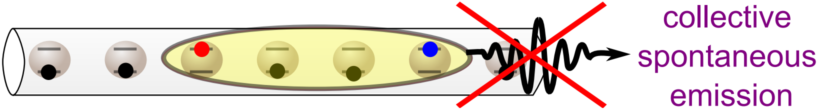
Subradiance in arrays of atoms coupled to photons

Alexander (Sasha) Poddubny

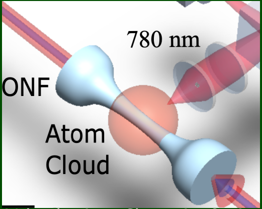
Department of Physics of Complex Systems



Weizmann Physics Colloquium, 2025 Dec 4

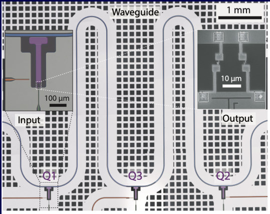
Atoms +1D Photons = waveguide QED

atoms near nanofiber



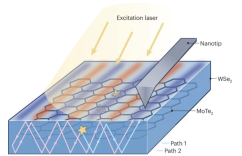
Vylegzhanin... Chormaic, Optica Quantum 1, 6 (2023)

Superconducting qubits



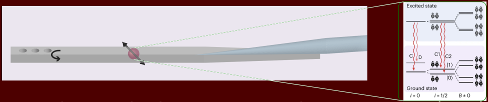
Shah...Mirhosseini, arXiv:2402.15701v1 (2024)

2D semiconductor + Fabry-Perót slab



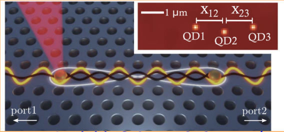
Moore...Basov, Nat. Photonics **19**, 833 (2025)

Quantum defects



Parker...Englund, Atatüre, Nat. Photonics **18**, 156 (2024)

Quantum dots



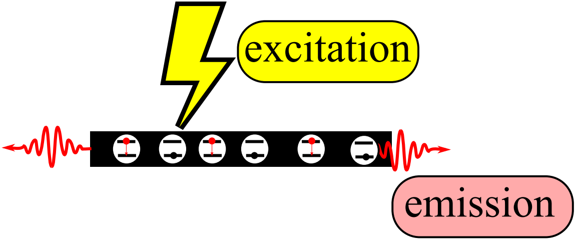
Tiranov...Lodahl ,Science **379**, 389 (2023)

potential applications: interconnects in quantum chips,quantum memory, entanglement generation

Review: Sheremet... ANP, Rev. Mod. Phys. **95**, 0105002 (2023)

micro-review: ANP, Nature Photonics (News and Views) **19**, 783 (2025)

What is the state of the atomic array after a long time?



Potential application for long-living states: quantum memory.
selected recent proposals:

1D: Asenjo-Garcia, Moreno-Cardoner, Albrecht, Kimble, and Chang, PRX **7**, 31024 (2017)
Kornovan, Corzo, Laurat, and Sheremet, PRA **100**, 63832 (2019)
Cech, Lesanovsky and Olmos, PRA **108**, L051702(2023)
Fasser, Ostermann, Ritsch, and Hotter, Optica Quantum **2**, 397 (2024)
1D + motion: Olmos and Lesanovsky, PRL **134**, 243602 (2025)
2D: Rubies-Bigorda, Walther, Patti, and Yelin, PRR **4**, 13110 (2022)

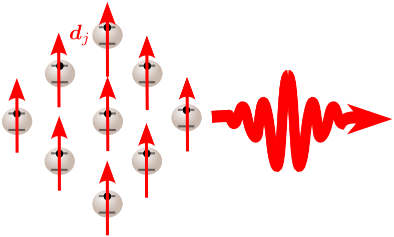
Bright and dark states

All *super*radiant states are alike,
but each *sub*radiant state is subradiant in its own way

Bright and dark states

All *super*radiant states are alike,
but each *sub*radiant state is subradiant in its own way

Bright (superradiant) state:

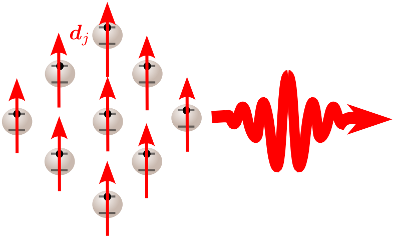


- Constructive interference
- Spontaneous decay rate is enhanced $\times N$

Bright and dark states

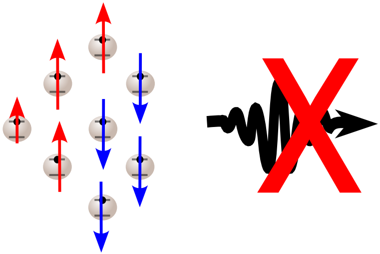
All *super*radiant states are alike,
but each *sub*radiant state is subradiant in its own way

Bright (superradiant) state:



- Constructive interference
- Spontaneous decay rate is enhanced $\times N$

Dark state examples:

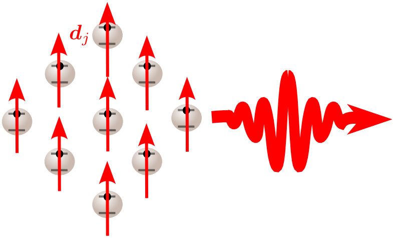


- Destructive interference
- No spontaneous decay

Bright and dark states

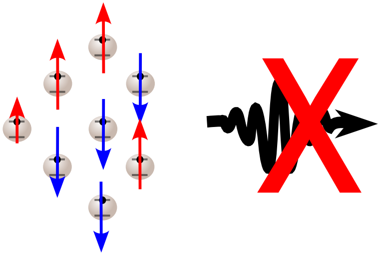
All *super*radiant states are alike,
but each *sub*radiant state is subradiant in its own way

Bright (superradiant) state:



- Constructive interference
- Spontaneous decay rate is enhanced $\times N$

Dark state examples:

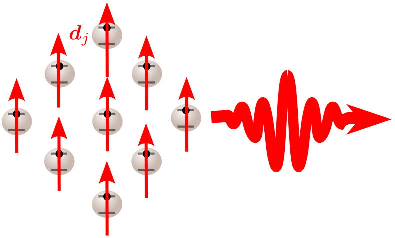


- Destructive interference
- No spontaneous decay
- Degeneracy $\sim 2^N$
  $\Rightarrow$ interactions are important
- What is the darkest state for a given setup?

Bright and dark states

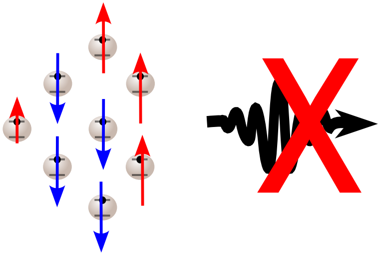
All *super*radiant states are alike,
but each *sub*radiant state is subradiant in its own way

Bright (superradiant) state:

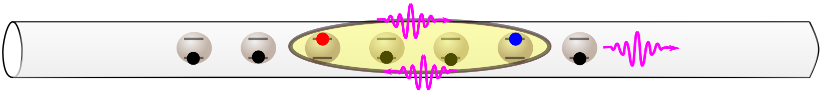


- Constructive interference
- Spontaneous decay rate is enhanced $\times N$

Dark state examples:



- Destructive interference
- No spontaneous decay
- Degeneracy $\sim 2^N$
  $\Rightarrow$ interactions are important
- What is the darkest state for a given setup?



Effective Hamiltonian:

$$H_{\text{eff}} = \sum_{j=1}^{N} \hbar\omega_0 \sigma_j^\dagger \sigma_j - \mathrm{i}\gamma_{1D} \underbrace{\sum_{j,j'=1}^{N} \sigma_j^\dagger \sigma_{j'} \mathrm{e}^{\mathrm{i}\omega_0 |z_j - z_{j'}|/c}}_{\text{long-range coupling of atoms via photons}}$$

$\sigma_j^\dagger \equiv |\mathrm{exc}\rangle\langle 0|$ — creation operator for atom excitation, $(\sigma_j^\dagger)^2 = 0$

photon-mediated coupling between atoms
is **infinite-range and dissipative**

Example: $N = 2$, single excitation

$\psi = (\psi_1 \sigma_1^\dagger + \psi_2 \sigma_2^\dagger)|0\rangle$
Schrödinger eq. with non-Hermitian Hamiltonian:

$$-\mathrm{i}\gamma_{1\mathrm{D}} \begin{pmatrix} 1 & \mathrm{e}^{\mathrm{i}\omega_0 d/c} \\ \mathrm{e}^{\mathrm{i}\omega_0 d/c} & 1 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \omega \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Eigenfrequencies: $\omega_\pm = -\mathrm{i}\gamma_{1\mathrm{D}}(1 \pm \mathrm{e}^{\mathrm{i}\omega_0 d/c}),$ Decay rates $= -\operatorname{Im}\omega_\pm$

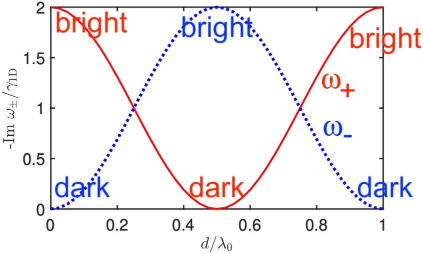
Example: $N = 2$, single excitation

$\psi = (\psi_1 \sigma_1^\dagger + \psi_2 \sigma_2^\dagger)|0\rangle$
Schrödinger eq. with non-Hermitian Hamiltonian:

$$-\mathrm{i}\gamma_{1D} \begin{pmatrix} 1 & \mathrm{e}^{\mathrm{i}\omega_0 d/c} \\ \mathrm{e}^{\mathrm{i}\omega_0 d/c} & 1 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \omega \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Eigenfrequencies: $\omega_\pm = -\mathrm{i}\gamma_{1D}(1 \pm \mathrm{e}^{\mathrm{i}\omega_0 d/c})$, Decay rates $= -\operatorname{Im}\omega_\pm$

Antisymmetric excitation
$\frac{1}{\sqrt{2}}(\sigma_1^\dagger - \sigma_2^\dagger)|0\rangle \equiv \uparrow\downarrow$
has decay rate
$-\operatorname{Im}\omega_- = \gamma_{1D}(1 - \cos\frac{\omega_0 d}{c})$

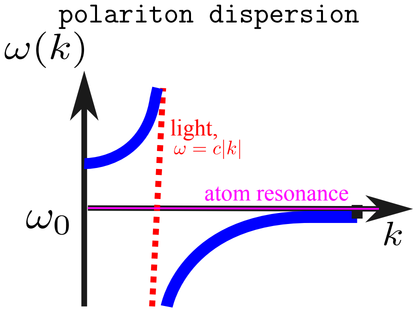


$\lambda_0 = 2\pi c/\omega_0$

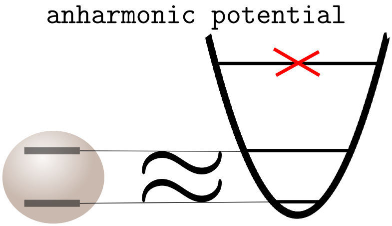
experiment for two ions: DeVoe and Brewer, PRL **76**, 2049 (1996)
experiment for two supercond. qubits: van Loo...Wallraff, Science **342**, 1494 (2013)
also: two lasers: Arwas, Gadasi, Gershenzon, Friesem, Davidson, and Raz, Sci Adv. **8**, eabm7454 (2022).

- Atom-photon coupling provides non-parabolic polariton dispersion.

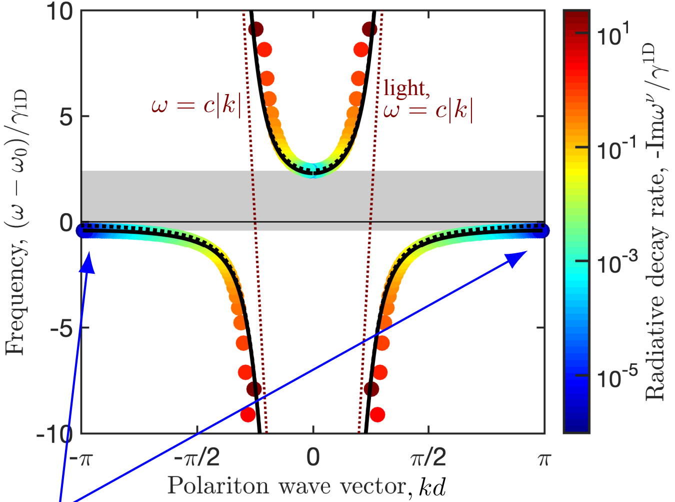
  $|\text{polariton}\rangle \approx \frac{|\text{matter}\rangle + |\text{photon}\rangle}{\sqrt{2}}$



- Anharmonicity of a 2-level atom potential provides polariton-polariton interaction



Decay rate in a periodic array (1 polariton)



Dark states,
$k \sim \pi/d$ mismatched from
light wave vector ω_0/c

Review: Sheremet, Petrov, Iorsh, Poshakinskiy and ANP, Rev. Mod. Phys. **95**, 015002 (2023)

Outline: darkest states with interactions

- 2 excitations,

$$\psi = \sum_{j_1 j_2 = 1}^{N} \sigma_{j_1}^\dagger \sigma_{j_2}^\dagger |0\rangle$$

ANP, PRA **101**, 043845 (2020)
ANP, J. Zhong and S. Fan, PRA **109**, L061501 (2024)
Shi and ANP, PRL **134**, 233602 (2025)

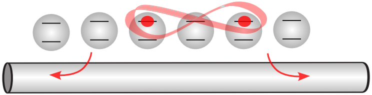
- multiple excitations

$$\psi = \sum_{j_1 \ldots j_m = 1}^{N} \sigma_{j_1}^\dagger \ldots \sigma_{j_m}^\dagger |0\rangle$$

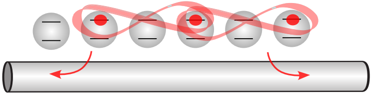
Poshakinskiy and ANP, PRL **127**, 173601 (2021)
Shi and ANP, PRA **110**, 053707(2024)

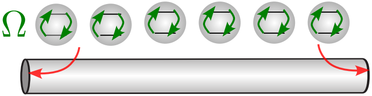
- strongly driven-dissipative dynamics, $\partial_t \rho = \mathcal{L}\rho$

ANP, PRA **106**, L031702 (2022)
Leppenen and ANP, arXiv:2507.19467 (2025)
Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)



Before Weizmann:
Alexander Poshakinskiy, Yongguan Ke (postdocs), Janet Zhong (MSc)
Weizmann:
Jiaming Shi(PhD), Maayan Elias(MSc)

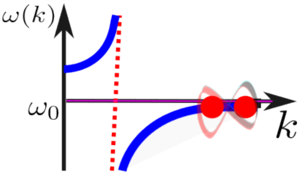




Shira Barnoy-Lapid (MSc)
Collaboration:
Prof. Ran Tessler (Math Dpt.)
Nikita Leppenen (PhD,Efi Shahmoon's group)

Darkest states in arrays with 2 excitations

fermionization for array period $d \approx 0, \frac{1}{2}\lambda_0, \lambda_0 \ldots$



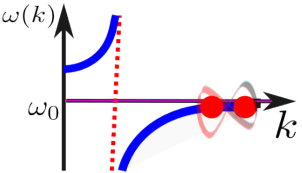
$k \approx \pi/d$,
$\psi(x_1, x_2) \propto |k_1, k_2\rangle - |k_2, k_1\rangle$

Zhang and Mølmer, PRL **122**, 203605 (2019)

ANP, PRA **101**, 043845 (2020)

Darkest states in arrays with 2 excitations

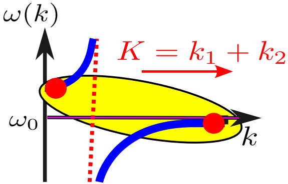
fermionization for array period $d \approx 0, \frac{1}{2}\lambda_0, \lambda_0 \ldots$



$k \approx \pi/d$,
$\psi(x_1, x_2) \propto |k_1, k_2\rangle - |k_2, k_1\rangle$

Zhang and Mølmer, PRL **122**, 203605 (2019)

dark bound pairs for array period $d \approx \frac{1}{12}\lambda_0, \frac{5}{12}\lambda_0, \frac{7}{12}\lambda_0 \ldots$



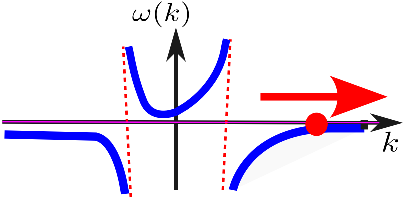
bound pair mass: $M \propto \frac{1}{\cos(3\omega_0 d/c)}$,
$M \to \infty$ @ $\omega_0 d/c = \pi/6$,

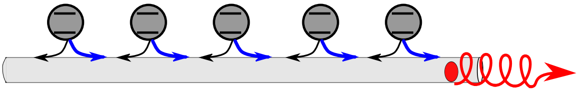
ANP, PRA **101**, 043845 (2020)

darkest states are either fermionized standing waves or bound pairs, depending on the array period d

Edge bound pairs for chirally coupled atoms

chiral polariton dispersion, $\varepsilon(k) \neq \varepsilon(-k)$



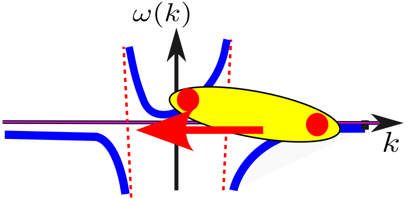


single-polariton localization scaling: ANP, Janet Zhong and Shanhui Fan, PRA **109**, L061501 (2024)

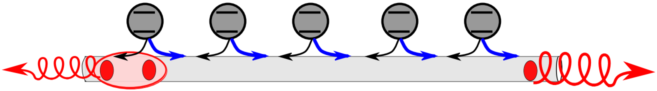
pairs on opposite edge: Jiaming Shi and ANP, PRL **134**, 233602 (2025)

Edge bound pairs for chirally coupled atoms

chiral polariton dispersion, $\varepsilon(k) \neq \varepsilon(-k)$



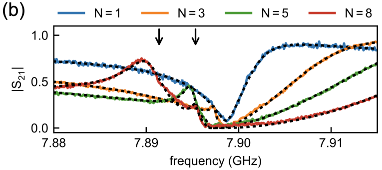
Bound photon pairs fly opposite to single photons
(directional dissociation+negative pair group velocity)



single-polariton localization scaling: ANP, Janet Zhong and Shanhui Fan, PRA **109**, L061501 (2024)

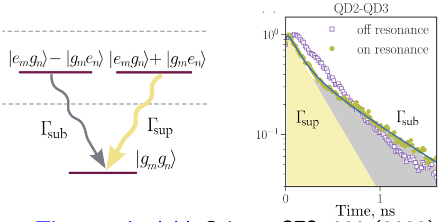
pairs on opposite edge: Jiaming Shi and ANP, PRL **134**, 233602 (2025)

Spectroscopy of subradiant states in transmon arrays



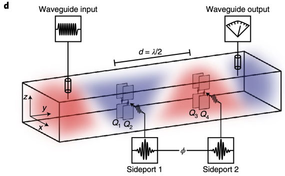
Brehm, ANP. . . Ustinov, npj Quantum Materials **6**, 10 (2021)

Subradiant tails in emission from 2 **quantum dots**



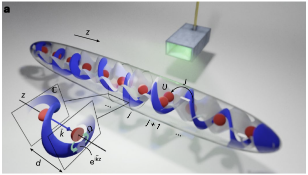
Tiranov...Lodahl ,Science **379**, 389 (2023)

Double-excited subradiant states with 4 transmons



Zanner. . . Kirchmair,Nat. Phys. **18**, 538 (2022)

Subradiance with **matter waves** in trapped atom arrays

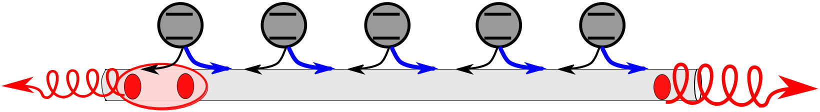


Kim, Lanuza and Schneble, Nat. Phys. **21**, 70 (2025)

Intermediate summary: bound pairs are important

- dark heavy bound pairs
  at array period $\lambda/12$, when $M \to \infty$

PRA **101**, 043845 (2020)

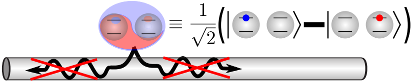


- dark bound pairs can fly opposite to single photons

PRL **134**, 233602 (2025)

Next: *multiple interacting excitations*

Recap for $N = 2$: subradiant dimer



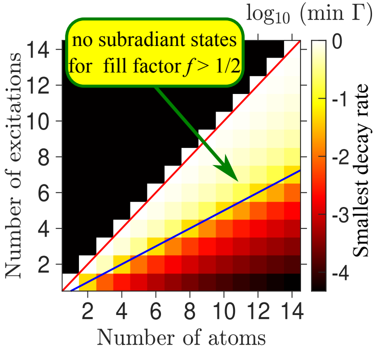
Antisymmetric (subradiant) dimer excitation $\frac{1}{\sqrt{2}}(\sigma_1^\dagger - \sigma_2^\dagger)|0\rangle$

1. Smaller subradiant dimers live longer

   Decay rate: $\gamma_{1D}(1 - \cos\frac{\omega_0 d}{c}) \propto d^2$ for $d \ll c/\omega_0$

2. Fully excited state $\sigma_1^\dagger \sigma_2^\dagger |0\rangle$ is a bright one.

Multiple-excited most-subradiant states



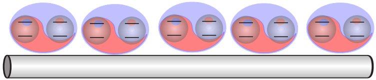
Ke…ANP, PRL **123**, 253601 (2019): ($N = 4$)
Poshakinskiy and ANP, PRL **127**, 173601 (2021): (any N)

Shi and ANP, PRA **110**, 053707 (2024)

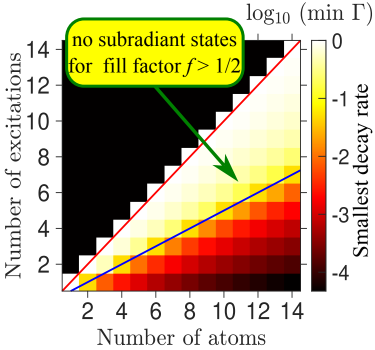
Multiple-excited most-subradiant states

- subradiant states only for fill-factor $f \leq \frac{1}{2}$
- darkest state for $f = 1/2$ is

$$|\psi\rangle = \frac{(\sigma_1^\dagger - \sigma_2^\dagger)}{\sqrt{2}} \frac{(\sigma_3^\dagger - \sigma_4^\dagger)}{\sqrt{2}} \dots \frac{(\sigma_{N-1}^\dagger - \sigma_N^\dagger)}{\sqrt{2}} |0\rangle$$



(small dimers live longer)



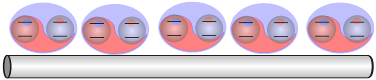
Ke. . . ANP, PRL **123**, 253601 (2019): ($N = 4$)
Poshakinskiy and ANP, PRL **127**, 173601 (2021): (any N)

Shi and ANP, PRA **110**, 053707 (2024)

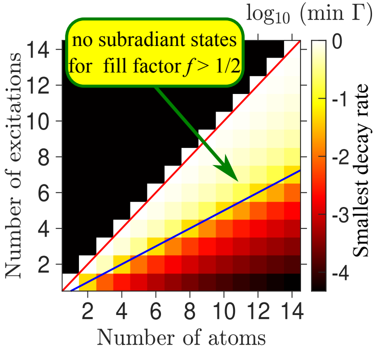
Multiple-excited most-subradiant states

- subradiant states only for fill-factor $f \le \frac{1}{2}$
- darkest state for $f = 1/2$ is

$$|\psi\rangle = \frac{(\sigma_1^\dagger - \sigma_2^\dagger)}{\sqrt{2}} \frac{(\sigma_3^\dagger - \sigma_4^\dagger)}{\sqrt{2}} \ldots \frac{(\sigma_{N-1}^\dagger - \sigma_N^\dagger)}{\sqrt{2}} |0\rangle$$



(small dimers live longer)



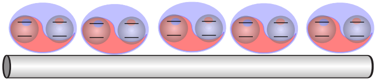
Ke…ANP, PRL **123**, 253601 (2019): ($N = 4$)
Poshakinskiy and ANP, PRL **127**, 173601 (2021): (any N)

Shi and ANP, PRA **110**, 053707 (2024)

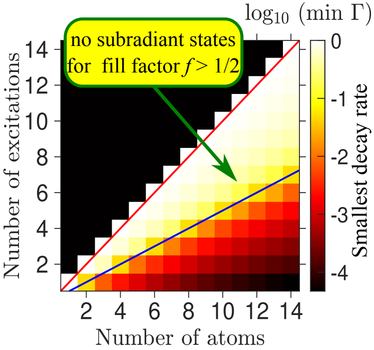
Multiple-excited most-subradiant states

- subradiant states only for fill-factor $f \leq \frac{1}{2}$
- darkest state for $f = 1/2$ is

$$|\psi\rangle = \frac{(\sigma_1^\dagger - \sigma_2^\dagger)}{\sqrt{2}} \frac{(\sigma_3^\dagger - \sigma_4^\dagger)}{\sqrt{2}} \ldots \frac{(\sigma_{N-1}^\dagger - \sigma_N^\dagger)}{\sqrt{2}} |0\rangle$$



(small dimers live longer)

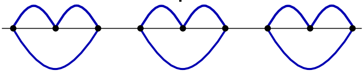


Ke…ANP, PRL **123**, 253601 (2019): ($N = 4$)
Poshakinskiy and ANP, PRL **127**, 173601 (2021): (any N)

multilevel atoms:

products of multimers:
trimers, quadrumers…

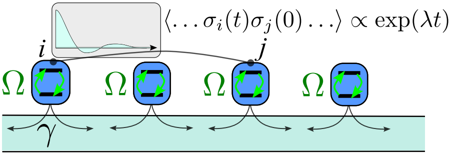
trimer product



$$\propto (\sigma_1^\dagger - \sigma_2^\dagger)(\sigma_1^\dagger - \sigma_3^\dagger)(\sigma_2^\dagger - \sigma_3^\dagger) \ldots |0\rangle$$

Shi and ANP, PRA **110**, 053707 (2024)

Quantum correlations in driven-dissipative dynamics

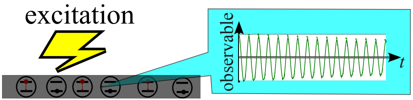


Lindblad master equation
for density matrix: $\partial_t \rho = \mathcal{L}\rho$

eigenstates: $\mathcal{L}\rho = \lambda\rho\,,$

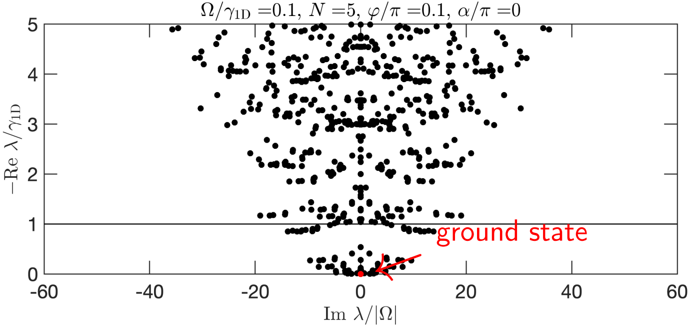
$$\mathcal{L}\rho = \underbrace{\mathcal{L}_0\rho}_{\text{coupling, dissipation}} + \underbrace{\mathrm{i}[\rho, V]}_{\text{driving}}, \quad V = \Omega \sum_{n=1}^{N} (\sigma_n^\dagger + \sigma_n)$$

Are there long-living correlations at strong driving?
(i.e. $|\operatorname{Re}\lambda| \ll \gamma$)



Related phenomena in systems with nonlinearity/interactions: limit cycles, time crystals

Spectrum of Liovillian Superoperator at Strong Driving

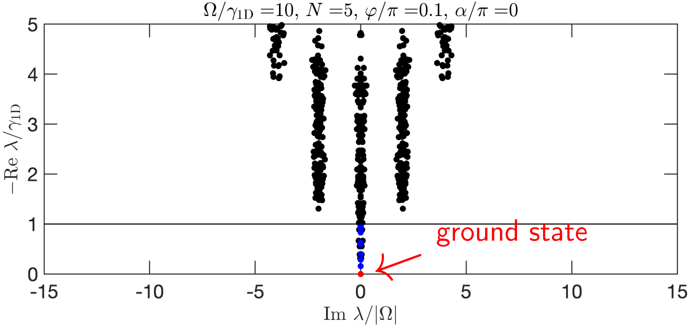


ANP, PRA **106**, L031702 (2022)

Leppenen and ANP, arXiv:2507.19467 (2025)

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Spectrum of Liovillian Superoperator at Strong Driving

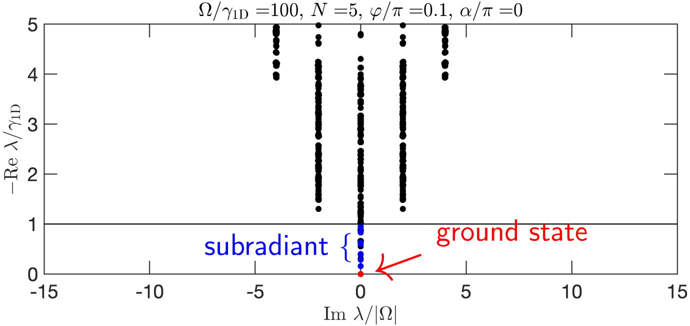


ANP, PRA **106**, L031702 (2022)

Leppenen and ANP, arXiv:2507.19467 (2025)

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Spectrum of Liovillian Superoperator at Strong Driving



If $\mathrm{Im}\,\lambda/\Omega = 0$ one can have $|\,\mathrm{Re}\,\lambda| < \gamma$

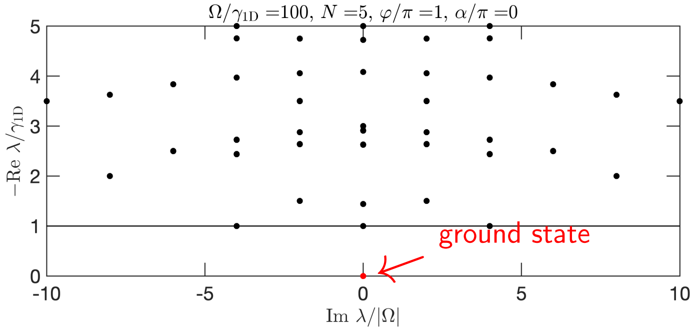
ANP, PRA **106**, L031702 (2022)

this is robust to disorder in ω_0

Leppenen and ANP, arXiv:2507.19467 (2025)

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Spectrum of Liovillian Superoperator at Strong Driving



If $\mathrm{Im}\,\lambda/\Omega = 0$ one can have $|\,\mathrm{Re}\,\lambda| < \gamma$

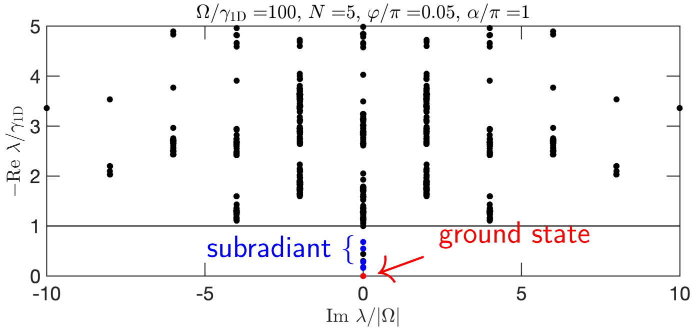
ANP, PRA **106**, L031702 (2022)

this is robust to disorder in ω_0

Leppenen and ANP, arXiv:2507.19467 (2025)

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Spectrum of Liovillian Superoperator at Strong Driving



If $\mathrm{Im}\,\lambda/\Omega = 0$ one can have $|\,\mathrm{Re}\,\lambda| < \gamma$

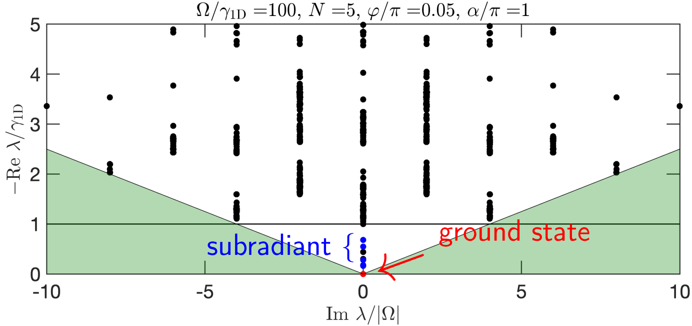
ANP, PRA **106**, L031702 (2022)

this is robust to disorder in ω_0

Leppenen and ANP, arXiv:2507.19467 (2025)

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Spectrum of Liovillian Superoperator at Strong Driving



If $\mathrm{Im}\,\lambda/\Omega = 0$ one can have $|\,\mathrm{Re}\,\lambda| < \gamma$

ANP, PRA **106**, L031702 (2022)

this is robust to disorder in ω_0

Leppenen and ANP, arXiv:2507.19467 (2025)

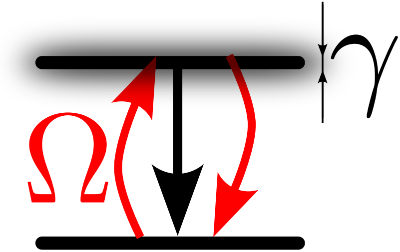
Theorem: no oscillating subradiant correlations at strong driving

$|\,\mathrm{Re}\,\lambda| > \frac{m\gamma}{2}, \quad m = \frac{\mathrm{Im}\,\lambda}{2|\Omega|} \in \mathbb{Z}$ for $\Omega \gg \gamma$

Shi, Leppenen, Tessler, and ANP, arXiv:2509.09993 (2025)

Ongoing work: any limit beyond simple 1D photon bath ?

Subradiance is incompatible with Rabi flips



Strong driving couples dark states to excited states with finite lifetime, hence destroys subradiance

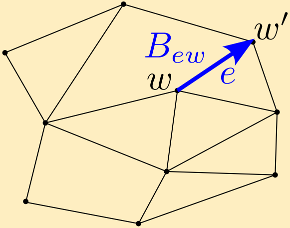
Backbone of proof: Laplacians

Differential operator

$$L = \frac{\partial^2}{\partial x^2} \to (\mathrm{i}k)^2 < 0$$

Laplacian of a graph

$$L = B^T B$$



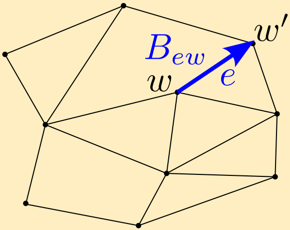
Backbone of proof: Laplacians

Differential operator

$$L = \frac{\partial^2}{\partial x^2} \to (\mathrm{i}k)^2 < 0$$

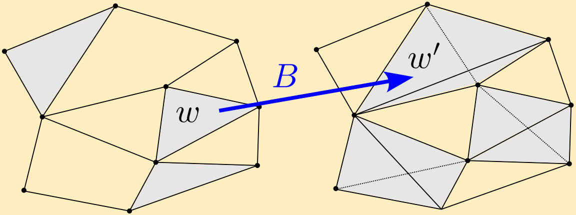
Laplacian of a graph

$$L = B^T B$$



Laplacian of a simplicial complex

$$\mathcal{L}\big|_{\mathrm{Im}\,\lambda = 2m|\Omega|} = \underbrace{-F}_{\text{diag., pos. definite}} + \underbrace{B^T B}_{\text{Laplacian}}$$



Mulas, Horak, and Jost, "Graphs, simplicial complexes and hypergraphs: spectral theory and topology", in "Higher-order systems" (Springer, 2022)

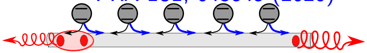
Here, simplicial complex is built on eigenstates of $V = \Omega \sum_{n=1}^{N} (\sigma_n^\dagger + \sigma_n)$ with momentum J_x,
$w \xrightarrow{B} w'$, $\langle w'|J_x|w'\rangle = \langle w|J_x|w\rangle + 1$
$\mathrm{Im}\,\lambda = 2\Omega(J_x - J_{x'}), \rho \propto |J_x\rangle\langle J_{x'}|$

Summary: Subradiance in waveguide QED

- Dark heavy bound pairs for special periods

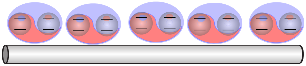
PRA **101**, 043845 (2020)

- Pairs fly opposite to singles



PRA **109**, L061501 (2024); PRL **134**, 233602 (2025)

- Dark multimer products



PRL **123**, 253601 (2019); **127**, 173601 (2021); PRA **110**, 110, 053707 (2024)

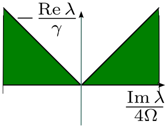
Review: Rev. Mod. Phys. **95**, 0105002 (2023)

- Strongly driven array can have subradiant correlations with $|\mathrm{Re}\,\lambda| \ll \gamma$

PRA **106**, L031702 (2022); arXiv:2507.19467 (2025)

but **only** if $\mathrm{Im}\,\lambda = 0$

arXiv:2509.09993 (2025)



Group: former: Sasha Poshakinskiy, Yongguan Ke, Janet Zhong, now: Jiaming Shi, Maayan Elias, Shira Barnoy-Lapid, Gad Horovitz, collaborators: Ran Tessler, Nikita Leppenen

Support: Minerva, ISF Quantum, ISF-DFG, CHE Quantum