Giant Atoms --- a new frontier in quantum optics

Franco Nori

RIKEN, Saitama, and University of Michigan, Ann Arbor

Krantz NanoArt

Quantum optics with giant atoms

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Brief Summary

In quantum optics, **atoms are usually approximated as point-like**, compared to the wavelength of the light they interact with.

However, recent advances in experiments with **artificial atoms built from superconducting circuits** have shown that this assumption can be violated [1, 2, 3].

[1] M. V. Gustafsson et al., Science 346, 207 (2014)
[2] B. Kannan et al., Nature 583, 775 (2020)
[3] A. M. Vadiraj et al., Physical Review A 103, 023710 (2021)

Instead, **these artificial atoms can couple to an electromagnetic field in a waveguide *at multiple points*,** **which are spaced (several or many) wavelength distances apart.**

Such systems are called **giant atoms**.

They have attracted increasing interest in the past few years (e.g., see the review in [4]).

[4] A. F. Kockum, in arXiv:1912.13012 ← **Excellent review, by a leader in this field**

In particular, **the interference effects due to the multiple coupling points allow giant atoms to** **interact with each other** **through the waveguide** ***without losing energy into the waveguide*** [5, 2].

I will briefly review some of these developments. We have also shown how a **giant atom coupled to a waveguide with varying impedance can give rise to chiral bound states** [6].

[5] A. F. Kockum, G. Johansson, F. Nori, Physical Review Letters 120, 140404 (2018).
The experiment verifying our prediction is in: B. Kannan et al., Nature 583, 775 (2020)

[6] X. Wang et al., Physical Review Letters 126, 043602 (2021)

The main message has been summarized.

Why? Because most people fall asleep after the first few slides.

Outline

- Introduction — atom sizes and their history
- One giant atom — frequency-dependent relaxation rate
- Multiple giant atoms — decoherence-free interaction
- Chiral quantum optics and giant atoms
- Chiral bound states
- Summary and outlook

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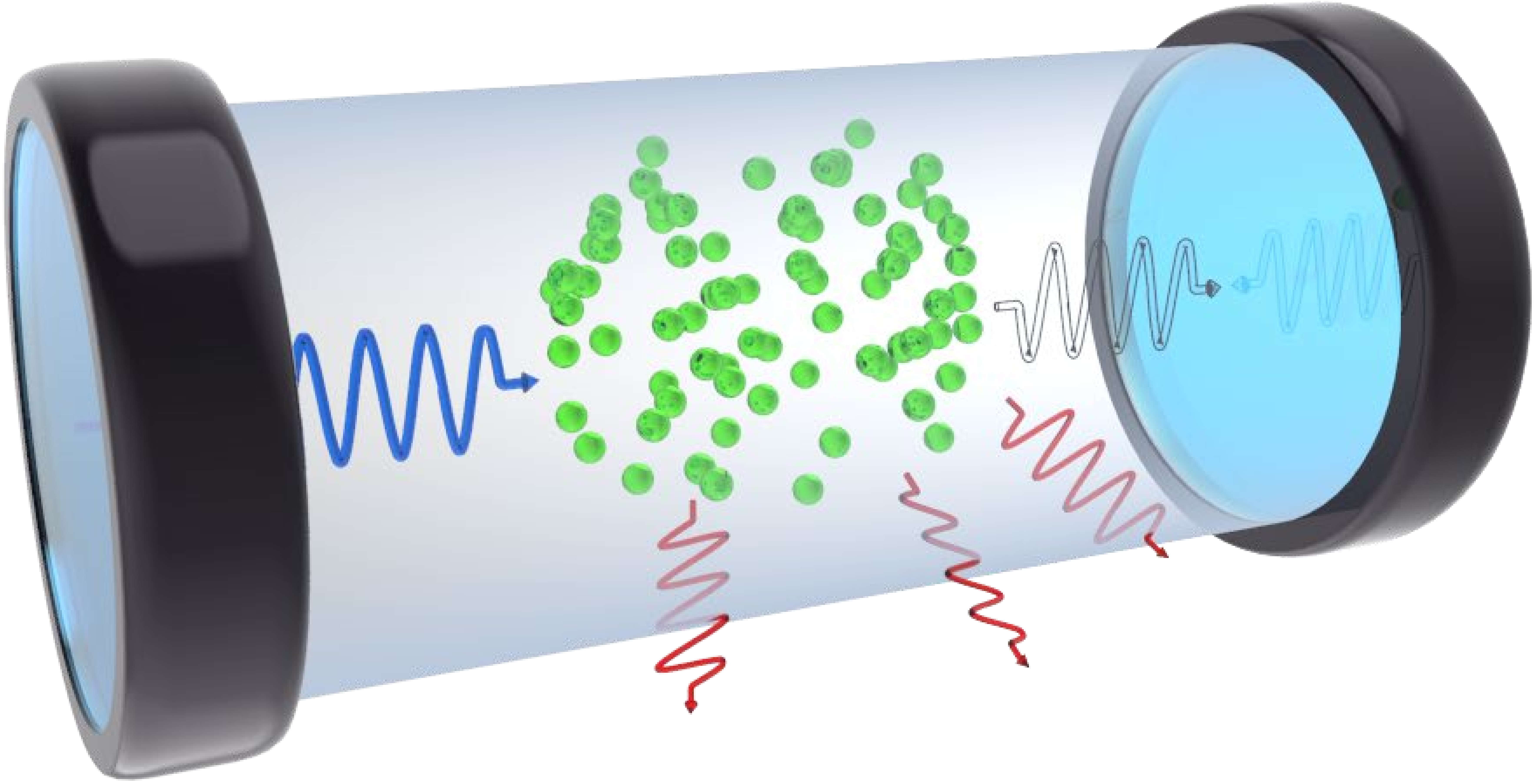
Quantum optics

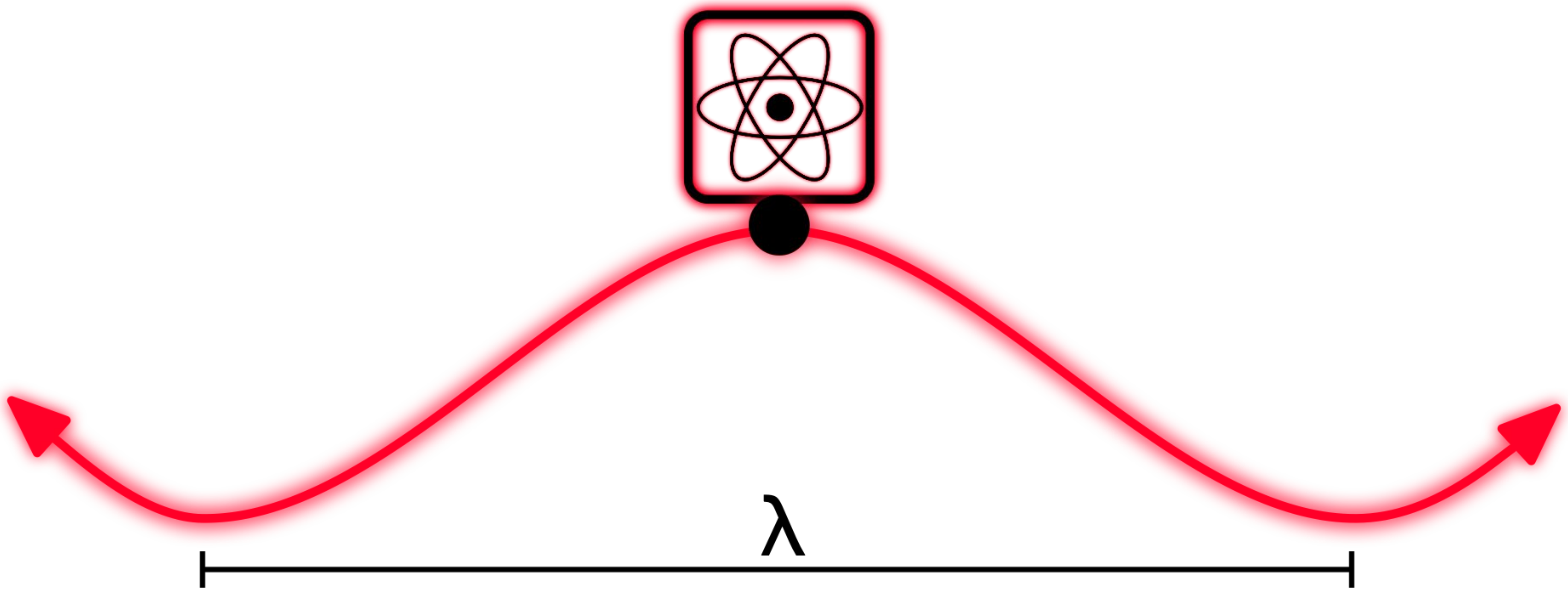


Interaction between light and matter at the level of photons and atoms

Is everything already solved?

Or are things just starting to get interesting?

Small atoms

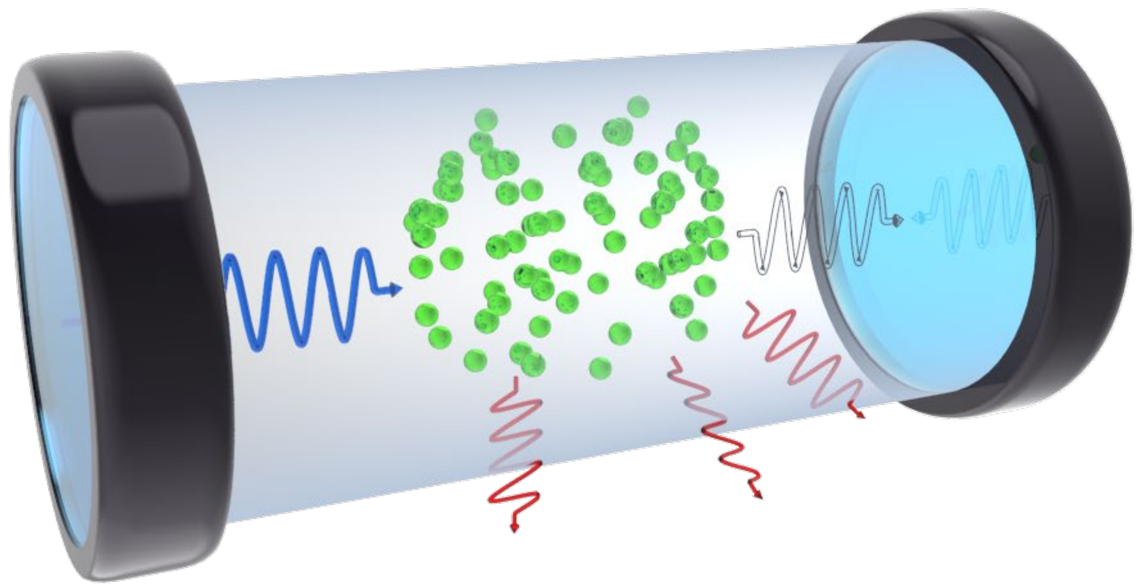


The size of an atom is usually small compared to the wavelength of the light it interacts with

Dipole approximation: Assuming the atom as point-like, neglecting spatial variations in the electromagnetic field

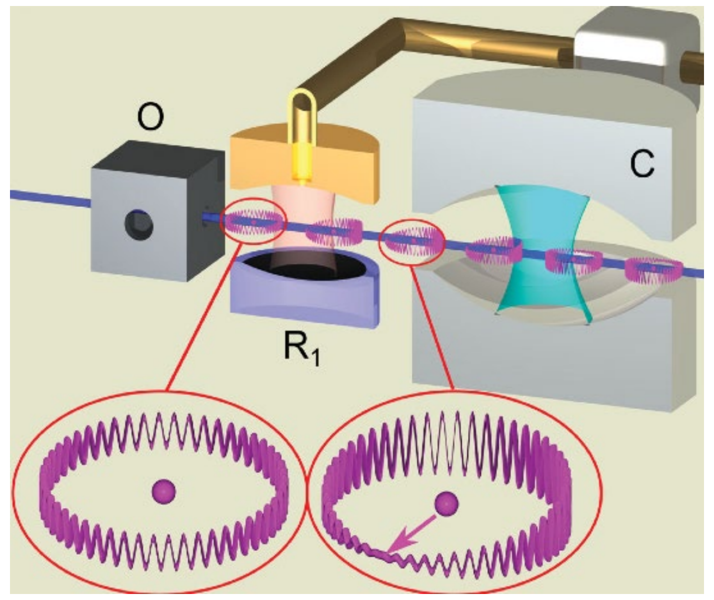
Small atoms

Atoms, optical light



$$r \approx 10^{-10}\,\mathrm{m}$$
$$\lambda \approx 10^{-7} - 10^{-6}\,\mathrm{m}$$
$$r/\lambda \approx 10^{-4} - 10^{-3}$$

Rydberg atoms, microwaves



Haroche, Nobel Lecture, Rev. Mod. Phys. **85**, 1083 (2013)

$$r \approx 10^{-8} - 10^{-7}\,\mathrm{m}$$
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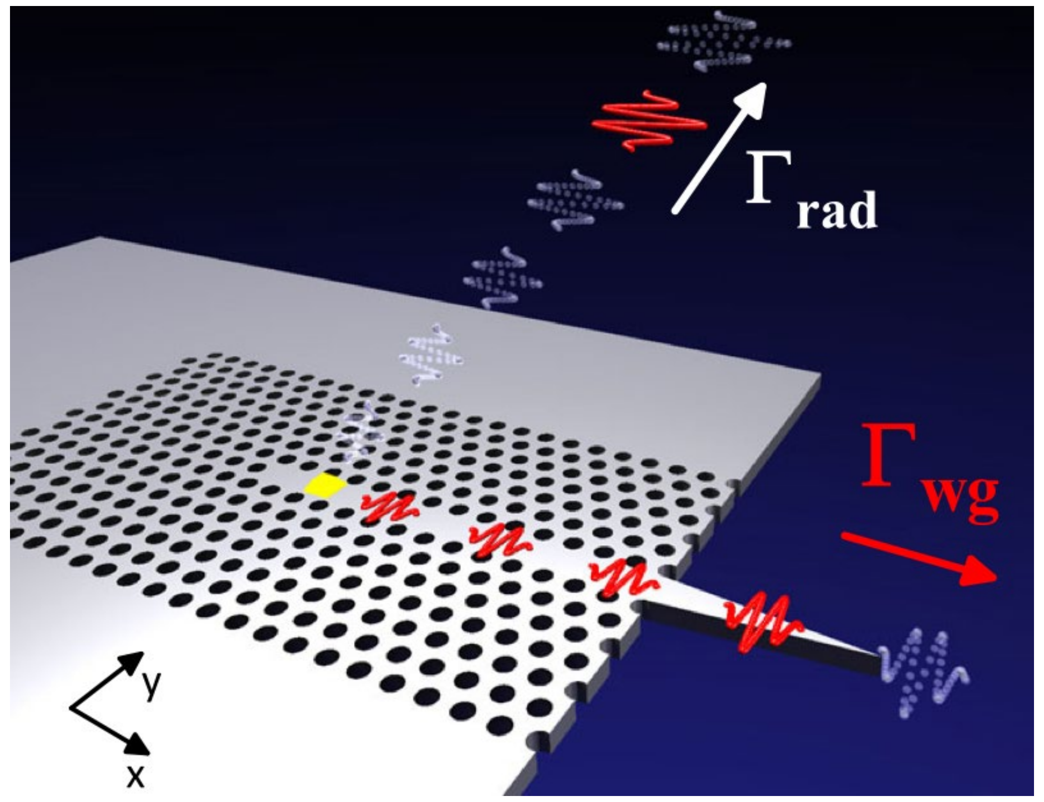
Quantum dots, photonic-crystal waveguide



Arcari et al., Phys. Rev. Lett **113**, 093603 (2014)

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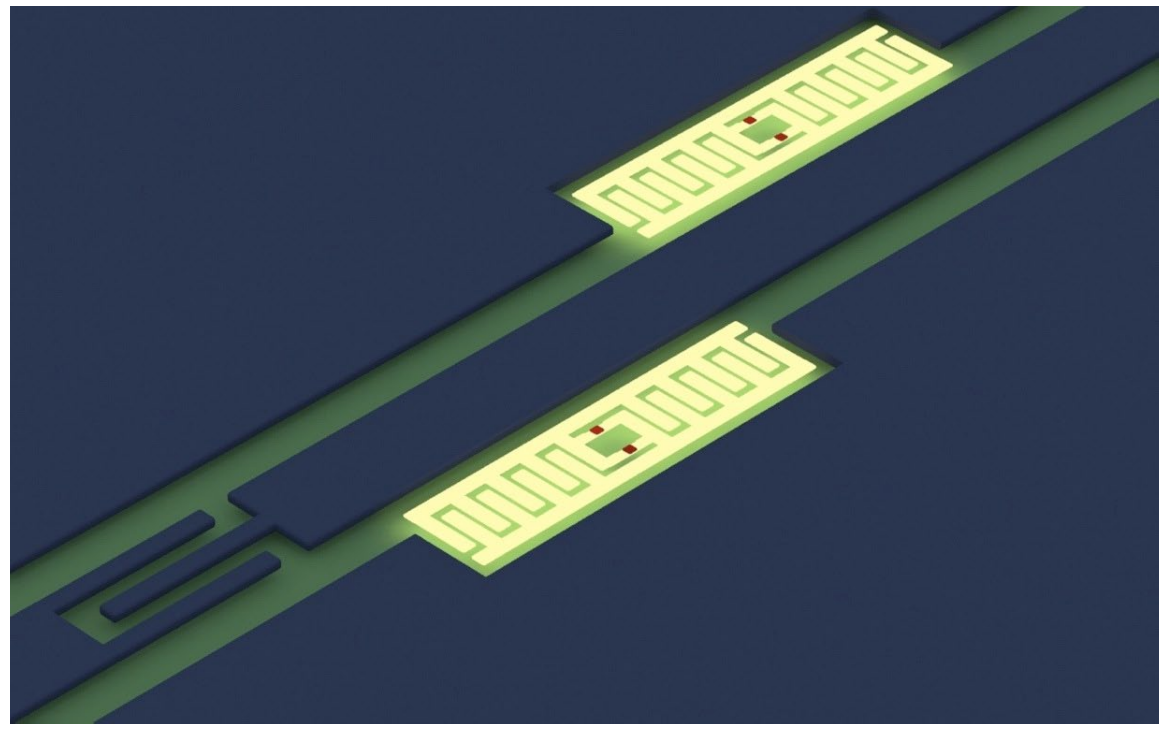
Superconducting qubits, microwaves



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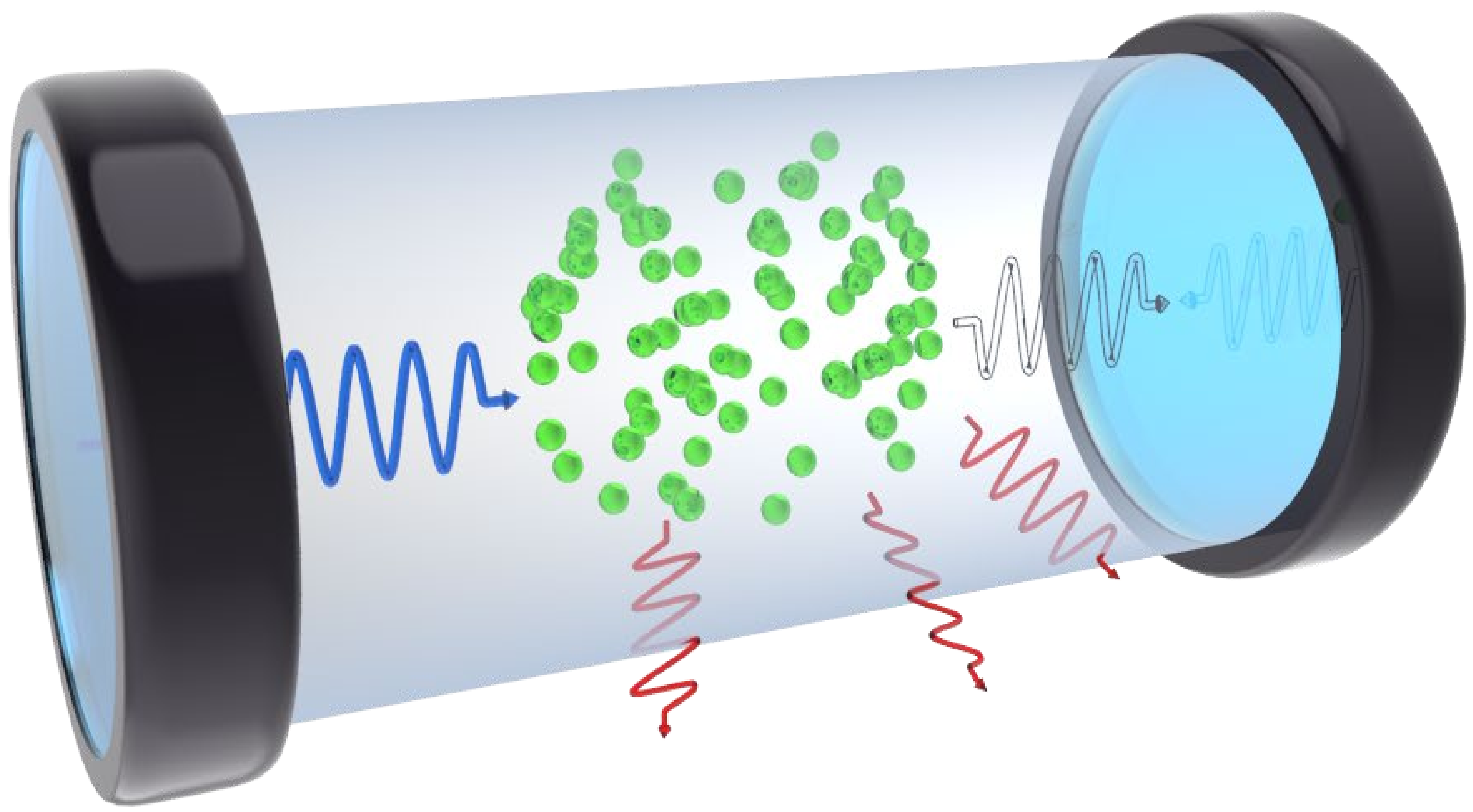
$$l \approx 10^{-5} - 10^{-3}\,\mathrm{m}$$
$$\lambda \approx 10^{-3} - 10^{-1}\,\mathrm{m}$$
$$l/\lambda \approx 10^{-4} - 1$$

Small atoms

Atoms, optical light



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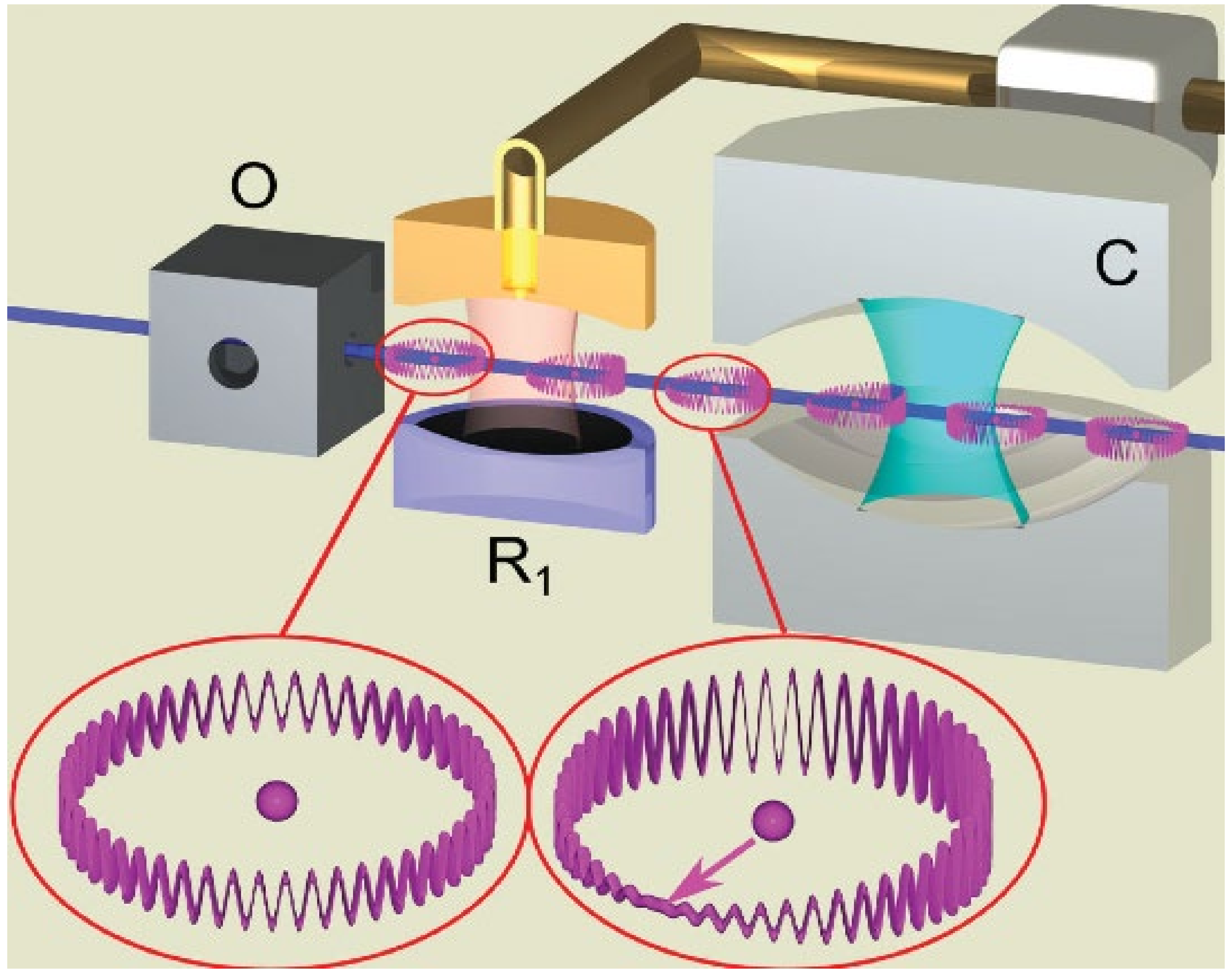

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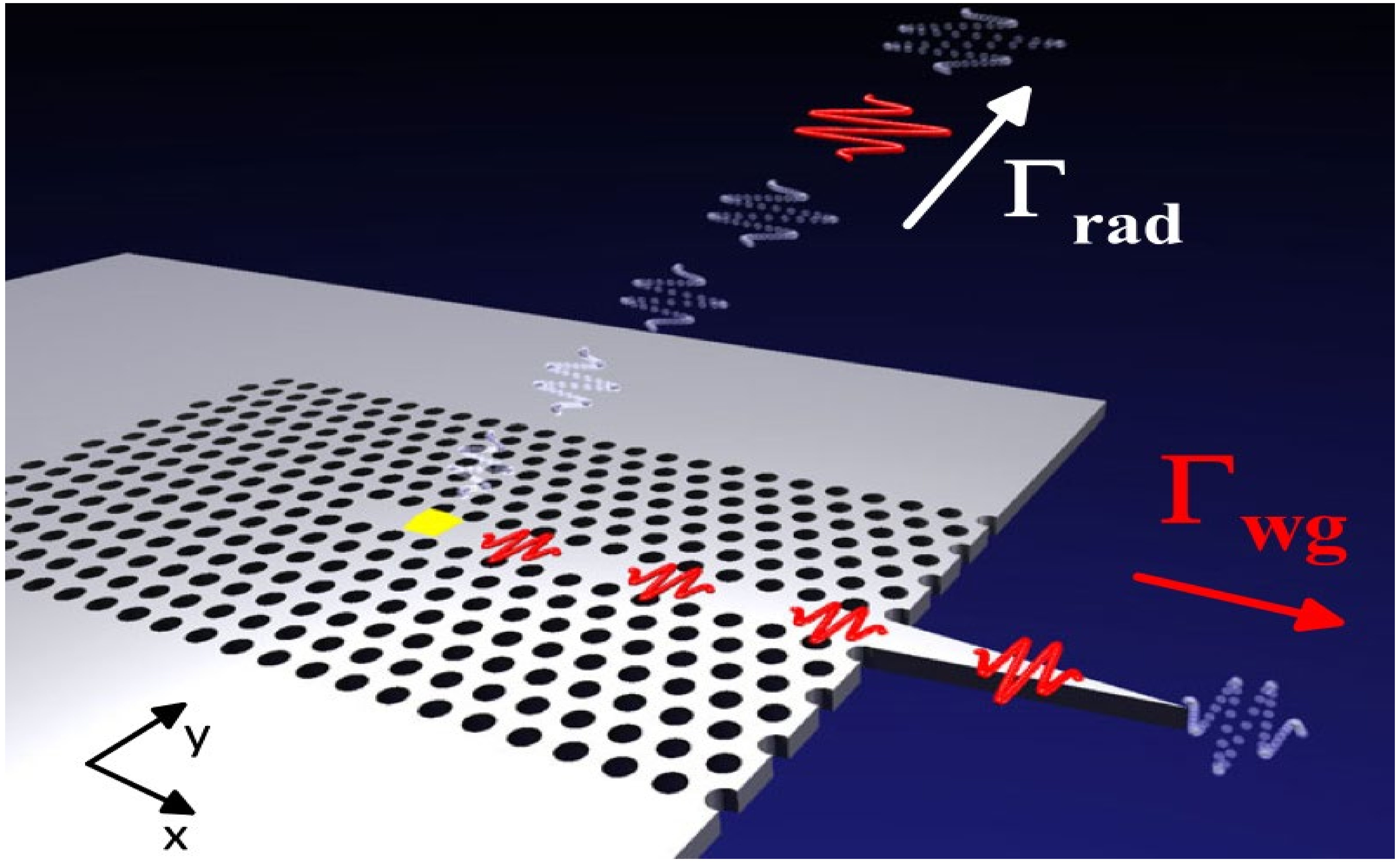

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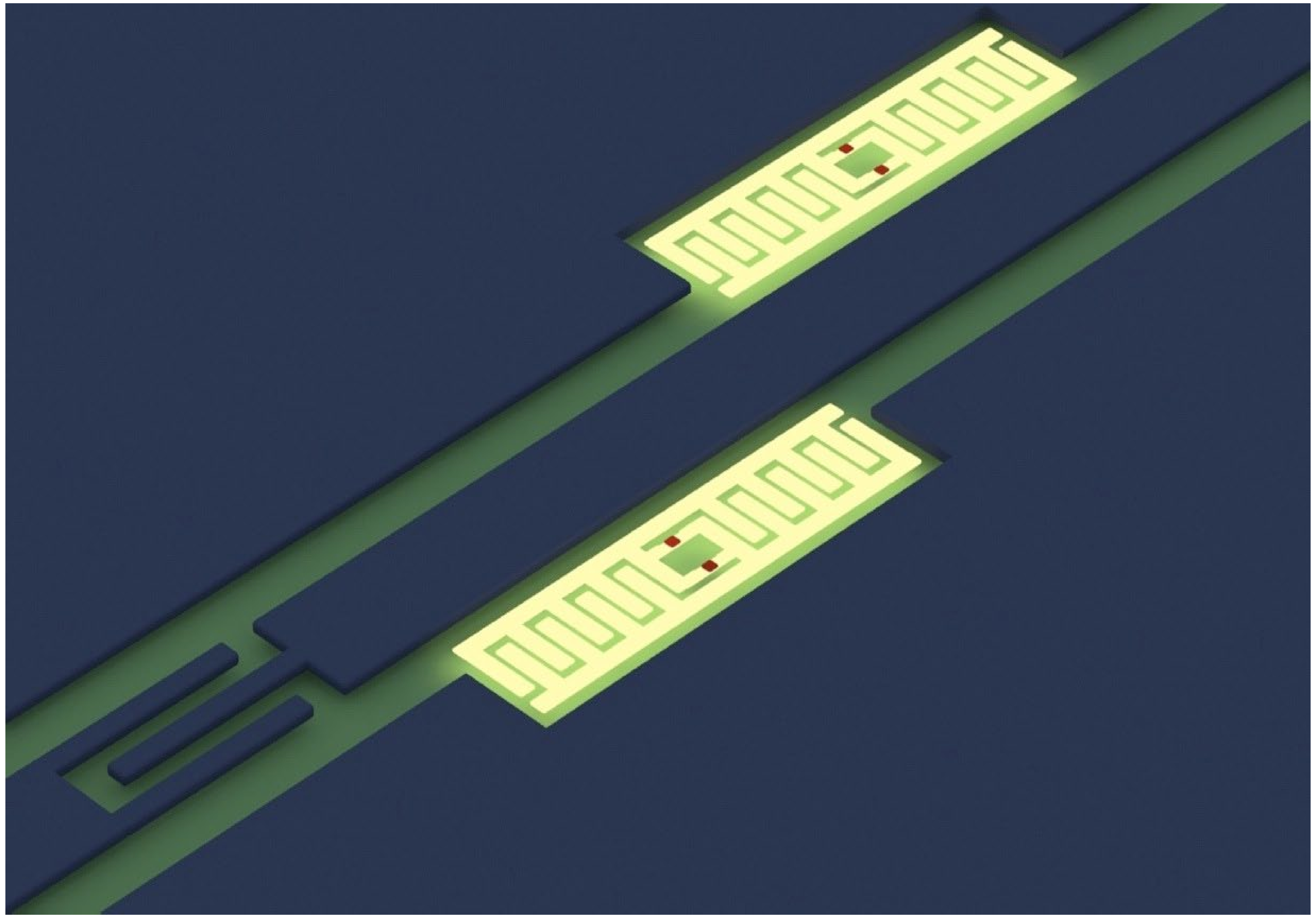

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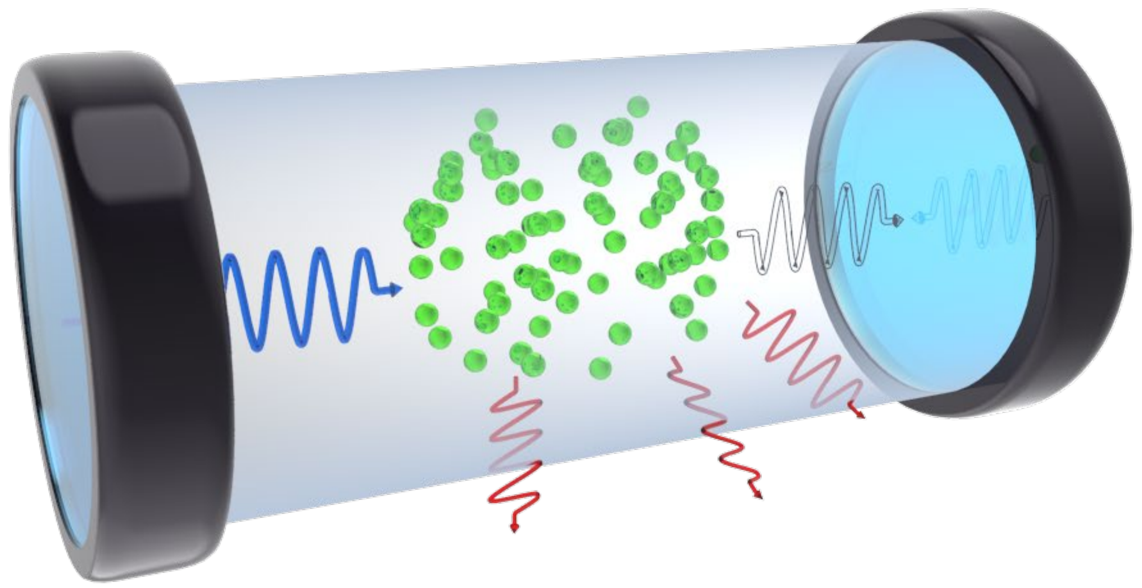
Small atoms

Atoms, optical light



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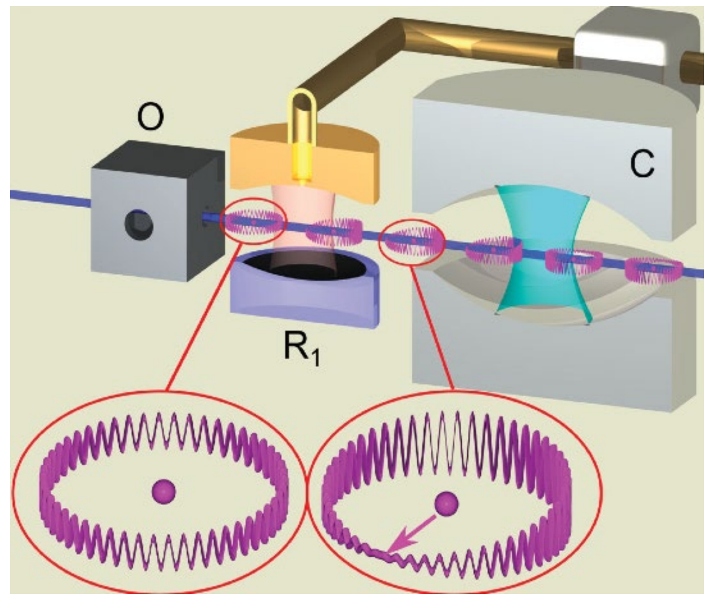

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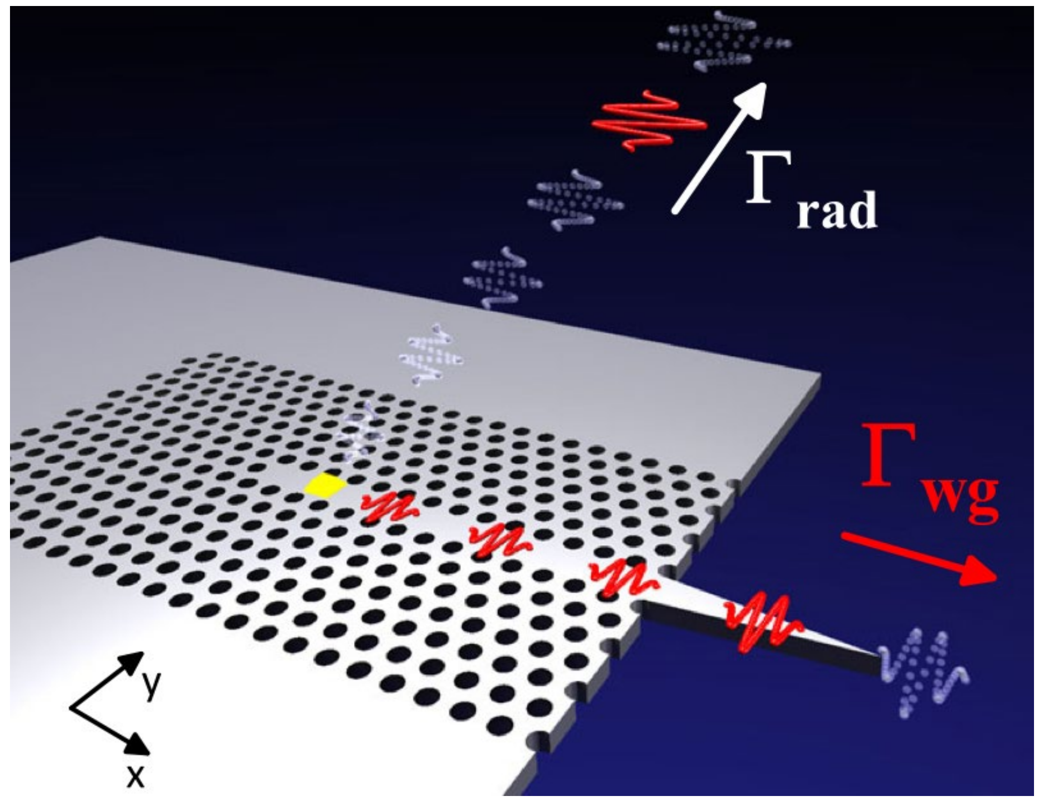

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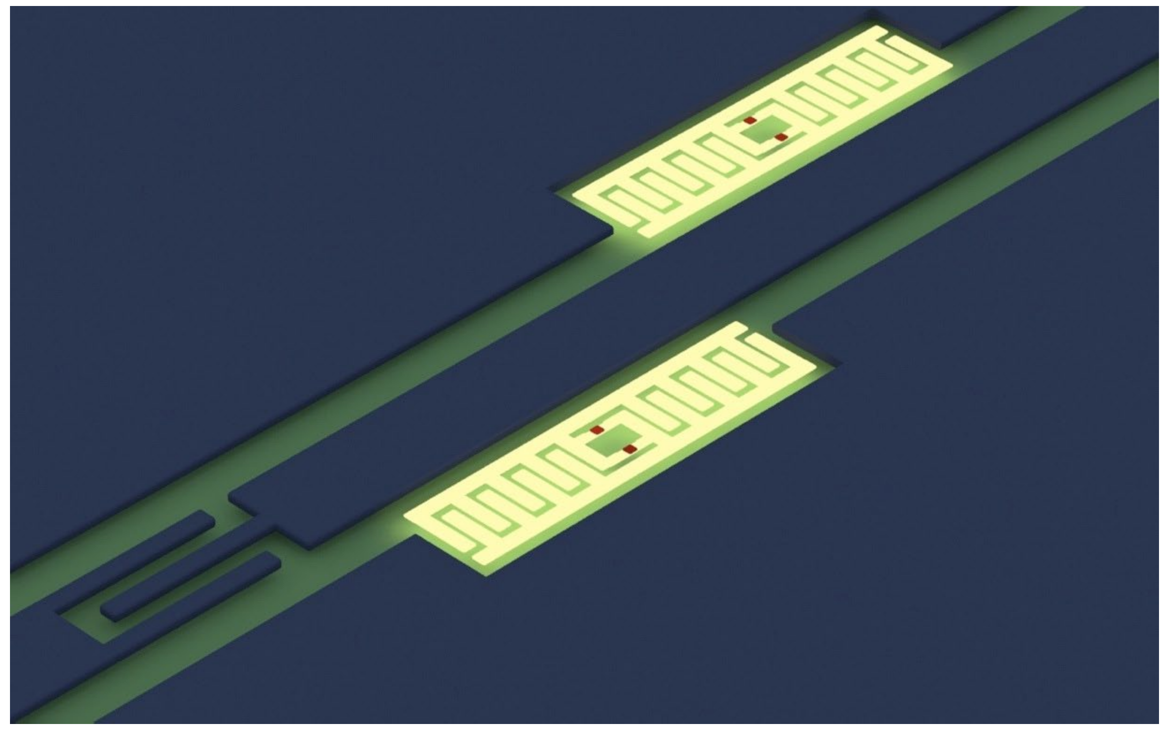

Krantz NanoArt

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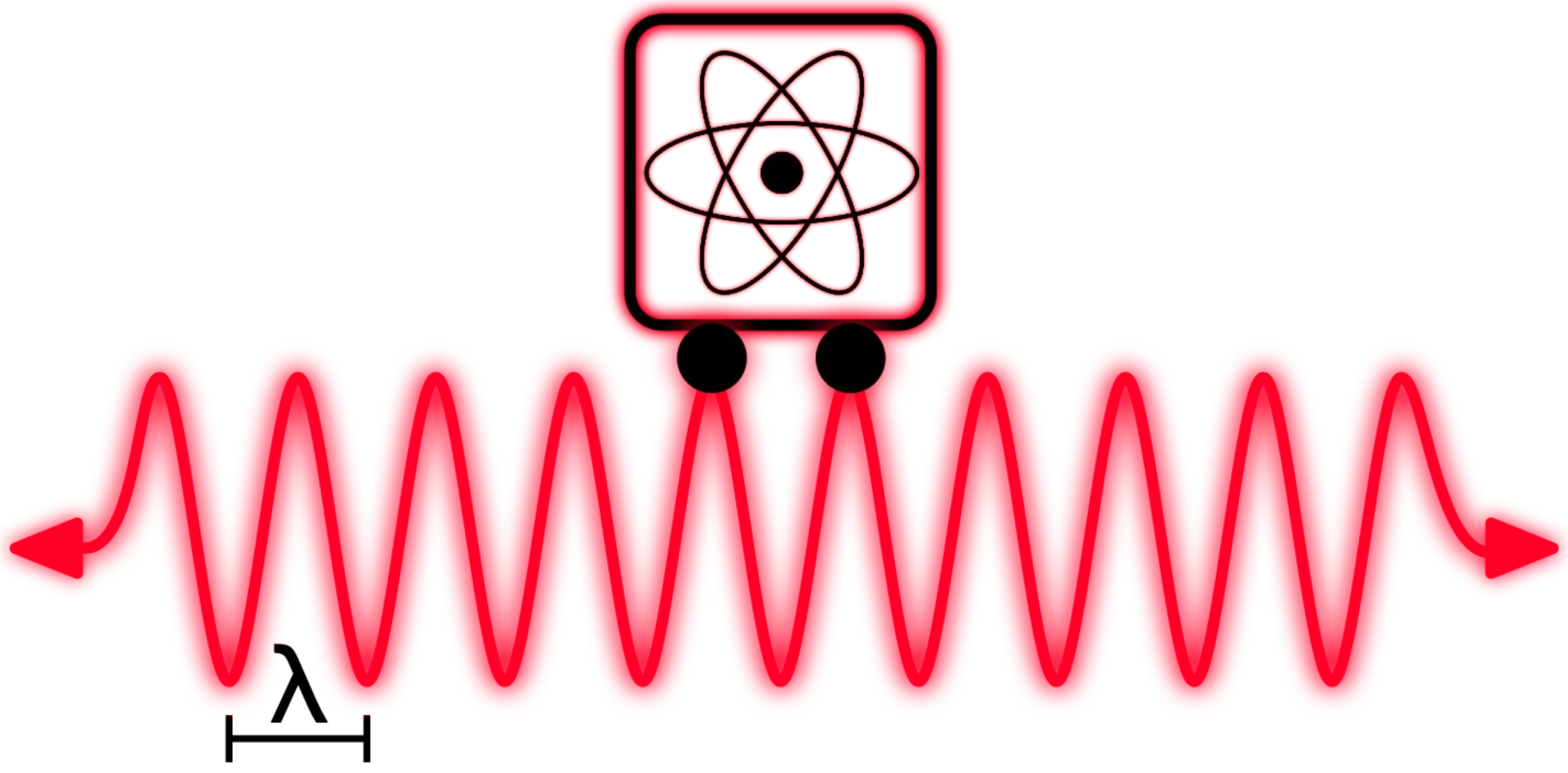
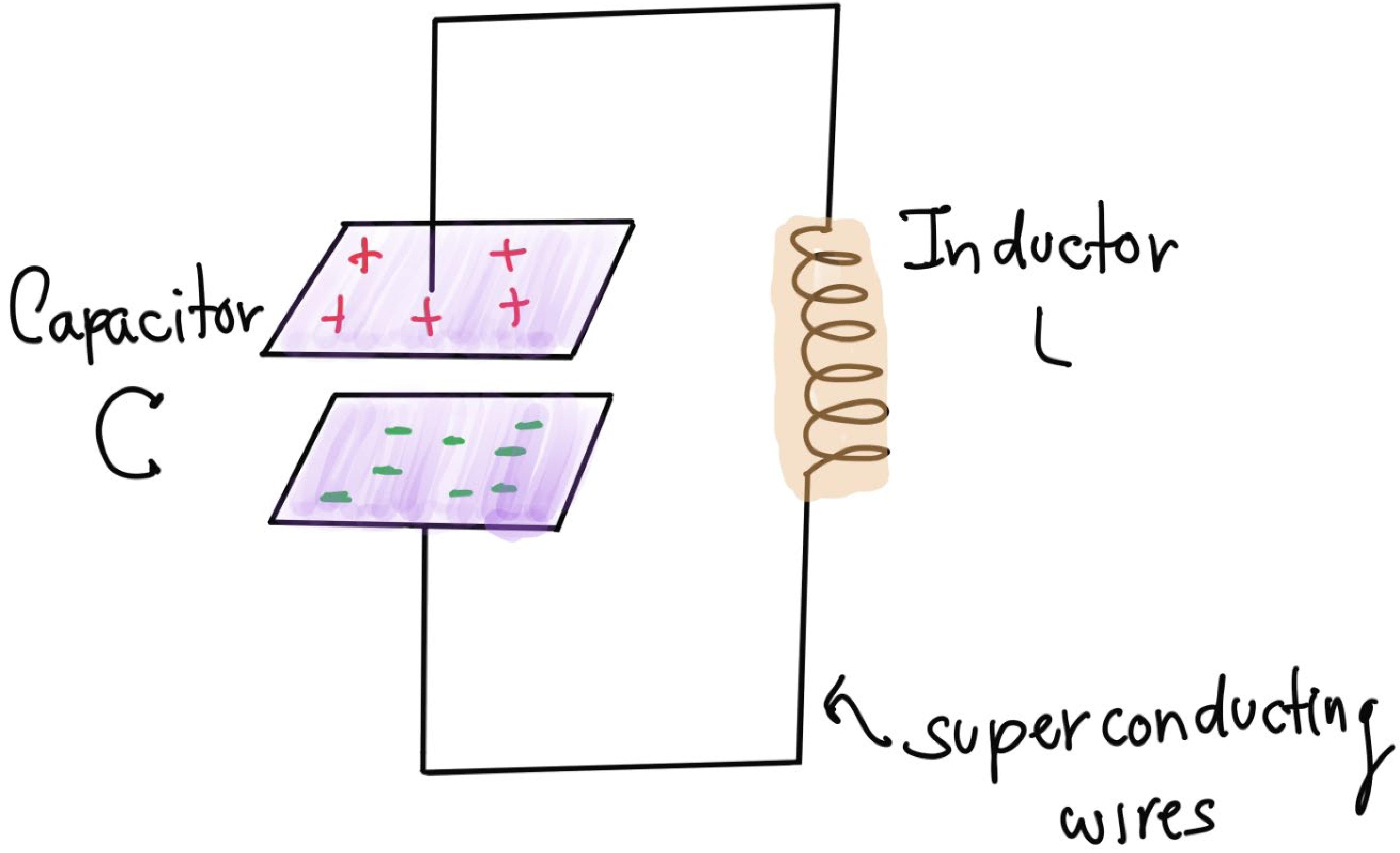
Giant atoms



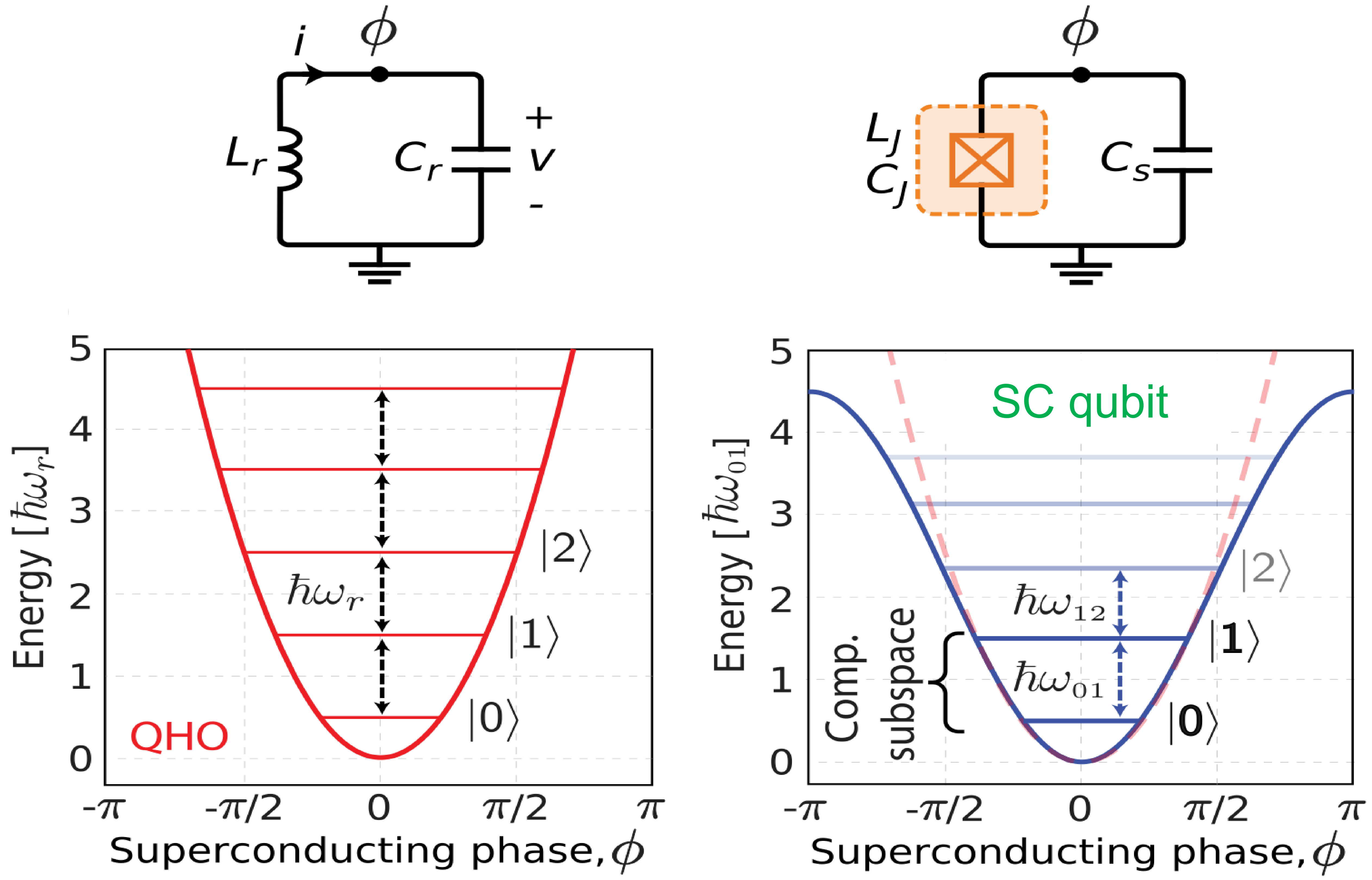
Atoms coupling to the electromagnetic field at multiple points, which can be wavelengths apart

Quantum Harmonic Oscillator (QHO):
Equally spaced energy levels.



Superconducting qubit as a large (but not giant) atom

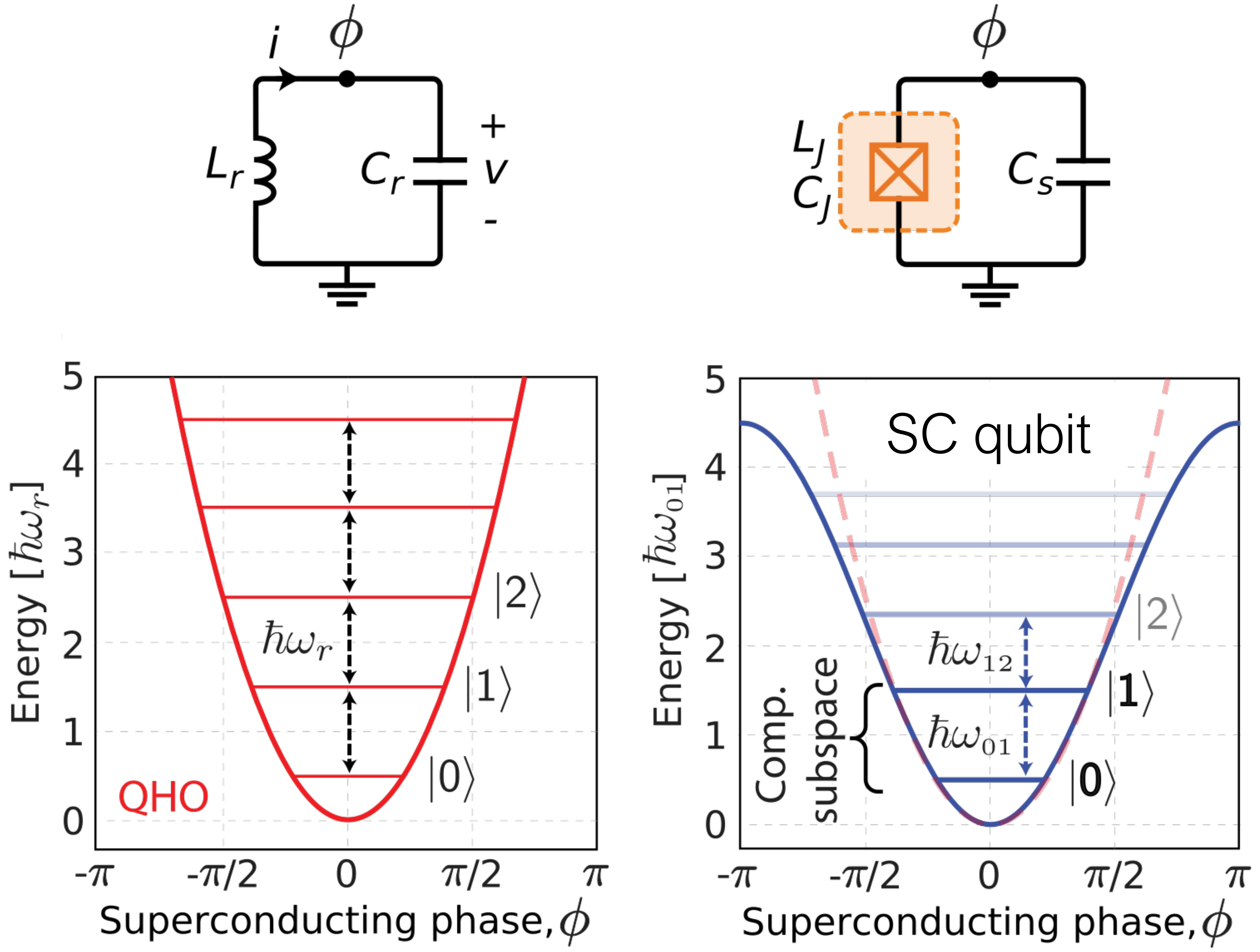
Quantum Harmonic Oscillator (QHO): Equally spaced energy levels.



Krantz et al., Appl. Phys. Rev. **6**, 021318 (2019)

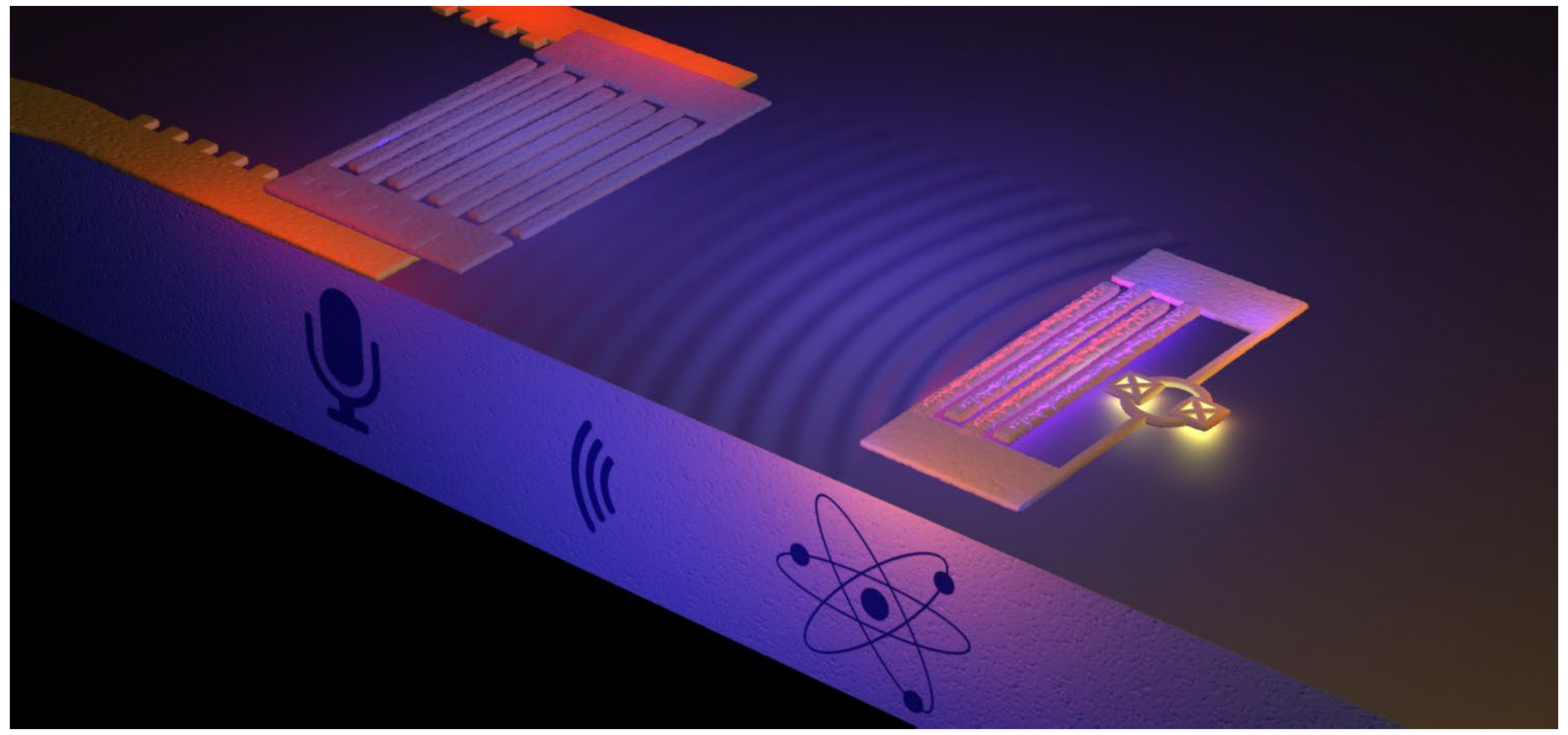
Superconducting qubits: ***LC*** **oscillators made anharmonic by the nonlinearity of Josephson junctions**

The first giant atom



Krantz et al., Appl. Phys. Rev. **6**, 021318 (2019)

Superconducting qubits: *LC* oscillators made anharmonic by the nonlinearity of Josephson junctions



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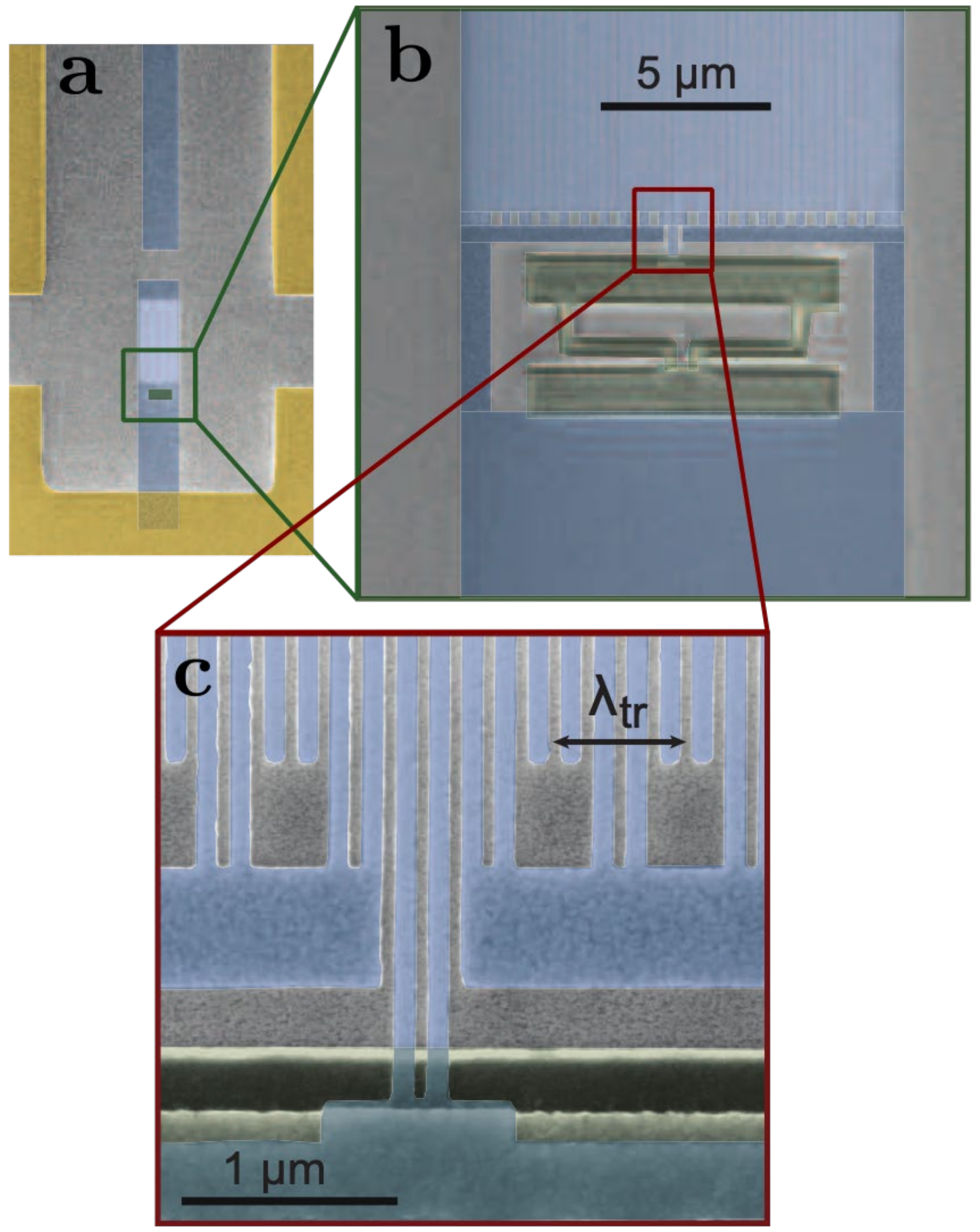


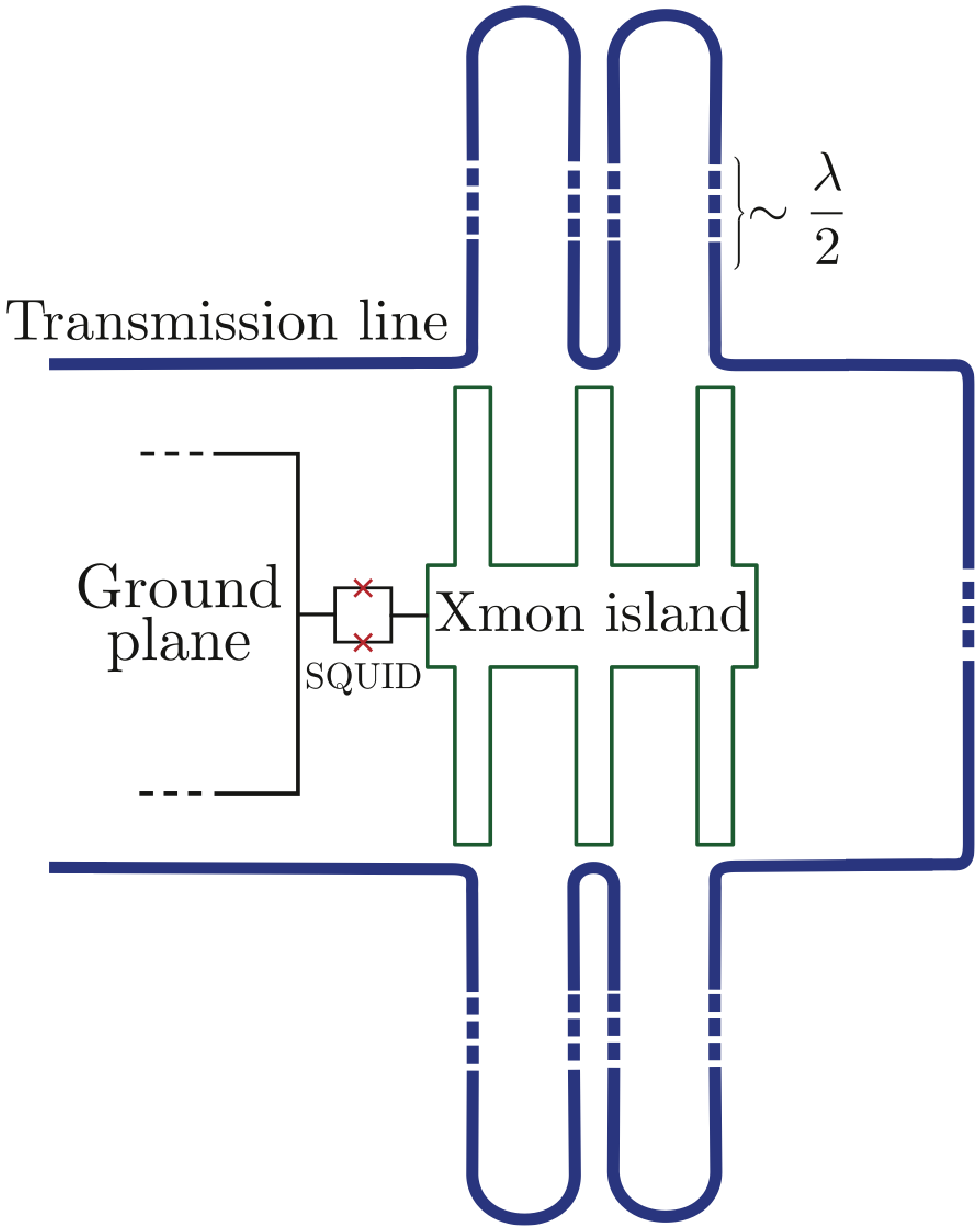
Coupling a superconducting qubit to surface acoustic waves through an interdigitated transducer (IDT)

$$l \approx 10^{-5} - 10^{-4}\,\mathrm{m}$$
$$\lambda \approx 10^{-6} - 10^{-5}\,\mathrm{m}$$
$$l/\lambda \approx 1 - 100$$

Gustafsson et al., Science **346**, 207 (2014)

More giant atoms

Superconducting qubits and microwaves
(meandering transmission line)

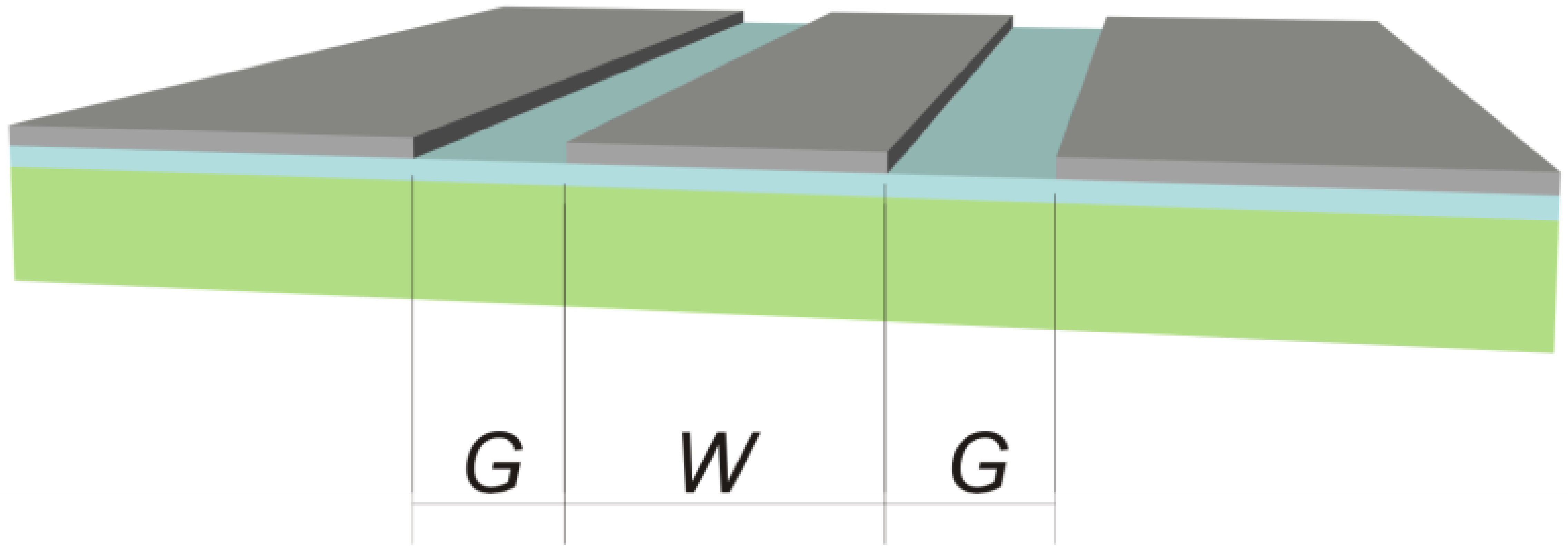


Kockum et al., Phys. Rev. A **90**, 013837 (2014)
Kannan et al., Nature **583**, 775 (2020)
Vadiraj et al., arXiv:2003.14167 (2020)

Coplanar Waveguide

- Superconducting **CoPlanar Waveguide (CPW)** **confines microwaves to the chip,** **creating a ~ 1D Electromagnetic environment.**

- CPW has a center conductor and 2 ground planes, like a cross-section of a coaxial cable.



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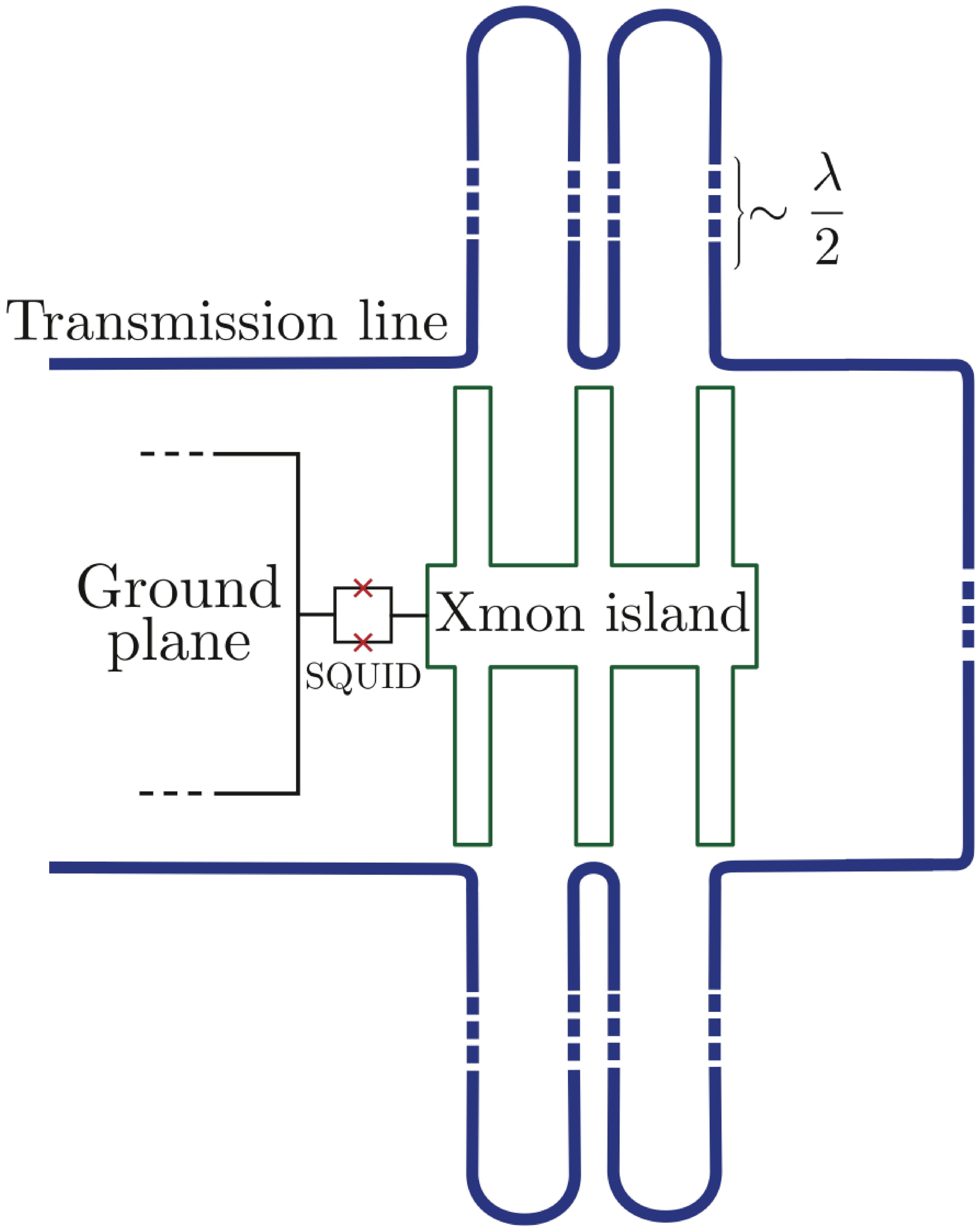
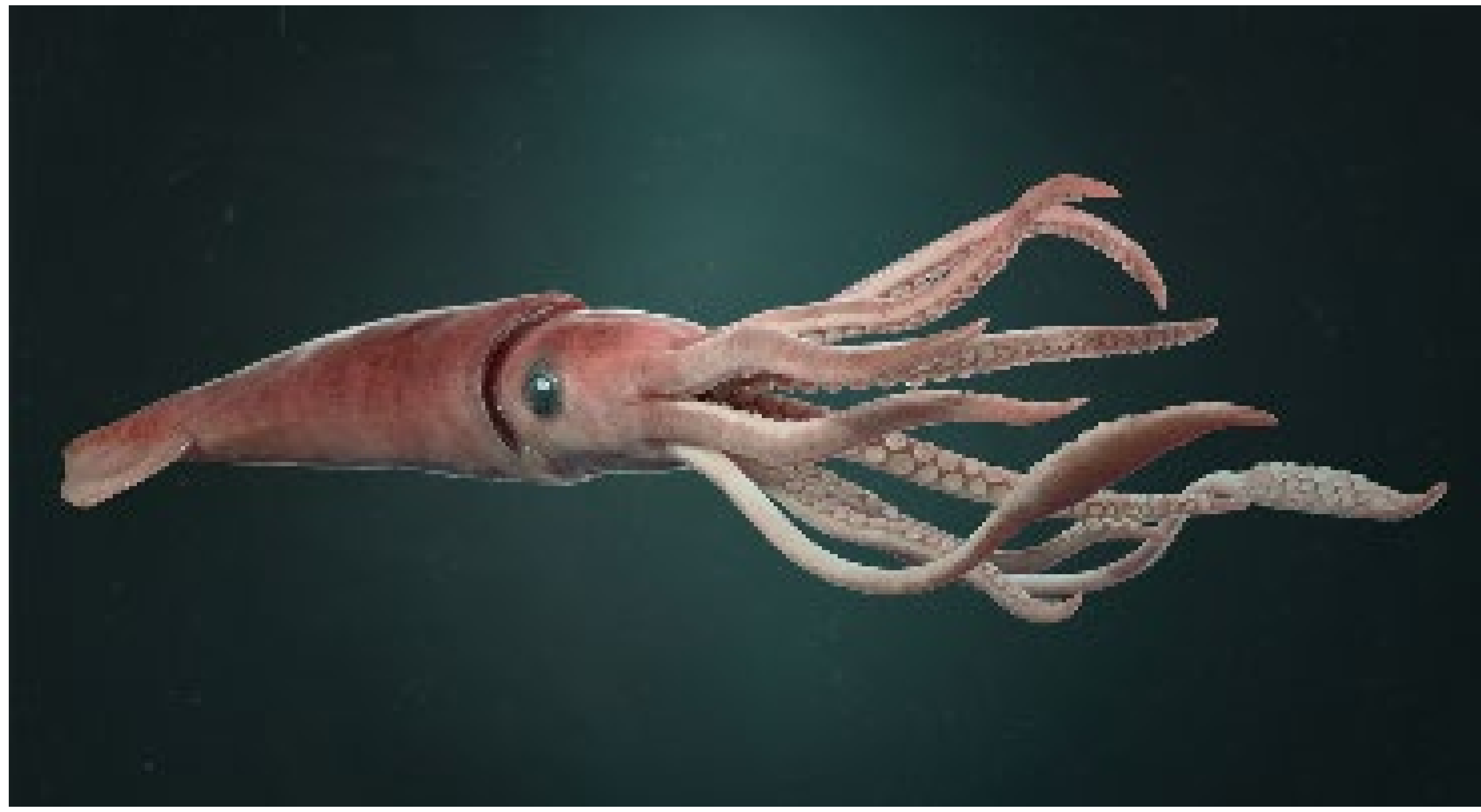
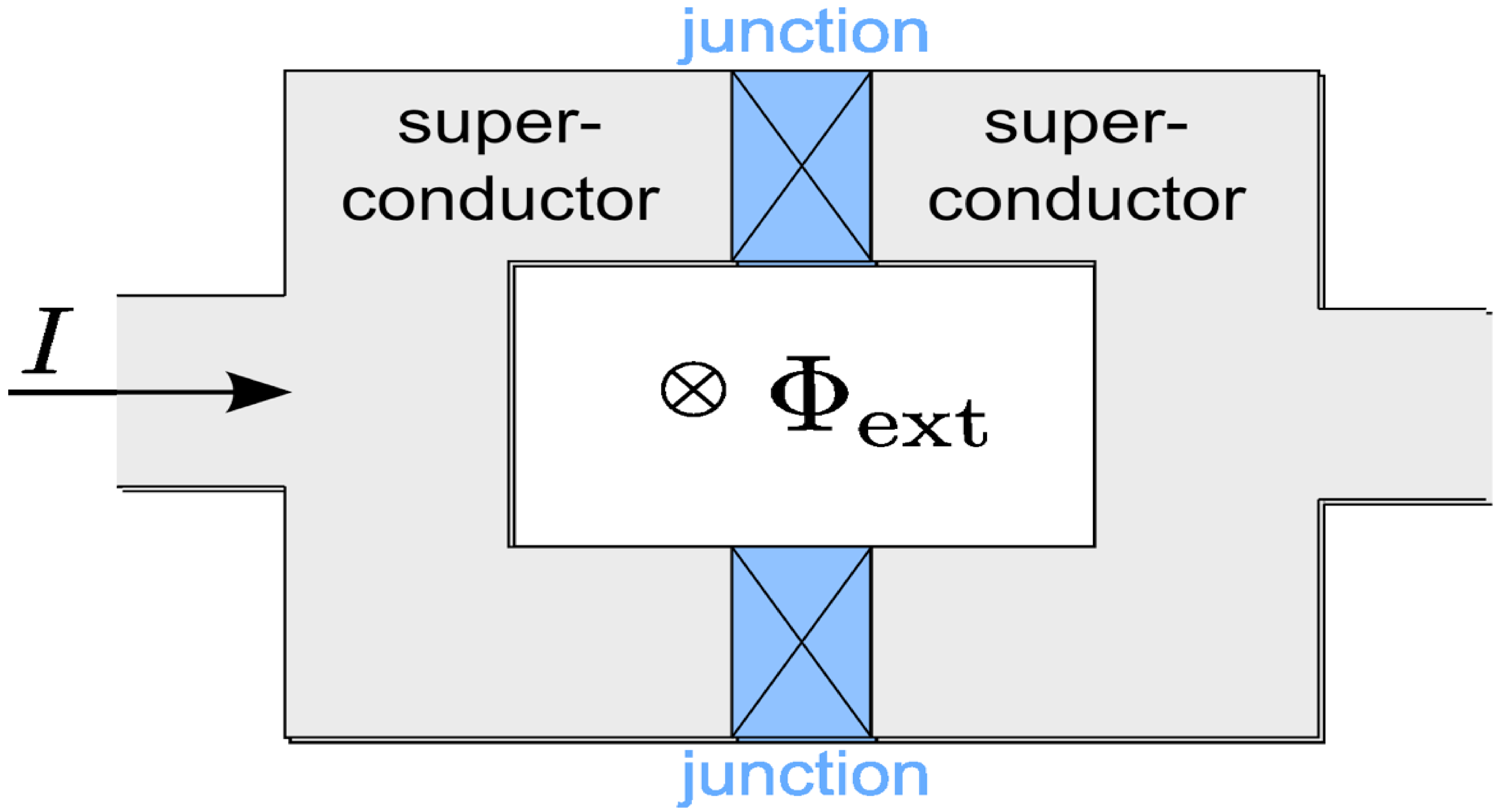


Kockum et al., Phys. Rev. A **90**, 013837 (2014)
Kannan et al., Nature **583**, 775 (2020)
Vadiraj et al., arXiv:2003.14167 (2020)

SQUID = Superconducting QUantum Interference Device

Not this type of squid:





- SQUID = two Josephson junctions in parallel, forming a loop
- It behaves like a flux-tunable inductor: $L_S(\Phi)$

Superconducting qubits, surface acoustic waves

Giant atoms

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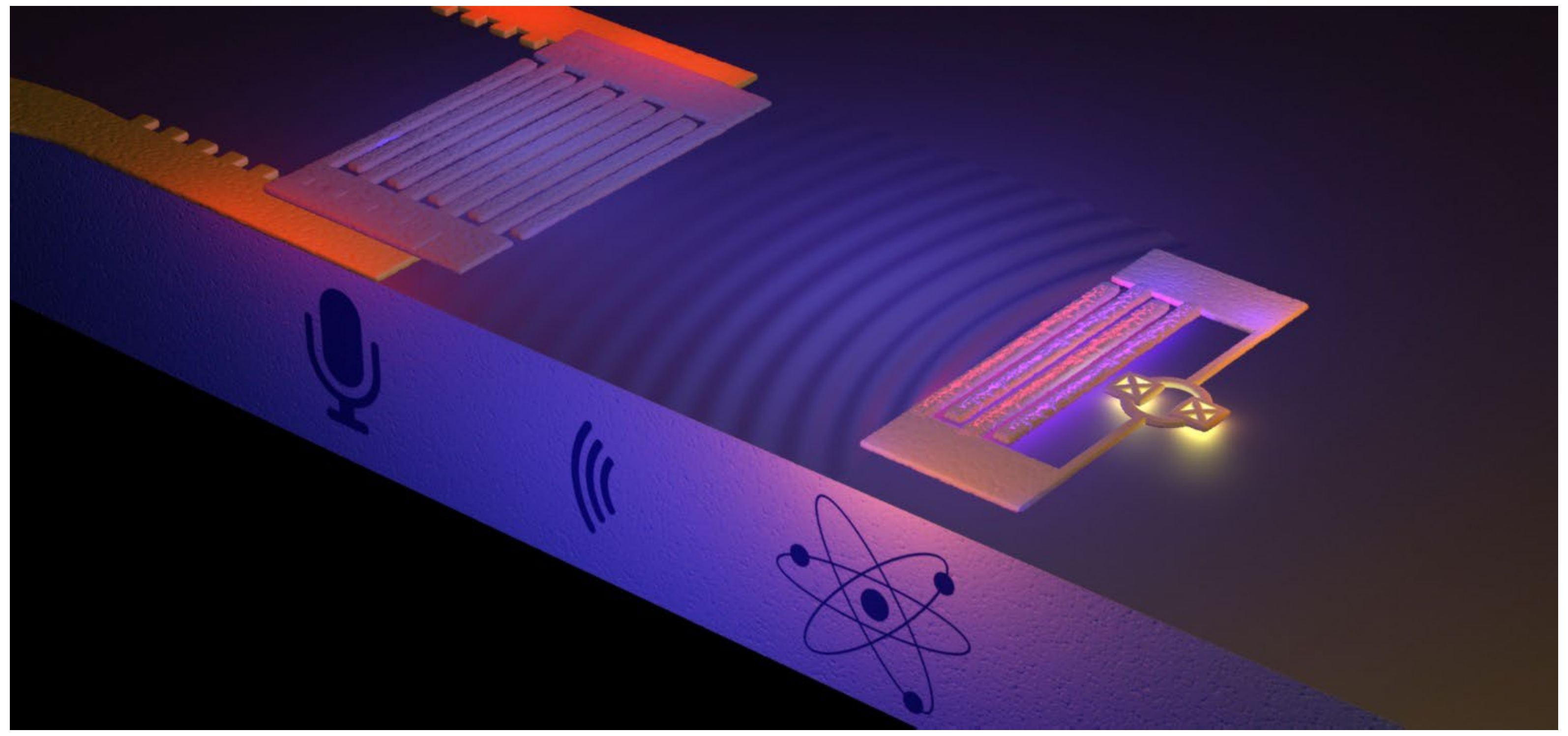

Gustafsson et al., Science **346**, 207 (2014)

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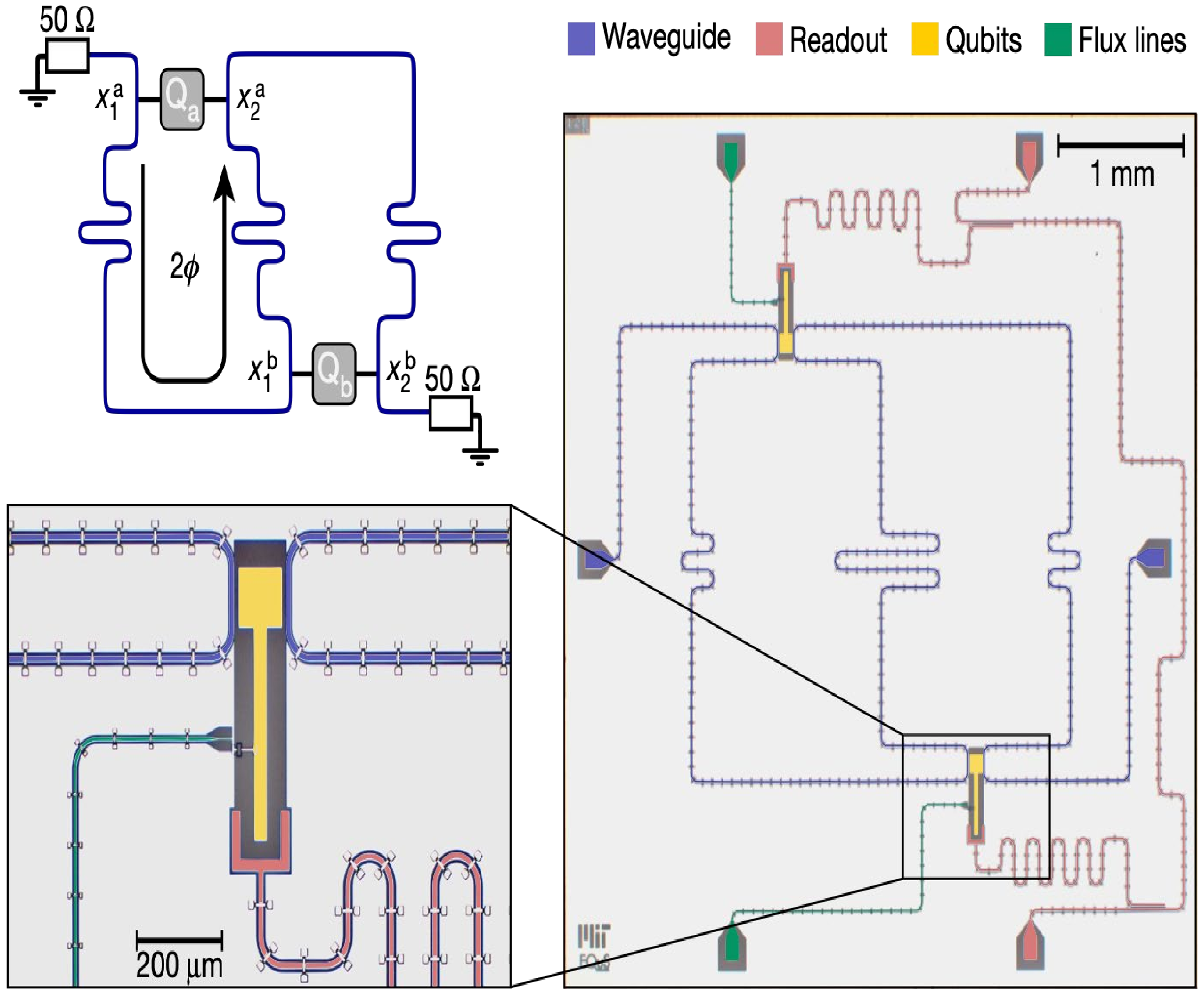
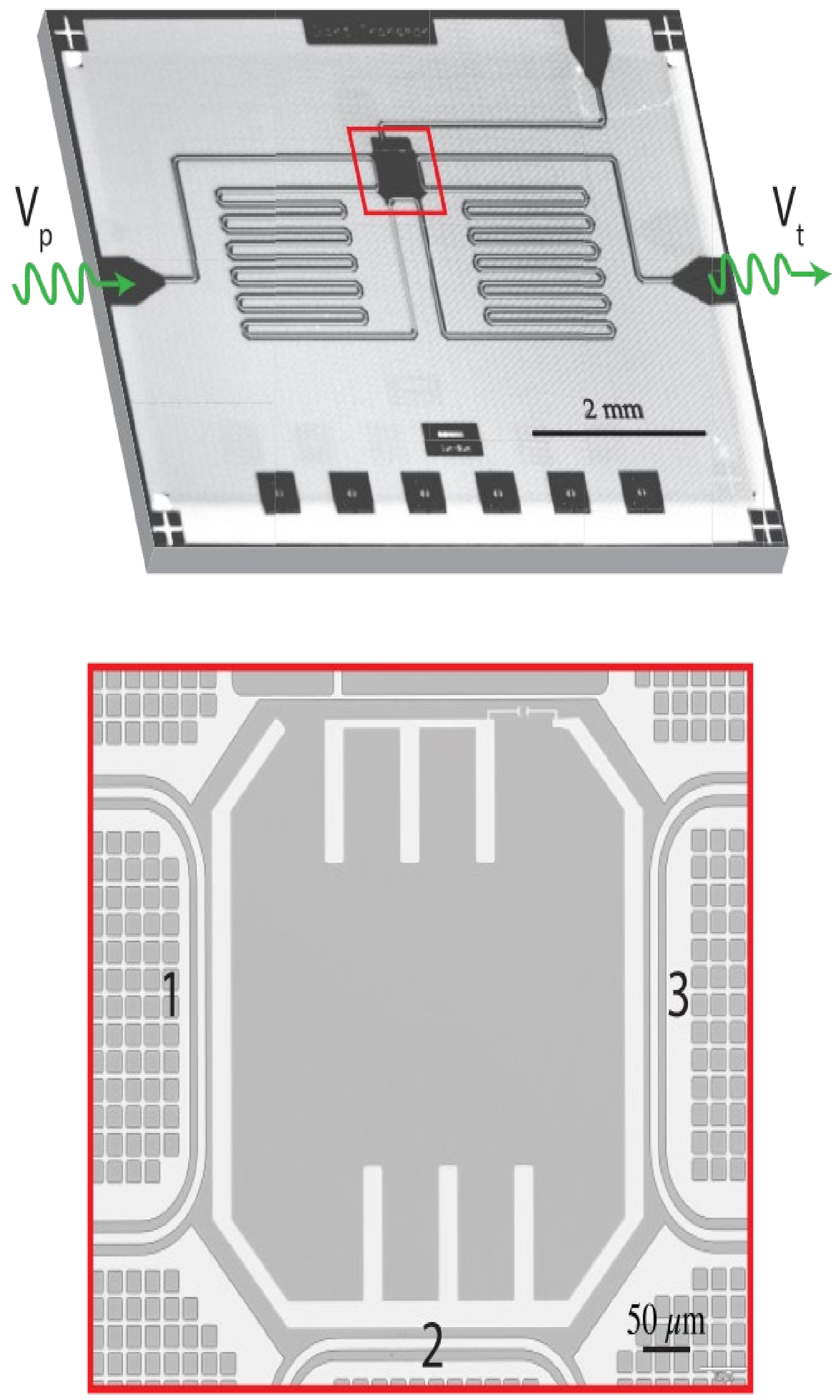


Kannan et al., Nature **583**, 775 (2020). This work verified our prediction



Vadiraj et al., Phys. Rev. A **103**, 023710 (2021)

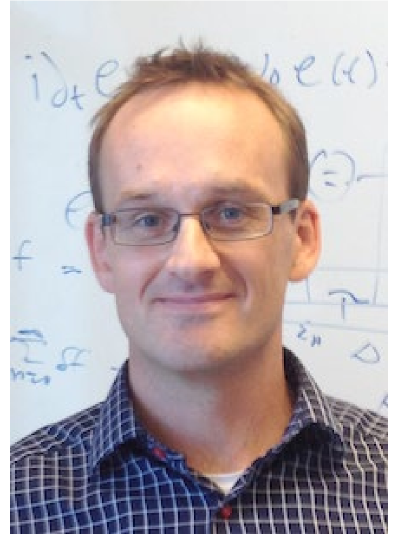
Collaborators on giant atoms

CHALMERS

Anton Frisk Kockum

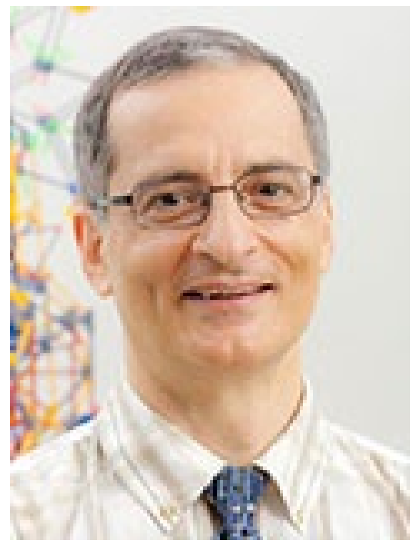
Per Delsing

Martin Gustafsson
Thomas Aref
Maria Ekström



Göran Johansson
Lingzhen Guo
Andreas Ask
Ariadna Soro Álvarez
Laura García-Álvarez

RIKEN



Franco Nori

Xin Wang
Tao Liu

William Oliver

Dan Campbell
Bharath Khannan

Peter Leek

Riccardo Manenti

Arne Grimsmo, Mikhail Pletyukhov, Florian Marquardt, Carlos Sánchez Muñoz, Nathan Shammah, …

Outline

- Introduction — atom sizes and their history
- One giant atom — frequency-dependent relaxation rate
- Multiple giant atoms — decoherence-free interaction
- Chiral quantum optics and giant atoms
- Chiral bound states
- Summary and outlook

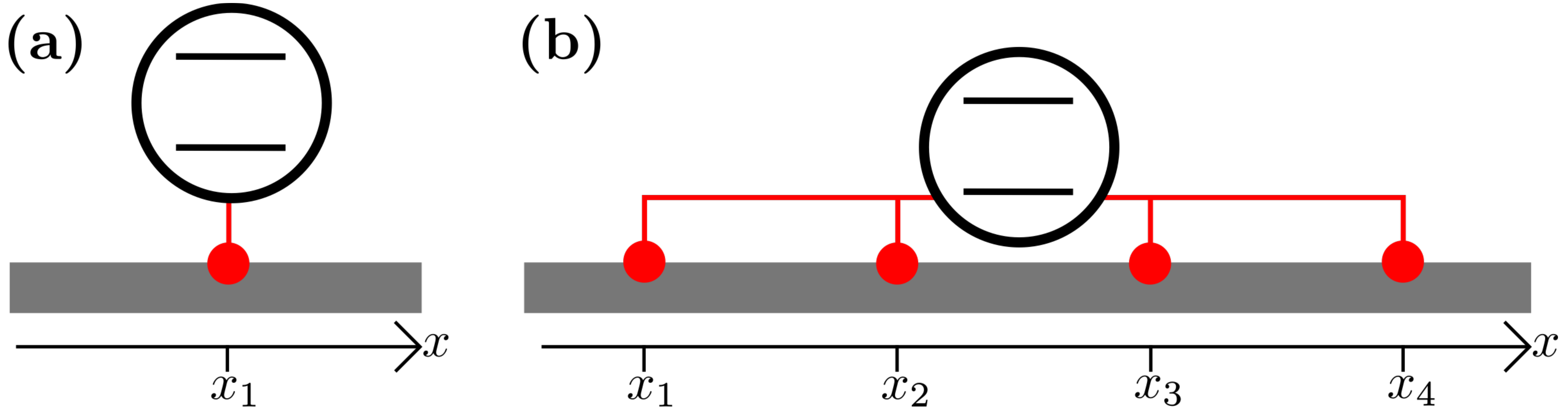
Theory for a giant artificial atom

Kockum, Delsing, and Johansson, Phys. Rev. A **90**, 013837 (2014)

Multiple coupling points give strong interference effects

Additional time scale: travel time across the atom $(x_N - x_1)/v$

We work in the limit where this is negligible compared to $1/\Gamma$



Interaction with waveguide modes

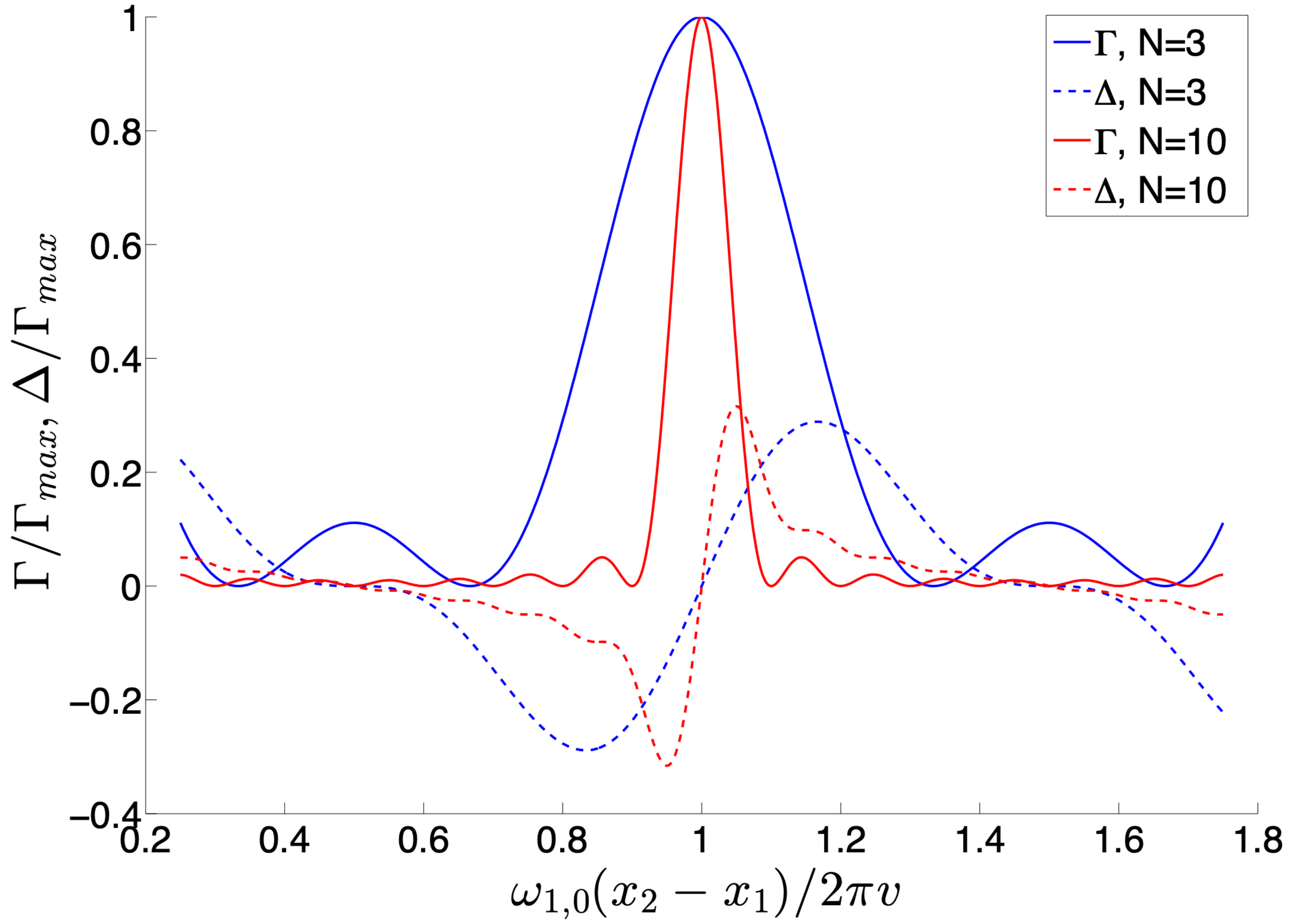
$$H_I = \boxed{\sum_{j,k} g_k \left[\left(a_{Rj} e^{i\omega_j x_k / v} \right.} + a_{Lj} e^{-i\omega_j x_k / v} \Big) |1\rangle\langle 0| + \left(a_{Rj}^\dagger e^{-i\omega_j x_k / v} + a_{Lj}^\dagger e^{i\omega_j x_k / v} \right) |0\rangle\langle 1| \Big]$$

Designing relaxation rates

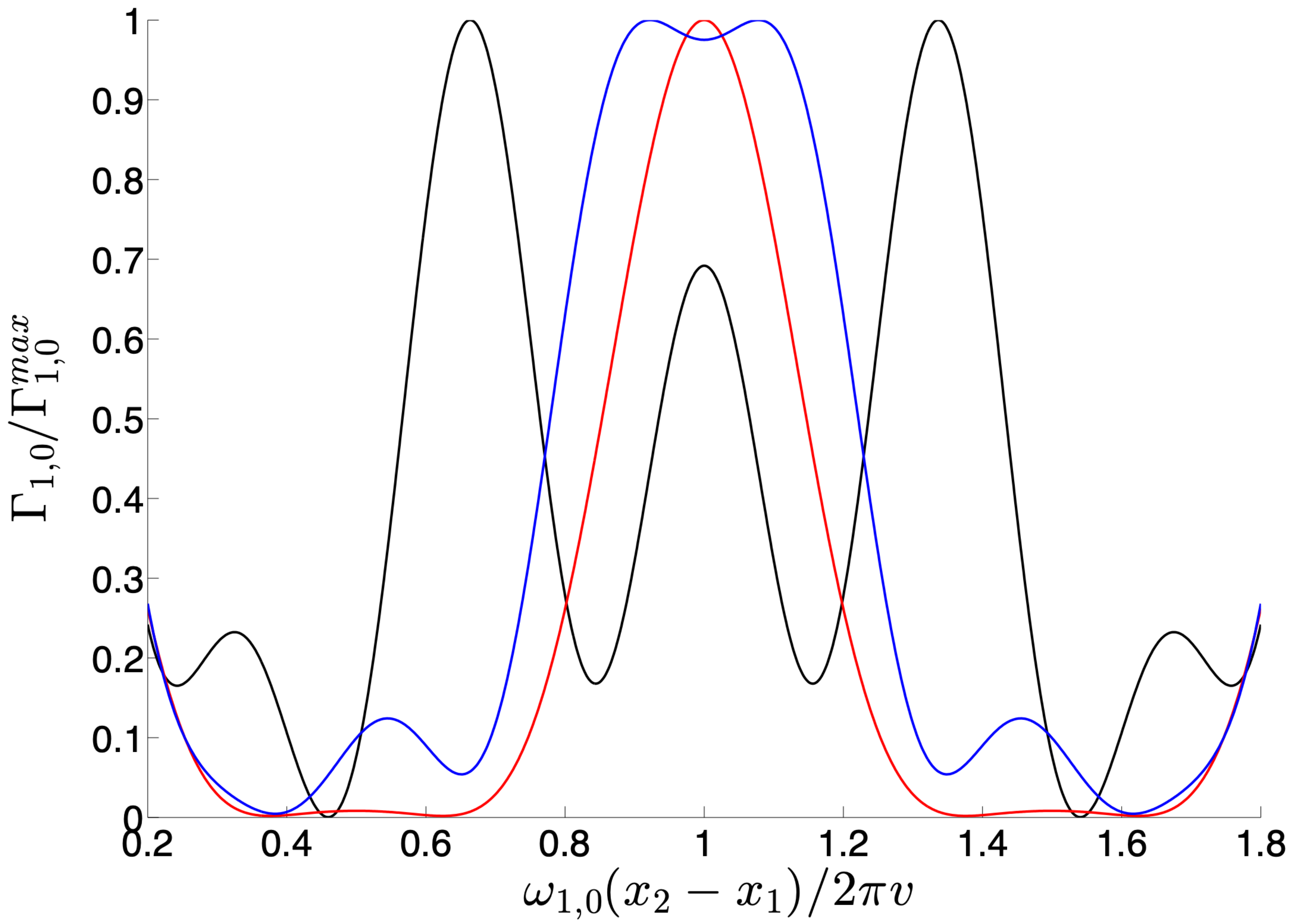
Relaxation rate $\Gamma = 4\pi J(\omega_{10}) \boxed{|A(\omega_{10})|^2}$

$$A(\omega_j) = \sum_k g_k e^{-i\omega_j x_k / v}$$

Discrete Fourier transform



Equal coupling strengths, equal spacings between connection points



4 connection points: designs for wide minima, wide maxima, multiple maxima
red curve, blue curve, black curve

- **Can mimic a structured environment**
- **Can design some atomic transitions to couple strongly while other transitions couple weakly to the environment**

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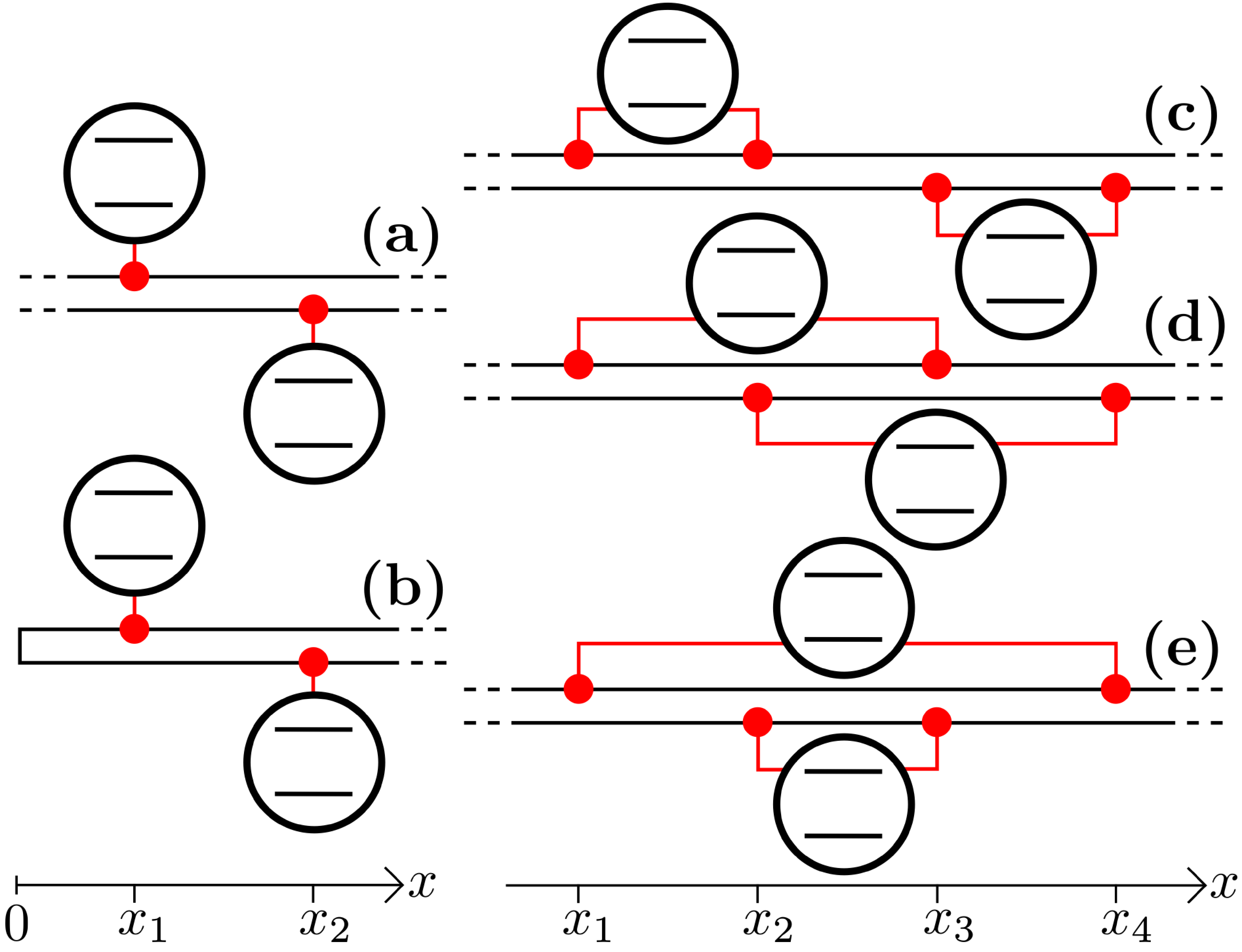
Two small atoms versus two giant atoms



← **Separated arrangement (*aabb*)**

← **Braided arrangement (*abab*)**

← **Nested arrangement (*abba*)**

Kockum, Johansson, and Nori, Phys. Rev. Lett. **120**, 140404 (2018)

Multiple giant atoms interacting without decoherence

We studied setups with **multiple giant atoms coupled at multiple points** to a 1D waveguide.

We show that **the giant atoms can be protected from decohering through the waveguide**, **but still have exchange interactions mediated by the waveguide.**

Unlike in decoherence-free subspaces, here **the entire multiatom Hilbert space** (2^N states for N atoms) **is protected from decoherence.**

This is not possible with "small" atoms.

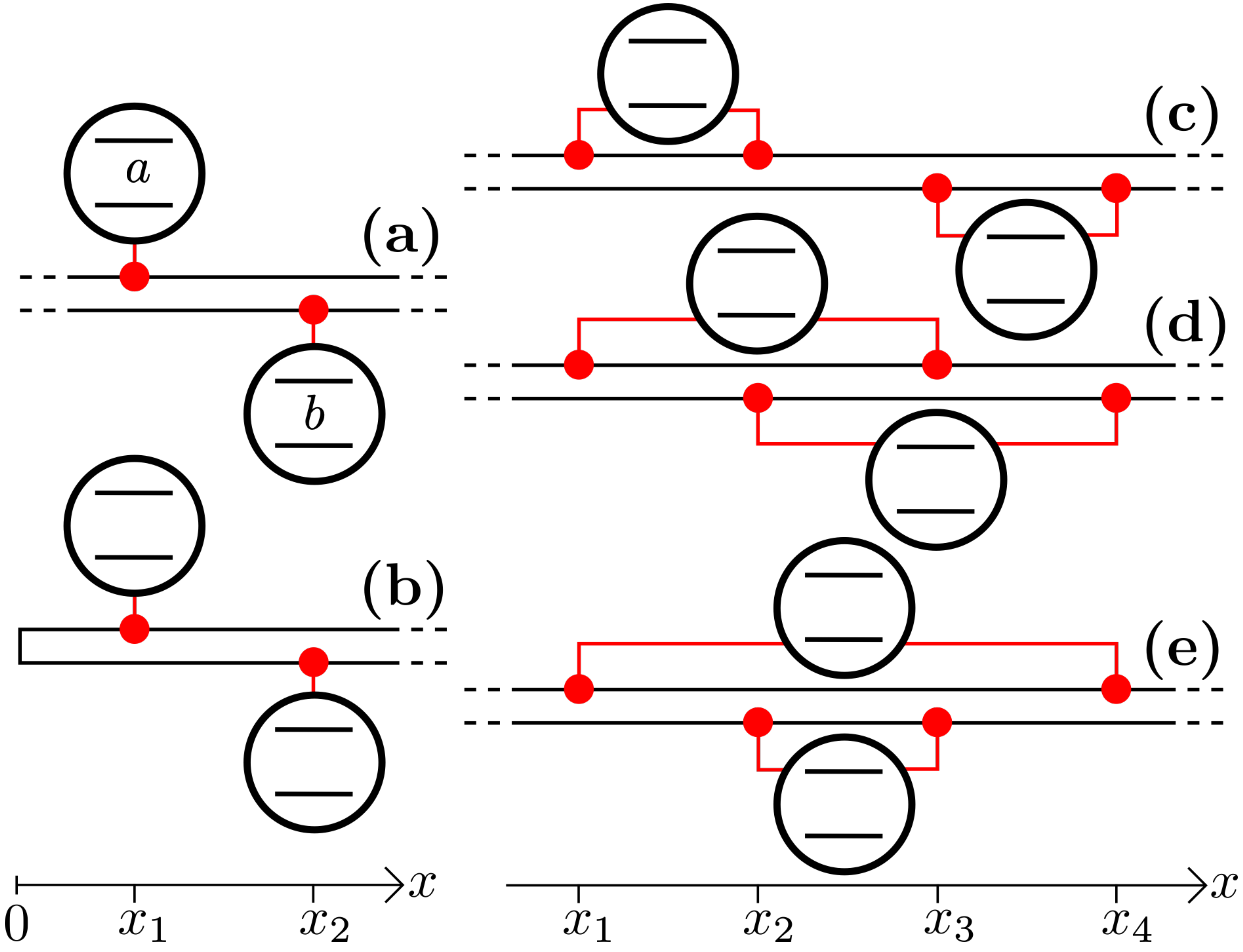
Kockum, Johansson, and Nori, Phys. Rev. Lett. **120**, 140404 (2018)

Multiple giant atoms interacting without decoherence

We further show how this **decoherence-free interaction** can be designed in **setups with multiple atoms** to implement, e.g., a 1D chain of atoms with nearest-neighbor couplings, or a collection of atoms with **all-to-all connectivity.**

Kockum, Johansson, and Nori, Phys. Rev. Lett. **120**, 140404 (2018)

Two small atoms versus two giant atoms



Master equation

$$\dot{\rho} = -i\left[\omega_a'\frac{\sigma_z^a}{2} + \omega_b'\frac{\sigma_z^b}{2} + \underbrace{g\left(\sigma_-^a\sigma_+^b + \sigma_+^a\sigma_-^b\right)}_{\text{Exchange interaction}}, \rho\right]$$

$$+ \underbrace{\Gamma_a \mathcal{D}\left[\sigma_-^a\right]\rho + \Gamma_b \mathcal{D}\left[\sigma_-^b\right]\rho}_{\text{Individual relaxation}}$$

$$+ \underbrace{\Gamma_{\text{coll}}\left[\left(\sigma_-^a\rho\sigma_+^b - \frac{1}{2}\left\{\sigma_+^a\sigma_-^b, \rho\right\}\right) + \text{H.c.}\right]}_{\text{Collective relaxation}}$$

Kockum, Johansson, and Nori, Phys. Rev. Lett. **120**, 140404 (2018)

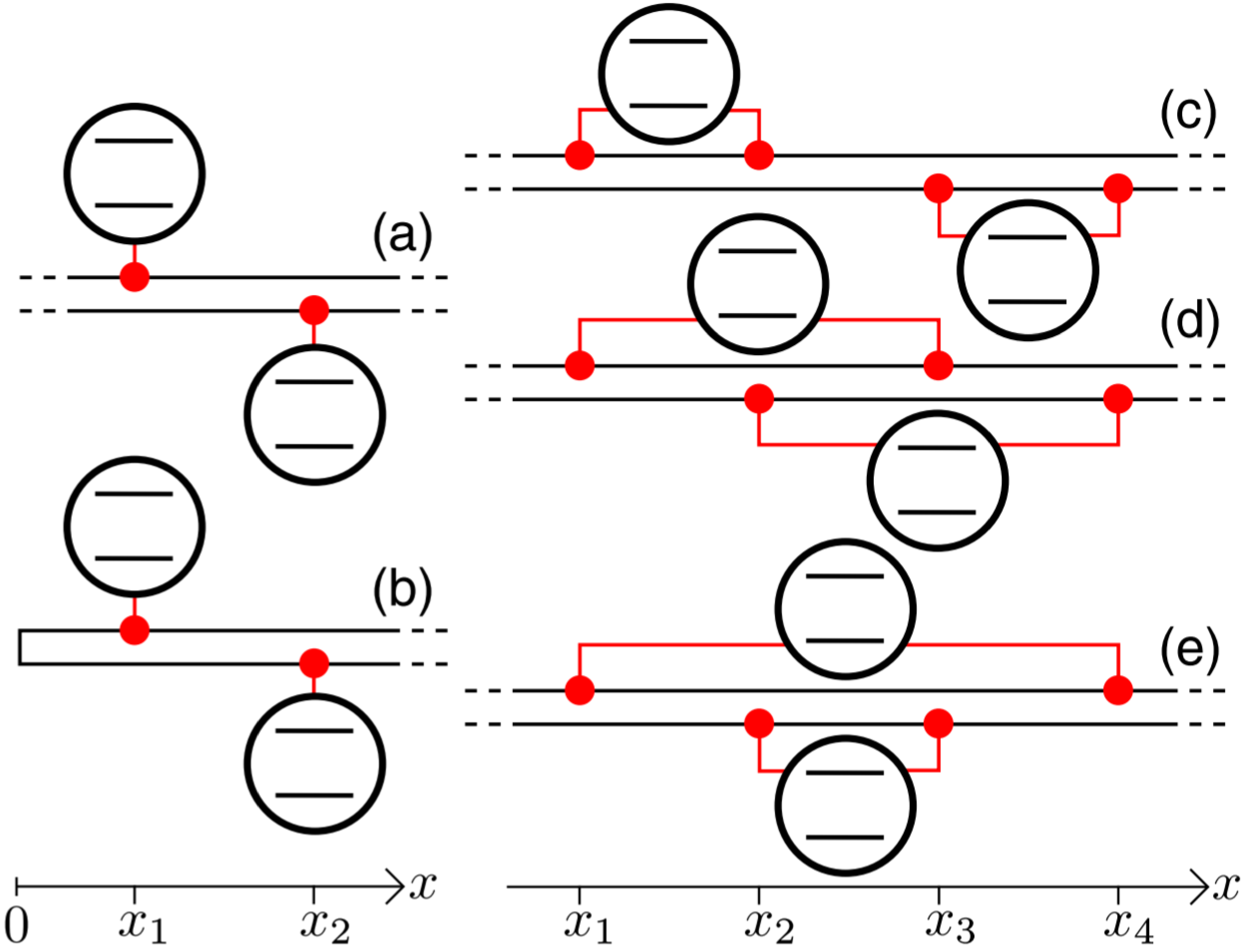


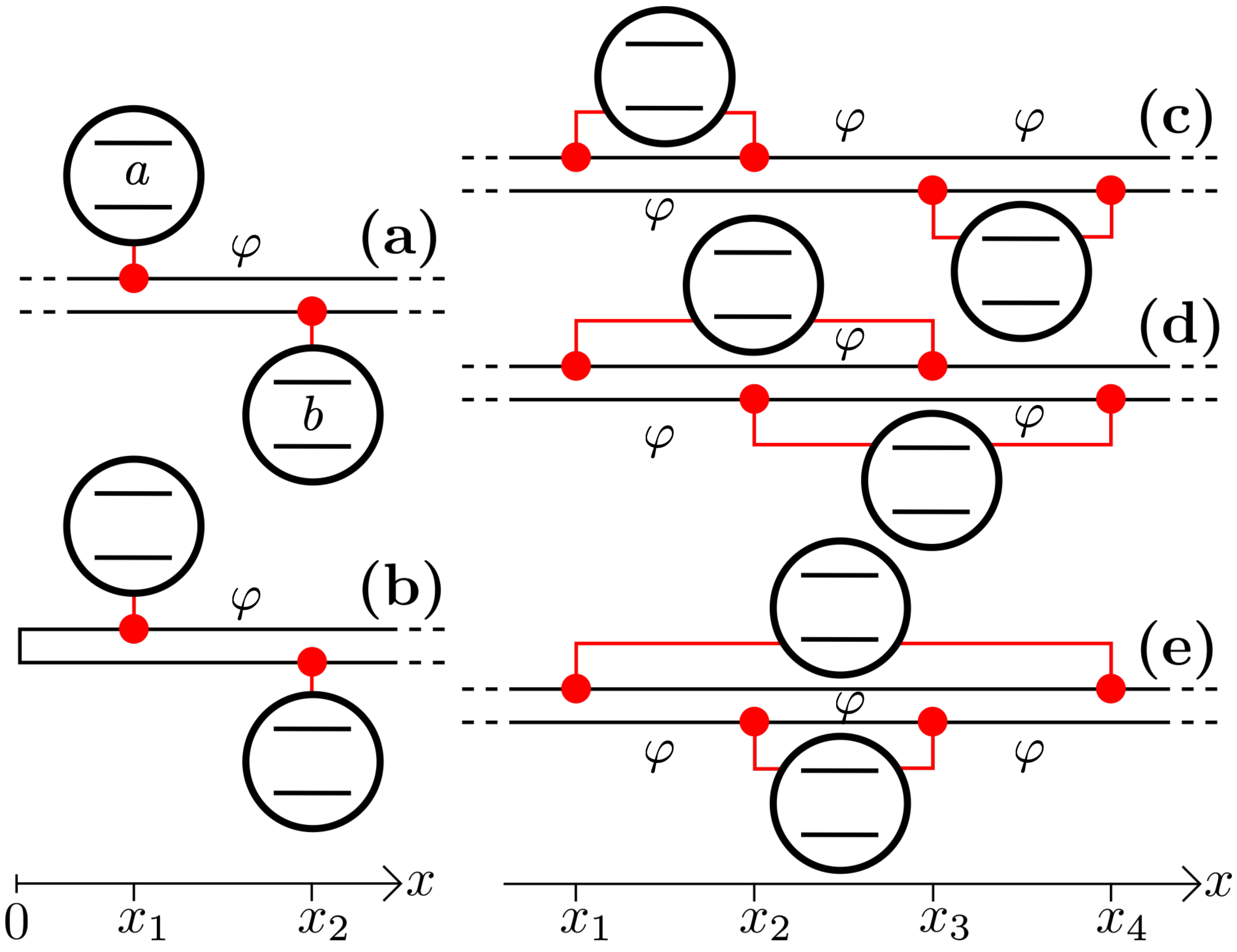
FIG. 1. Sketches of (a) two small atoms coupled to an open transmission line, (b) two small atoms coupled to a semi-infinite transmission line, (c) two separate giant atoms, (d) two braided giant atoms, and (e) two nested giant atoms. Red circles denote connection points. The atom with the leftmost connection point is denoted a and the other b.

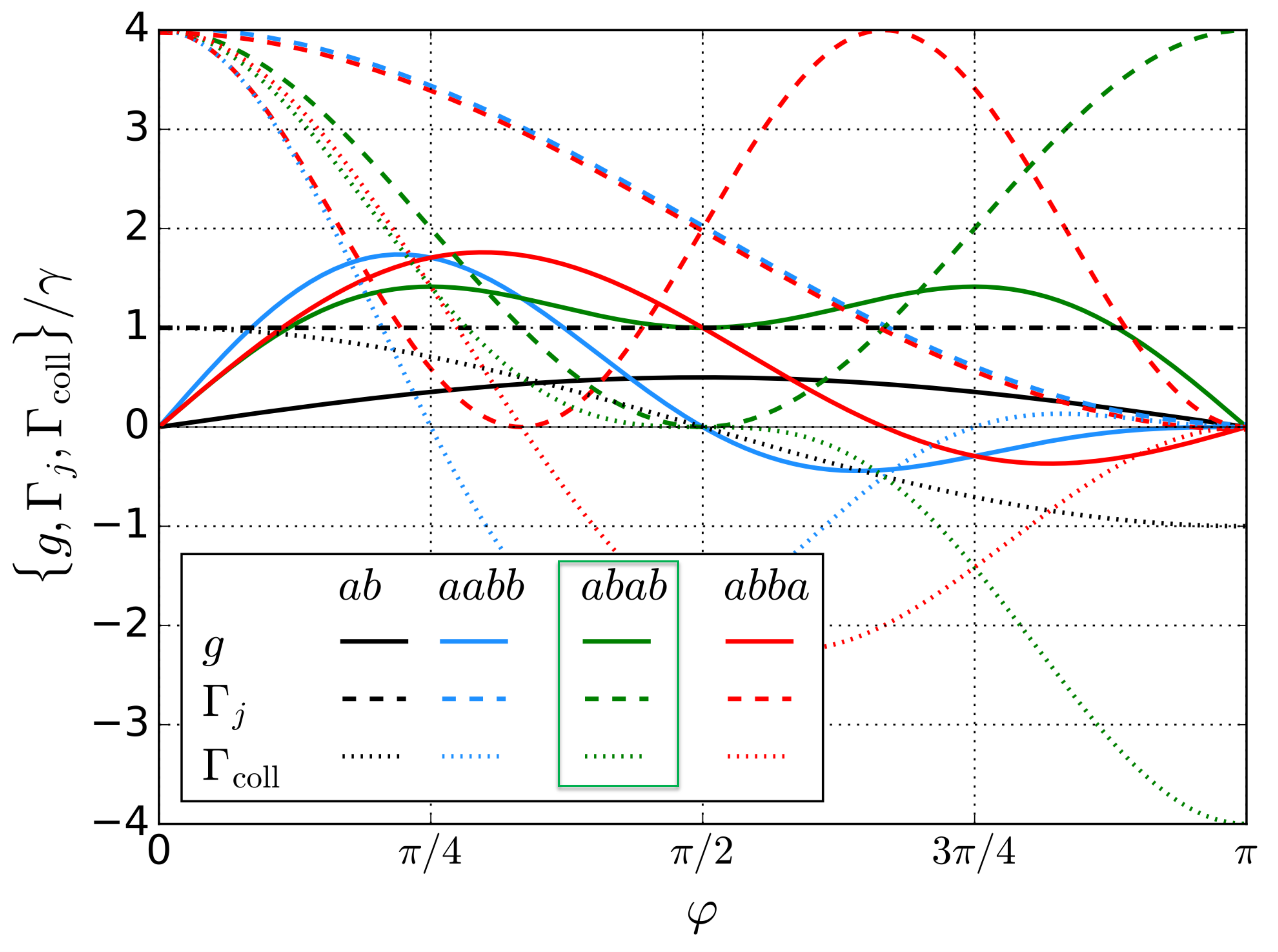
TABLE I. Frequency shifts, exchange interaction strengths, and decoherence rates for the setups from Fig. 1. In fields with two entries, the first corresponds to atom a and the second to atom b.

Setup	Frequency shift $\delta\omega_j$	Exchange interaction g	Individual decay Γ_j	Collective decay Γ_{coll}
Small atoms	0	$(\gamma/2)\sin\varphi$	γ	$\gamma\cos\varphi$
Small atoms +mirror	$(\gamma/2)\sin\varphi$; $(\gamma/2)\sin 3\varphi$	$(\gamma/2)(\sin\varphi + \sin 2\varphi)$	$\gamma(1+\cos\varphi)$; $\gamma(1+\cos 3\varphi)$	$\gamma(\cos\varphi + \cos 2\varphi)$
Separate giant atoms	$\gamma\sin\varphi$	$(\gamma/2)(\sin\varphi+2\sin 2\varphi+\sin 3\varphi)$	$2\gamma(1+\cos\varphi)$	$\gamma(\cos\varphi+2\cos 2\varphi+\cos 3\varphi)$
Braided giant atoms	$\gamma\sin 2\varphi$	$(\gamma/2)(3\sin\varphi + \sin 3\varphi)$	$2\gamma(1+\cos 2\varphi)$	$\gamma(3\cos\varphi + \cos 3\varphi)$
Nested giant atoms	$\gamma\sin 3\varphi$; $\gamma\sin\varphi$	$\gamma(\sin\varphi + \sin 2\varphi)$	$2\gamma(1+\cos 3\varphi)$; $2\gamma(1+\cos\varphi)$	$2\gamma(\cos\varphi + \cos 2\varphi)$

Kockum, Johansson, and Nori, Phys. Rev. Lett. **120**, 140404 (2018)

Two small atoms versus two giant atoms





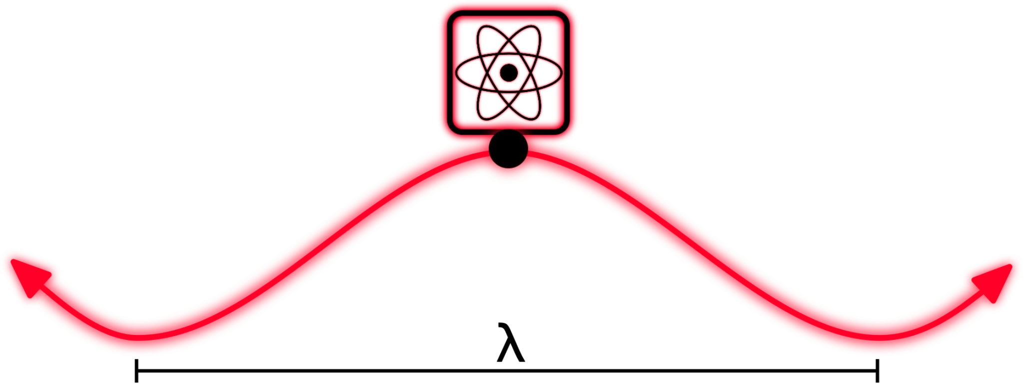
“Braided setup” (d) is the only one that enables completely protected interaction

- Only in the case of braided giant atoms it is possible to have $g \neq 0$ when the individual relaxation rates $\Gamma_j = 0$, $\forall j$, i.e., a decoherence-free interaction.

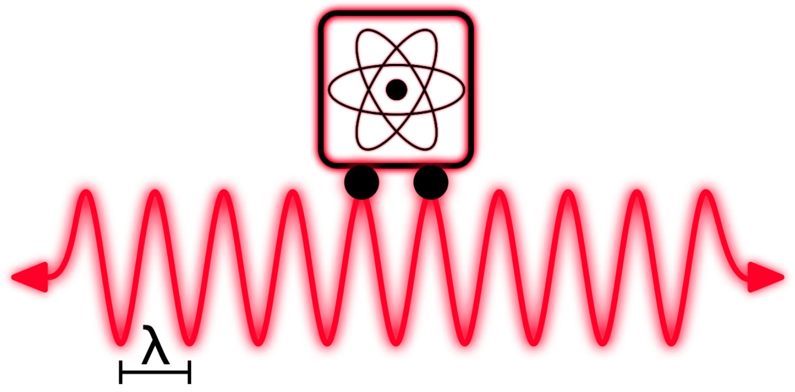
- This can be understood as follows: *individual* relaxation rates $\Gamma_j = 0$ implies that the phase acquired traveling between the connection points of atom j is $(2n + 1)\pi$, for some integer n.

- The *collective* decay is set by interference between emission from connection points belonging to different atoms; but the sum of these contributions will be zero when the emission from two connection points of one atom interfere destructively.


Braided giant atoms
Q_a
Q_b
γ
ϕ
ϕ
ϕ
x_1^a
x_1^b
x_2^a
x_2^b
X_1^a
X_2^a
X_1^b
X_2^b
Krantz NanoArt



Summary of this part



- Giant atom = atom coupled to a waveguide at multiple points, separated by (several or many) wavelengths.

- **Multiple coupling points** $\longrightarrow$ **interference effects** $\longrightarrow$ **designable frequency-dependent relaxation rate for a single giant atom.**

- **Two "braided" giant atoms can completely decouple their entire Hilbert space** (not just a single dark state) from the waveguide (no decay) but **still have a strong** (!) **exchange interaction** mediated by the waveguide. This is not possible with small atoms.

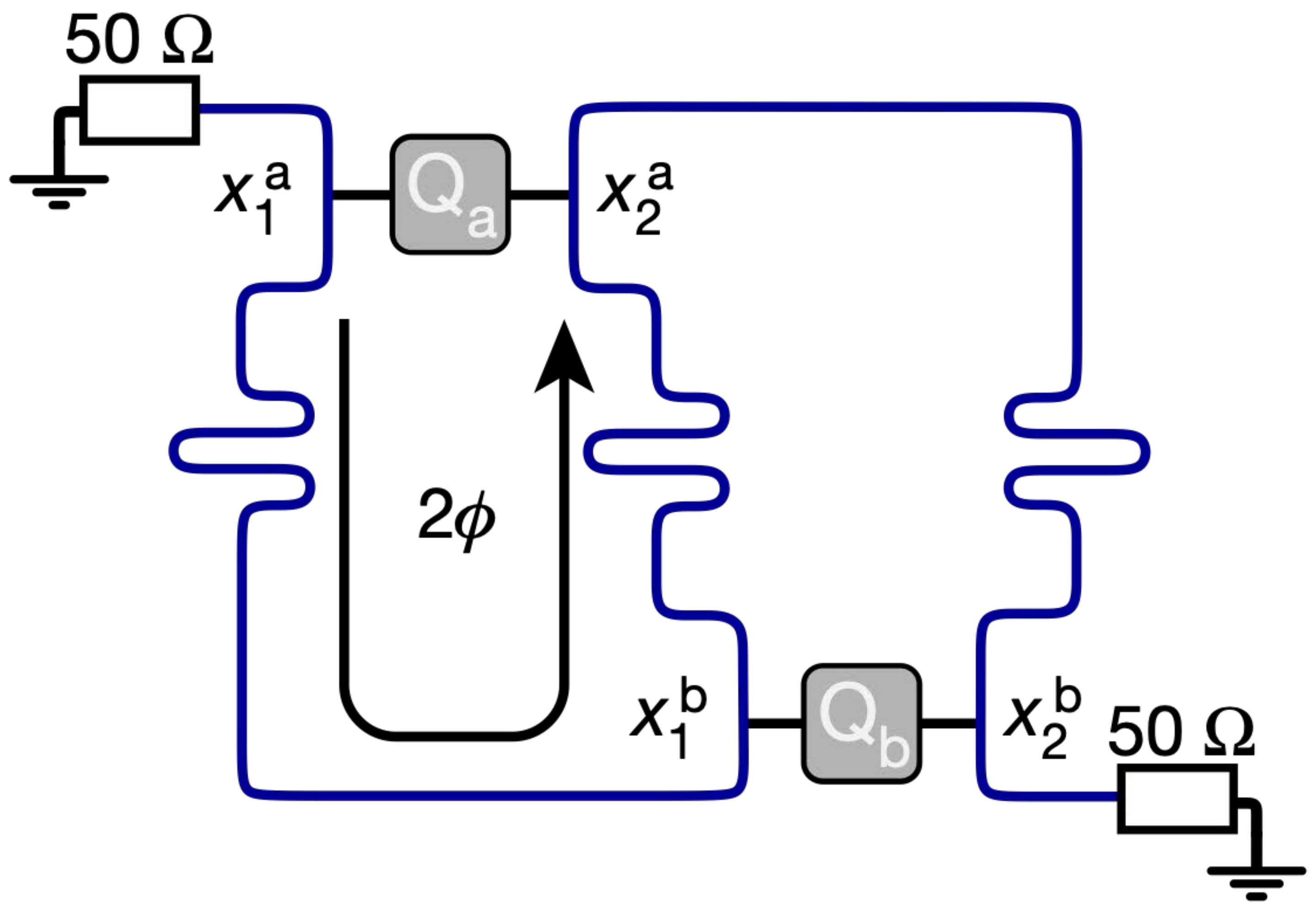
Outline

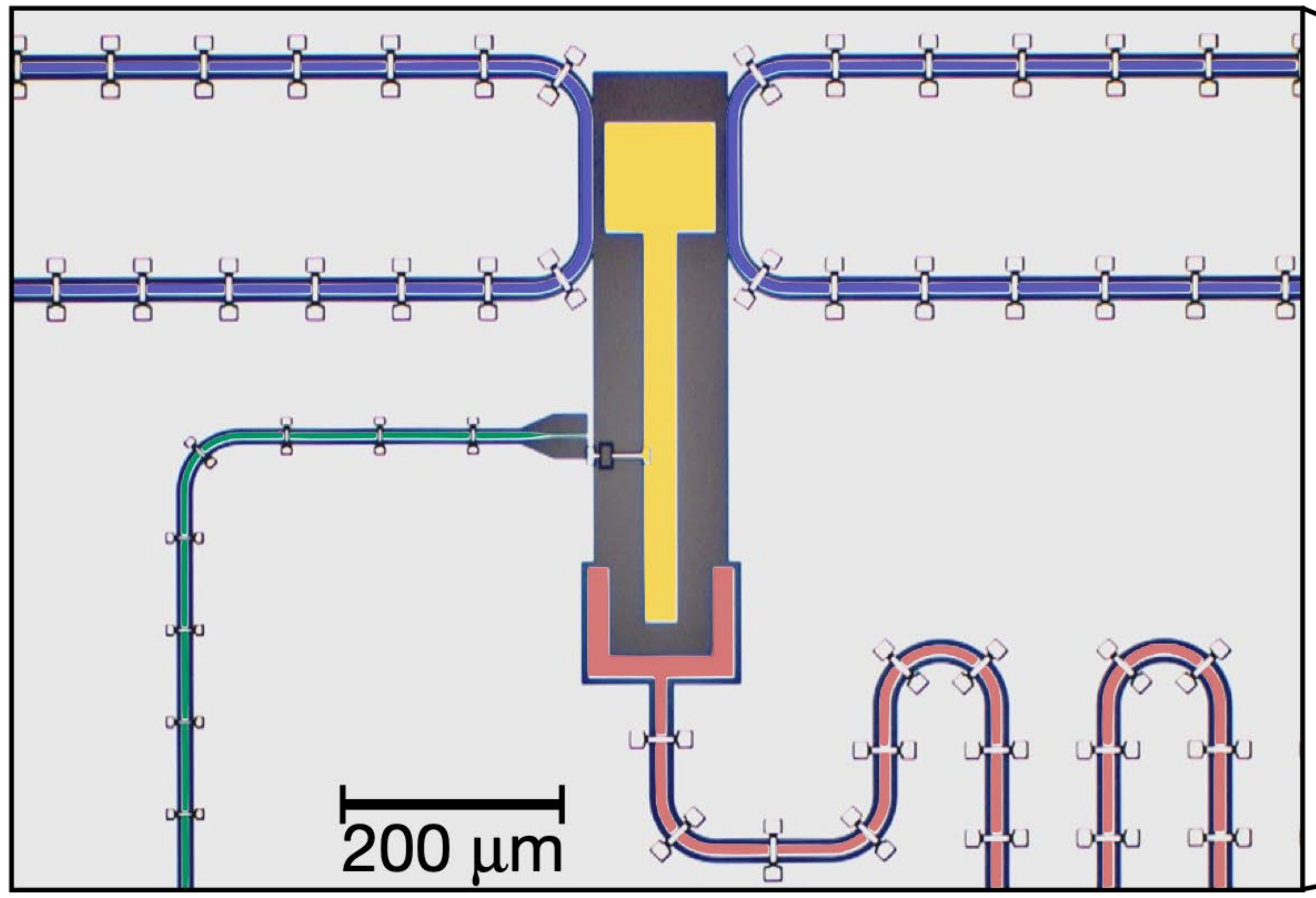
- Introduction — atom sizes and their history
- One giant atom — frequency-dependent relaxation rate
- Multiple giant atoms — decoherence-free interaction
- Multiple giant atoms — experimental demonstration
- Summary and outlook

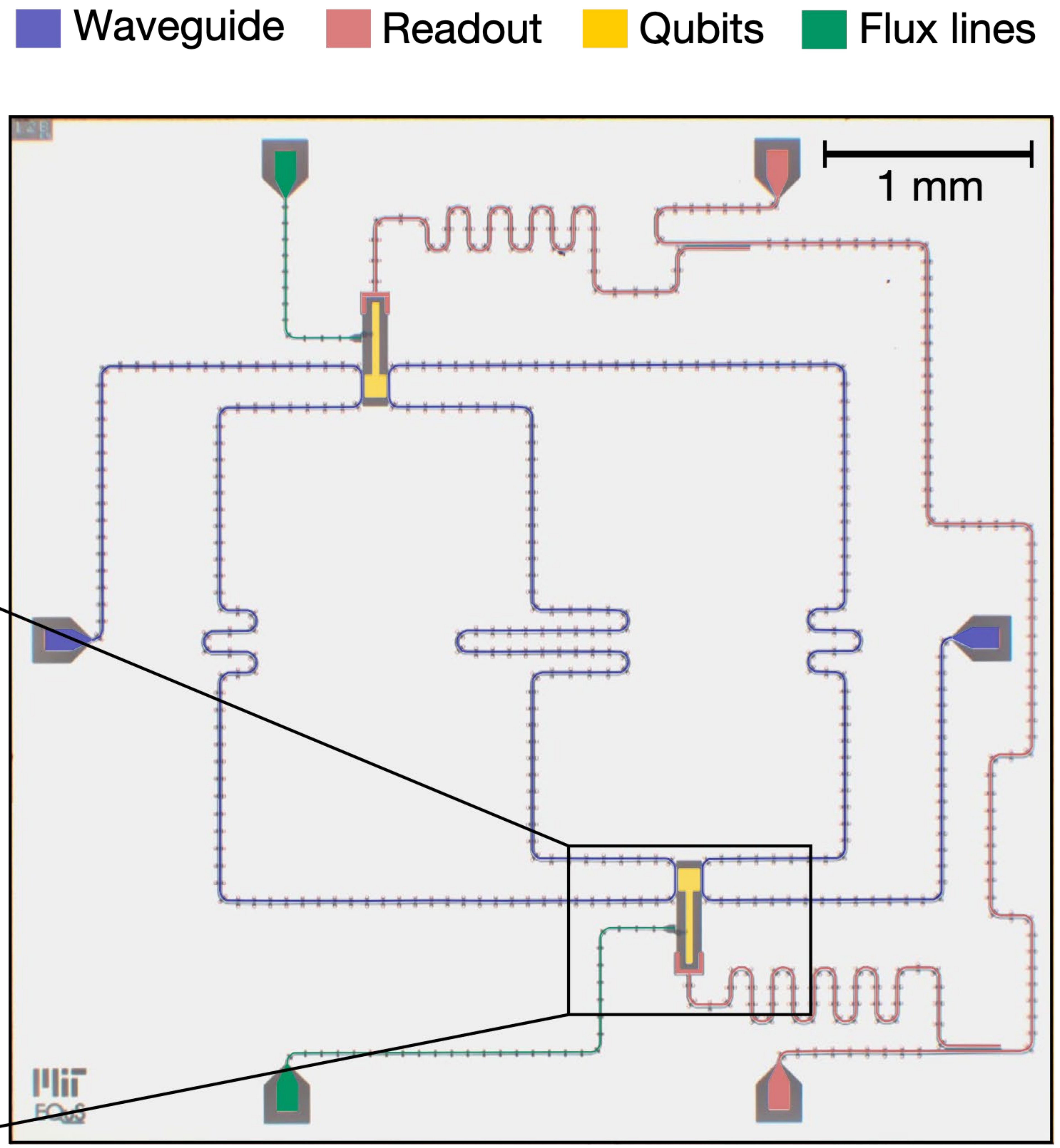
Giant atoms in superconducting circuits

Long meandering transmission line (blue) creates multiple wavelength distances between coupling points.

Readout resonators (red) and **control lines (green)** for each **qubit (yellow).**





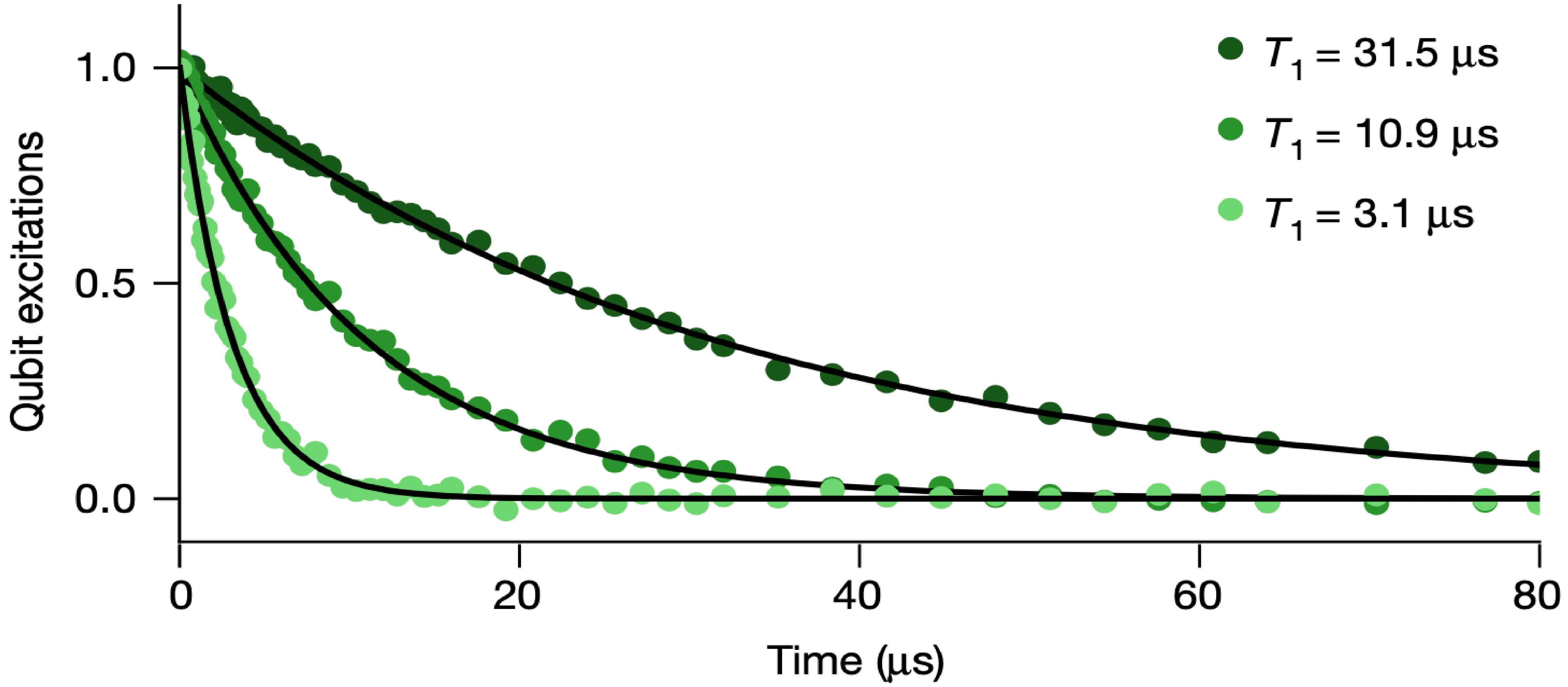


Kannan et al., Nature **583**, 775 (2020)

Frequency-dependent relaxation rate

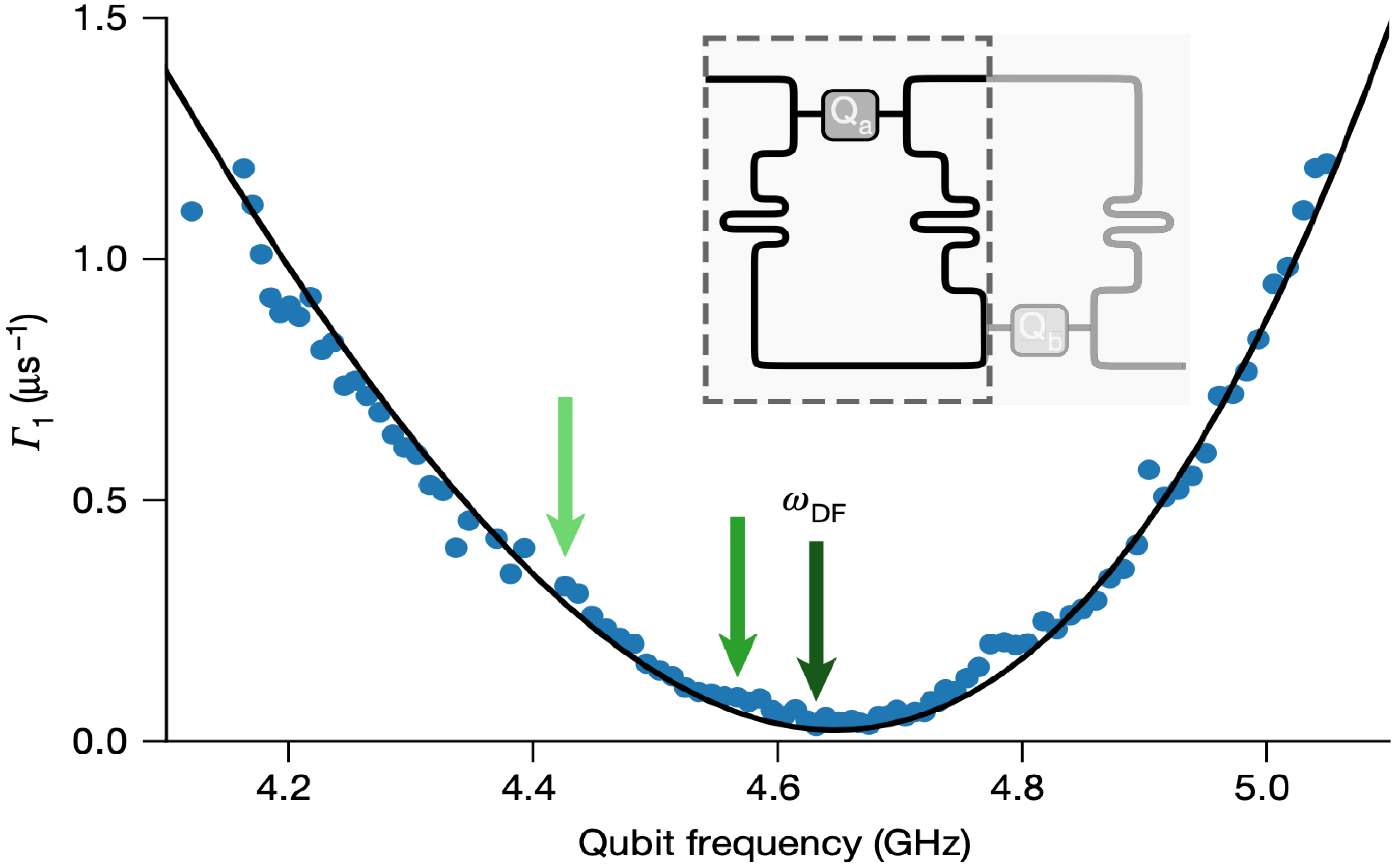
Tunable coupling for a single giant atom.

T_1 traces and fits for qubit Q_a at three different qubit frequencies.
The fitted T_1 values are given in the top right.



The measured relaxation rate $\Gamma_1 = 1/T_1$ for qubit Q_a as a function of its frequency, with the fit to the theory (solid line).

The three green arrows correspond to the relaxation rate for the T_1 traces shown in a.



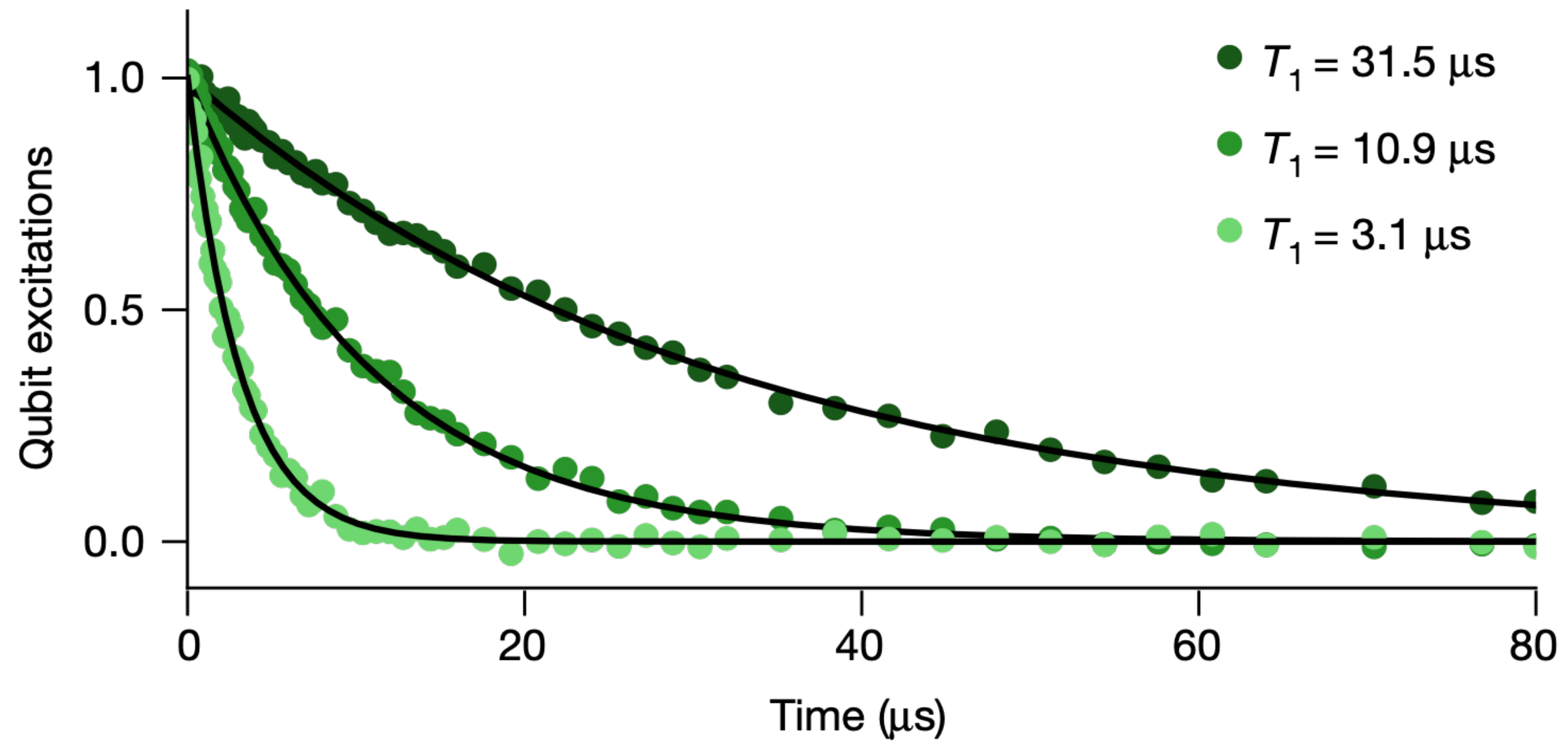
The **qubit decouples from the waveguide at a decoherence-free frequency** $\omega_{DF}/2\pi = 4.645$ GHz with a lifetime of $T_1 = 31.5$ μs.

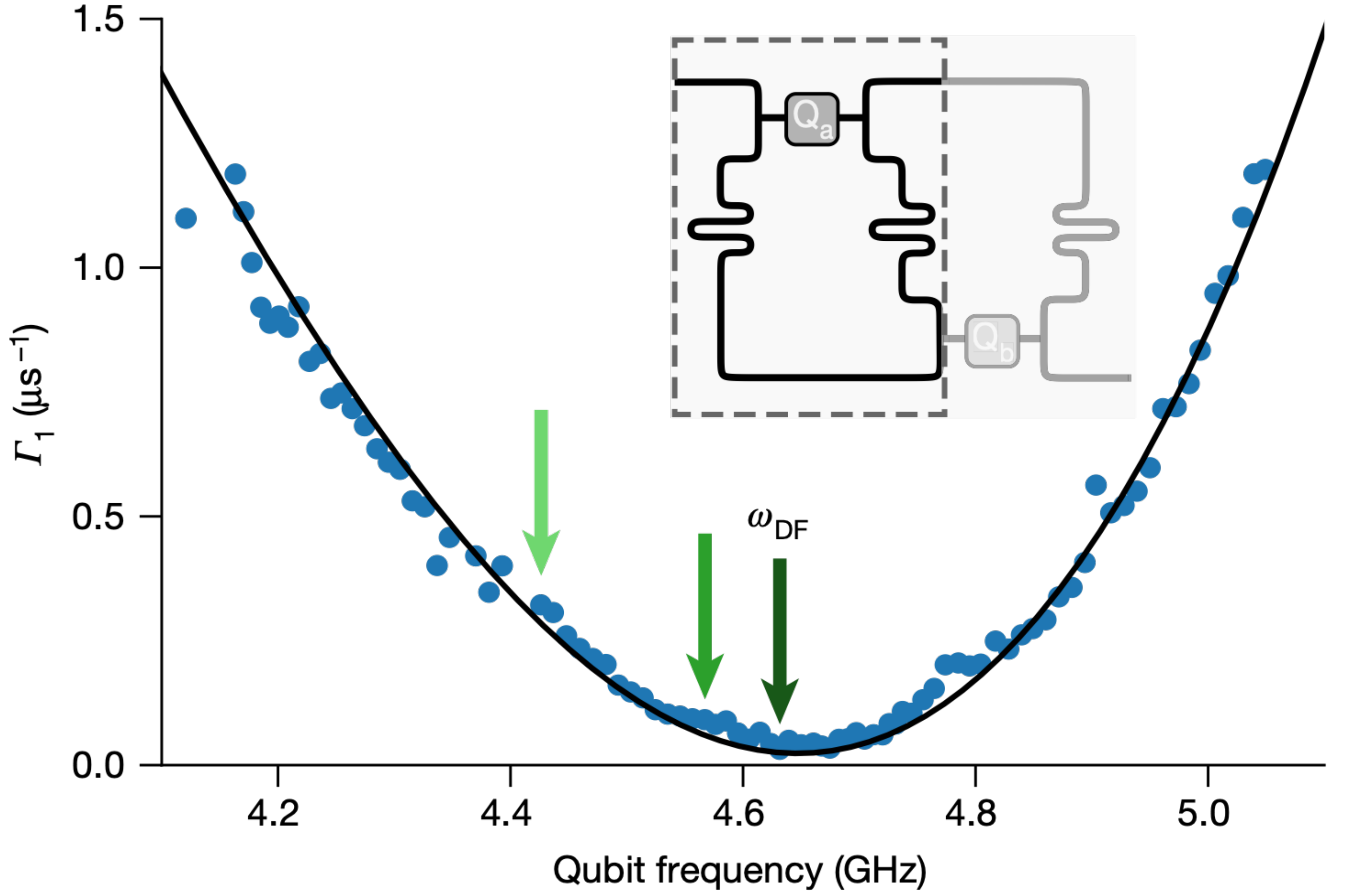
Frequency-dependent relaxation rate

Exciting one qubit, monitoring through the readout resonator

Changing the relaxation rate by more than one order of magnitude

$$\Gamma_1 = 2\gamma(\omega)[1 + \cos(2\phi)] + \gamma_{\rm nr}$$
$$\phi = 2\pi \Delta x / \lambda(\omega)$$





Decoherence-free interactions between two giant atoms.

The **measured exchange-interaction strengths** between the qubits from avoided level crossings versus the qubit frequencies.

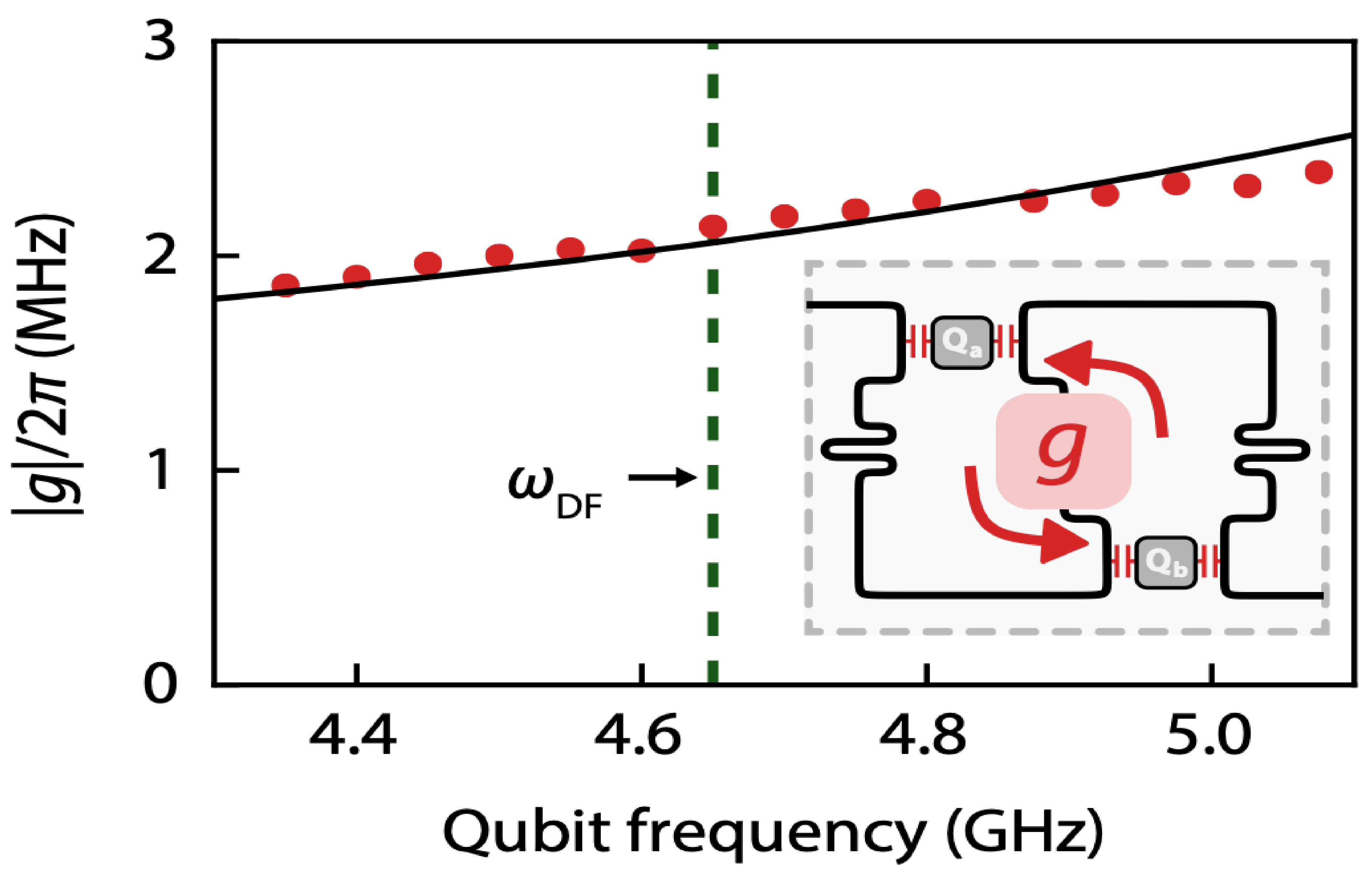
The fit to theory (solid line) is plotted with the data (red dots) and the decoherence-free frequency is shown (dashed vertical line).

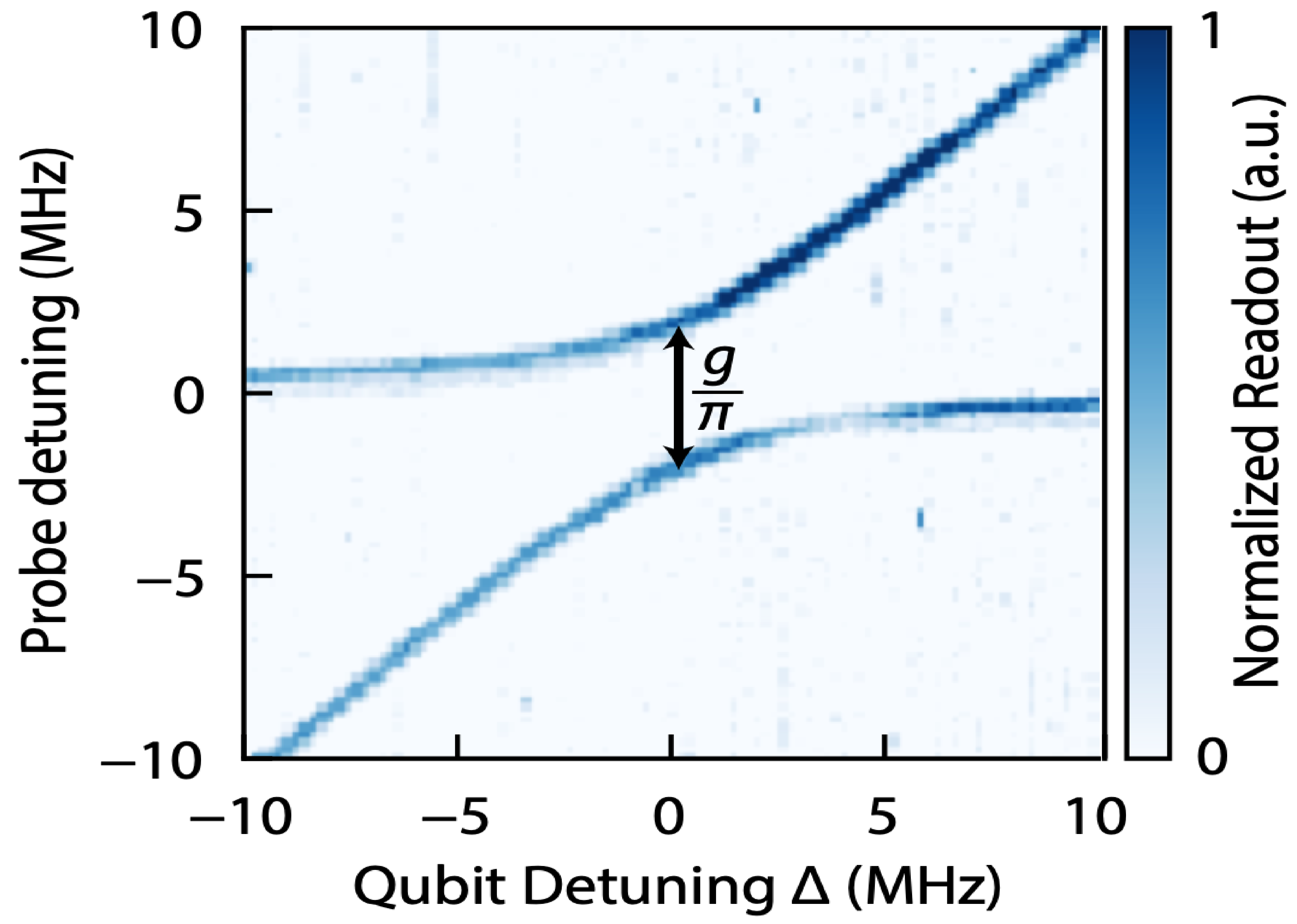
The qubit spectroscopy of **an avoided level crossing centered at the decoherence-free frequency** $\omega_{DF}/2\pi = 4.645$ GHz.

The frequency of the applied drive is swept to probe the qubit frequencies for multiple qubit detunings Δ.

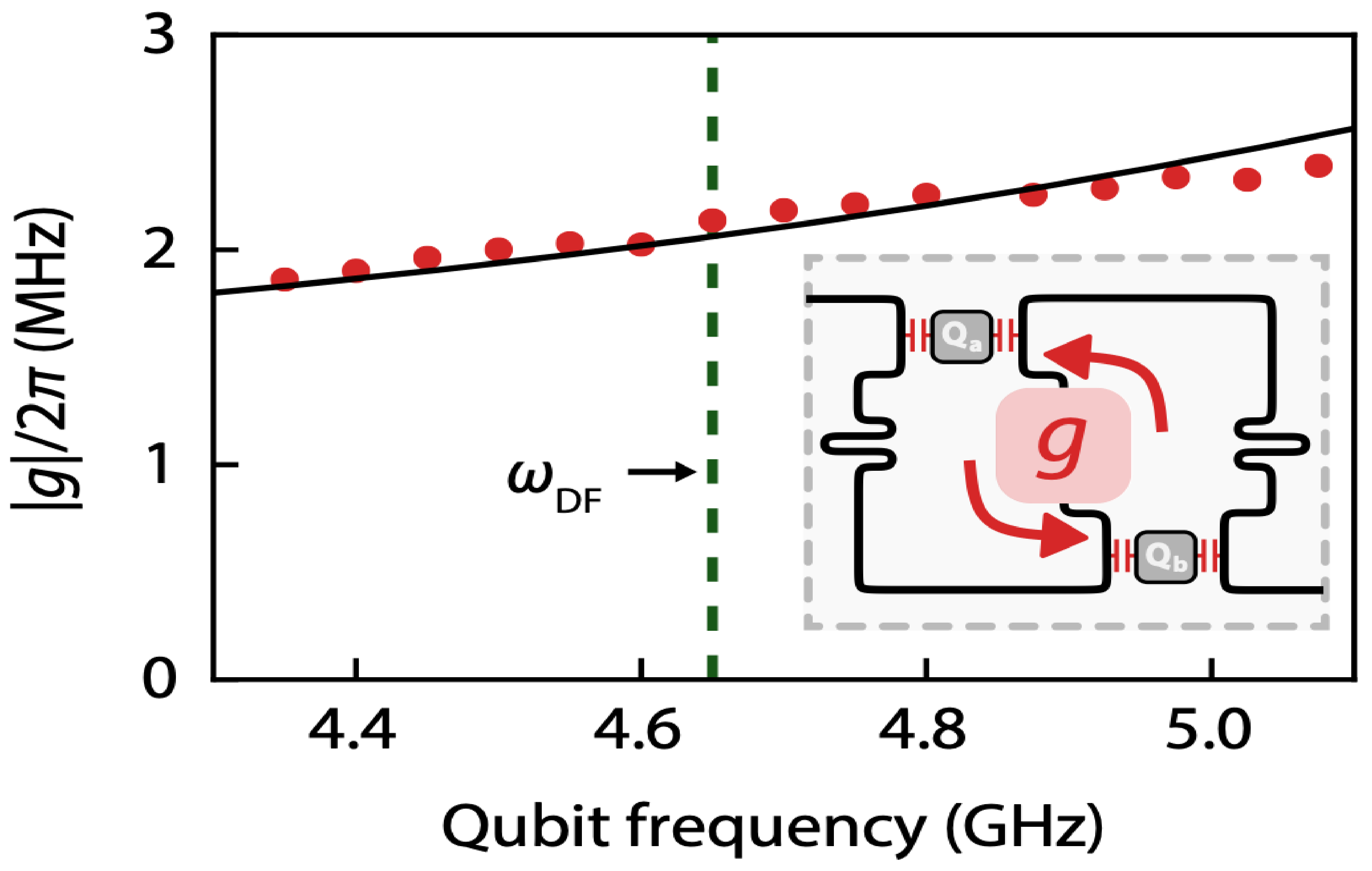
The readout signals for each qubit are normalized and summed together to obtain both branches of the crossing.

Even though **the qubits are decoupled from spontaneous emission into the waveguide, a qubit exchange interaction that is mediated by virtual photons in the waveguide is measured** to be $g/2\pi = 2$ MHz.



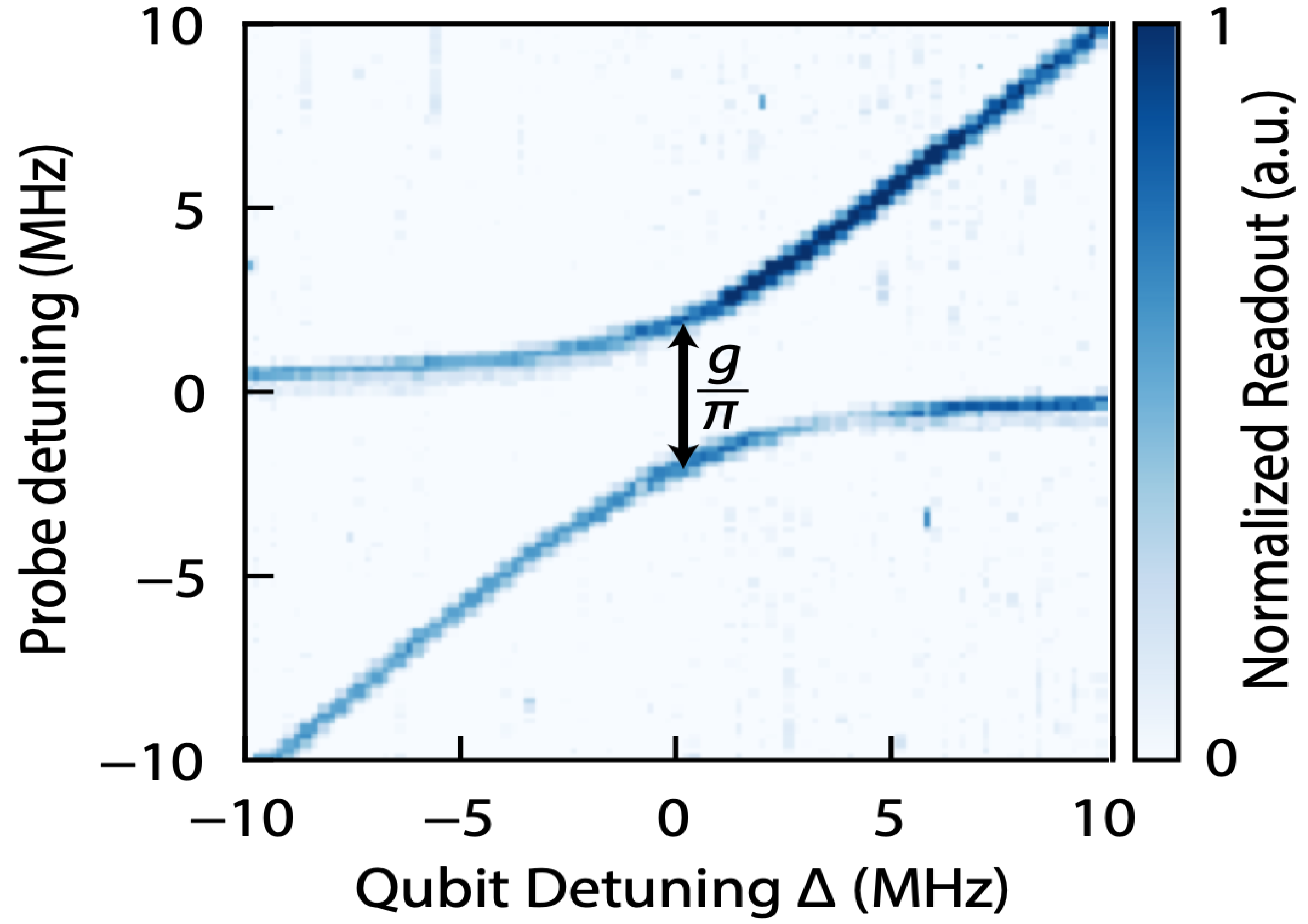


Protected interaction



Tuning both qubit frequencies in sync to find interaction strength on resonance.

Non-zero interaction at the frequency protected from relaxation into the waveguide.



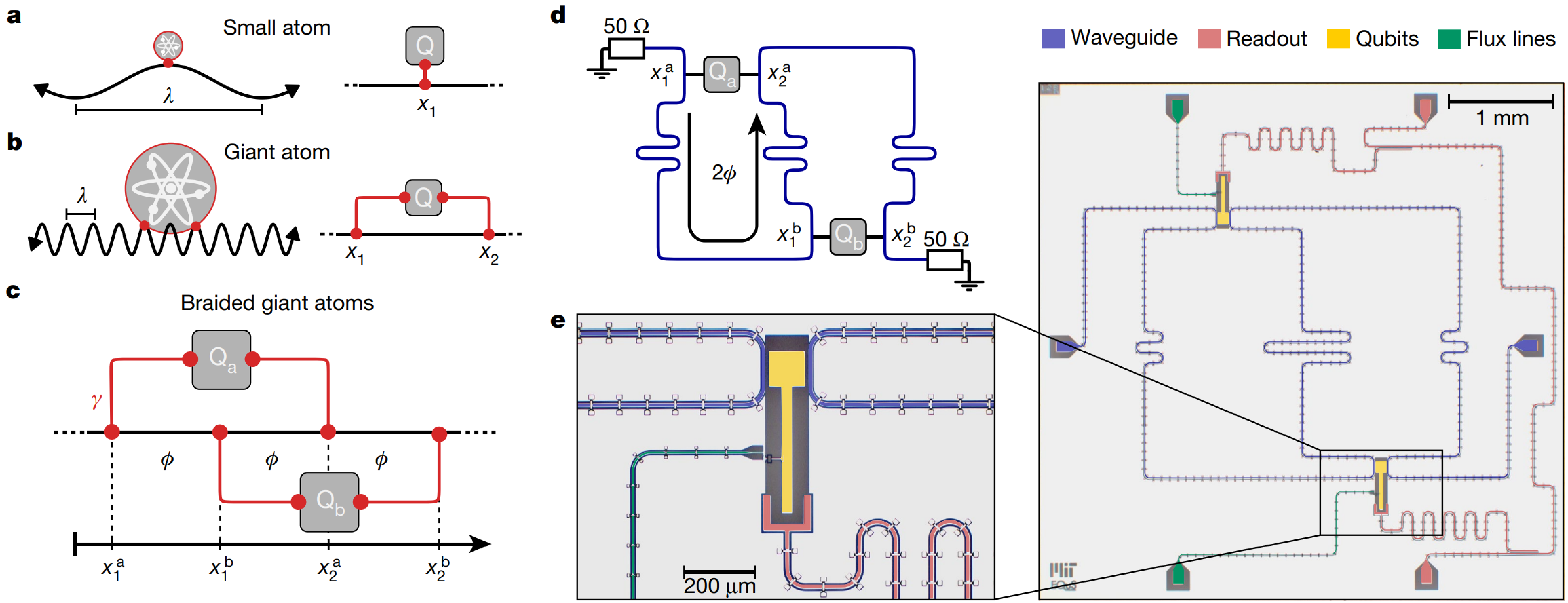
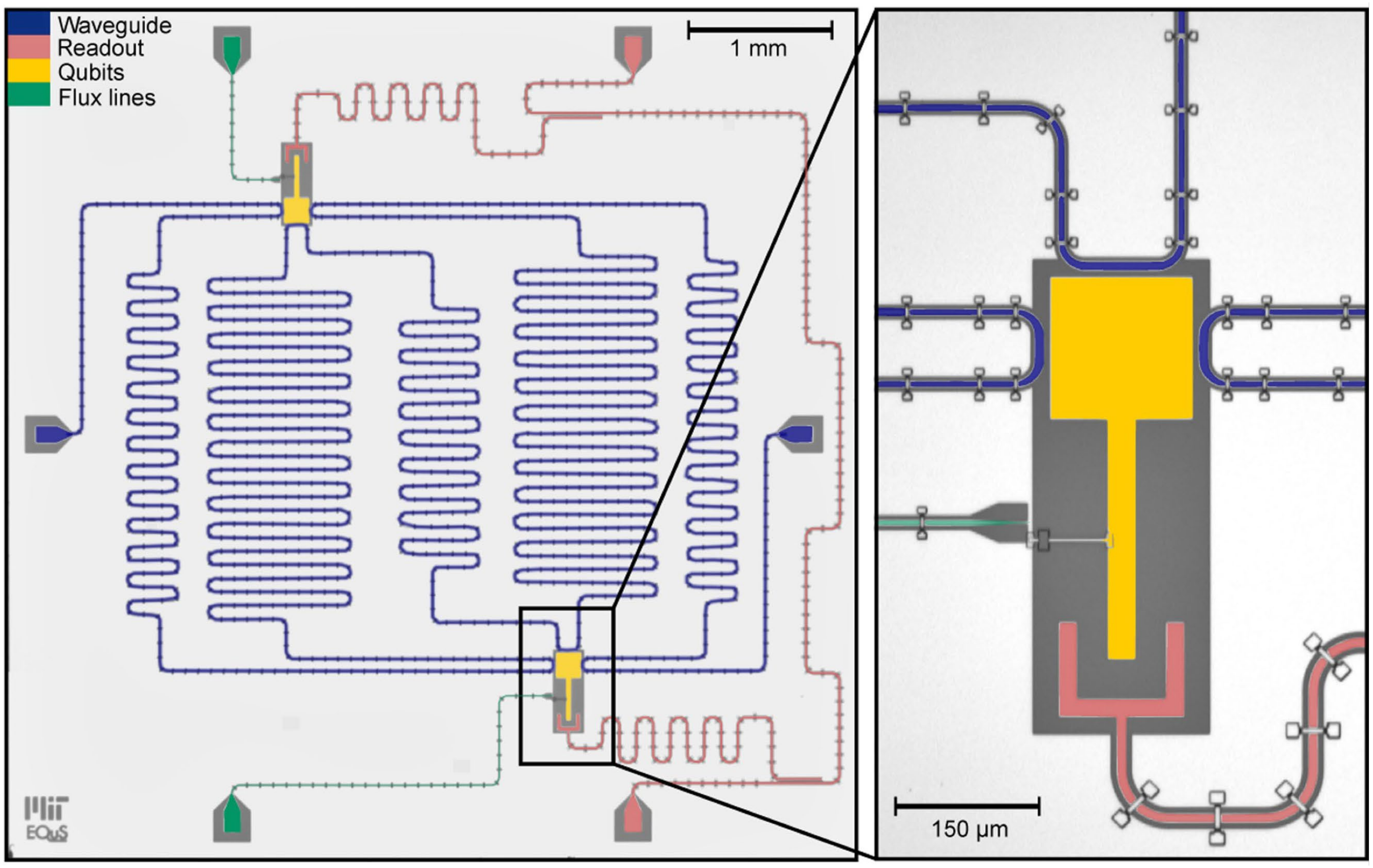
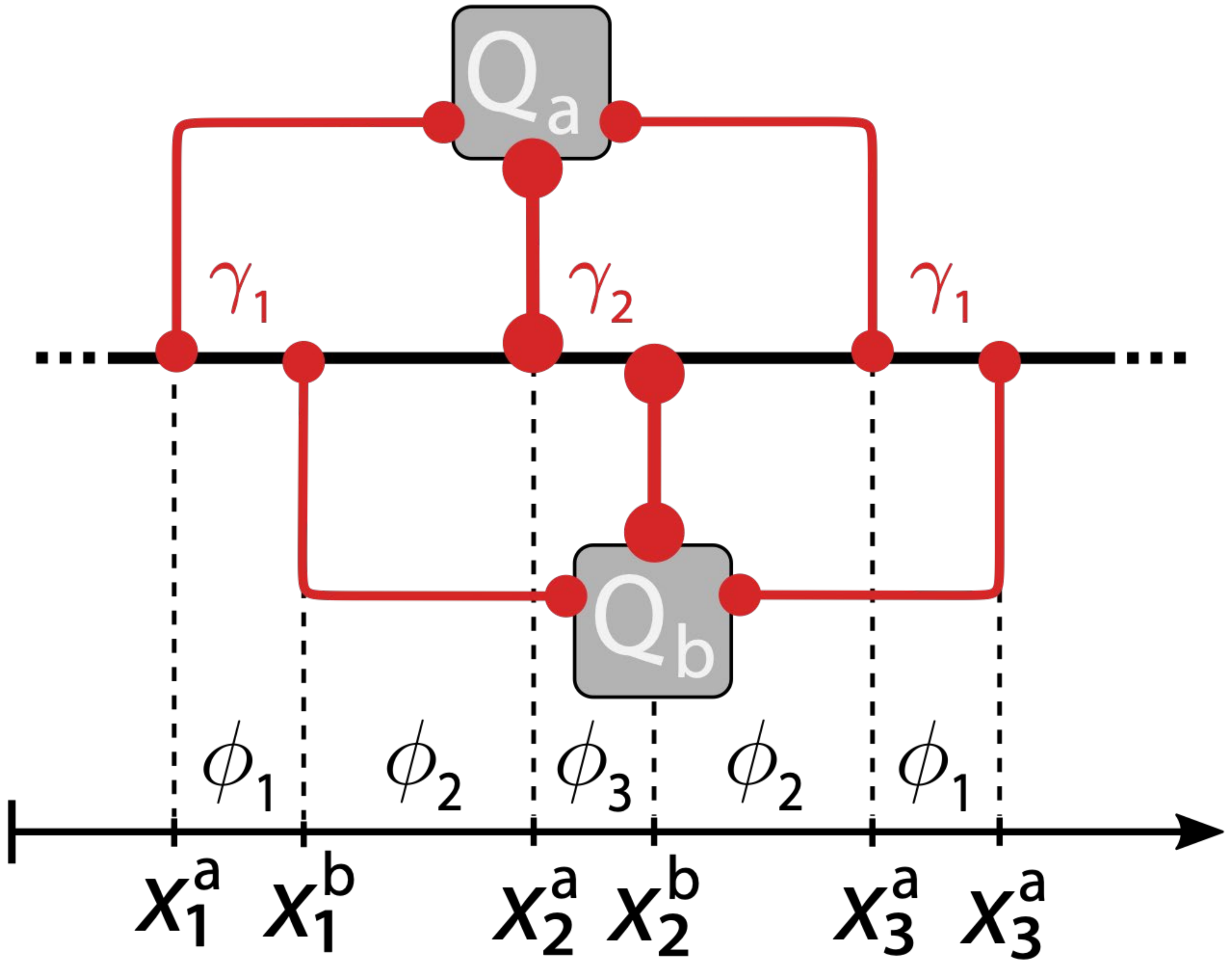


Fig. 1 | Giant atoms with superconducting qubits. a, A schematic diagram of a small atom. The small atom is treated as a point-like object because it is much smaller than λ, the wavelength of the mode it interacts with. **b**, A giant atom, formed by coupling a small atom to a mode at two discrete, distant locations. **c**, The configuration of two braided giant atoms, coupled twice to a waveguide with equal strength. The phase difference between coupling points $\phi = \omega(x_1^b - x_1^a)/v = \omega(x_2^a - x_1^b)/v = \omega(x_2^b - x_2^a)/v$ is varied by tuning the qubit frequencies ω. **d**, **e**, A schematic diagram (**d**) and a false-colour optical micrograph image (**e**) of a device in the configuration shown in **c**. Each qubit (yellow) has a readout resonator (red) and flux line (green) for independent readout and flux control. The central waveguide (blue) is terminated to 50 Ω.

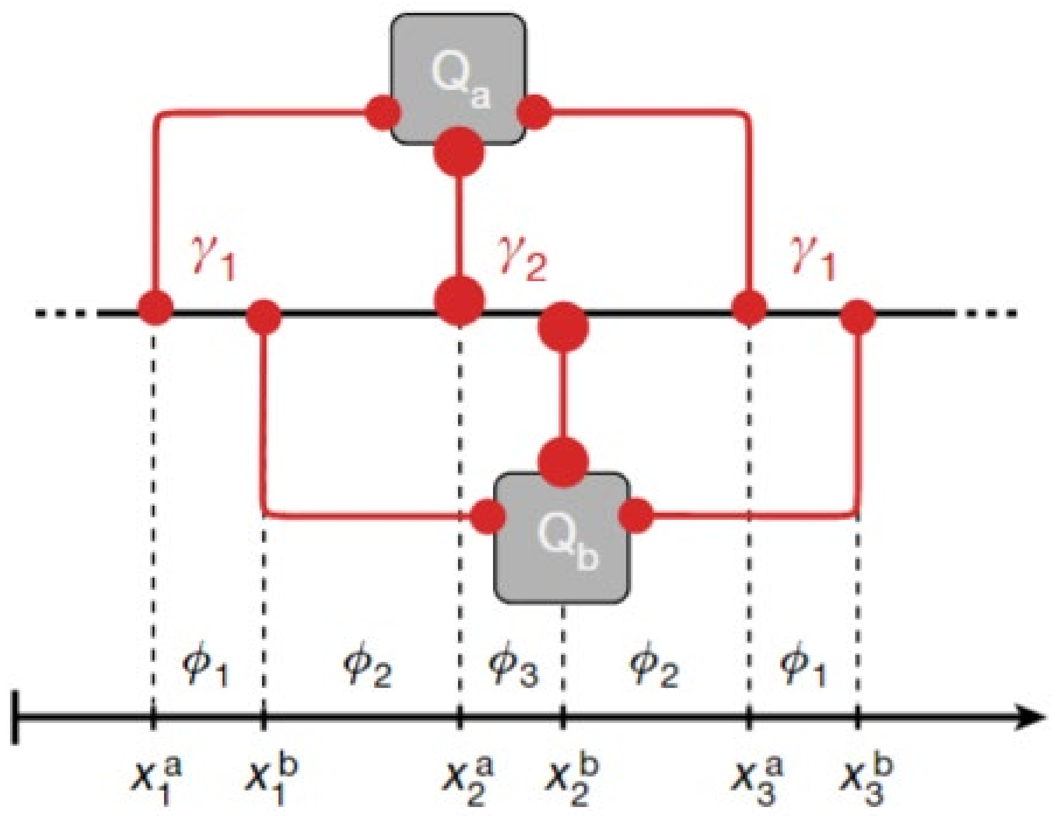
A design with three coupling points

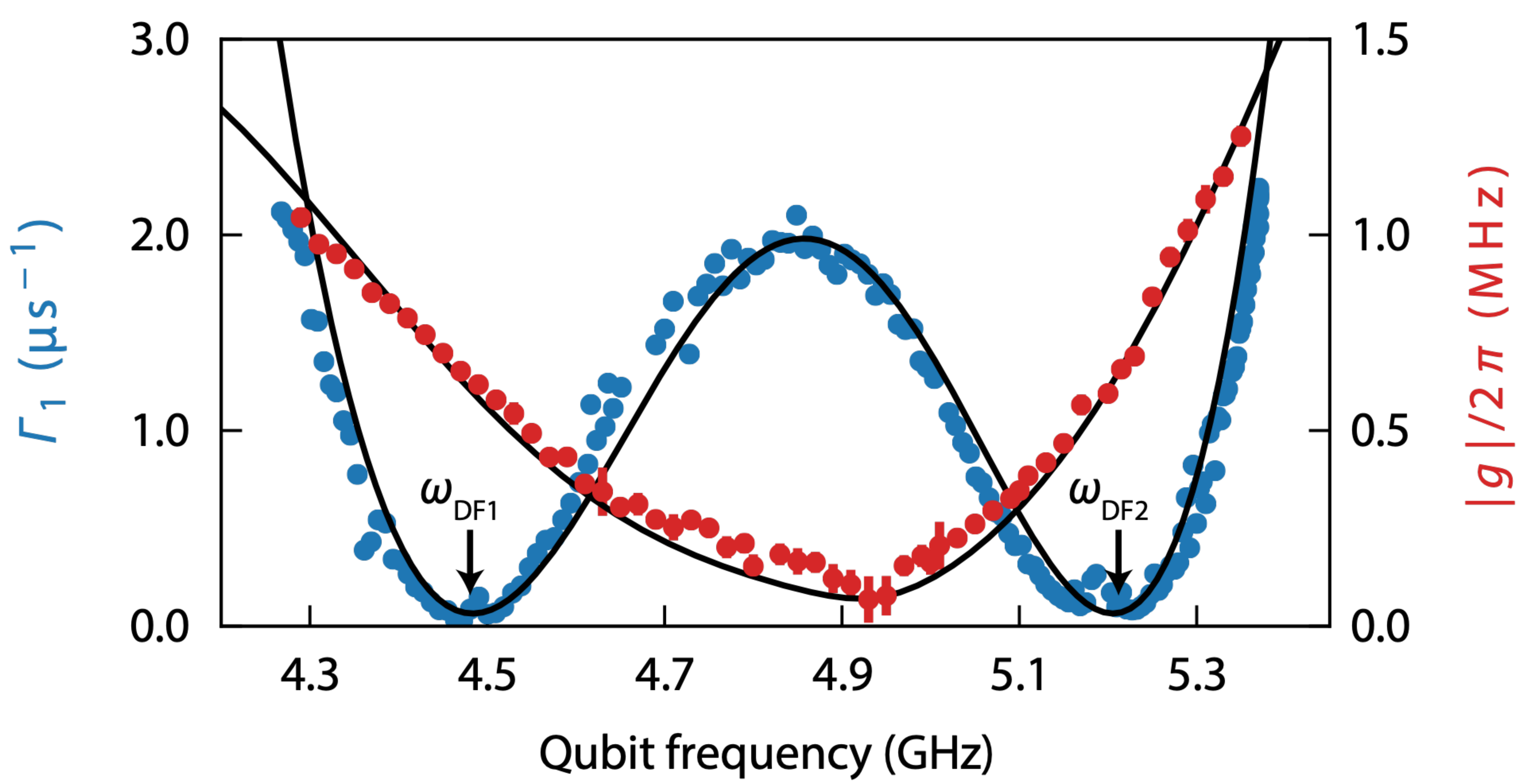




Unequal coupling strengths and spacings

The measured and fitted **single-qubit relaxation rates (blue)** and **resonant $\Delta = 0$ exchange-interaction strengths between Q_a and Q_b (red)** for the configuration of giant atoms shown here:



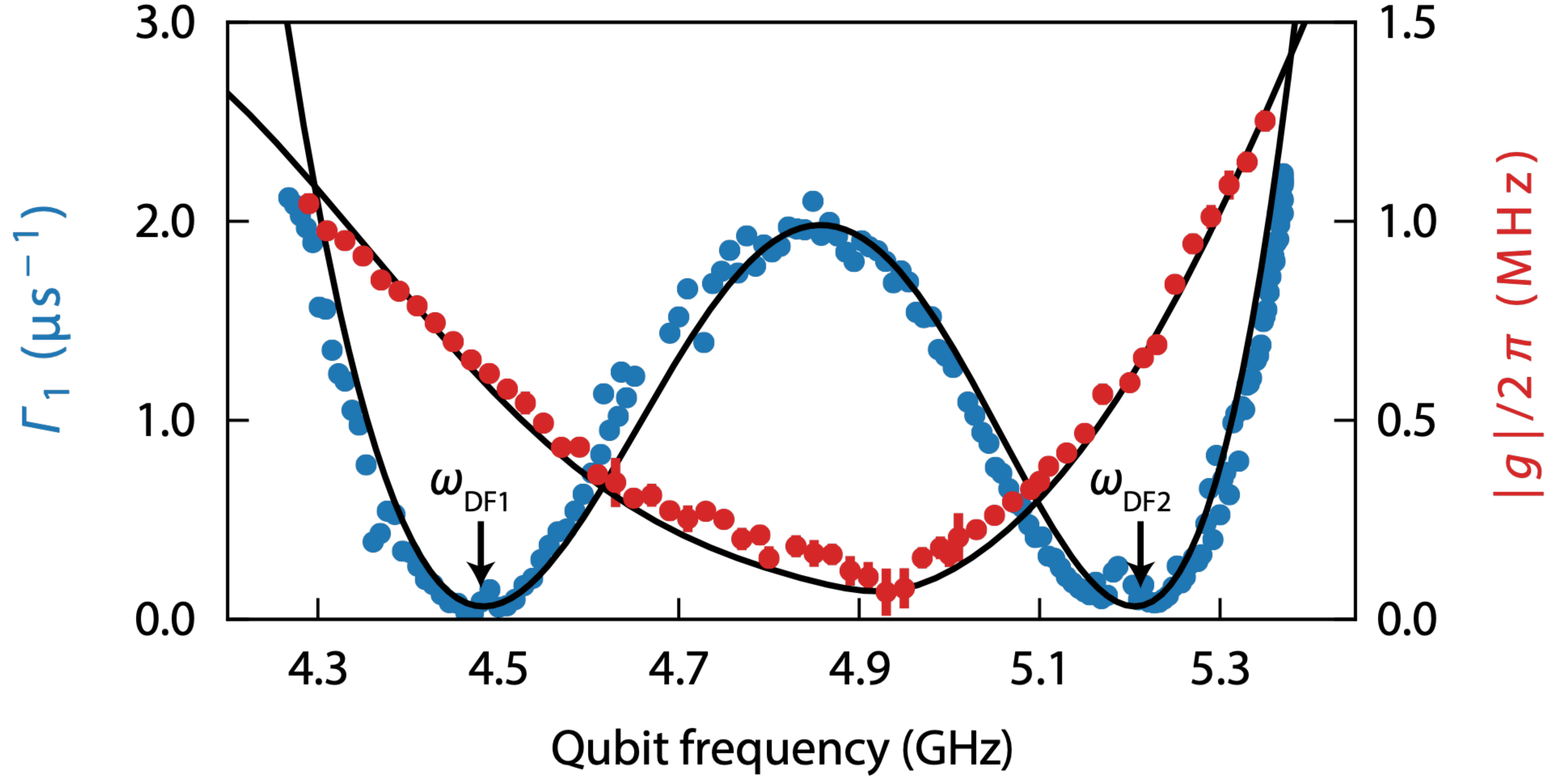


The error bars show the standard deviation of the fitted value; some errors are smaller than the symbol size.

The design has two decoherence-free frequencies at $\omega_{DF1} / 2\pi = 4.51$ GHz and $\omega_{DF2} / 2\pi = 5.23$ GHz.

The coupling strengths inferred from the fits are $\gamma_1 /2\pi = 1.58$ MHz and $\gamma_2 /2\pi = 3.68$ MHz at a reference frequency $\omega_0/2\pi = 5.23$ GHz.

Tunable protected interaction — universal gates

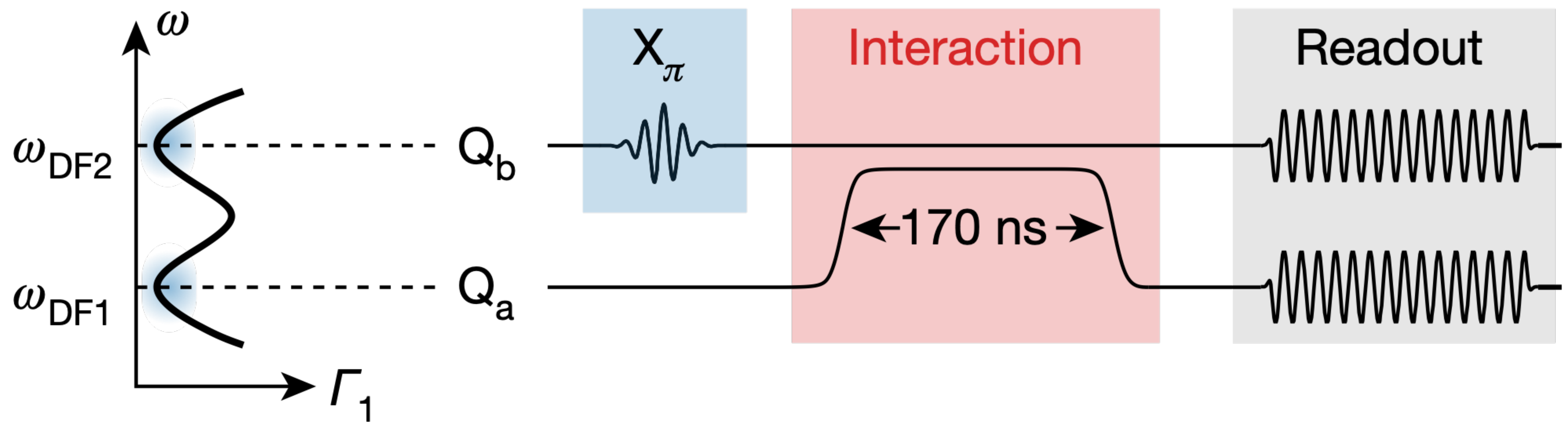


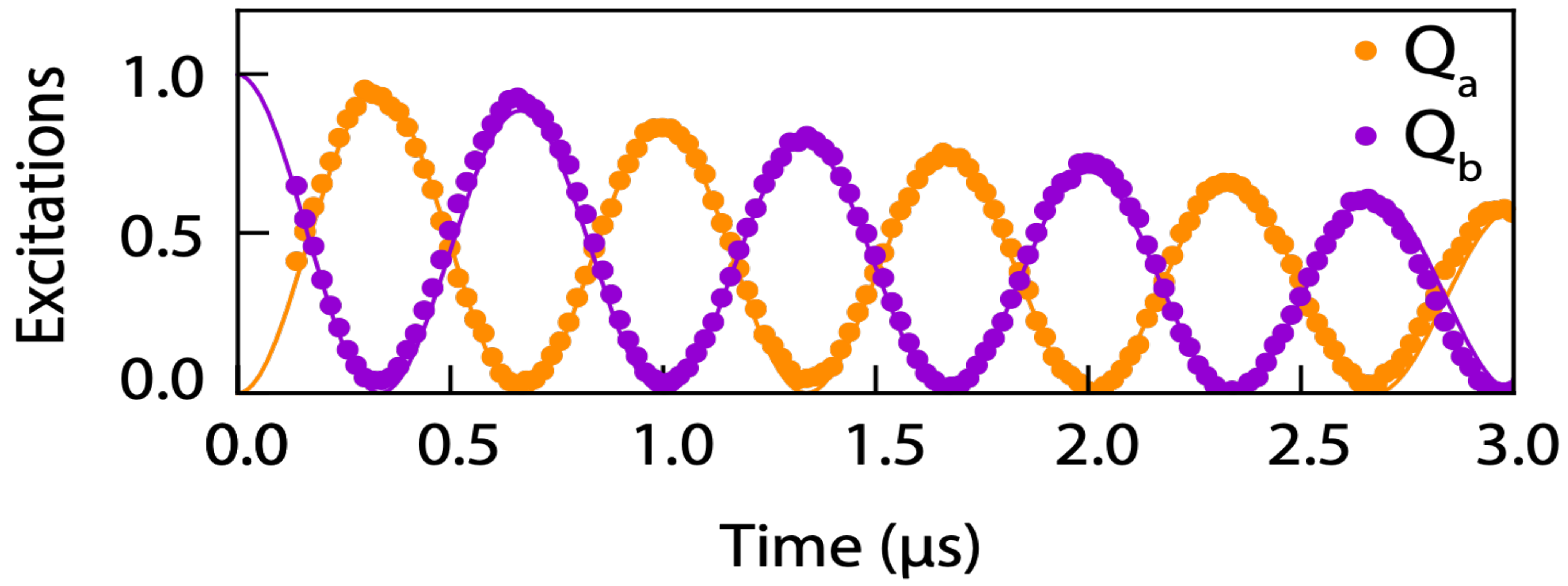
Two frequencies at which the qubits are protected from relaxation

Enables turning protected interaction on and off by detuning the qubits

$\sqrt{i\mathrm{SWAP}}$ preparing $(|01\rangle - i|10\rangle)/\sqrt{2}$ with 94% fidelity

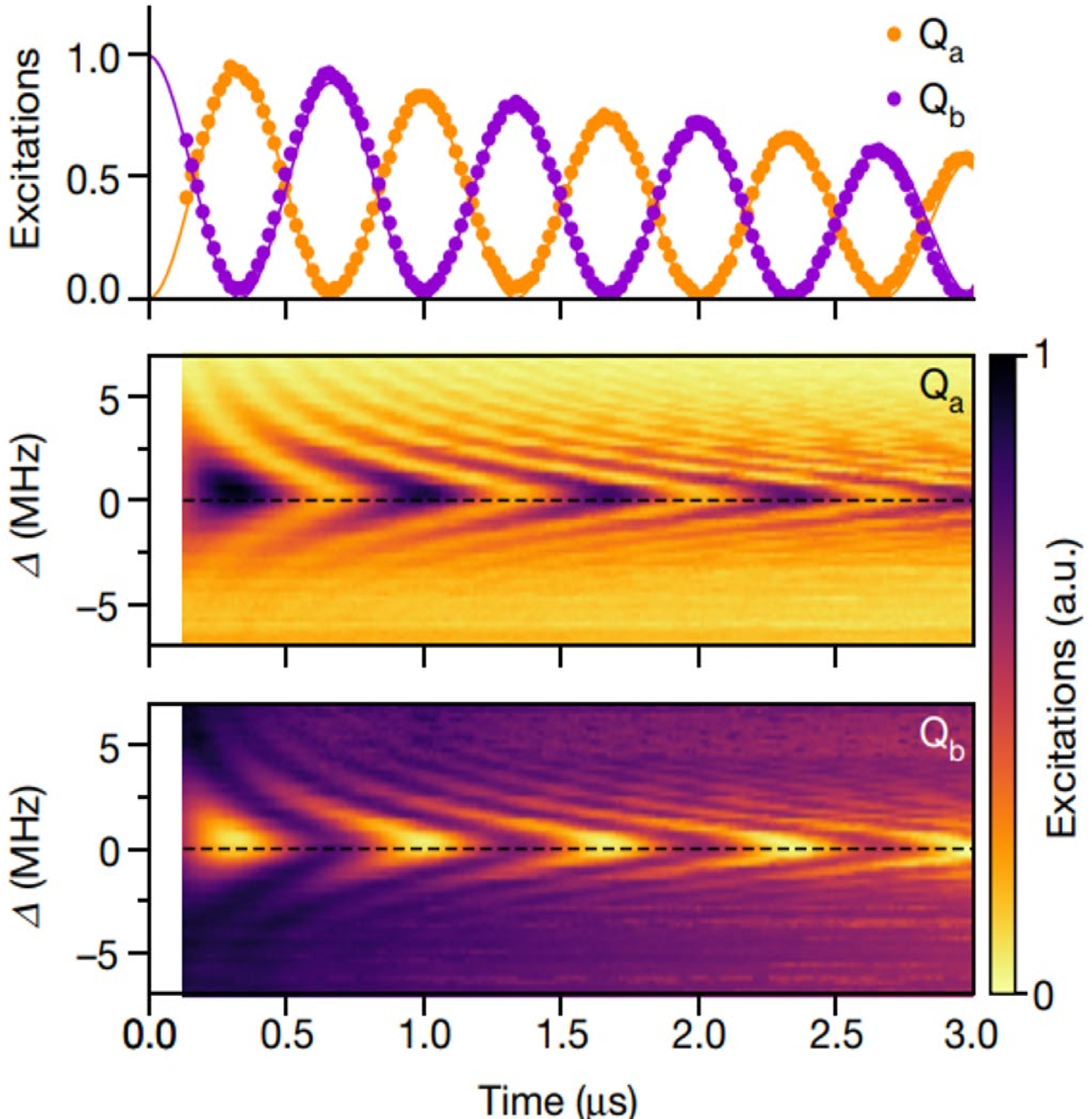
Universal gate set!





The time-domain chevron pattern **demonstrating the exchange coupling between the qubits** at the upper decoherence-free frequency ω_{DF2} as a function of interaction time and **qubit–qubit detuning Δ**.

The excitation will swap maximally with a period $\pi/g = 680$ ns when $\Delta = 0$ and is suppressed as $|\Delta|$ increases.



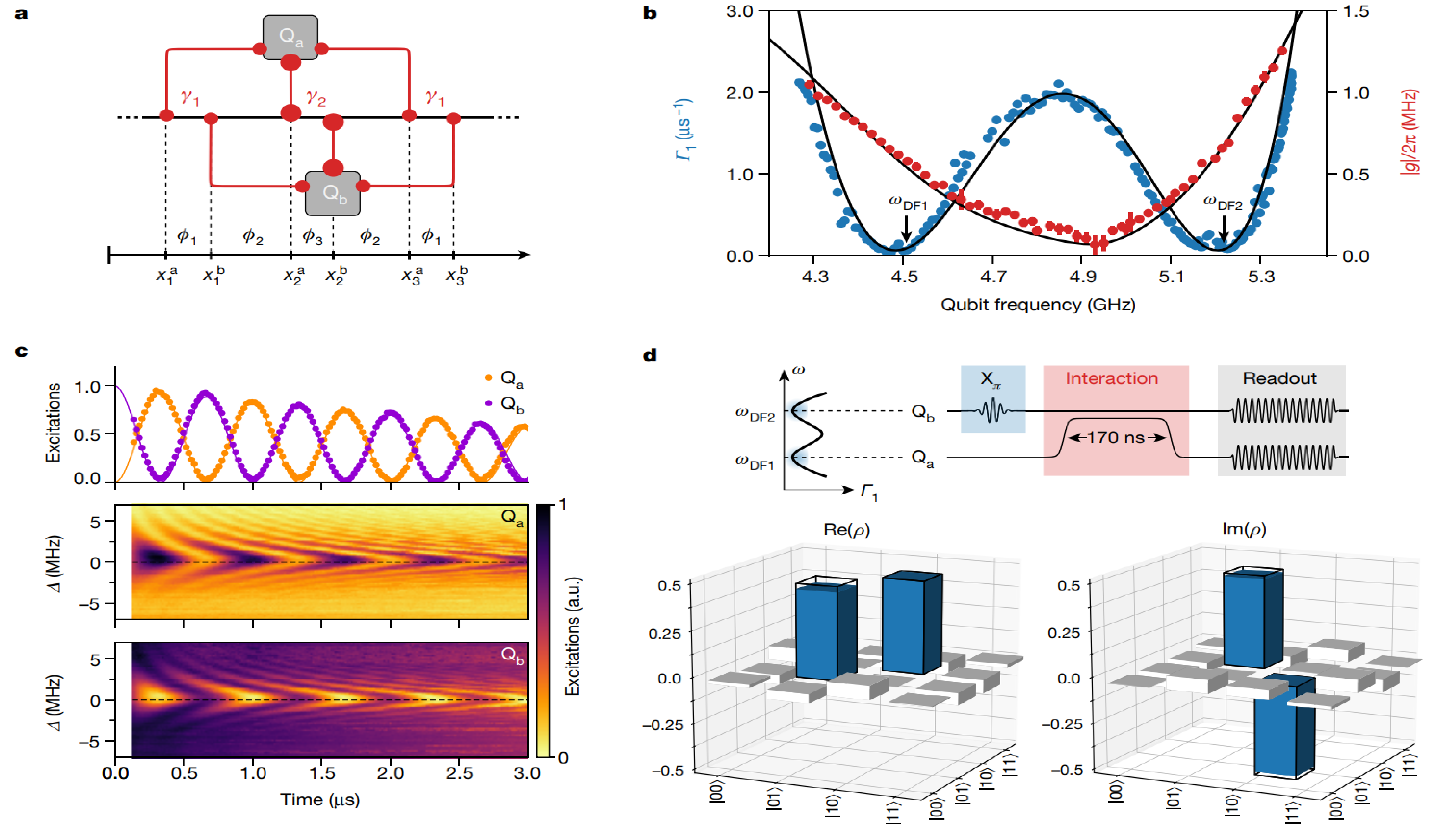


Fig. 4 | Entangling qubits in waveguide QED with engineered giant-atom geometries. a, A schematic diagram of a giant-atom device with two qubits coupled to the waveguide at three points. The first and last coupling points for each qubit are designed to be equal in strength (γ_1), and the central coupling point is larger ($\gamma_2 > \gamma_1$). The ratios ϕ_1/ϕ_2, ϕ_1/ϕ_3 and ϕ_2/ϕ_3 are fixed in hardware by the relative length of the waveguide segments. **b**, The measured and fitted single-qubit relaxation rates (blue) and resonant $\Delta = 0$ exchange-interaction strengths between Q_a and Q_b (red) for the configuration of giant atoms shown in **a**. The error bars show the standard deviation of the fitted value; some errors are smaller than the symbol size. The design has two decoherence-free frequencies at $\omega_{DF1}/2\pi = 4.51$ GHz and $\omega_{DF2}/2\pi = 5.23$ GHz. The coupling strengths inferred from the fits are $\gamma_1/2\pi = 1.58$ MHz and $\gamma_2/2\pi = 3.68$ MHz at a reference frequency $\omega_0/2\pi = 5.23$ GHz. **c**, The time-domain chevron pattern demonstrating the exchange coupling between the qubits at the upper decoherence-free frequency ω_{DF2} as a function of interaction time and qubit–qubit detuning Δ. The excitation will swap maximally with a period $\pi/g = 680$ ns when $\Delta = 0$ and is suppressed as $|\Delta|$ increases. **d**, Top, the pulse sequence for preparing the entangled state $(|01\rangle - i|10\rangle)/\sqrt{2}$. Q_a is placed at ω_{DF1}, and Q_b is placed at ω_{DF2} and excited with a π pulse. Q_a is then brought onto resonance $\Delta = 0$ and interacts with Q_b for a time $\pi/4g = 170$ ns. Q_a is then returned to ω_{DF1} and tomography readout pulses are applied. Bottom, the real and imaginary parts of the qubit density matrix obtained for this pulse sequence, with matrix elements—ideally non-zero—shaded in blue. The state-preparation fidelity is 94%.

Nature 583, pp. 775–779 (2020).

Article

Waveguide quantum electrodynamics with superconducting artificial giant atoms

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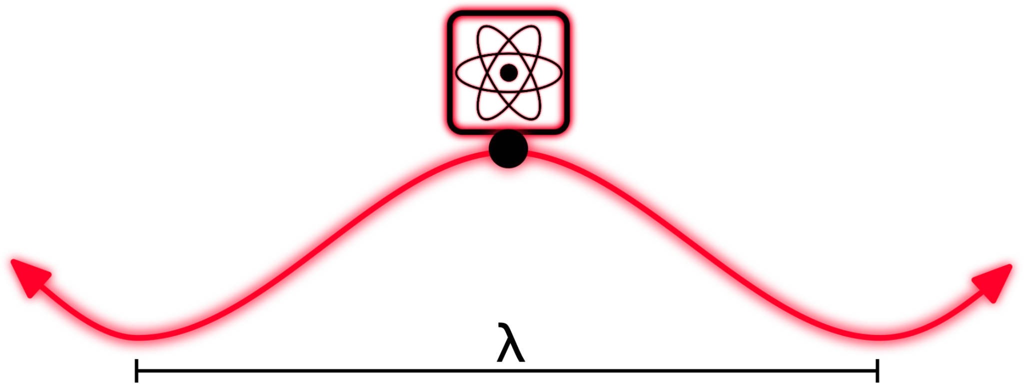
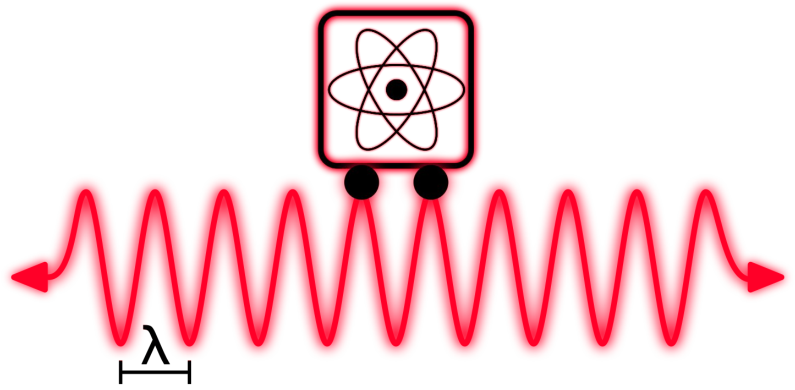
Bharath Kannan[1,2]✉, Max J. Ruckriegel[1], Daniel L. Campbell[1], Anton Frisk Kockum[3], Jochen Braumüller[1], David K. Kim[4], Morten Kjaergaard[1], Philip Krantz[1,8], Alexander Melville[4], Bethany M. Niedzielski[4], Antti Vepsäläinen[1], Roni Winik[1], Jonilyn L. Yoder[4], Franco Nori[5,6], Terry P. Orlando[1,2], Simon Gustavsson[1] & William D. Oliver[1,2,4,7]✉



Brief Summary



- Giant atom = atom coupled to a waveguide at multiple points, separated by (several or many) wavelengths.

- **Multiple coupling points** $\longrightarrow$ **interference effects** $\longrightarrow$ **designable frequency-dependent relaxation rate for a single giant atom.**

- **Two "braided" giant atoms can completely decouple their entire Hilbert space** (not just a single dark state) from the waveguide (no decay) but **still have a strong** (!) **exchange interaction** mediated by the waveguide. This is not possible with small atoms.

A few additional proposals for future experiments

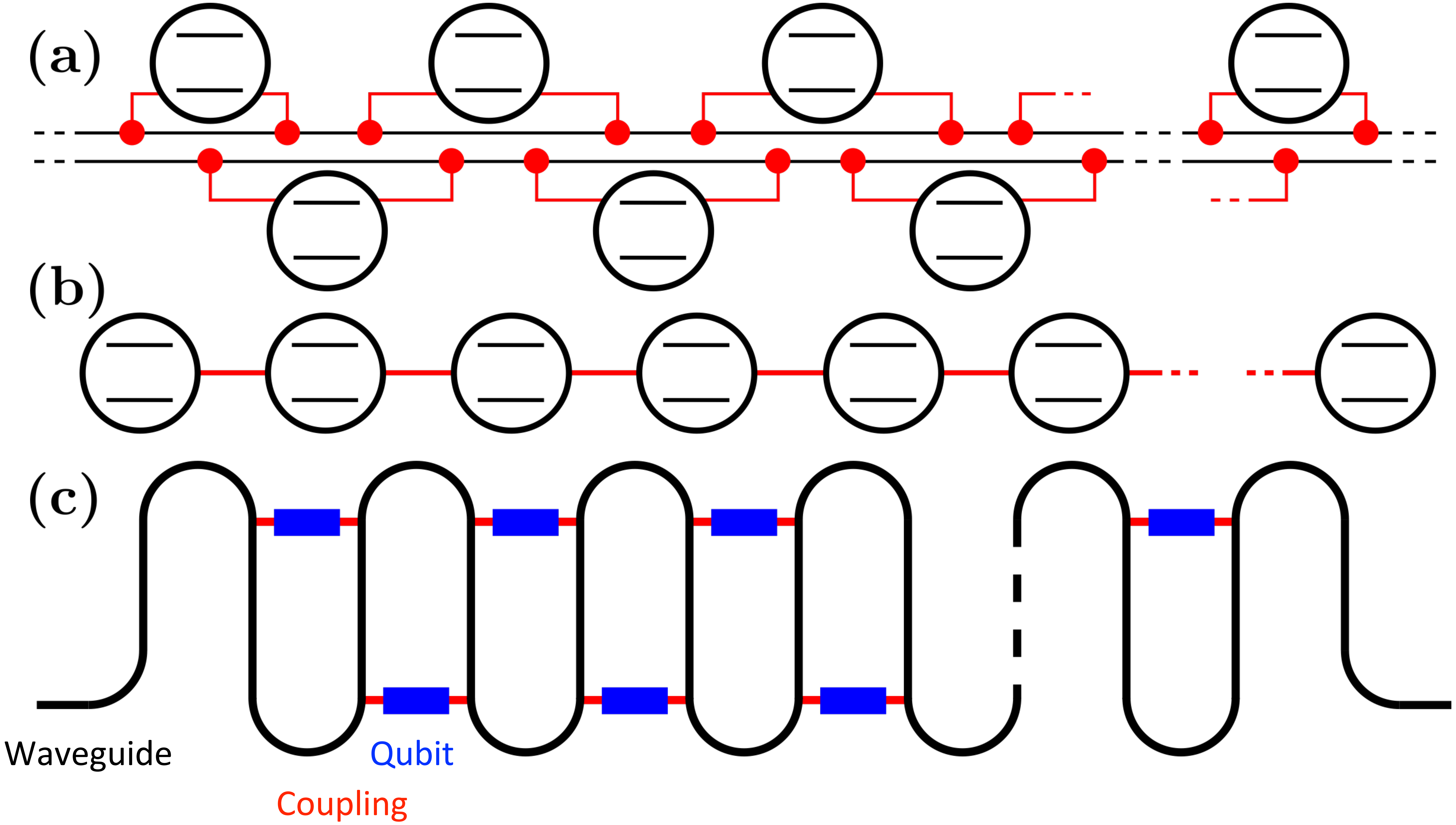
Setup for protected 1D spin chain

Intuition from two atoms generalizes to many since interactions are pairwise

The sign and amplitude of each nearest-neighbour coupling can be designed separately

$$g_{j,j+1} = \sqrt{\gamma_{(j+1)_1}\gamma_{j_2}} \sin \varphi_{(j+1)_1,j_2}$$

Space for readout and control lines for each qubit



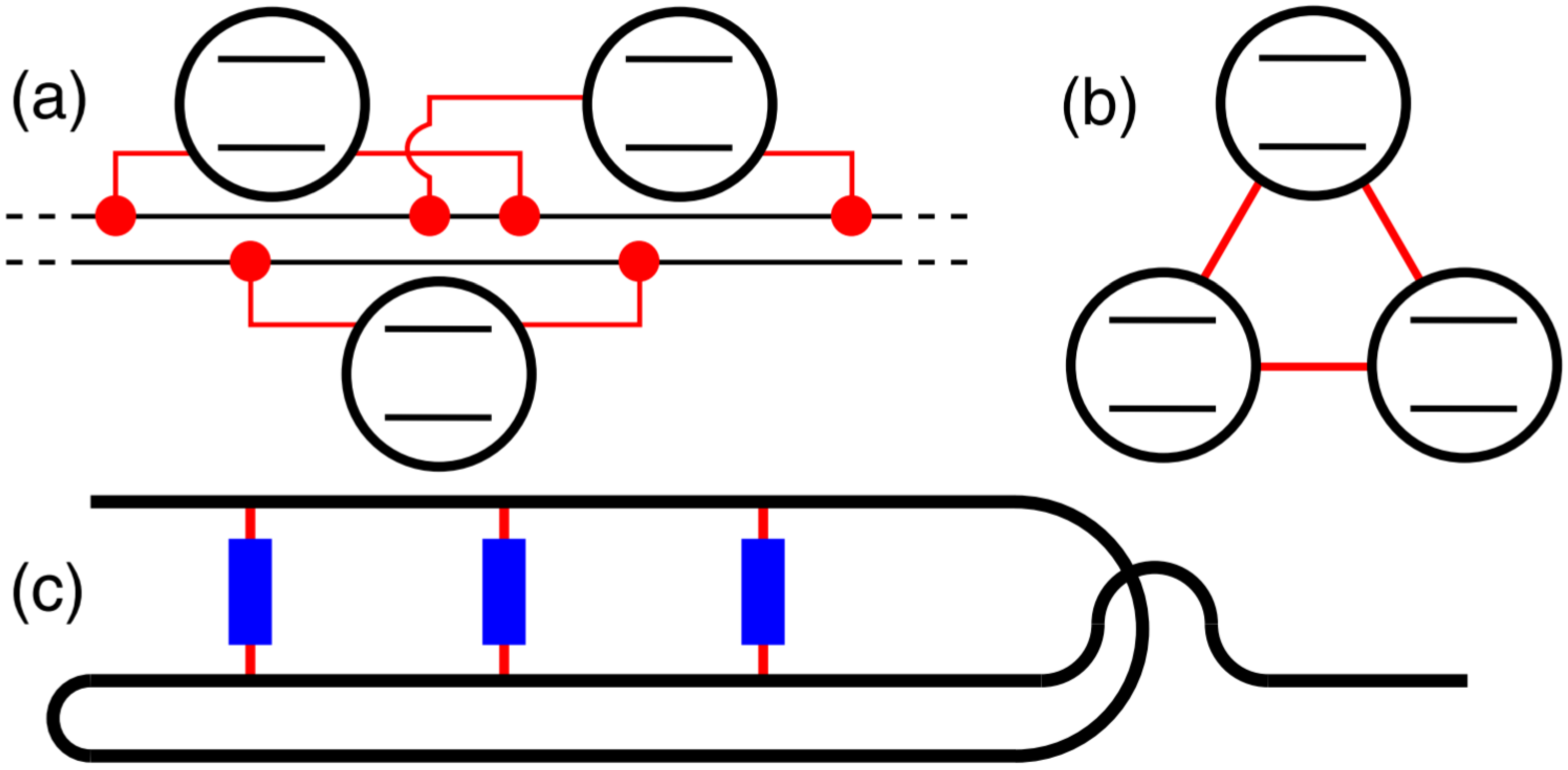
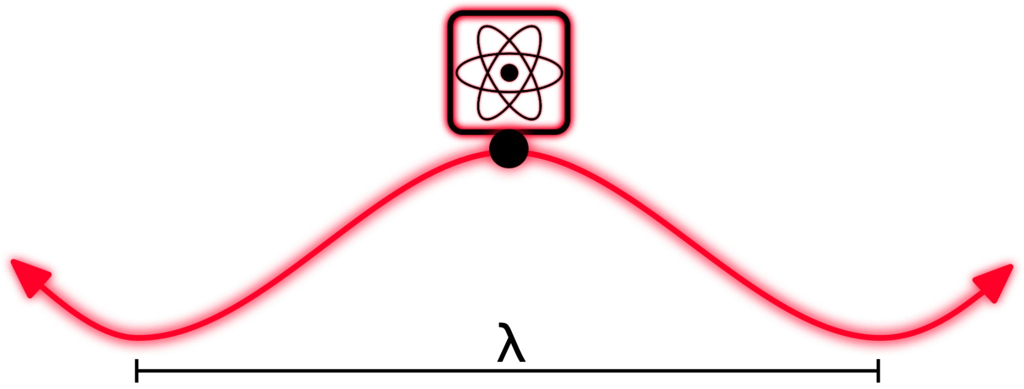
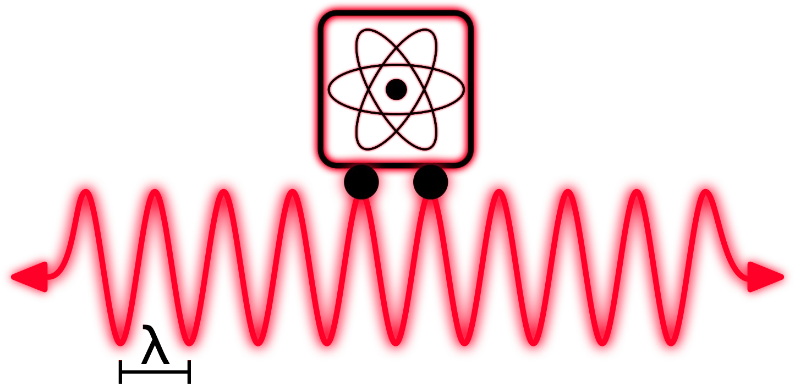


FIG. 4. Sketch of a setup with three giant atoms realizing protected all-to-all coupling. (a) The layout of the connection points. (b) The effective system. (c) A possible implementation with superconducting circuits. The symbols used are the same as in Fig. 3.



Brief Summary



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Outline

- Introduction — atom sizes and their history
- One giant atom — frequency-dependent relaxation rate
- Multiple giant atoms — decoherence-free interaction
- Chiral bound states
- Summary and outlook

Chiral bound states

Wang, Liu, Kockum, Li, and Nori, Phys. Rev. Lett. **126**, 043602 (2021)

We propose **tunable chiral bound states** in a system composed of superconducting giant atoms and a Josephson photonic-crystal waveguide (PCW), with no analog in other quantum setups.

The chiral bound states arise due to **interference in the nonlocal coupling of a giant atom to multiple points of the waveguide.**

The **chirality can be tuned** by changing either the atom-waveguide coupling or the external bias of the photonic-crystal waveguide.

Chiral bound states

Wang, Liu, Kockum, Li, and Nori, Phys. Rev. Lett. **126**, 043602 (2021)

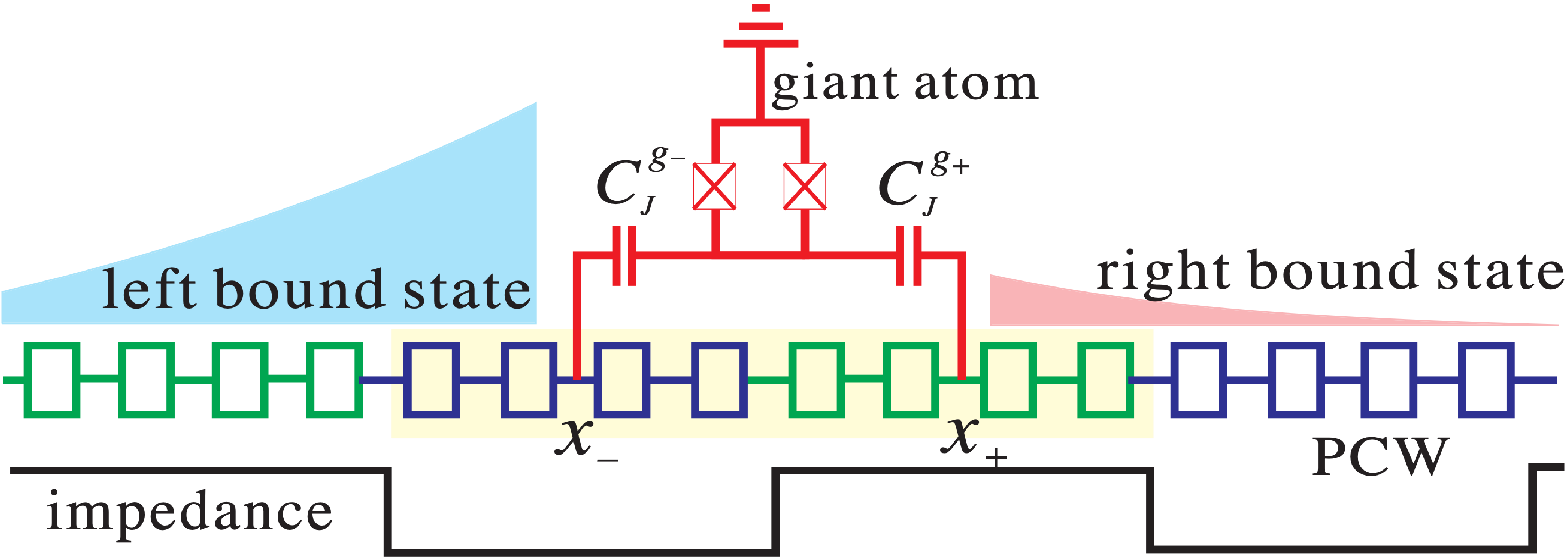
Furthermore, the **chiral bound states can induce directional dipole-dipole interactions** between multiple giant atoms coupling to the same waveguide.

Our proposal is ready to be implemented in experiments with superconducting circuits, where it can be used as a tunable toolbox to realize topological phase transitions.

Outline

- Introduction — atom sizes and their history
- Basics for giant atoms — frequency-dependent relaxation rate
- Adding time delay — creating oscillating bound states
- Modulating the waveguide — creating chiral bound states
- Summary and outlook

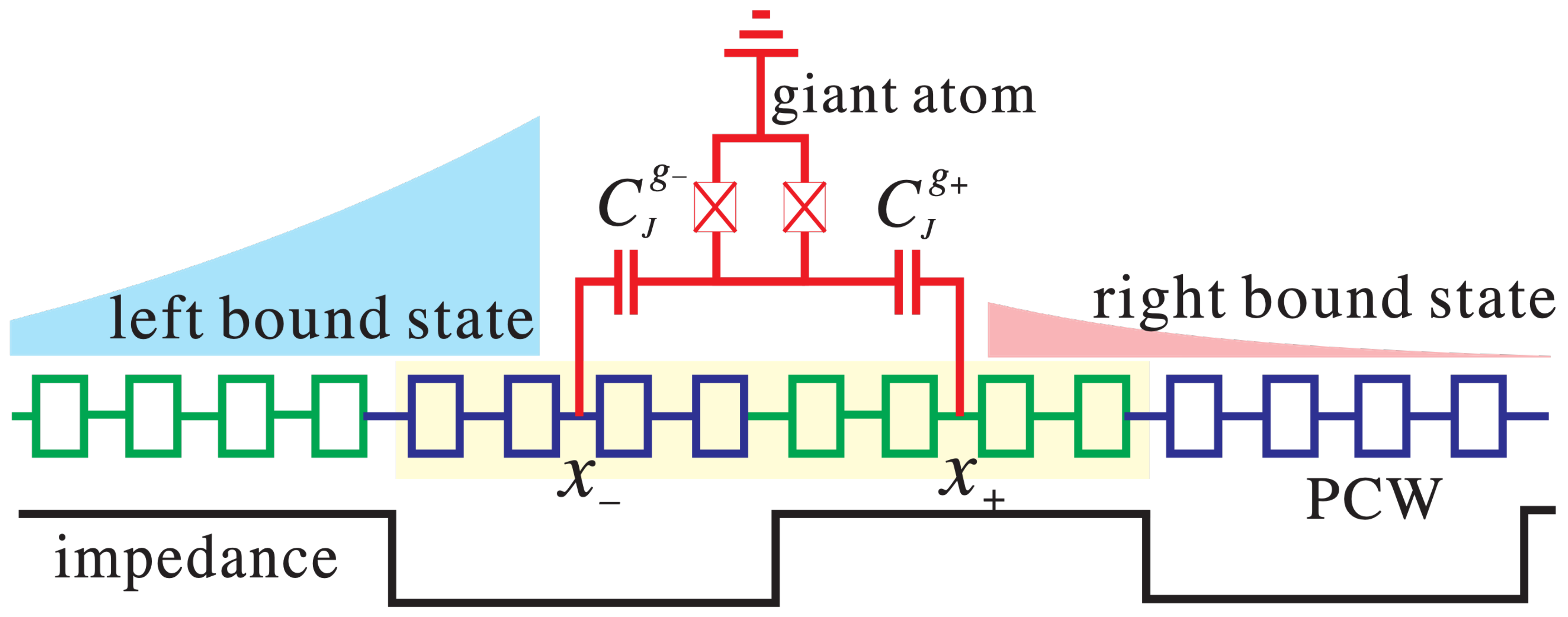
Setup with a modulated waveguide

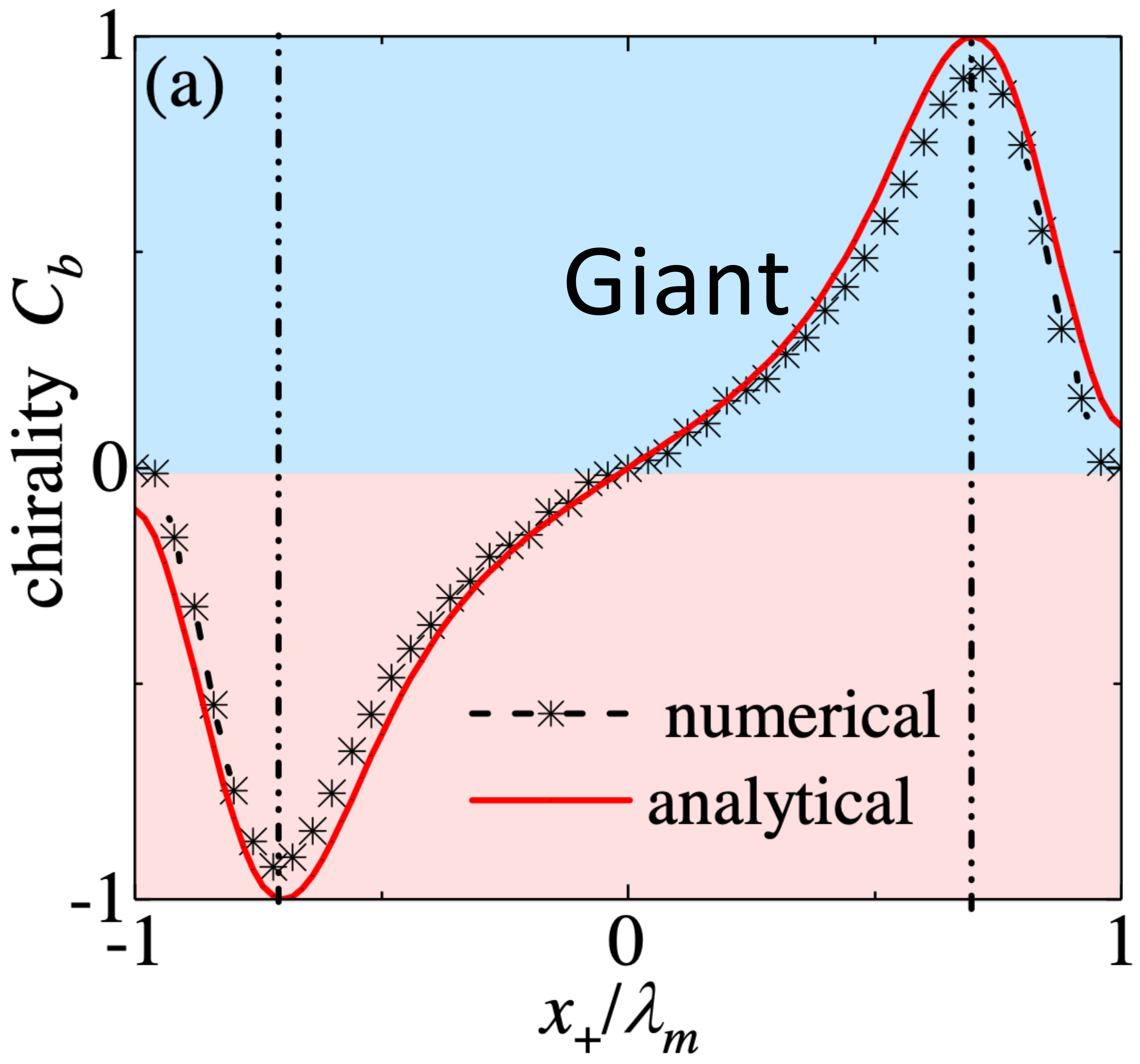


Waveguide impedance varying periodically in space, **enabling bound states** and also creating the opportunity to break translational symmetry

Wang et al., Phys. Rev. Lett. **126**, 043602 (2021)

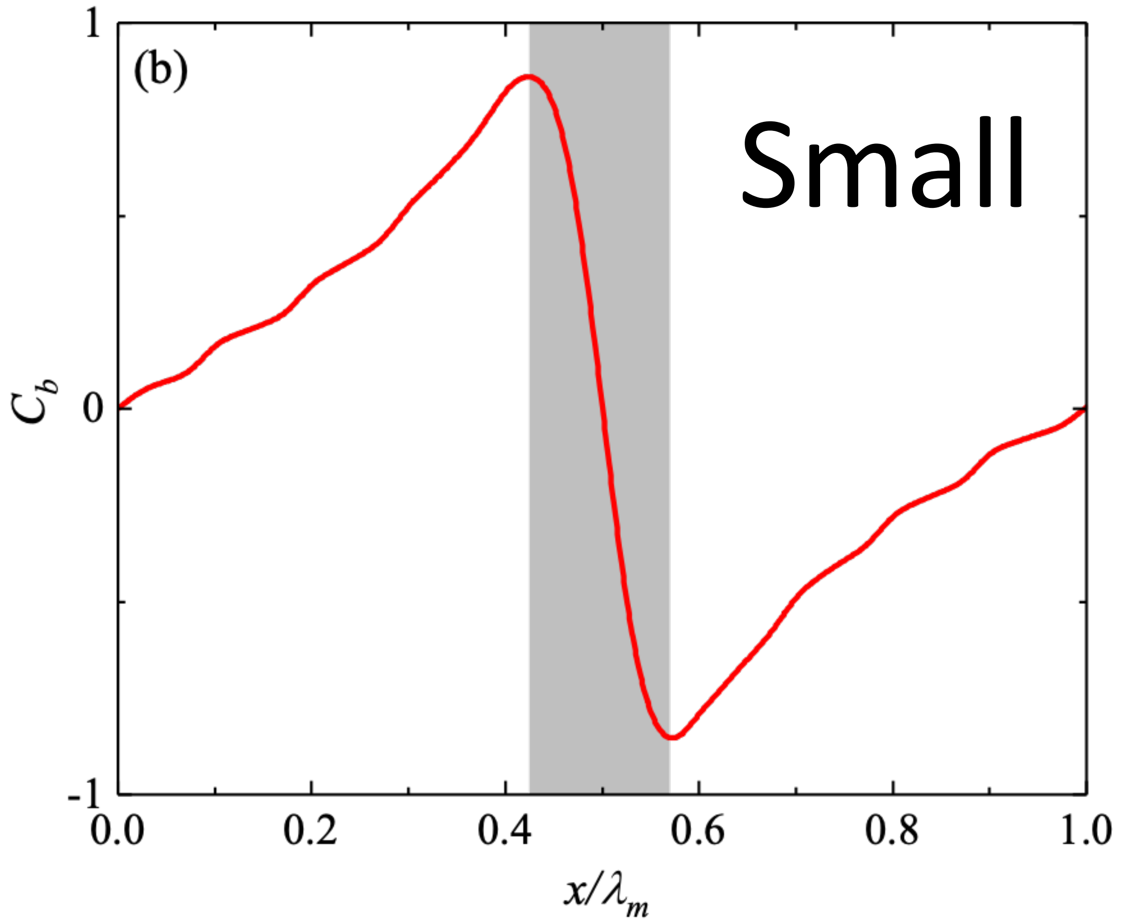
Quantifying the chirality of the bound state





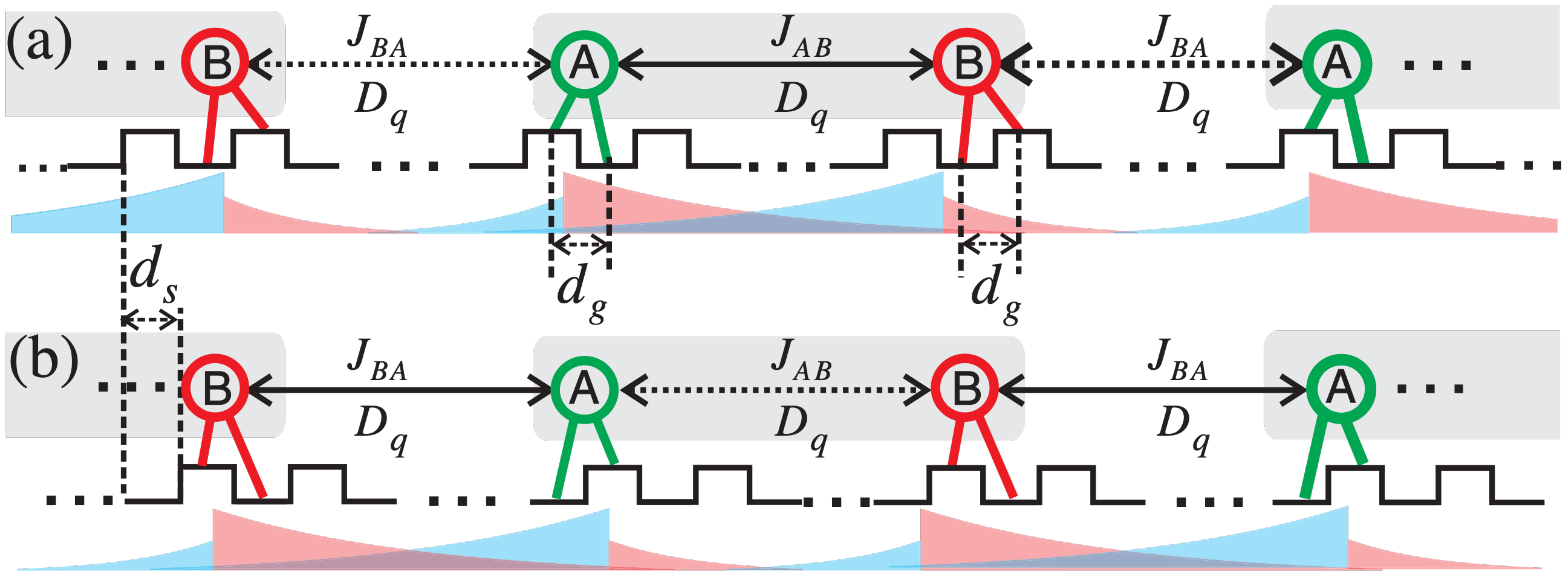
Chirality

$$C_b = \frac{\Phi_L - \Phi_R}{\Phi_L + \Phi_R}, \qquad \Phi_{R/L} = \left| \int_{\pm\infty}^{x_\pm} |\phi_b(x')|^2 dx' \right|$$



Fixing one coupling point at $x_- = 0$
Tuning the position of the other coupling point allows us to reach perfect chirality in both directions. But a small atom does not achieve perfect chirality.

Interaction between chiral bound states



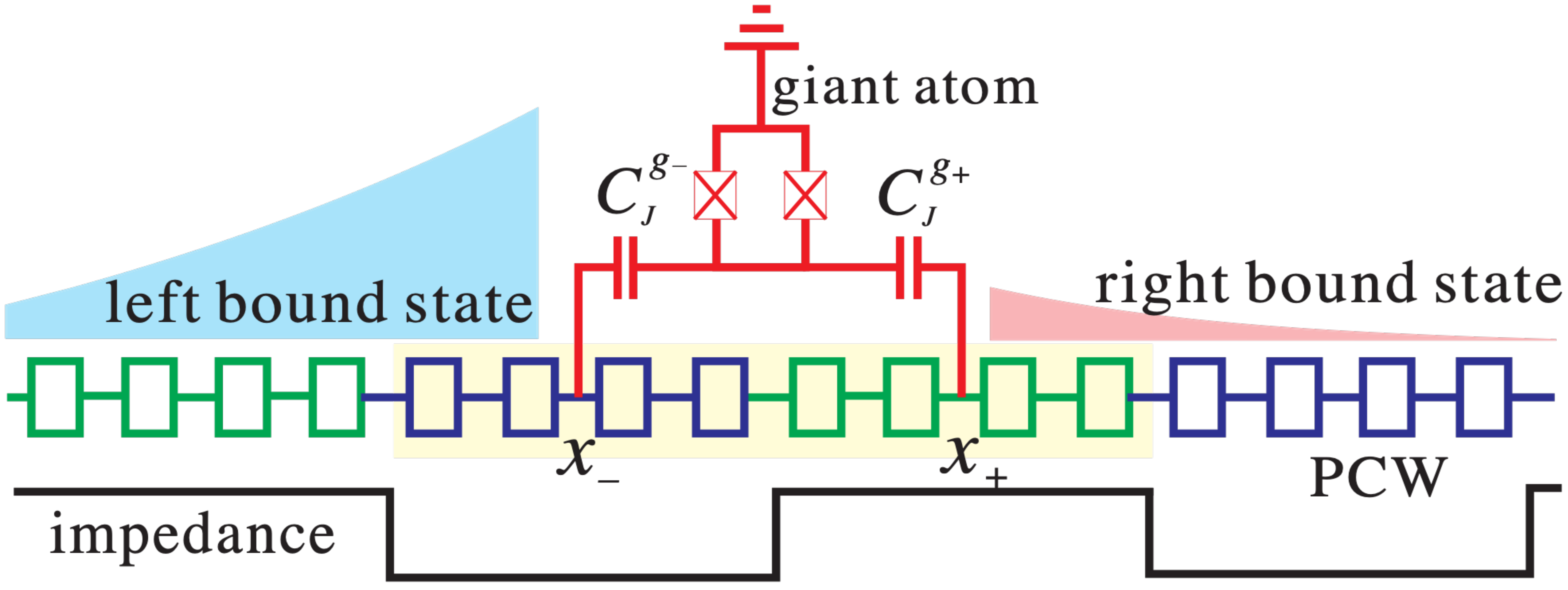
- The overlap between the states determines the strength of a protected exchange interaction between the atoms (just like for small atoms)
- With the chiral bound states, we can realize a Su-Schrieffer-Heeger model in this way
  [cf. Bello et al., Sci. Adv. **5**, eeaw0297 (2019); Kim et al., Phys. Rev. X **11**, 011015 (2021) for chiral bound states from SSH]
- Coupling directions can be switched by changing the waveguide modulation

Chiral bound states

Wang, Liu, Kockum, Li, and Nori, Phys. Rev. Lett. **126**, 043602 (2021)

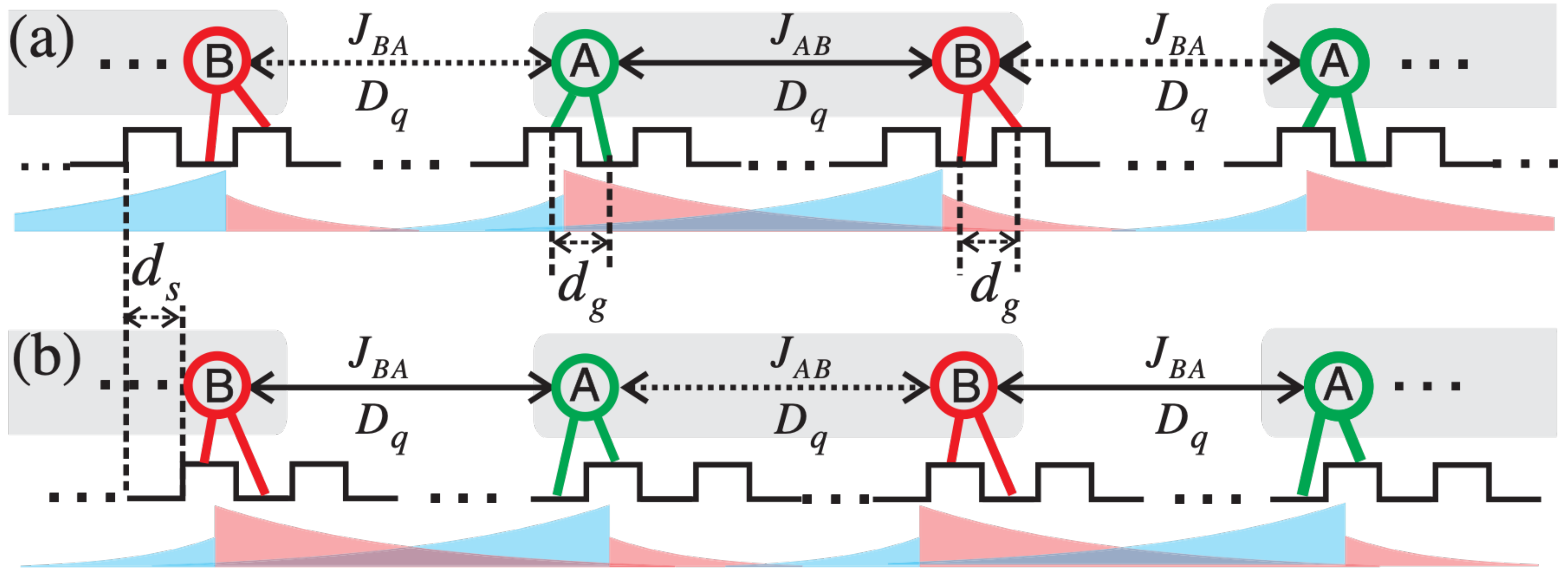
Giant atom coupled to a "Josephson photonic-crystal waveguide"

Some chirality in the bound state around a small atom, but interference in a giant atom enables perfect chirality



Su-Schrieffer-Heeger model

$$H_{\rm qc} = \sum_i [J_{AB}(t)\sigma_{Ai}^-\sigma_{Bi}^+ + J_{BA}(t)\sigma_{Bi}^-\sigma_{Ai+1}^+ + \text{H.c.}]$$
$$+ \sum_i \Delta_q(t)(\sigma_{Ai}^z - \sigma_{Bi}^z),$$



Outline

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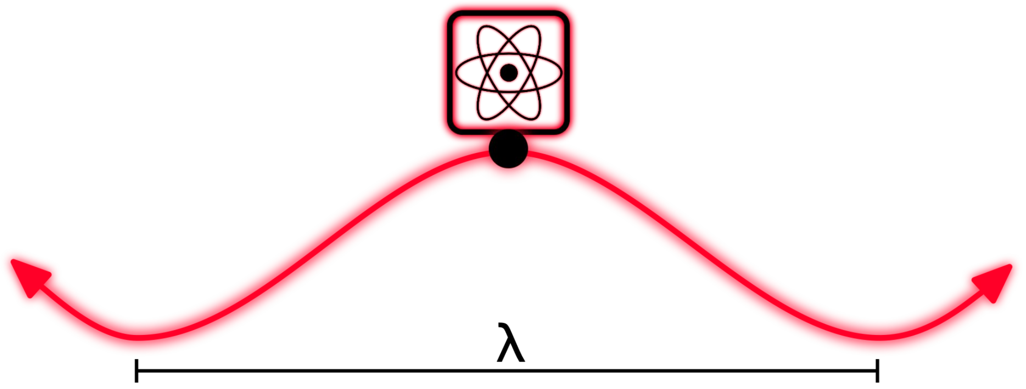
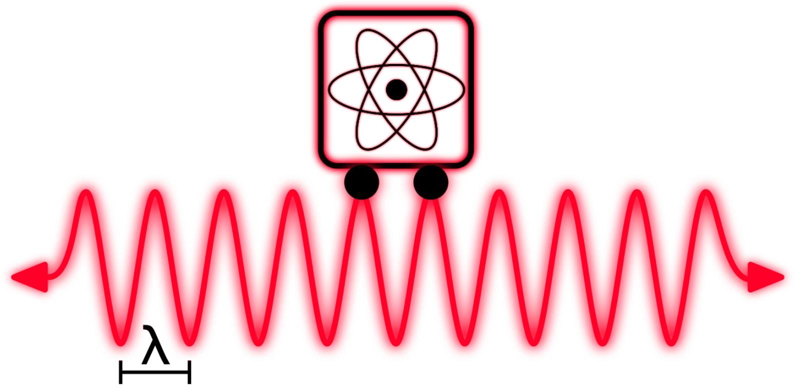
- One giant atom — frequency-dependent relaxation rate
- Multiple giant atoms — decoherence-free interaction
- Chiral quantum optics and giant atoms
- Chiral bound states
- Summary and outlook

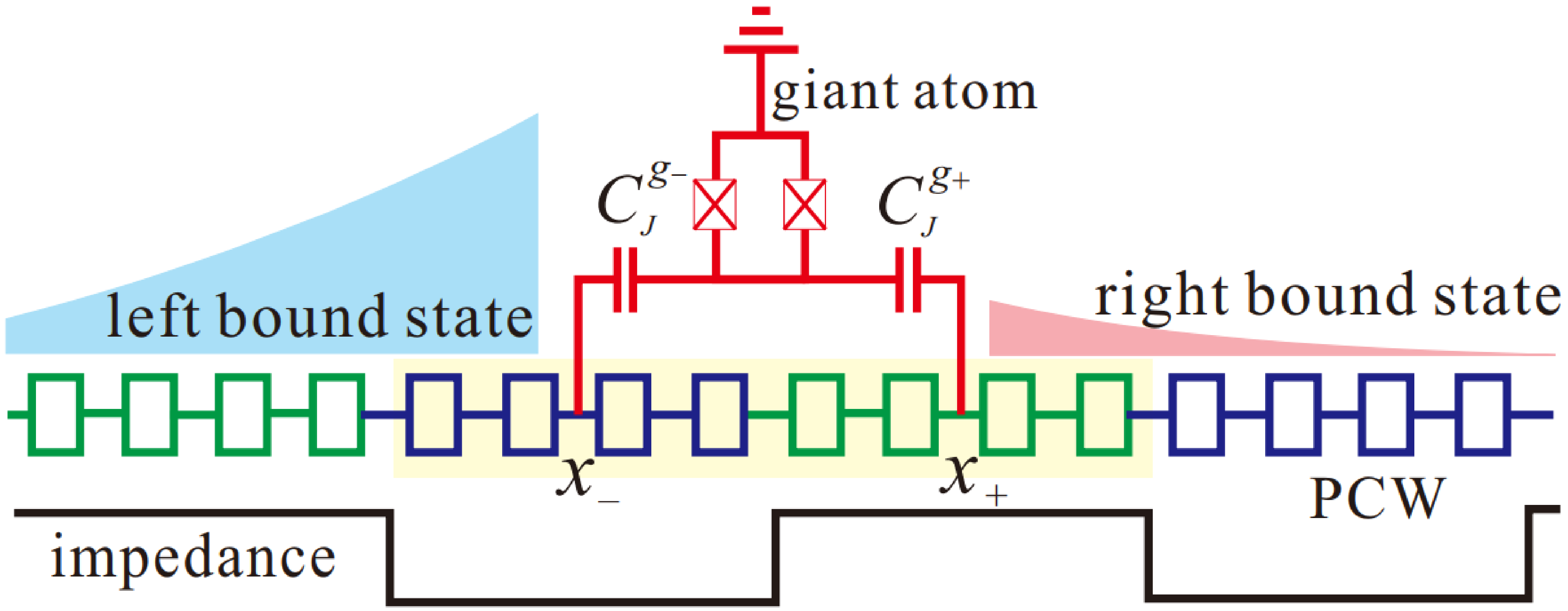


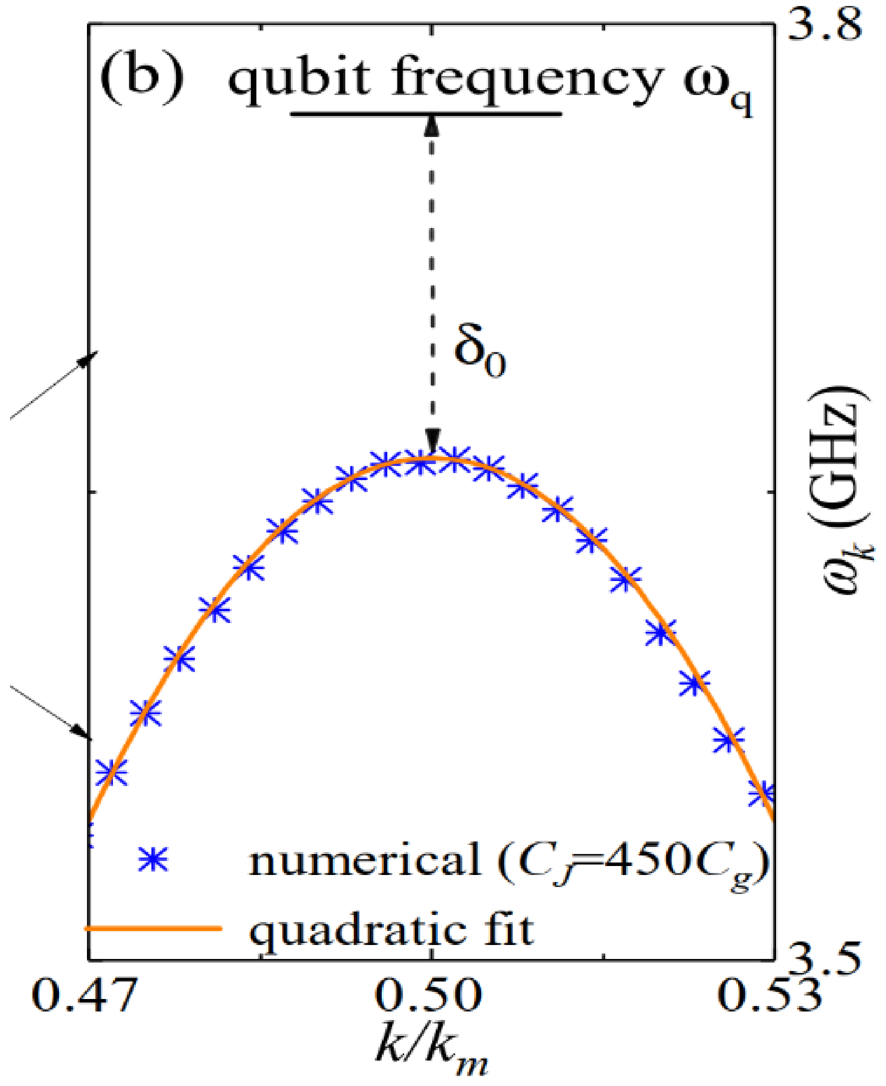
Summary and outlook



- Giant atom = atom coupled to a waveguide at multiple points, separated by wavelengths
- **Multiple coupling points $\rightarrow$ interference effects $\rightarrow$ designable frequency-dependent relaxation rate for a single giant atom**
- **Two "braided" giant atoms can completely decouple** their entire Hilbert space (not just a single dark state) from the waveguide (no decay) **but still have a strong (!) exchange interaction** mediated by the waveguide. This is not possible with small atoms.
- The decoherence-free interaction survives if the coupling to the waveguide is chiral. Giant atoms can have dark states in the chiral setting, which small atoms cannot.
- Giant atoms coupled to a waveguide with a band structure can have perfectly chiral bound states.
- Outlook: do other phenomena in waveguide QED change when making atoms giant?

Chiral bound state





The superconducting giant atom interacts with the SQUID-PCW at two points $x_\pm$:

$$H_{\mathrm{int}} = \sum_{k\in\mathrm{BZ}} \Delta_k (a_k^\dagger a_k) + \sum_{k\in\mathrm{BZ}} (g_k a_k^\dagger \sigma_- + g_k^* a_k \sigma_+),$$

The interacting strength with mode k are contributed by two coupling points：

$$g_k = \sum_{i=\pm} g_k^i e^{ikx_i} u_k(x_i), \quad g_k^\pm = \frac{e}{\hbar}\frac{C_J^{g\pm}}{C_\Sigma}\sqrt{\frac{\hbar\omega(k)}{C_t}} \simeq \frac{e}{\hbar}\frac{C_J^{g\pm}}{C_\Sigma}\sqrt{\frac{\hbar\omega_q}{C_t}},$$

The bound state is derived from the following equations:

$$|\psi_b\rangle = \cos(\theta)|e,0\rangle + \sin\theta \sum_k c_k |g,1_k\rangle,$$

$$c_k = \frac{g_k}{\tan\theta(\epsilon_b - \Delta_k)},$$

$$\epsilon_b = \sum_{k\in\mathrm{BZ}} \frac{|g_k|^2}{(\epsilon_b - \Delta_k)},$$

$$\tan\theta = \sum_{k\in\mathrm{BZ}} \frac{|g_k|^2}{(\epsilon_b - \Delta_k)^2}.$$

The photonic part in the real space is

$$\phi_b(x) = \sin\theta \langle x| \sum_{k\in\mathrm{BZ}} c_k a_k^\dagger |0\rangle$$
$$= \sum_{k\in\mathrm{BZ}} \frac{c_k \sin\theta}{\sqrt{L}} \int dx' \langle x| e^{-ikx'} u_k^*(x') \phi^\dagger(x')|0\rangle.$$

Chiral bound state

Different from small atom, each coupling point in giant atoms produces a local photonic bound state. Those spatially separated sub-bound-states interfere with each other due to phase difference.

$$\phi_b(x) = \phi_b^+(x) + \phi_b^-(x),$$

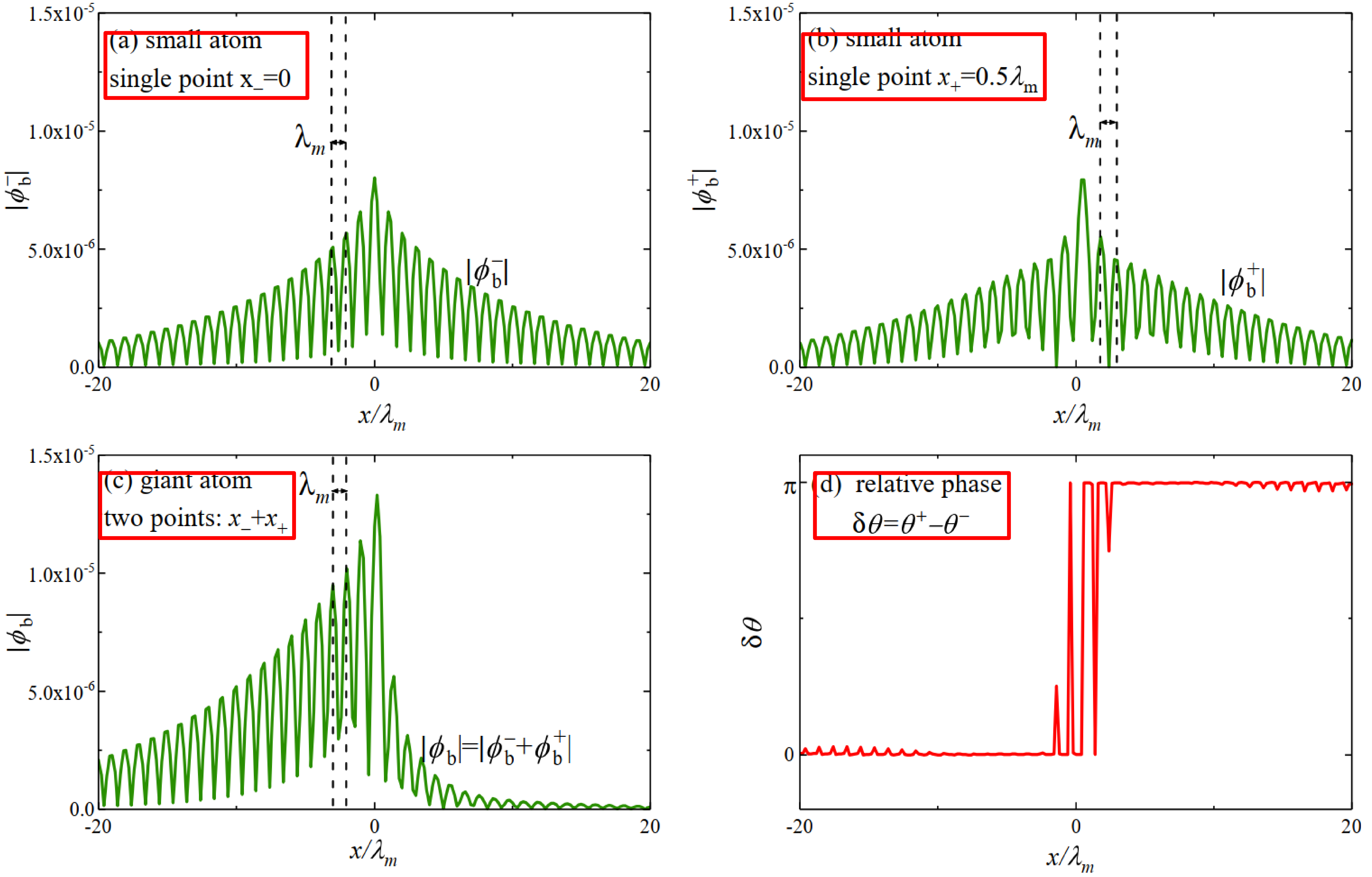
$$\phi_b^\pm(x) \simeq \frac{\sqrt{L}}{2\pi} \int_{k\in \mathrm{BZ}} \frac{g_k^\pm e^{ikx_\pm} u_k(x_\pm) u_k^*(x) e^{-ikx}}{\epsilon_b - \Delta_k} dk = A_b^\pm(x) e^{i\theta_\pm(x)},$$

$$\{x_-, x_+\} = \{0, 0.5\lambda_m\}$$

For two coupling points at high and low impedance positions, the phase relation is asymmetric along the waveguide, and satisfies

$$\delta\theta = \theta_+ - \theta_- \simeq 0 \qquad x < 0$$

$$\delta\theta = \theta_+ - \theta_- \simeq \pi \qquad x > 0$$



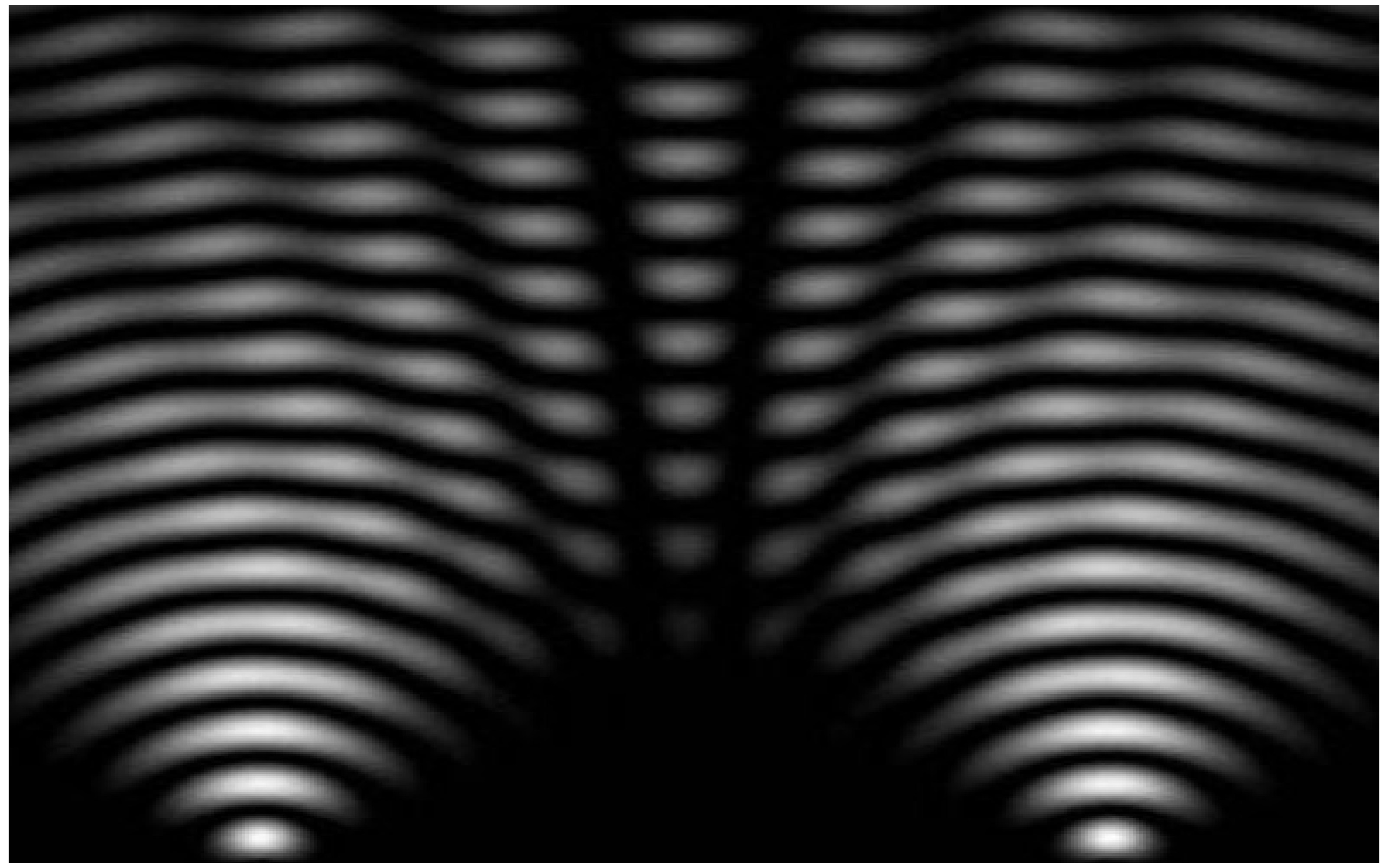
On the right-hand side, the interference is destructive, and the bound state vanishes;
On the left hand, the interference is constructive, the bound state is significantly enhanced.
The asymmetric interference relation results in chiral bound state.

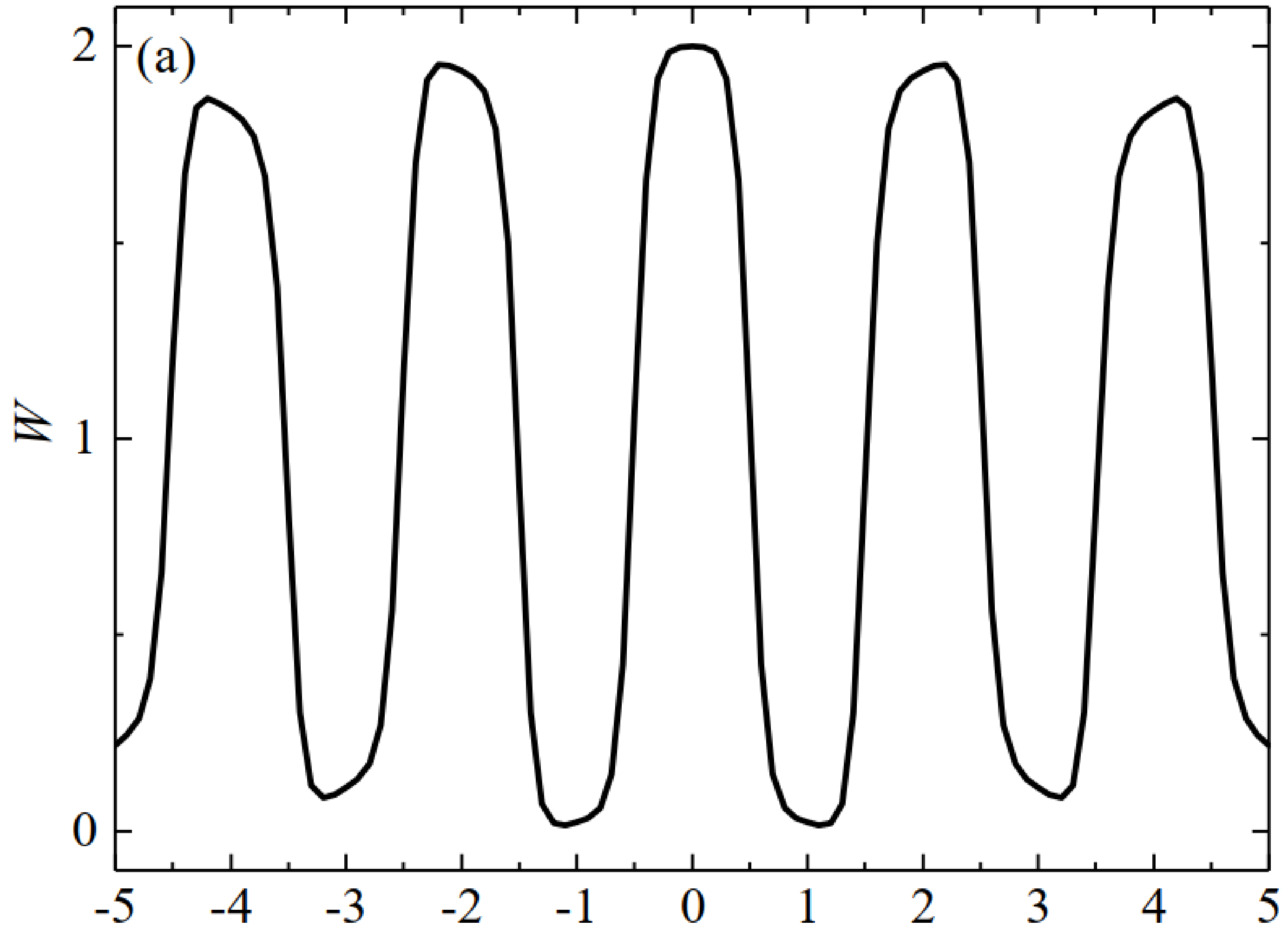
Chiral bound state

The interference between two sub-bound-states is very similar to the double slit interference, where spatial separation also leads to certain interference patterns on a screen. We can also define the interference visibility for the bound state as

$$W = \frac{\int_{-\infty}^{\infty} dx |\phi_b(x)|^2}{\int_{-\infty}^{\infty} dx |\phi_b^+(x)|^2 + \int_{-\infty}^{\infty} dx |\phi_b^-(x)|^2},$$

$W = 0$ ($W = 2$) represents the bound state that totally vanishes (is maximum enhanced) due to interference. By changing the separating distance between two coupling points, W oscillates between 0 ~2.





$$e^{ikx_+}u_k(x_+) = e^{ik(x_- + d_g)}u_k(x_- + d_g) \simeq \begin{cases} -e^{ikx_-}u_k(x_-), & d_g = (2N+1)\lambda_m, \quad W = 0 \\ +e^{ikx_-}u_k(x_-), & d_g = 2N\lambda_m, \quad W = 2 \end{cases}$$

Chiral bound state

The chiral bound state can be phenomenologically interpreted as a result of interference. The chiral factor can be obtained via quantitative analysis.

In small atoms, the coupling strength is momentum-independent. That is

$$g_k \simeq g_{k_0}$$

However, for giant atoms, the coupling with the waveguide strongly depends on momentum k. Their relation can be approximated as

$$g_k \simeq (A + iB\delta k),$$

$$C_\pm = A \pm B\sqrt{\frac{\delta_0}{\alpha_m}}.$$

Finally, the bound state is derived as

$$\phi_b(x) = A_m[C_-\Theta(-x) + C_+\Theta(x)]\exp\left(-\frac{|x|}{L_{\mathrm{eff}}}\right),$$

$\Theta(x) \rightarrow$ step functions

$C_- \gg C_+ \rightarrow$ left chiral bound state

$C_+ \gg C_- \rightarrow$ right chiral bound state