Nanoscale Coherent Light Source

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Contents

- Author information
- Introduction
- Theoretical model
- Continuous collective emission
- Photon statistics and spectral properties
- Thresholdless behavior
- Conclusion

Author information

- He concluded his university studies at Innsbruck in 1989 with a PhD in physics
- In 1993, he did his habilitation in theoretical physics
- he has been leading a Quantum Optics and Cavity Quantum Electrodynamics research group at the university of Innsbruck

- main research interests
  - Cavity Cooling, Self-Organization, Quantum Thermodynamics, Light Forces, Superradiant Lasing and Quantum Metrology

https://www.uibk.ac.at/th-physik/cqed/research.htm

Introduction

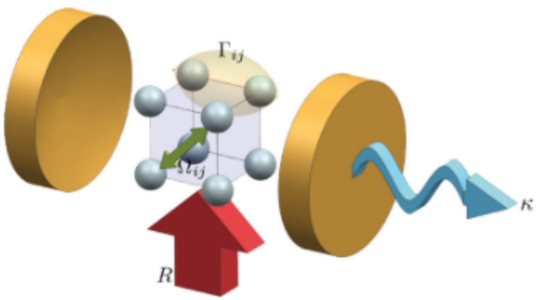
- Conventional laser = optical cavity + gain medium(inverted emitters)
- Most minimal gain medium (single atom)
- Macroscopic optical resonator → limiting the frequency stability of laser
  - @ Bad cavity regime → solved
  - Properties of emitted light governed by gain medium rather than the resonator

Towards a Superradiant Laser

The smallest possible laser

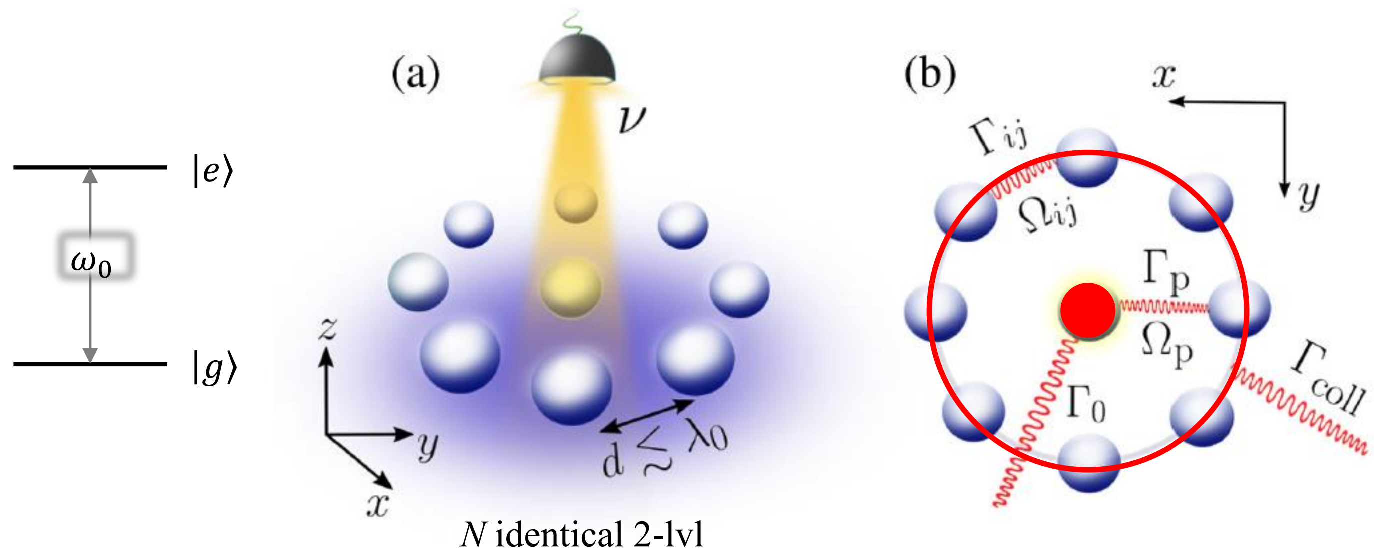
A single inverted atom in an optical micro resonator forms the smallest possible laser system as a coherent source of light. The laser light generated by the atom through stimulated emission exhibits strong forces which in turn provide for self-trapping and cooling of the atom. When operated on an ultra narrow clock transition one enters the super radiant operating regime which allows precise and accurate operation on the atomic clock transition wavelength. Our research in this field is embedded in the European Quantum Flagship iqClock Consortium.

- T. Maier, S. Kraemer, L. Ostermann and H. Ritsch: Optics Express 22, 11 (2014)
- C. Hotter, D. Plankensteiner, L. Ostermann and H. Ritsch: Optics Express 27, 31193 (2019)
- R. Holzinger, L. Ostermann and H. Ritsch: arXiv:1905.01483 (2019)

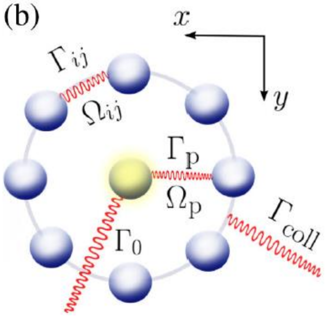


Theoretical model

- Ring geometry of $\boldsymbol{N}$ identical two-level atoms with interatomic distance of $\boldsymbol{d}$ ($\lesssim \lambda_0$: subwavelength scale)
- All transition dipoles are chosen pointing at z direction
- An additional gain atom at the center of the ring
- Pump the gain atom incoherently at a rate $\boldsymbol{\nu}$
- Spontaneous emission rate Γ_0



Theoretical model



- Atomic ring as a *resonator* coupled to center atom as a *gain medium*
- Hamiltonian in the interaction picture

$$H = \sum_{i,j:i\neq j} \Omega_{ij}\sigma_i^+\sigma_j^-$$

Ω_{ij}: collective coupling rate

- Γ_{ij} : Collective spontaneous emission rate
- Incoherent pumping of the central atom
- Master equation :

$$\dot{\rho} = i[\rho, H] + \mathcal{L}_\Gamma[\rho] + \mathcal{L}_\nu[\rho]$$

Photon input from pump

$$\mathcal{L}_\nu[\rho] = \frac{\nu}{2}\left(2\sigma_p^+\rho\sigma_p^- - \sigma_p^-\sigma_p^+\rho - \rho\sigma_p^-\sigma_p^+\right)$$

$$\mathcal{L}_\Gamma[\rho] = \sum_{i,j} \frac{\Gamma_{ij}}{2}\left(2\sigma_i^-\rho\sigma_j^+ - \sigma_i^+\sigma_j^-\rho - \rho\sigma_i^+\sigma_j^-\right)$$

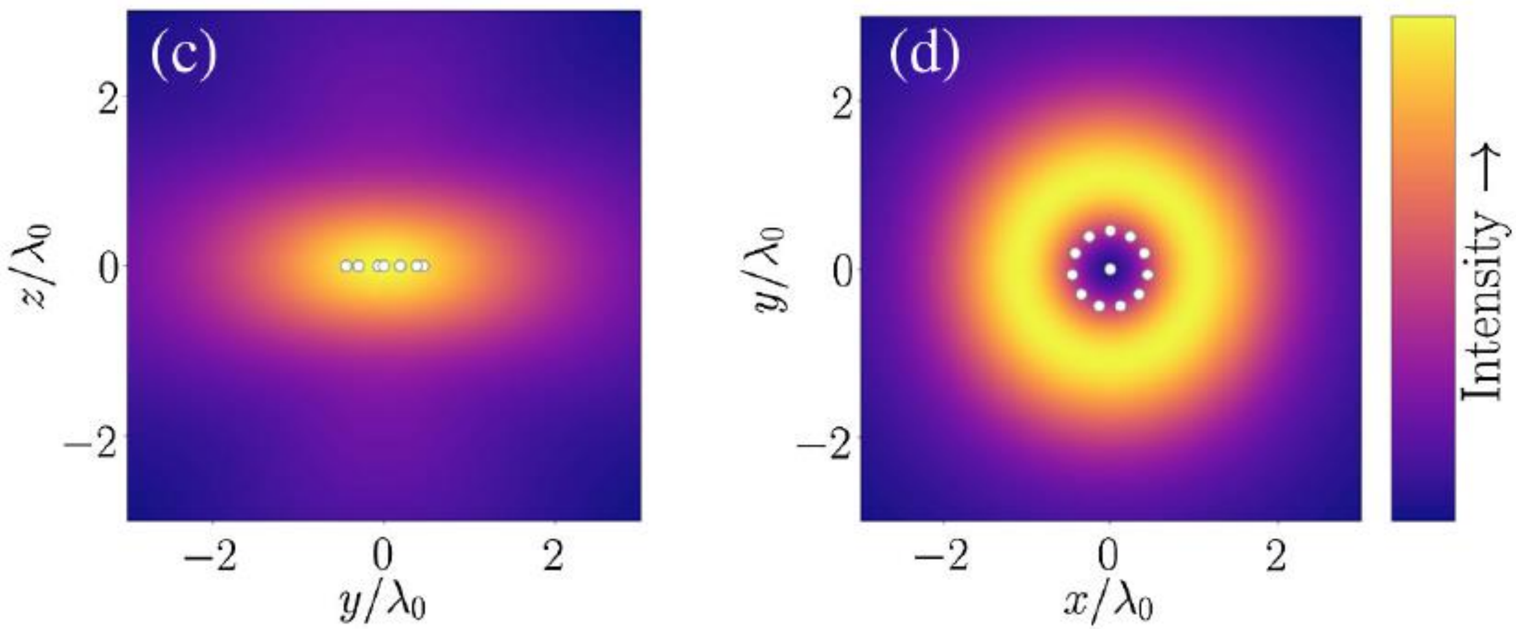
Photon output to bath

- Output intensity

$$I(\boldsymbol{r}) = \langle \boldsymbol{E}^+(\boldsymbol{r})\boldsymbol{E}^-(\boldsymbol{r})\rangle$$

Theoretical model

- Steady state intensity



$$N = 11, d = \frac{\lambda_0}{5}, \nu = 0.1\Gamma_0$$

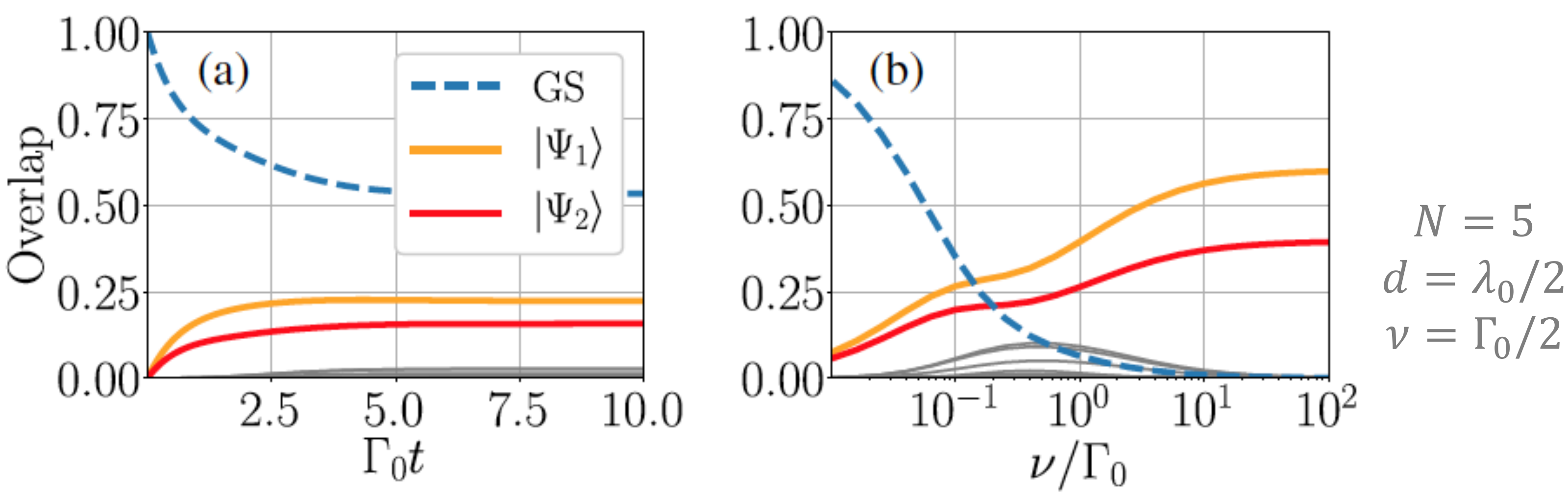
Continuous collective emission

- Symmetric excitation state

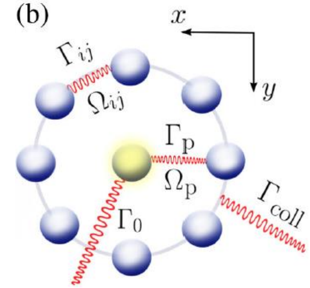
$$|\Psi_{sym}\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \sigma_j^+ |g\rangle^{\otimes N}$$

- Predominant eigenstates : symmetric single excitation state

$$|\Psi_i\rangle = a_i |g\rangle^{\otimes N} \otimes |e\rangle + b_i |\Psi_{sym}\rangle \otimes |g\rangle \qquad \text{for } i \in \{1,2\}$$



Continuous collective emission



- Assuming only the symmetric state in the ring is populated

$$H_{sym} = \Omega_{sym}\sigma_{sym}^{+}\sigma_{sym}^{-} + \sqrt{N}\Omega_{p}\left(\sigma_{sym}^{+}\sigma_{p}^{-} + H.c.\right)$$

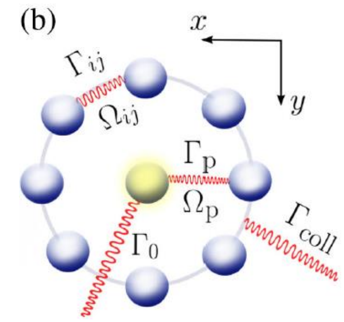
$\Omega_{sym} = \sum_{j=2}^{N}\Omega_{1j}$: dipole energy shift of the symmetric state

$\sigma_{sym}^{-} \equiv |g\rangle^{\otimes N}\langle\Psi_{sym}| \otimes \mathbb{I}_{p}$: symmetric subspace lowering Op.

Ring atoms are taking the role of resonator

Continuous collective emission

- For case of no dissipative coupling ($\Gamma_p = 0$)

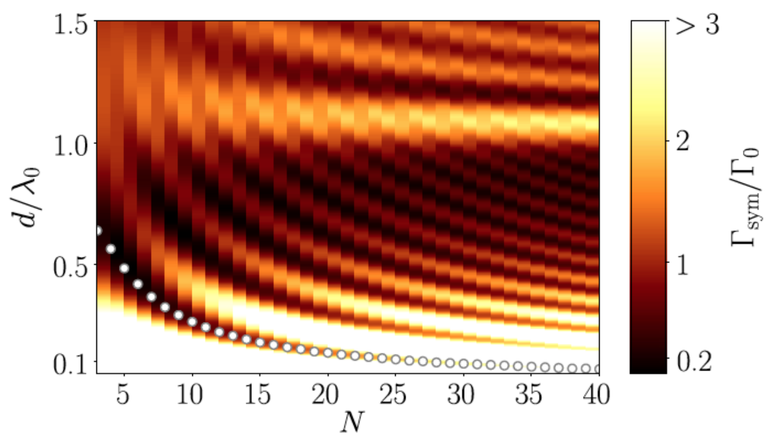


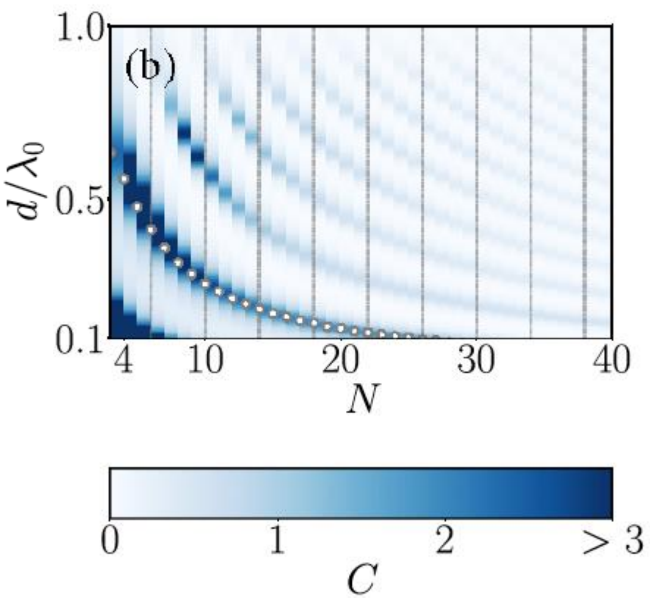
$$\mathcal{L}[\rho] = \mathcal{L}_v[\rho] + \mathcal{L}_0[\rho] + \mathcal{L}_{sym}[\rho]$$

$$\mathcal{L}_0[\rho] = \frac{\Gamma_0}{2}\left(2\sigma_p^- \rho \sigma_p^+ - \sigma_p^+ \sigma_p^- \rho - \rho \sigma_p^+ \sigma_p^-\right)$$

$$\mathcal{L}_{sym}[\rho] = \frac{\Gamma_{sym}}{2}\left(2\sigma_{sym}^- \rho \sigma_{sym}^+ - \sigma_{sym}^+ \sigma_{sym}^- \rho - \rho \sigma_{sym}^+ \sigma_{sym}^-\right)$$

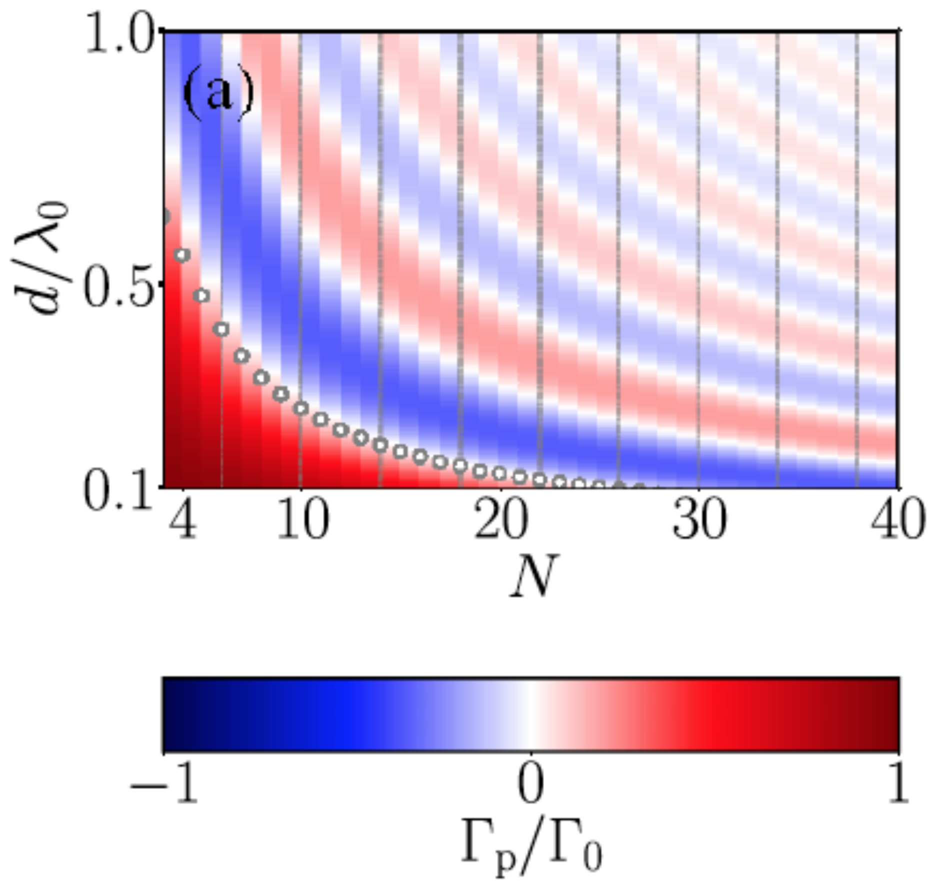
- Define cooperativity : $C \equiv \frac{N\Omega_p^2}{\Gamma_0 \Gamma_{sym}}$





Continuous collective emission

- Dissipative coupling of between central gain atom and outer ring atoms



Photon statistics and spectral properties

- Intensity correlation function :

$$g^{(2)}(0) = \frac{\sum_{ijkl}\langle \sigma_i^+ \sigma_j^+ \sigma_k^- \sigma_l^- \rangle}{|\sum_{mn}\langle \sigma_m^+ \sigma_n^- \rangle|^2}$$

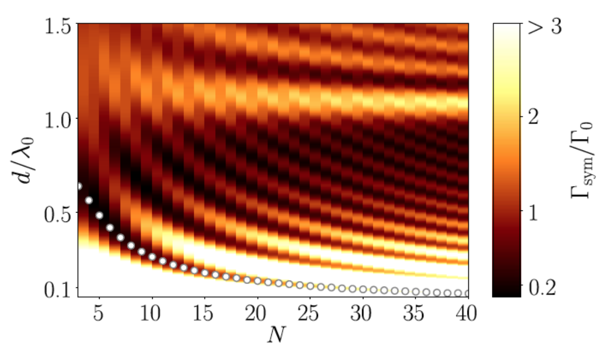
- Light emission :

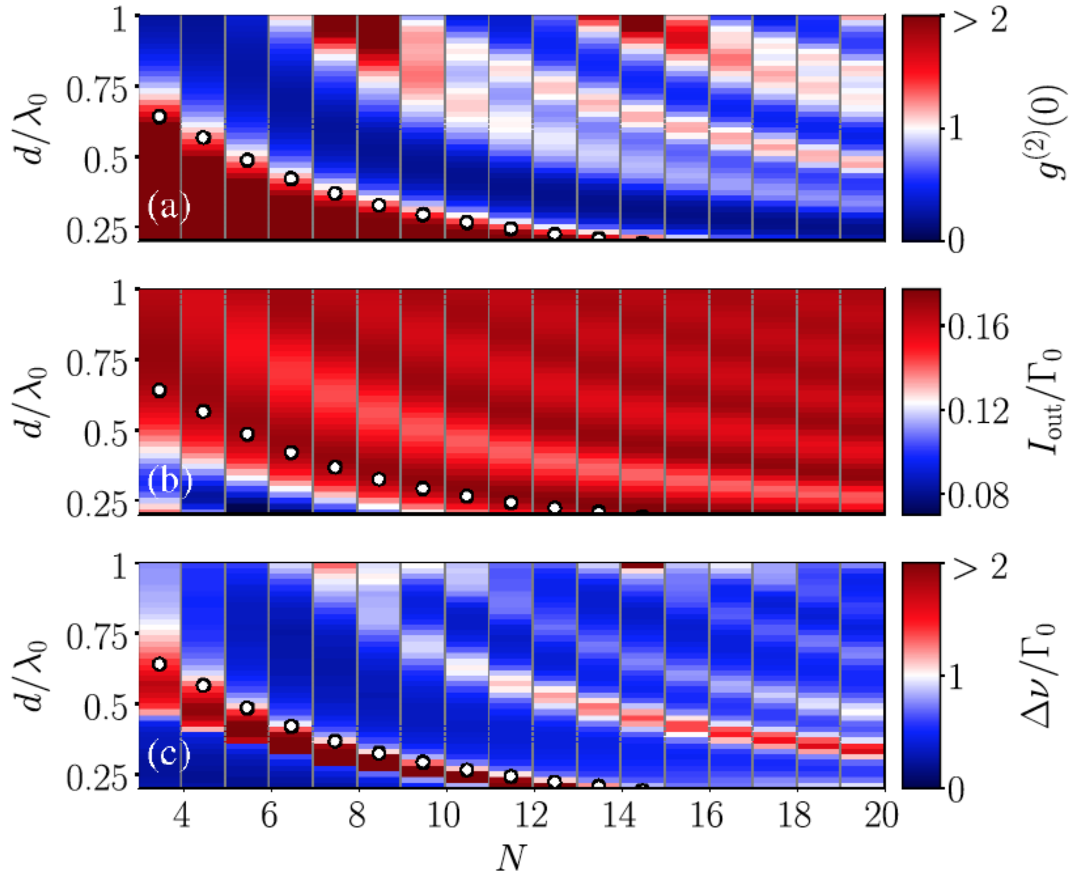
$$I_{OUT} \equiv \sum_{ij} \Gamma_{ij} \langle \sigma_i^+ \sigma_j^- \rangle$$

- Linewidth from $g^{(1)}(\tau)$:

$$g^{(1)}(\tau) \equiv \sum_{i,j} \langle \sigma_i^+(\tau) \sigma_j^- \rangle$$

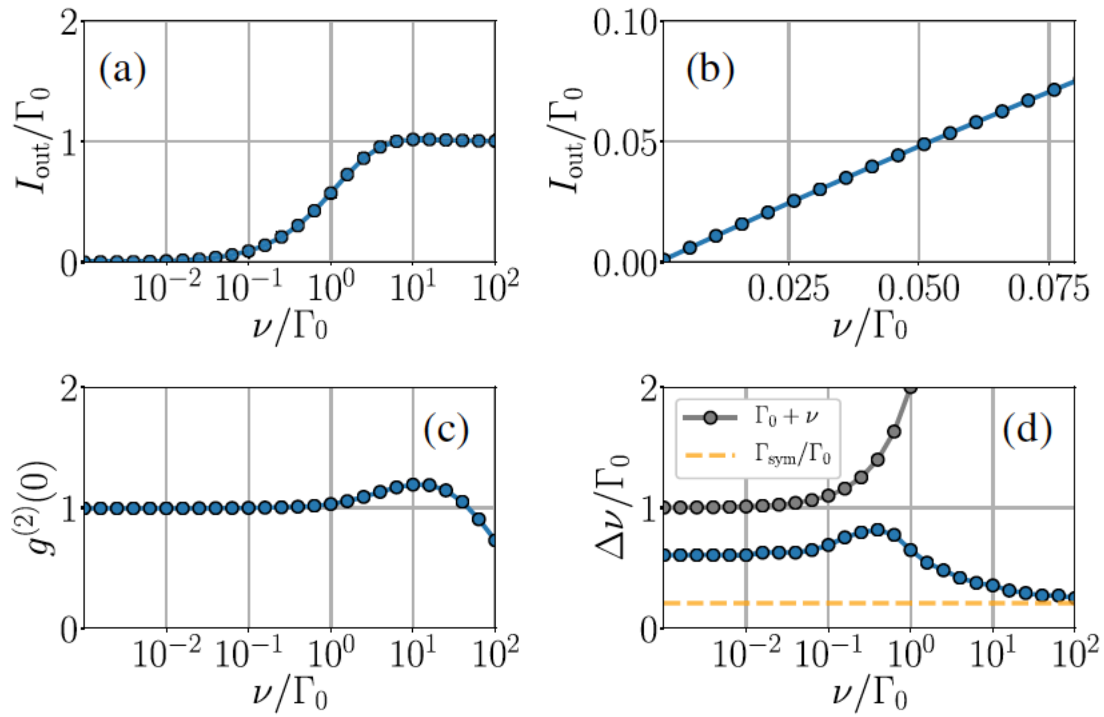
Lorentzian shape





Thresholdless behavior

- Investigate output light as a function of the pump strength of the gain atom



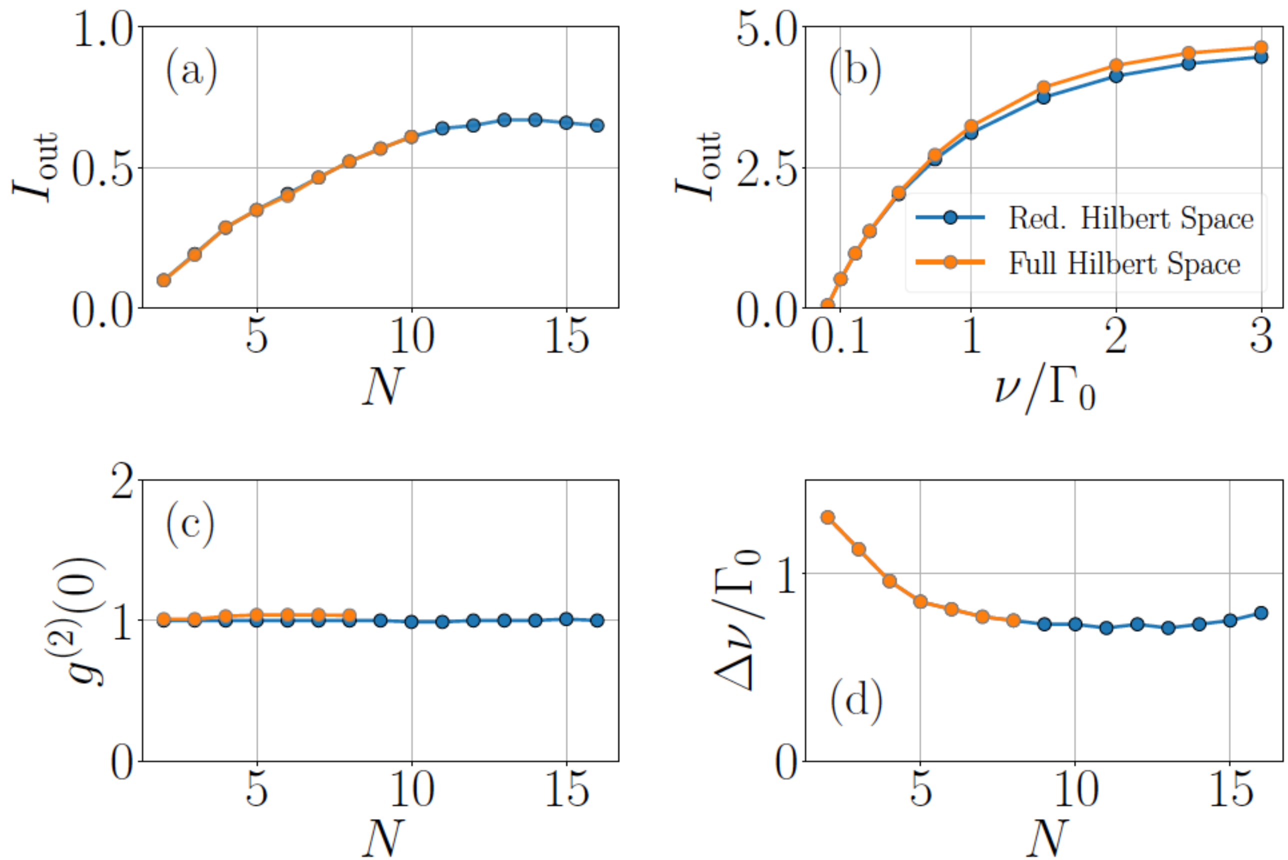
$N = 5$
$d = \lambda_0/2$
$\nu = \Gamma_0/2$

Conclusion

- Designed minimal, subwavelength sized laser
- By analogy to the Jaynes-Cumming model, the outer ring atoms take on the role of a high-Q cavity with the central atom providing for gain
- Under suitable condition, the laser produces coherence light source
- In the limit of single excitation with collective subradiant state, it behaves like thresholdless laser
- No principal lower physical limits on the size of the system so that very high density arrays of such lasers on a surface are possible

Supple.

- Truncating the Hilbert space at low excitation



Supple.

- Ring atomic cavity

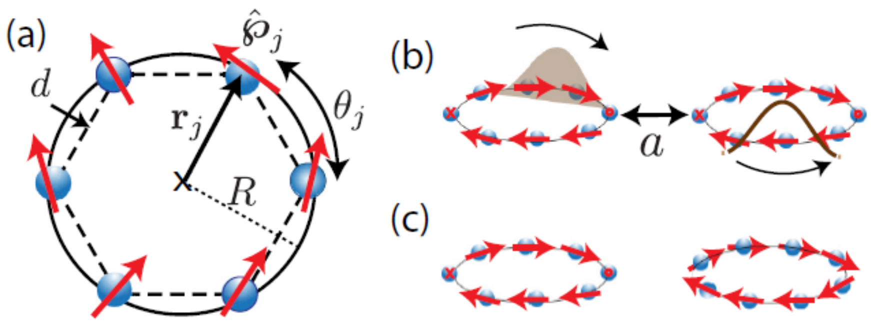


FIG. 1. Scheme of the system. (a) A single ring with interparticle distance d, radius R, and angular position given by $\theta_j = 2\pi(j-1)/N$. The red arrows show the dipoles' (arbitrary) orientations $\hat{\wp}_j$. (b, c) A single wave-packet excitation is transferred between two in-plane rings separated by the distance a. Panels (b) and (c) correspond to the site-site and site-edge configurations for tangential dipoles, respectively.

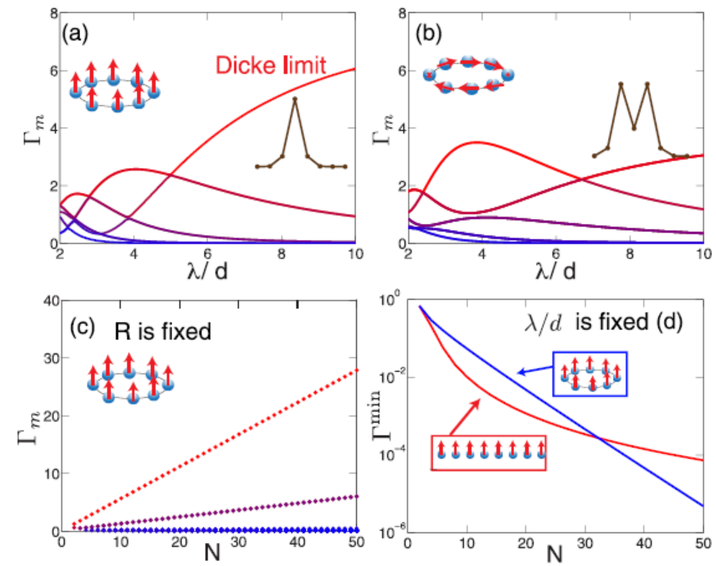


FIG. 2. Single ring radiative properties. (a) Collective decay rates Γ_m (in units of Γ_0) as a function of λ/d, for a ring of $N = 8$ emitters with transverse polarization and a single excitation. In the Dicke limit, $\lambda/d \to \infty$, only a single bright mode with a decay rate on the order of $N\Gamma_0$ is present, and $N-1$ modes are dark. (b) Identical setup as in panel (a) but for tangential polarization. Two bright modes arise in the Dicke limit at $m = \pm 1$. (c) Γ_m (in units of Γ_0) for a ring of fixed radius $R = 0.15\lambda$ with transverse polarization, when increasing the density of emitters. For the bright mode, $\Gamma \sim N\Gamma_0$. (d) Decay rate (log scale) of the most subradiant eigenmode vs the atom number, for a ring (blue circles) and an open linear chain (red circles), both with $\lambda = 3d$. The lifetime of the most subradiant mode in the ring increases exponentially with the atom number.

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