Atom-photon bound states in modern quantum optics

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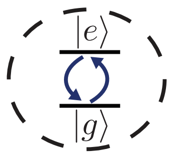
qunipa

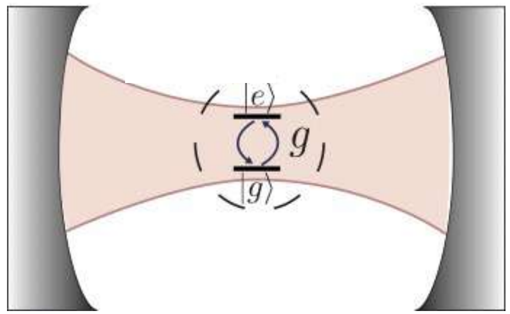
NYU Abu Dhabi, 17 Feb 2025

‘traditional’ quantum optics

atom in free space



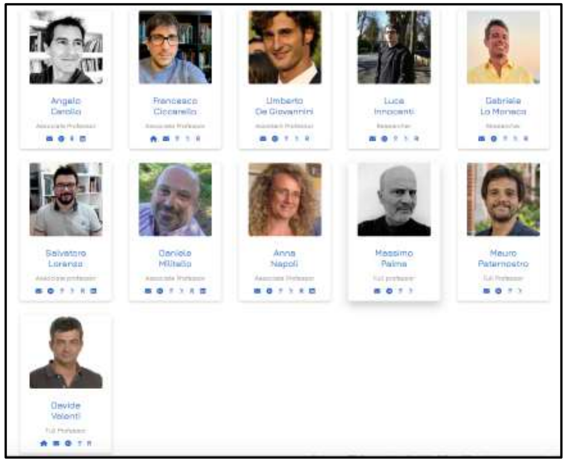
atom in a cavity



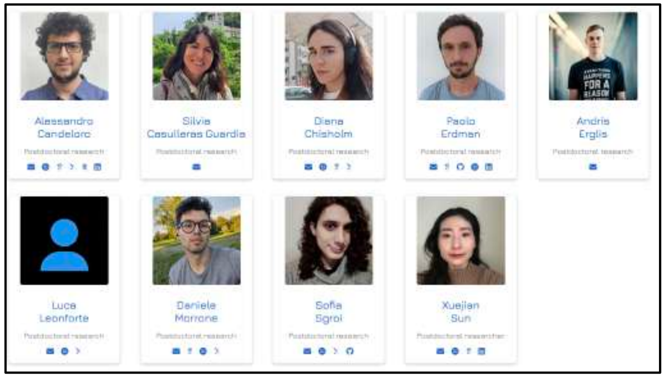
changing the electromagnetic bath affects atom-photon interactions

quantum theory group in Palermo

staff

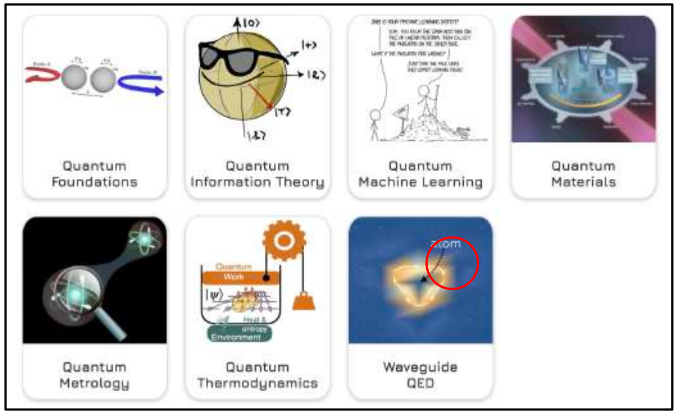


Post Docs



PhDs

research lines



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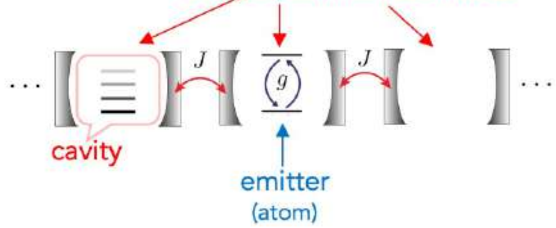
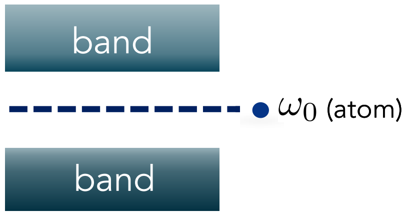
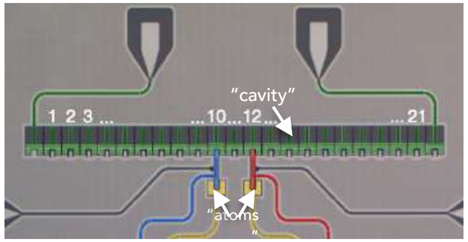
quantum optics in artificial photonic lattices

photonic lattice: coupled cavities/resonators



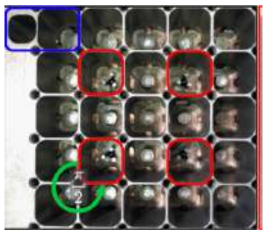


implementations: circuit QED, ultracold atoms etc



M Scigliuzzo, G Calajò, F Ciccarello, D Perez Lozano, A Bengtsson, P Scarlino, A Wallraff, D Chang, P Delsing & S Gasparinetti, PRX 12, 031036 (2022)

"atom"

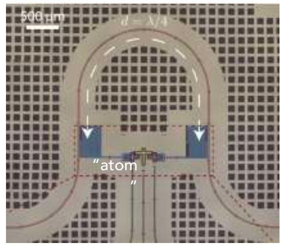


2D lattice & magnetic field

J. C. Owens, M. G. Panetta, B. Saxberg, G. Roberts, S. Chakram, R. Ma, A. Vrajitoarea, J. Simon, D. I. Schuster, Nat. Phys. 18, 1048 (2022)

giant atoms

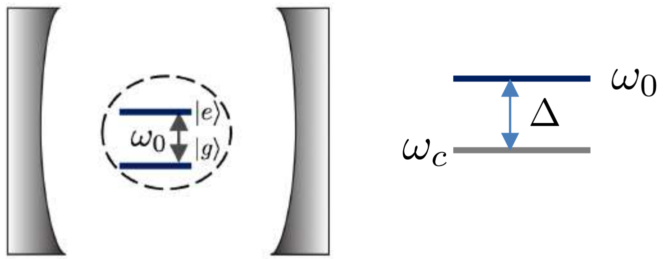
«atom» coupled non-locally at many coupling points



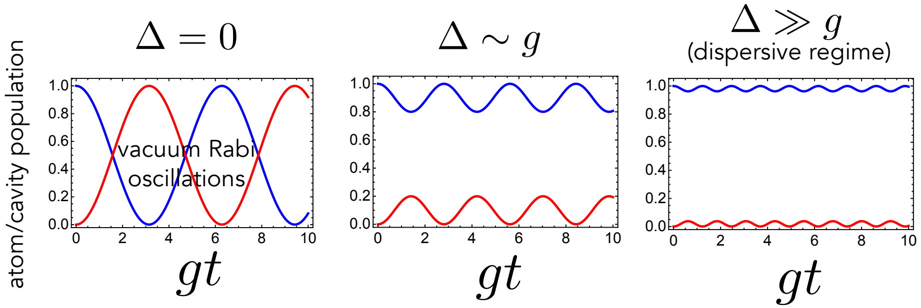
C. Joshi, F. Yang, & M. Mirhosseini, PRX 13, 021039 (2023)

cavity QED: dispersive regime

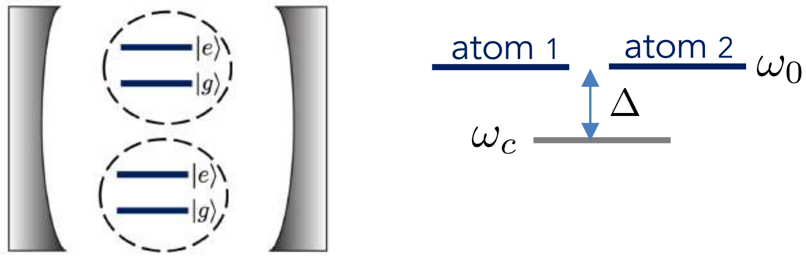
atom in a cavity



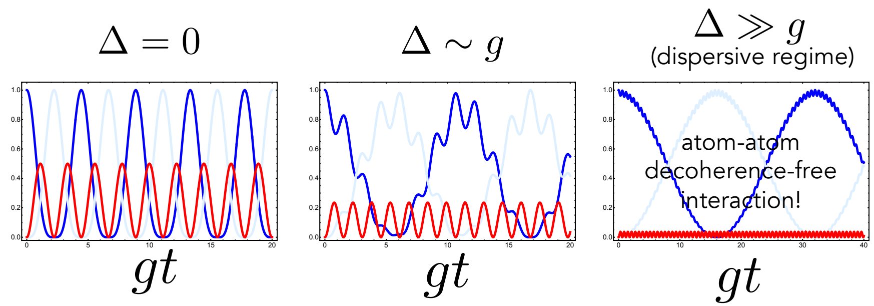
$$H = \omega_0 \sigma_+ \sigma_- + \omega_c b^\dagger b + g \left(\sigma_- b^\dagger + \text{H.c.} \right)$$



<u>two</u> atoms in a cavity

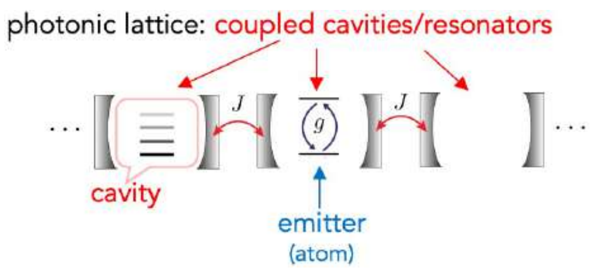


$$H = \omega_0 \sum_{i=1,2} \sigma_{i+} \sigma_{i-} + \omega_c b^\dagger b + g \sum_{i=1,2} \left(\sigma_{i-} b^\dagger + \text{H.c.} \right)$$

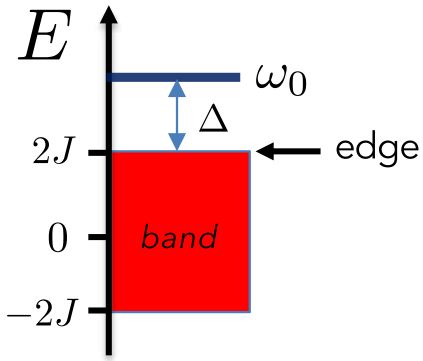


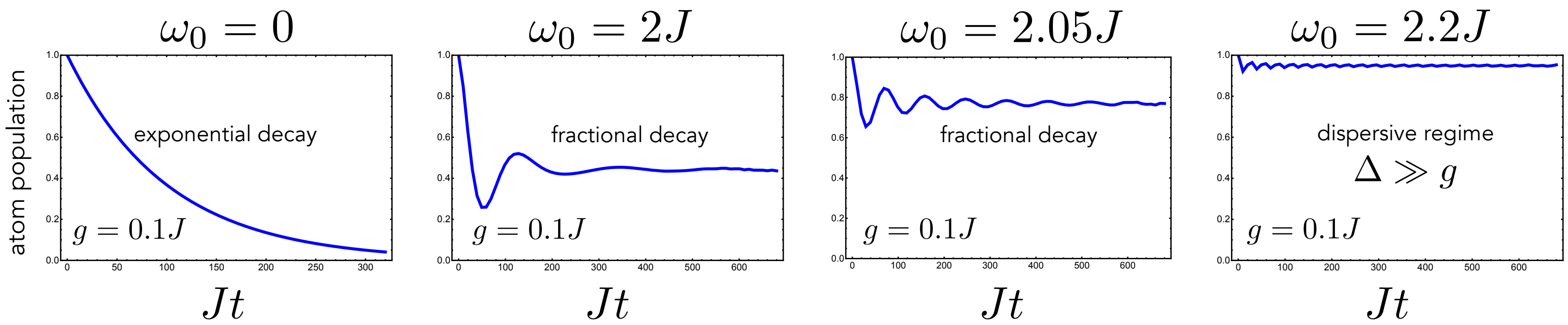
$$H_{\text{eff}} = \frac{g^2}{2\Delta} \left(\sigma_{1+} \sigma_{2-} + \text{H.c.} \right)$$

atom coupled to a coupled-cavity array

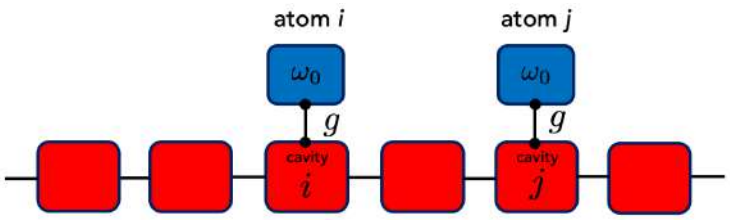


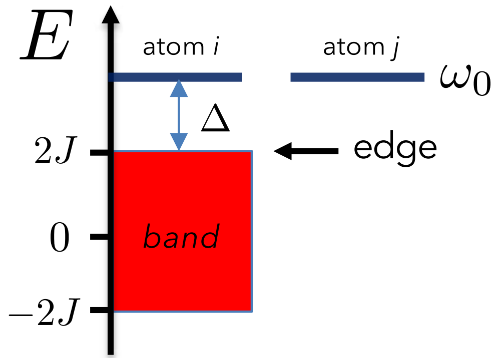
$$H = \omega_0\sigma_+\sigma_- \underbrace{-J\sum_n\left(b^\dagger_{n+1}b_n + \text{H.c.}\right)}_{=H_B} + g(b^\dagger_0\sigma_- + \text{H.c.})$$





two atoms coupled to a coupled-cavity array





dispersive regime $\Delta \gg g$

$$H_{\text{eff}} = \sum_{ij} K_{ij}\sigma_j^\dagger \sigma_i \quad \text{with} \quad K_{ij} \propto \frac{g^2}{\sqrt{J\Delta}} e^{-\frac{|i-j|}{\lambda}}$$

exponential inter-atomic potential

$$\lambda = \sqrt{\frac{J}{\Delta}}$$

interaction range

Douglas et al, Nat. Photon 2015

Δ experimentally tunable ➡ λ experimentally tunable

Sundaresan et al, PRX 2019; Scigliuzzo et al PRX 20223

shown to be a resource for variational quantum simulators

Tabares et al., PRL 2023

atom-photon bound state

general model of an atom coupled to a photonic bath:

$$H = \omega_0 \sigma_+ \sigma_- + H_B + g(\sigma_- b_v^\dagger + \text{H.c.})$$

with $$H_B = \sum_x \omega_x b_x^\dagger b_x + \sum_{x \neq x'} J_{xx'} b_x^\dagger b_{x'}$$

single-excitation sector: $|e\rangle|\text{vac}\rangle \to |e\rangle$, $|g\rangle\, b_x^\dagger |\text{vac}\rangle \to |x\rangle$

excitation on the atom — excitation on cavity x

general (single-excitation) «dressed state»:

$$|\Psi\rangle \propto |e\rangle + g|\psi\rangle \text{ with } H|\Psi\rangle = \omega|\Psi\rangle$$

single-photon state: $|\psi\rangle = \sum_x \alpha_x |x\rangle$

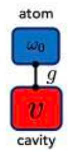
atom-photon bound state: $|\Psi\rangle$ normalizable

$$|\Psi_{\text{BS}}\rangle = \mathcal{N}(|e\rangle + g|\psi_{\text{BS}}\rangle) \quad \text{with} \quad H|\Psi\rangle = \omega_{\text{BS}}|\Psi\rangle$$

normalization factor

in fact: $|\psi\rangle$ spatially localized state

example 1: BS in cavity-QED

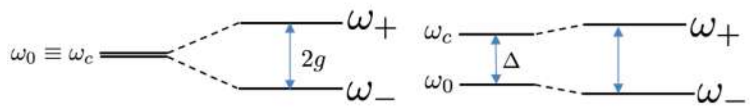


JC dressed states:

$$|\Psi_+\rangle = \sin\tfrac{\theta}{2}|e\rangle + \cos\tfrac{\theta}{2}|v\rangle\,,\quad |\Psi_-\rangle = \cos\tfrac{\theta}{2}|e\rangle - \sin\tfrac{\theta}{2}|v\rangle$$

$\tan\theta = -\frac{2g}{\Delta}$

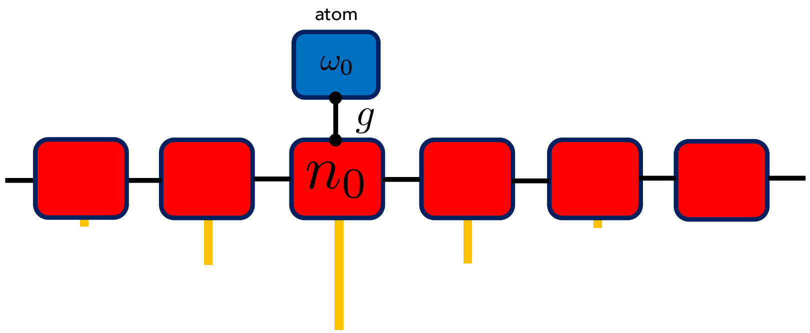
$$\omega_{\text{BS},\pm} = \omega_c + \tfrac{\Delta}{2} \pm \sqrt{g^2 + \left(\tfrac{\Delta}{2}\right)^2}$$



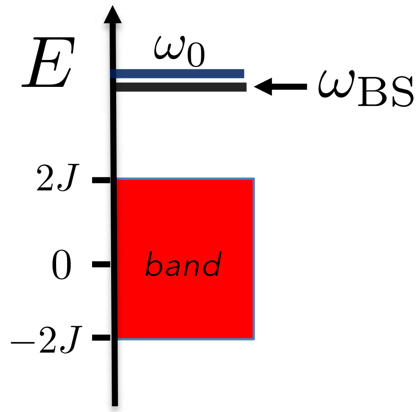
zero detuning — dispersive regime

$\Delta \gg g$

example 2: BS in a coupled-cavity array



single-photon localized states ψ



$$g \neq 0 \qquad |\Psi_{\rm BS}\rangle = \mathcal{N}\left(|e\rangle + g|\psi_{\rm BS}\rangle\right)$$

$$\psi_{\rm BS}(n) = \frac{(-1)^{|n-n_0|}}{2\sqrt{J\delta}} e^{-\frac{|n-n_0|}{\lambda}}$$

exponential shape

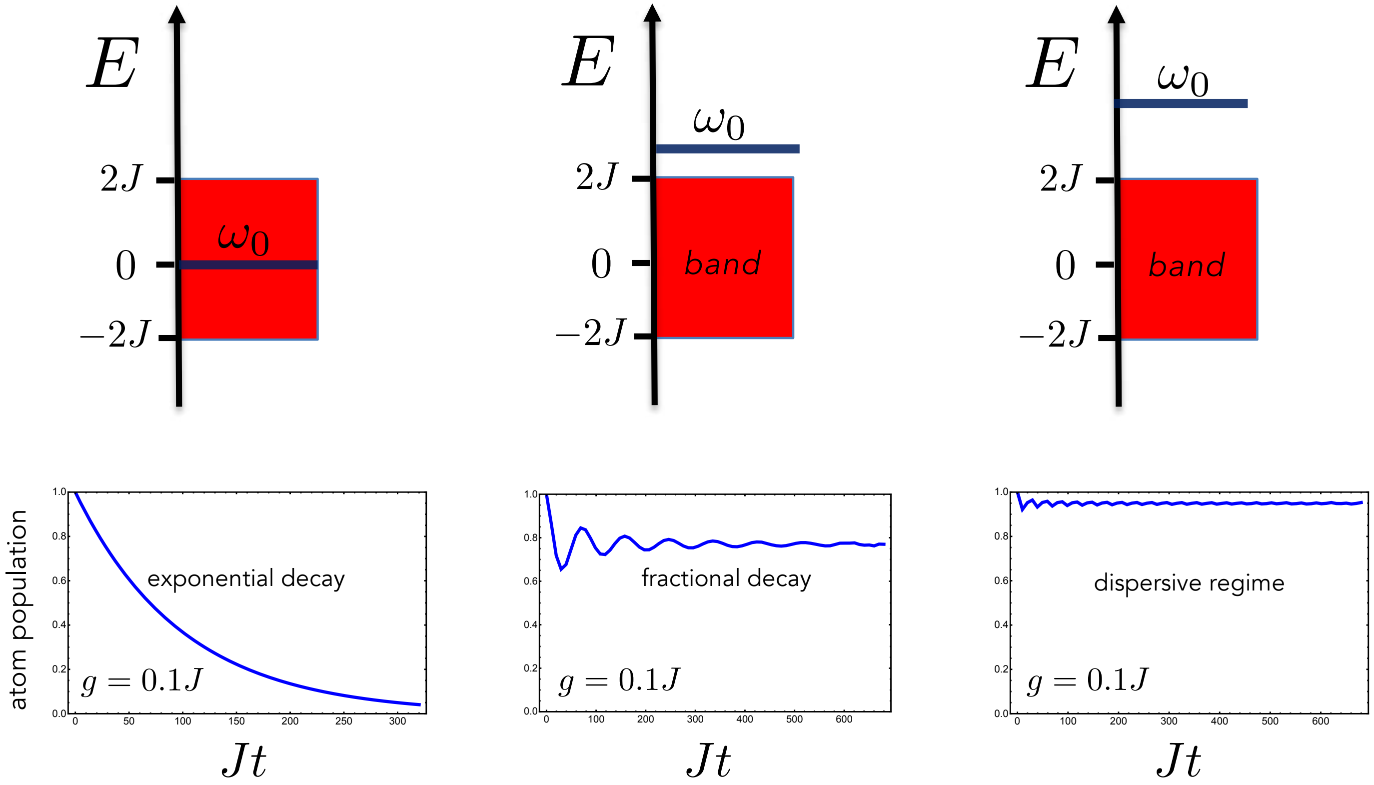
$$\lambda = \sqrt{\frac{J}{\Delta}}$$

localization length

..recall:

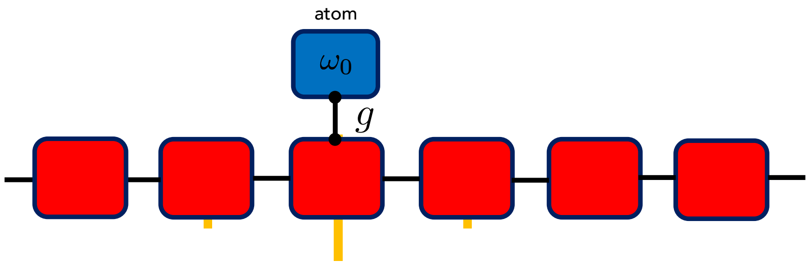
$$K_{ij} \propto \frac{g^2}{\sqrt{J\Delta}} e^{-\frac{|i-j|}{\lambda}}$$

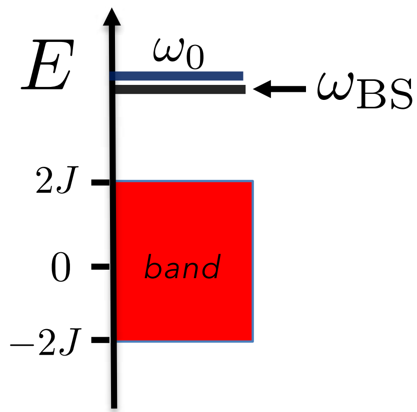
connection to fractional decay



no BS!

weak-coupling BS





very small g :
$$|\Psi_{\rm BS}\rangle \simeq |e\rangle + g\,|\psi_{\rm BS}\rangle$$
$$\omega_{\rm BS} \simeq \omega_0$$
(to the lowest non-trivial order)

general property (provided that BS exists)

decoherence-free Hamiltonian & BS

set of atoms coupled to a photonic bath:

$$H = \omega_0 \sum_j \sigma_{j+}\sigma_{j-} + H_B + g \sum_j (\sigma_- b^\dagger_{x_j} + \mathrm{H.c.})$$

with $H_B = \sum_x \omega_x b^\dagger_x b_x + \sum_{x \neq x'} J_{xx'} b^\dagger_x b_{x'}$

master equation in the Markovian regime:

$$\dot{\rho} = -i[H_{\mathrm{eff}}, \rho] + \mathcal{D}[\rho]$$

$$H_{\mathrm{eff}} = \sum_{j,j'} (\omega_0 \delta_{jj'} + \mathcal{K}_{jj'}) \sigma_{j+}\sigma_{j'-}$$

$$\mathcal{D}[\rho] = \sum_{j,j'} \gamma_{jj'} \left[\sigma_{j'-}\rho\sigma_{j+} - \frac{1}{2} \{\rho, \sigma_{j+}\sigma_{j'-}\} \right]$$

$$\mathcal{K}_{jj'} = g^2 \frac{\langle x_j|G_B(\omega_0^+)|x_{j'}\rangle + \langle x_{j'}|G_B(\omega_0^+)|x_j\rangle^*}{2}$$

$$\gamma_{jj'} = i g^2 \left(\langle x_j|G_B(\omega_0^+)|\chi_{j'}\rangle - \langle \chi_{j'}|G_B(\omega_0^+)|\chi_j\rangle^* \right)$$

Theorem

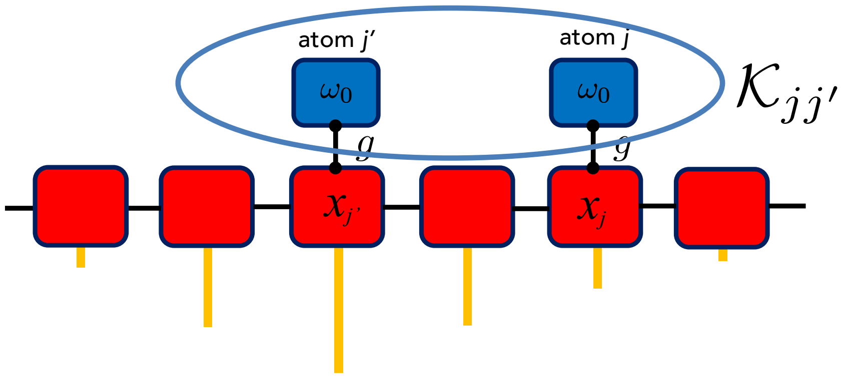
$$\gamma_{jj'} = 0 \Longleftrightarrow$$ there exists a weak-coupling BS for each atom

$$|\Psi^j_{\mathrm{BS}}\rangle = |e_j\rangle + g|\psi^j_{\mathrm{BS}}\rangle$$

decoherence-free evolution

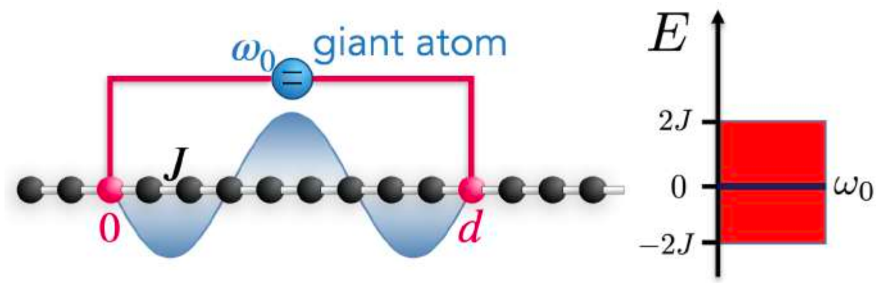
$\dot{\rho} = -i[H_{\mathrm{eff}}, \rho]$ with $\mathcal{K}_{jj'} = g^2 \langle x_j|\psi^{j'}_{\mathrm{BS}}\rangle$

L. Leonforte, X. Sun, D. Valenti, B. Spagnolo, F. Illuminati, A. Carollo, F. Ciccarello, Quantum Sci. Technol. 10, 015057 (2025)



single-photon localized states $\psi^{j'}$

giant atoms

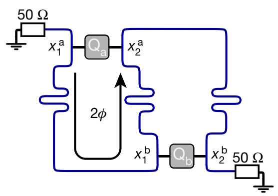


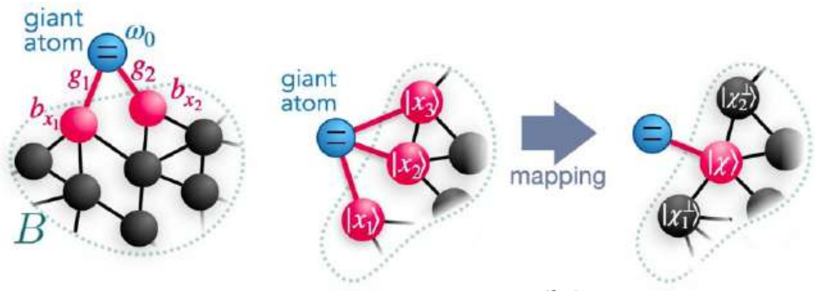
BS in the continuum!

many giant atoms:
decoherence-free Hamiltonian in the continuum

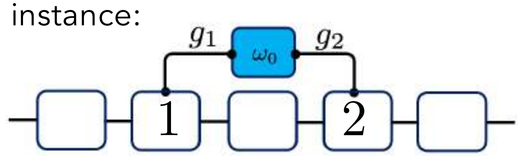
Kockum, Johansson, Nori, PRL 2018 (theory)

Kannan et al, Nature 2020
(MIT experiment)





instance:



$$g_1 = g_2 = g$$
$$|\chi\rangle = \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle)$$

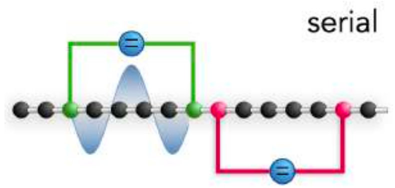
previous theory can be generalized:

$$\gamma_{jj'} = 0 \quad \Longleftrightarrow$$ there exists a weak-coupling BS for each atom

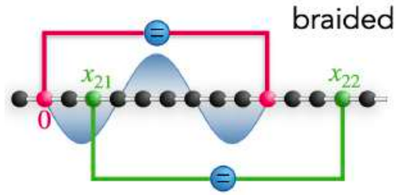
$$\dot{\rho} = -i[H_{\text{eff}}, \rho] \quad \text{with} \quad \mathcal{K}_{jj'} = g^2 \langle \chi_j | \psi_{\text{BS}}^{j'} \rangle$$

L. Leonforte, X. Sun, D. Valenti, B. Spagnolo, F. Illuminati,
A. Carollo, F. Ciccarello, Quantum Sci. Technol. 10, 015057 (2025)

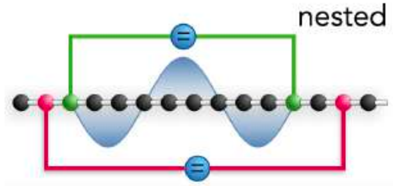
giant atoms



$\langle \chi_1 | \psi_{\mathrm{BS}}^2 \rangle = 0 \quad H_{\mathrm{eff}} = 0$



$\langle \chi_1 | \psi_{\mathrm{BS}}^2 \rangle \neq 0 \quad H_{\mathrm{eff}} \neq 0$



$\langle \chi_1 | \psi_{\mathrm{BS}}^2 \rangle = 0 \quad H_{\mathrm{eff}} = 0$

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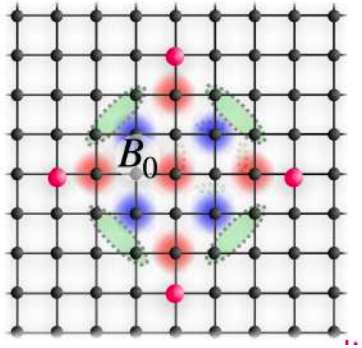
A. Carollo, F. Ciccarello, Quantum Sci. Technol. 10, 015057 (2025)

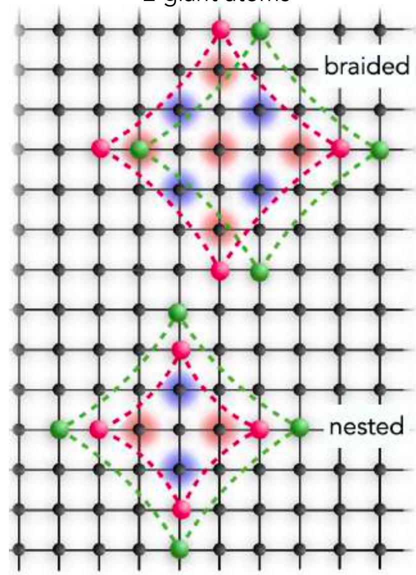
2D example:

1 giant with 4 coupling points



BS in the continuum

2 giant atoms



braided: $H_{\mathrm{eff}} \neq 0$

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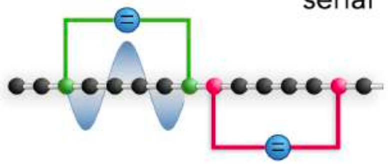
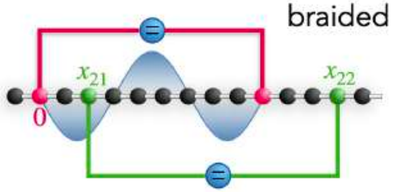
giant atoms

serial



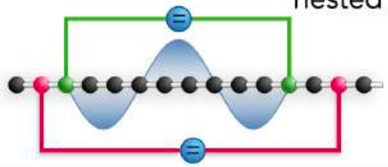
$\langle \chi_1 | \psi^2_{\mathrm{BS}} \rangle = 0 \quad H_{\mathrm{eff}} = 0$

braided



$\langle \chi_1 | \psi^2_{\mathrm{BS}} \rangle \neq 0 \quad H_{\mathrm{eff}} \neq 0$

nested

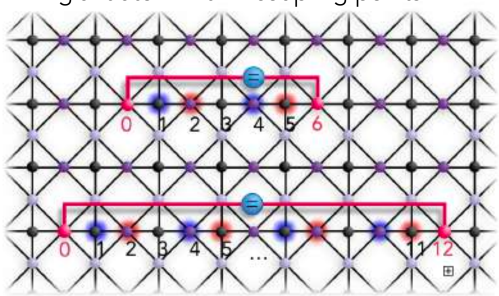


$\langle \chi_1 | \psi^2_{\mathrm{BS}} \rangle = 0 \quad H_{\mathrm{eff}} = 0$

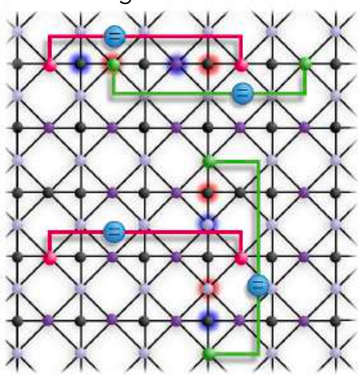
L. Leonforte, X. Sun, D. Valenti, B. Spagnolo, F. Illuminati,
A. Carollo, F. Ciccarello, Quantum Sci. Technol. 10, 015057 (2025)

2D example:

giant atom with 2 coupling points



2 giant atoms



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A. Carollo, F. Ciccarello, Quantum Sci. Technol. 10, 015057 (2025)

general criterion to find (giant) atom BSs based on «vacancy-like dressed states»:

Leonforte, Carollo, Ciccarello, PRL 2021

collaborators

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Peter Rabl
(TU Munich)

Dominik Schneble
(Stonybrook)

F Ciccarello, P Lodahl, D Schneble
"Waveguide QED", Optics and Photonics News 2024

take-home messages

- an atom coupled to a photonic bath can form BSs
- BSs can mediate decoherence-free Hamiltonians (under weak coupling)
- any decoherence-free open dynamics occurs because atoms form BSs
- if so, when BSs overlap atom sites a non-zero decoherence-free interaction (DFI) occurs
- a giant atom can seed BSs and DFIs unattainable with normal atoms, in particular BSs in the continuum and in 2D