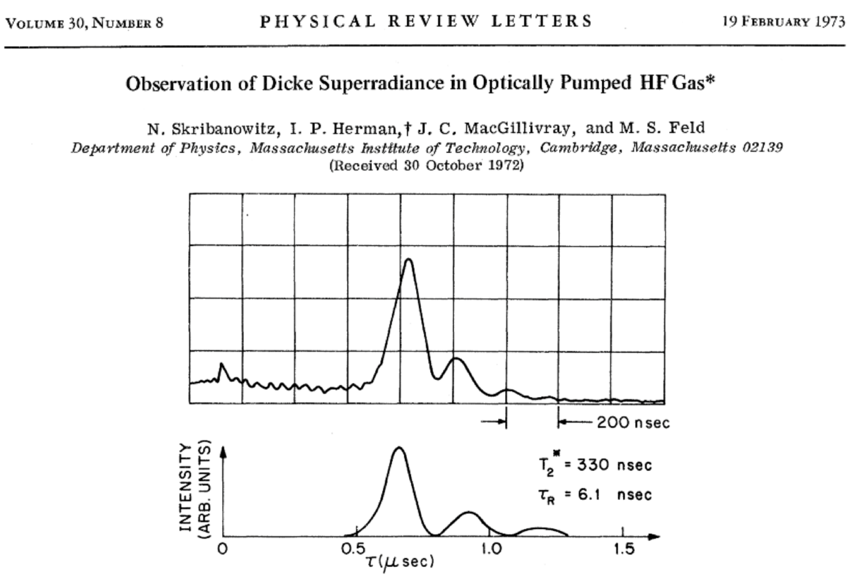
$d \ll \lambda$

time

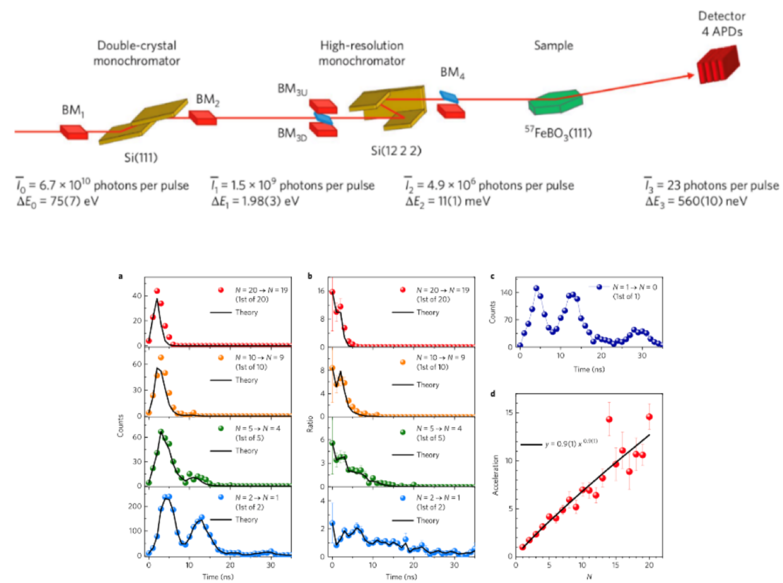
Review by M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982).

초방사 연구의 발전과정

- 1960년대 레이저의 발명으로 실험적 접근 시도.
- 원자간 거리가 파장보다 작아야 발생, 기술적으로 매우 어려운 실험으로 악명 높음.
- 2000년대에 들어와 나노기술의 발달로 보다 정교한 실험 가능해 짐. 다양한 물리계(양자점, NV center, 원자핵, etc)에서 관측됨.



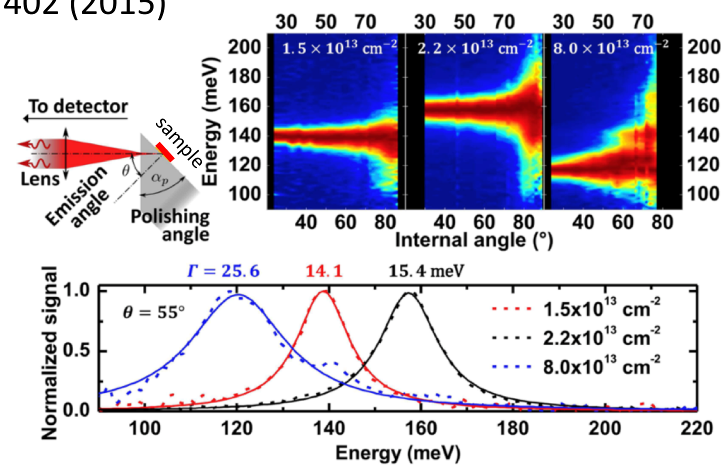
최초의 초방사 실험 (M. S. Feld, 1973)



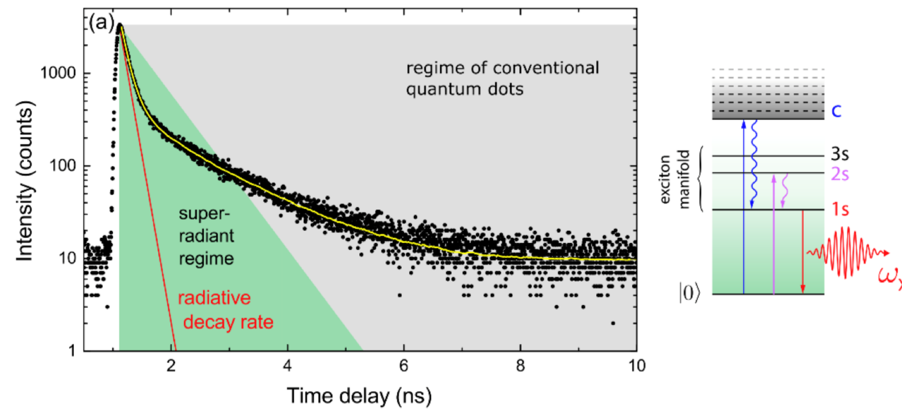
원자핵 X-ray 초방사, A. I. Chmakov *et al.*, Nat. Phys. **14**, 261 (2018)

반도체, 양자점, NV center의 초방사

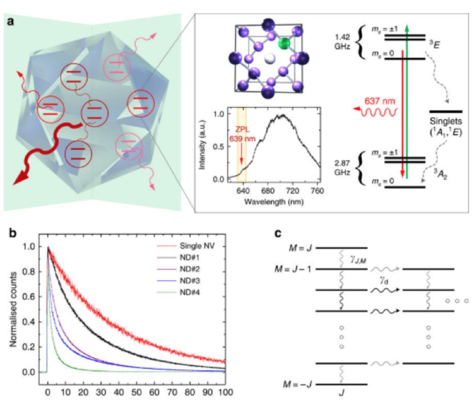
Superradiant emission from a collective excitation in a semiconductor (plasmon): T. Laurent *et al*., PRL **115**, 187402 (2015)



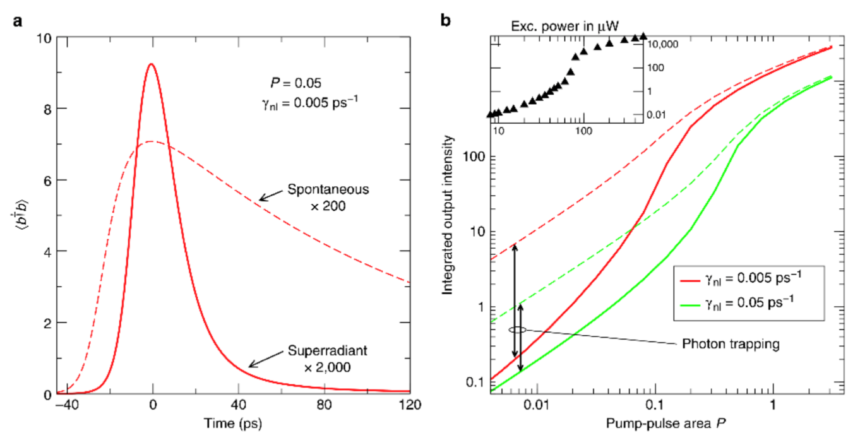
Single-photon superradiance from quantum dots: P. Tighineanu *et al*., PRL **116**, 163604 (2016)



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



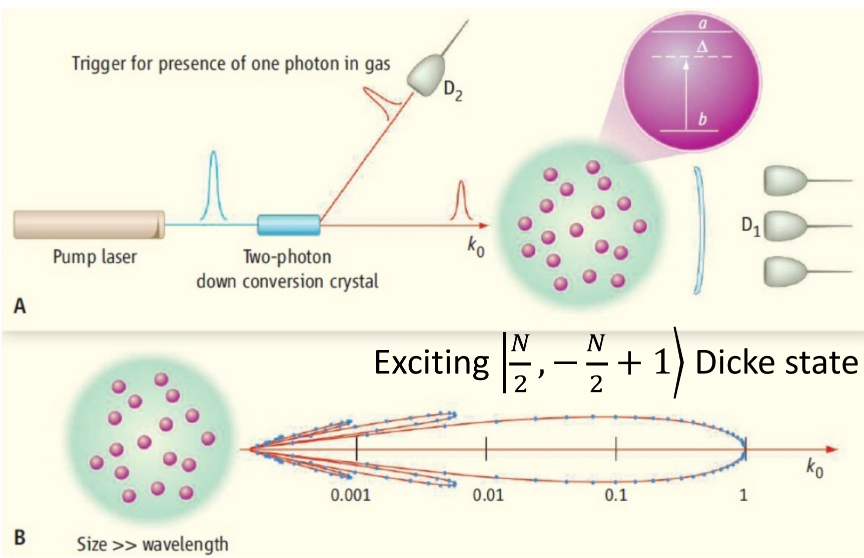
Superradiant …in quantum-dot nanolasers: F. Jahnke *et al*., Nat. Comm. **7**, 11540 (2016)



원자 위상제어에 의한 초방사

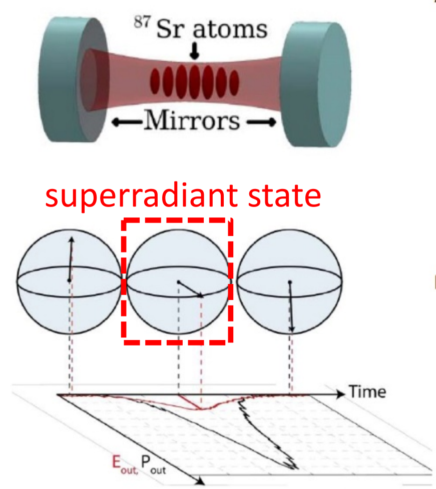
- 2010년 이후 원자의 양자역학적 중첩상태를 직접적으로 제어하여 초방사를 정교히 제어하는 연구가 시도됨.
- 양자정보, 원자광시계 등에 응용 기대.

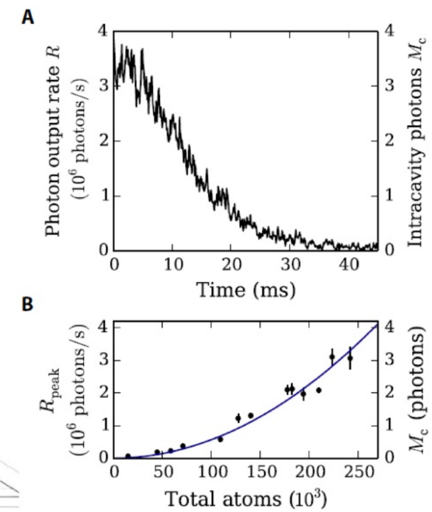
단광자 초방사 (Marlan Scully)



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

초방사 레이저 (J. Thompson)





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

Dicke vs. phase-controlled superradiance

- 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)→ Dicke ladder by Dicke states

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

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

$$\xrightarrow[\text{bright state}]{M=0} \frac{1}{4}\Gamma_\mathrm{a}N(N+2) \sim \frac{\Gamma_\mathrm{a}}{4}N^2$$

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

$$|\Psi_\mathrm{atom}\rangle = \prod_i \frac{1}{\sqrt{2}}\left(|\mathrm{e}_i\rangle + e^{i\phi}|\mathrm{g}_i\rangle\right)$$ →superradiant state

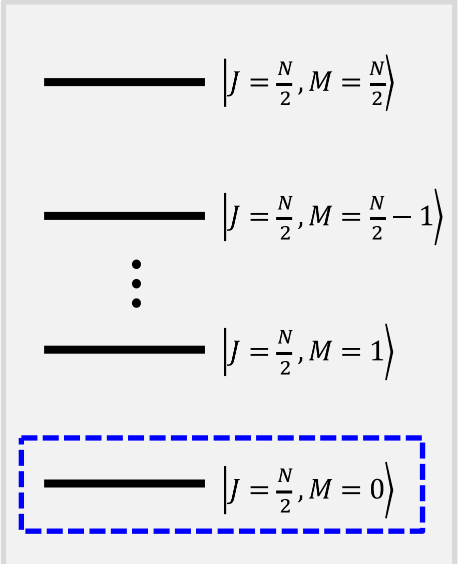
- Largest contribution from the bright state, so its emission rate

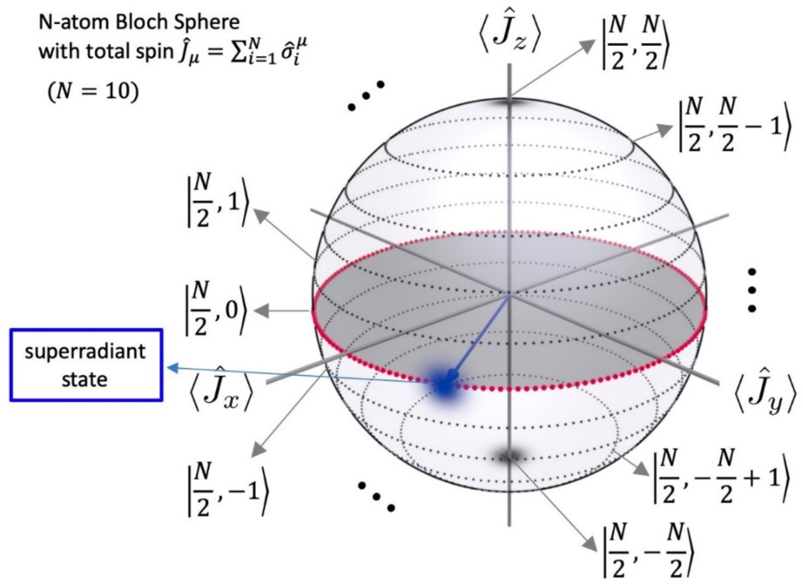
$$N\Gamma_\mathrm{a}\rho_\mathrm{ee} + N(N-1)\Gamma_\mathrm{a}|\rho_\mathrm{eg}|^2$$

$$\xrightarrow[\rho_\mathrm{eg}=\rho_\mathrm{ee}=1/2]{} \frac{1}{4}\Gamma_\mathrm{a}N(N+1) \sim \frac{\Gamma_\mathrm{a}}{4}N^2$$

Equally strong as the bright state!

Dicke Ladder

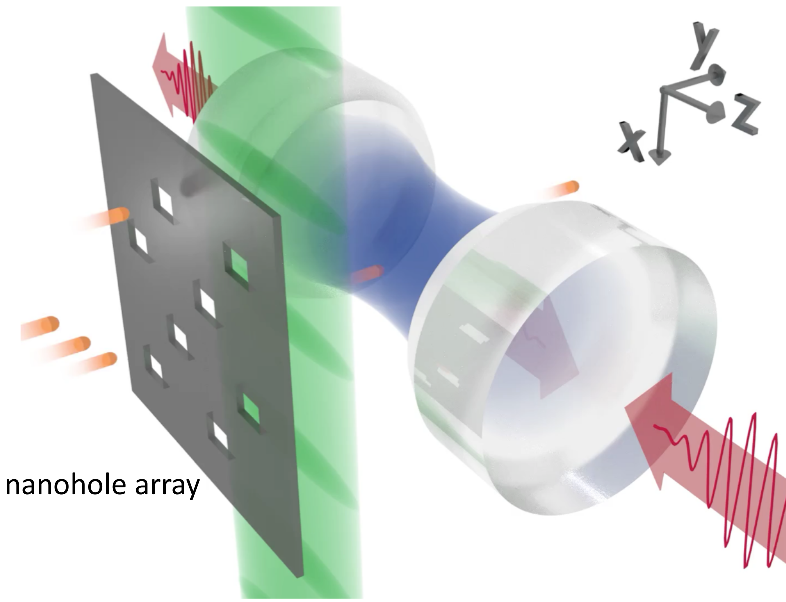


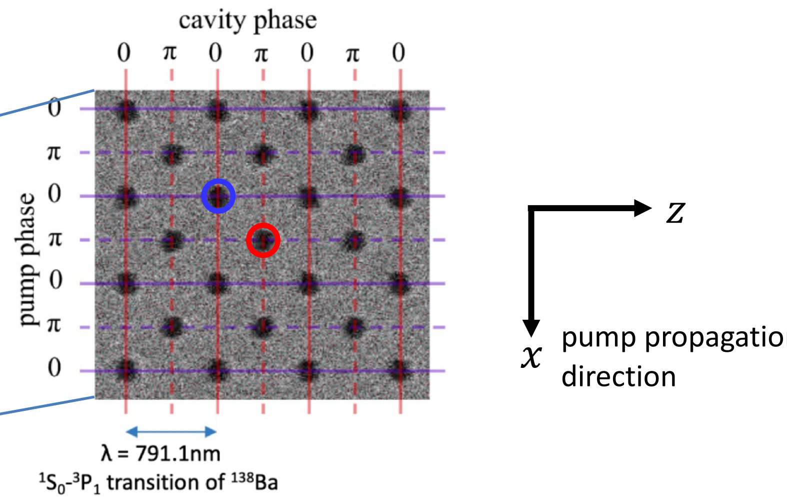


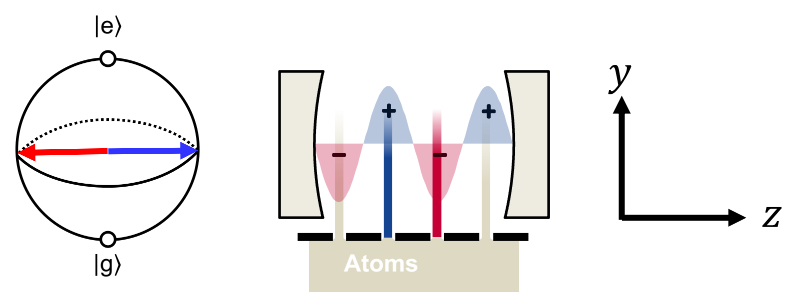
Phase control for every atom

- 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)







Mean photon number in the cavity

- The steady-state field from the master equation

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

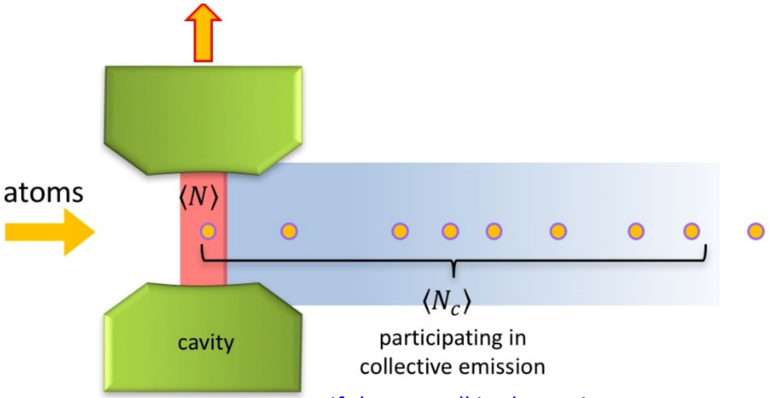
Enhancement by the superradiance

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

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

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

superradiance by *time-separated* atoms

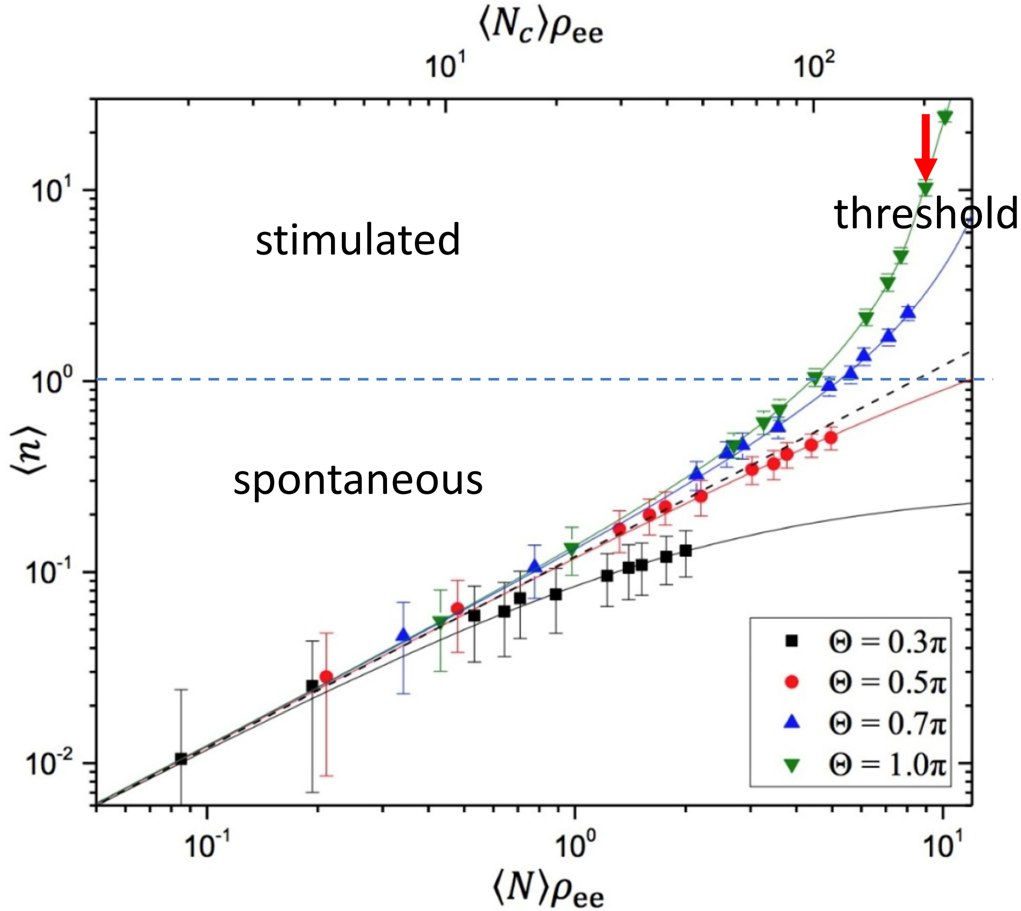


as if they are all in the cavity at the same time for time τ, repeatedly.

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

$\langle N\rangle$: Number of atoms in the cavity
$\langle N_{\text{c}}\rangle$: 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)

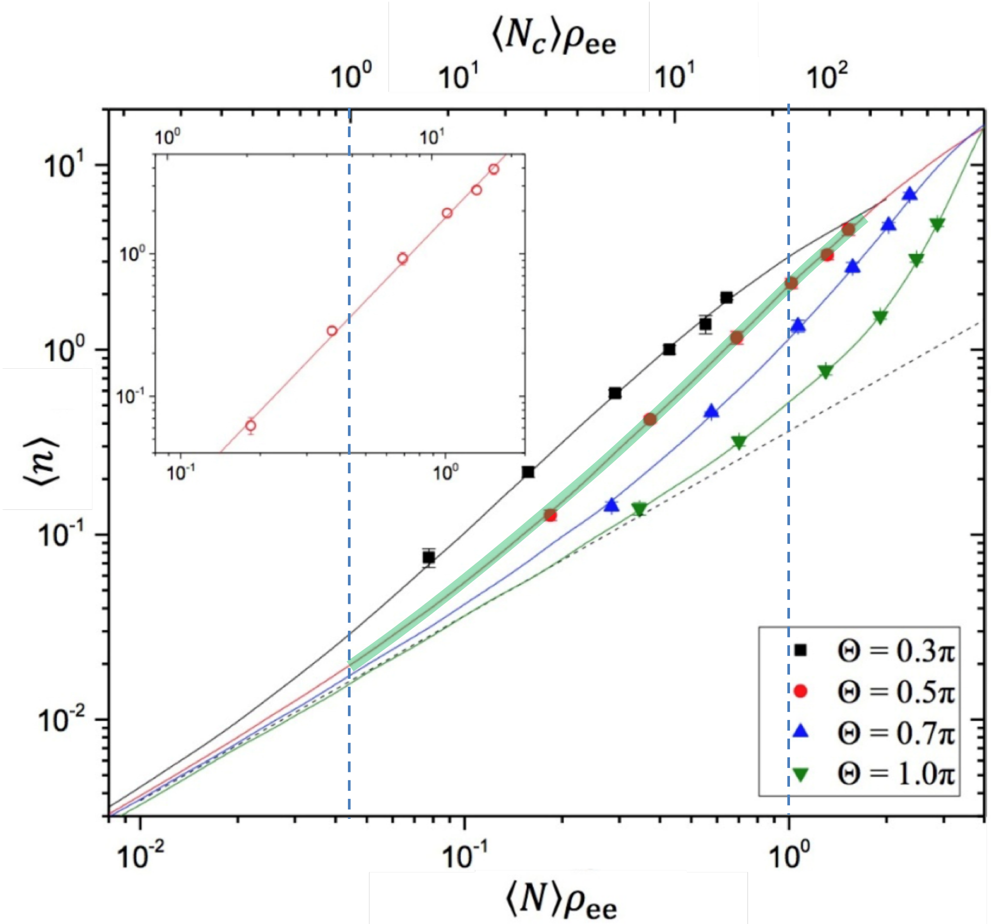
Lasing threshold – noncollective case



- Clear threshold for $\Theta = \pi$ (pump pulse area, 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)

Coherent single-atom superradiance

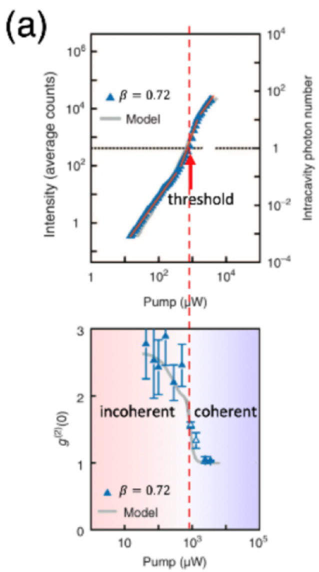


- Log-log slope ($\Theta = 0.5\pi$) = 1.67±0.01 → $\langle n \rangle \propto \langle N \rangle^{1.67}$
  – Without non-collective effect : $\langle n \rangle_C \propto \langle N \rangle^{1.94}$ → the single-atom superradiance

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

Photon statistics of thresholdless lasing

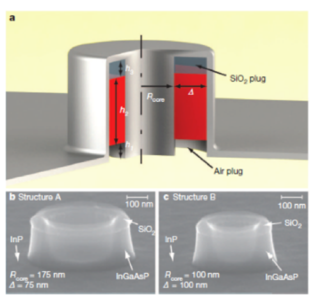
- In conventional thresholdless lasing, output is incoherent below threshold even when the threshold in output power disapperes.
- For coherent superradiance, threshold is absent and the light is always coherent.

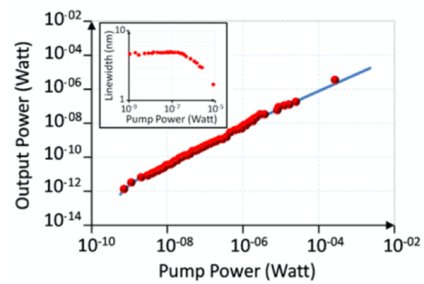


일반 문턱없는 레이저

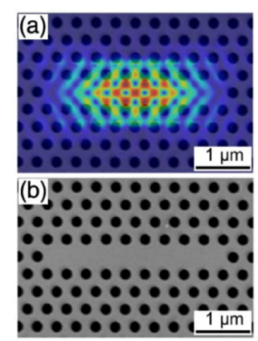
S. Kreinberg et al., Light: Science & Applications **6**, e17030 (2017)

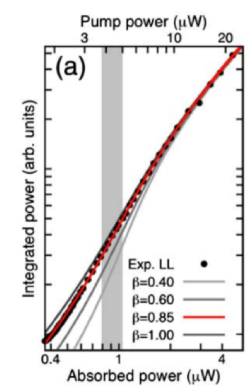
Thresholdless nanoscale coaxial lasers: M. Khajavikhan *et al.*, Nature **482**, 204 (2012)





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





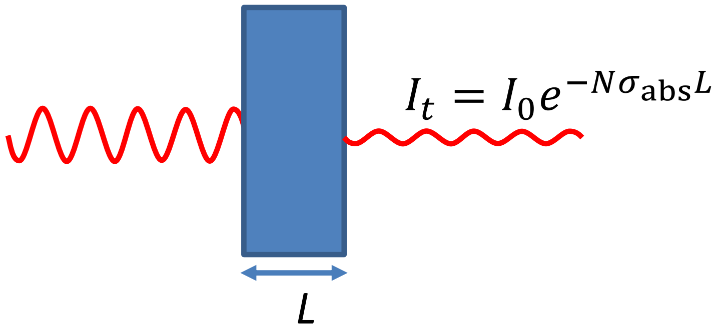
$$\beta = \frac{\text{공진기 모드로의 방출분}}{\text{전체 자발방출분}}$$

Enhanced photon “absorption” by correlated atoms

초방사의 시간 역과정→초흡수

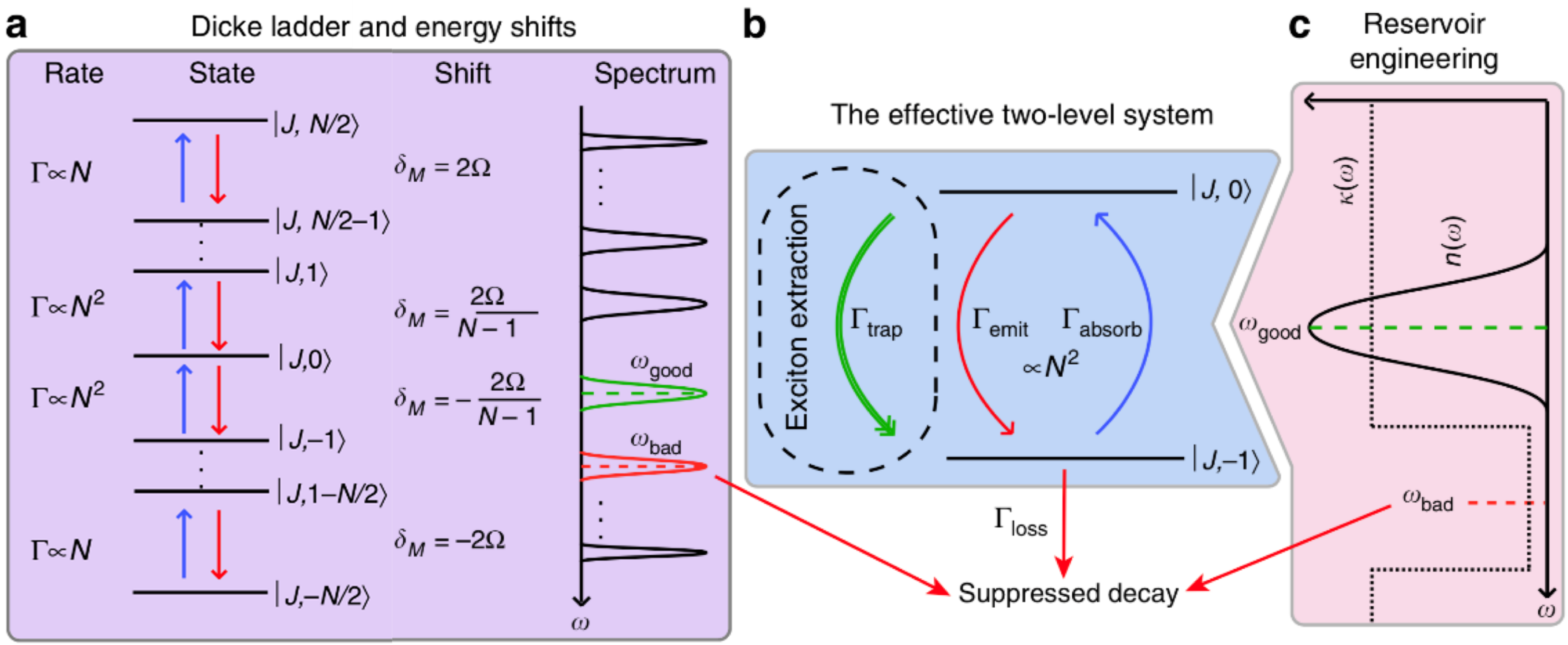
Absorption by correlated atoms – superabsorption?

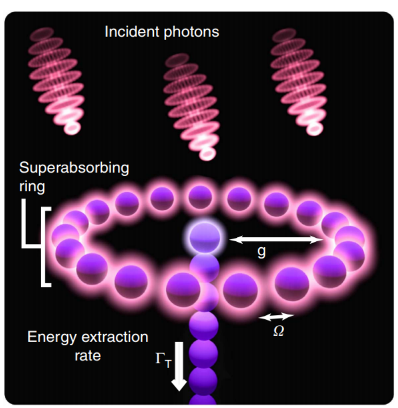
- (Ordinary absorption) ∝ (Number of atoms in the beam path)
- Superabsorption, ∝ (Number of atoms)^2, would be desirable for light-energy harvesting (solar cell, photosynthesis, *etc*)
- In nature, superaborption does not exist.



ordinary absorption

Absorption by correlated atoms – superabsorption?

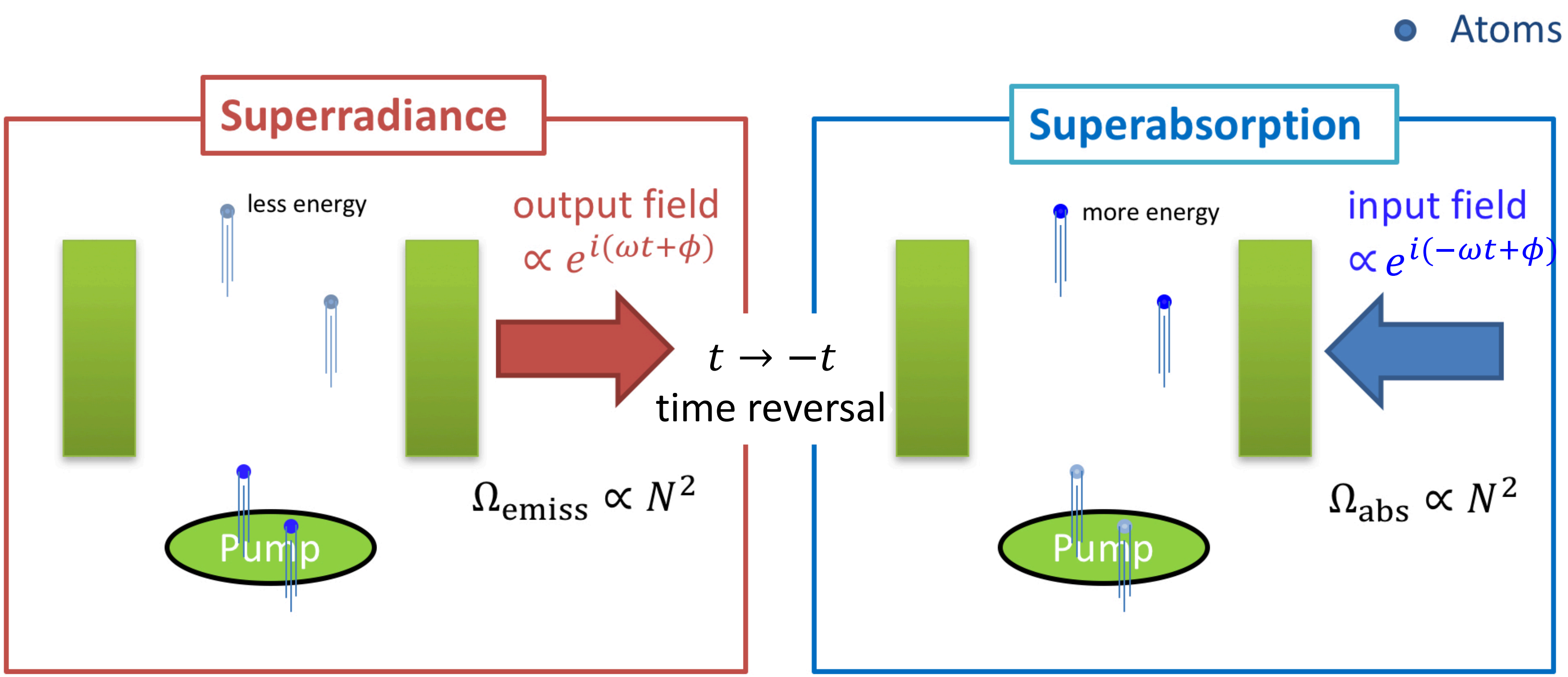




“Superabsorption of light via quantum engineering,” K. D. B. Higgins *et al.*, Nat. comm. **5**, 4705 (2014) [Theory]; “Light-harvesting with guide-slide superabsorbing condensed-matter nanostructures,” W. M. Brown and E. M. Gauger, arXiv:1803.08036v2 (2019) [Theory].

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

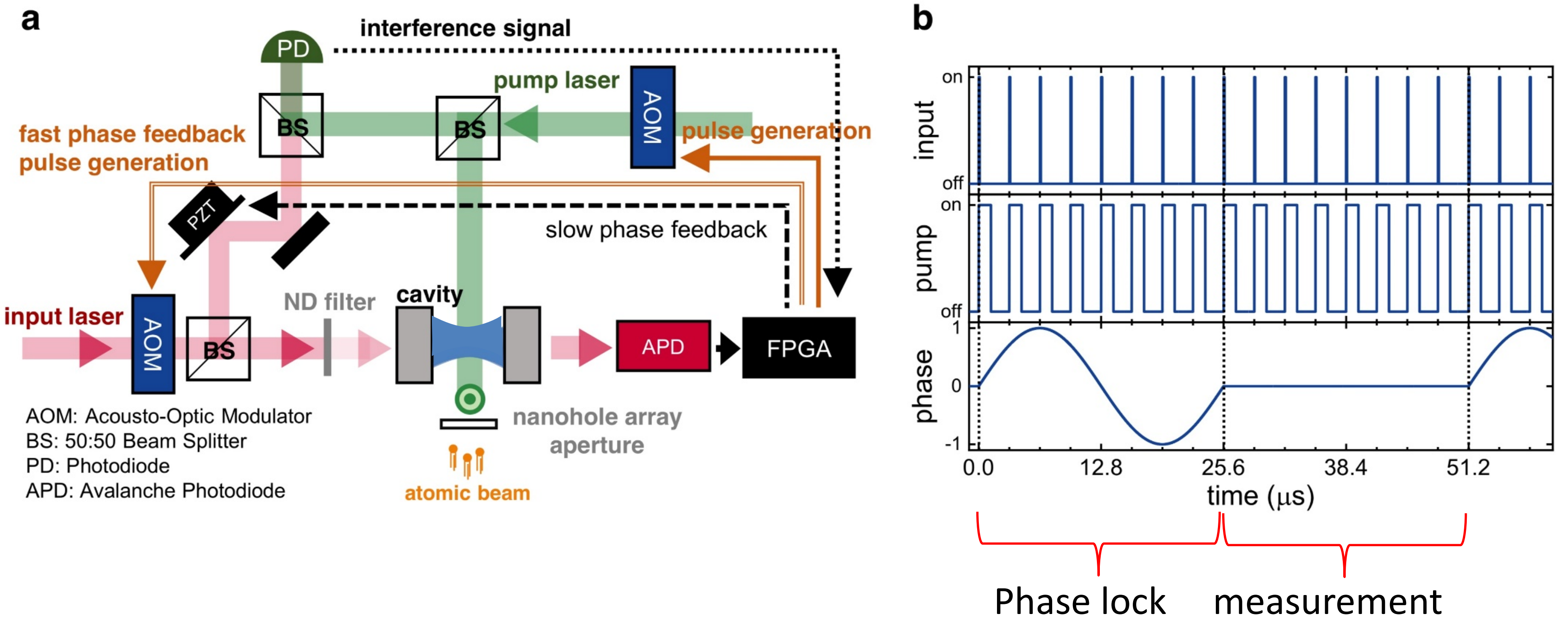
$$\hat{U}(t)|\Psi\rangle_a|0\rangle_p = |\Psi'\rangle_a|\alpha\rangle_p$$

Then

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

Phase locking setup

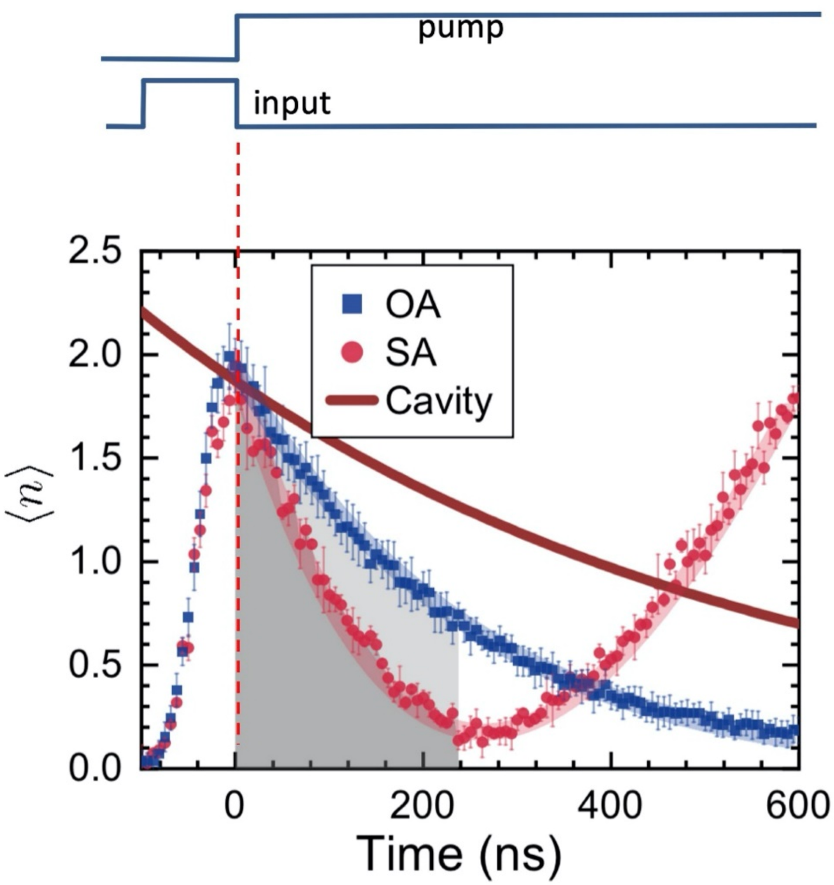
- The phase of the input laser is locked to that of the pump laser (preparing superposition state) with a phase offset, which is adjusted to induce superabsorption.

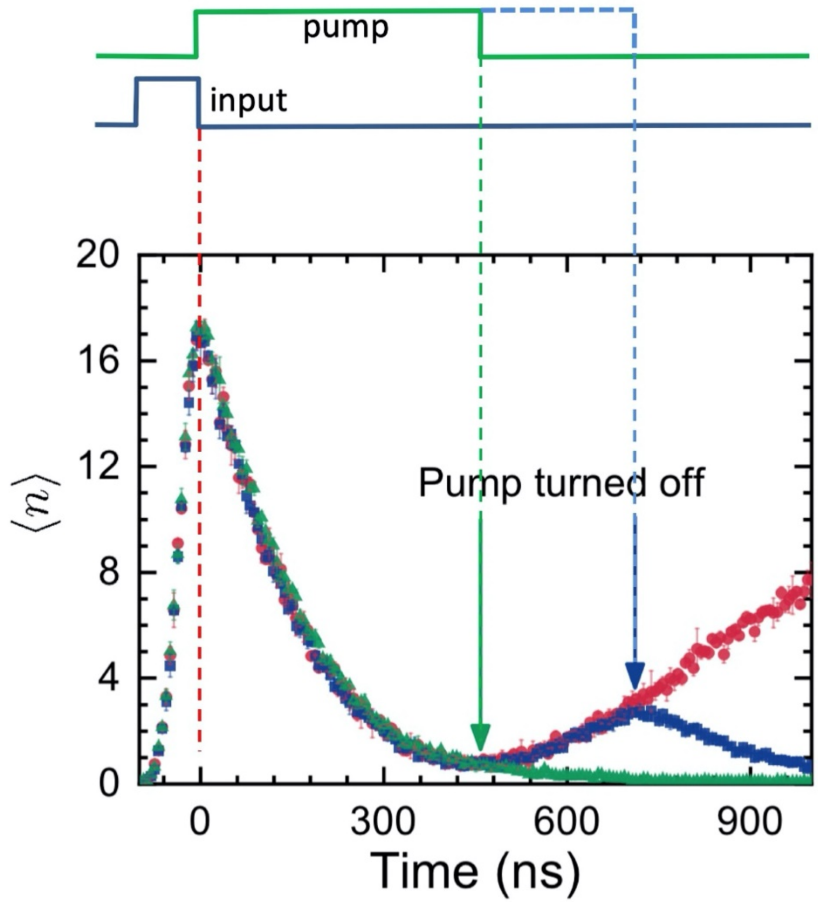


Experimental results

OA: ordinary absorption
SA: superabsorption

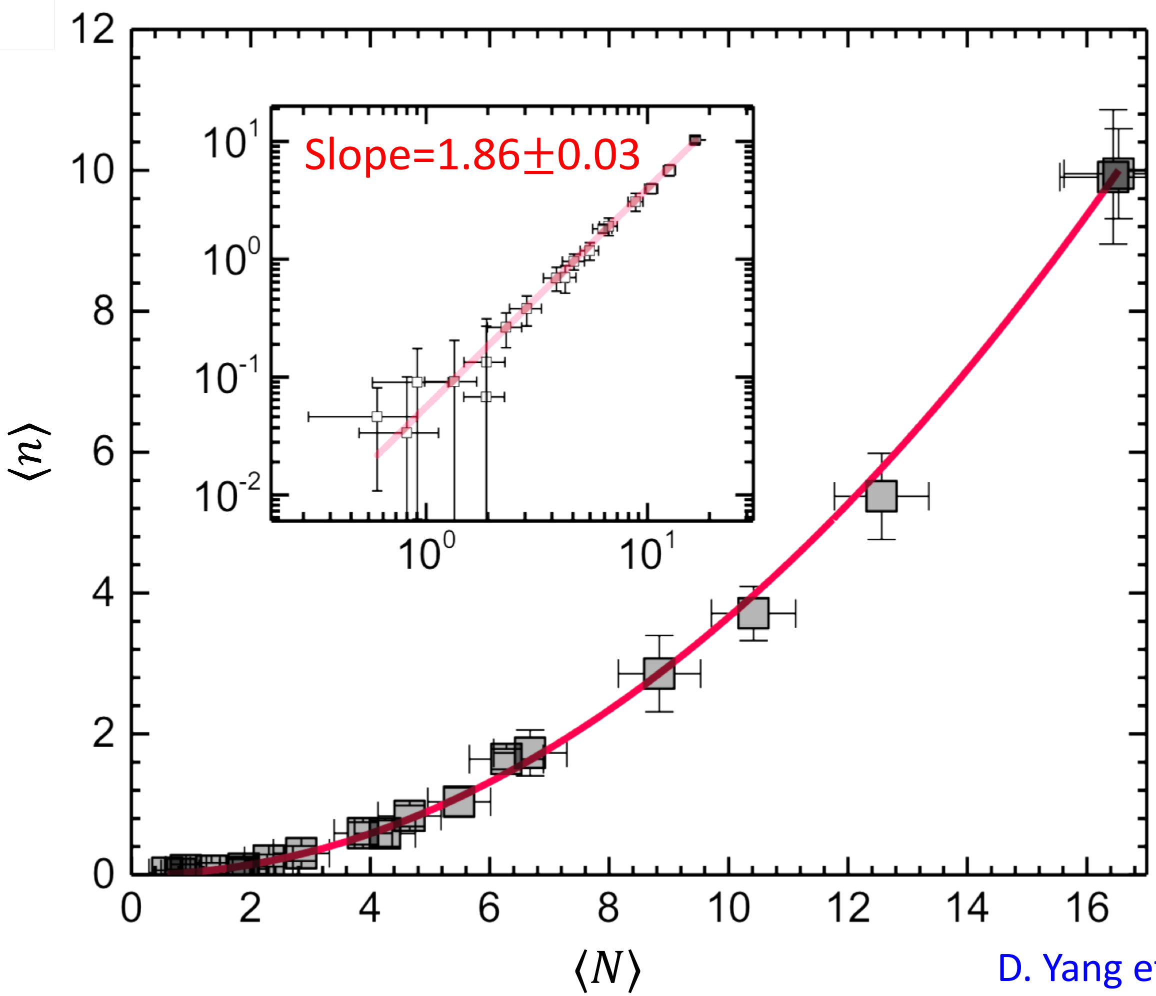
D. Yang et al., arXiv: 1906.06477





N=6.8 for both. For OA, N≃35 atoms are needed to get the same degree of absorption as SA

N^2 dependence of superabsorption

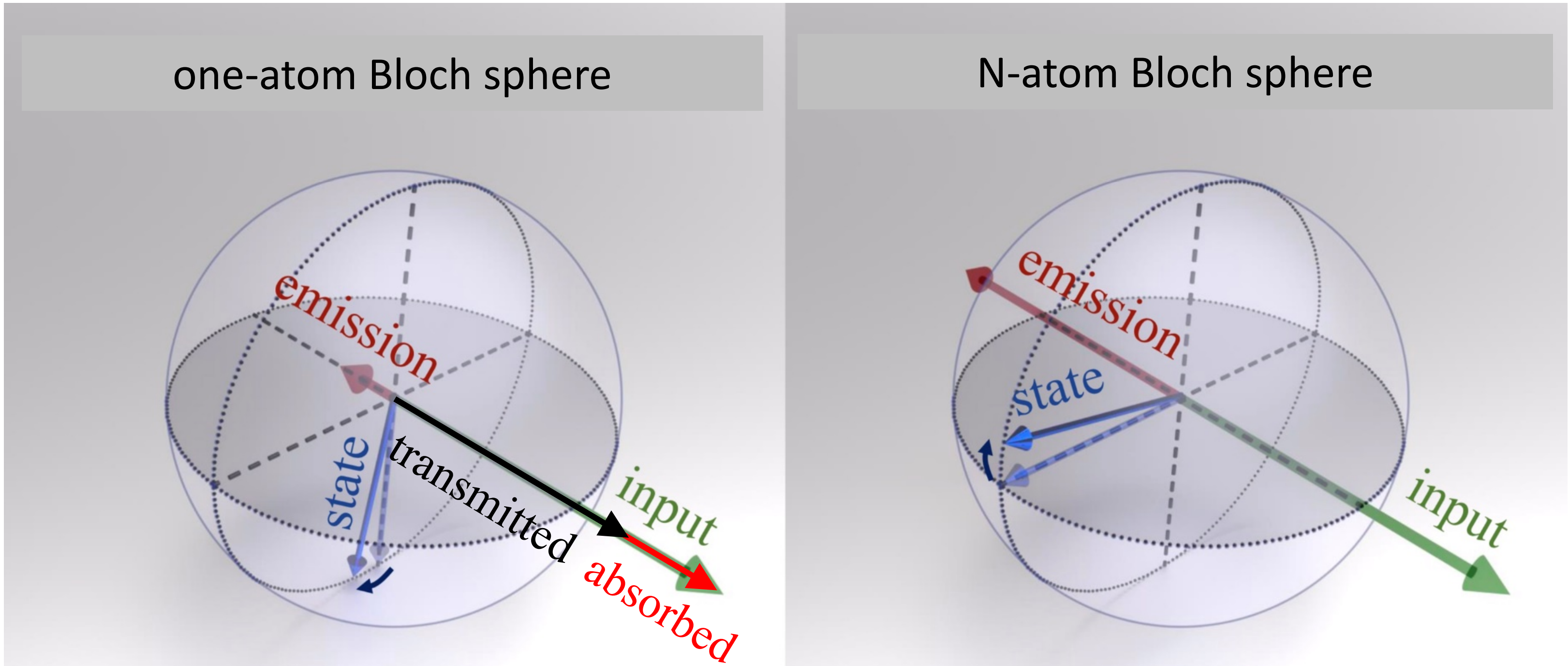


D. Yang et al., arXiv: 1906.06477

- Maximum number of photons completely absorbed during a time interval T is proportional to the square of the number of atoms in the cavity.

→ definitive evidence of superabsorption.

Free-space superabsorption



Ordinary ground-state absorption

Superabsorption

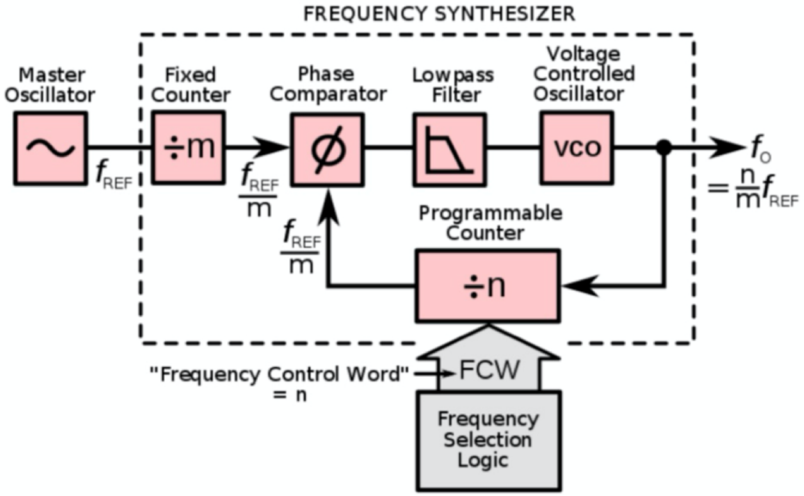
- An N-atom superradiant state as a macro dipole emits a stronger output, which destructively interferes with the input field, resulting in superabsorption.
- The cavity is not needed in this picture → free-space superabsorption should be possible.

Direct optical frequency synthesis by repeated phase injection, axion dark matter detection, etc.

초방사의 응용: 직접적 광학 주파수의 합성, AXION 검출기 등

직접적 광학주파수 합성(DOFS)이란?

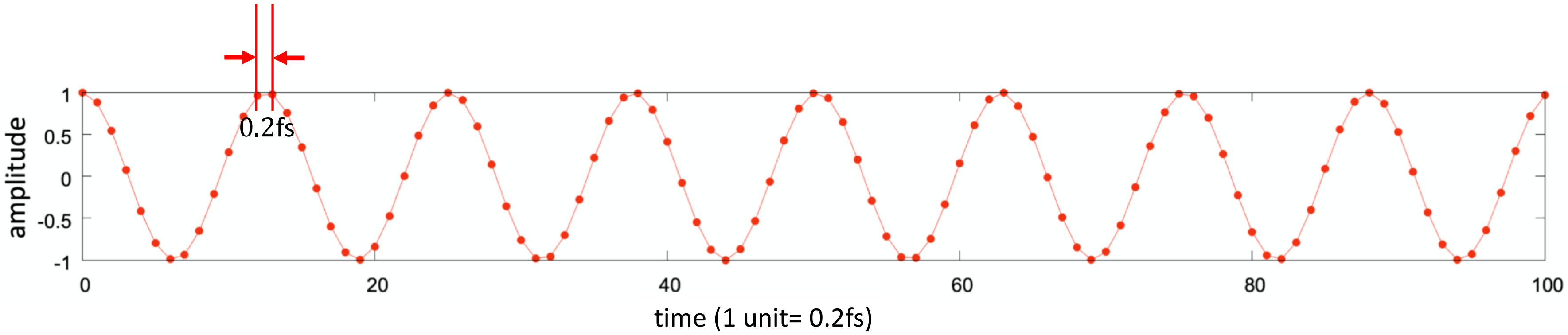
- 전기전자기술에서 직접적 디지털 주파수 합성(direct digital frequency synthesis)으로 원하는 주파수를 마이크로파 영역까지 만들어 낼 수 있음.
- 광학영역(파장이 수백 나노미터, 주파수 수백 THz)에서 이산적인(discrete) 시간에 진폭값을 직접 출력하여 원하는 주파수의 파동을 만드는 기술을 DOFS(direct optical frequency synthesis)라 부르겠음.



direct digital frequency synthesis

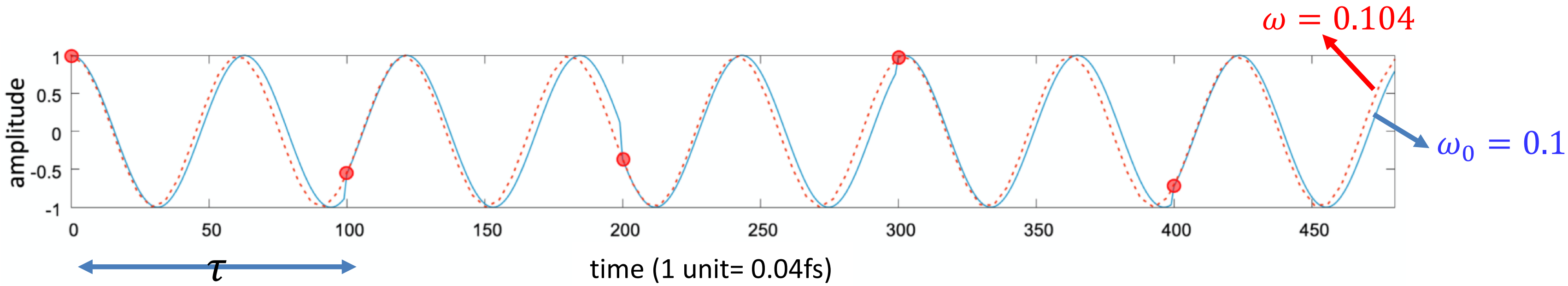
DOFS의 어려움

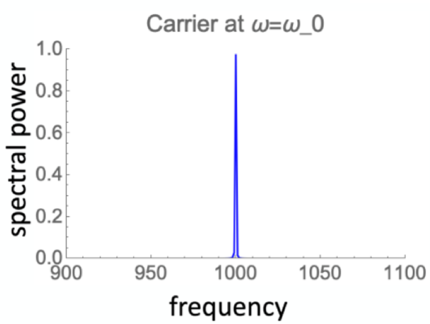
- 600nm 빛의 주기는 약 2펨토초에 불과.
- Nyquist-Shannon의 표본화 정리에 의하면 신호를 변환하는 시간간격이 적어도 1펨토초 이하가 되어야 하는데(주기당 2번 sampling), 전기적으로 그렇게 짧은 신호처리가 기존 기술(~Tb/s)로는 불가능.

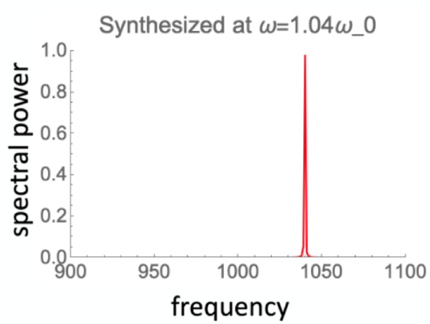


반복적 위상보정을 통한 DOFS

- 주기보다 무척 큰 시간간격 τ 으로 위상을 보정하면 어떻게 될까?
- 시간구간 $t_k = \tau \cdot k \le t < t_{k+1}$ 동안 $E_k(t) = \cos(\omega_0 t + \Delta \cdot t_k)$ 출력.
- $\omega_0 = 0.1$ (carrier), $\tau = 100, \Delta = \omega - \omega_0 = 0.004 \rightarrow \omega = 0.104$ 합성됨.
- 시간 τ 동안 축적된 위상 어긋남 $\Delta \cdot \tau < \pi$ 라는 조건만 만족하면 됨 (추후설명).





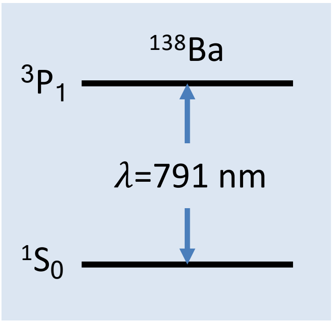


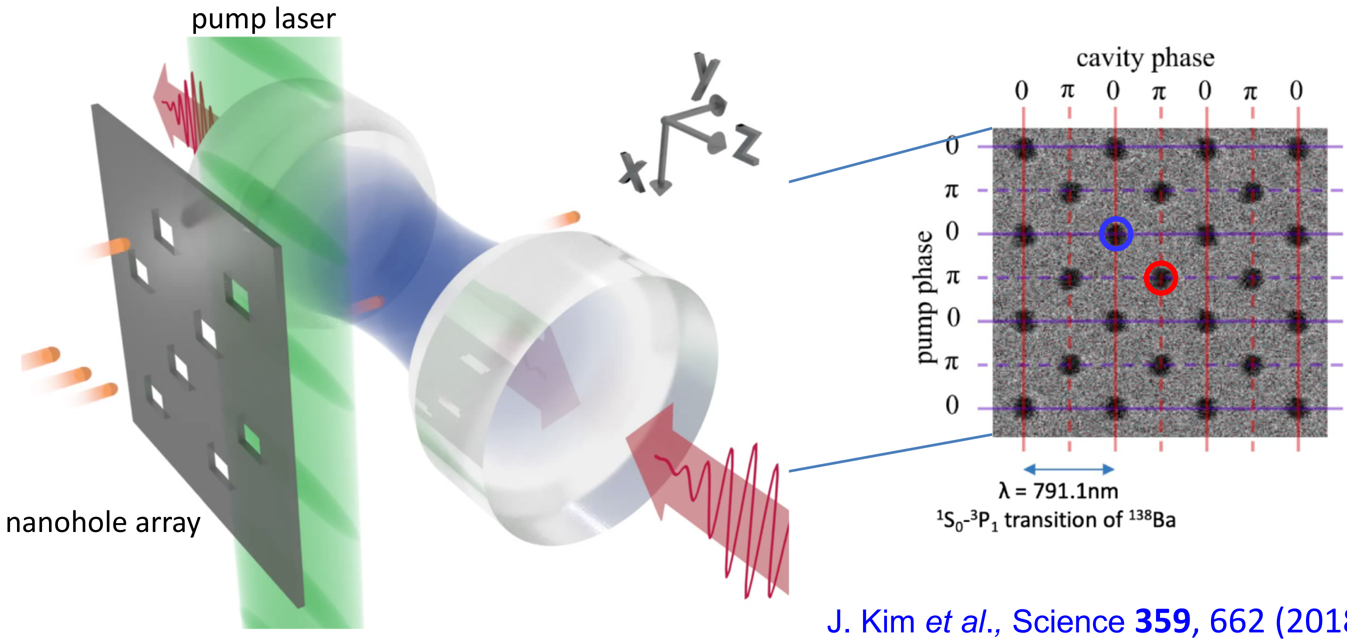
$f = \dfrac{\frac{0.104}{2\pi}}{0.04\text{fs}} = 4.1\times 10^{14}\text{Hz},\ T = 2.4\text{fs}$

스펙트럼에서 수평축 1눈금은 주파수 0.0001에 해당

결맞은 초방사를 이용한 DOFS의 구현

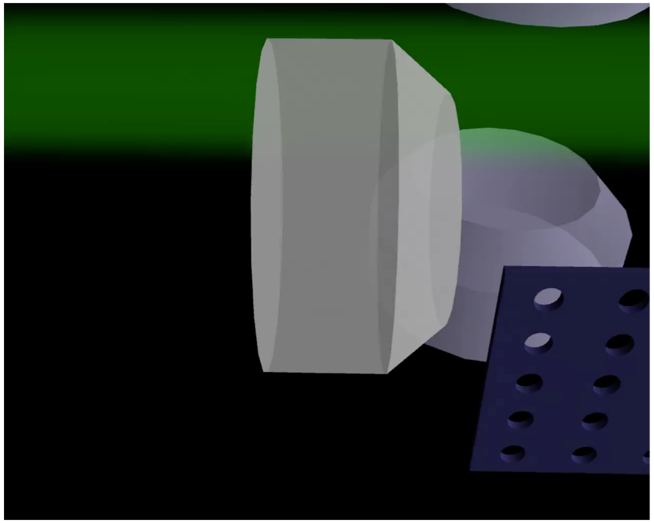
- 이준위 원자(바륨-138)의 양자중첩상태와 공진기의 상호작용을 이용.
- k번째 원자를 $|\psi_k\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{g}\rangle + e^{i\Delta\cdot t_k}|\mathrm{e}\rangle\right)$로 준비, 시간 t_k에 공진기에 주입. 원자간 평균시간간격 τ(~100ns).
- k번째 원자는 공진기 안에서 위상 $\Delta \cdot t_k$를 갖고 주파수 ω_0의 광자 방출 →DOFS에 의해 새로운 주파수 $\omega = \omega_0 + \Delta$ 가 합성됨 (결맞은 초방사 과정).
- 나노격자를 이용, 원자의 위상을 정렬하고 제어함.



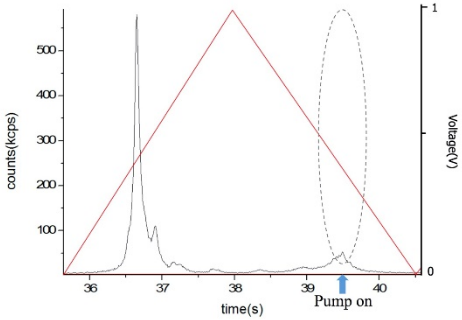


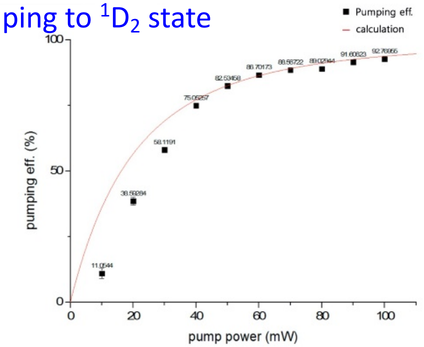
J. Kim *et al.*, Science **359**, 662 (2018)

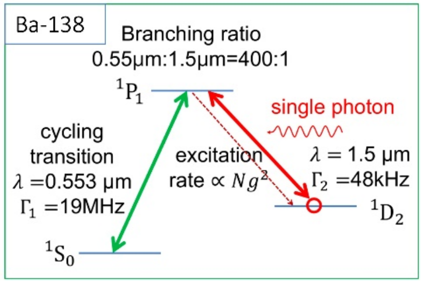
상온 단광자 검출기, Axion 암흑물질 검출기

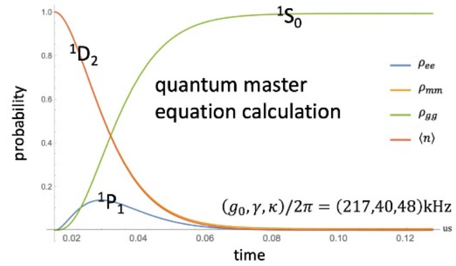


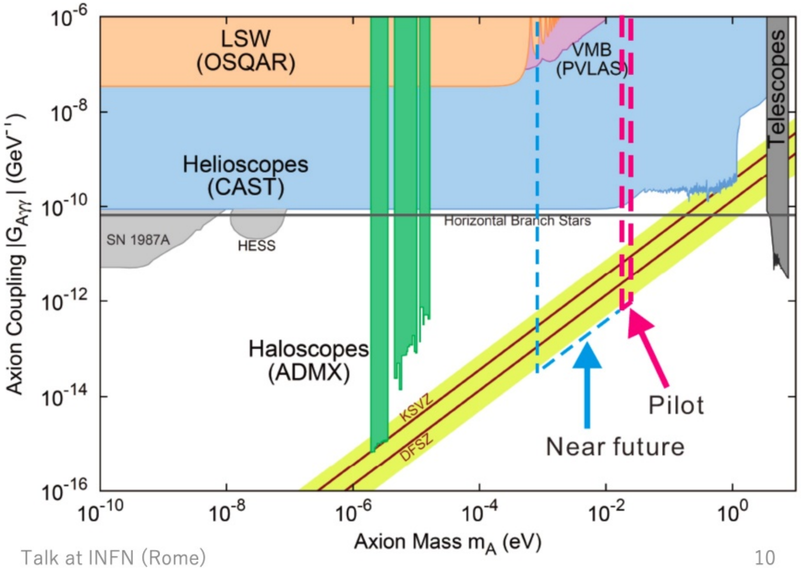
Optical pumping to $^1D_2$ state





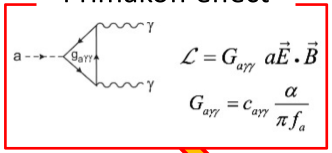


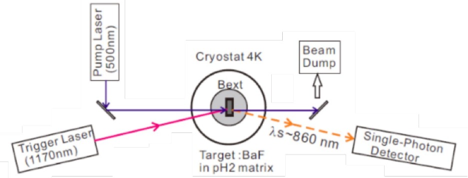


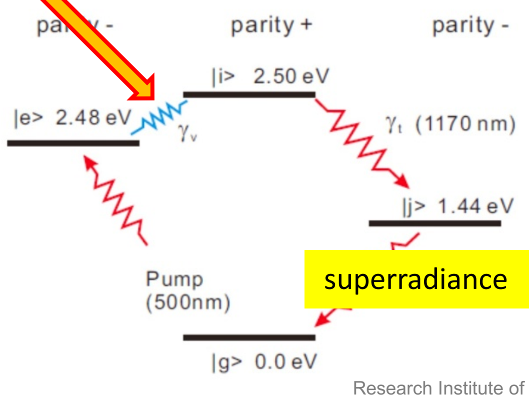


with Prof. Noboru Sasao at RIIS, Okayama U.

Primakoff effect







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ITRC (카이스트)	인공지능을 위한 양자컴퓨팅 기초 원천기술 연구	2018.6-2021.12	1.5억/4년
중견연구자 지원사업	양자중첩상태의 반복적 위상 주입을 이용한 직접적 광학 주파수의 합성	2020.3-2025.2	20억/5년