Few-Body Physics of Emitter(s) Coupled to Bath

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Supported by the NSF.

All Four Lectures At A Glance

Lecture 1:
1D fermions → Tunneling dynamics.

Interaction fully characterized by s-wave scattering length. Trap-shape non-universal.

Lecture 2:
Helium dimer → Dissociative dynamics.

Initial state nearly fully universal. Laser-molecule interaction acts in non-universal region.

Lecture 3:
Spin-orbit coupling → Fate of discrete scale invariance?

Two-body interactions lead to two-parameter Efimov scenario. Single-particle dispersion leads to generalized radial scaling law (five-parameter Efimov scenario).

Lecture 4:
Emitter(s) coupled to bath → Radiation dynamics.

Emitter(s) Coupled to Cavity Array

Lecture 4:
Emitter(s) coupled to cavity array $\rightarrow$
Radiation dynamics.

Very rough idea:

Emitter $=$ two-level system (atom, quantum dot,…): States $|e\rangle$ and $|g\rangle$.

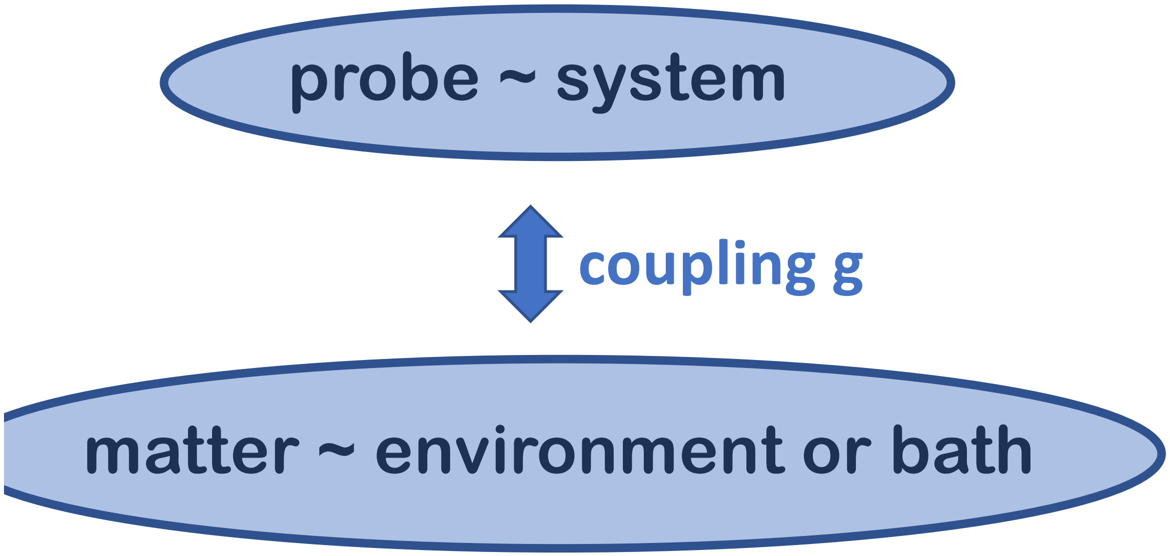
Initialize in $|e\rangle$.

How does probability P_e to be in state $|e\rangle$ change?

Depends on
- how the emitter is coupled to cavity array and
- the characteristics of the cavity array.

Want to consider situation where the cavity array exhibits universal physics. More specifically, want universal two-body bound state.

Broad Motivation



Very broad motivation of our work:

What can we learn by having two probes as opposed to one probe?
We gain access to spatial correlations (not accessible with one probe).

How much more information can we extract if we use two probes that are entangled?

More Specifically

probe ~ system
two two-level emitters

coupling g

matter ~ environment or bath
photonic crystal with Kerr-like non-linearity (non-trivial mode structure)

Perspective 1:
Use the mode structure of the environment to modify the radiance of the system (e.g., super- and sub-radiance).

Perspective 2:
Deduce the mode structure from the dynamics of the probe.

How Does Cavity Array Look Like?

Want to consider situation where the cavity array exhibits universal physics. More specifically, want universal two-body bound state.

Tight-binding + non-linearity:

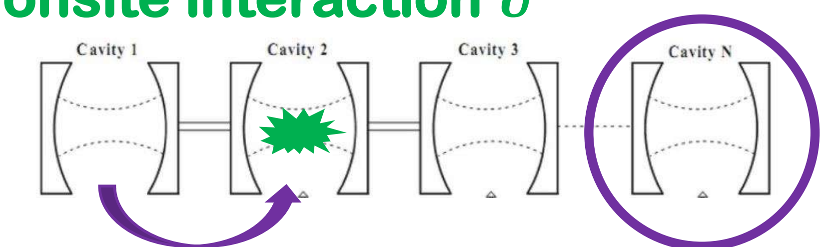
$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n\right)}$$

$$\boxed{+\frac{U}{2} \sum_{n=1}^{N} \underbrace{\hat{a}_n^\dagger \hat{a}_n^\dagger \hat{a}_n \hat{a}_n}_{\hat{n}_n(\hat{n}_n - 1)}.}$$

Discrete space: $n = 1, 2, \cdots, N$!

If we want to have a bound state, then we need to have photon-photon interactions: assume presence of Kerr-like non-linearity ($U \neq 0$). This is an effective or induced interaction (photons are massless and non-interacting).

onsite interaction U

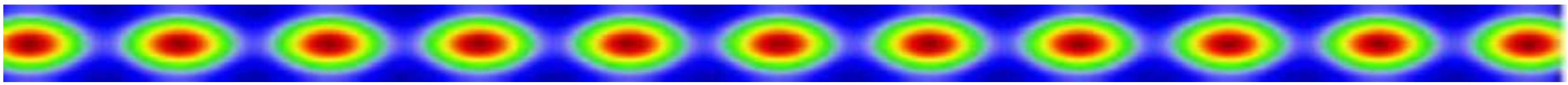


tunneling J

single-mode cavity ω_c

Photon-Photon Bound State: When Is It Universal?

Images of 1D and 2D photonic crystals



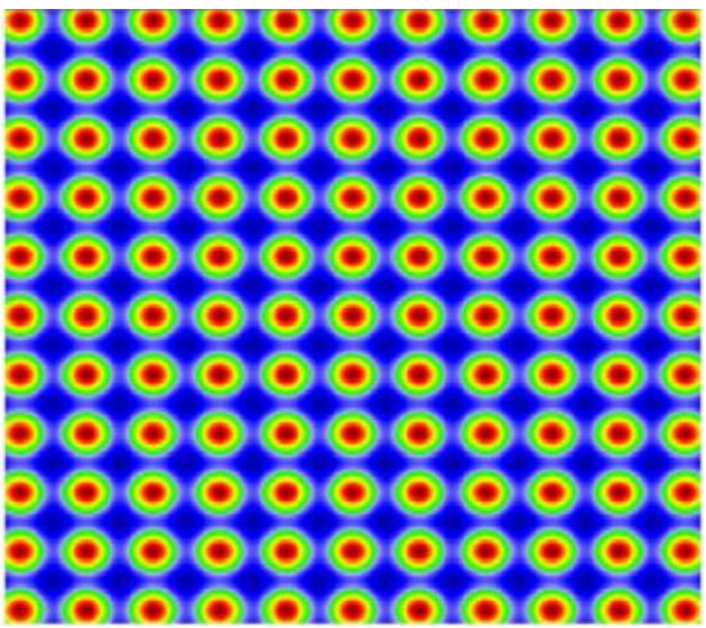


Figure from A. Piper, D. V. Timotijevic, and D. M. Jovic, Phys. Scr. T157, 014023 (2013).

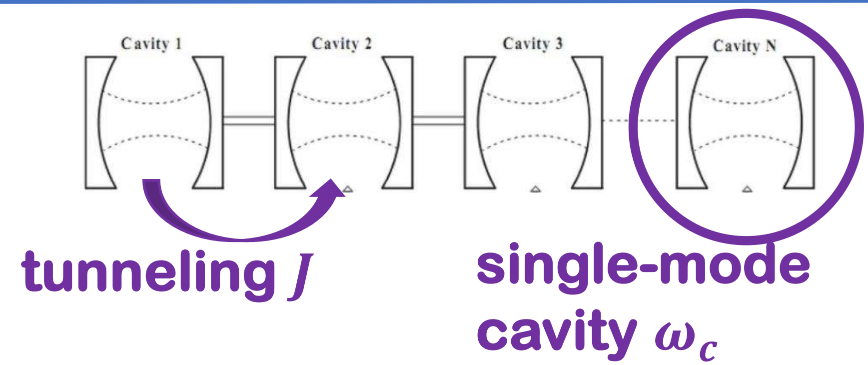
Question: If we have a regular crystal structure with lattice spacing a, what is the condition on the size of the two-body bound state for the state to be universal?

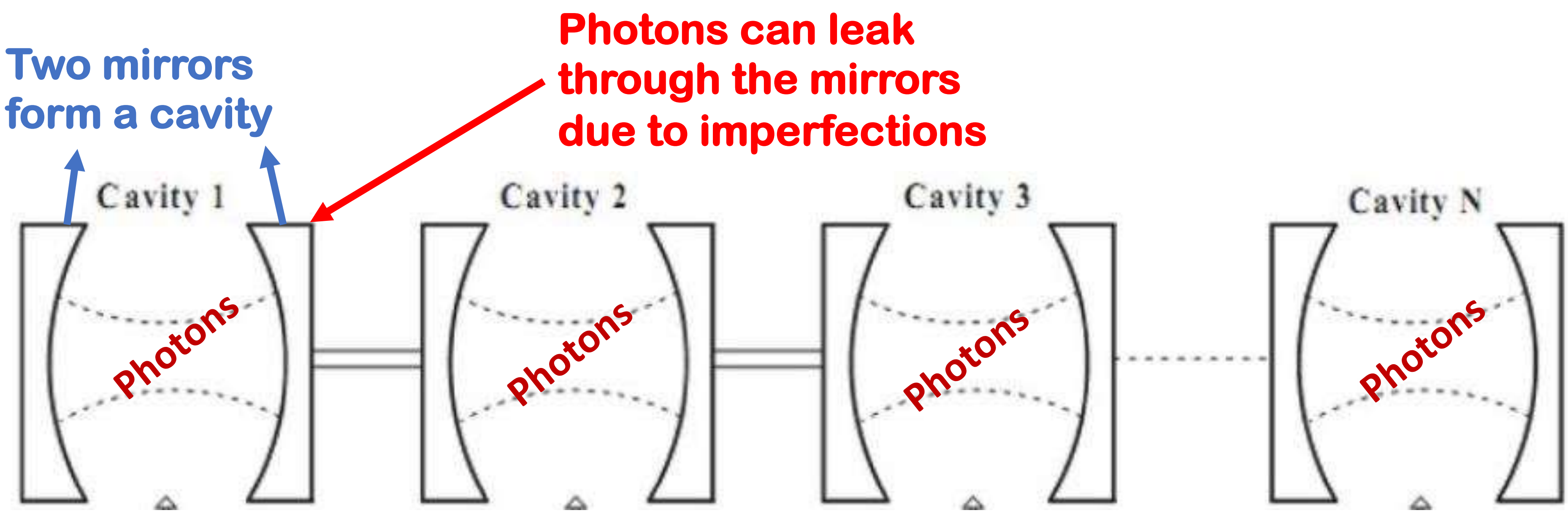
Cavity Array With Single Excitation

Tight-binding + ~~non-linearity~~:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n \right)}$$

$$\boxed{+ \cancel{\frac{U}{2} \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n^\dagger \hat{a}_n \hat{a}_n}.}$$





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$$\boxed{\cancel{+\frac{U}{2} \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n^\dagger \hat{a}_n \hat{a}_n}.}$$

Photon number operator:
$\hat{N} = \sum_{n=1}^{N} \hat{a}_n \hat{a}_n^\dagger$.

Since $[\hat{N}, \hat{H}_b] = 0$, the Hamiltonian $\hat{H}_b$ can be diagonalized separately for $\langle \hat{N} \rangle = 1, 2, \cdots$.

Single-photon energy:
$E_k = \hbar\omega_c - 2J\cos(ka)$.

Single-photon wave number k is a good quantum number: $ka \in [-\pi, \pi]$.
Energy band of width $4J$.

Approximately quadratic around $k = 0$ but not near band edge: Non-trivial single-particle dispersion.

Group velocity: $v_g = \hbar^{-1} \frac{\partial E_k}{\partial k}$
$\Longrightarrow \; v_g = \frac{2Ja}{\hbar} \sin(ka)$.

Cavity Array With Single Excitation

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Group velocity: $v_g = \hbar^{-1}\frac{\partial E_k}{\partial k}$

$\Rightarrow \ v_g = \frac{2Ja}{\hbar}\sin(ka).$

Question:
How far does single photon travel during characteristic time?

Sub-question:
What is the characteristic time of the cavity array?

Cavity Array With Single Excitation

Tight-binding + ~~non-linearity~~:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n \right)}$$
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Group velocity: $v_g = \hbar^{-1} \frac{\partial E_k}{\partial k}$

$\Longrightarrow \; v_g = \frac{2Ja}{\hbar} \sin(ka).$

Question: What is the effective mass of the photons "trapped" in the cavity array?

Single Emitter:
Single-Excitation Bound State

$$\hat{H} = \boxed{\hat{H}_s} + \boxed{\hat{H}_b} + \boxed{\hat{H}_{sb}}$$

$$\hat{H}_s = \frac{\hbar\omega_e}{2}\sum_{j=1}^{N_e}\left(\hat{\sigma}_j^z + \hat{1}_j\right)$$

$$\hat{H}_{sb} = g\sum_{j=1}^{N_e}\left(\hat{a}_{n_j}\hat{\sigma}_j^+ + \hat{a}_{n_j}^\dagger\hat{\sigma}_j^-\right)$$

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tight-binding + ~~non-linearity~~

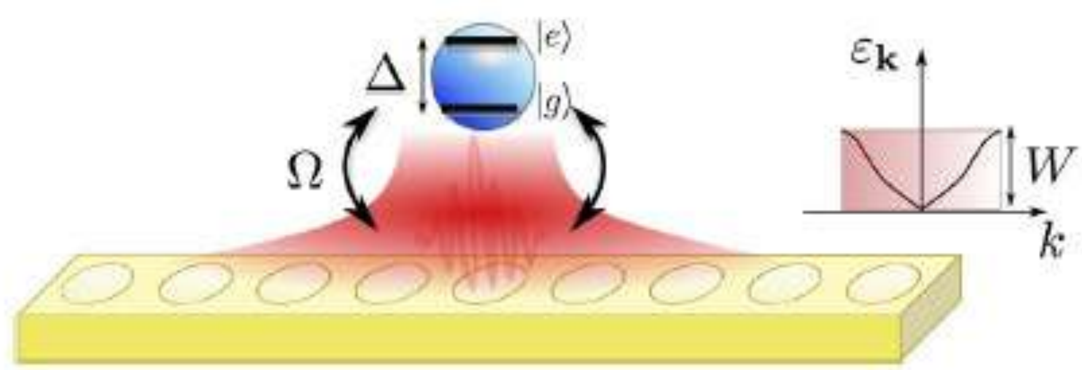

FIG. 1. Single impurity with energy Δ coupled through Ω to a bath with dispersion relation $\varepsilon_{\mathbf{k}}$ and a bandwidth W. A bosonic bound state (in red) localizes around the impurity.

Figure taken from Shi, Wu, Gonzalez-Tudela, and Cirac, PRX 6, 021027 (2016).

Emitter-photon bound state! Superposition of $|e\rangle$ and $|g\rangle$.

Cavity Array With Two Excitations

Tight-binding + ~~non-linearity~~:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n \right)}$$
$$\boxed{\cancel{+\frac{U}{2} \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n^\dagger \hat{a}_n \hat{a}_n}.}$$

We have k_1 and k_2.

Just as in the "usual" case, it turns out to be convenient to switch to relative and center-of-mass wave vectors: q and K.
K is a good quantum number.

For $U = 0$:

$$E_{q,K} = E_{k_1} + E_{k_2} =$$
$$2\hbar\omega_c - 4J \cos\left(\frac{Ka}{2}\right) \cos(qa) =$$
$$2\hbar\omega_c - 2J_K \cos(qa)$$

$E_{q,K}$ depends parametrically on K.

For each K, q can take a range of values: energy band or scattering continuum.

Cavity Array With Two Excitations

Tight-binding + ~~non-linearity~~:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n\right)}$$

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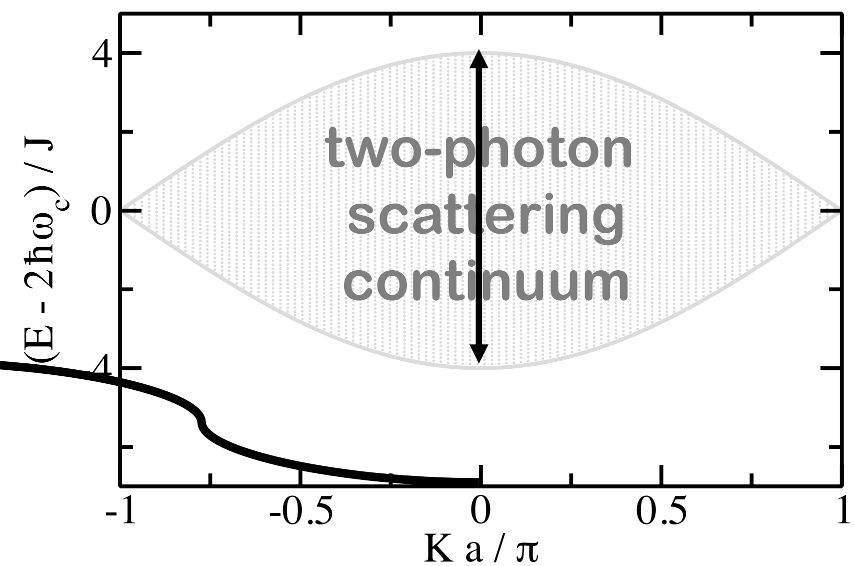

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Cavity Array With Two Excitations

Tight-binding + non-linearity:

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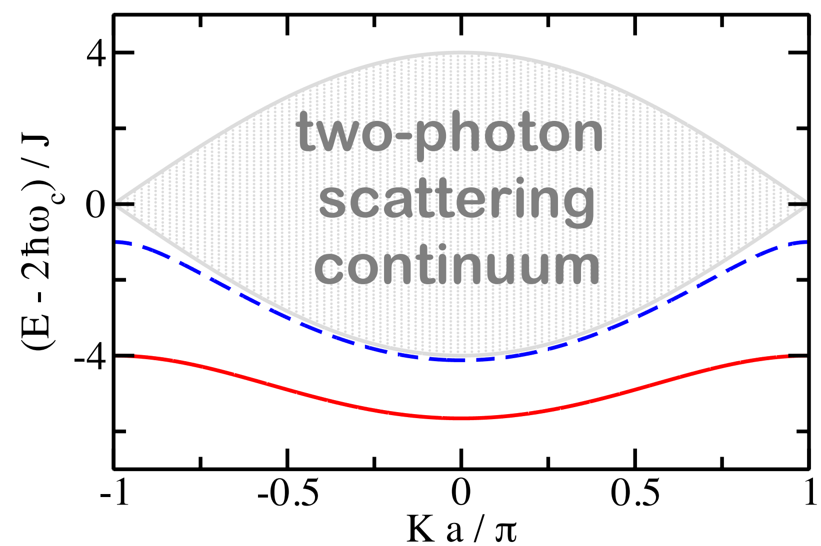

For $U \neq 0$: Scattering continuum is unchanged (does not depend on U).
However, there also exists exactly one two-photon bound state:

$$E_{K,b} = 2\hbar\omega_c + \mathrm{sign}(U)\left[U^2 + 16J^2\cos^2\left(\frac{Ka}{2}\right)\right]^{1/2}$$

Negative U:

$$\frac{U}{J} = -1$$

$$\frac{U}{J} = -4$$

Cavity Array With Two Excitations

Tight-binding + non-linearity:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n \right)}$$
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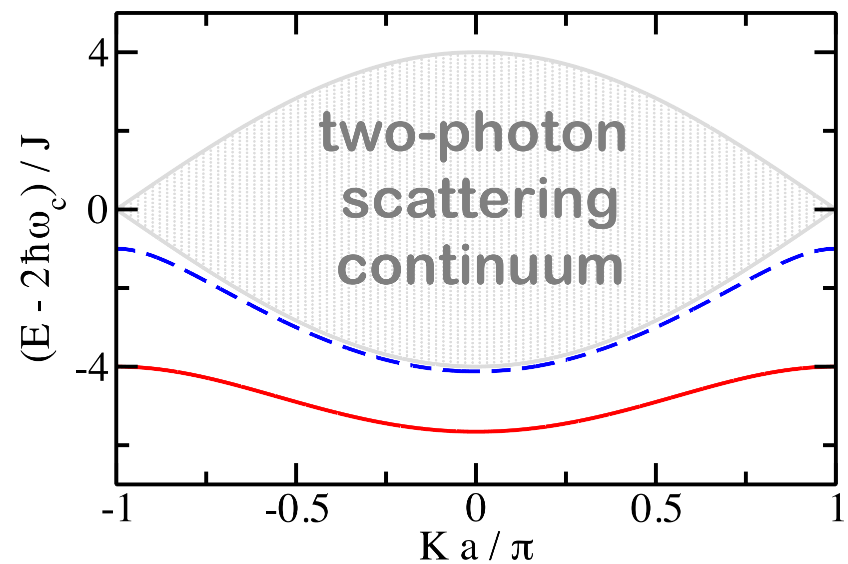

Question:
What is the binding energy of "red" state?
What is the binding energy of "blue" state?

Negative U:

$$\frac{U}{J} = -1$$
$$\frac{U}{J} = -4$$

Cavity Array With Two Excitations

Tight-binding + non-linearity:

$$\hat{H}_b = \boxed{\hbar\omega_c \sum_{n=1}^{N} \hat{a}_n^\dagger \hat{a}_n - J \sum_{n=1}^{N} \left(\hat{a}_n^\dagger \hat{a}_{n+1} + \hat{a}_{n+1}^\dagger \hat{a}_n\right)}$$
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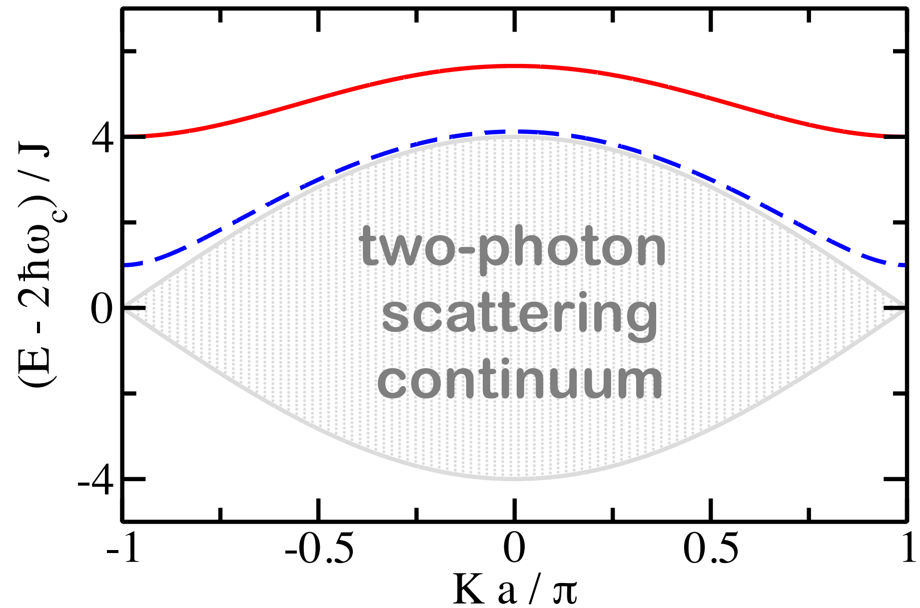


Positive U:

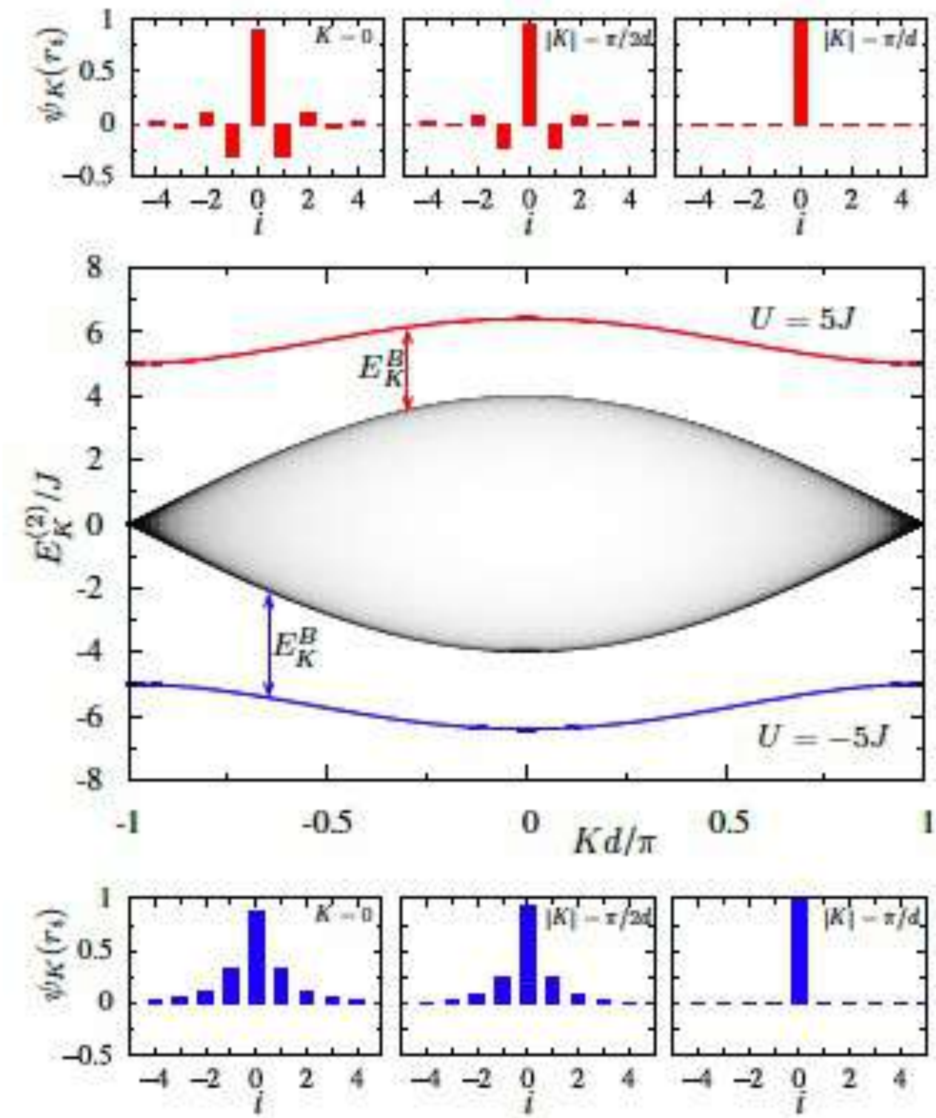
$\frac{U}{J} = 1$

$\frac{U}{J} = 4$

Repulsively bound pair!!!

Cavity Array With Two Excitations: Two-Photon Wave Function

From Valiente and Petrosyan, JPB 41, 161002 (2008).



Three-Body Bound States?

- Same tight-binding Hamiltonian as discussed here supports deeply-bound and weakly-bound three-body states (“3” and “2+1” states). See M. Valiente, D. Petrosyan, and A. Saenz, PRA 81, 011601(R) (2010) for details.

- Anisotropic Heisenberg model: Collective excitations in quantum magnets (magnons) exhibit Efimov effect. See Y. Nishida, Y. Kato, and C. D. Batista, Nat. Phys. 9, 93 (2013) for details.

Coupling Emitter(s) To Cavity Array

$$\hat{H} = \boxed{\hat{H}_s} + \boxed{\hat{H}_b} + \boxed{\hat{H}_{sb}}$$

$$\hat{H}_s = \frac{\hbar\omega_e}{2}\sum_{j=1}^{N_e}\left(\hat{\sigma}_j^z + \hat{1}_j\right)$$

$$\hat{H}_{sb} = g\sum_{j=1}^{N_e}\left(\hat{a}_{n_j}\hat{\sigma}_j^+ + \hat{a}_{n_j}^\dagger\hat{\sigma}_j^-\right)$$

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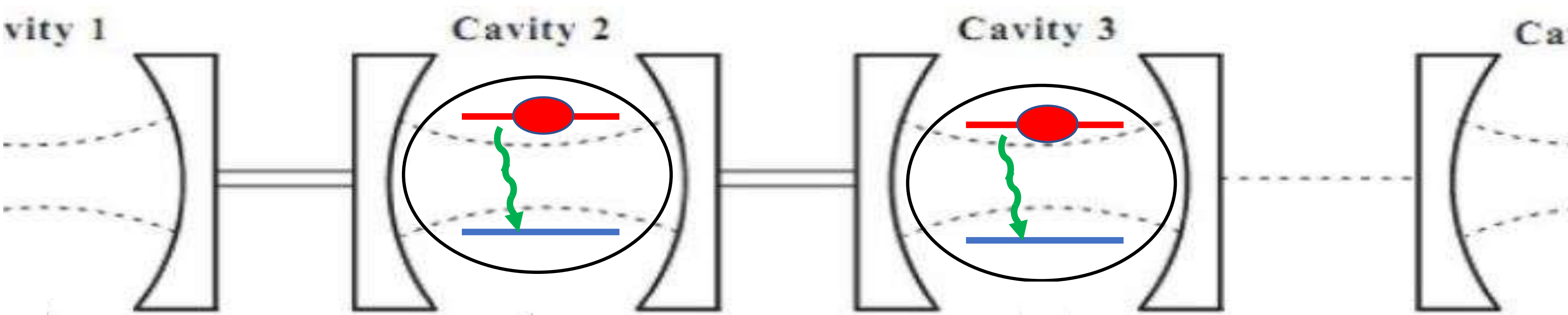
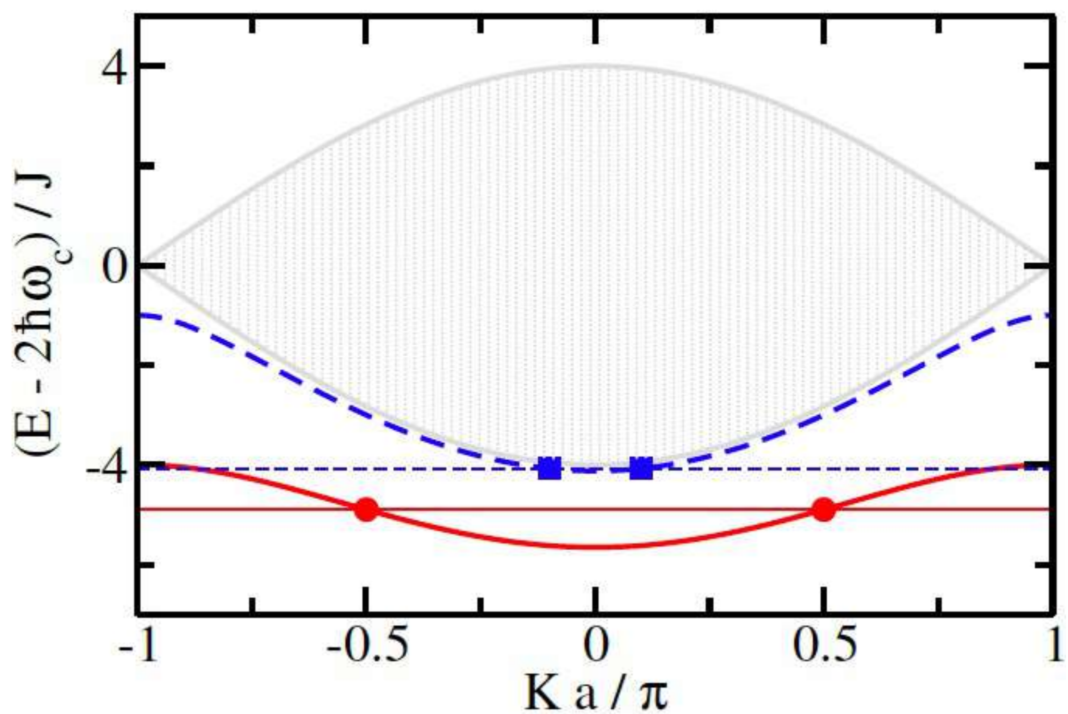
$$\boxed{+\frac{U}{2}\sum_{n=1}^{N}\hat{a}_n^\dagger\hat{a}_n^\dagger\hat{a}_n\hat{a}_n.}$$

tight-binding + non-linearity

Two-Level Emitter in Resonance with Two-Photon Bound State





Chose the energy spacing $\hbar\omega_e$ of emitter levels to be in resonance with energy of two-photon bound state (~ "non-trivial mode").

Correlated dynamics of two emitters separated by distance $\mathbf{x} = 0, a, 2a, \ldots.$

Comparison With Dicke Model (Single Radiation Mode)

$$\hat{H} = \boxed{\hat{H}_s} + \boxed{\hat{H}_b} + \boxed{\hat{H}_{sb}}$$

$$\hat{H}_s = \frac{\hbar\omega_e}{2}\sum_{j=1}^{N_e}\left(\hat{\sigma}_j^z + \hat{1}_j\right)$$

$$\hat{H}_{sb} = g\sum_{j=1}^{N_e}\left(\hat{a}_{n_j}\hat{\sigma}_j^+ + \hat{a}_{n_j}^\dagger\hat{\sigma}_j^-\right)$$

$$\hat{H}_b = \hbar\omega_c\sum_{n=1}^{N}\hat{a}_n^\dagger\hat{a}_n - J\sum_{n=1}^{N}\left(\hat{a}_n^\dagger\hat{a}_{n+1} + \hat{a}_{n+1}^\dagger\hat{a}_n\right) + \frac{U}{2}\sum_{n=1}^{N}\hat{a}_n^\dagger\hat{a}_n^\dagger\hat{a}_n\hat{a}_n.$$

$$\hat{H} = \boxed{\hat{H}_s} + \boxed{\hat{H}_b} + \boxed{\hat{H}_{sb}}$$

$$\hat{H}_s = \frac{\hbar\omega_e}{2}\sum_{j=1}^{N_e}\left(\hat{\sigma}_j^z + \hat{1}_j\right)$$

$$\hat{H}_{sb} = g\sum_{j=1}^{N_e}\left(\hat{a}\,\hat{\sigma}_j^+ + \hat{a}^\dagger\,\hat{\sigma}_j^-\right)$$

$$\hat{H}_b = \hbar\omega_c\,\hat{a}^\dagger\hat{a}$$

R. H. Dicke,
Phys. Rev. 93, 99 (1954)

Dicke Model: Superradiance

$$\hat{H} = \boxed{\hat{H}_s} + \boxed{\hat{H}_b} + \boxed{\hat{H}_{sb}}$$

$$\hat{H}_s = \frac{\hbar\omega_e}{2} \sum_{j=1}^{N_e} \left(\hat{\sigma}_j^z + \hat{1}_j\right)$$

$$\hat{H}_{sb} = g \sum_{j=1}^{N_e} \left(\hat{a}\, \hat{\sigma}_j^+ + \hat{a}^\dagger\, \hat{\sigma}_j^-\right)$$

$$\hat{H}_b = \hbar\omega_c\, \hat{a}^\dagger \hat{a}$$

R. H. Dicke,
Phys. Rev. 93, 99 (1954)

Superradiance occurs when a group of N_e emitters interact with a common light field.
If the wavelength of the light is much greater than the separation of the emitters, then the emitters interact with the light in a collective and coherent fashion. This causes the group to emit light as a high intensity pulse (with rate proportional to N_e^2).
This is a surprising result, drastically different from the expected exponential decay (with rate proportional to N_e) of a group of independent atoms.

Text adapted from Wikipedia.

Superradiance Vs. Subradiance

Superradiance: Enhancement of spontaneous emission by constructive interatomic interference.

Subradiance: Cooperative inhibition of spontaneous emission by a destructive interatomic interference.

Coupling Emitter(s) To Cavity Array

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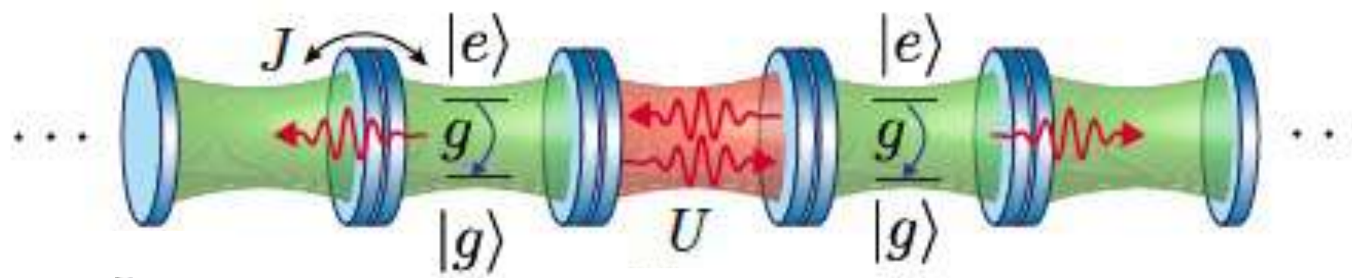
$$\boxed{+\frac{U}{2}\sum_{n=1}^{N}\hat{a}_n^\dagger\hat{a}_n^\dagger\hat{a}_n\hat{a}_n.}$$

tight-binding + non-linearity

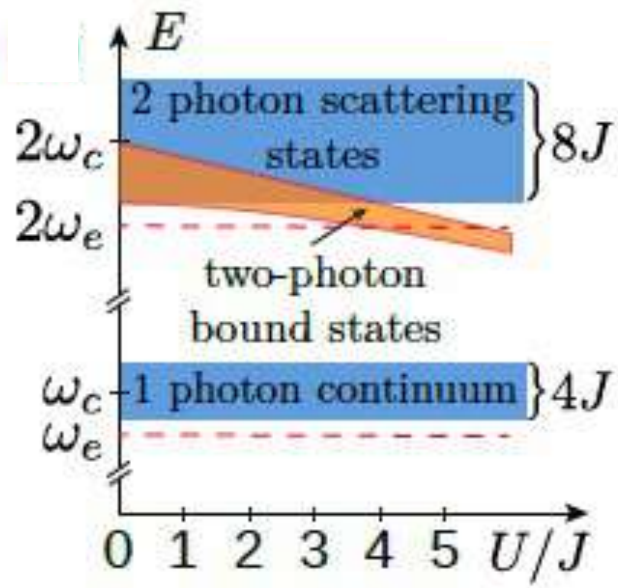
Four- and Many-Emitter Case Studied Using Master Equation

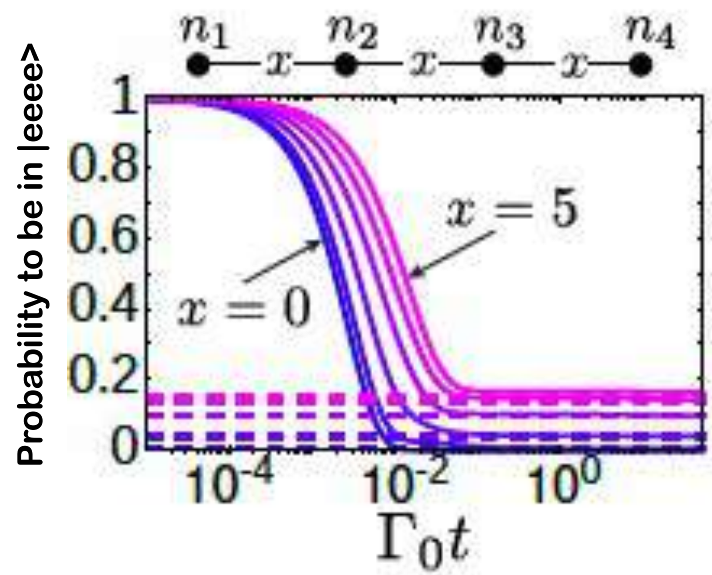
Figures taken from Wang, Jaako, Kirton, Rabl, PRL 124, 213601 (2020).

1D waveguide QED set-up:



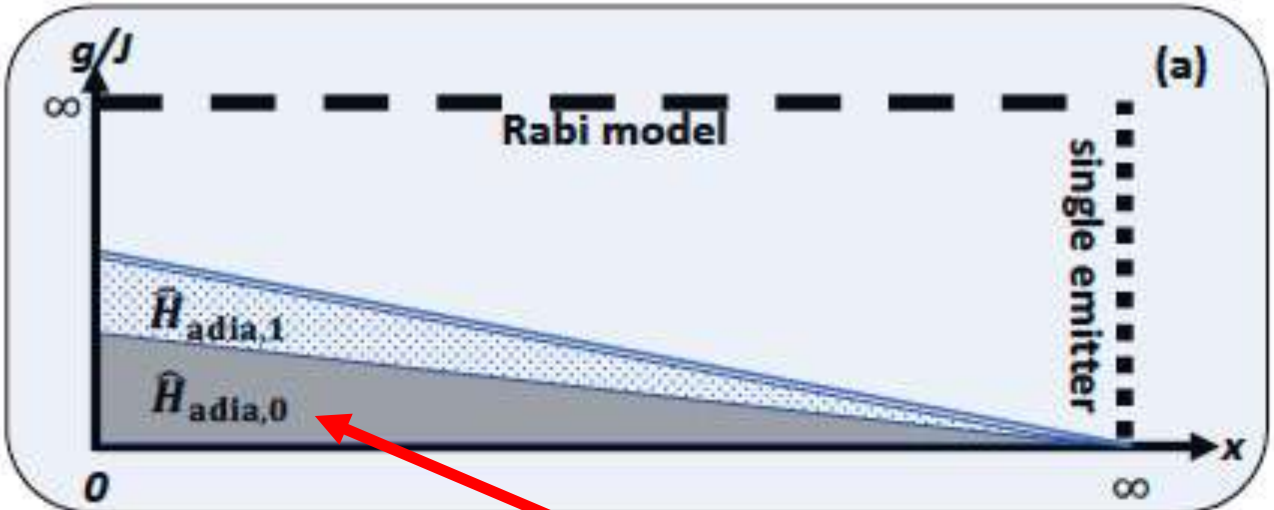
Two-level systems (emitters: atom, quantum dot, superconducting qubit) coupled to nanophotonic or microwave waveguide.





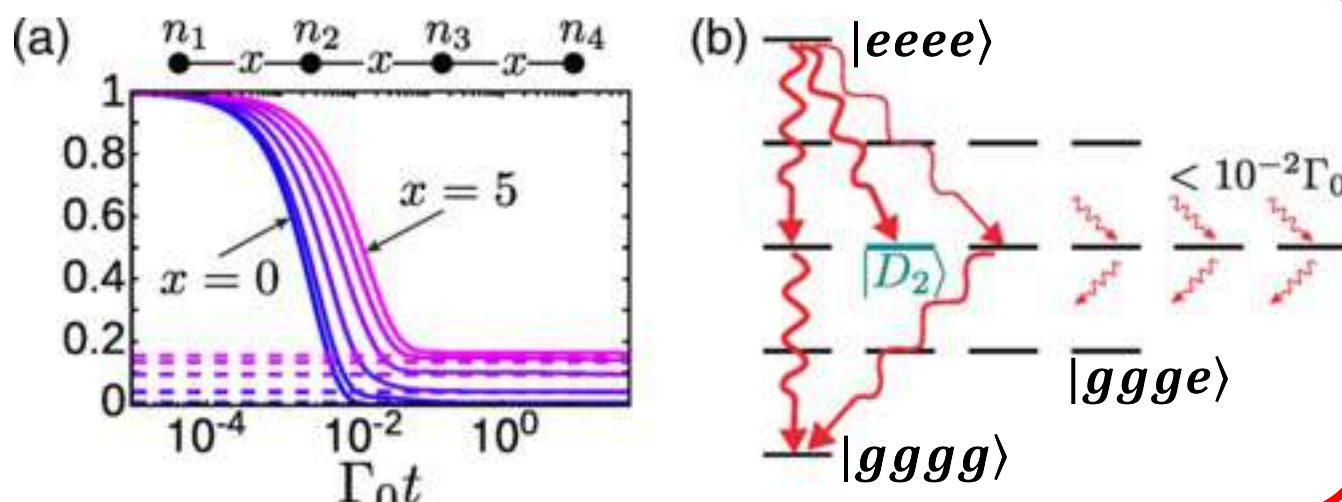
Can also think about this in context of dissipative system dynamics.

Parameter Space for Fixed U/J and Fixed $\hbar(\omega_c - \omega_e)/J$



Adiabatic Hamiltonian assumes that states such as $|eeeg\rangle$, $|eege\rangle$, ... can be removed from Hilbert space.
Must break down for $x \to \infty$.

Wang, Jaako, Kirton, and Rabl: PRL 124, 213601 (2020): Supercorrelated Radiance in Nonlinear Photonic Waveguides (results based on master equation)



Solve Time-Dependent Schroedinger Equation for $\hat{H}$

Time-dependent Schroedinger equation:

$$\imath\hbar\frac{\partial\Psi(t)}{\partial t} = \hat{H}\Psi(t)$$

Ansatz (we are working in two-excitation sub-space):

$$\begin{aligned}|\Psi\rangle(t) = \quad & \exp(-2\imath\omega_e t)[c_{ee}(t)|g,g,\mathrm{vac}\rangle + \\ & \sum_k c_{1k}(t)\hat{a}_k^\dagger|e,g,\mathrm{vac}\rangle + \\ & \sum_k c_{2k}(t)\hat{a}_k^\dagger|g,e,\mathrm{vac}\rangle + \\ & \sum_K c_{K,b}(t)\hat{P}_{K,b}^\dagger|g,g,\mathrm{vac}\rangle + \\ & \sum_{K,q} c_{K,q}(t)\hat{P}_{K,q}^\dagger|g,g,\mathrm{vac}\rangle],\end{aligned}$$

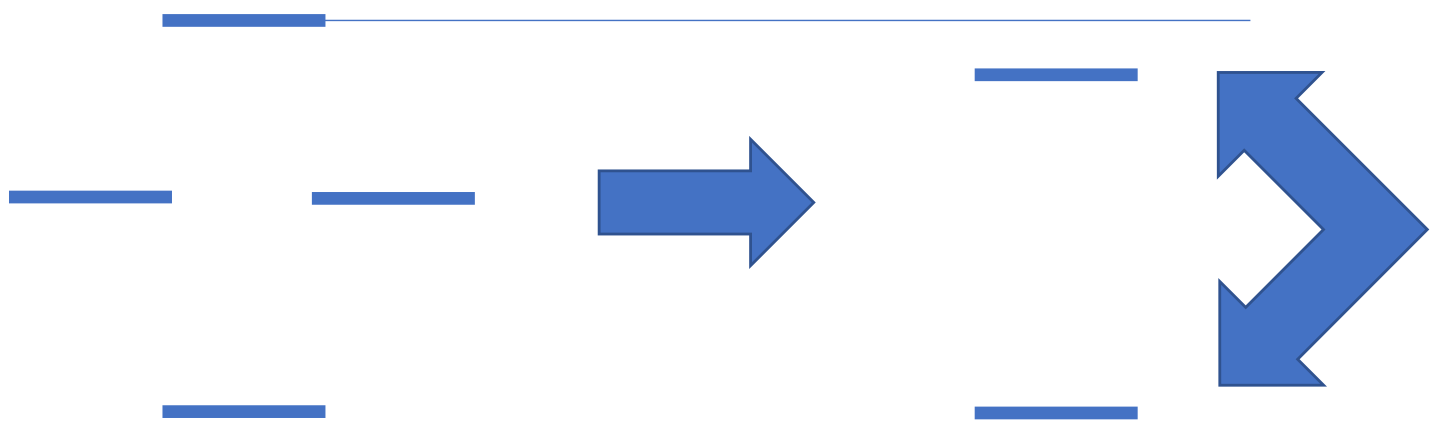
Plugging ansatz into time-dependent Schroedinger equation yields differential equations for $\dot{c}_{ee}(t), \dot{c}_{1k}(t), \dot{c}_{2k}(t), \dot{c}_{K,b}(t), \dot{c}_{K,q}(t)$.

Solve Time-Dependent Schroedinger Equation for $\hat{H}$

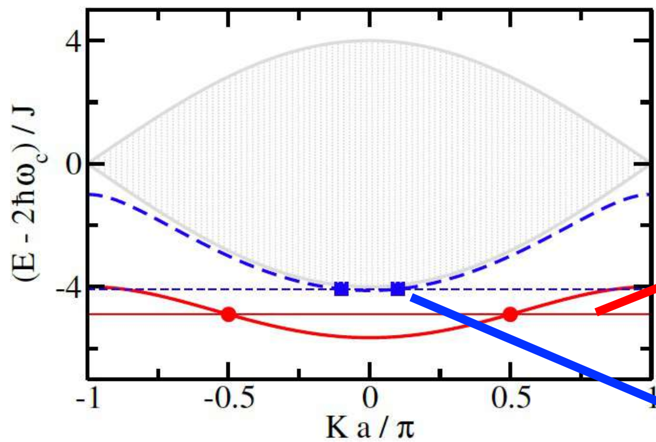
For suitable parameter combination, one finds $\dot{c}_{1k}(t) \approx 0$ and $\dot{c}_{2k}(t) \approx 0$.
If these coefficients are set equal to zero, then $c_{1k}(t)$ and $c_{2k}(t)$ can be (adiabatically) eliminated from equations.

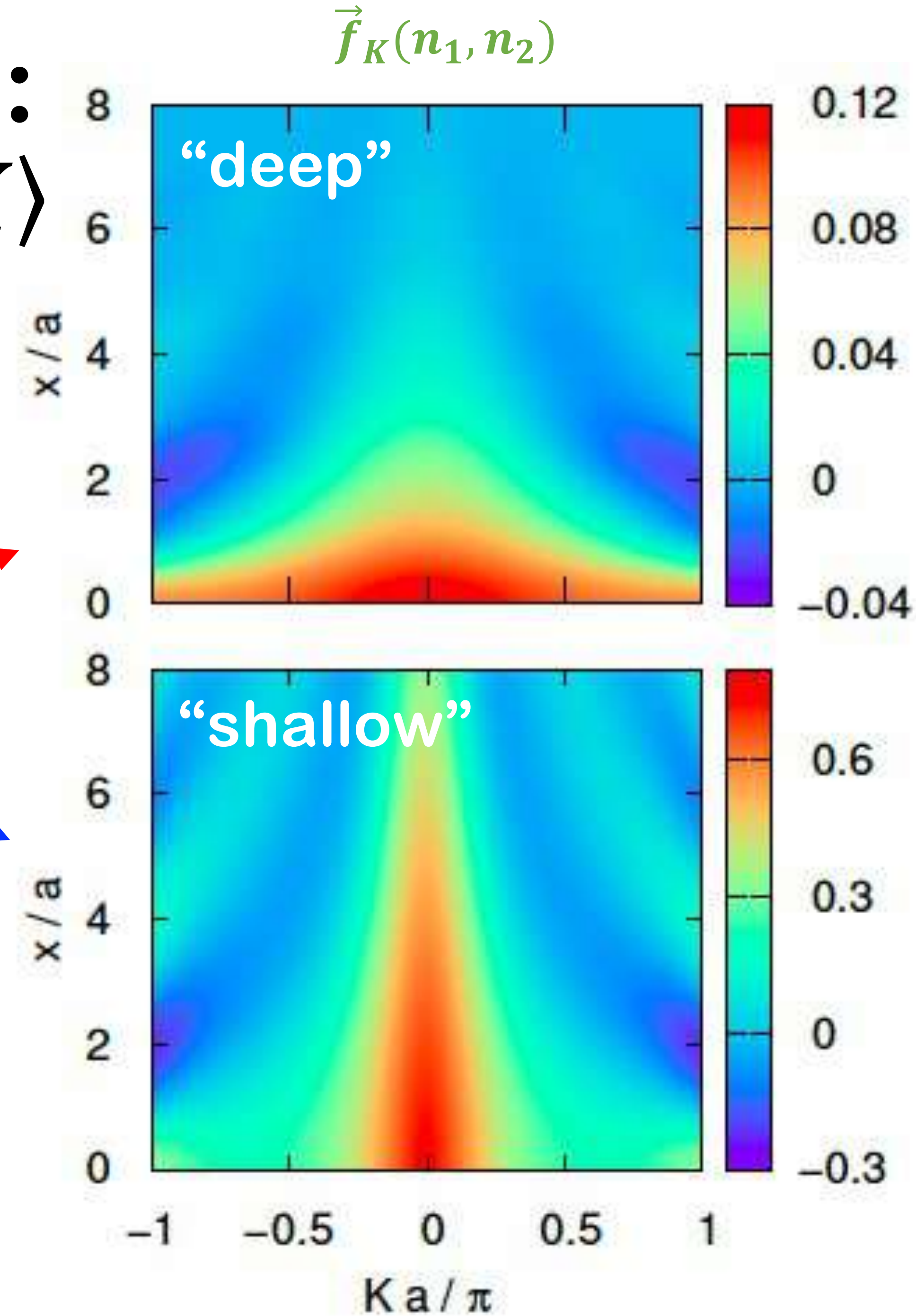
$$\boxed{\hat{H}_{sb} = g \sum_{j=1}^{N_e} \left(\hat{a}_{n_j} \hat{\sigma}_j^{+} + \hat{a}_{n_j}^{\dagger} \hat{\sigma}_j^{-} \right)}$$

Physical picture:



Effective Coupling: $|ee, vac\rangle$ and $|gg, K\rangle$

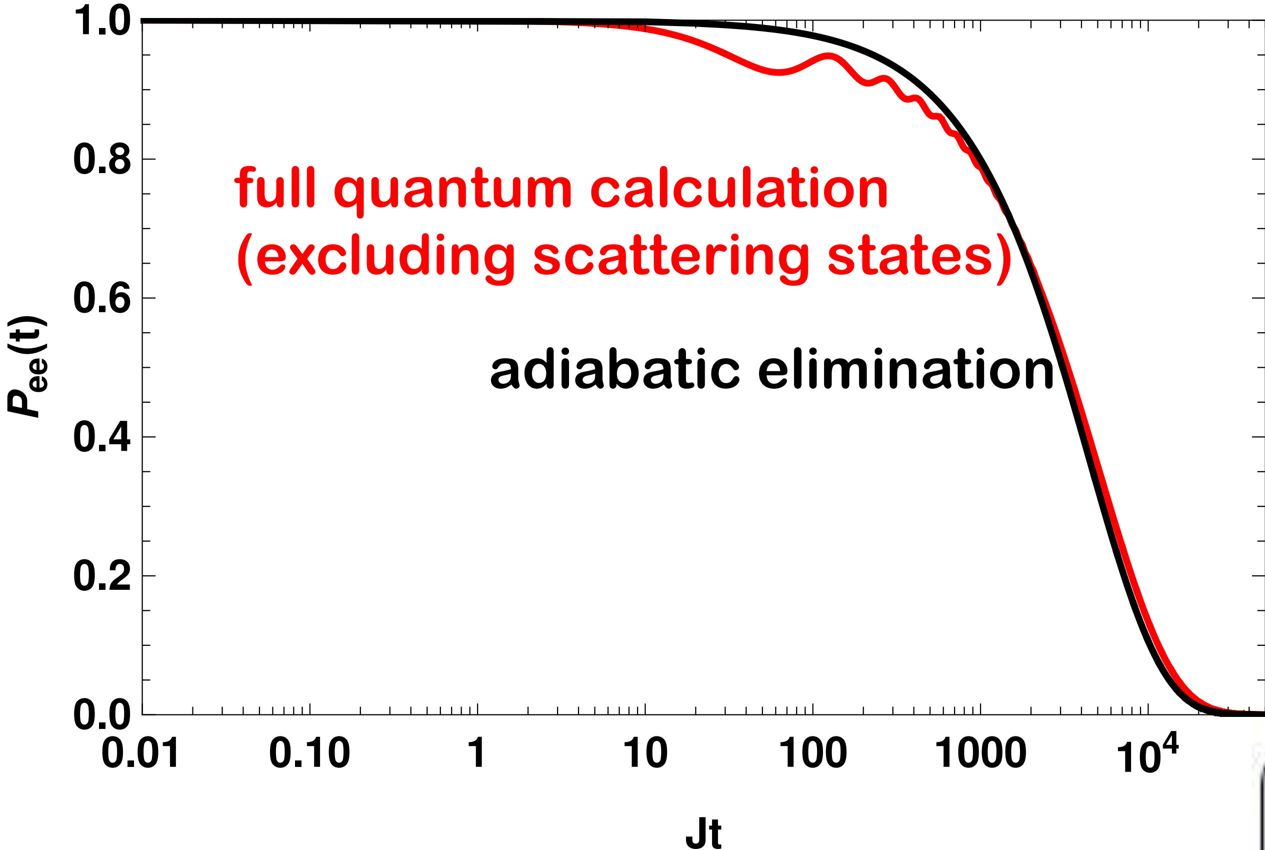




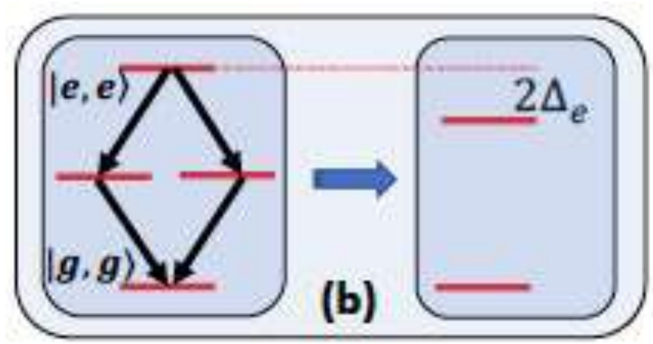
$$\imath\hbar\frac{\partial}{\partial t}\begin{pmatrix} c_{ee} \\ \vec{c}_{K,b} \end{pmatrix} = \underline{H}_{\text{adia}}\begin{pmatrix} c_{ee} \\ \vec{c}_{K,b} \end{pmatrix}$$

$$\underline{H}_{\text{adia}} = \begin{pmatrix} 2\Delta_e & 0 \\ 0 & \underline{\Delta}_{K,b} \end{pmatrix} - g^2\begin{pmatrix} 0 & \left[\vec{f}_K(n_1,n_2)\right]^T \\ \boxed{\vec{f}_K(n_1,n_2)} & \underline{G}_{K,K'}(n_1,n_2) \end{pmatrix}$$

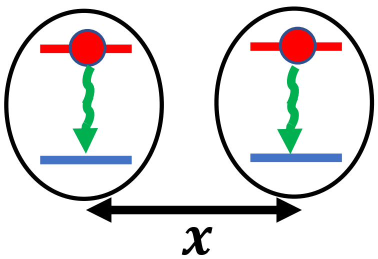
Example Of Dynamics: Initial State $|ee\rangle$

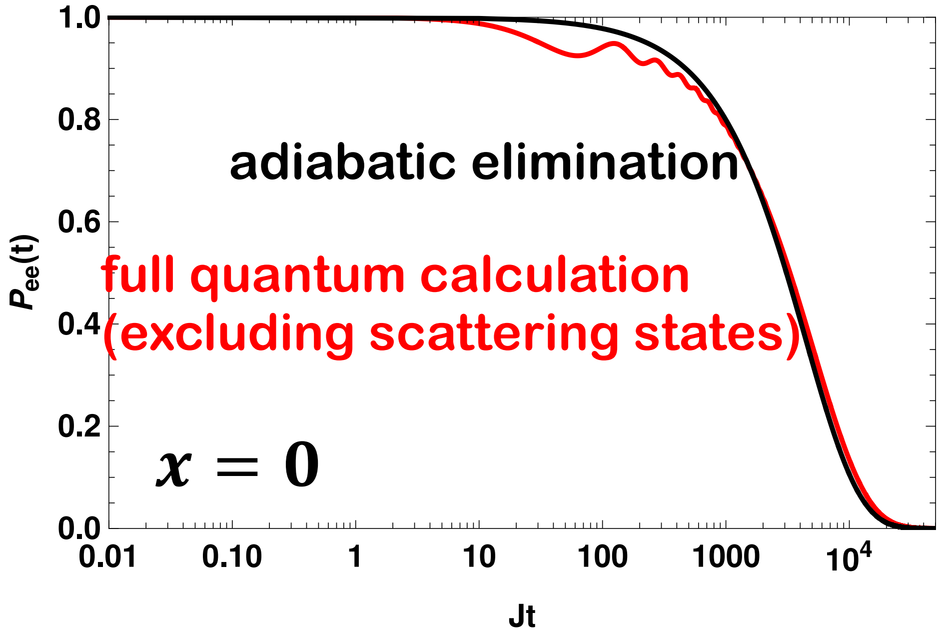


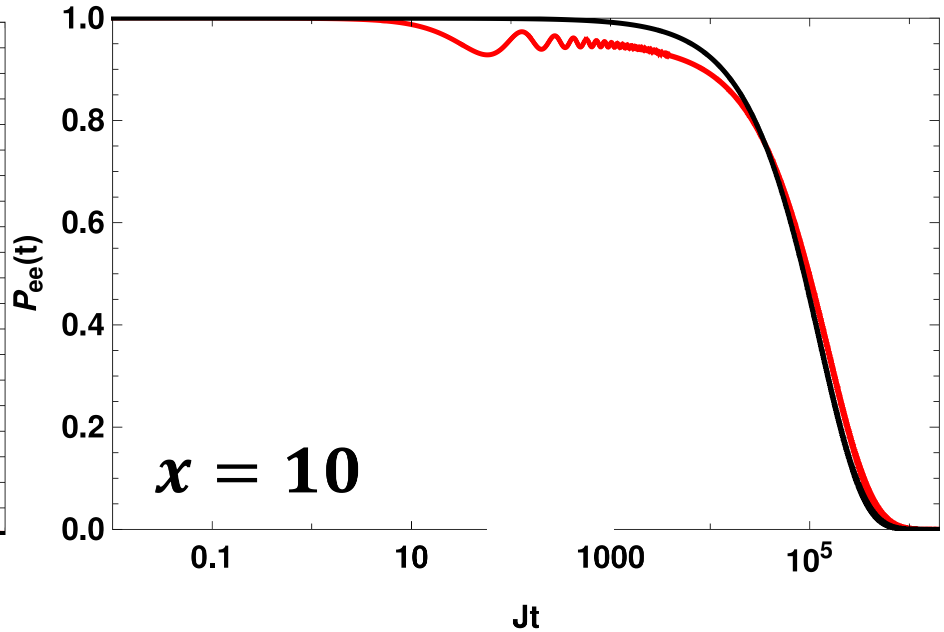
$$\frac{U}{J} = -1.$$
$$\frac{\delta}{J} = 2.04.$$
$$\frac{g}{J} = 0.02.$$
$$\frac{x}{a} = 0.$$



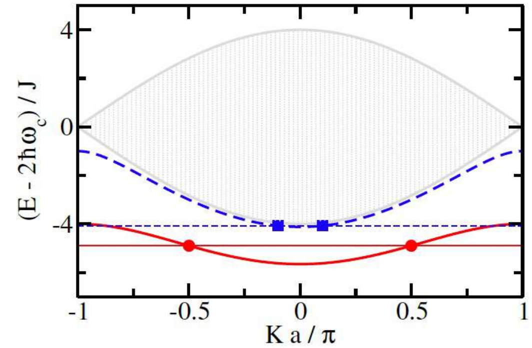
Example Of Dynamics: Initial State $|ee\rangle$

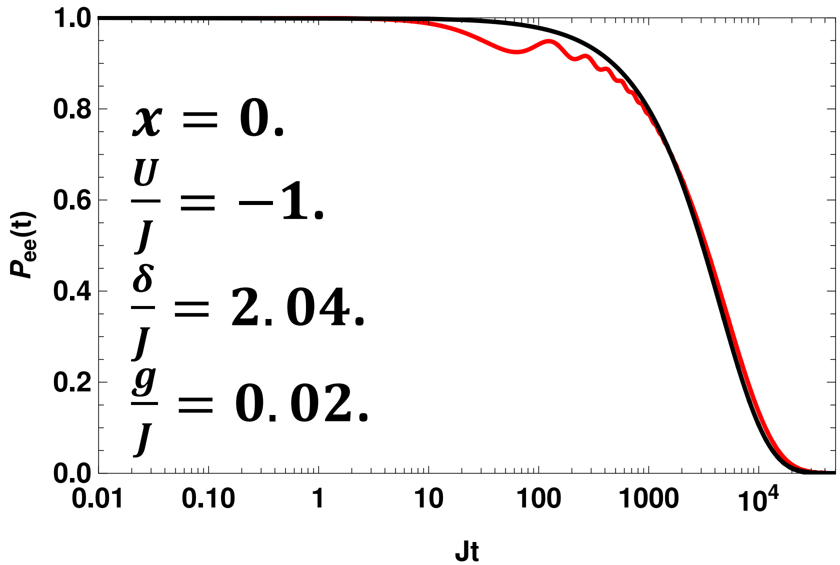


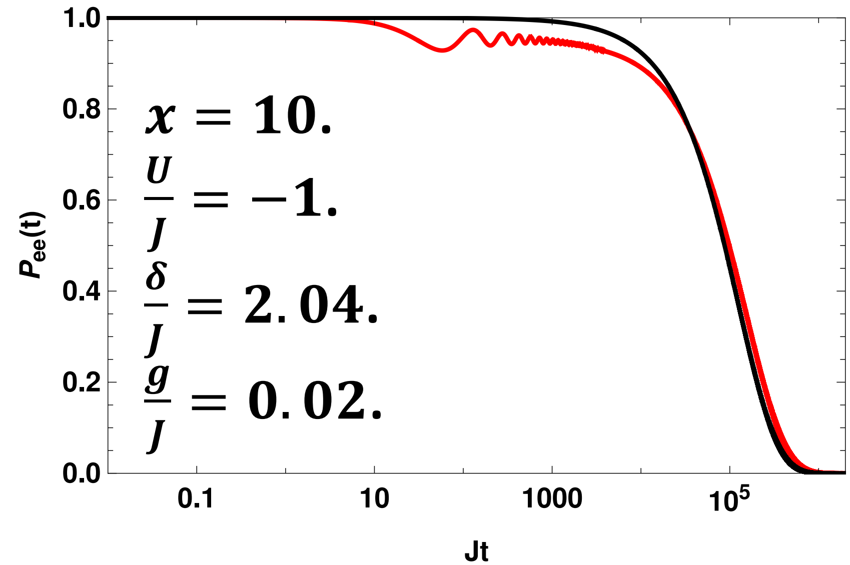


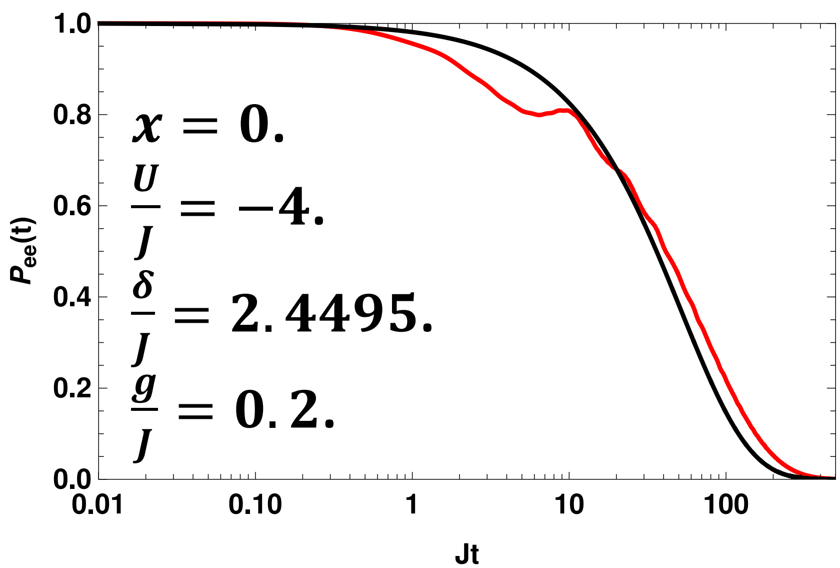


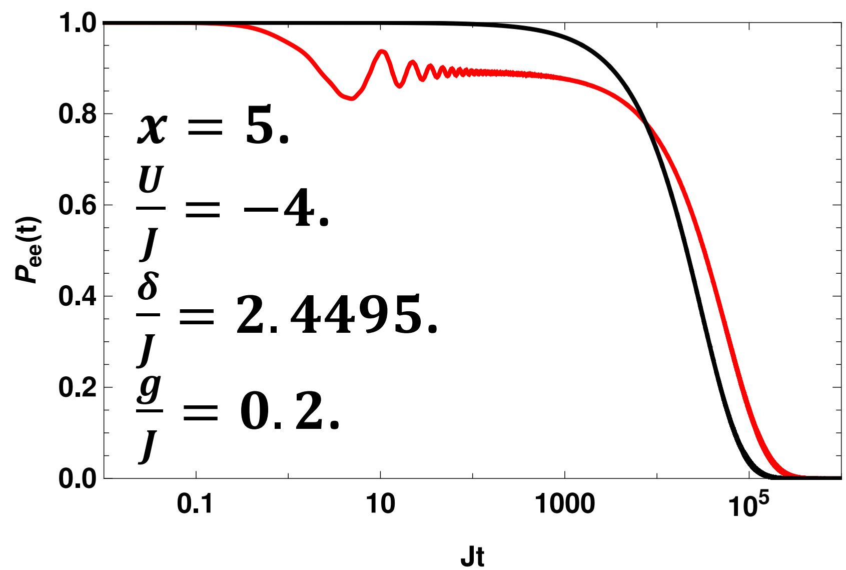
Example Of Dynamics: Initial State $|ee\rangle$











Summary and Outlook

Discrete lattice systems support universal states.

Coupling of emitters to cavity array provides unique opportunity to study impact of non-trivial mode structure.

Interesting radiation dynamics.

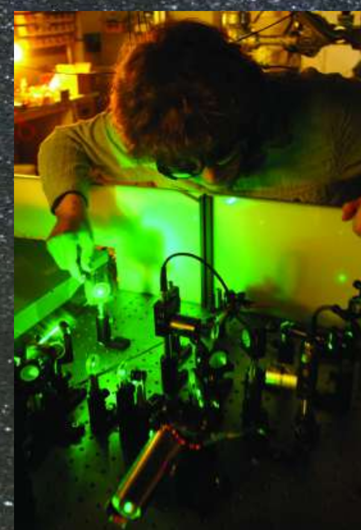
Opportunity to study dissipative dynamics in different regimes.

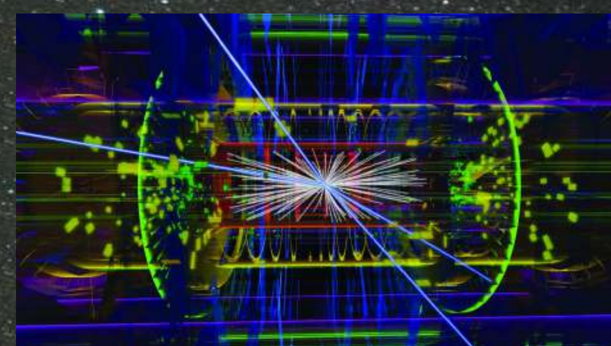
Alternative framework: Master equation.

Thank You!

Many thanks to current graduate students Jugal Talukdar and Dave Hill, as well as summer REU student Claire Kvande.

Want to join OU as a graduate student?





Ph.D. in Physics

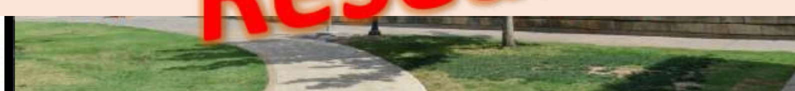
Homer L. Dodge

Astronomy and Astrophysics

supernovae | cosmology | extragalactic astronomy | nucleosynthesis | observational astronomy | star formation | exoplanets | disk/planetary dynamics

New Building with High Quality Laboratory Space!

Campuswide Quantum Initiative: Center for Quantum Research and Technology!



cosmology | quantum field theory