INSTITUTO DE FÍSICA FUNDAMENTAL

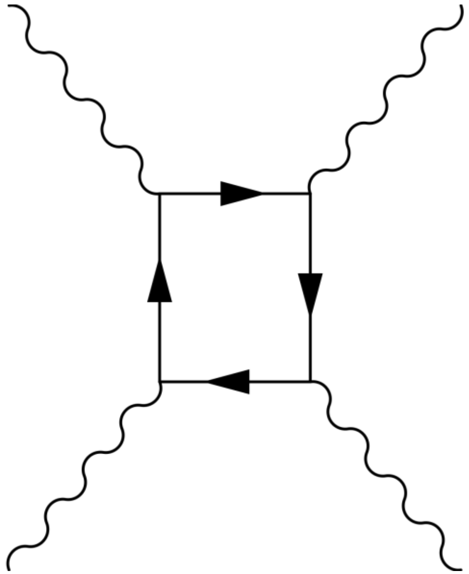
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Two photon control quantum gates in Circuit QED

Tomás Levy-Yeyati, Carlos Vega, Tomás Ramos, and Alejandro González-Tudela

Photonic Quantum Computing: Why?

- Photons: great carriers of quantum information
  - Weak interactions → Low decoherence



$\sigma \propto \mathcal{O}(\alpha^4)$

Photonic Quantum Computing: Why?

- Photons: great carriers of quantum information
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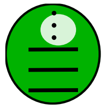
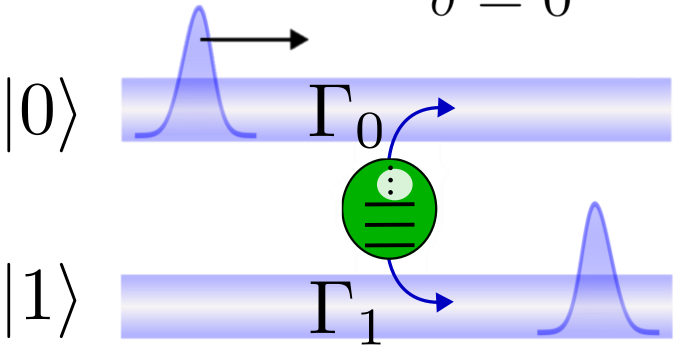
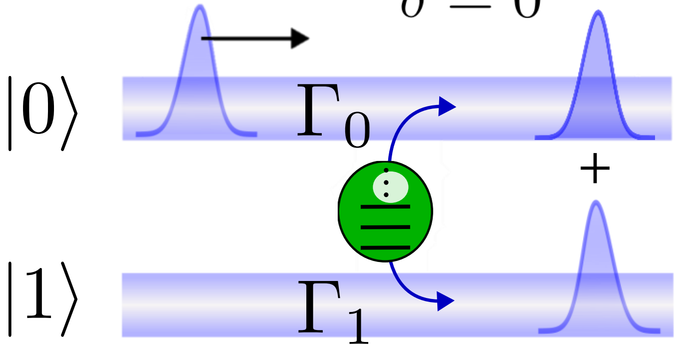
- Guided photonic "flying" qubits
  - Single qubit rotations: linear scatterers 

X Gate: $\Gamma_0 = \Gamma_1$
$\delta = 0$



H Gate: $\Gamma_0 = \left(3 + 2\sqrt{2}\right)\Gamma_1$
$\delta = 0$



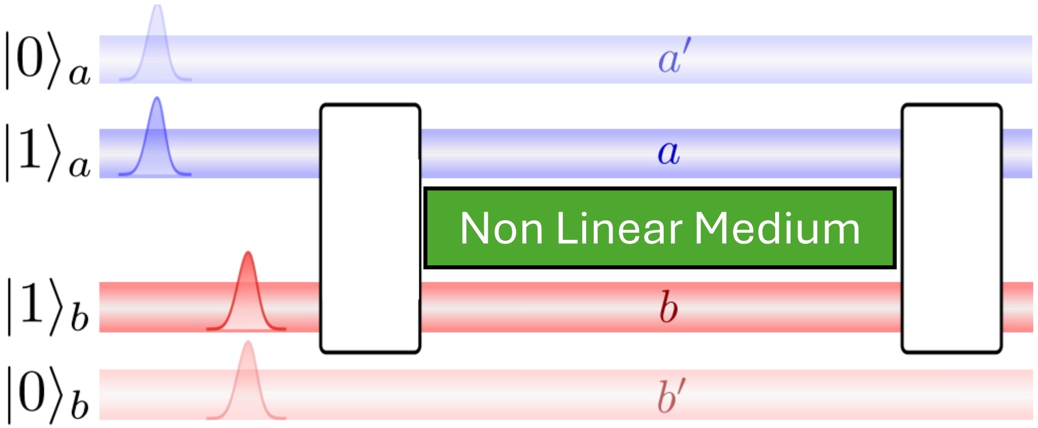
$\delta \longrightarrow$ Photon-cavity detuning

Photonic Quantum Computing: Challenges

- First Issue: Chirality
- Second Issue: Absence of interactions
  - Conditional two qubit gates $\hat{G}\left(|1\rangle_a \otimes |1\rangle_b\right) \neq \hat{G}\left(|1\rangle_a\right) \otimes \hat{G}\left(|1\rangle_b\right)$

CZ Gate

$$
\begin{aligned}
|0\rangle_a \otimes |0\rangle_b &\rightarrow \; |0\rangle_a \otimes |0\rangle_b\,, \\
|0\rangle_a \otimes |1\rangle_b &\rightarrow \; |0\rangle_a \otimes |1\rangle_b\,, \\
|1\rangle_a \otimes |0\rangle_b &\rightarrow \; |1\rangle_a \otimes |0\rangle_b\,, \\
|1\rangle_a \otimes |1\rangle_b &\rightarrow \; e^{i\pi}|1\rangle_a \otimes |1\rangle_b\,.
\end{aligned}
$$



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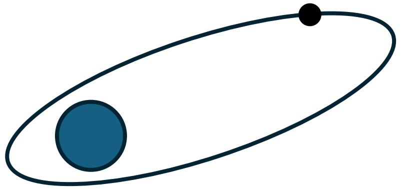
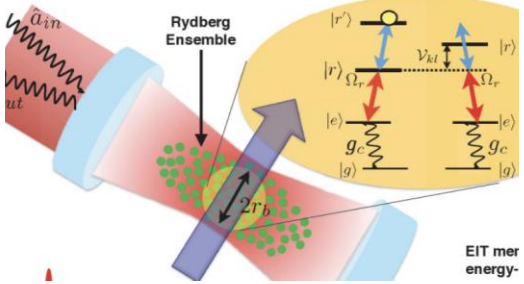


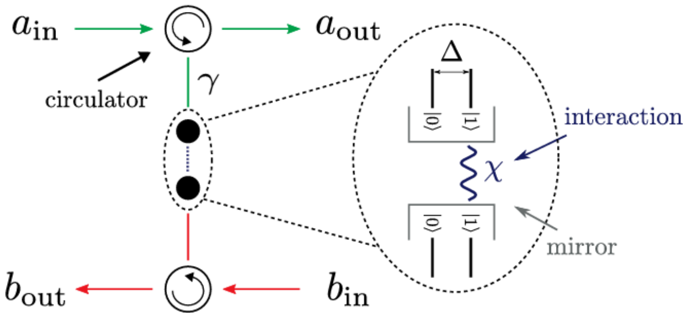
Rydberg atoms

Sumanta Das, Andrey Grankin, et. al.
Phys. Rev. A **93**, 040303(R) (2016)



Cross-Kerr non-linearities

Daniel J. Brod and Joshua Combes
Phys. Rev. Lett. **117**, 080502 (2016)



Photonic Quantum Computing: Challenges

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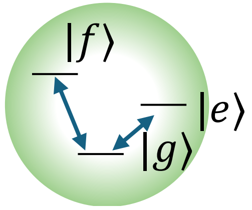
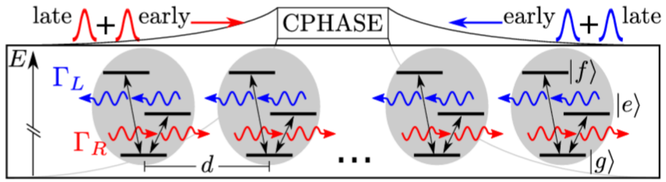


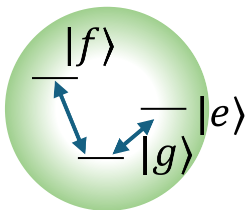
Three-level system

B. Schrinski, M. Lamaison, and A. S. Sørensen
Phys. Rev. Lett. **129**, 130502 (2022)



Photonic Quantum Computing: Challenges

- <u>First Issue</u>: Chirality
- <u>Second Issue</u>: Absence of interactions
  - Conditional two qubit gates $\hat{G}\left(|1\rangle_a \otimes |1\rangle_b\right) \neq \hat{G}\left(|1\rangle_a\right) \otimes \hat{G}\left(|1\rangle_b\right)$



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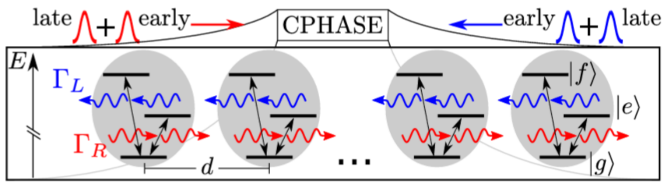
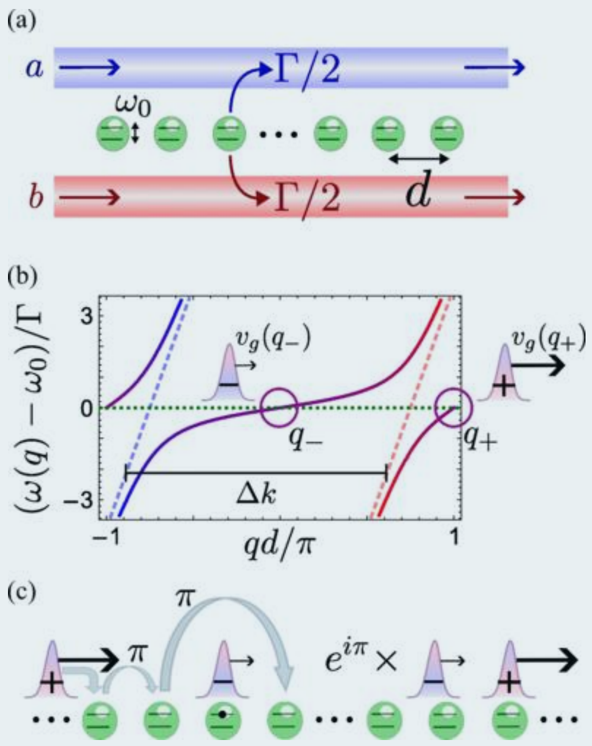


<u>Open Questions</u>:
- Simple structures? Two-Level Systems
- Without spin-orbit coupling? S.c. Circuits

Passive Photonic CZ Gate with Two-Level Emitters in Chiral Multimode Waveguide QED

Tomás Levy-Yeyati*, Carlos Vega, Tomás Ramos, and Alejandro González-Tudela†

PRX Quantum **6**, 010342 – **Published 5 March, 2025**



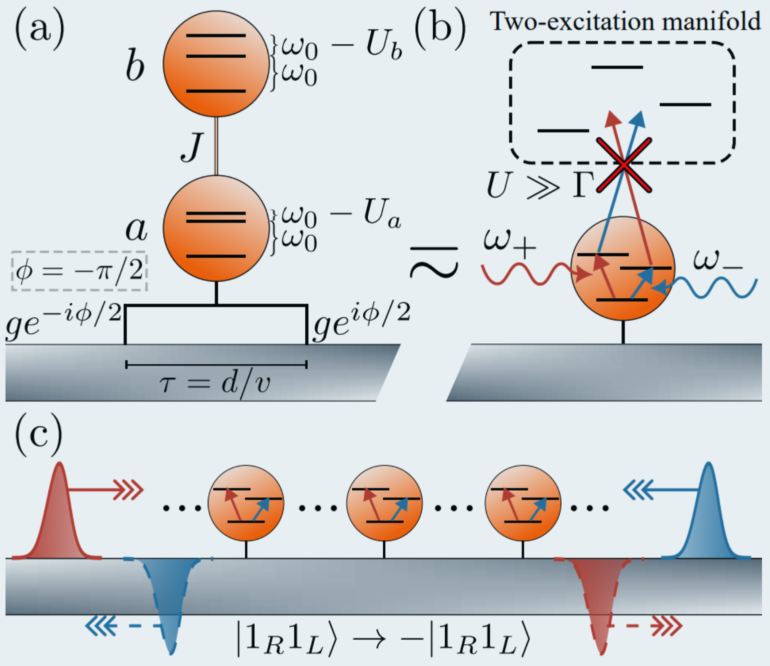
Two-Level Systems

arXiv:2507.05377

[Submitted on 7 Jul 2025]

Engineering giant transmon molecules as mediators of conditional two-photon gates

Tomás Levy-Yeyati, Tomás Ramos, Alejandro González-Tudela



S.c. Circuits

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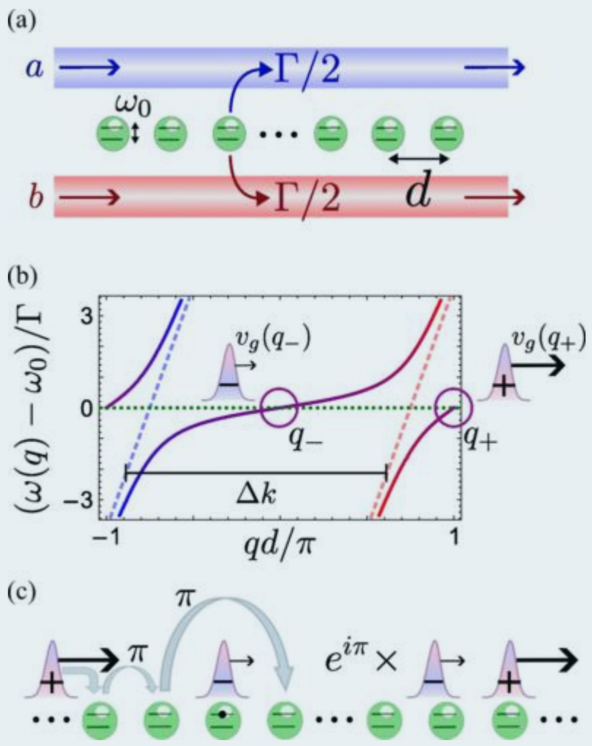

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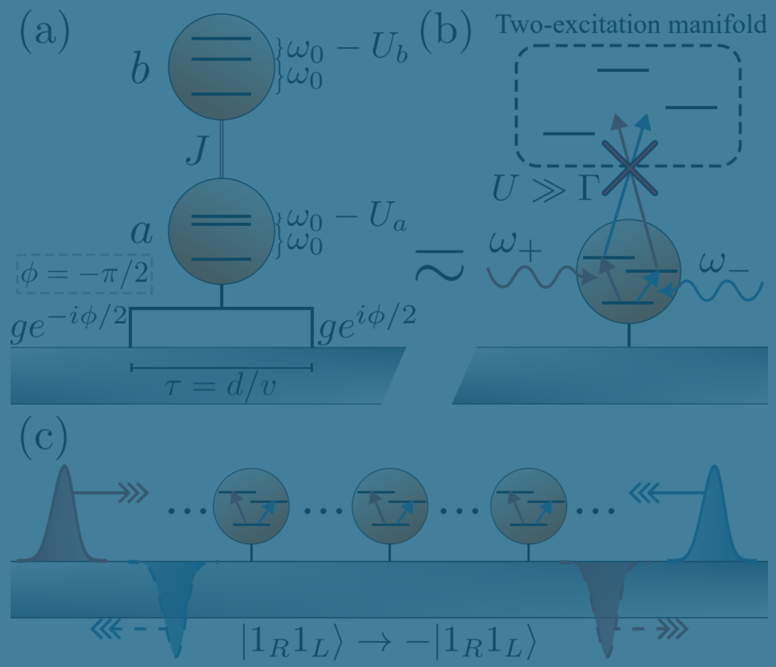
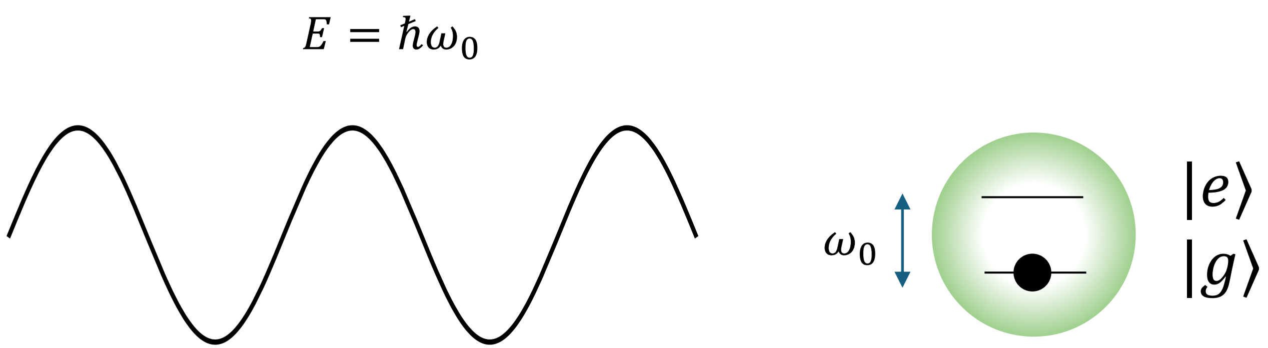


S.c. Circuits

Linear scattering in chiral WQED

- Coupling of light to two-level emitter:

  Simplest quantum non-linear medium

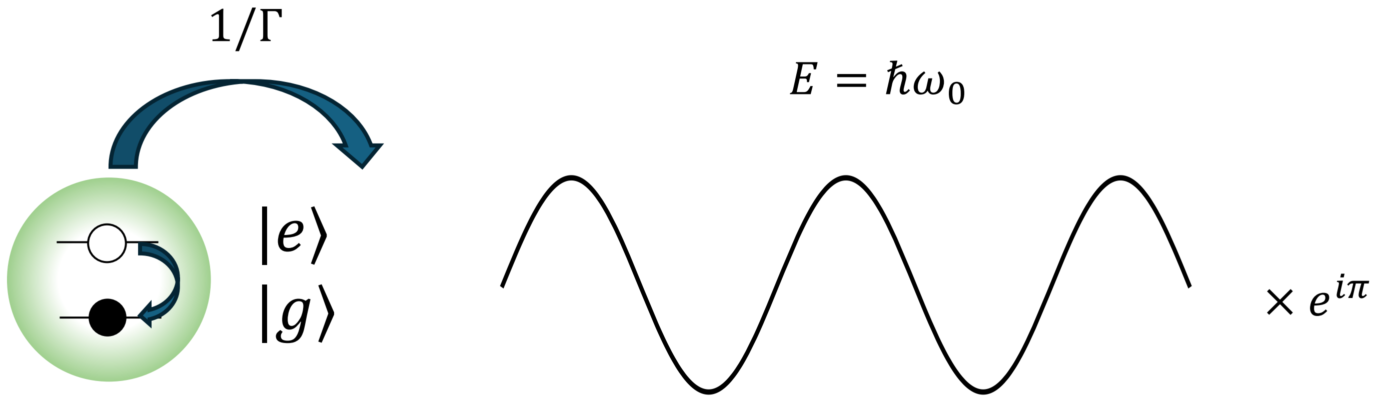


Single-photon input

Linear scattering in chiral WQED

- Coupling of light to two-level emitter:

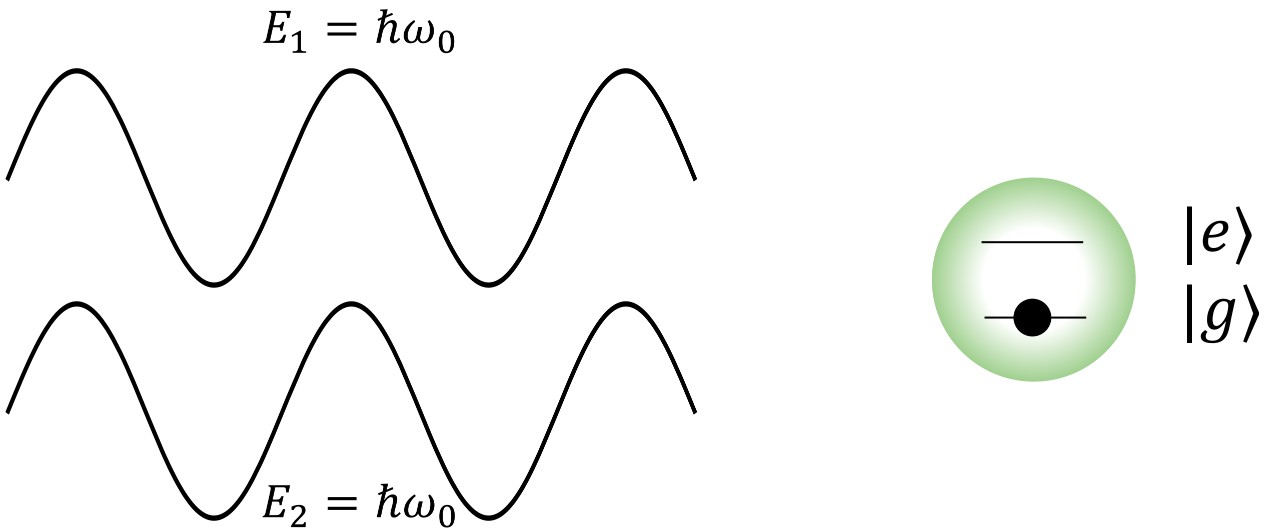
  Simplest quantum non-linear medium



Single-photon input

Non-linear scattering in chiral WQED

- Coupling of light to two-level emitter:
  Simplest quantum non-linear medium



Two-photon input

$$\left\langle \omega_0 + \frac{\Delta}{2}; \omega_0 - \frac{\Delta}{2} \right| \hat{S} \left| \omega_0; \omega_0 \right\rangle = t(\omega_0)t(\omega_0)\ \delta(\Delta) - \frac{2}{\pi}\frac{\Gamma}{\Gamma^2 + \Delta^2}$$

Non-linear scattering in chiral WQED

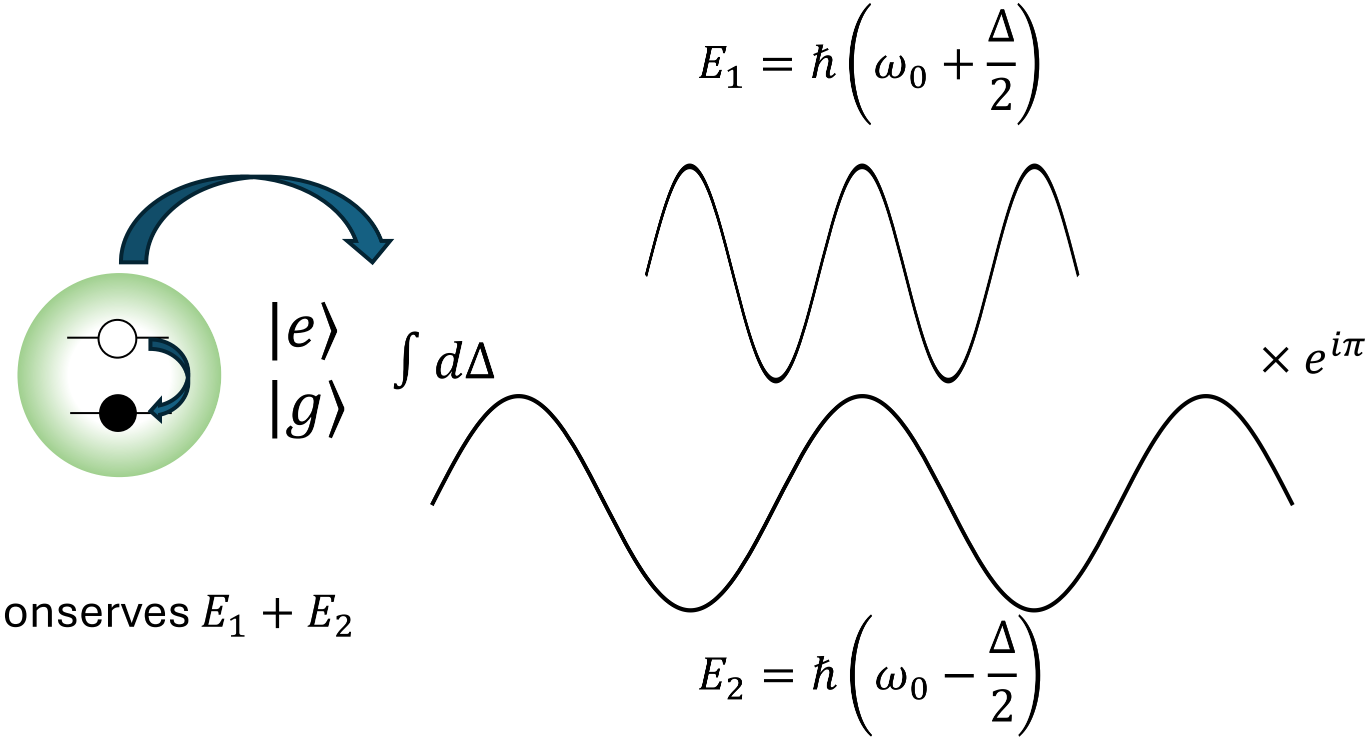
- Coupling of light to two-level emitter:

  Simplest quantum non-linear medium

$\Delta \sim \Gamma$

Jeffrey H. Shapiro
Phys. Rev. A **73**, 062305 (2006)

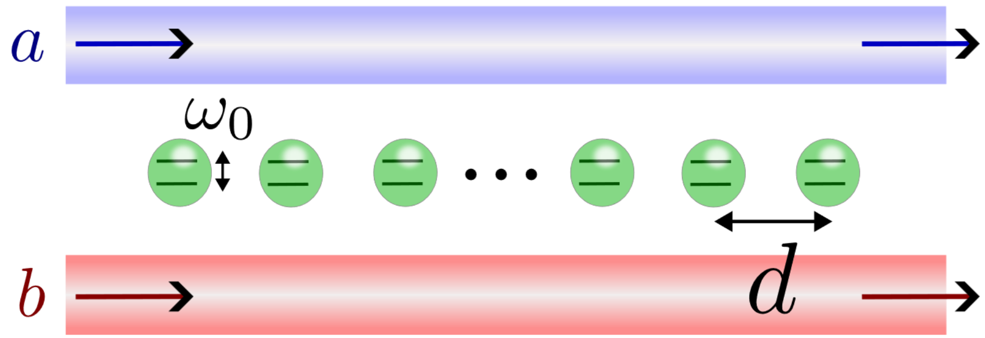
Jung Tsung Shen and Shanhui Fan
Phys. Rev. A **76**, 062709 (2007)

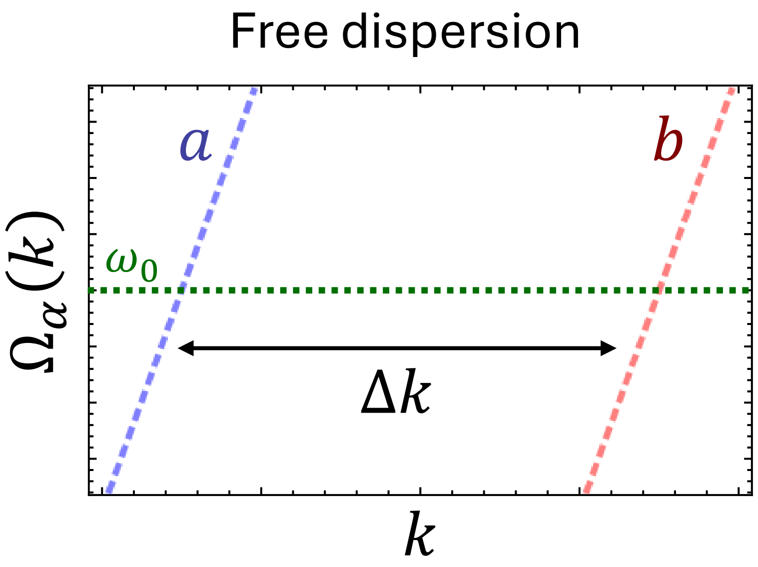


Two-photon input

Non-linear phase ✓ + Issue: Frequency correlations (inelastic scattering)

Chiral multi-mode waveguide QED





$$\hat{H}_S = \omega_0 \sum_{n=1}^{N} \hat{\sigma}_n^\dagger \hat{\sigma}_n \qquad \hat{H}_B = \sum_{\alpha=a,b} \int dk\, \hat{\alpha}_k^\dagger \Omega_\alpha(k) \hat{\alpha}_k$$

$$x_n = nd$$

α-photon creation operator: $\hat{\alpha}_k^\dagger$

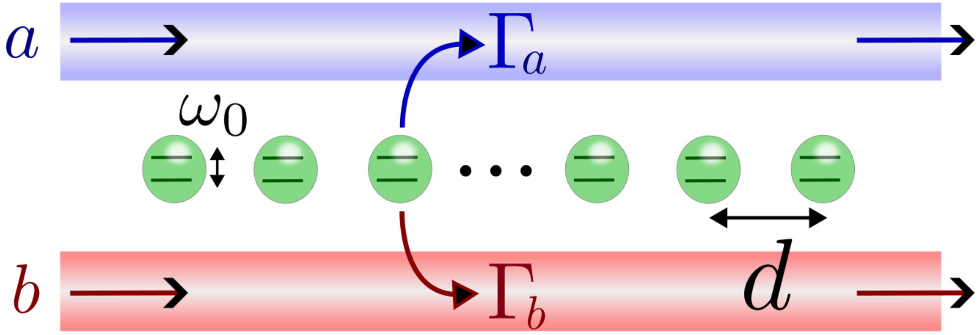
nth emitter dipole operator: $|e\rangle_n = \hat{\sigma}_n^\dagger |g\rangle_n$

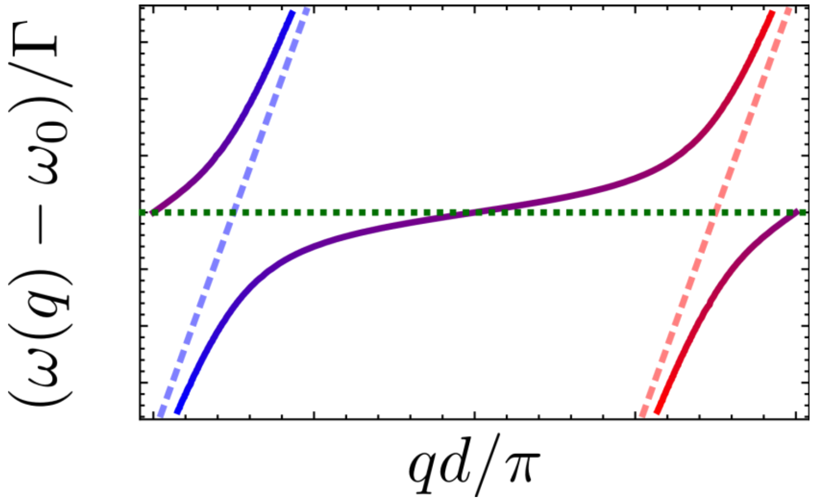
$$\Omega_\alpha(k) \approx \omega_0 + c_\alpha(k - k_\alpha)$$

$$\Delta k = k_b - k_a$$

$$k_0 = \frac{k_a + k_b}{2}$$

Chiral multi-mode waveguide QED





$$\hat{H}_S = \omega_0 \sum_{n=1}^{N} \hat{\sigma}_n^\dagger \hat{\sigma}_n$$

$$\hat{H}_B = \sum_{\alpha=a,b} \int dk\, \hat{\alpha}_k^\dagger \Omega_\alpha(k) \hat{\alpha}_k$$

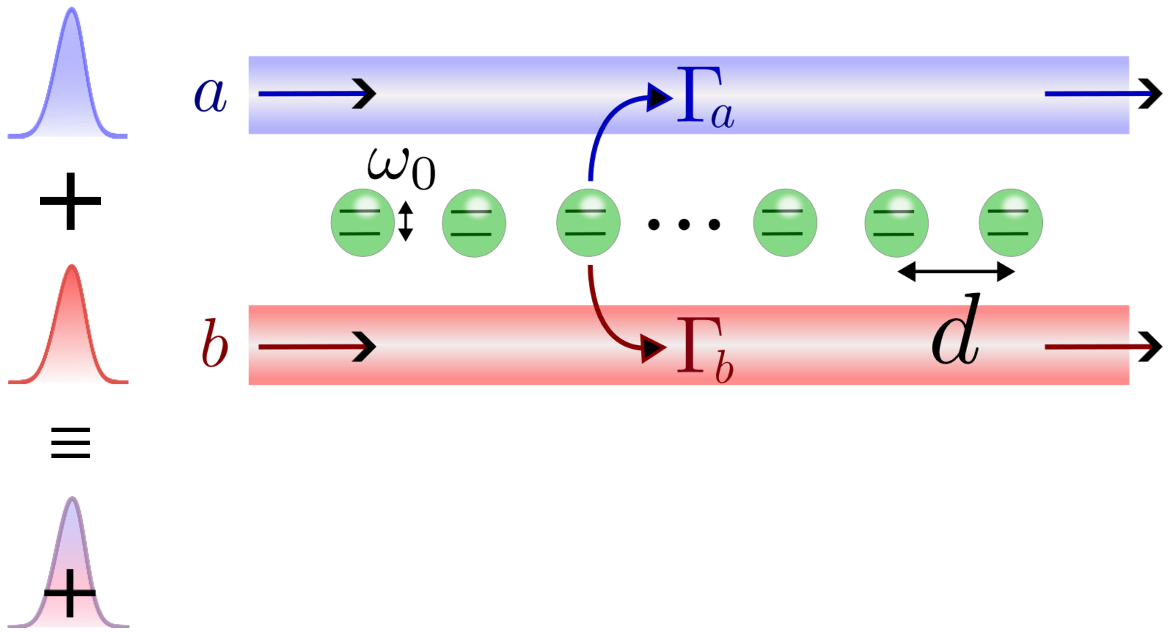
$$\hat{H}_{\text{int}} = \sum_{n=1}^{N} \sum_{\alpha=a,b} \sqrt{\Gamma_\alpha c_\alpha} \left(\hat{\alpha}_{x_n}^\dagger \hat{\sigma}_n + \text{H.c.} \right)$$

$$\hat{H} = \hat{H}_S + \hat{H}_B + \hat{H}_{int}$$

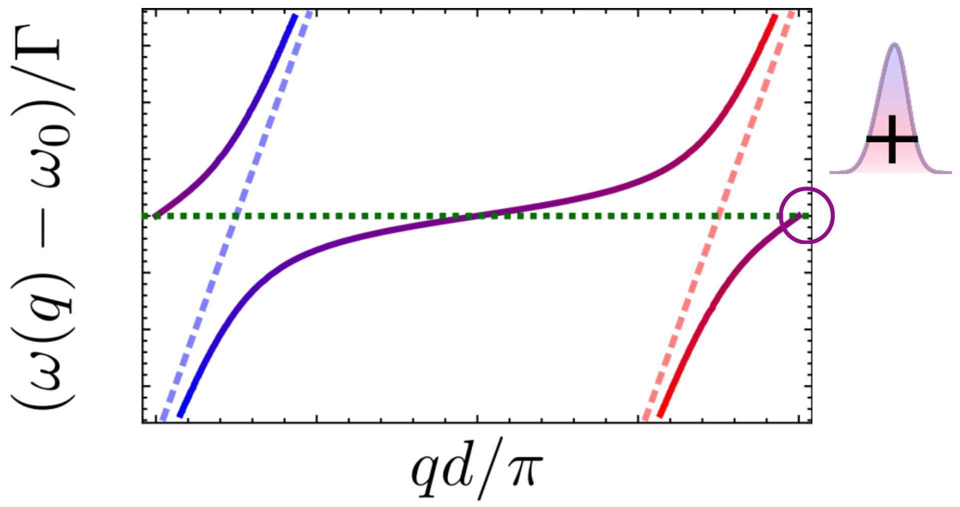
Chiral multi-mode waveguide QED

Single-Photon

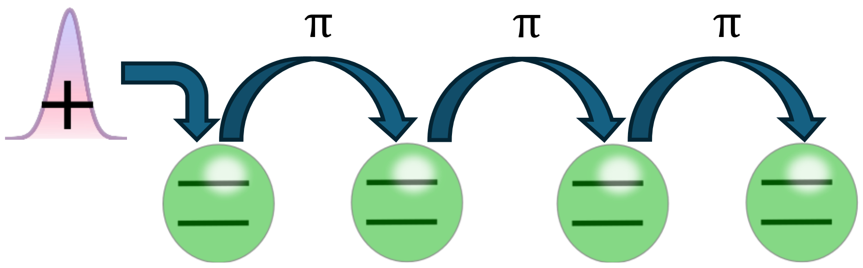
For $\Gamma_a = \Gamma_b = \Gamma/2$



Polariton dispersion



$$\hat{S}(\omega_0) = e^{ik_0 d}\begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$$



Chiral multi-mode waveguide QED

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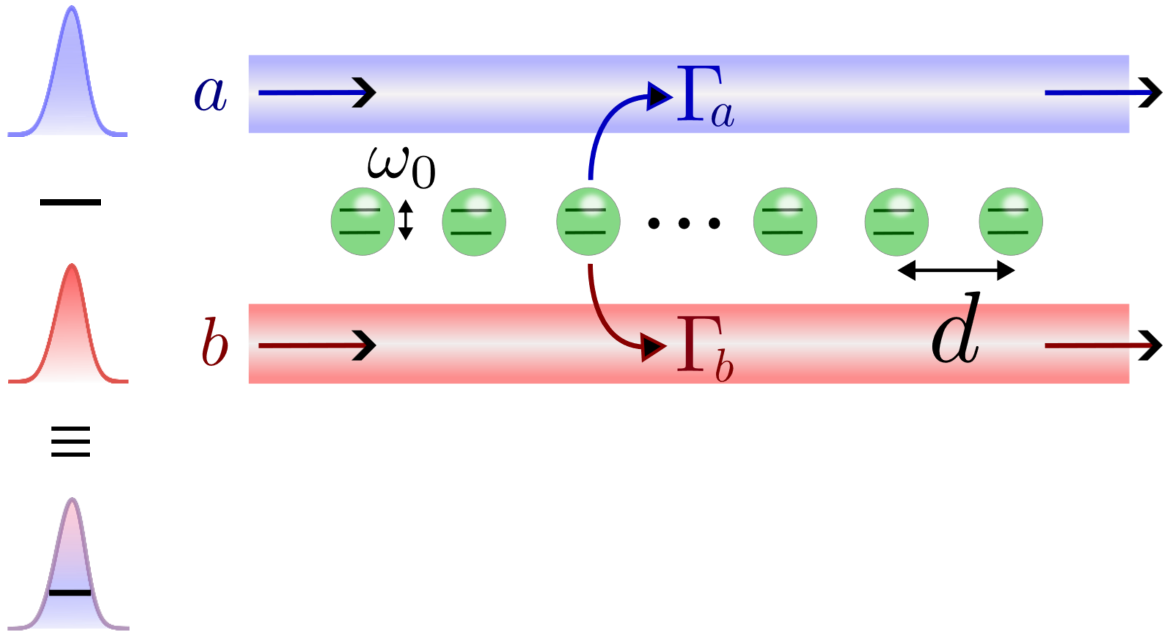

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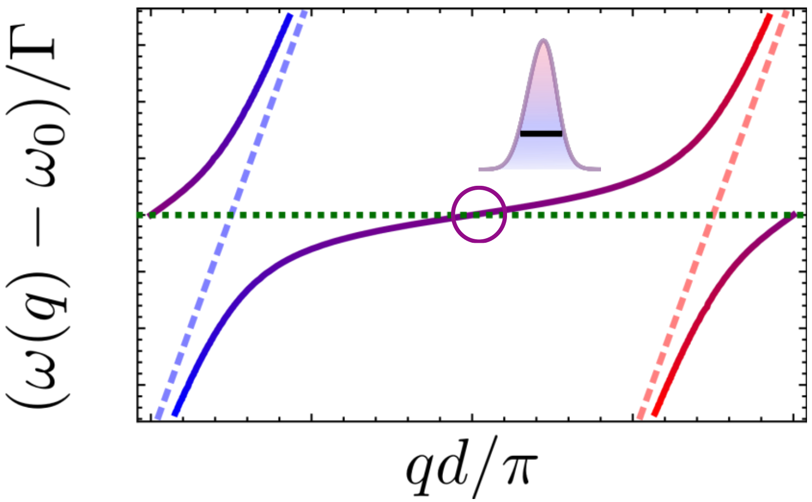

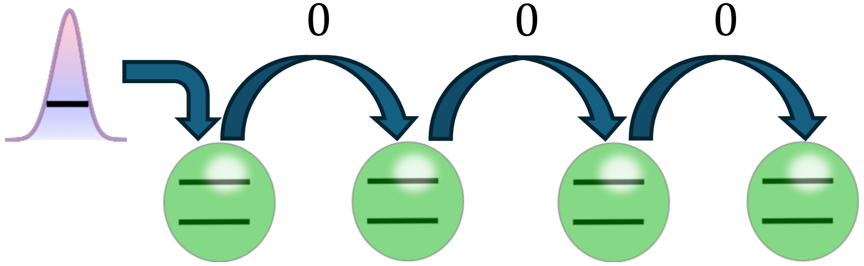

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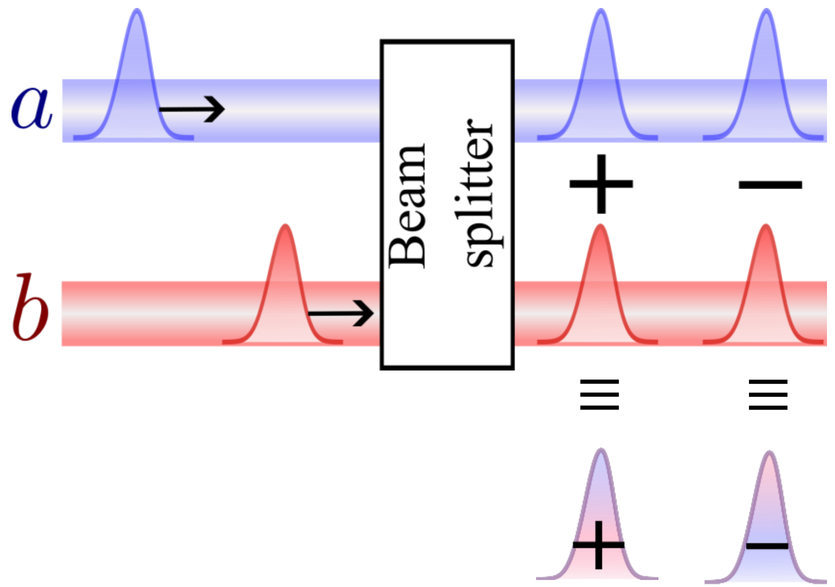

For $\Gamma_a = \Gamma_b = \Gamma/2$

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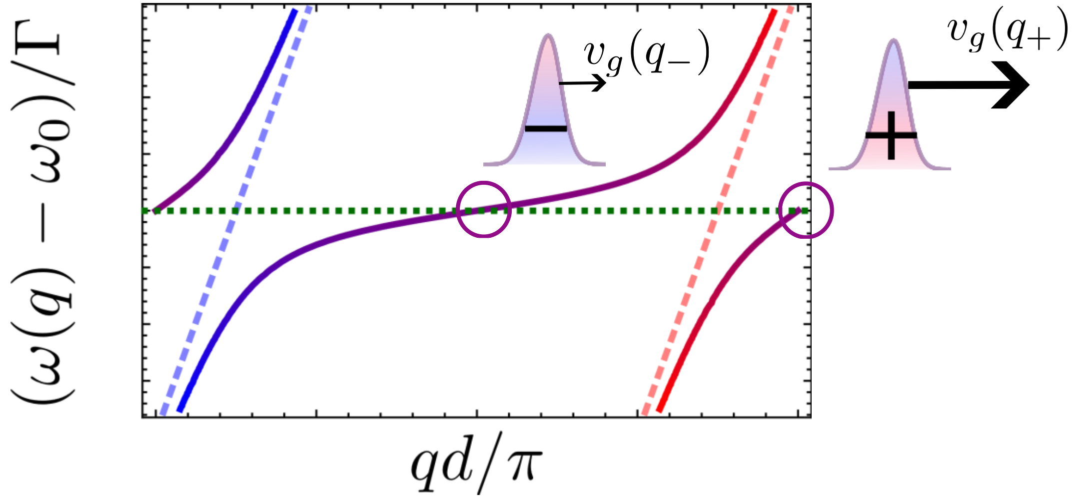


For $\Delta kd \neq n\pi$ $v_g(q_+) \neq v_g(q_-)$

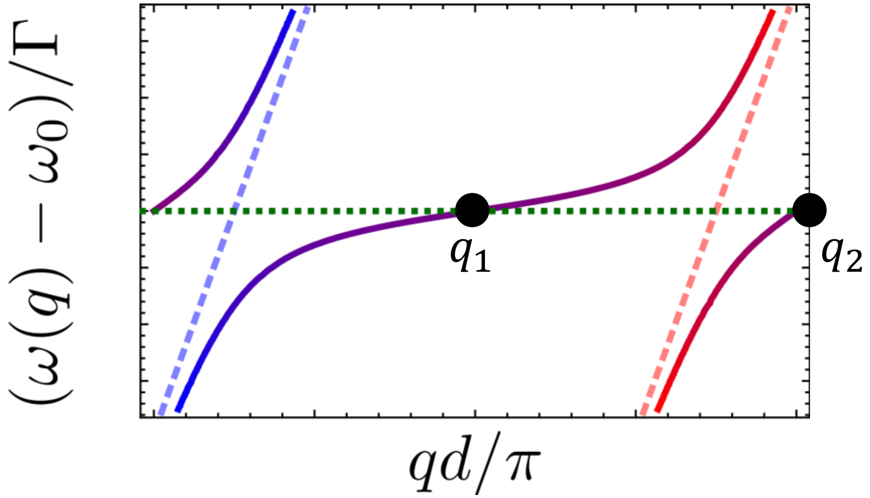
Chiral multi-mode waveguide QED

Two-Photon $N = 1$

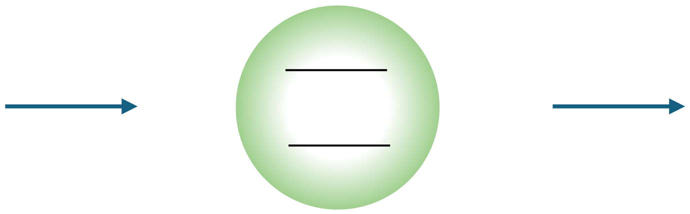
- **Elastic scattering**
- Inelastic scattering

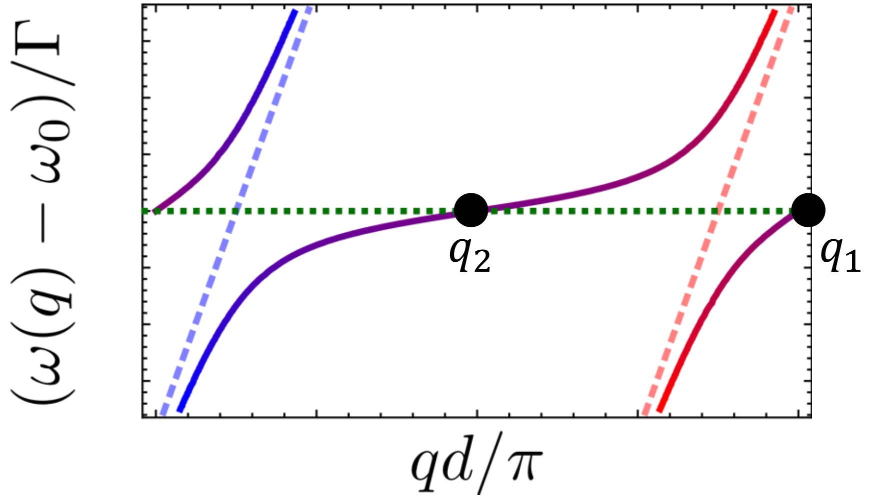
Total energy, $E = \omega_1 + \omega_2$, conservation

Non-linear phase shift



$t_{\text{el}} = e^{i\pi}$





Chiral multi-mode waveguide QED

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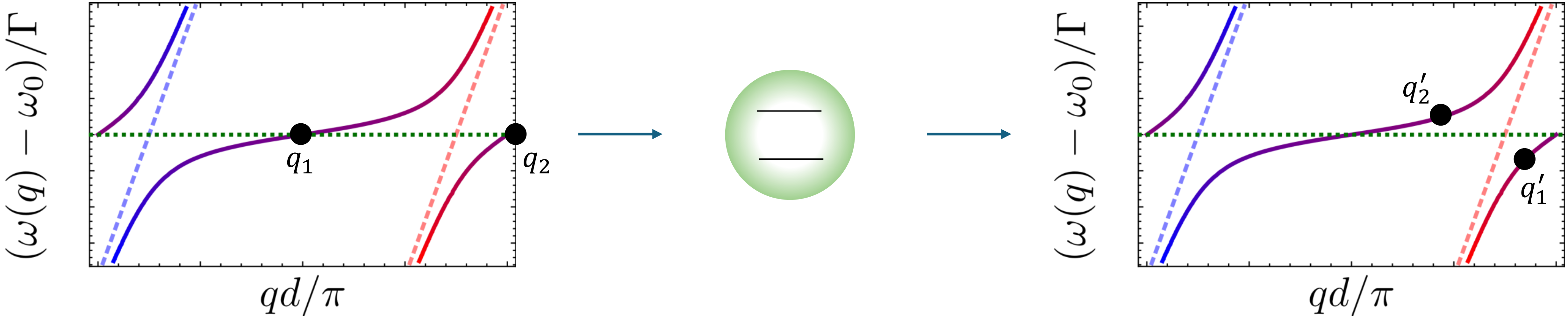
<u>Continuum of inelastic outputs</u>



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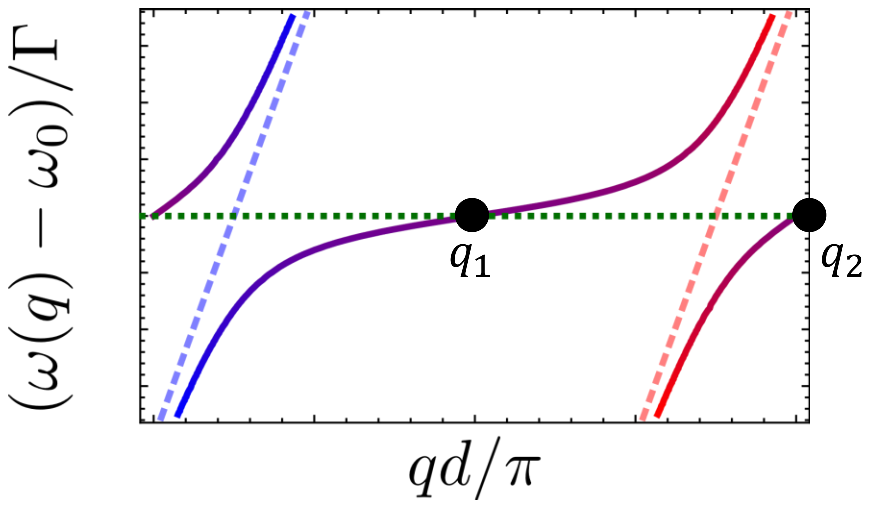

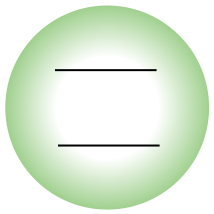

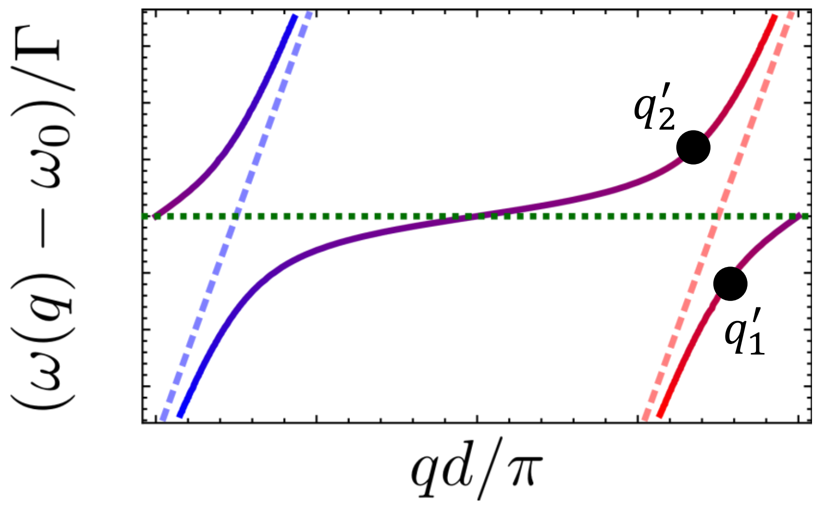

Chiral multi-mode waveguide QED

Two-Photon $N = 1$

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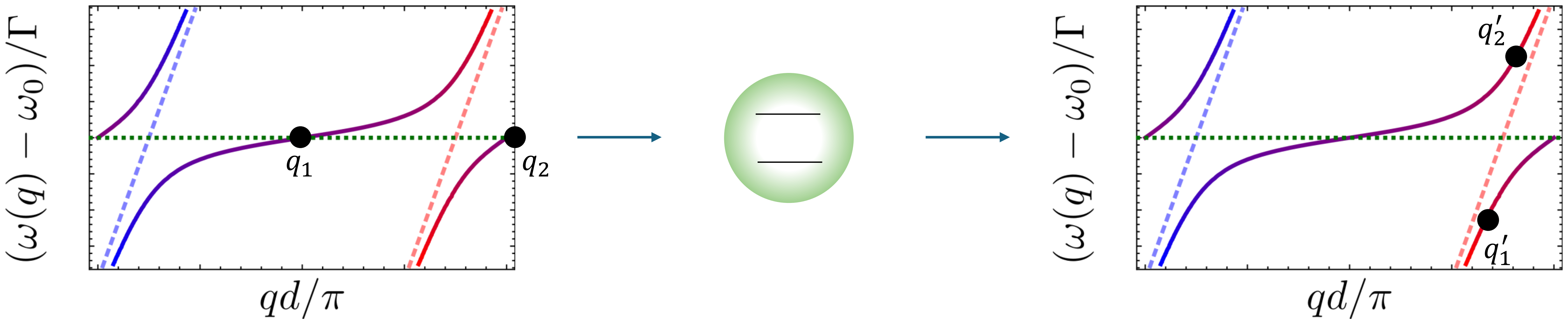
Total energy, $E = \omega_1 + \omega_2$, conservation

<u>Continuum of inelastic outputs</u>



Chiral multi-mode waveguide QED

Two-Photon $N \to \infty$

Total quasimomentum, $K = q_1 + q_2$, conservation

Total energy, $E = \omega_1 + \omega_2$, conservation

$$\hat{H}_{\text{eff}} = -i \sum_{\alpha} \sum_{n} \frac{\Gamma_\alpha}{2} \hat{\sigma}_n^\dagger \hat{\sigma}_n - i \sum_{\alpha} \sum_{n>m} \Gamma_\alpha e^{ik_\alpha (x_n - x_m)} \hat{\sigma}_n^\dagger \hat{\sigma}_m$$

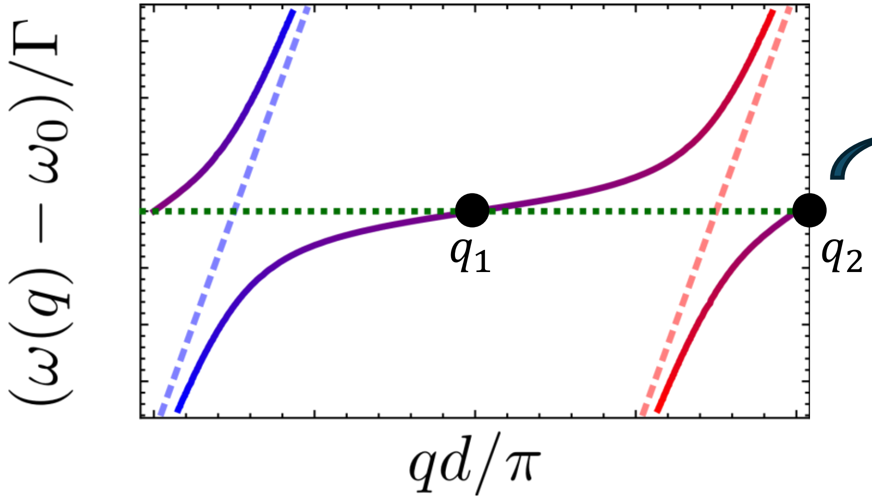
Chiral multi-mode waveguide QED

Two-Photon $N \to \infty$

Total quasimomentum, $K = q_1 + q_2$, conservation

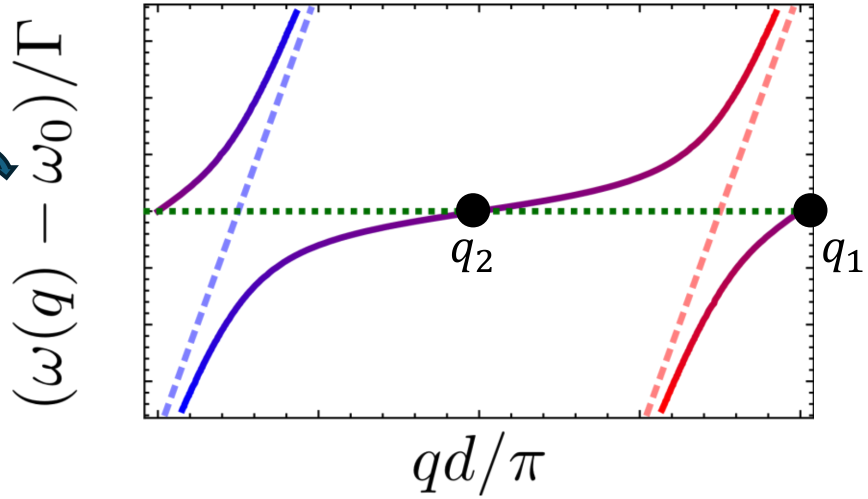
Total energy, $E = \omega_1 + \omega_2$, conservation

- **Elastic scattering**
- Inelastic scattering



Non-linear phase shift

$$t_{\mathrm{el}} = e^{i\pi}$$



Chiral multi-mode waveguide QED

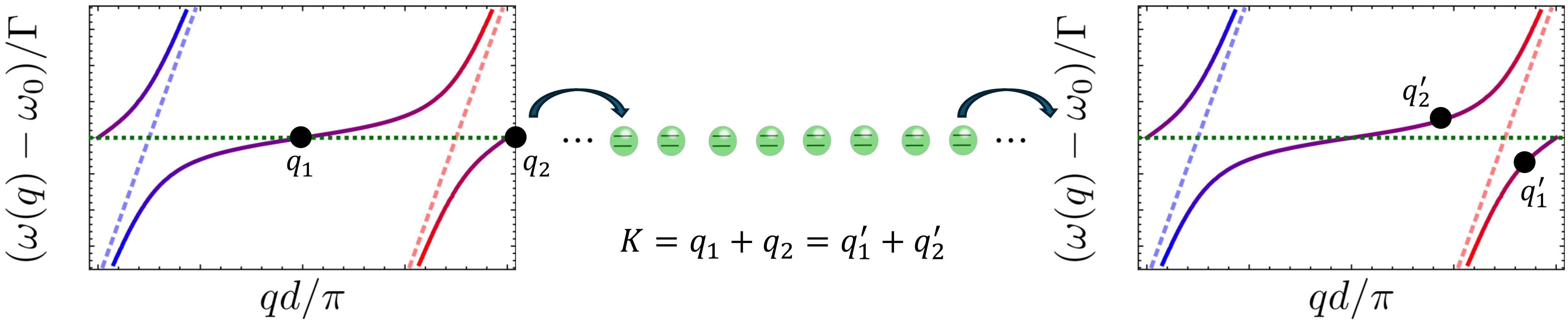
Two-Photon $N \to \infty$

- Elastic scattering
- **Inelastic scattering**

Total quasimomentum, $K = q_1 + q_2$, conservation

Total energy, $E = \omega_1 + \omega_2$, conservation

Continuum of inelastic outputs supressed



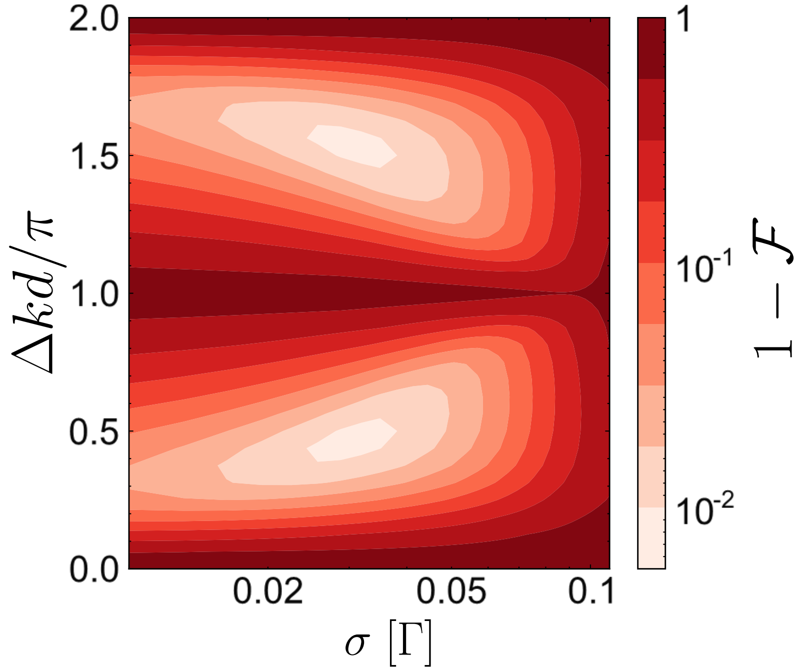
$\mathrm{Im}[q'] \neq 0$

The inelastic component is a finite-time resonance (scattering resonance)

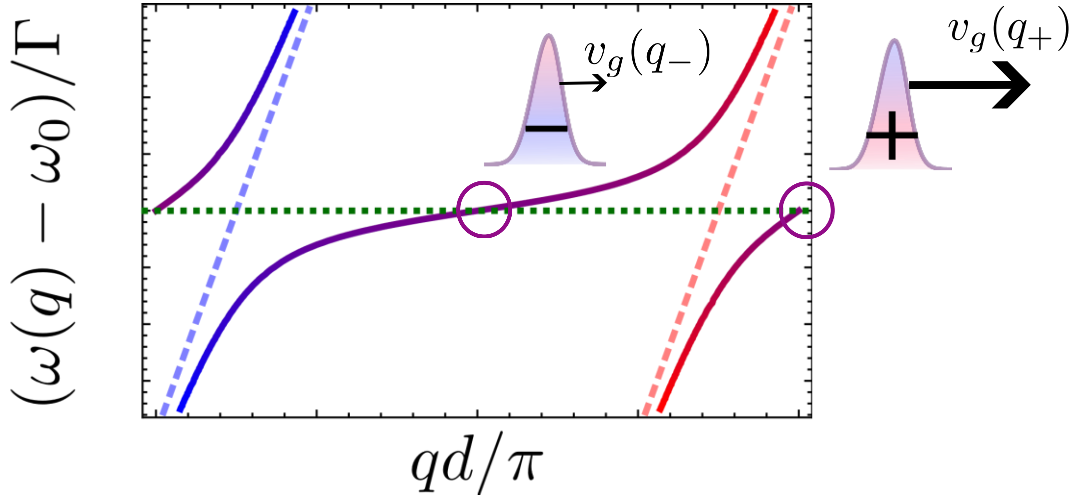
Chiral multi-mode waveguide QED

Two-Photon

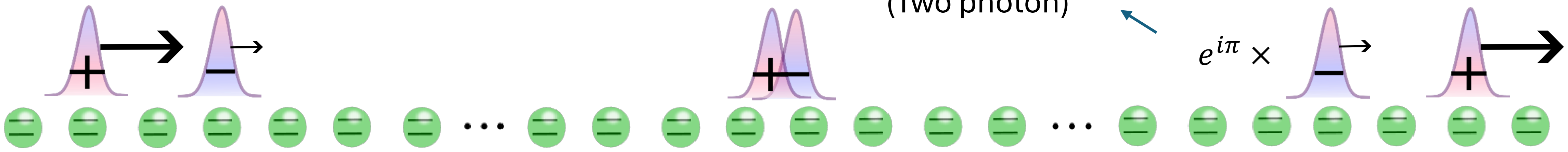
For $\Gamma_a = \Gamma_b = \Gamma/2$



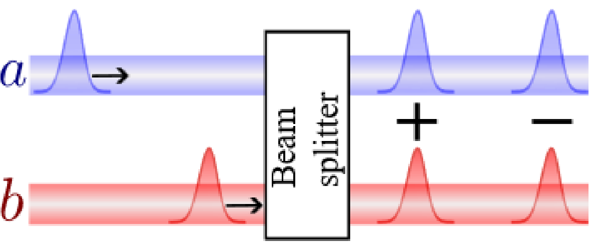
Polariton dispersion



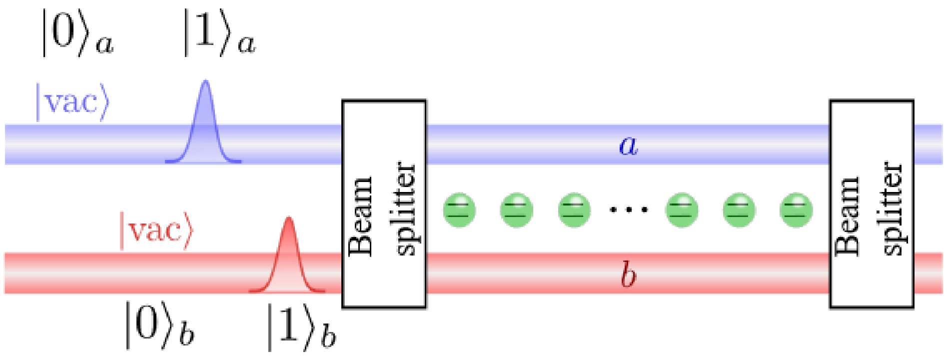
Non-linear phase
(Two photon)



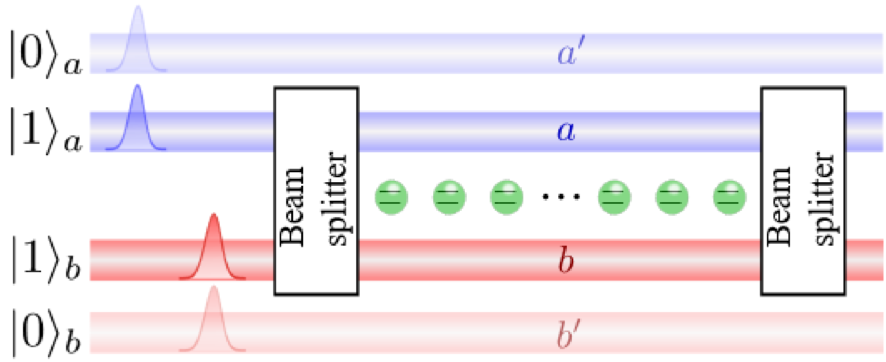
Possible Implementations



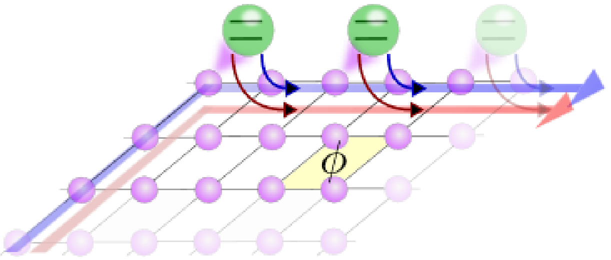
Photon-number encoding



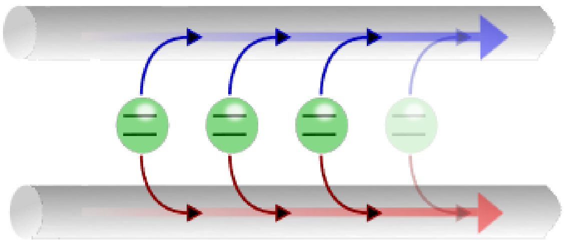
Dual-rail encoding



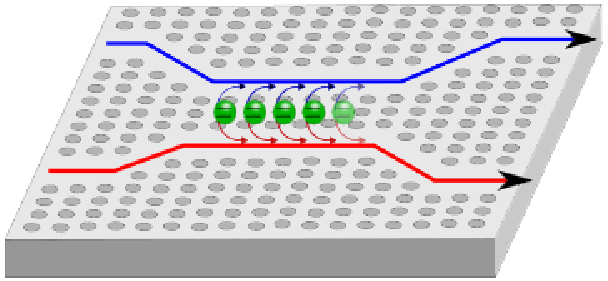
Photonic Chern insulators' edges



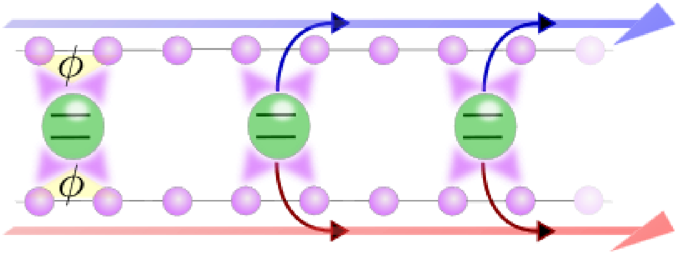
Spin-orbit coupled fibers



Spin-orbit coupled PhC waveguides



Effective chirality with giant-atoms

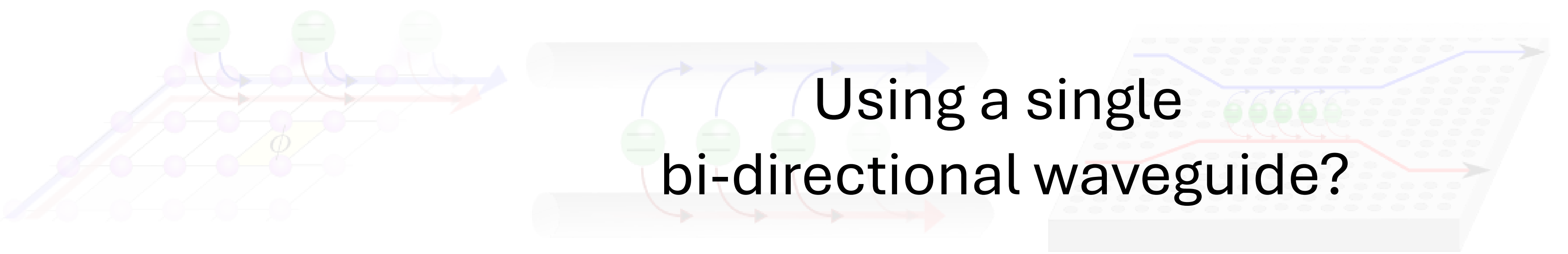


*Not real implementations, just artistic representations

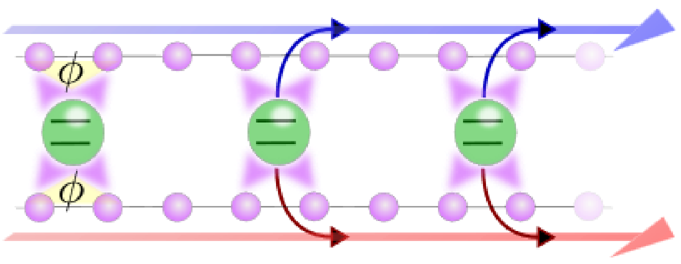
C. Joshi, F. Yang and M. Mirhosseini
Phys. Rev. X **13**, 021039 (2023)

B. Kannan, A. Almanakly, et. al.
Nat. Phys. **19**, 394-400 (2023)

Possible Implementations



Effective chirality with giant-atoms



Using a single
bi-directional waveguide?

*Not real implementations, just artistic representations

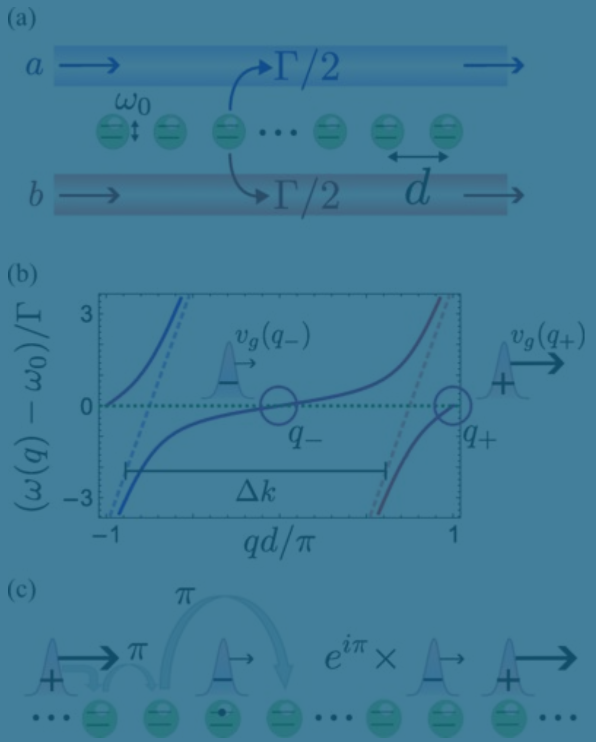
C. Joshi, F. Yang and M. Mirhosseini
Phys. Rev. X 13, 021039 (2023)

B. Kannan, A. Almanakly, et. al.
Nat. Phys. **19**, 394-400 (2023)

Passive Photonic CZ Gate with Two-Level Emitters in Chiral Multimode Waveguide QED

Tomás Levy-Yeyati*, Carlos Vega, Tomás Ramos, and Alejandro González-Tudela†

PRX Quantum 6, 010342 – Published 5 March, 2025



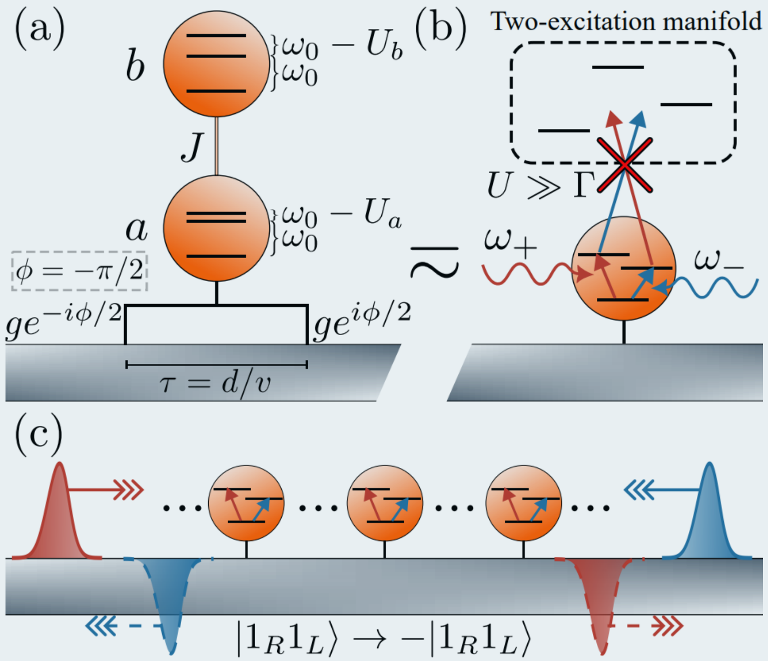
Two-Level Systems

arXiv:2507.05377

[Submitted on 7 Jul 2025]

Engineering giant transmon molecules as mediators of conditional two-photon gates

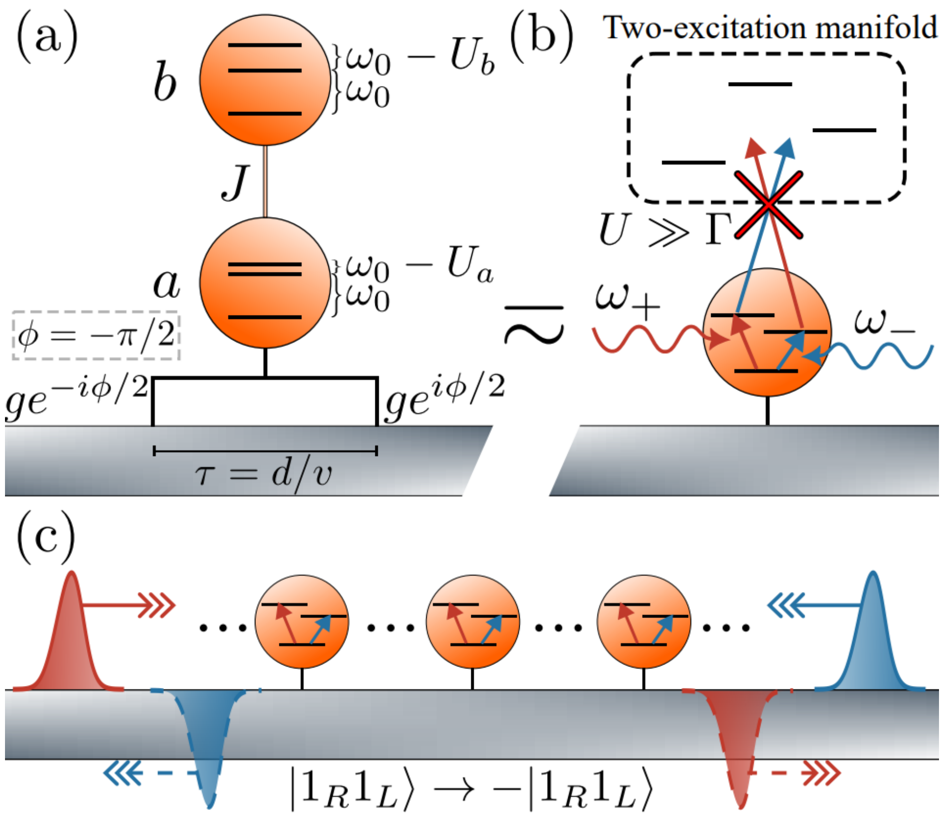
Tomás Levy-Yeyati, Tomás Ramos, Alejandro González-Tudela



S.c. Circuits

CZ Gate with giant transmon molecules

Single-Photon



$$\hat{H}_M = \omega_0 \left(\hat{a}^\dagger \hat{a} + \hat{b}^\dagger \hat{b}\right) + J\left(\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a}\right)$$

$$\hat{V} = -\frac{U_a}{2}\hat{a}^\dagger \hat{a}\left(\hat{a}^\dagger \hat{a} - 1\right) - \frac{U_b}{2}\hat{b}^\dagger \hat{b}\left(\hat{b}^\dagger \hat{b} - 1\right)$$

$$\hat{H}_B = \int dk\ \omega_k\ \hat{c}_k^\dagger \hat{c}_k$$

$$\omega_k = v|k|$$

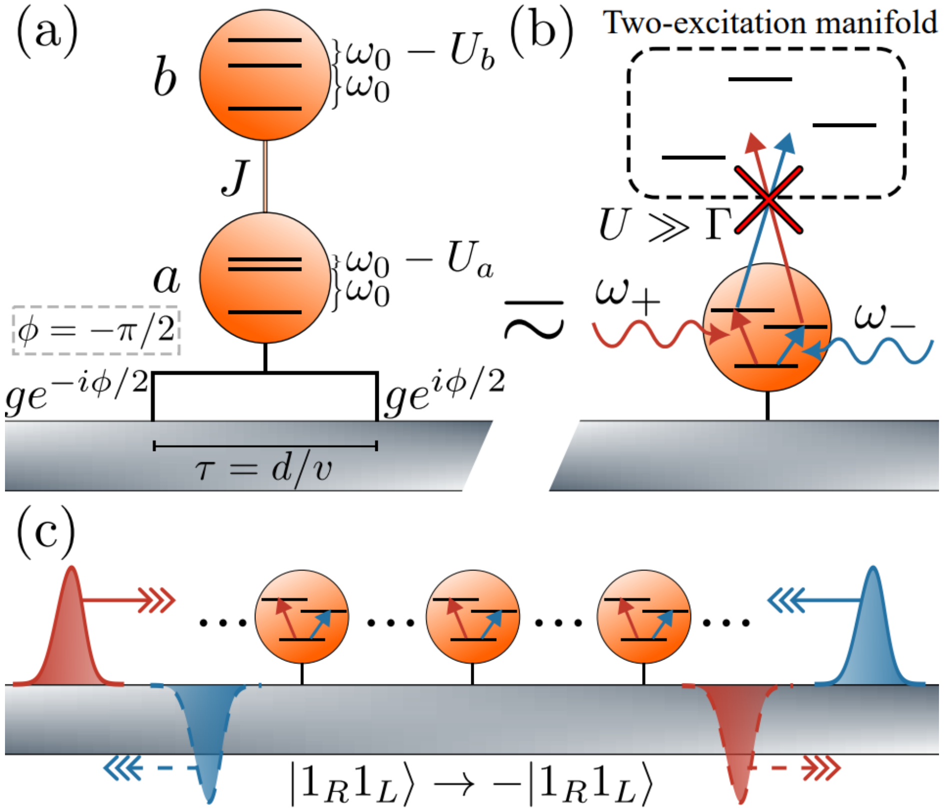
$$\hat{H}_I = \int dk\ g(k)\ \hat{a}^\dagger \hat{c}_k + \text{H.c.}$$

$$g(k) = \sqrt{\frac{2}{\pi}} g \cos\left(\frac{kd + \phi}{2}\right)$$

A. Frisk Kockum
"Quantum Optics with Giant Atoms– the First Five Years." Springer, Singapore (2021)

CZ Gate with giant transmon molecules

Single-Photon



Giant (non-local coupling)

$$\hat{H}_I = \int dk\ g(k)\ \hat{a}^\dagger \hat{c}_k + \text{H.c.}$$

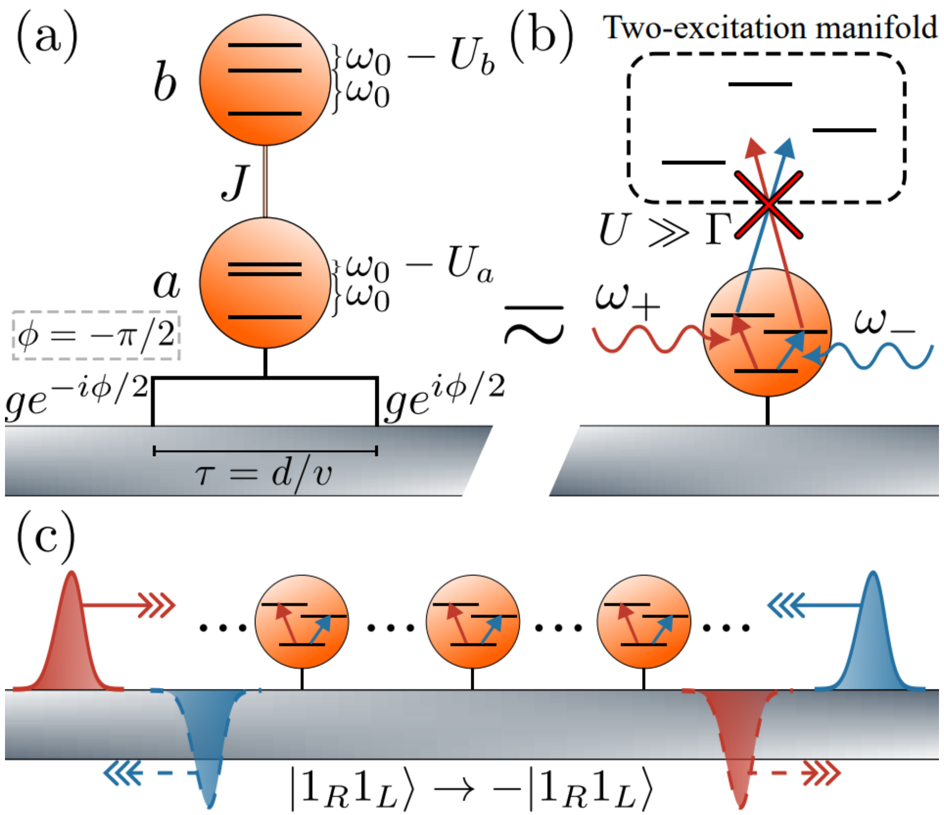
$$g(k) = \sqrt{\frac{2}{\pi}} g \cos\left(\frac{kd + \phi}{2}\right)$$

$$\Gamma_{R/L}(\omega) = \frac{\Gamma}{2}[1 \pm \sin(\omega\tau)]$$

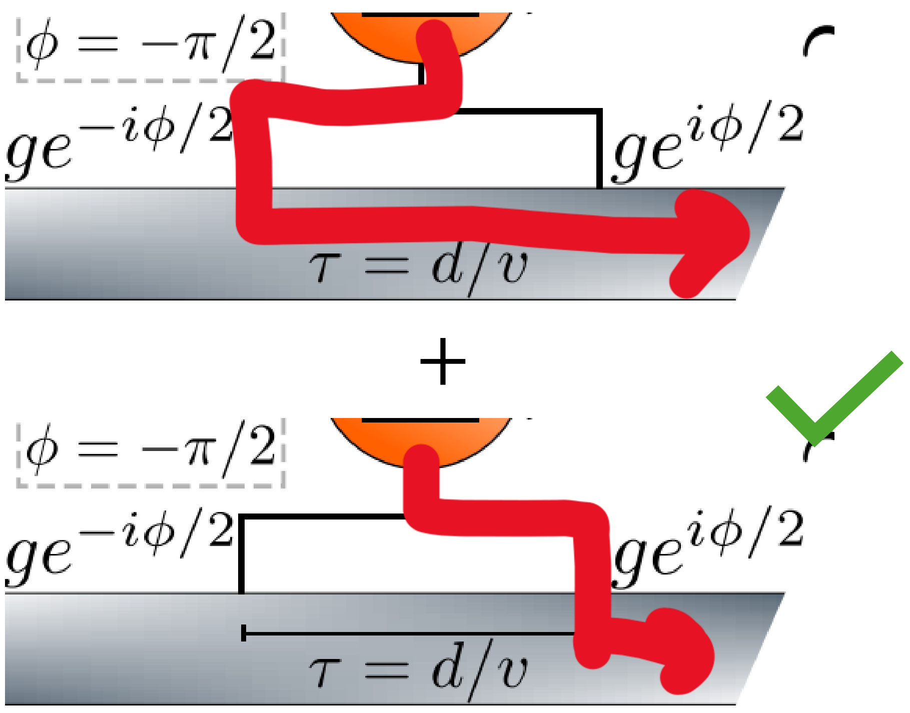
Frequency dependent chirality

CZ Gate with giant transmon molecules

Single-Photon



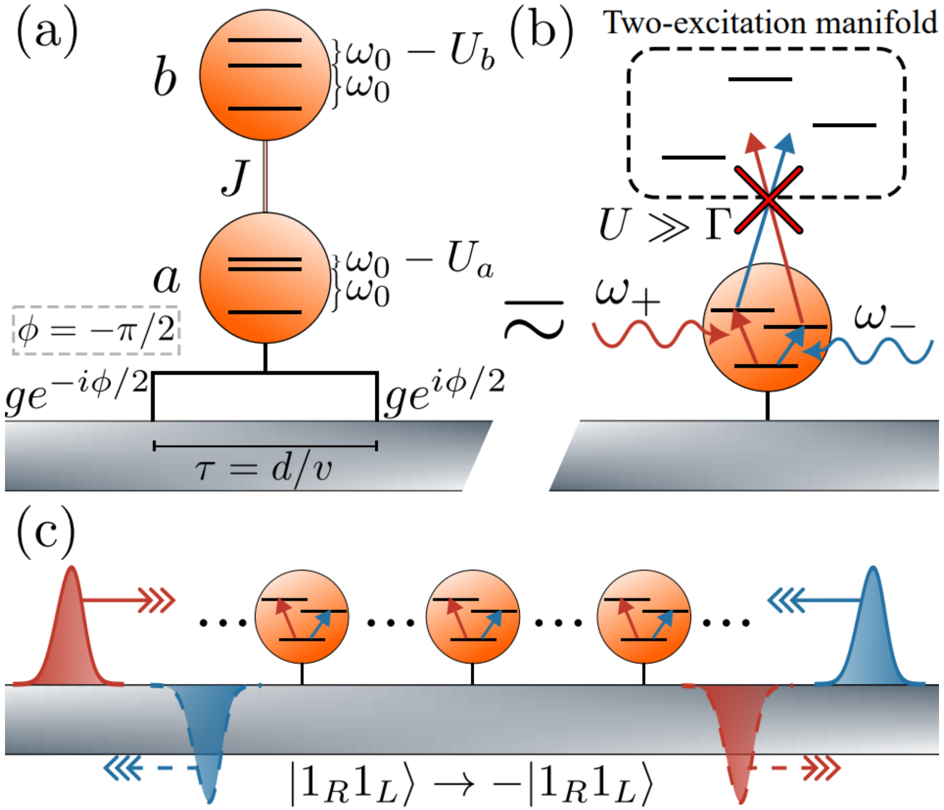
If $\omega\tau = \pi/2$



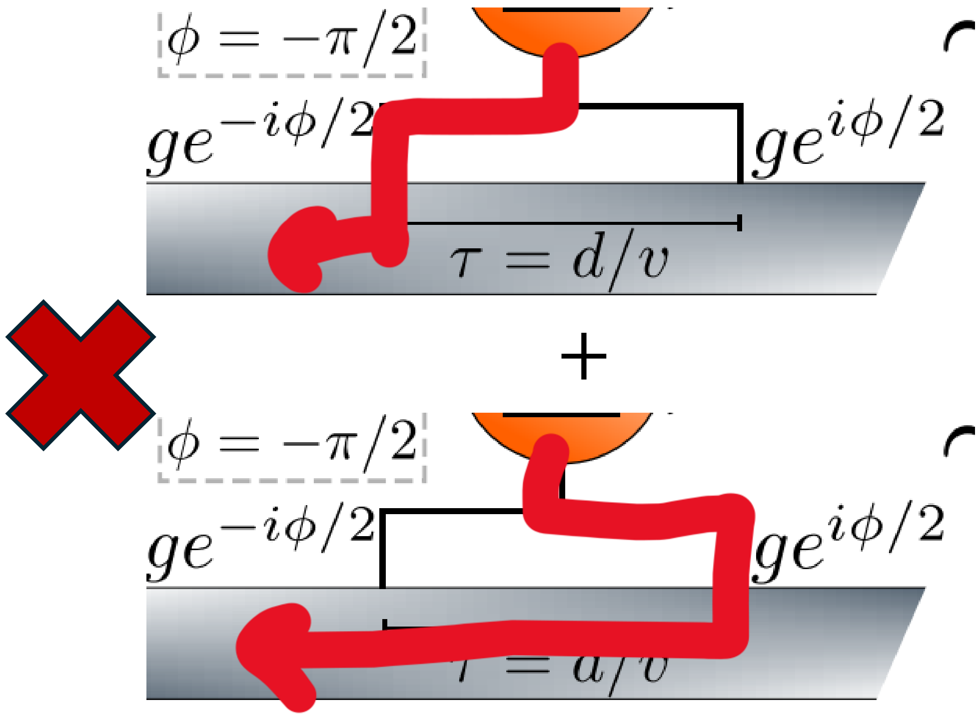
$$e^{i\frac{\pi}{4}-i\frac{\pi}{4}} + e^{-i\frac{\pi}{4}+i\frac{\pi}{4}} = 2$$

CZ Gate with giant transmon molecules

Single-Photon



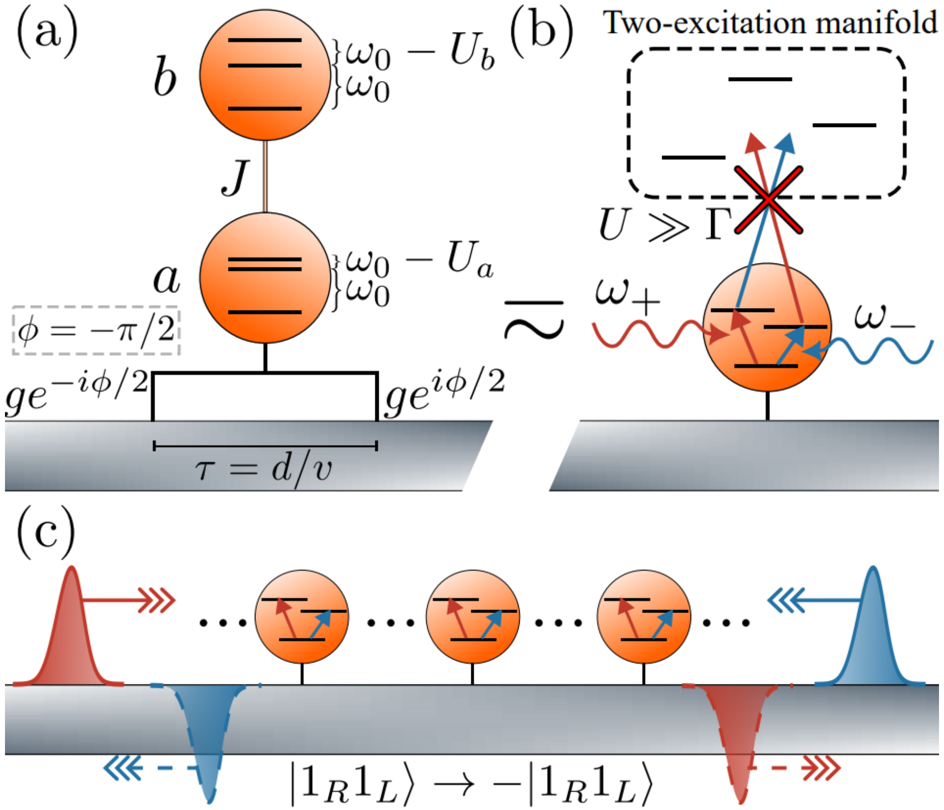
If $\omega\tau = \pi/2$



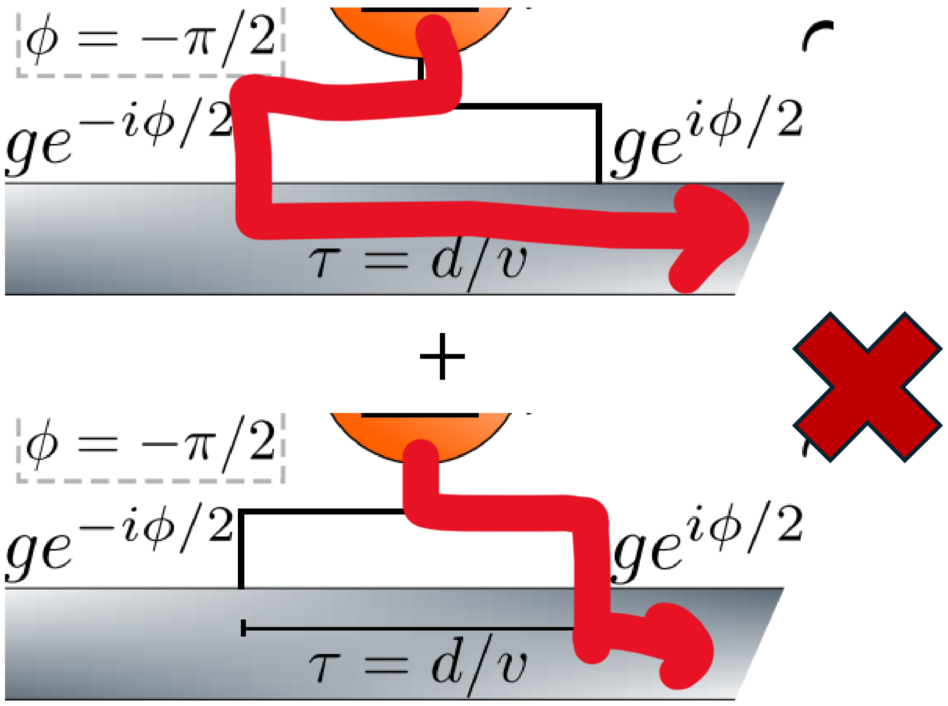
$$e^{i\frac{\pi}{4}+i\frac{\pi}{4}} + e^{-i\frac{\pi}{4}-\frac{i\pi}{4}} = 0$$

CZ Gate with giant transmon molecules

Single-Photon



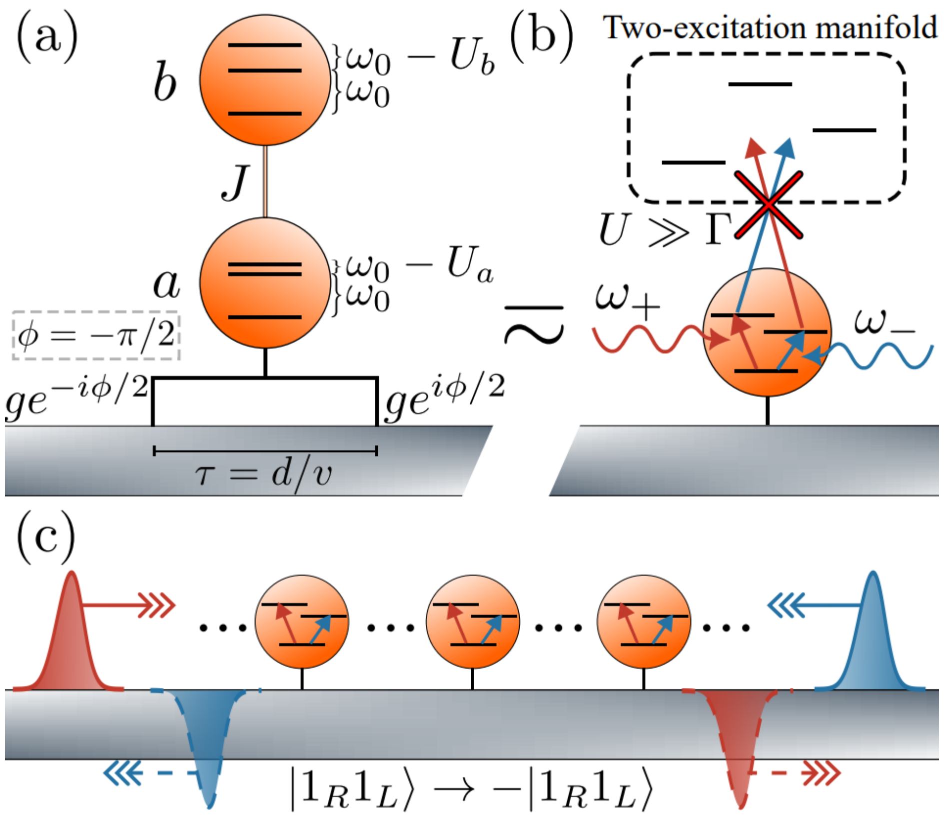
If $\omega\tau = 3\pi/2$



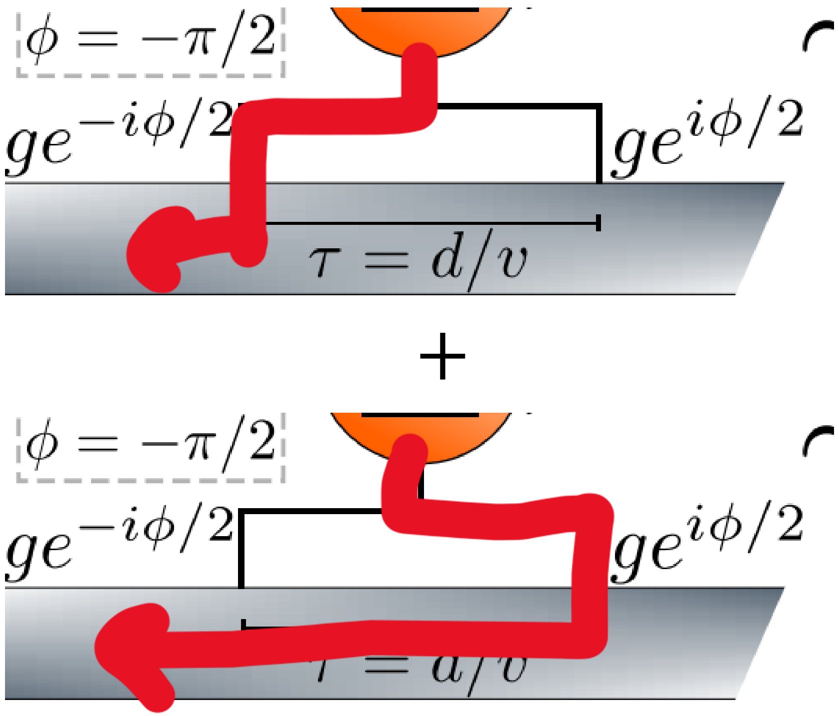
$$e^{i\frac{\pi}{4}-i\frac{3\pi}{4}} + e^{-i\frac{\pi}{4}+i\frac{3\pi}{4}} = 0$$

CZ Gate with giant transmon molecules

Single-Photon



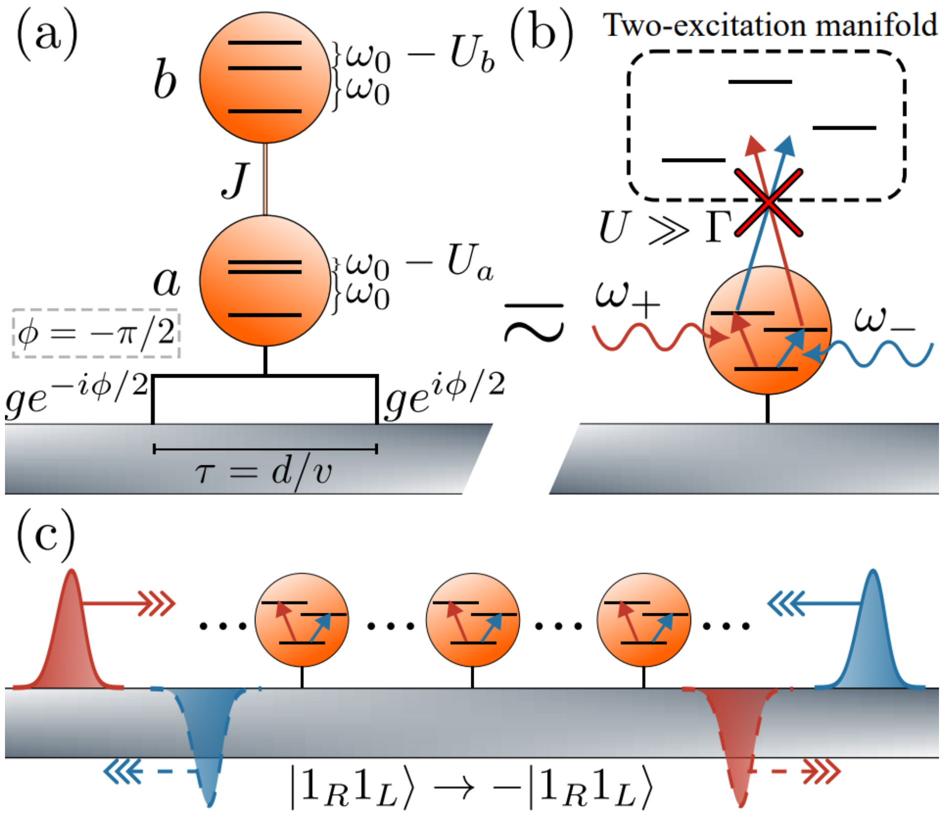
If $\omega\tau = 3\pi/2$



$$e^{i\frac{\pi}{4}+i\frac{3\pi}{4}} + e^{-i\frac{\pi}{4}-i\frac{3\pi}{4}} = -2$$

CZ Gate with giant transmon molecules

Single-Photon



Molecule (dimer)

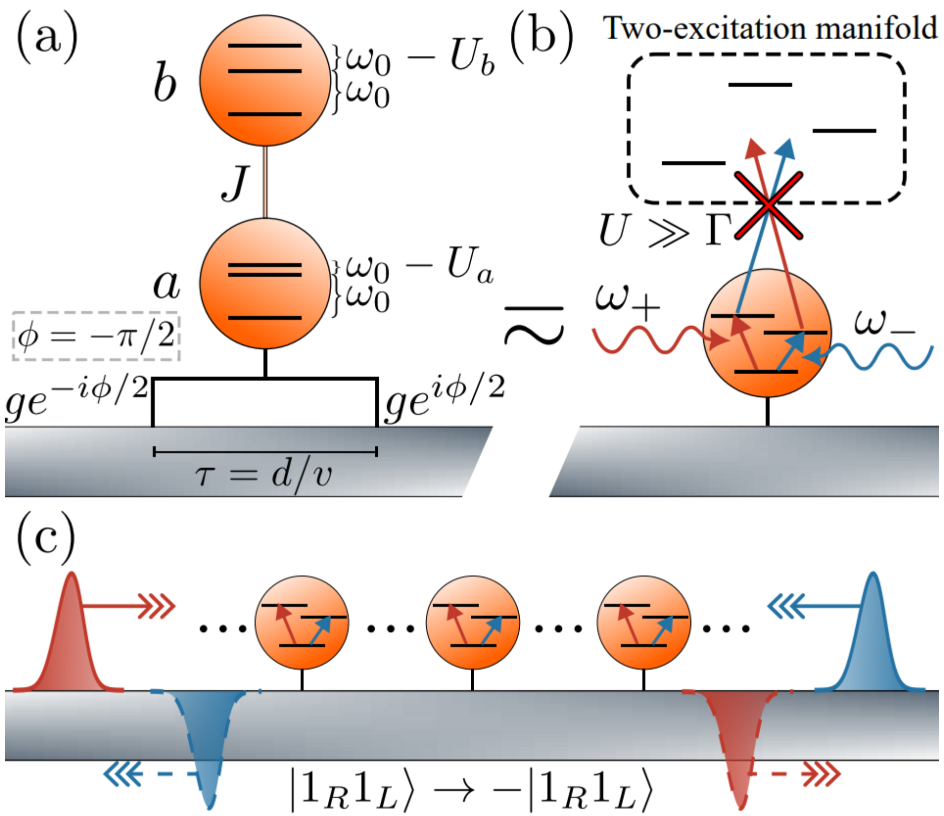
$$\hat{H}_M = \omega_0 \left(\hat{a}^\dagger \hat{a} + \hat{b}^\dagger \hat{b}\right) + J\left(\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a}\right)$$

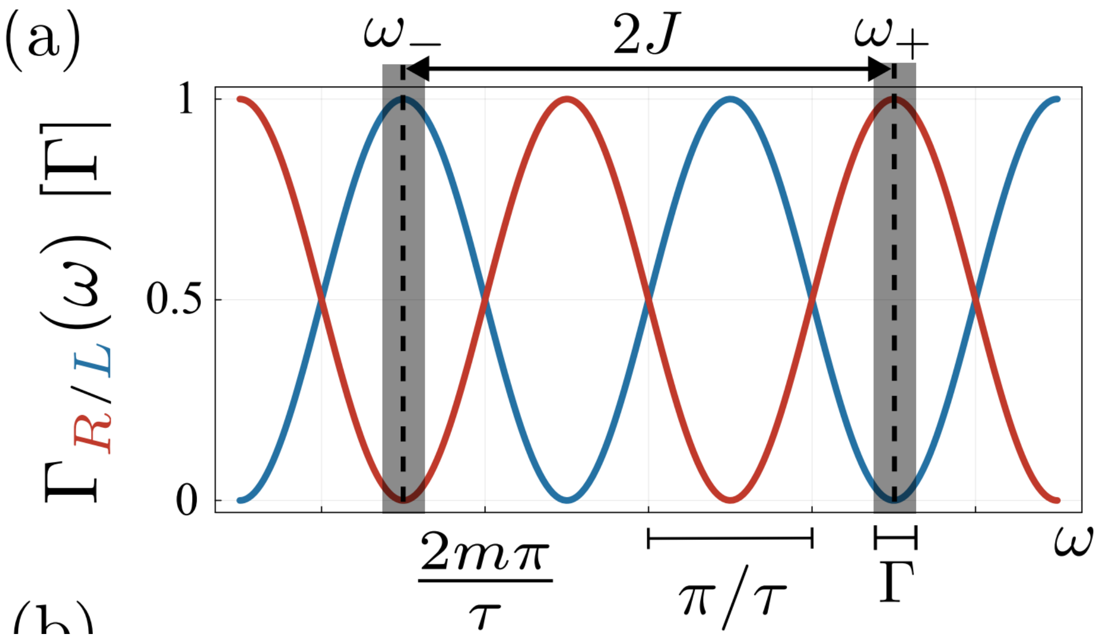
$$\omega_\pm = \omega_0 \pm J$$

Two resonances within single excitation manifold

CZ Gate with giant transmon molecules

Single-Photon



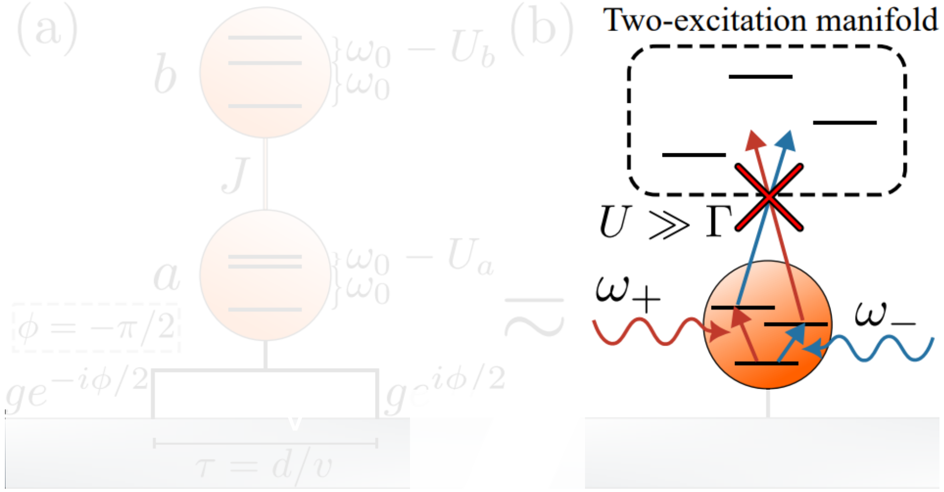


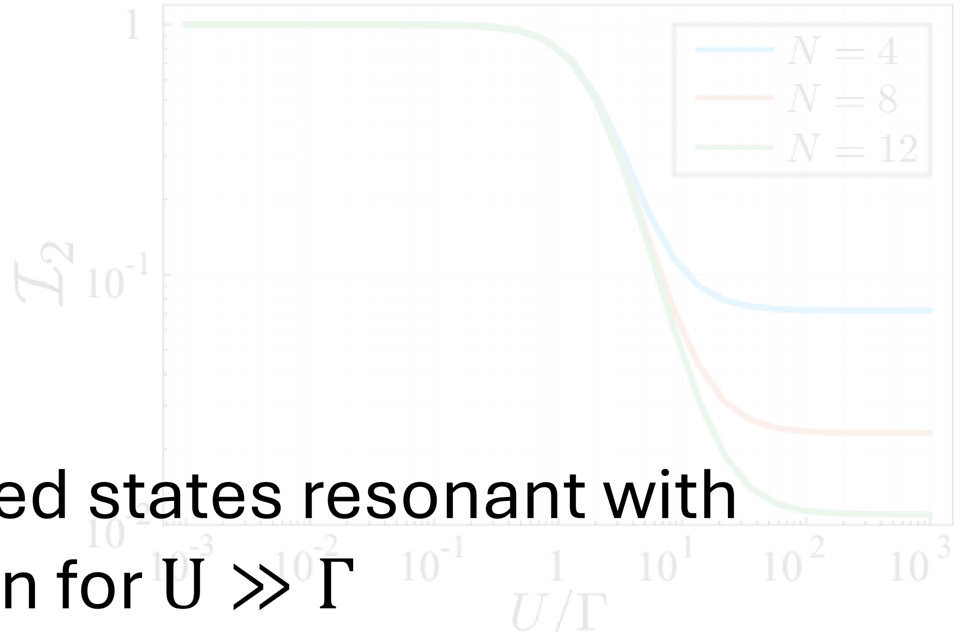
$$\Gamma_{R/L}(\omega) = \frac{\Gamma}{2}\left[1 \pm \sin(\omega\tau)\right]$$

State dependent chirality

CZ Gate with giant transmon molecules

Two-Photon

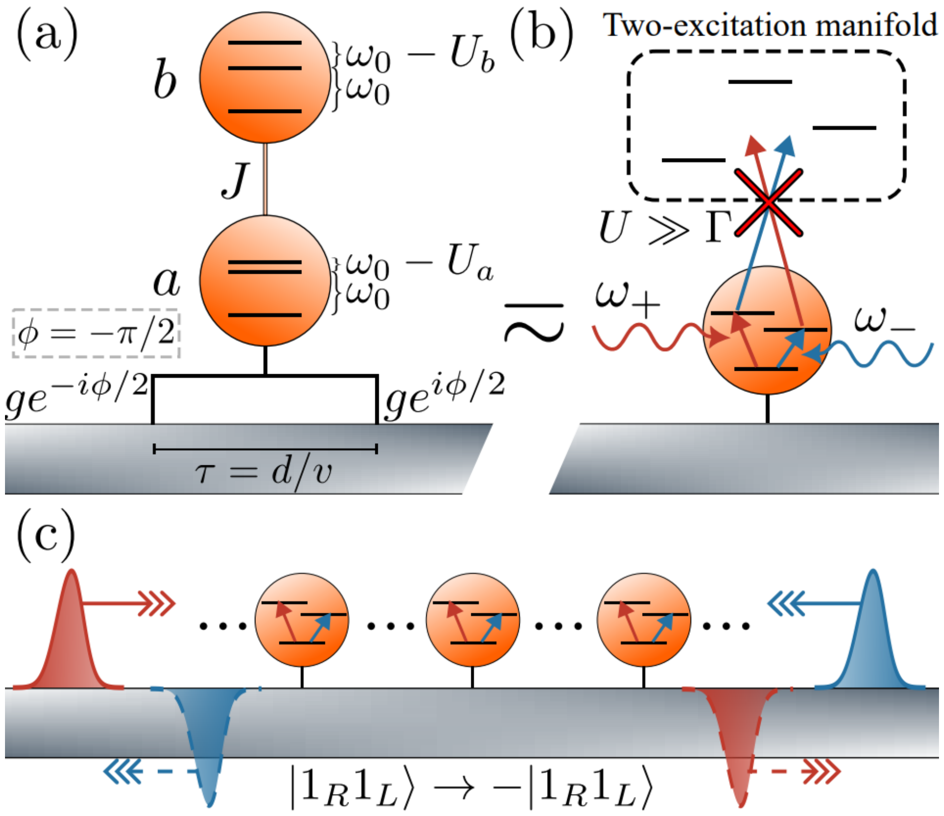


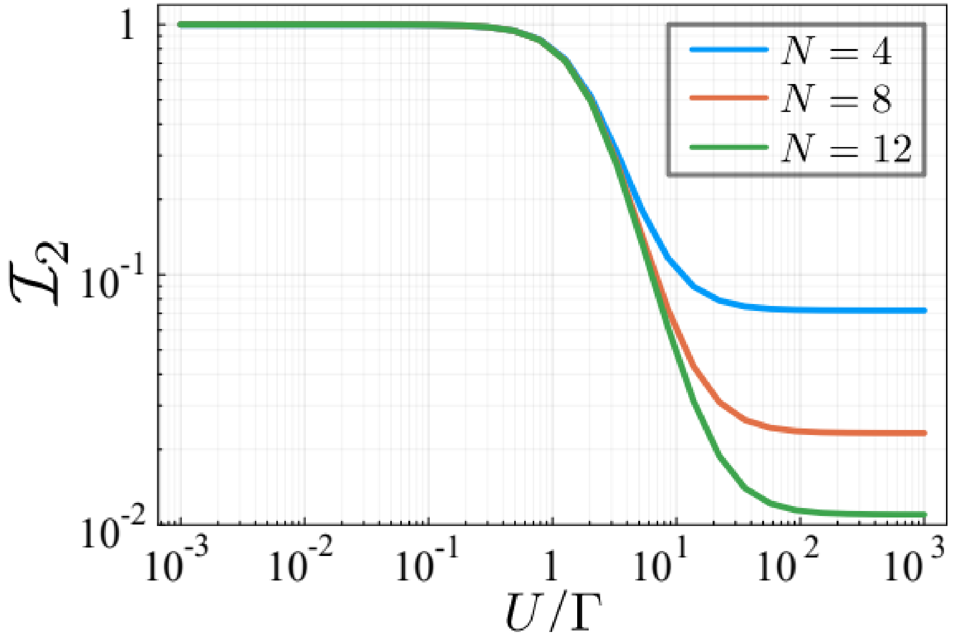


Issue: The molecule has twice-excited states resonant with the input photons for $U \ll \Gamma$ and even for $U \gg \Gamma$

CZ Gate with giant transmon molecules

Two-Photon





$$\hat{d}^\dagger{}_+ = \frac{1}{\sqrt{2}} \left(\hat{a}^\dagger + \hat{b}^\dagger\right)$$

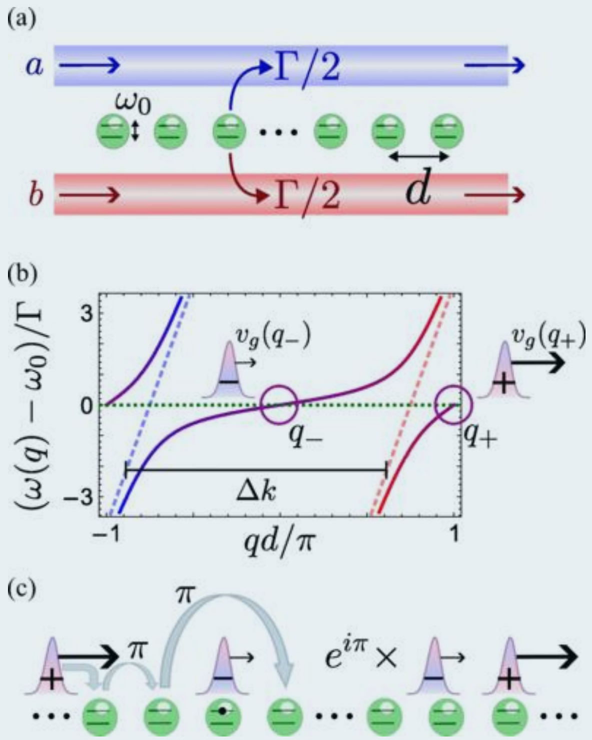
For U $\gg$ Γ the transition is forbidden due to a selection rule $\langle E = 2\omega_0 | \hat{d}^\dagger{}_+ \hat{d}^\dagger{}_- | 0 \rangle \to 0$

Questions?

Passive Photonic CZ Gate with Two-Level Emitters in Chiral Multimode Waveguide QED

Tomás Levy-Yeyati*, Carlos Vega, Tomás Ramos, and Alejandro González-Tudela†

PRX Quantum **6**, 010342 – **Published 5 March, 2025**

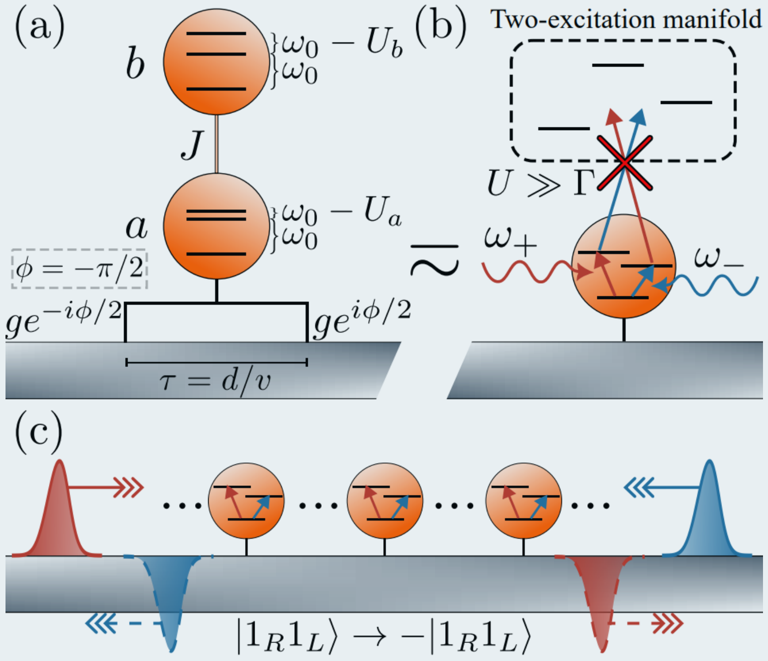


arXiv:2507.05377

[Submitted on 7 Jul 2025]

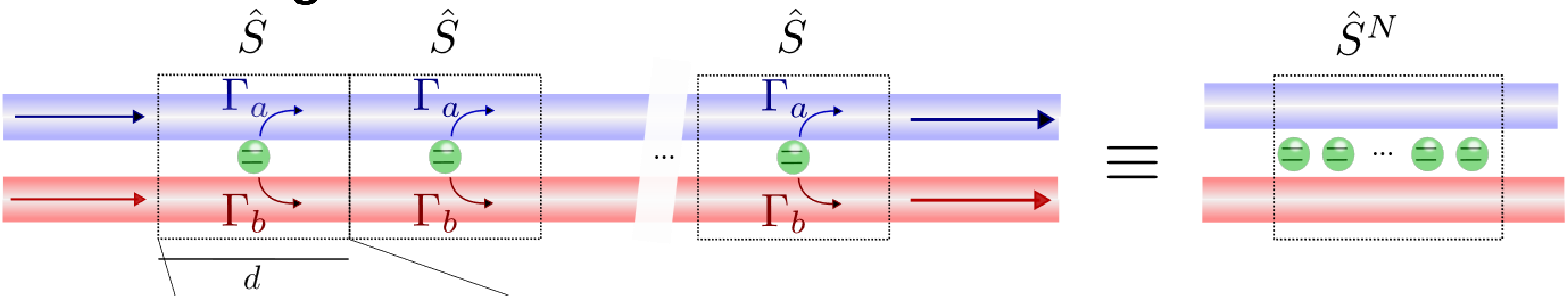
Engineering giant transmon molecules as mediators of conditional two-photon gates

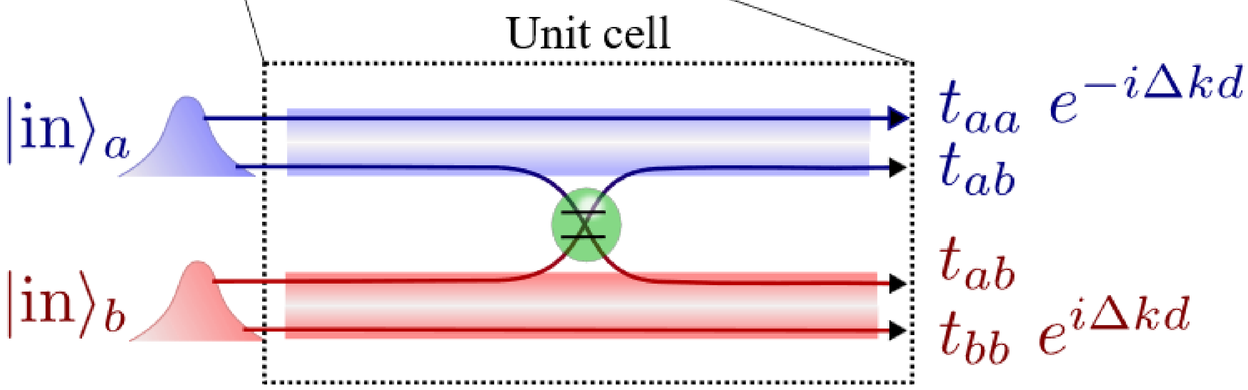
Tomás Levy-Yeyati, Tomás Ramos, Alejandro González-Tudela



Chiral multi-mode waveguide QED

Single-Photon





$$|\Psi\rangle = \left[C_e\hat{\sigma}^\dagger + \sum_{\alpha=a,b}\int dx\ \phi_\alpha(x)\hat{a}^\dagger(x)\right]|vac\rangle$$

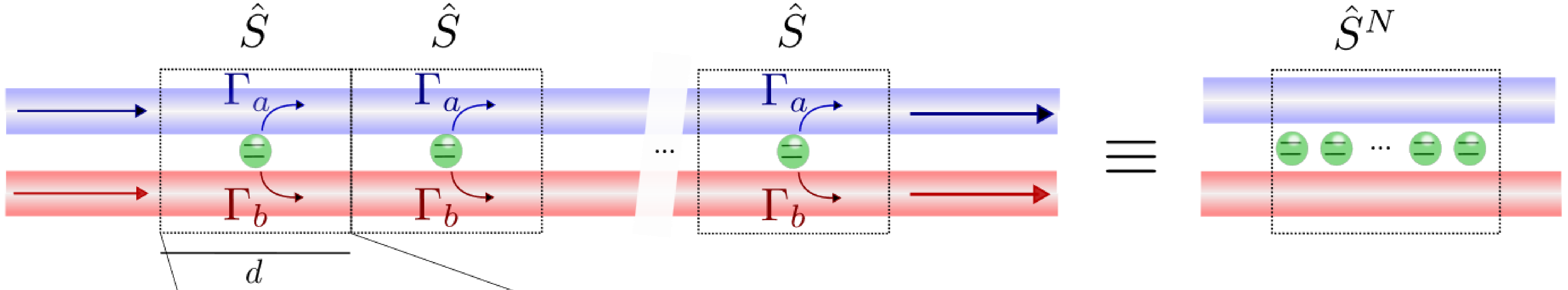
$$\phi_\alpha(x>0) = e^{ik_\alpha x}\left[\sum_{\beta=a,b} t_{\alpha\beta}(\omega)\ \phi_\beta(0^-)\right]$$

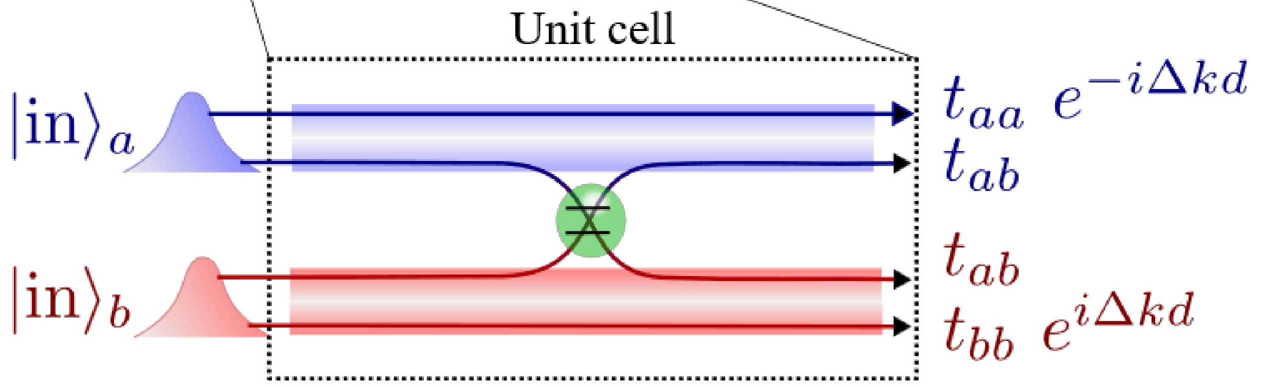
$$\hat{H}|\Psi\rangle = \omega|\Psi\rangle$$

$$\hat{s} = \begin{pmatrix} t_{aa}(\omega) & t_{ab}(\omega) \\ t_{ab}(\omega) & t_{bb}(\omega) \end{pmatrix}$$

Chiral multi-mode waveguide QED

Single-Photon





$$t_{aa}(\omega) = \frac{\Gamma_b - \Gamma_a - 2i(\omega - \omega_0)}{\Gamma_a + \Gamma_b - 2i(\omega - \omega_0)}$$

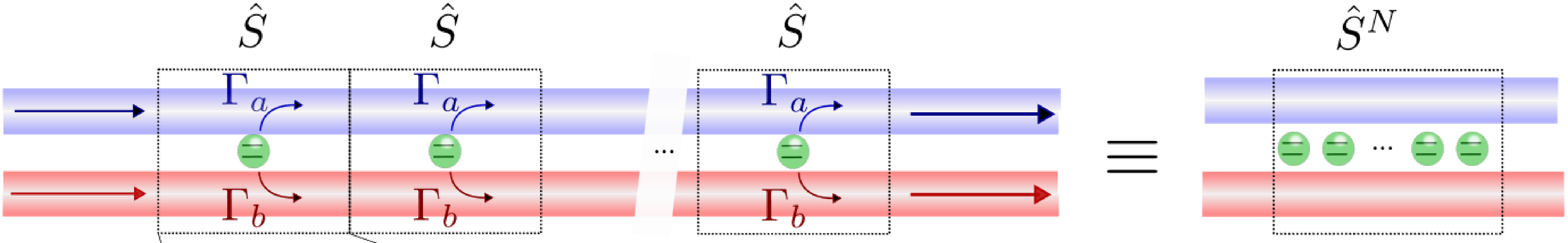
$$t_{bb}(\omega) = \frac{\Gamma_a - \Gamma_b - 2i(\omega - \omega_0)}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

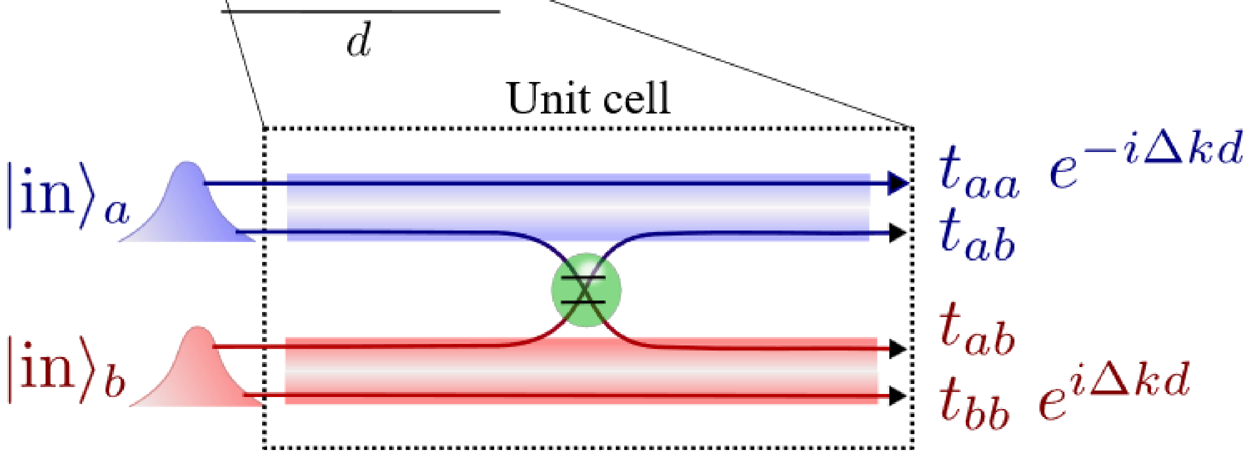
$$t_{ab}(\omega) = \frac{-2\sqrt{\Gamma_a \Gamma_b}}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

$$\hat{s} = \begin{pmatrix} t_{aa}(\omega) & t_{ab}(\omega) \\ t_{ab}(\omega) & t_{bb}(\omega) \end{pmatrix}$$

Chiral multi-mode waveguide QED

Single-Photon





$$t_{aa}(\omega) = \frac{\Gamma_b - \Gamma_a - 2i(\omega - \omega_0)}{\Gamma_a + \Gamma_b - 2i(\omega - \omega_0)}$$

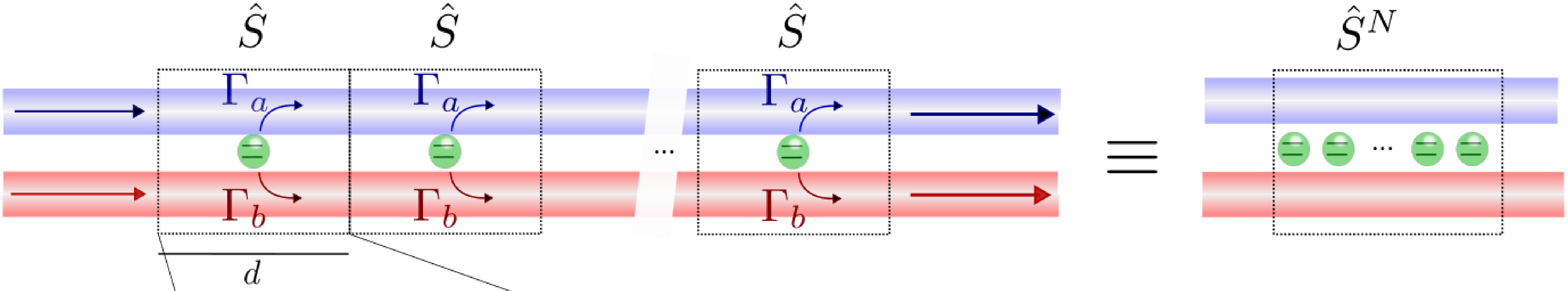
$$t_{bb}(\omega) = \frac{\Gamma_a - \Gamma_b - 2i(\omega - \omega_0)}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

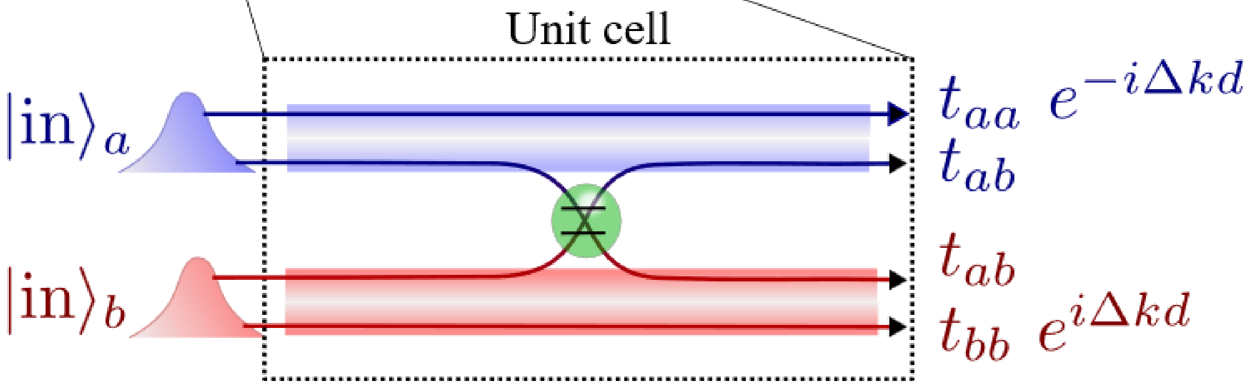
$$t_{ab}(\omega) = \frac{-2\sqrt{\Gamma_a \Gamma_b}}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

$$\hat{P} = e^{ik_0 d/2} \begin{pmatrix} e^{-i\Delta k d/2} & 0 \\ 0 & e^{i\Delta k d/2} \end{pmatrix}$$

Chiral multi-mode waveguide QED

Single-Photon





$$t_{aa}(\omega) = \frac{\Gamma_b - \Gamma_a - 2i(\omega - \omega_0)}{\Gamma_a + \Gamma_b - 2i(\omega - \omega_0)}$$

$$t_{bb}(\omega) = \frac{\Gamma_a - \Gamma_b - 2i(\omega - \omega_0)}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

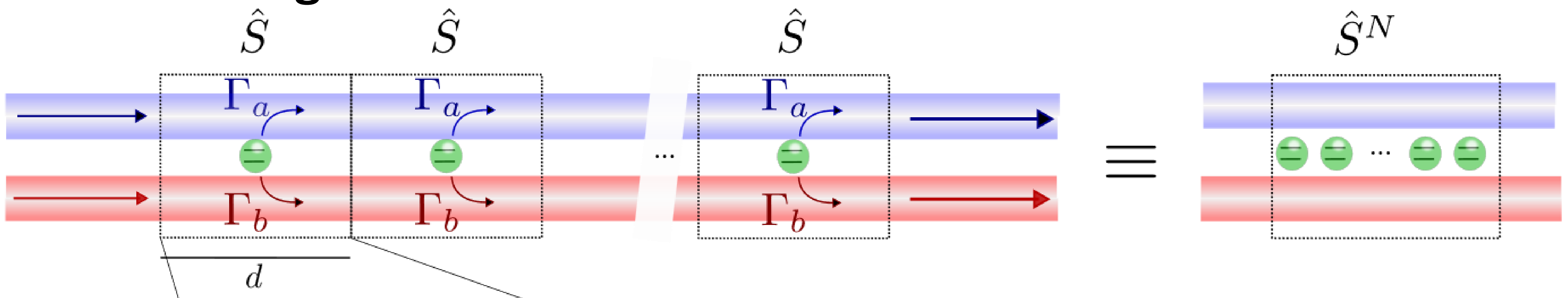
$$t_{ab}(\omega) = \frac{-2\sqrt{\Gamma_a \Gamma_b}}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

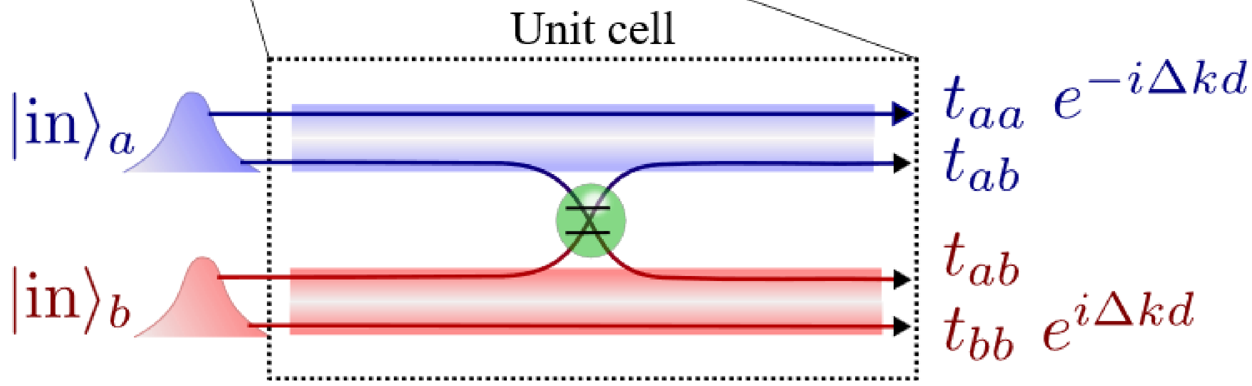
$$|out\rangle = \hat{S}^N |in\rangle$$

$$\hat{S} = \hat{P}\hat{s}\hat{P}$$

Chiral multi-mode waveguide QED

Single-Photon





$$t_{aa}(\omega) = \frac{\Gamma_b - \Gamma_a - 2i(\omega - \omega_0)}{\Gamma_a + \Gamma_b - 2i(\omega - \omega_0)}$$

$$t_{bb}(\omega) = \frac{\Gamma_a - \Gamma_b - 2i(\omega - \omega_0)}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

$$t_{ab}(\omega) = \frac{-2\sqrt{\Gamma_a\Gamma_b}}{\Gamma_b + \Gamma_a - 2i(\omega - \omega_0)}$$

$$\hat{S}|\omega\rangle_\mu = e^{i(k_0+q_\mu)d}|\omega\rangle_\mu \qquad \hat{S} = \hat{P}\hat{s}\hat{P}$$

Chiral multi-mode waveguide QED

Two-Photon $N = 1$

Total energy, $E = \omega_1 + \omega_2$, conservation

$$\hat{s}|\omega_1\omega_2\rangle_{\alpha\lambda} = \sum_{\beta,\nu} \int_{\omega_1>\omega_2} d\omega_1 d\omega_2 \; t_{\beta\alpha}(\omega_1) t_{\nu\lambda}(\omega_2) |\omega_1\omega_2\rangle_{\beta\nu}$$

Chiral multi-mode waveguide QED

Two-Photon $N = 1$

Total energy, $E = \omega_1 + \omega_2$, conservation

$$\hat{s}|\omega_1\omega_2\rangle_{\alpha\lambda} = \sum_{\beta,\nu}\int_{\omega_1>\omega_2} d\omega_1 d\omega_2\, t_{\beta\alpha}(\omega_1)t_{\nu\lambda}(\omega_2)|\omega_1\omega_2\rangle_{\beta\nu}$$

$$-\frac{1}{\pi}\sum_{\beta,\nu}\int_{\omega_1>\omega_2} d\omega_1 d\omega_2\, [t_{\beta\alpha}(\omega_1) - \delta_{\beta\alpha}][t_{\nu\lambda}(\omega_2) - \delta_{\nu\lambda}]|B_E\rangle_{\beta\nu}$$

$$|B_E\rangle_{\beta\nu} = \int_{\omega_1'>\omega_2'} d\omega_1' d\omega_2'\, \delta(E - \omega_1' - \omega_2')\left[\frac{1}{\frac{\Gamma}{2} - i(\omega_1' - \omega_0)} + \frac{1}{\frac{\Gamma}{2} - i(\omega_2' - \omega_0)}\right]|\omega_1'\omega_2'\rangle_{\beta\nu}$$

Chiral multi-mode waveguide QED

Two-Photon finite N

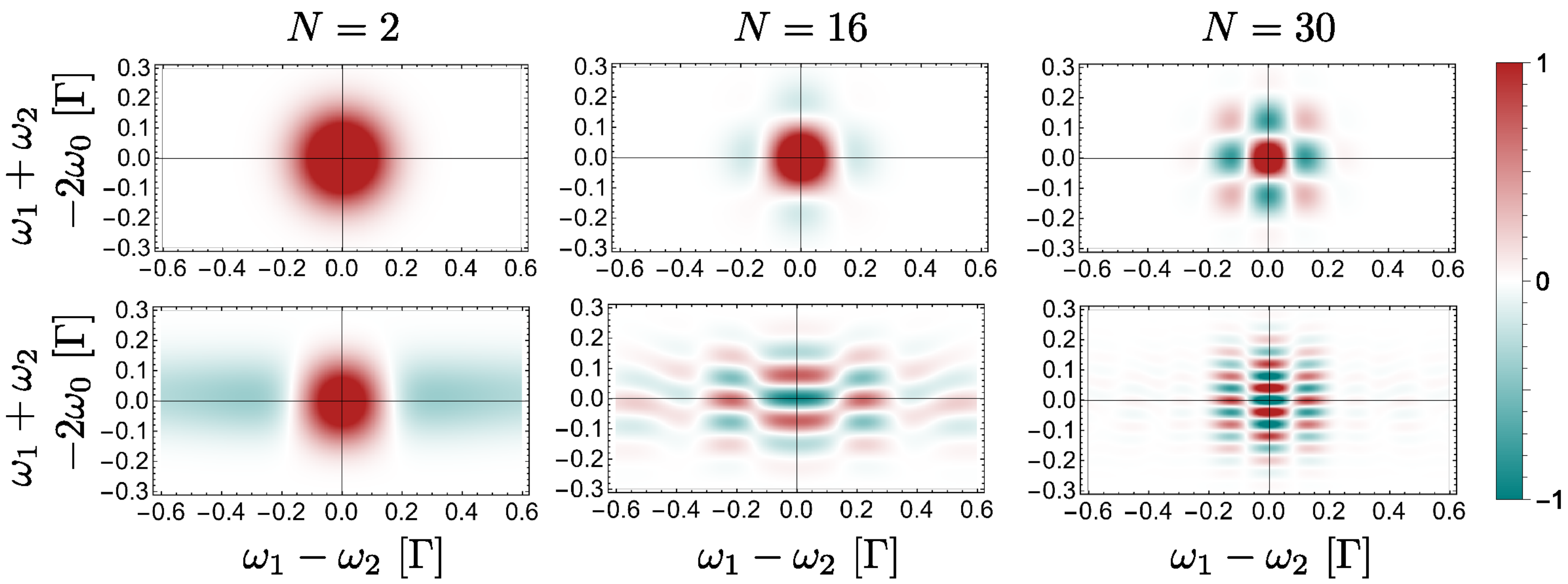
Total quasimomentum, $K = q_1 + q_2$, conservation

Total energy, $E = \omega_1 + \omega_2$, conservation

Continuum of inelastic outputs supressed

Input

Output

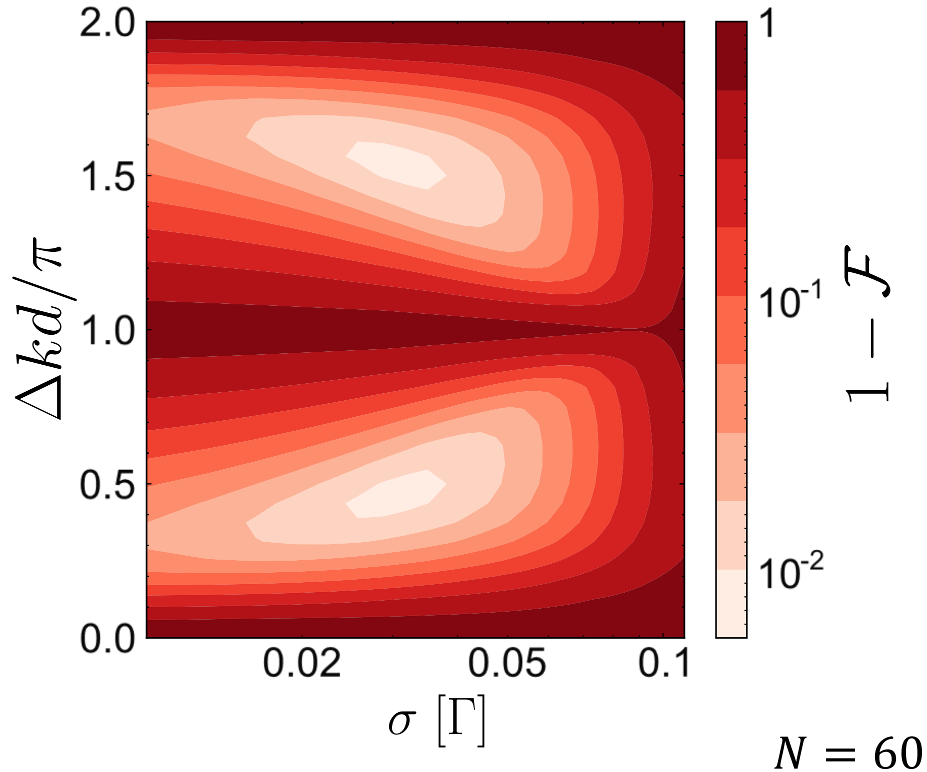


$$|out\rangle = \hat{S}^N|in\rangle$$

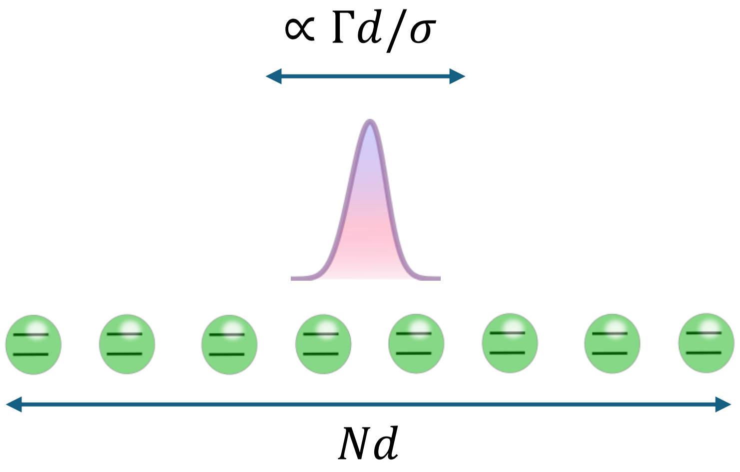
$$\langle out_{ideal}|out\rangle$$

Fidelities

- Finite number of emitters N
- Finite frequency bandwidth σ



$N = 60$



Optimal σ

$$\Gamma/N \lesssim \sigma \ll \Gamma$$

Fit inside the array

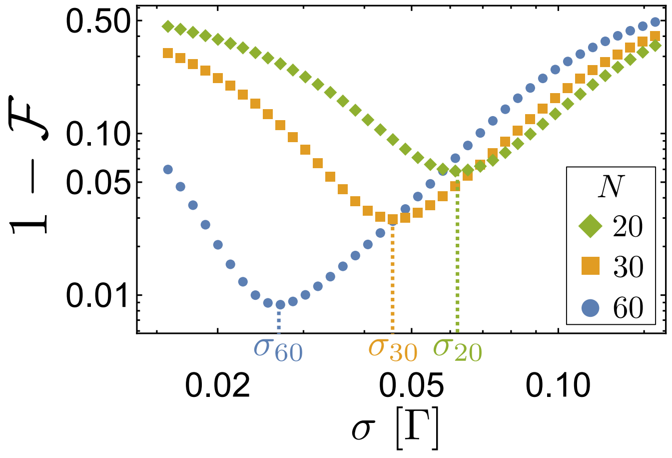
Well defined frequency

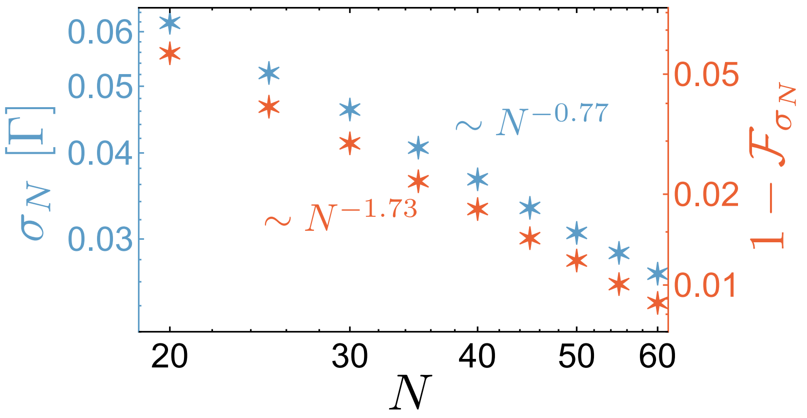
$$|out\rangle = \hat{S}^N|in\rangle$$

$$\langle out_{ideal}|out\rangle$$

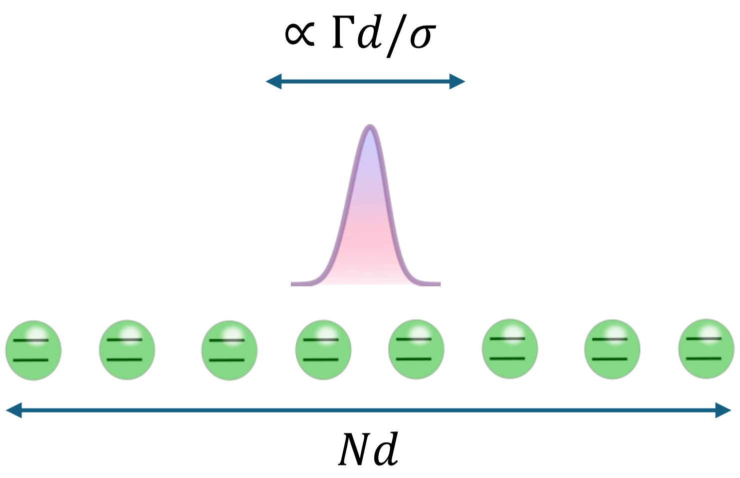
Fidelities

- Finite number of emitters N
- Finite frequency bandwidth σ





$\Delta kd = 3\pi/2$



Optimal σ

$$\Gamma/N \lesssim \sigma \ll \Gamma$$

Fit inside the array

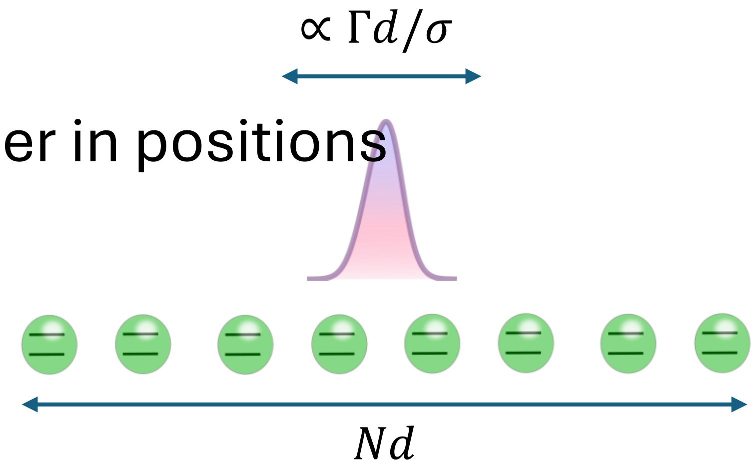
Well defined frequency

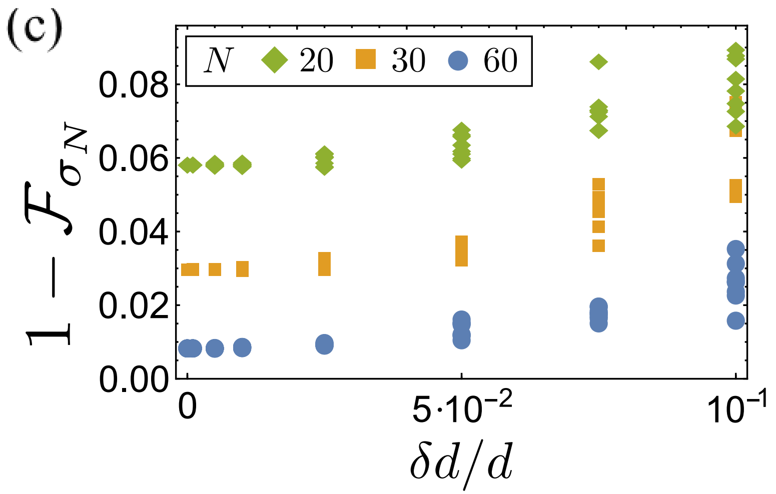
$$|out\rangle = \hat{S}^N |in\rangle$$

$$\langle out_{ideal}|out\rangle$$

Fidelities

- Chirality of waveguides → Roboust against disorder in positions





Optimal σ

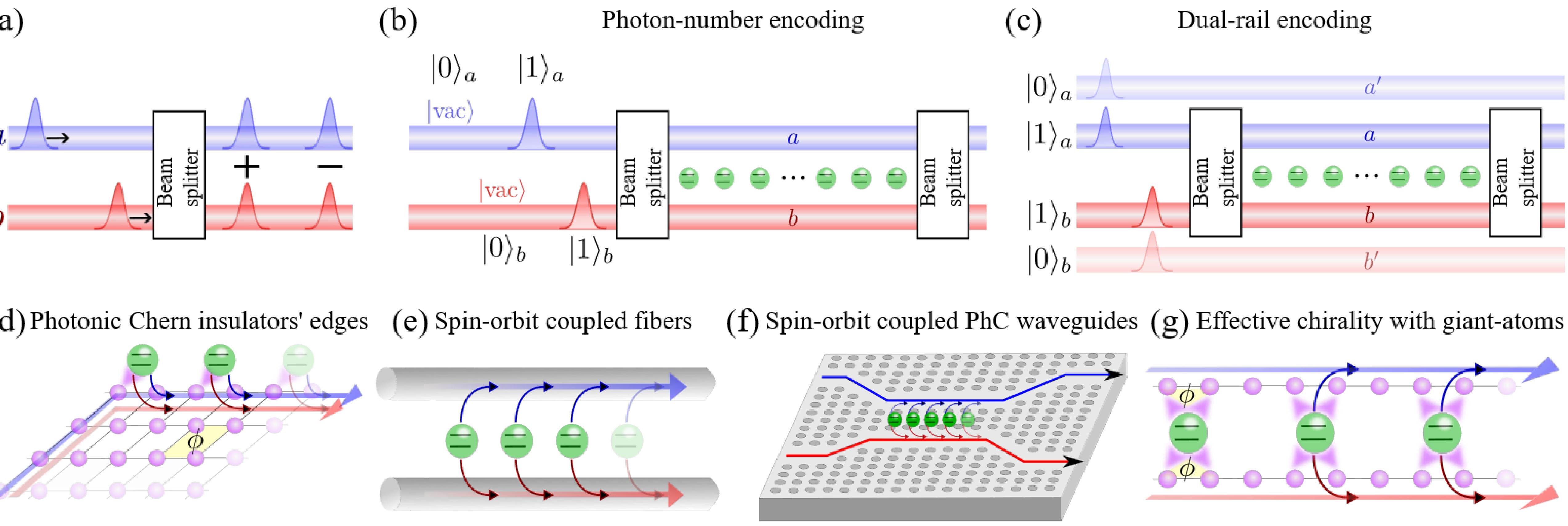
$$\Gamma/N \lesssim \sigma \ll \Gamma$$

Fit inside the array

Well defined frequency

$\Delta k d = 3\pi/2$

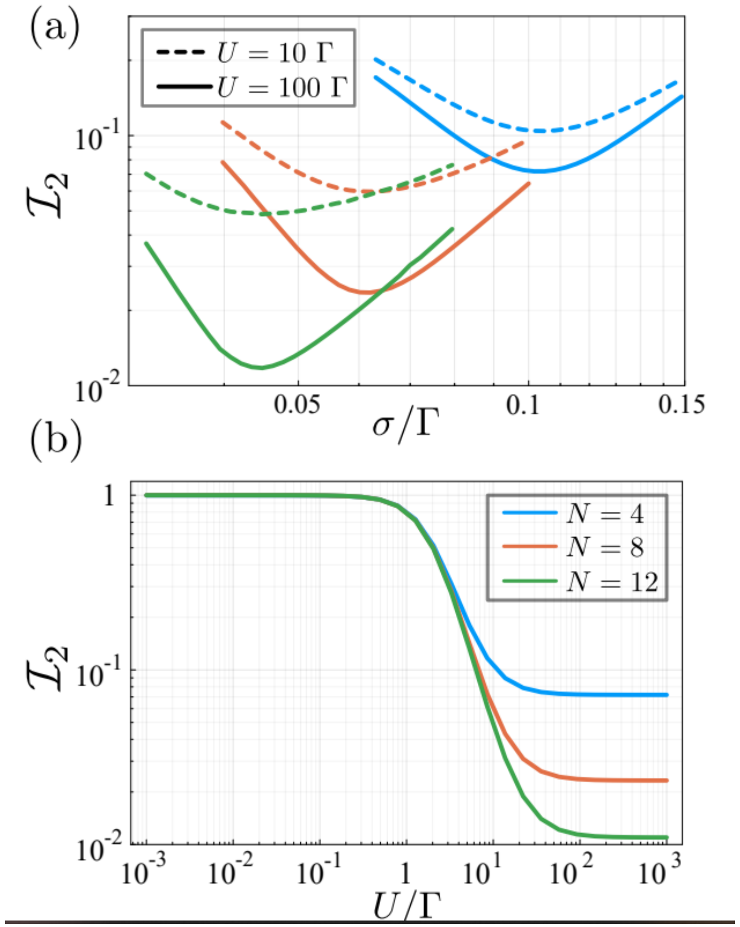
Implementations



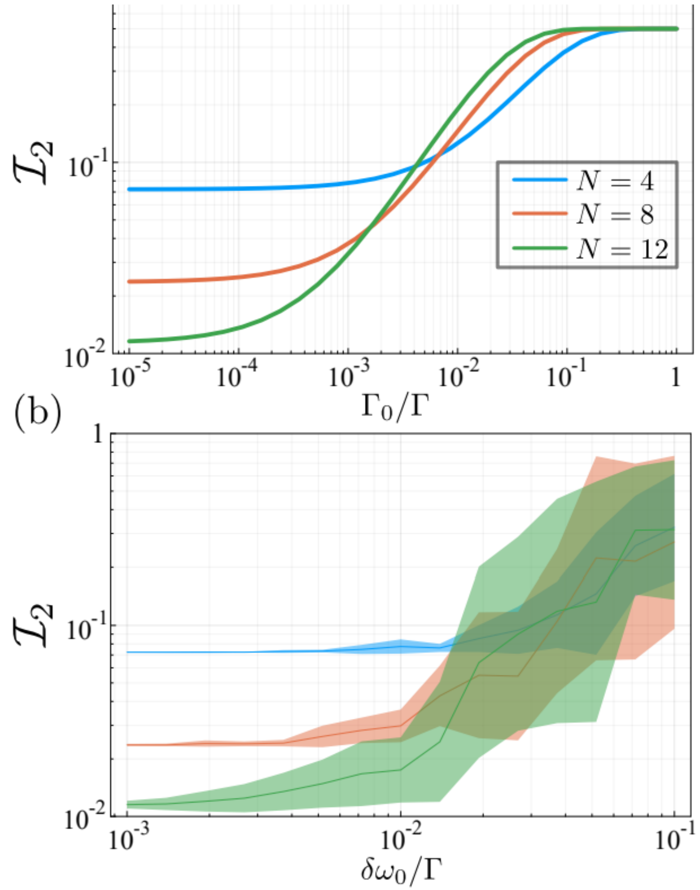
C. Joshi, F. Yang and M. Mirhosseini
Phys. Rev. X **13**, 021039 (2023)

B. Kannan, A. Almanakly, et. al.
Nat. Phys. **19**, 394-400 (2023)

Fidelities

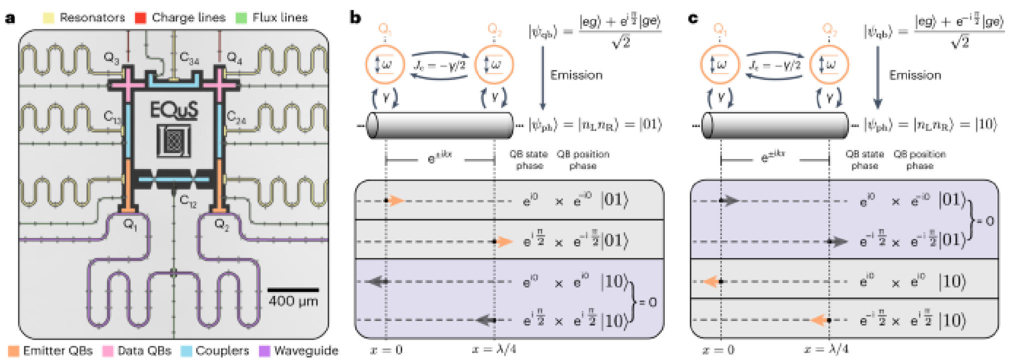


(a)
U = 10 Γ
U = 100 Γ
$\mathcal{I}_2$
10^{-1}
10^{-2}
0.05
0.1
0.15
σ/Γ
(b)
$N = 4$
$N = 8$
$N = 12$
1
10^{-1}
10^{-2}
10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3}
U/Γ



$\mathcal{I}_2$
10^{-1}
10^{-2}
$N = 4$
$N = 8$
$N = 12$
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
Γ_0/Γ
(b)
1
10^{-1}
10^{-2}
10^{-3} 10^{-2} 10^{-1}
$\delta\omega_0/\Gamma$

Experiments



On-demand directional microwave photon emission using waveguide quantum electrodynamics

Bharath Kannan, Aziza Almanakly, Youngkyu Sung, Agustin Di Paolo, David A. Rower, Jochen Braumüller, Alexander Melville, Bethany M. Niedzielski, Amir Karamlou, Kyle Serniak, Antti Vepsäläinen, Mollie E. Schwartz, Jonilyn L. Yoder, Roni Winik, Joel I-Jan Wang, Terry P. Orlando, Simon Gustavsson, Jeffrey A. Grover & William D. Oliver

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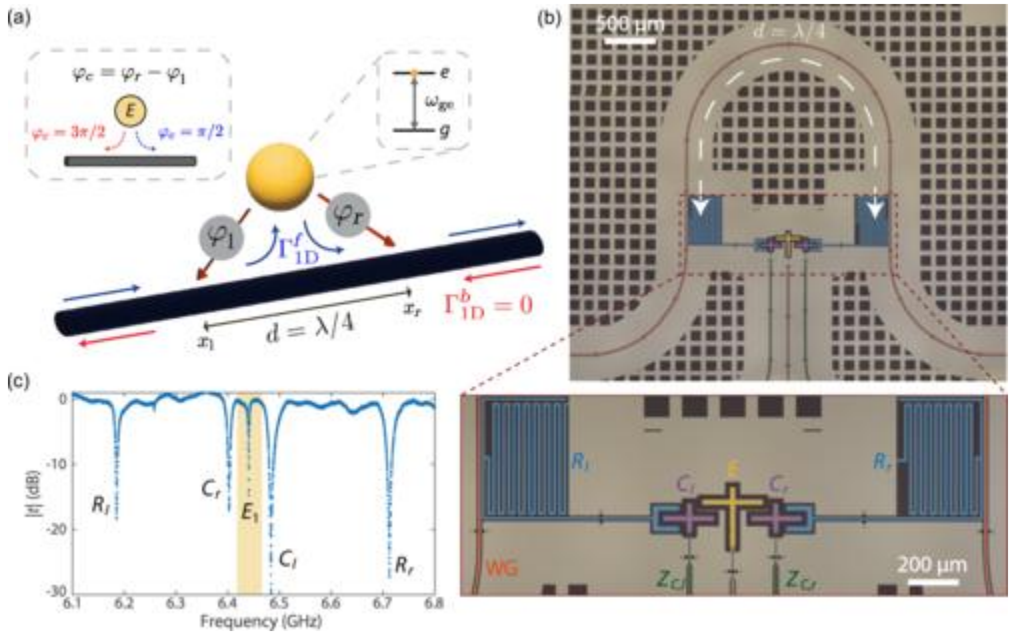

Resonance Fluorescence of a Chiral Artificial Atom

Chaitali Joshi*, Frank Yang*, and Mohammad Mirhosseini†

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Phys. Rev. X **13**, 021039 – **Published 26 June, 2023**

DOI: https://doi.org/10.1103/PhysRevX.13.021039