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Stark effect enables universal entanglement in a quantum network

Nanolight 2022, Benasque

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Stephen Hanham,

Giovanni Barontini

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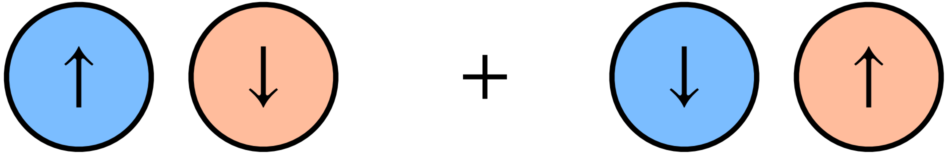
Motivation: Quantum Entanglement

- What is quantum entanglement?



The two particles in a quantum superposition…

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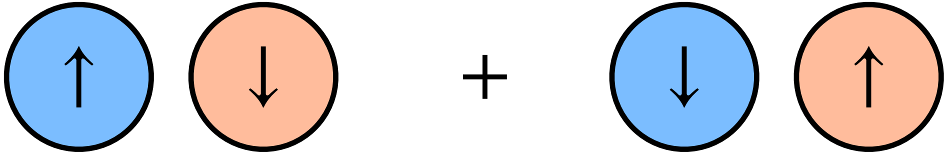
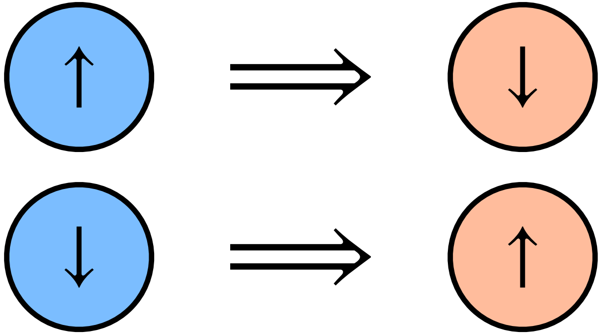


The two particles in a quantum superposition…

…so when measured they are ***perfectly*** (anti-)***correlated***



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Motivation: Quantum Entanglement

- What is quantum entanglement?
- Why is it useful?

Classical computation

New bit depends on
state of previous bit

1	→	1 0	→	1 0 0	→	1 0 0 1	→	1 0 0 1 0	…

↘

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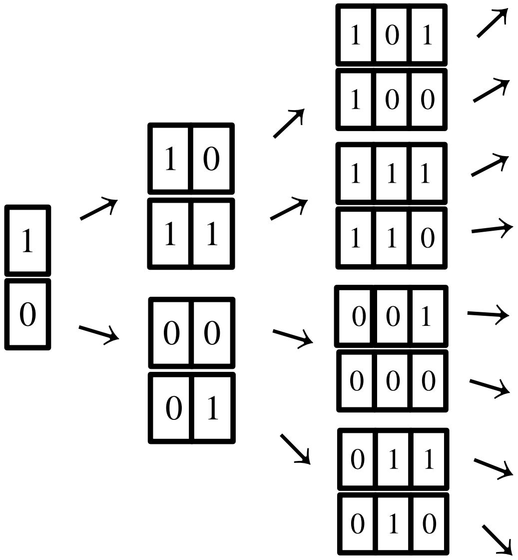
Motivation: Quantum Entanglement

- What is quantum entanglement?
- Why is it useful?

New bit depends on state of previous bit

Classical computation $\boxed{1} \rightarrow \boxed{1|0} \rightarrow \boxed{1|0|0} \rightarrow \boxed{1|0|0|1} \rightarrow \boxed{1|0|0|1|0} \quad \cdots$

Quantum computation



New qubit added in superposition which depends on previous

. . .

QC explore much larger state space simultaneously

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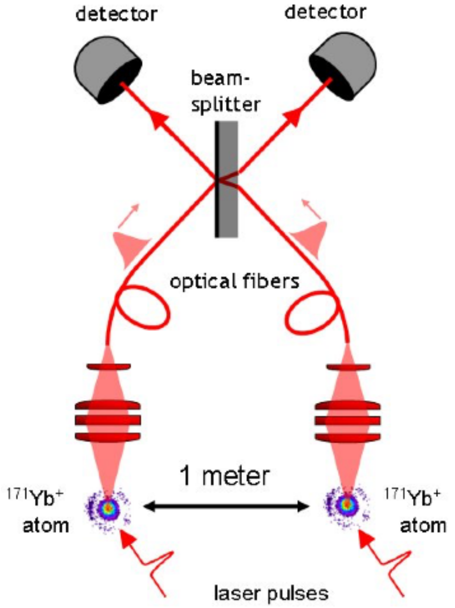
Motivation: Quantum Entanglement

- What is quantum entanglement?
- Why is it useful?
- How do we create it?

Remote Entanglement

Principle of two node entanglement



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Rempe group:
Nature, 484(7393), 195-200, 2012

Monroe group:
Nature Physics, *11*(1), 37-42, 2014
Nature, *449*(7158), 68-71, 2007

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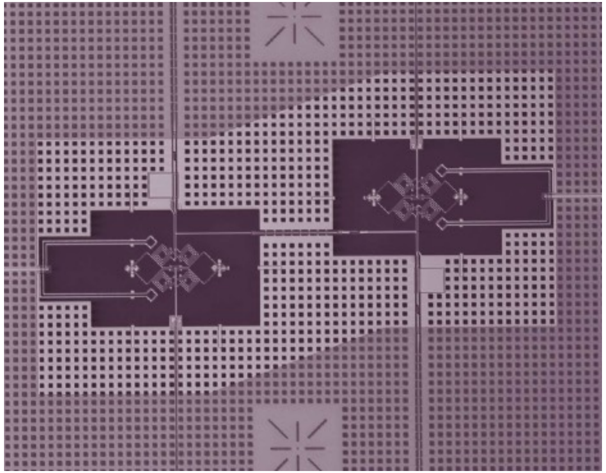
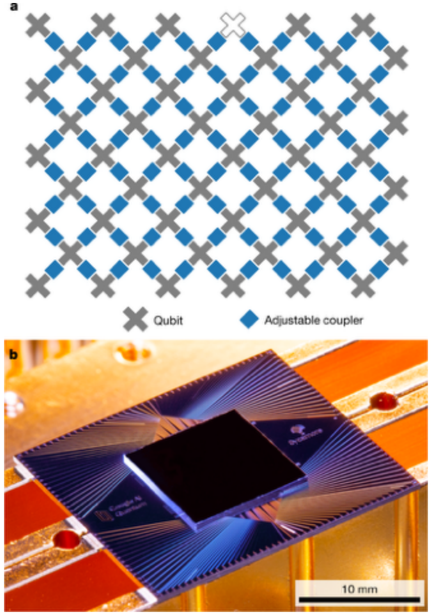
Local Entanglement



Science, *313*(5792), 1423-1425, 2006
Martinis group

Google's Sycamore processor:
53 local qubits



Nature, 574(7779), 505-510, 2019
Martinis group

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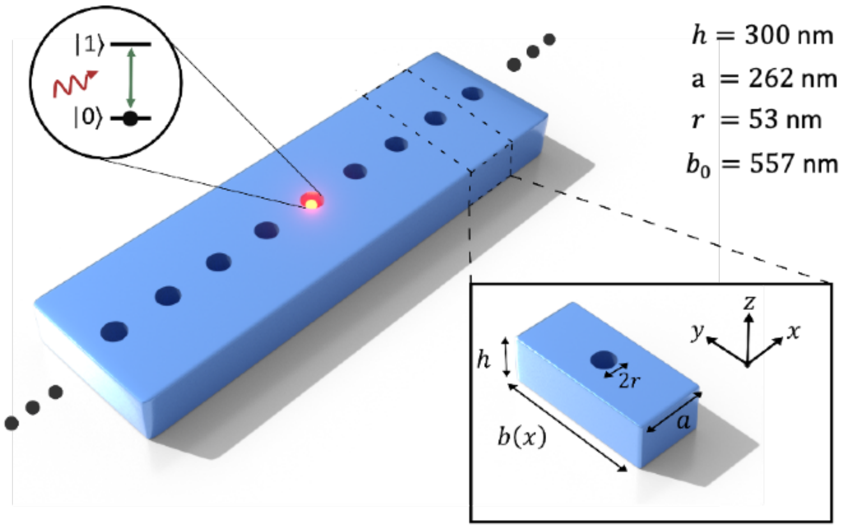
Nanophotonic Crystal Resonator: Design

- Periodic structure in Si_3N_4 nano beam
- Air band at $780\,\mathrm{nm}$



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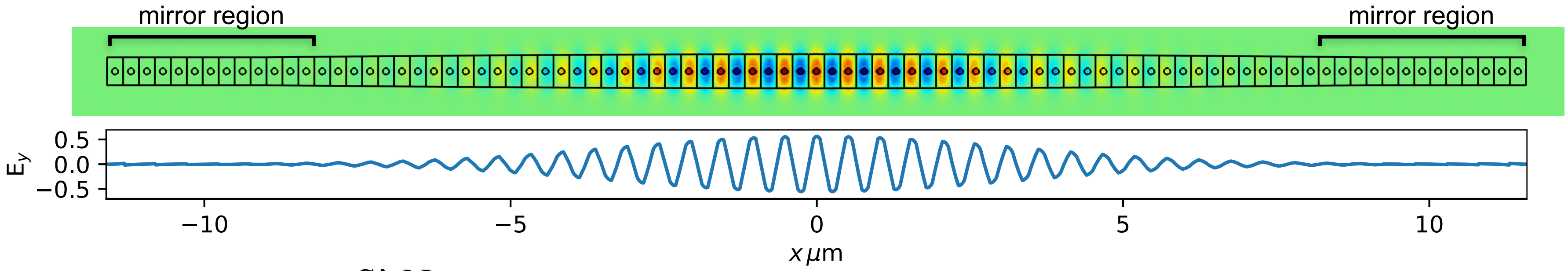
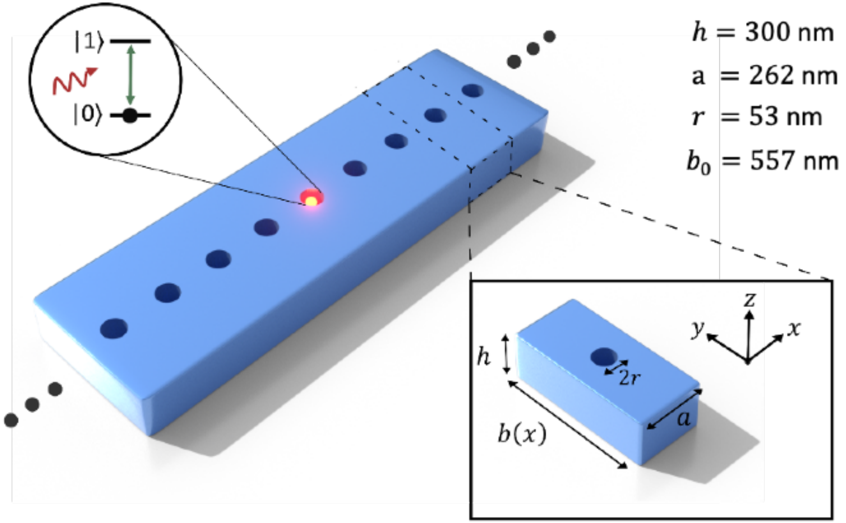


- Periodic structure in Si_3N_4 nano beam
- Air band at $780\,\mathrm{nm}$
- Gradual variation of beam width confines mode
- Bandgap at ends which act like mirrors
- Field concentrated in holes where QE's located



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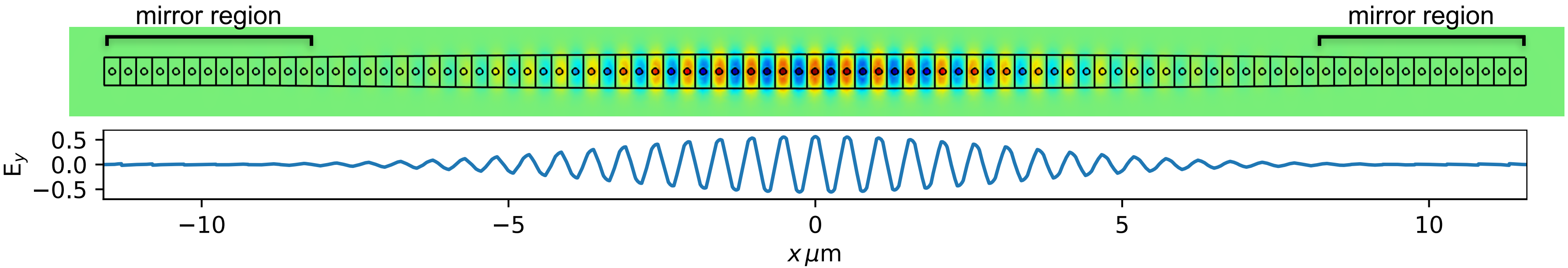
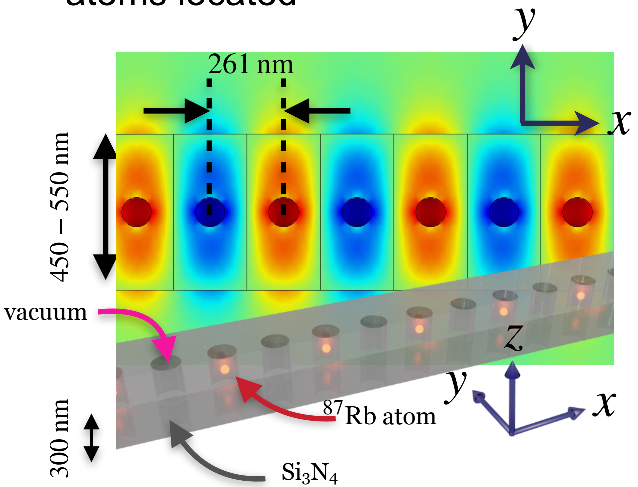
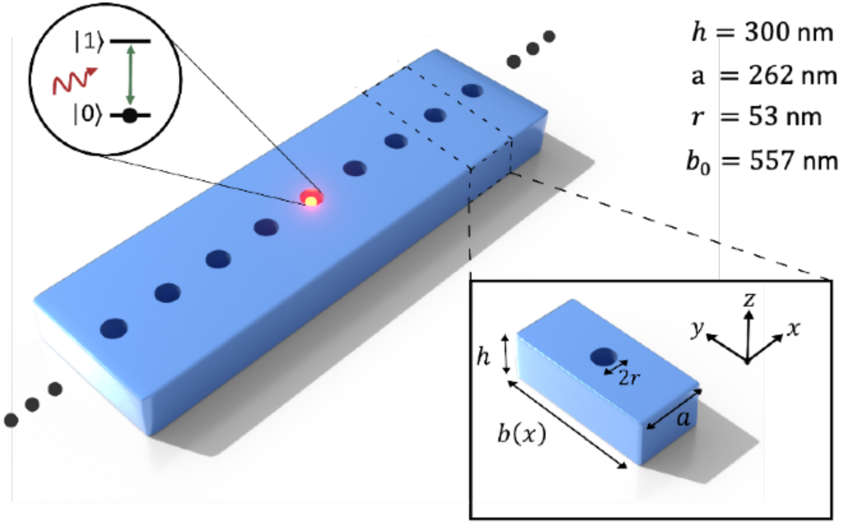


- Field concentrated in holes where ^{87}Rb atoms located





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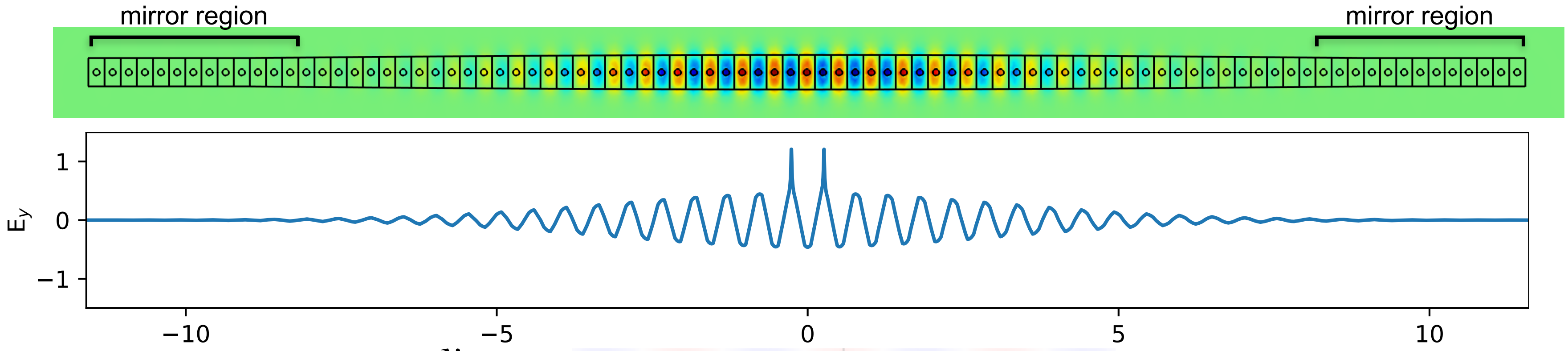
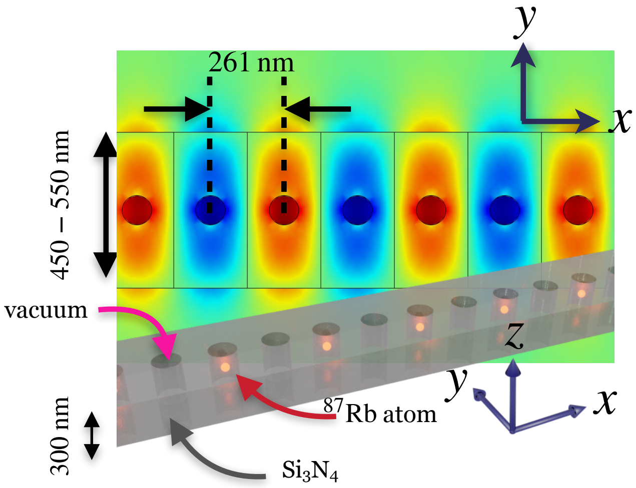
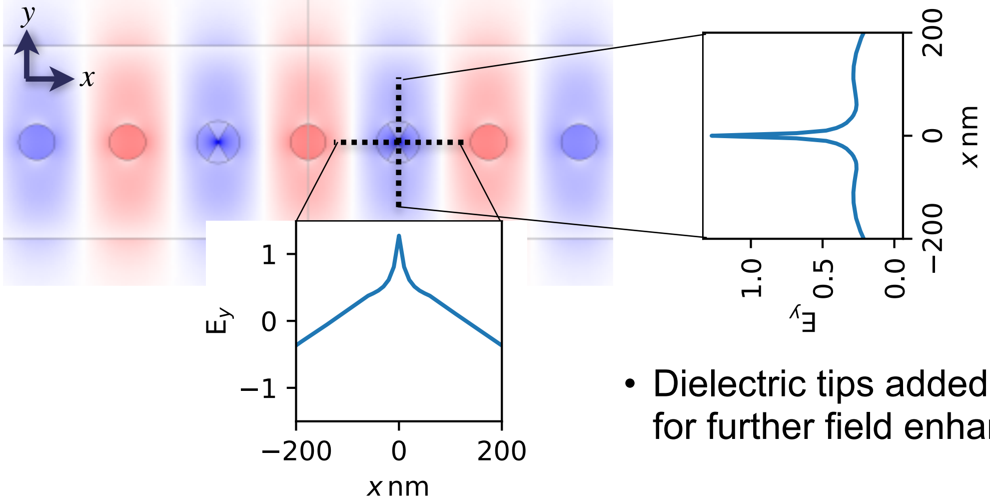
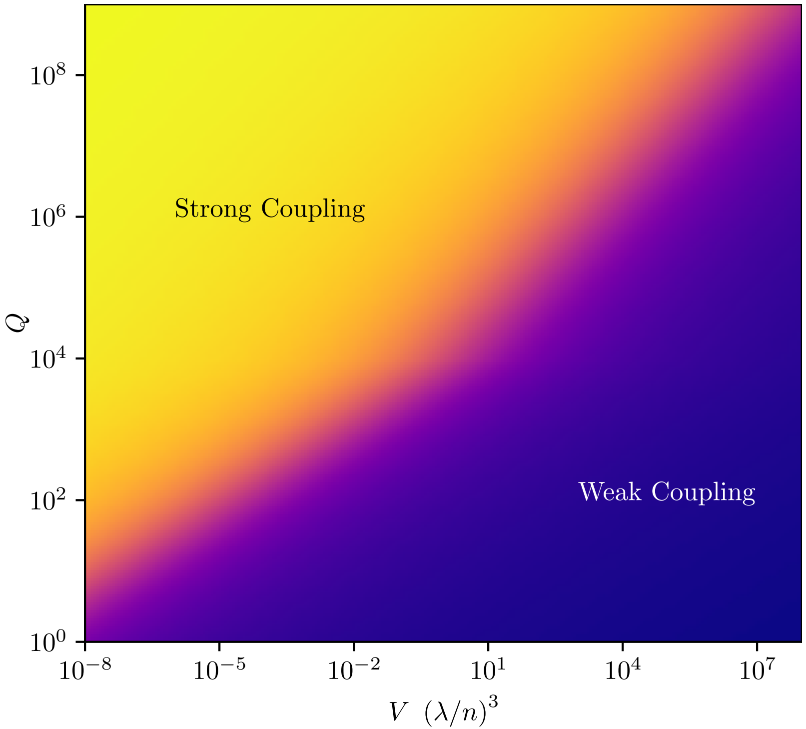






- Dielectric tips added in holes for further field enhancement

Our Nanophotonic Crystal v.s. Other Resonators



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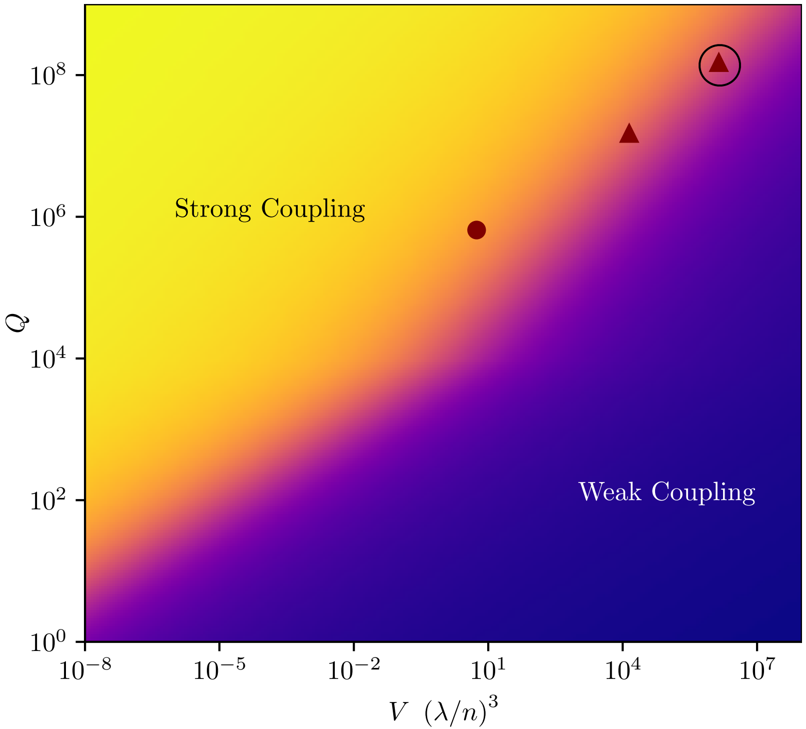

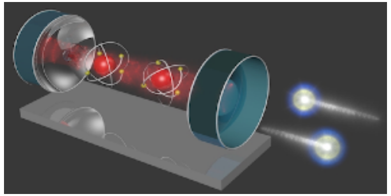

$C = g^2/\kappa\gamma = 4.1$

$\{g, \kappa, \gamma\} = 2\pi\{7.8, 2.3, 3.0\}$ GHz

Welte '17

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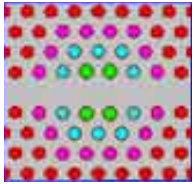

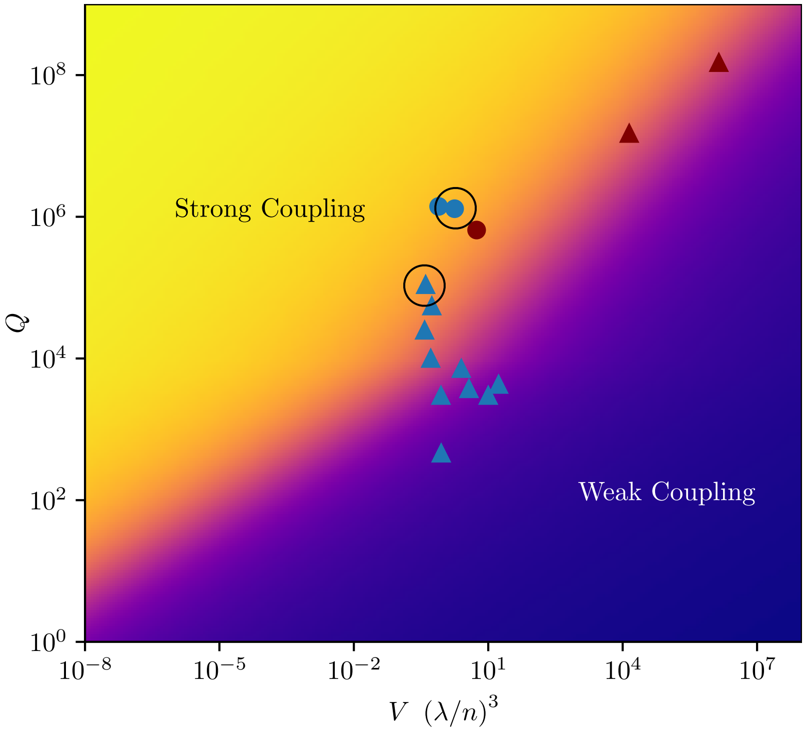

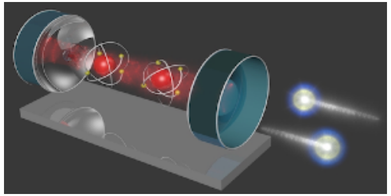

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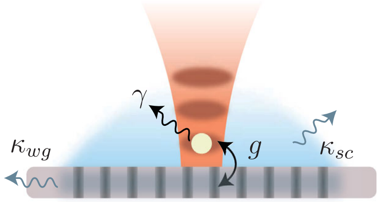

$\{g, \kappa, \gamma\} = 2\pi\{1.24, 0.006, 2.77\}$ GHz
Samutpraphoot '20

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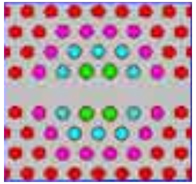
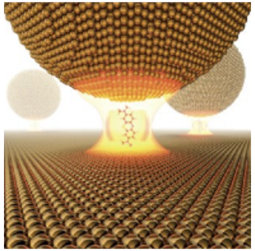
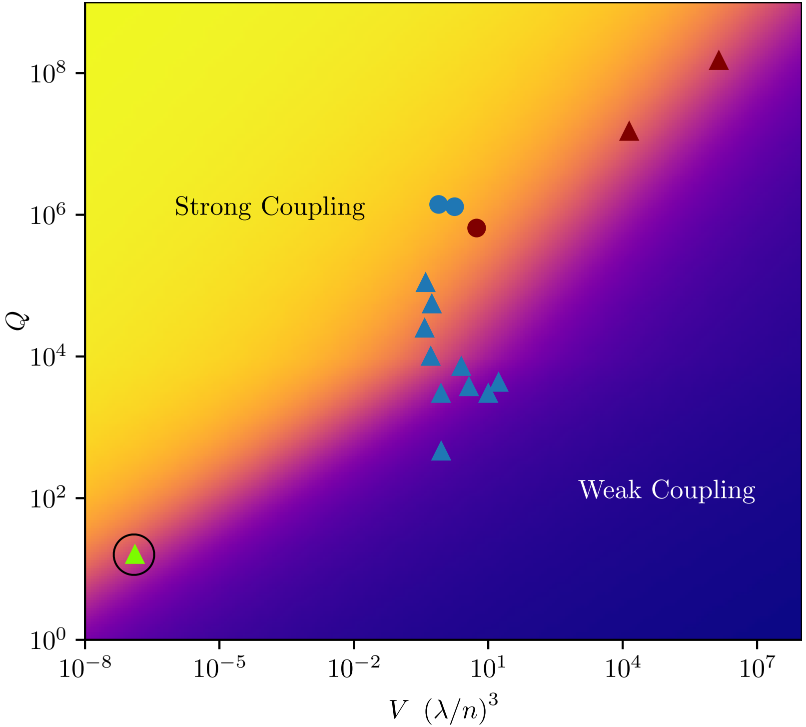


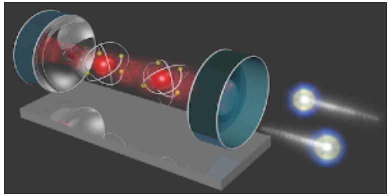


$C = g^2/\kappa\gamma = 1$

$\{g, \kappa, \gamma\} = 2\pi\{2.1, 57, 0.30\}$ GHz

Chikkaraddy '16





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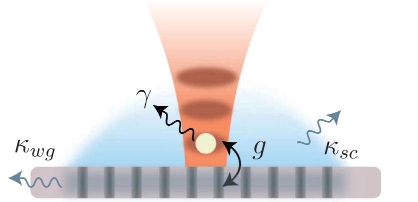

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Samutpraphoot '20

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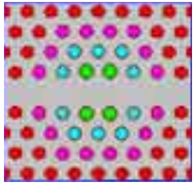
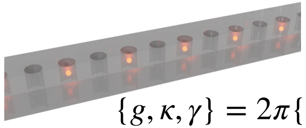


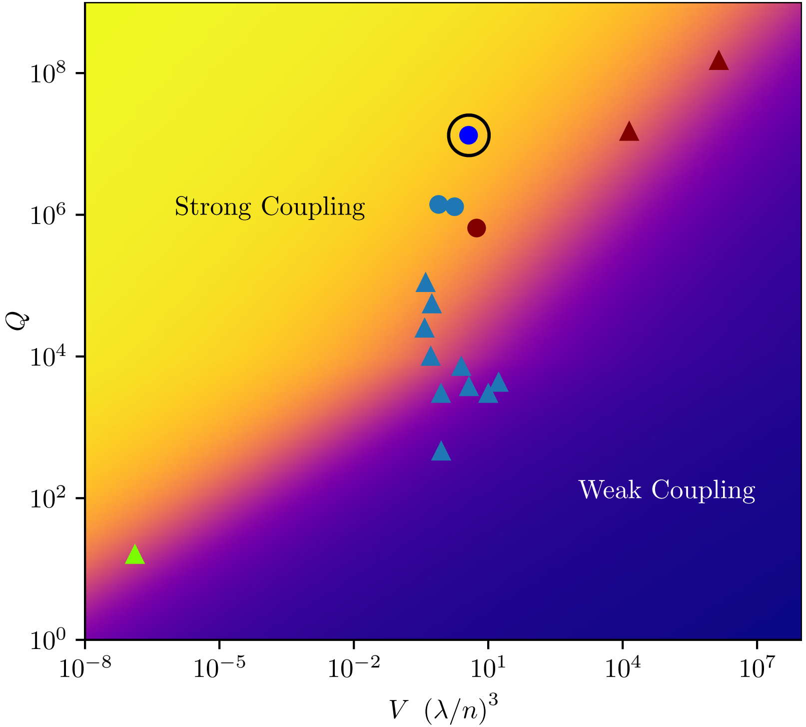
$V = 0.275\,(\lambda/n)^3$

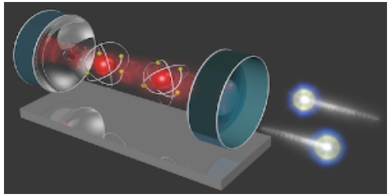
$Q = 1.3 \times 10^7$



$C = 6.7 \times 10^5$

$\{g, \kappa, \gamma\} = 2\pi\{12, 0.006, 0.036\}$ GHz





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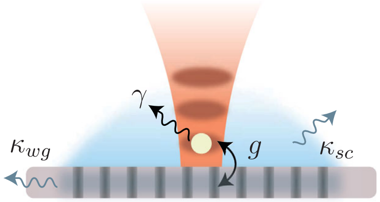
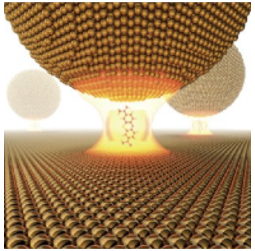
Welte '17



$\{g, \kappa, \gamma\} = 2\pi\{1.24, 0.006, 2.77\}$ GHz

Samutpraphoot '20



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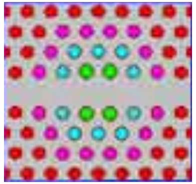

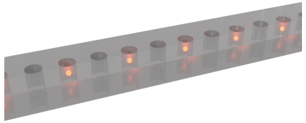

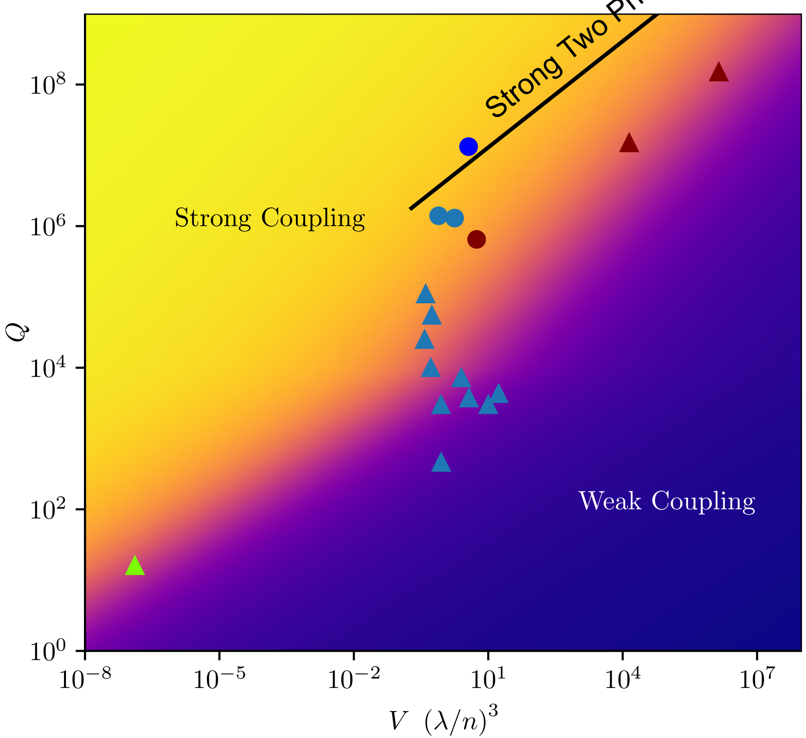

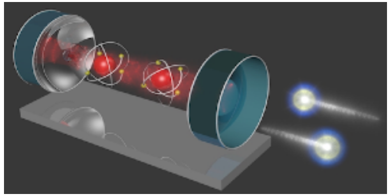

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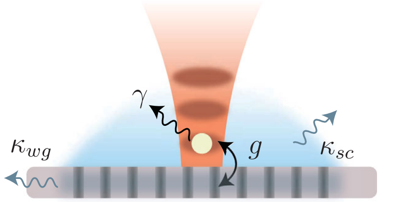

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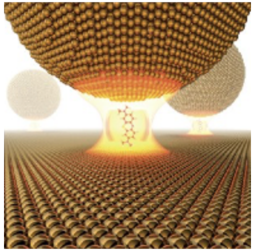
Samutpraphoot '20



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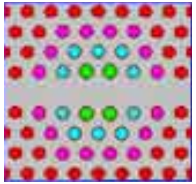

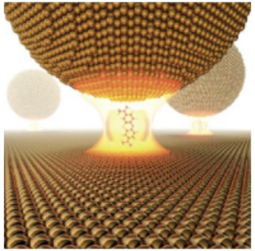

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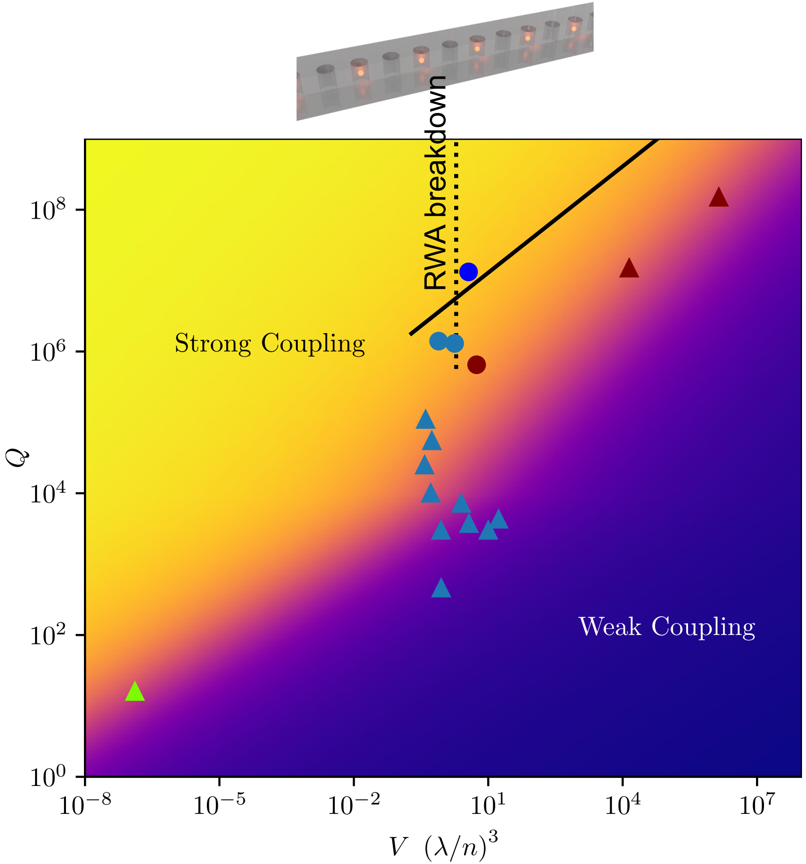

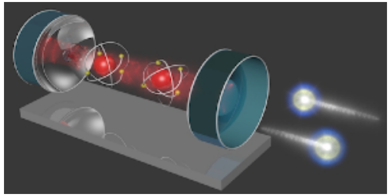

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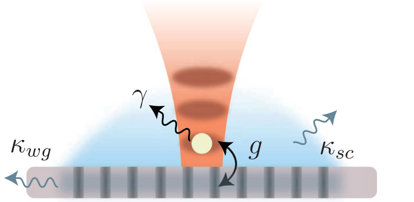

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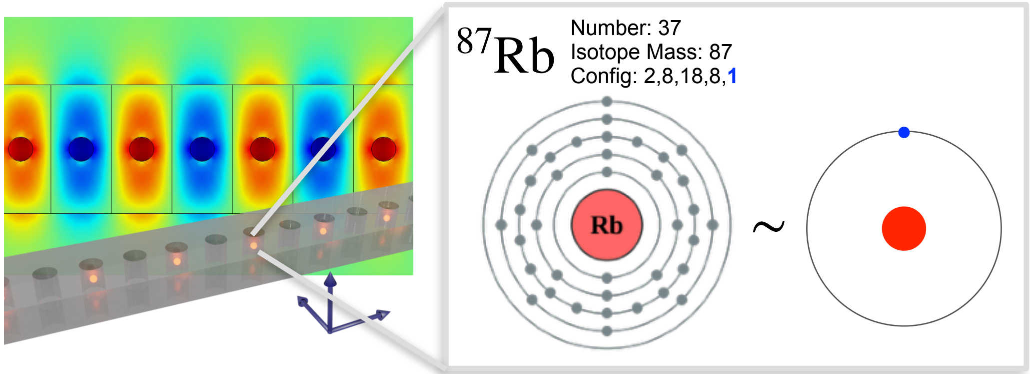
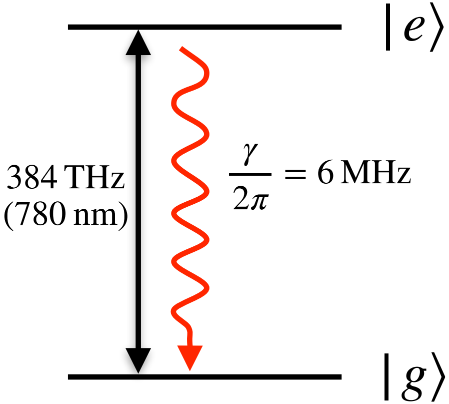
Rubidium atom





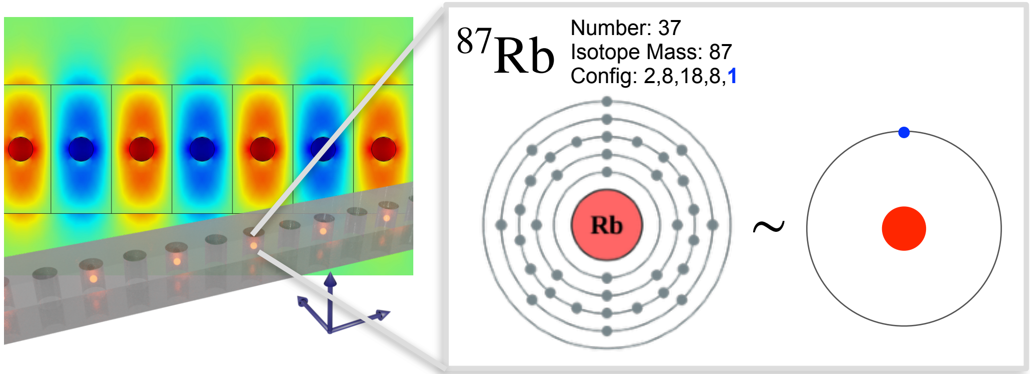
Dipole moment

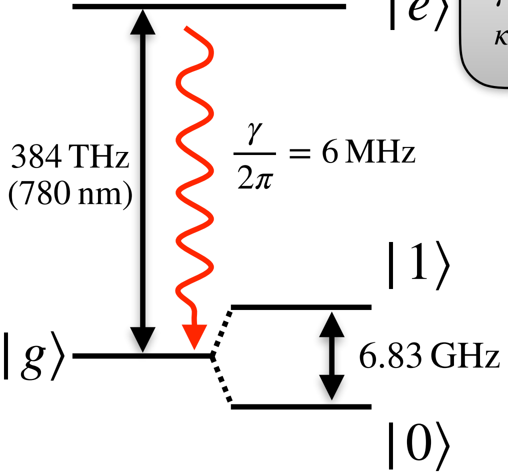
$$\mu = 3.58 \times 10^{-29}\,\mathrm{Cm}$$

Vacuum coupling strength

$$g = \frac{\mu \cdot \mathbf{E}}{\hbar} = 2\pi \times 12\,\mathrm{GHz}$$

Rubidium atom

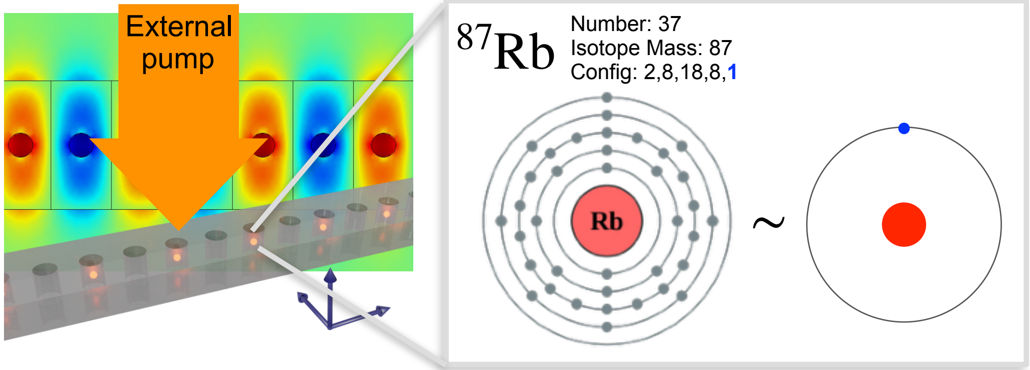




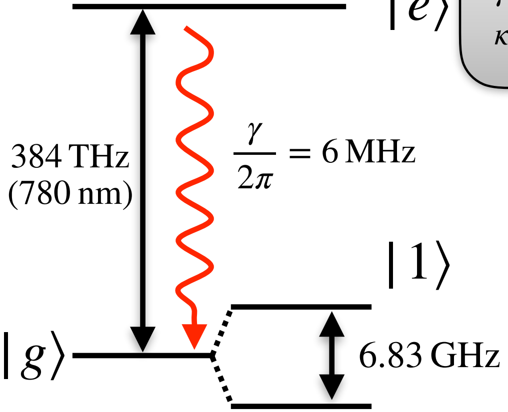
$g = 2\pi \times 12$ GHz
$\gamma = 2\pi \times 6$ MHz
$\kappa = 2\pi \times 36$ MHz

Rubidium atom in the photonic crystal

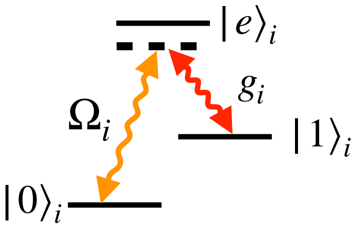
$g = 2\pi \times 12\,\mathrm{GHz}$
$\gamma = 2\pi \times 6\,\mathrm{MHz}$
$\kappa = 2\pi \times 36\,\mathrm{MHz}$



Resonator can mediate ground state transitions

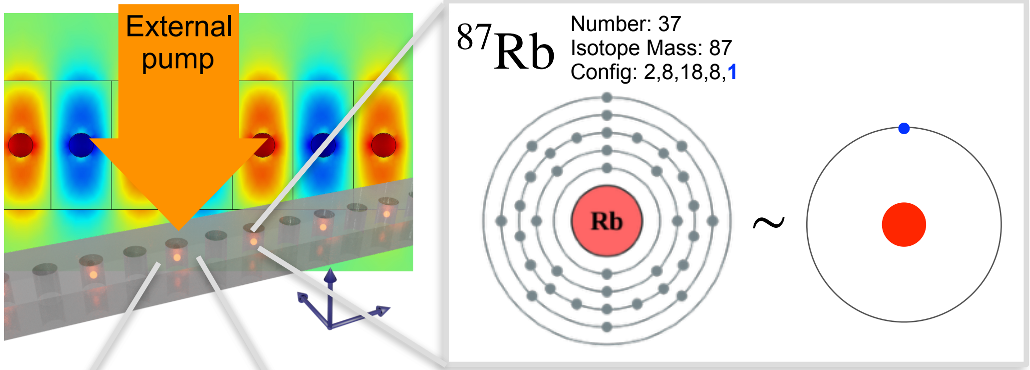


Quantum information stored in ground states

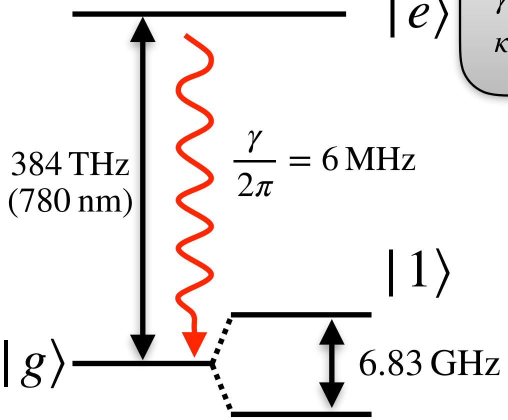


$$H = \underbrace{a^\dagger a \omega}_{\text{Resonator mode energy}} + \underbrace{\Delta_g \sigma_z/2}_{\text{Atom energy}} + \underbrace{g(\sigma_{e1}a + \sigma_{1e}a^\dagger)}_{\text{Resonator-atom interaction}} + \underbrace{\frac{\Omega}{2}\left(\sigma_{e0}e^{-i\Delta_p t} + \sigma_{0e}e^{i\Delta_p t}\right)}_{\text{Pump-atom interaction}}$$

3-level-systems



$g = 2\pi \times 12\,\text{GHz}$
$\gamma = 2\pi \times 6\,\text{MHz}$
$\kappa = 2\pi \times 36\,\text{MHz}$



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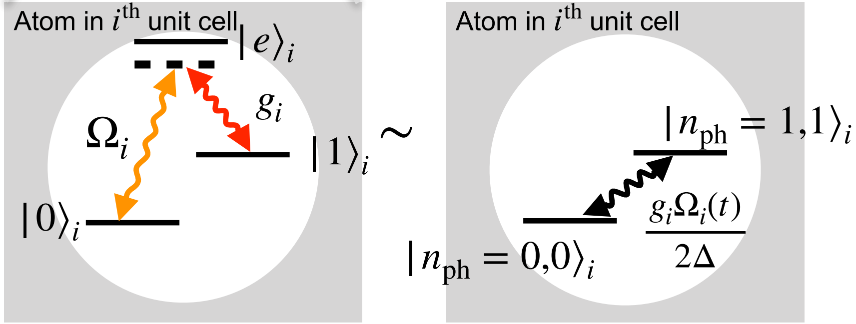
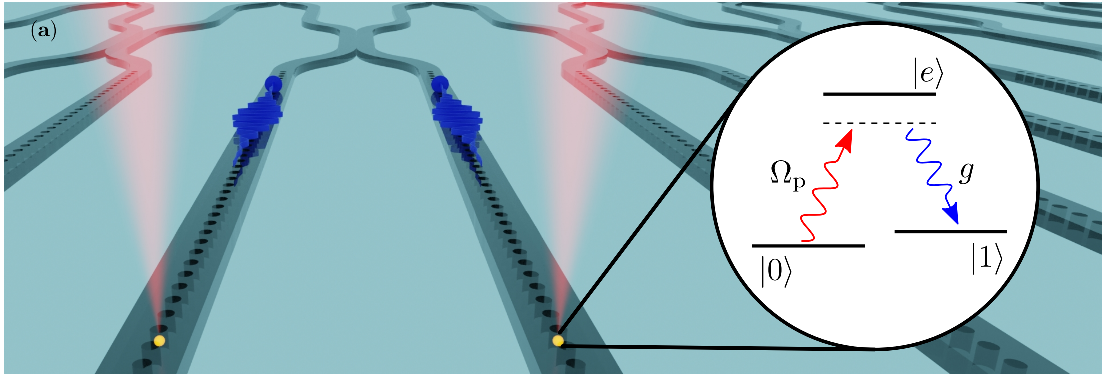
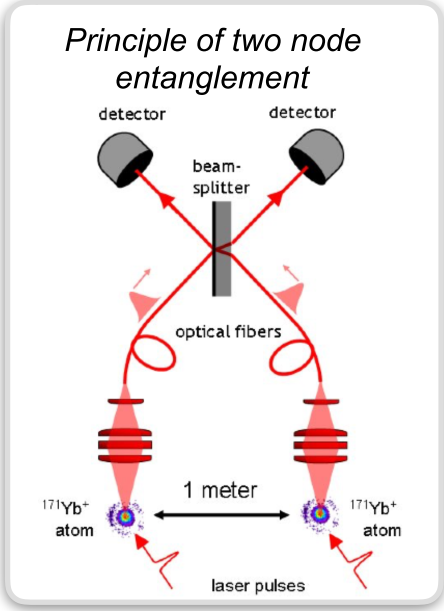
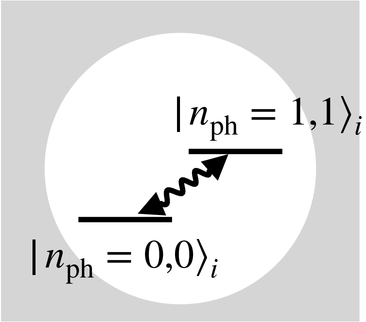


$$H = \underbrace{a^\dagger a \omega}_{\text{Resonator mode energy}} + \underbrace{\Delta_g \sigma_z/2}_{\text{Atom energy}} + \underbrace{\frac{g\Omega}{2\Delta}\left(\sigma_{10}a^\dagger b + \sigma_{01}ab^\dagger\right)}_{\text{Effective (Raman) interaction}}$$

Remote entanglement in the photonic crystal







$$H = a^\dagger a \omega + \Delta_g \sigma_z/2 + \frac{g\Omega}{2\Delta}\left(\sigma_{10} a^\dagger b + \sigma_{01} a b^\dagger\right)$$

Time evolution follows SE $i\partial_t|\psi\rangle = H|\psi\rangle$.

General solution:

$$|\psi(t)\rangle = \cos\theta(t)|0,0\rangle + \sin\theta(t)|1,1\rangle$$

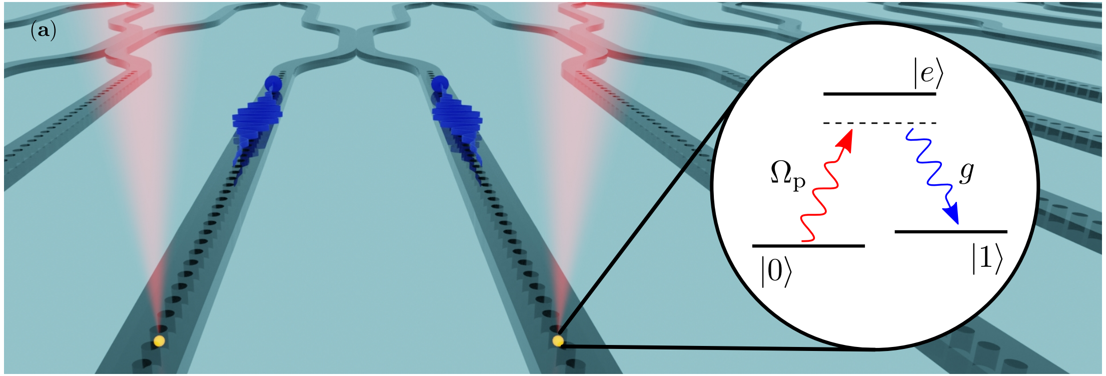
Atom and photon ***maximally entangled*** when $\theta = \pi/4$:

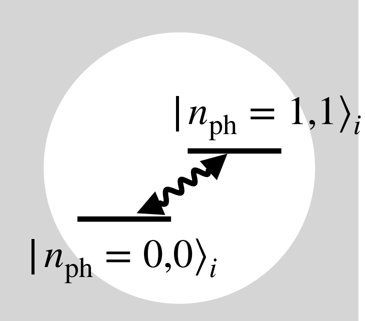
$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|0,0\rangle + |1,1\rangle\right)$$

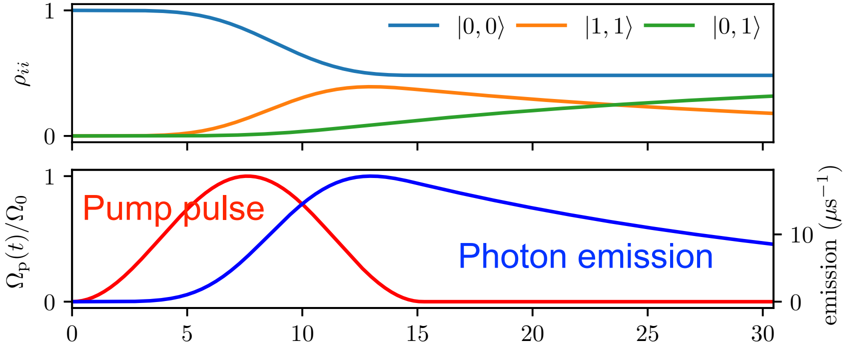
Resonator photon decays over time and emitted photon can be measured

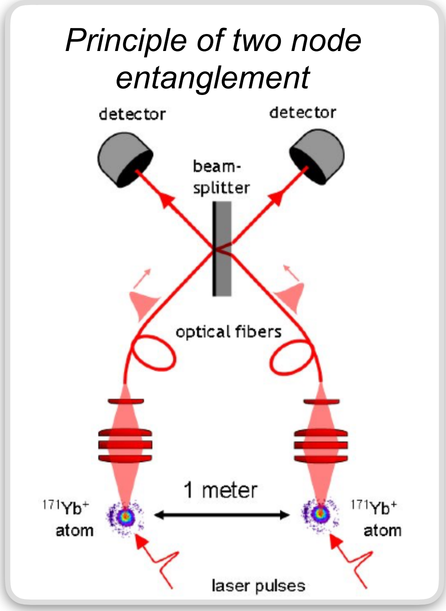
Monroe group:
Nature Physics, *11*(1), 37-42, 2014
Nature, *449*(7158), 68-71, 2007

Remote entanglement in the photonic crystal









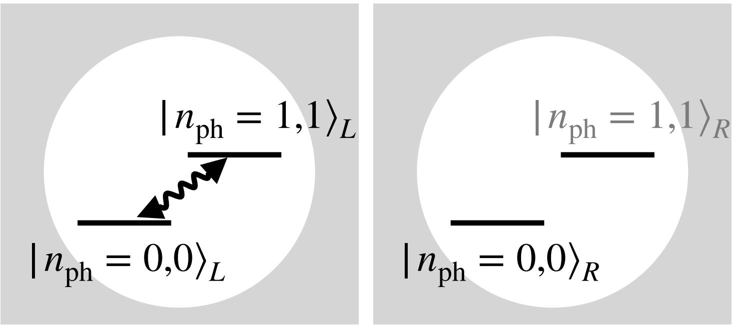
Monroe group:
Nature Physics, *11*(1), 37-42, 2014
Nature, *449*(7158), 68-71, 2007

Local entanglement in the photonic crystal

Photons in the resonator act as quantum bus
which allow atoms to communicate:

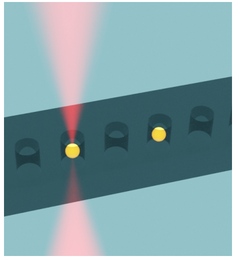
Left atom

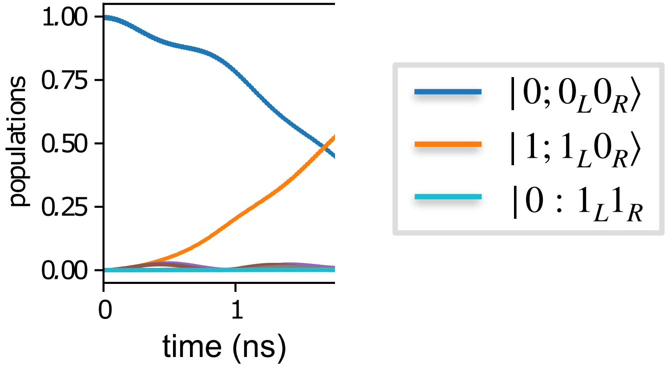
Right atom



$$H = a^\dagger a \omega + \sum_i \Delta_g \sigma_z^{(i)}/2 + \frac{g\Omega_L}{2\Delta}\left(\sigma_{10}^{(L)} a^\dagger b + \sigma_{01}^{(L)} a b^\dagger\right)$$

pump 1 on





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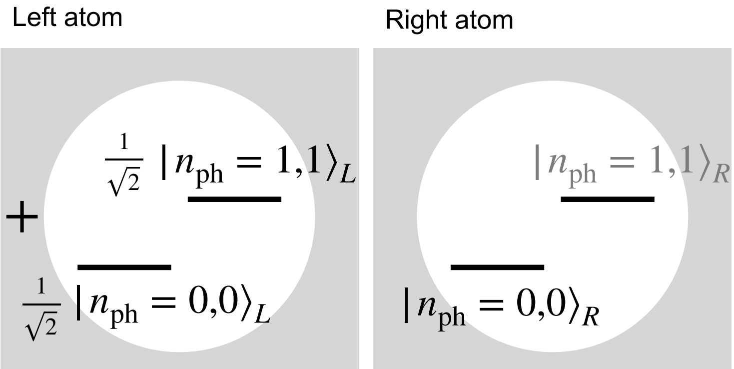

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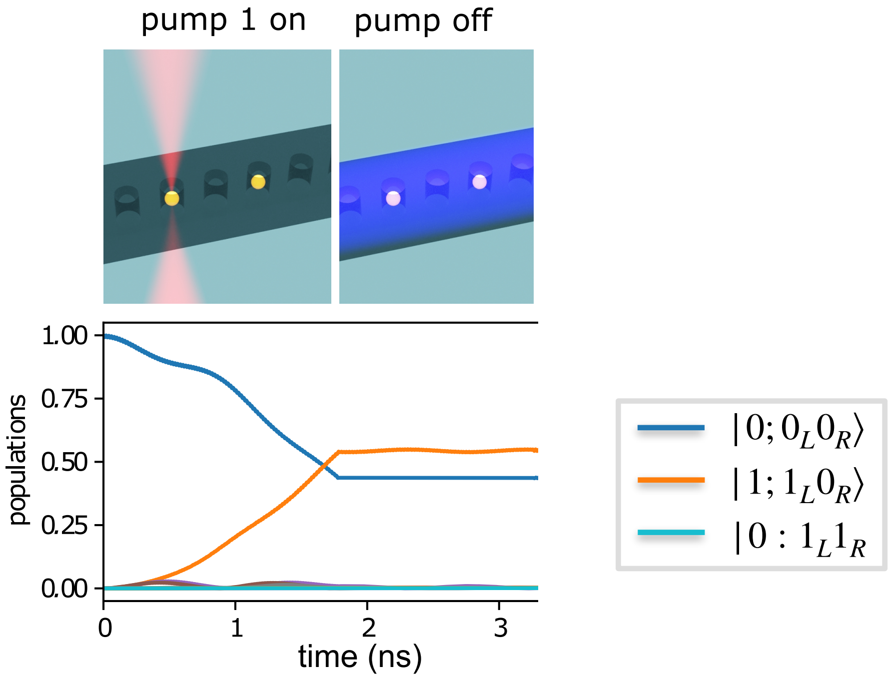
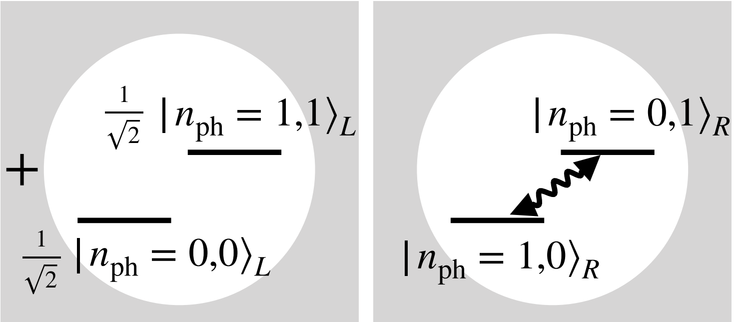
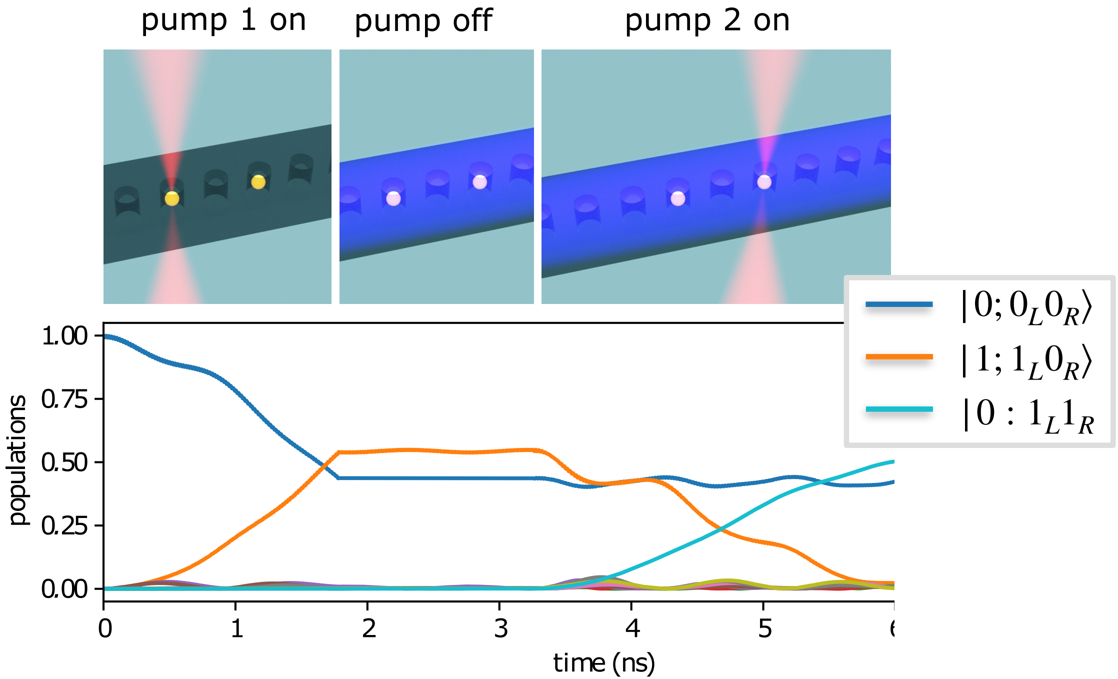


Local entanglement in the photonic crystal

Conditional operation
Drive right atom ***IF*** there is a photon in resonator mode



$$H = a^\dagger a\omega + \sum_i \Delta_g \sigma_z^{(i)}/2 + \frac{g\Omega_R}{2\Delta}\left(\sigma_{10}^{(R)} a^\dagger b + \sigma_{01}^{(R)} a b^\dagger\right)$$



Local entanglement in the photonic crystal

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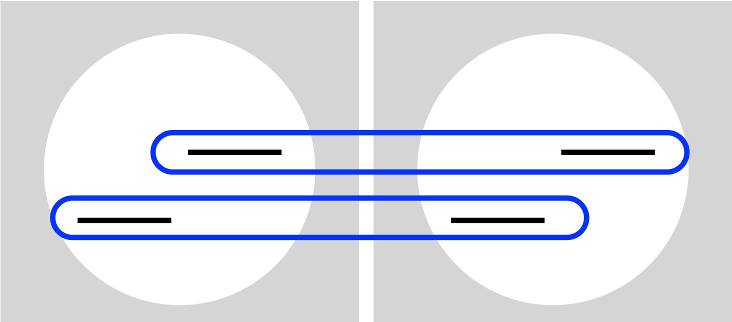
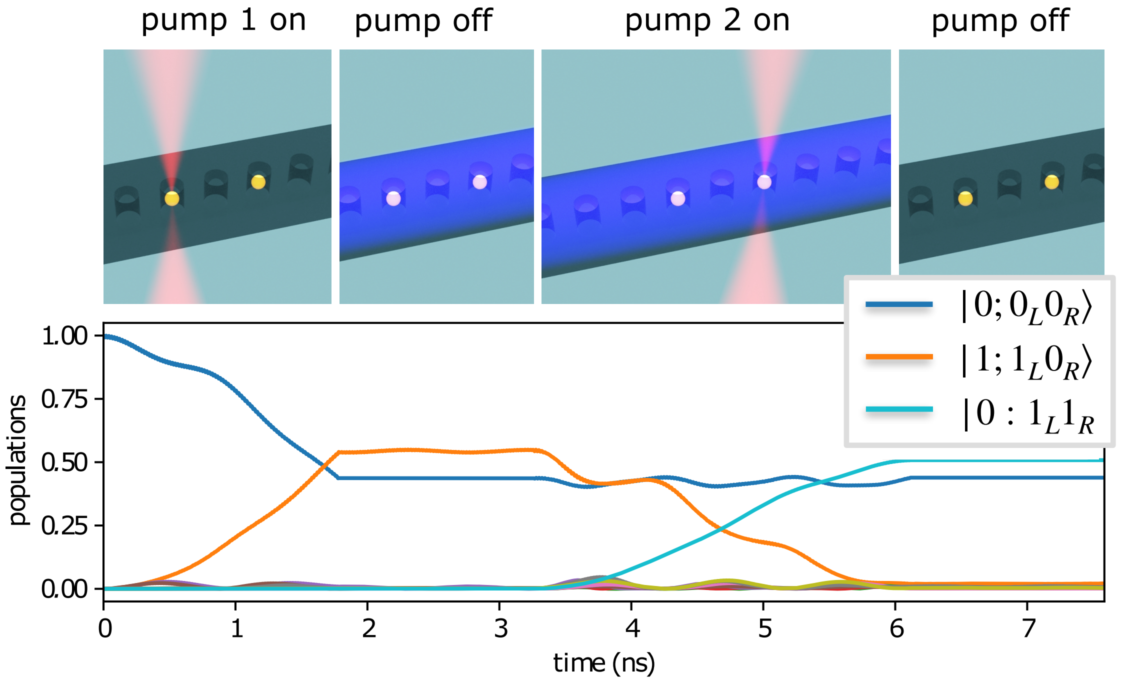


$$\frac{1}{\sqrt{2}}\ |n_{\mathrm{ph}} = 0, 1_L, 1_R\rangle$$

$$+$$

$$\frac{1}{\sqrt{2}}\ |n_{\mathrm{ph}} = 0, 0_L, 0_R\rangle$$



Local entanglement in the photonic crystal

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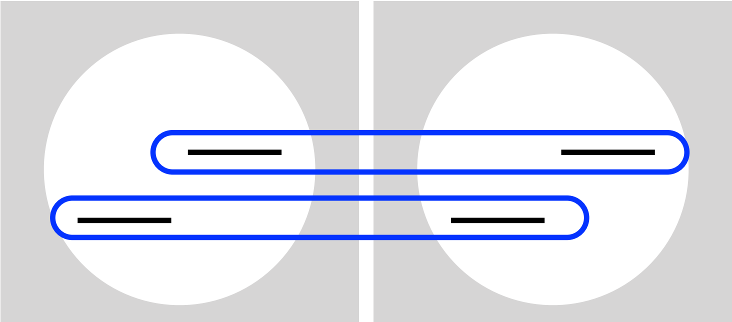
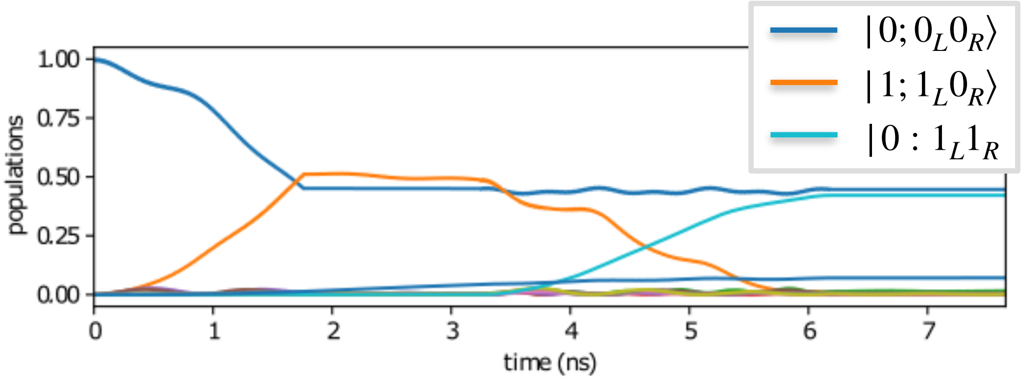
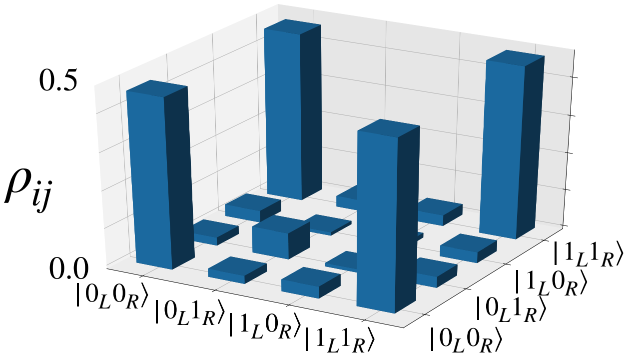
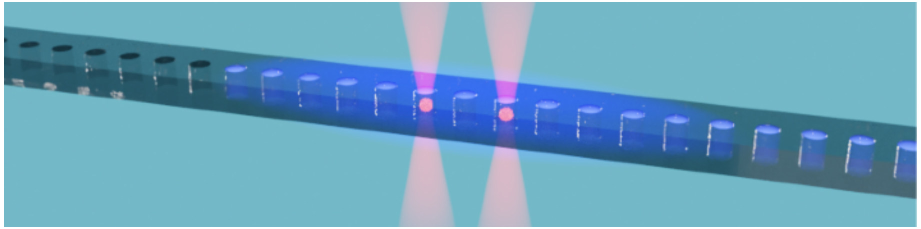




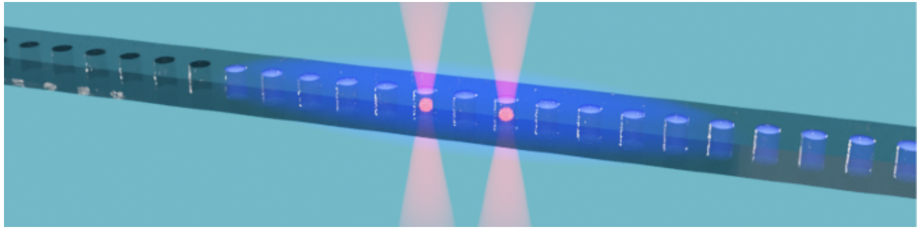
$$\frac{1}{\sqrt{2}}\,|n_{\text{ph}} = 0{,}1_L{,}1_R\rangle$$
$$+$$
$$\frac{1}{\sqrt{2}}\,|n_{\text{ph}} = 0{,}0_L{,}0_R\rangle$$



Combining local and networked entanglement



Combining local and networked entanglement



Both atoms collectively excited

$$|c\rangle = |2; 1_L 1_R\rangle$$

$$\Delta_c = \Delta_p + \Delta_g$$

$$|b\rangle = \frac{1}{\sqrt{2}}\left(|1; 1_L 0_R\rangle + |1; 0_L 1_R\rangle\right)$$

$$\Delta_c = \Delta_p + \Delta_g$$

$$|a\rangle = |0; 0_L 0_R\rangle$$

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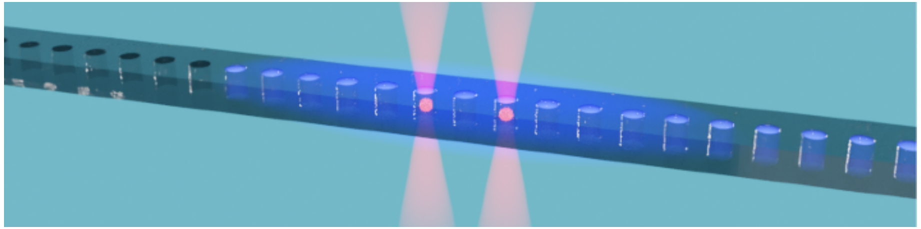

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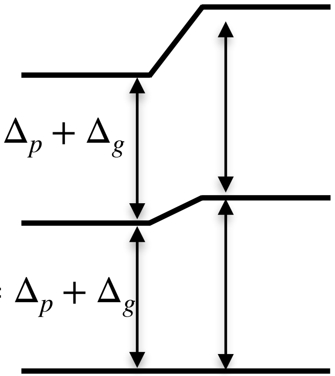
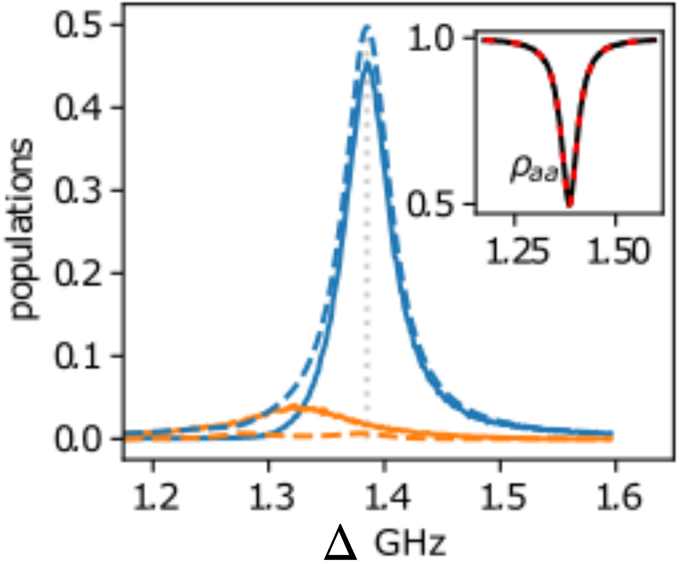
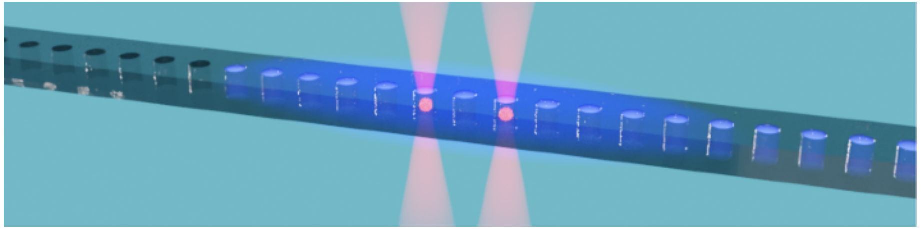
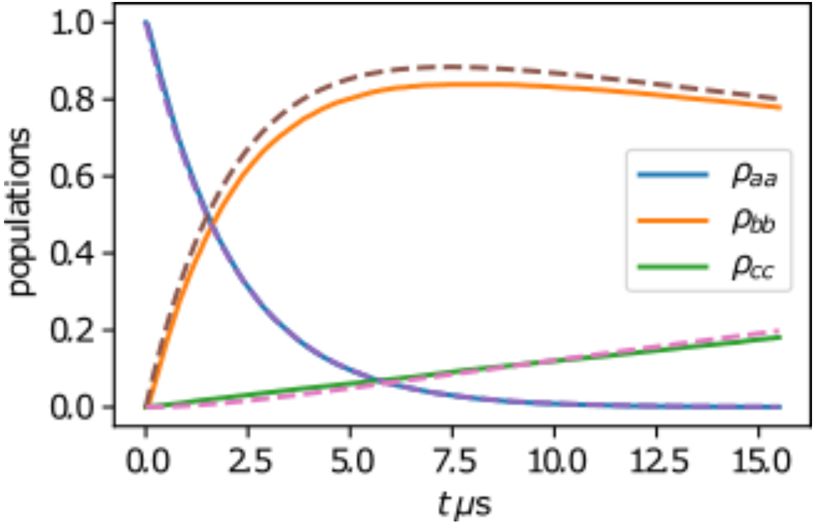




Combining local and networked entanglement

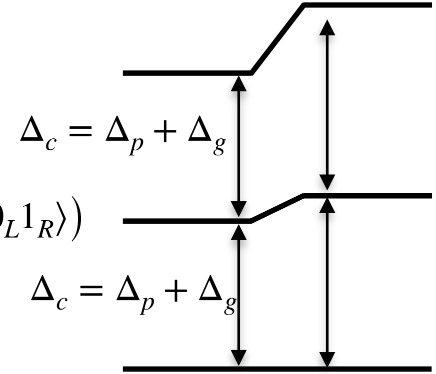


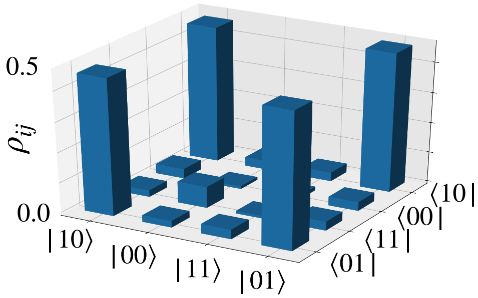


$$|c\rangle = |2;1_L1_R\rangle$$

$$|b\rangle = \frac{1}{\sqrt{2}}\left(|1;1_L0_R\rangle + |1;0_L1_R\rangle\right)$$

$$|a\rangle = |0;0_L0_R\rangle$$





Acknowledgments

Thank you for listening!

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Angus Crookes
Kalun Bedingfield

Giovanni Barontini

THE ROYAL SOCIETY

All results to appear in upcoming papers shortly