Quantum computing with exciton-polariton condensates

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Plan

Introduction to exciton-polaritons

Cavity + quantum well, Light-matter hybridisation.
Polariton, Condensate.
Micropillars.
Few photon regime.

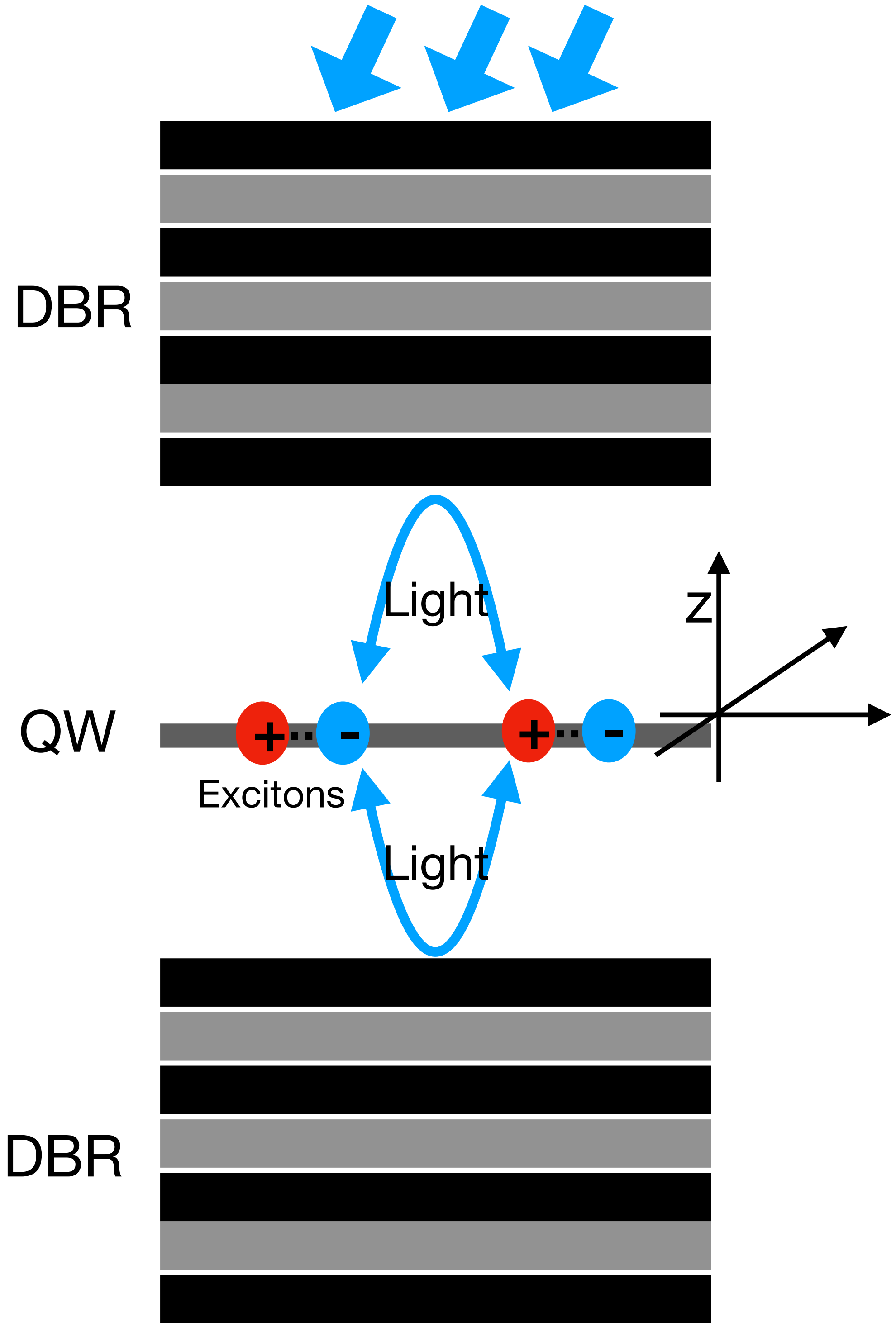
Quantum com. scheme based on exciton-polaritons

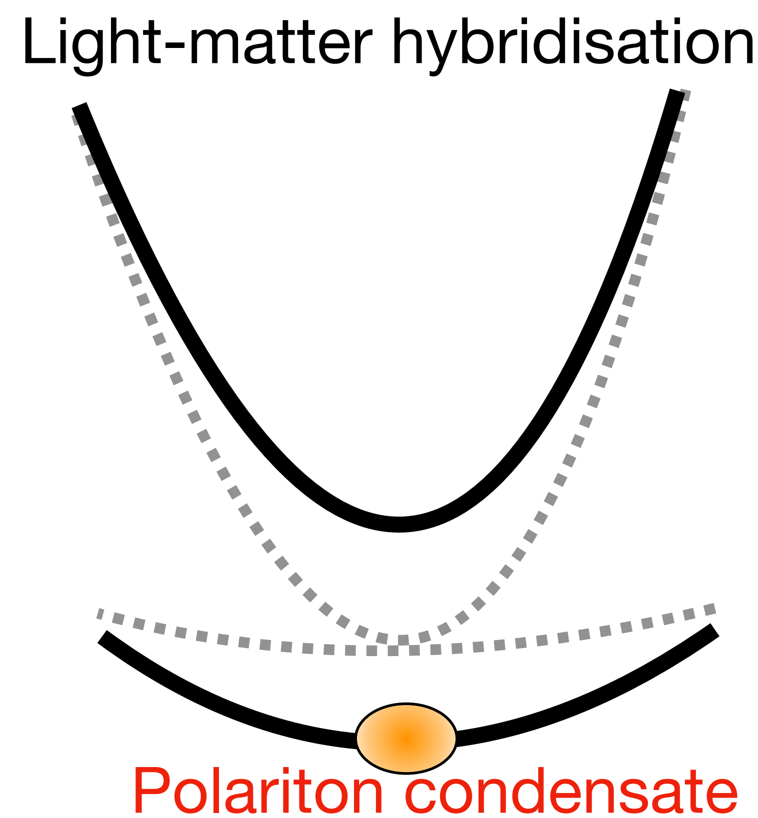
Theoretical scheme.
Sigle qubit gate control.
Two qubit gates.
Readout.

Some possible advantages

Scalability and size.
Operation temperatures.
Operating cost.

Exciton polaritons in semiconductor cavities





Classical mean-field description

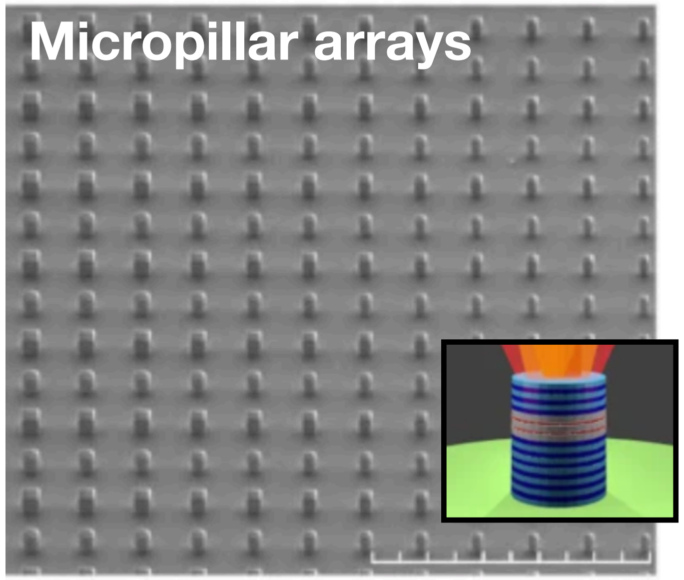
$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m^*}\nabla^2\psi + \alpha|\psi|^2\psi + i(P-\gamma)\psi + F$$

- $\alpha|\psi|^2\psi$: Nonlinearity / Interaction
- P: Non-resonant
- γ: Decay
- F: Resonant

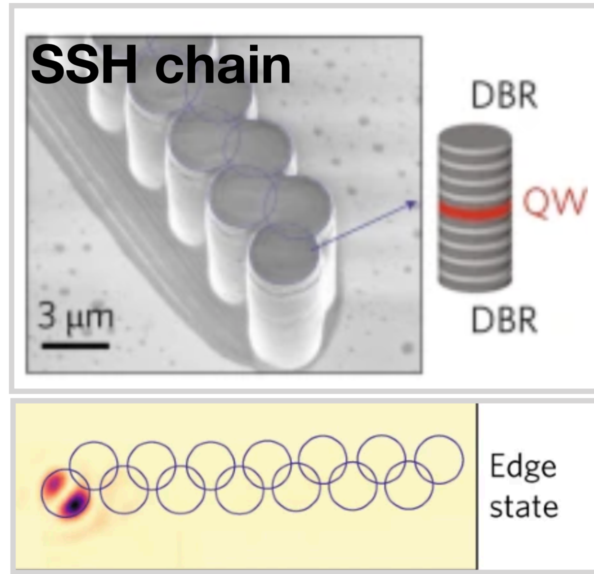
<u>**Exciton-polariton condensate**</u>

- Large occupation in a single cavity mode.
- Described by nonlinear GP equation.
- Driven-dissipation system.

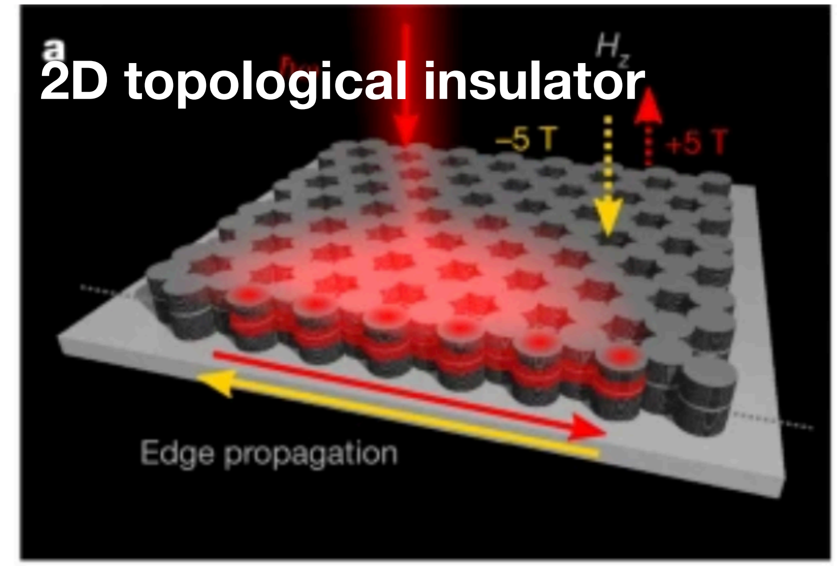
Semiconductor micropillars



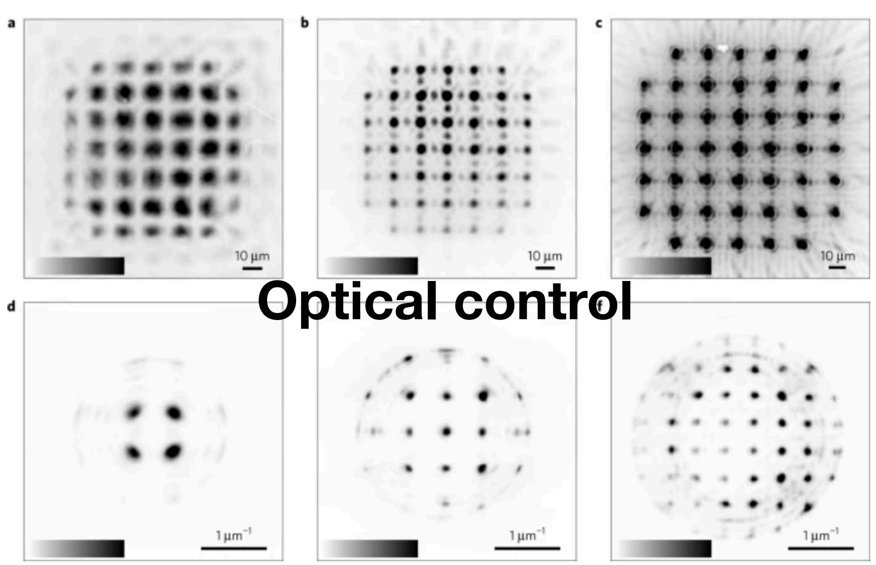
Nature Comm. vol 5, 3260 (2014)



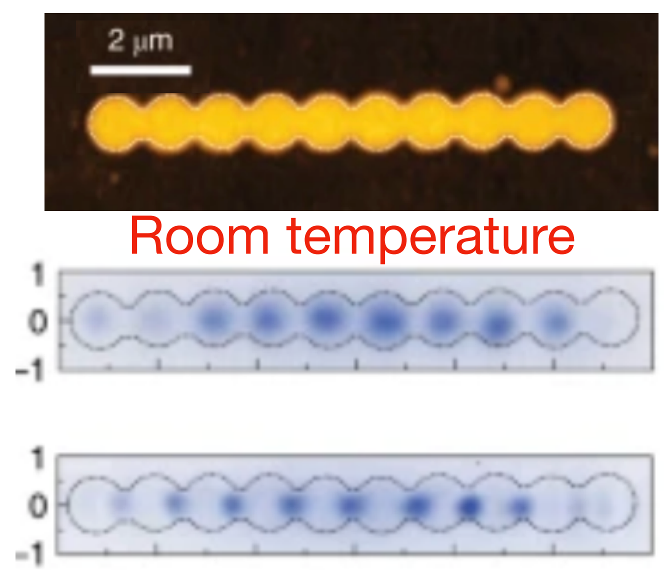
Nature Photonics, vol. 11, 651-656 (2017)



Nature, vol. 562, 552-556(2018)



Nature Materials vol.16, 1120–1126 (2017)

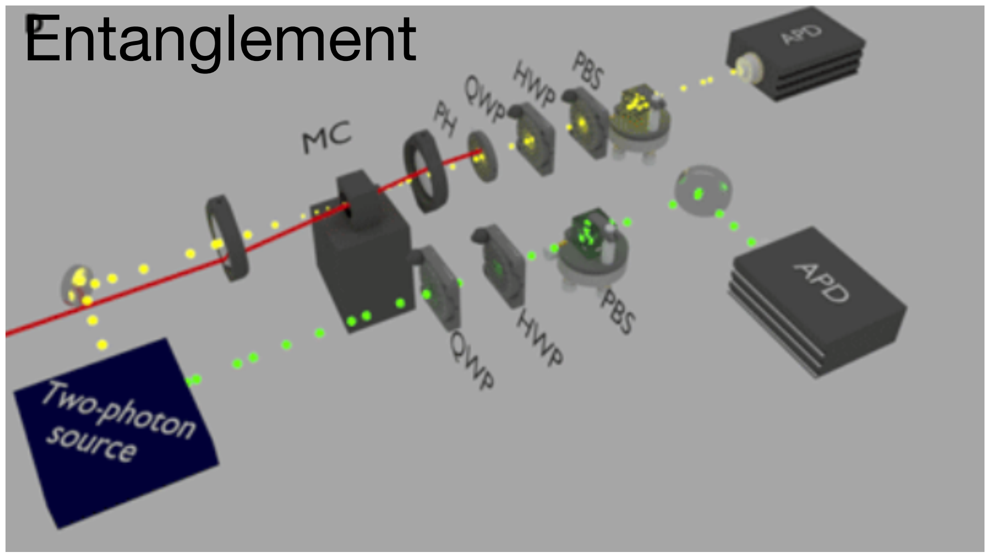


Nature Physics vol. 16, Pages 301–306(2020)

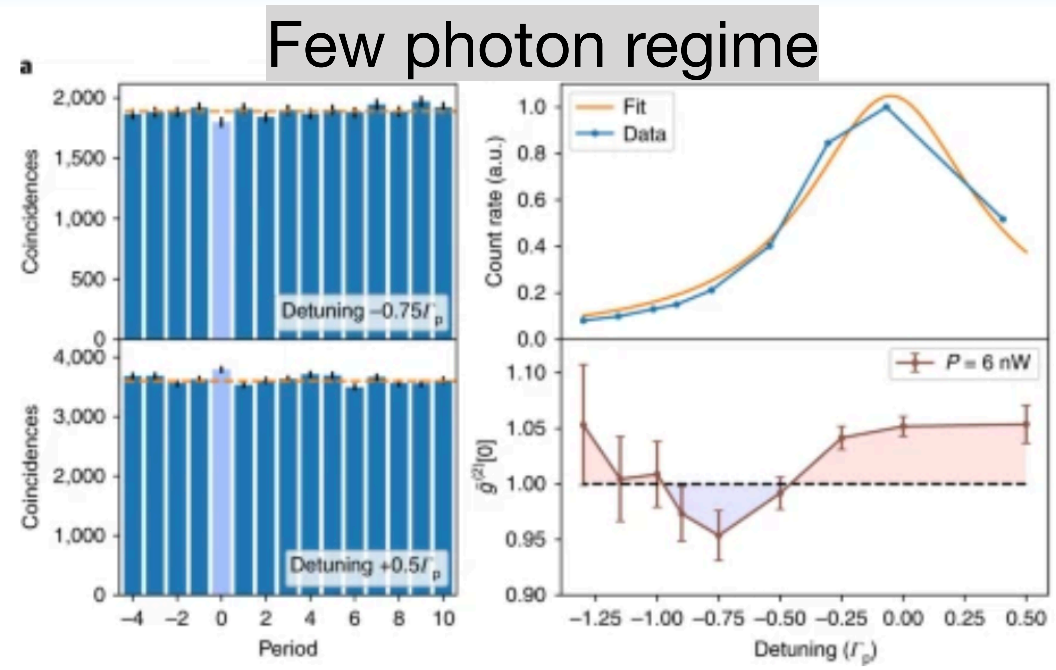
- Graphs of pillars.
- Topological lasing.
- Optical control.
- Small effective mass. Large de Broglie wavelength.
- Can condensate at room temperature.

Classical mean-field!

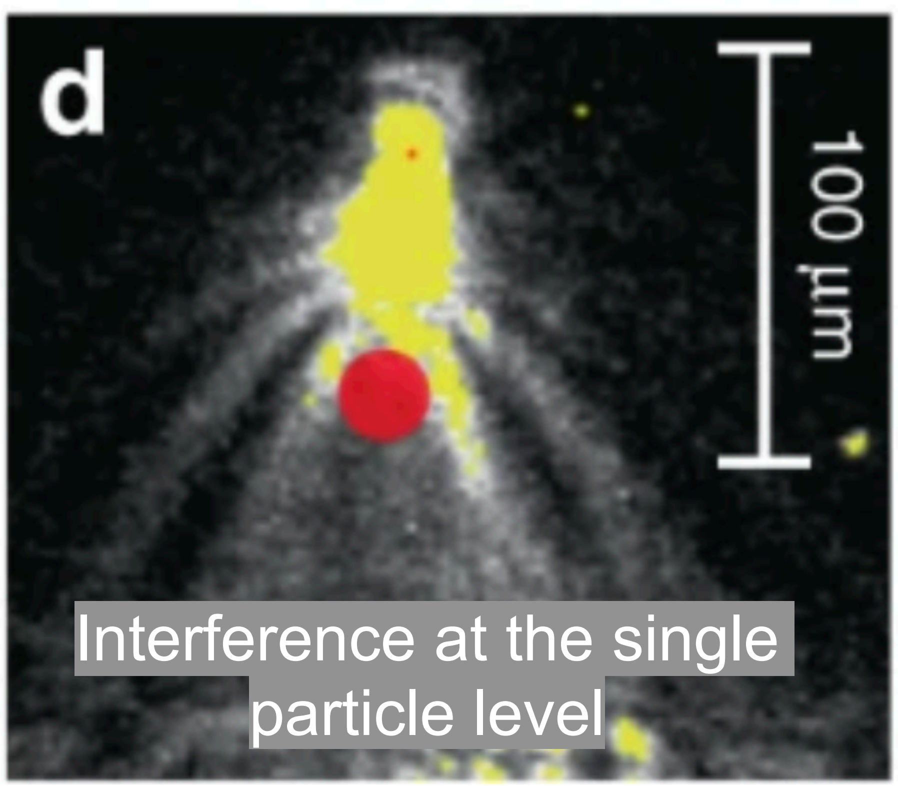
Polaritons in quantum regime



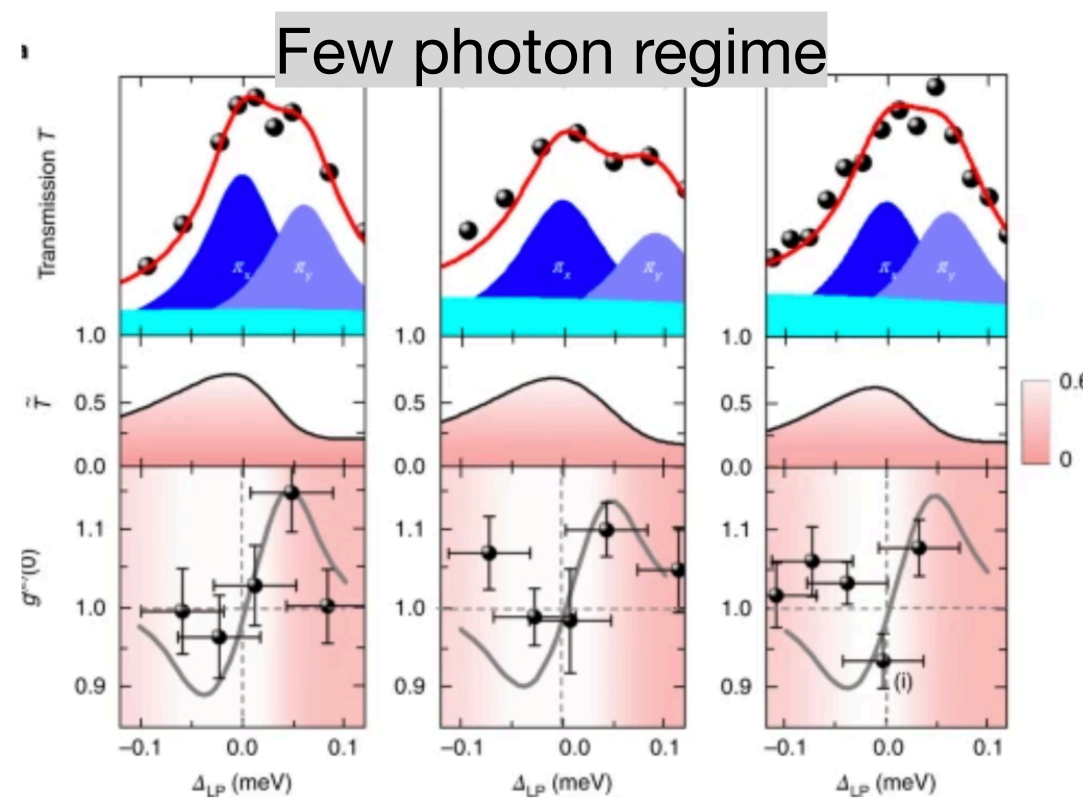
Science Advances Vol. 4, no. 4, eaao6814 (2018)



Nature Materials, vol. 18, 219–222(2019).



Light: Science & Applications vol. 9, num 85 (2020)



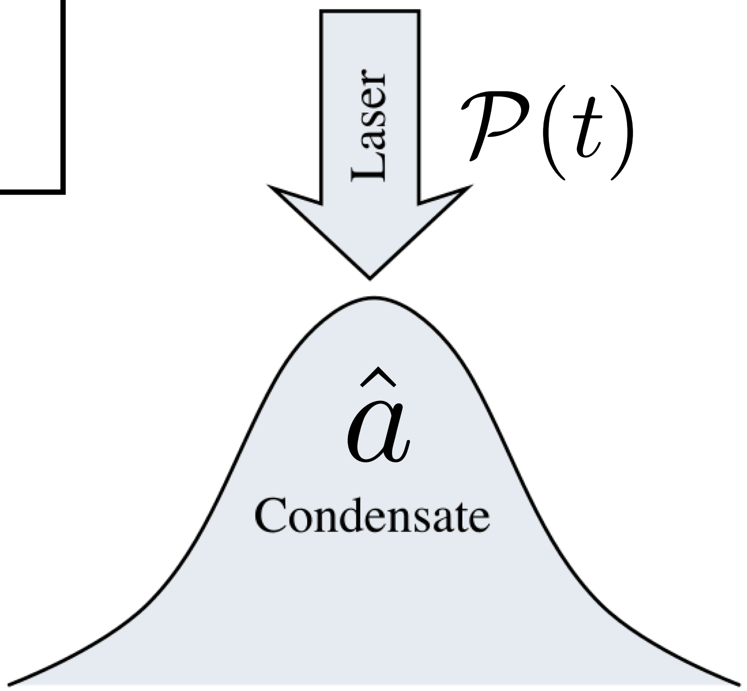
Nature Materials vol. 18, 213–218(2019)

Requirements for quantum computing

- Qubit formation.
- Universal gate set.
- Control.
- Prob or readout.
- Fabrication technologies.
- Scalability.

Forming qubits with exciton-polaritons

$$H = \Delta\, \hat{a}^\dagger \hat{a} + \alpha\, \hat{a}^\dagger \hat{a}^\dagger \hat{a}\hat{a} + \mathcal{P}(t)^* \hat{a}^\dagger + \mathcal{P}(t)\hat{a},$$



$$\hat{N} = \hat{a}^\dagger \hat{a} \qquad \hat{a} = \sqrt{\hat{N}} e^{-i\hat{\theta}} \qquad [\hat{\theta}, \hat{N}] = i$$

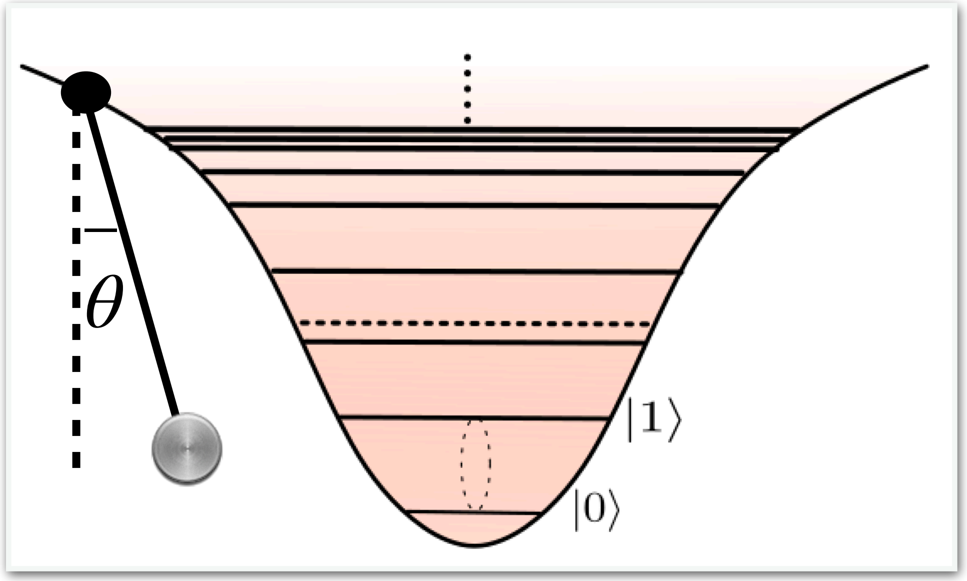
$$H = \Delta \hat{N} + \alpha \hat{N}(\hat{N} - 1) + 2P\sqrt{\hat{N}} \cos(\varphi - \hat{\theta})$$

$$\hat{N} = N_c + \hat{n}$$

$$H = C + \Omega\, \hat{n} + \alpha \hat{n}^2 + 2P\sqrt{(N_c + \hat{n})}\ \cos(\varphi - \hat{\theta}),$$

$$\sqrt{\langle \hat{n}^2 \rangle}/N_c \ll 1$$

$$H_f = \Omega \hat{n} + \alpha \hat{n}^2 + 2P\sqrt{N_c}\ \cos(\varphi - \hat{\theta})$$



Oscillator, but not harmonic!

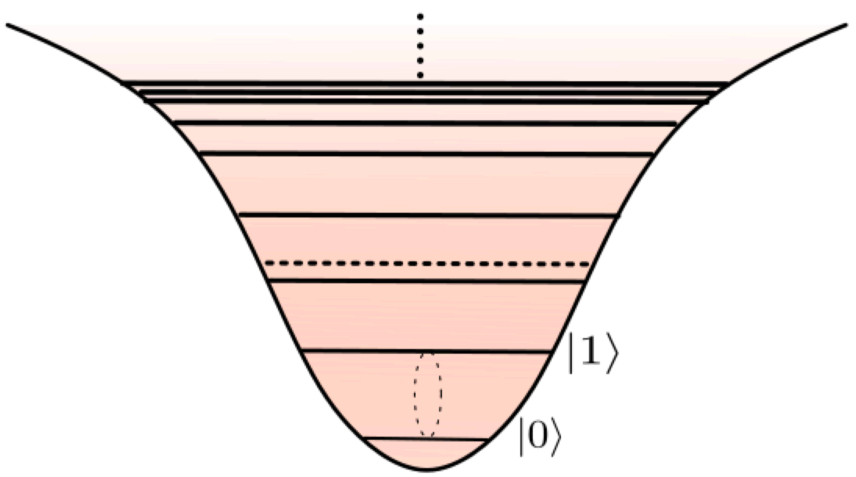
npj Quantum Info. 6, 16 (2020).

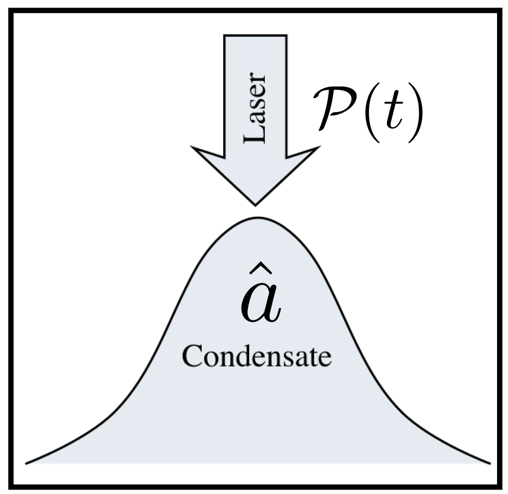
Forming qubits with exciton-polaritons

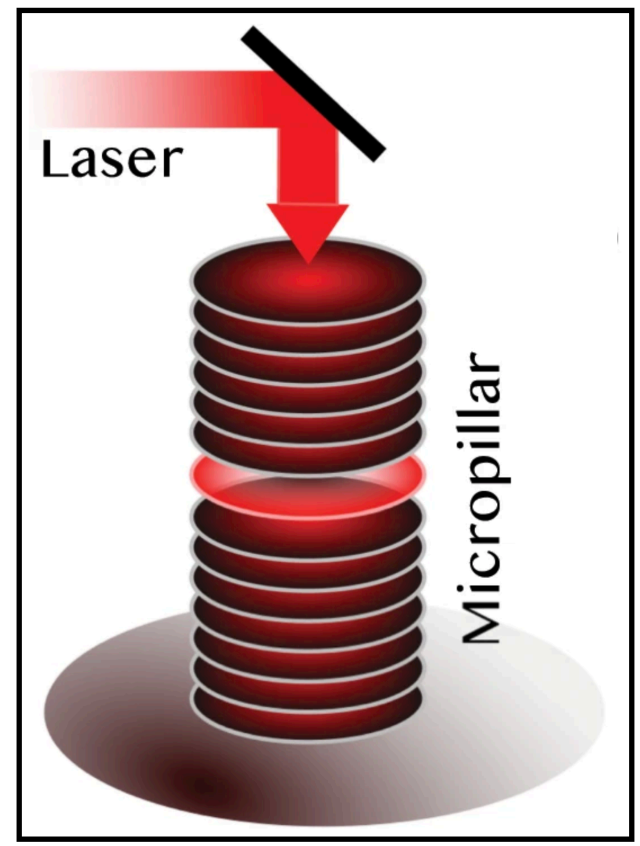
$$H_f = \Omega \hat{n} + \alpha \hat{n}^2 + 2P\sqrt{N_c}\ \cos(\varphi - \hat{\theta})$$

$$\hat{n}|n\rangle = n|n\rangle \quad \exp(\pm i\hat{\theta})|n\rangle = |n \pm 1\rangle$$

$$H_f = \sum_n \left[\left(\Omega n + \alpha\, n^2\right) |n\rangle\langle n| + P\sqrt{N_c}\left(e^{i\varphi}|n\rangle\langle n+1| + e^{-i\varphi}|n+1\rangle\langle n|\right) \right]$$







$$\hat{H}_q = \boldsymbol{E} \cdot \hat{\boldsymbol{\sigma}}$$

$$E_x = P\sqrt{N_c}\cos\varphi,\ E_y = P\sqrt{N_c}\sin\varphi,$$
$$E_z = (\alpha - \omega)/2.$$

npj Quantum Info. 6, 16 (2020).

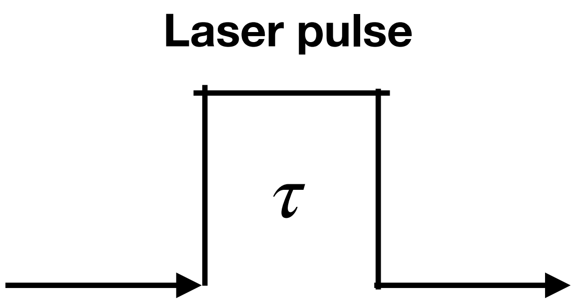
P -> strength of the Laser

φ -> phase of the Laser

ω -> Laser detuning

Fully controllable only by the laser.

Single qubit gates



$$U_\epsilon(\beta) = \exp(-i\tau H_q/\hbar)$$

$$U_\epsilon(\beta) = \mathbb{1}\cos\beta - i\boldsymbol{\epsilon}.\hat{\boldsymbol{\sigma}}\sin\beta$$

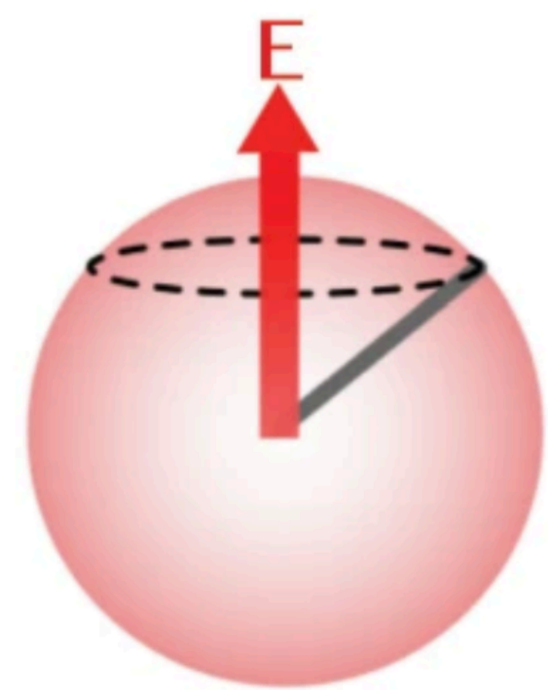
$$\beta = \tau E/\hbar \quad E = \sqrt{P^2 N_c + (a-\omega)^2/4}.$$

$$\epsilon = \boldsymbol{E}/E$$

$$E_x = P\sqrt{N_c}\cos\varphi,$$
$$E_y = P\sqrt{N_c}\sin\varphi,$$
$$E_z = (a-\omega)/2.$$

$$U_\epsilon(\beta) = \begin{bmatrix} \cos\beta - i\sin\beta\cos\xi & -i\sin\beta\sin\xi\; e^{-i\varphi} \\ -i\sin\beta\sin\xi\; e^{i\varphi} & \cos\beta + i\sin\beta\cos\xi \end{bmatrix}$$

$$\boldsymbol{\epsilon} = (\sin\xi\cos\varphi,\ \sin\xi\sin\varphi,\ \cos\xi)$$



Bloch sphere rotation

Any single qubit gate. *npj Quantum Info. 6, 16 (2020).*

Two-qubit quantum gates

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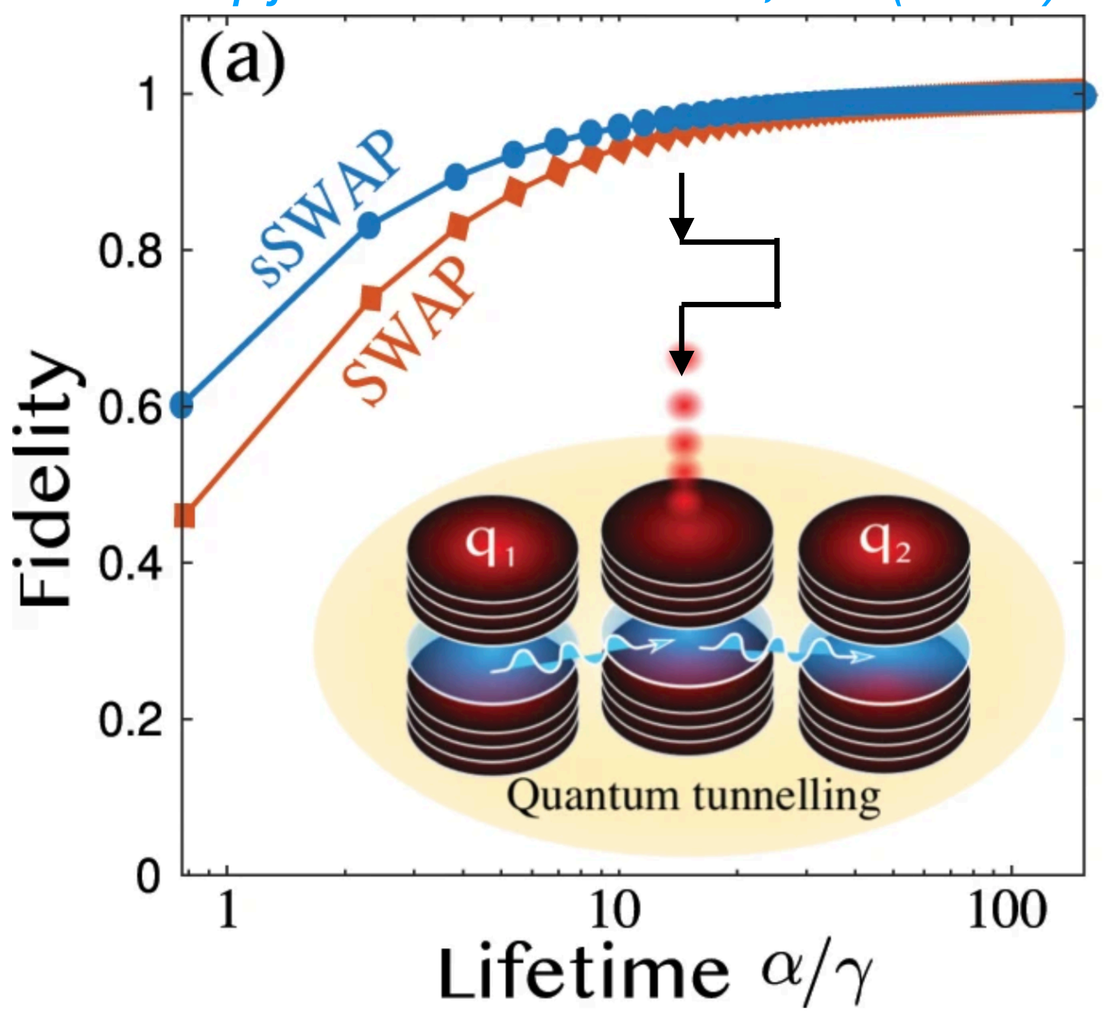
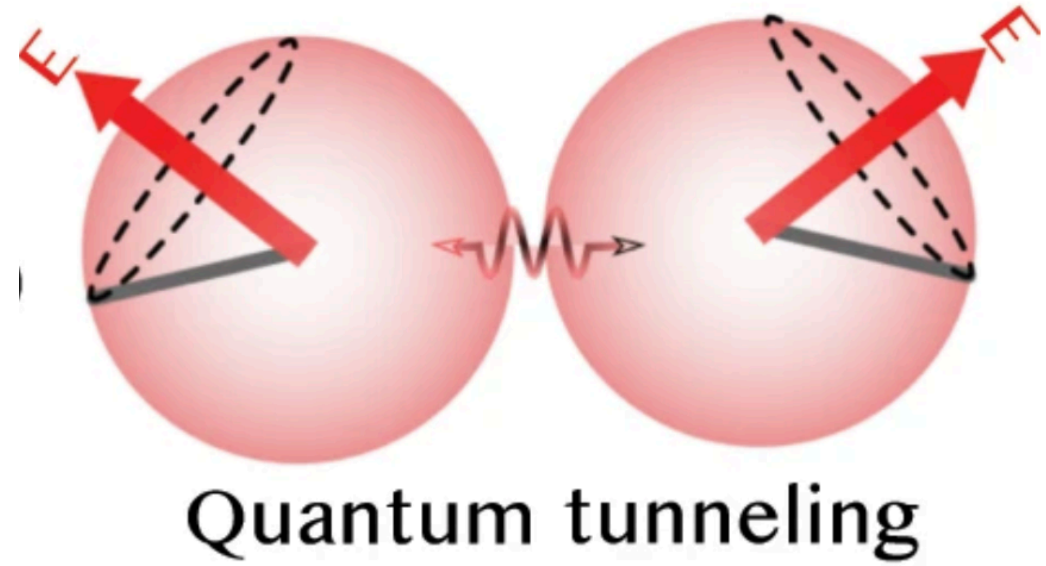
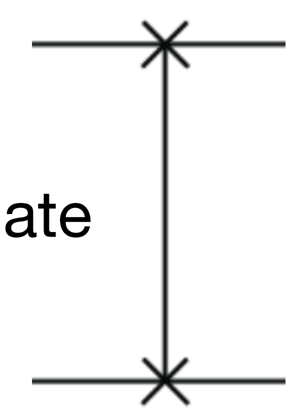




$$H_{12} = \sum_{j=1,2} H_j + J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1)$$

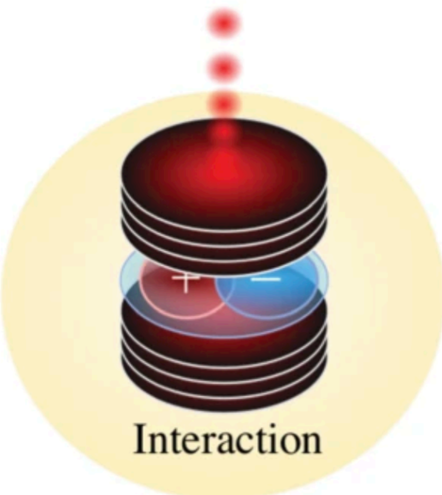
$$H_{q_1 q_2} = \sum_{j=1,2} \boldsymbol{E}^j \cdot \hat{\boldsymbol{\sigma}}^j + E_T(\hat{\sigma}_+^1 \hat{\sigma}_-^2 + \hat{\sigma}_+^2 \hat{\sigma}_-^1)$$

SWAP gate

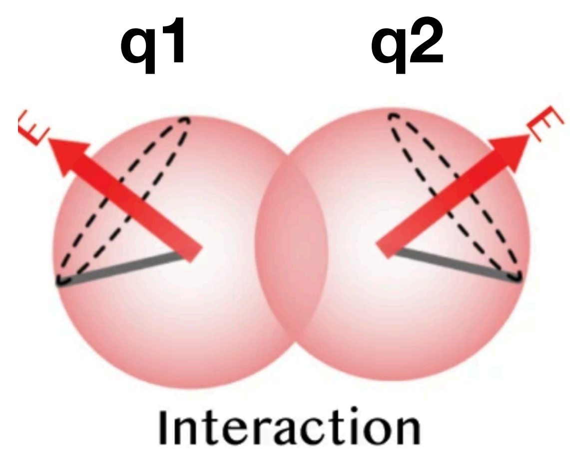


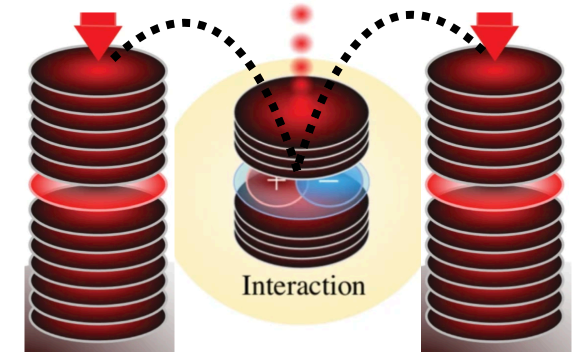
$$\sqrt{\mathrm{SWAP}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2}(1+i) & \frac{1}{2}(1-i) & 0 \\ 0 & \frac{1}{2}(1-i) & \frac{1}{2}(1+i) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Two-qubit cNOT gate



$$H_{12} = \sum_{j=1,2} H_j - 2\alpha_{12}\, \hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_2 \hat{a}_1$$





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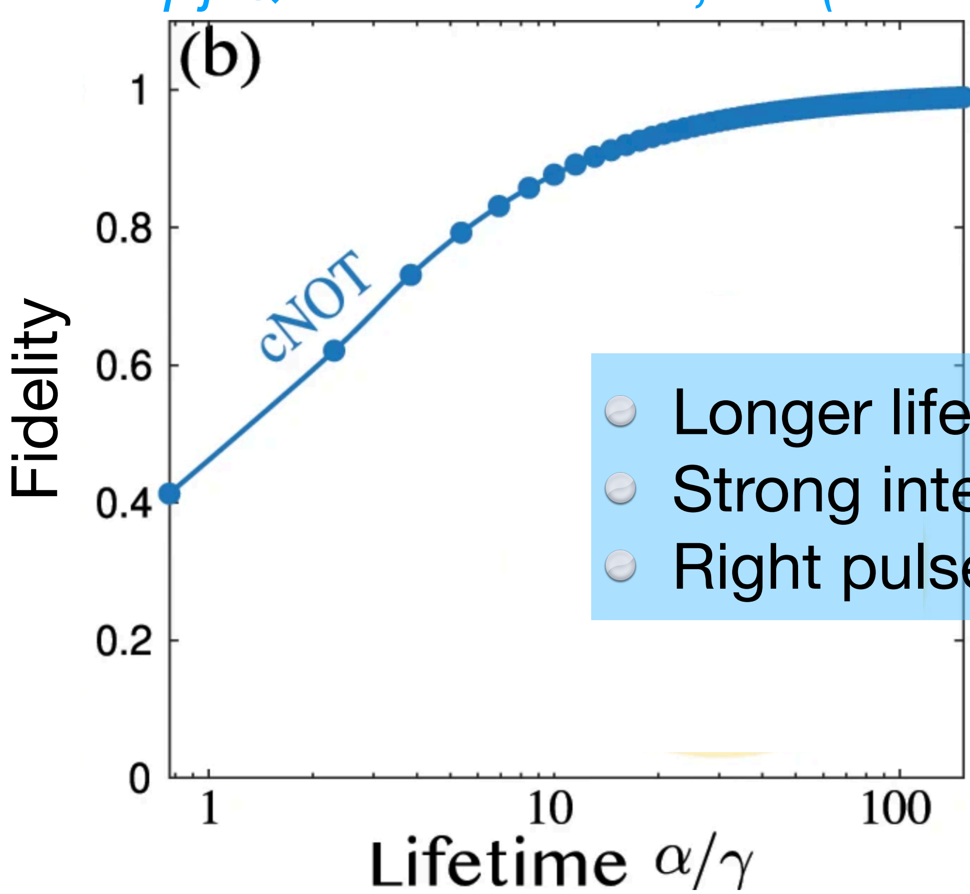
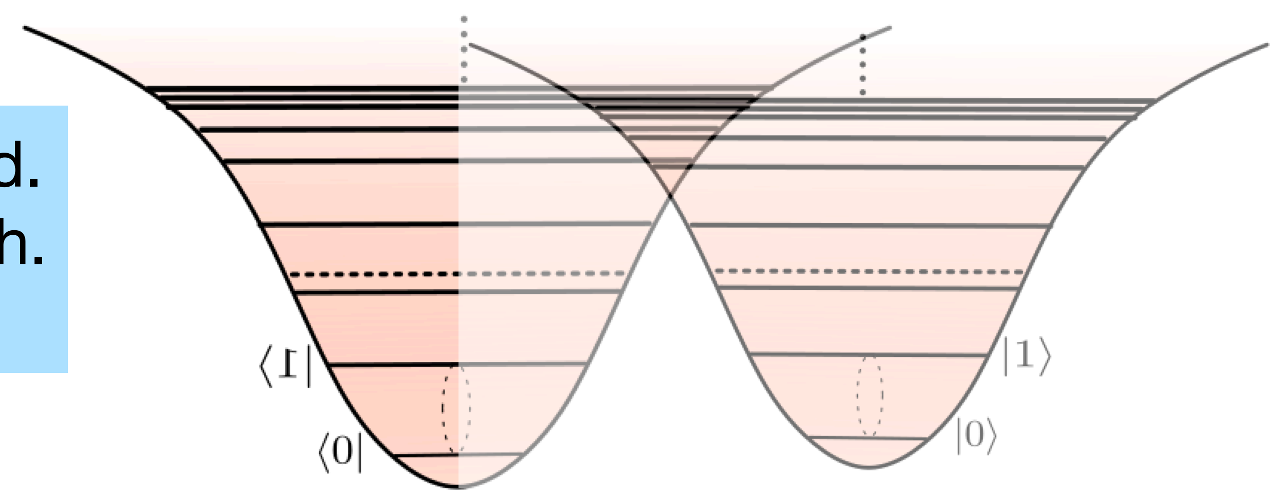
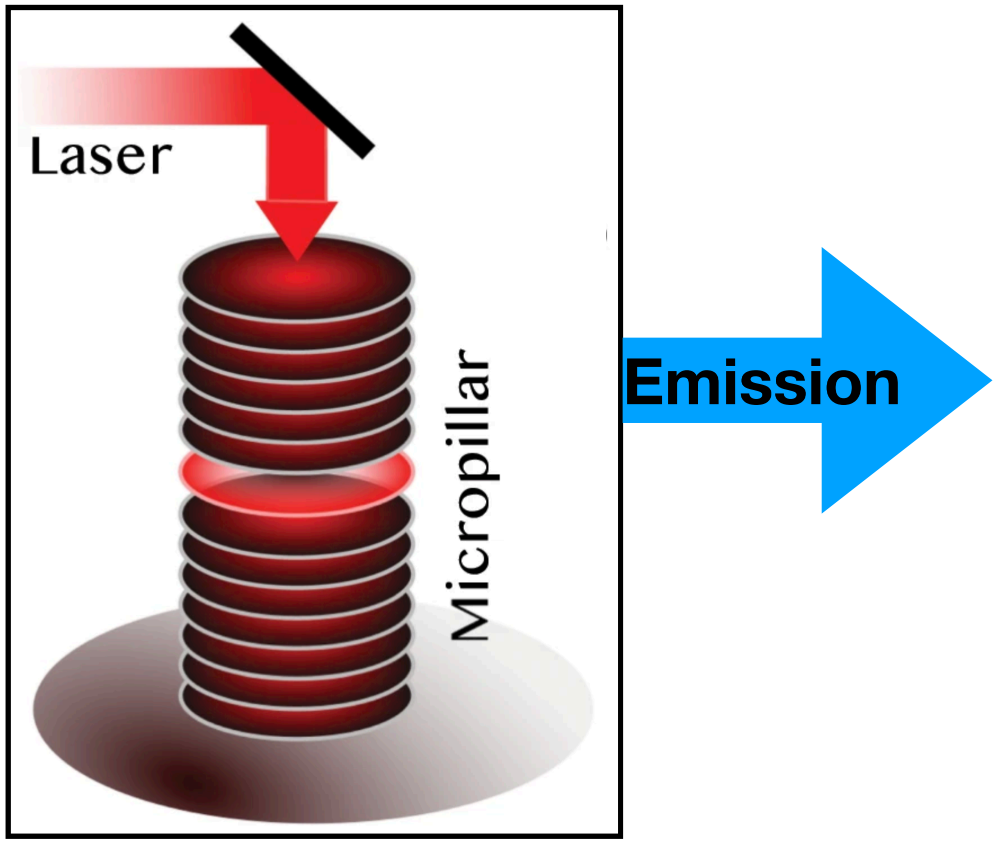


$$H_{q_1 q_2} = \sum_{j=1,2} \boldsymbol{E}^j . \hat{\boldsymbol{\sigma}}^j - E_z^{12} \left(\mathbb{1} + \sigma_z^1\right) \left(\mathbb{1} + \sigma_z^2\right)$$

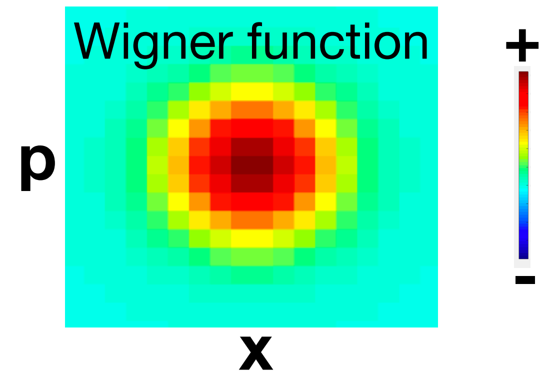
- Longer life time is required.
- Strong interaction strength.
- Right pulse durations.



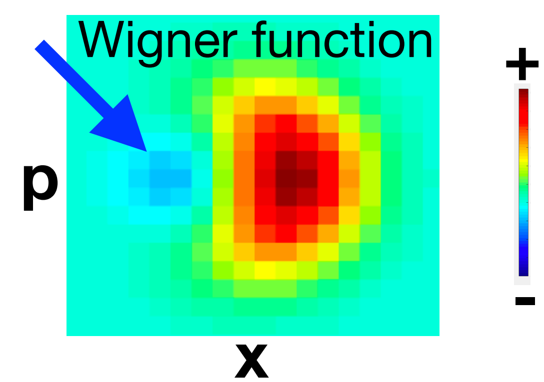
Reading out

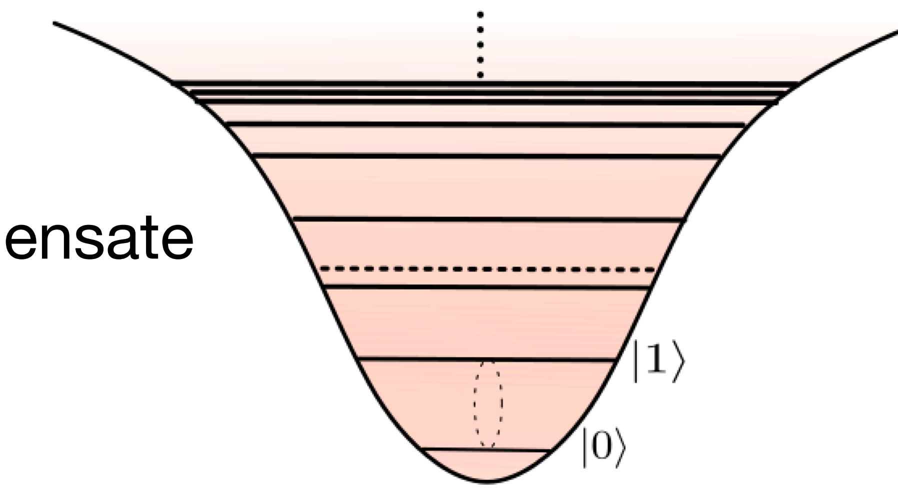


$|0\rangle$ Condensate



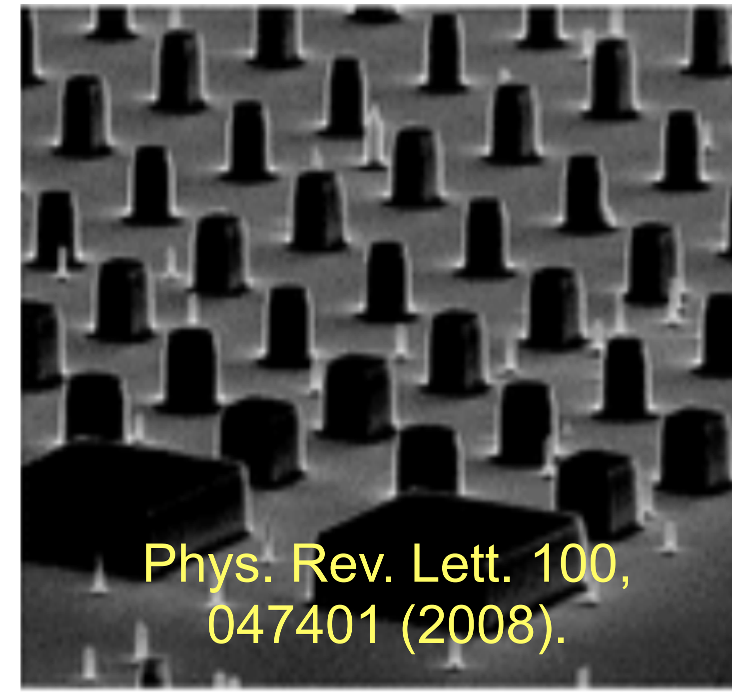
$|1\rangle$ Particle added condensate

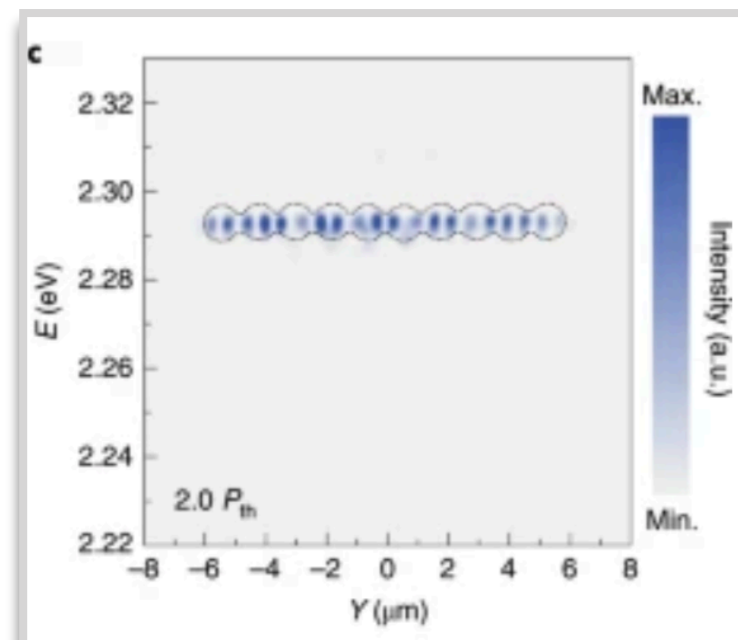




Scalability

- Available in micron scales.
- 1000s of them can be fabricated in a single sample.
- Potentially can operate at room temperature.
- Even if they operate at cryogenic temp, they are small and thus require smaller cryogenic space.
- Energy efficient and optically controlled.
- Advanced fabrication technologies are available.


Phys. Rev. Lett. 100, 047401 (2008).



Nature Physics volume 16, 301–306(2020)

Summary

- Qubit: in semiconductor micropillars.
- Universal gate set: interaction between micropillars allows quantum gates.
- Control: controllable via external laser pulses (phase, amplitude and duration).
- Prob: driven dissipative system. Look in the emission.
- Fabrication technologies: existing semiconductor technologies.
- Scalability: in principle scalable.

End