Quantum information processing with atoms coupled to waveguides and cavities

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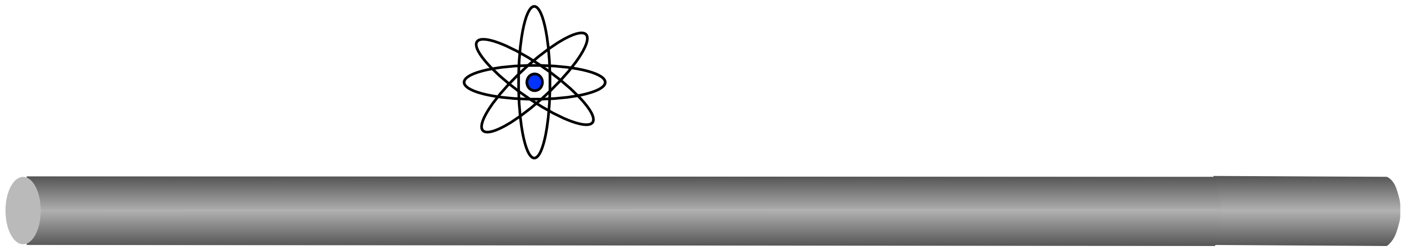
Quantum Plasmonics, March 2015

Emitters coupled to waveguides

Plasmonics: Strong confinement => emitters decay to wire



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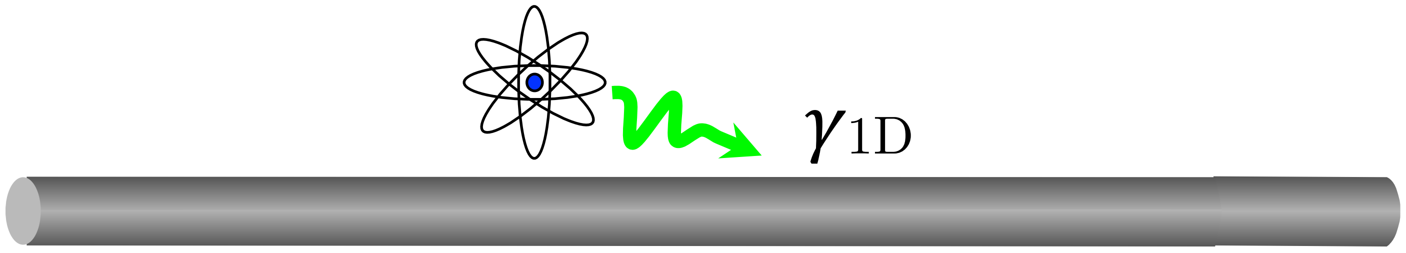

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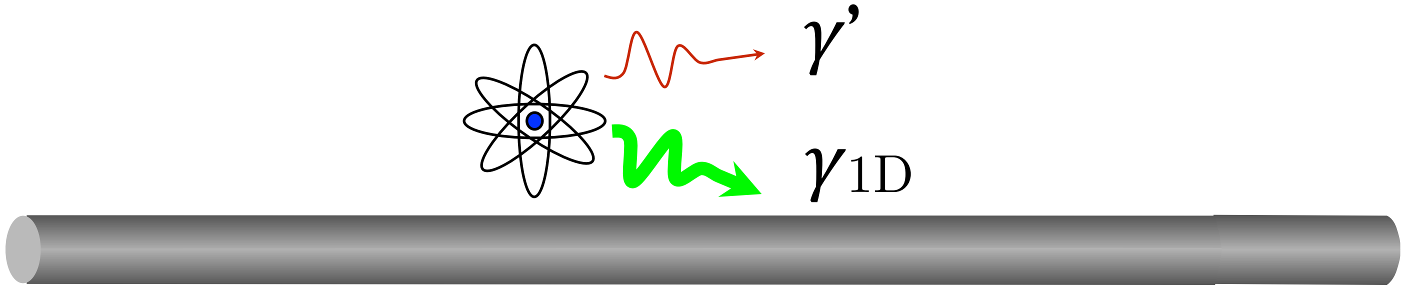

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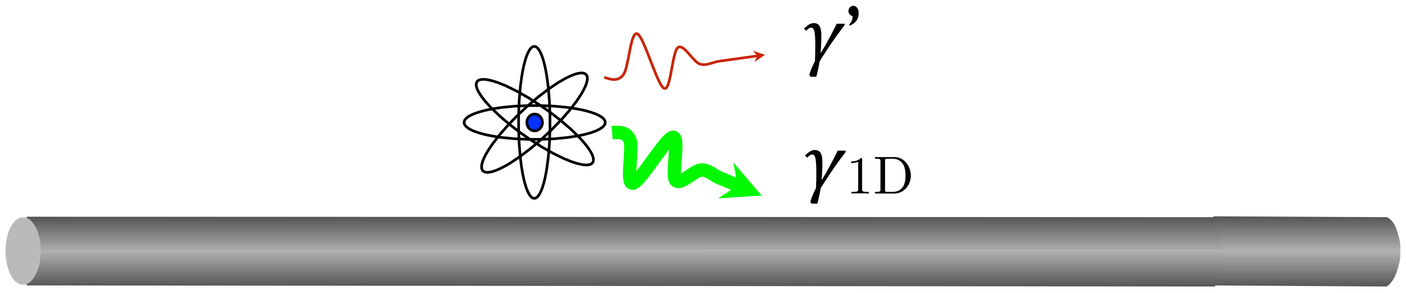

Theoretical model: Two level system coupled to waveguide.

Figure of merit $\beta = \frac{\gamma_{1D}}{\gamma_{1D} + \gamma'}$

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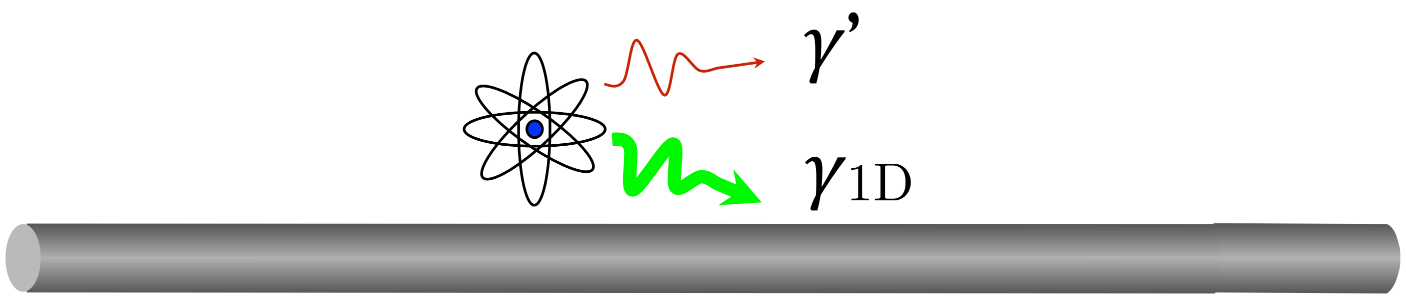

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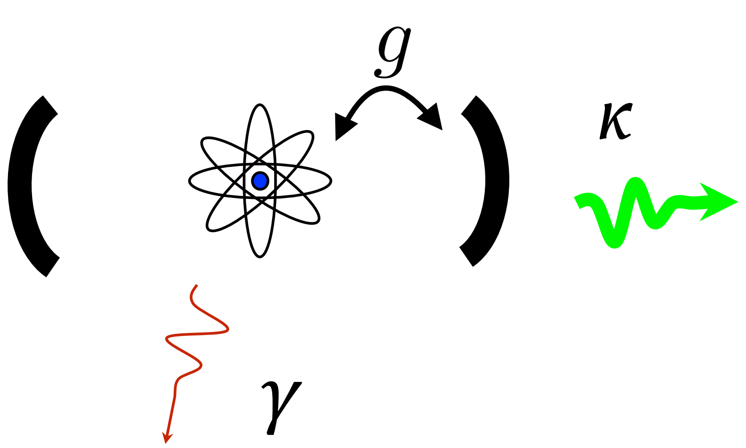
Mathematically equivalent setup: Atom in broad cavity



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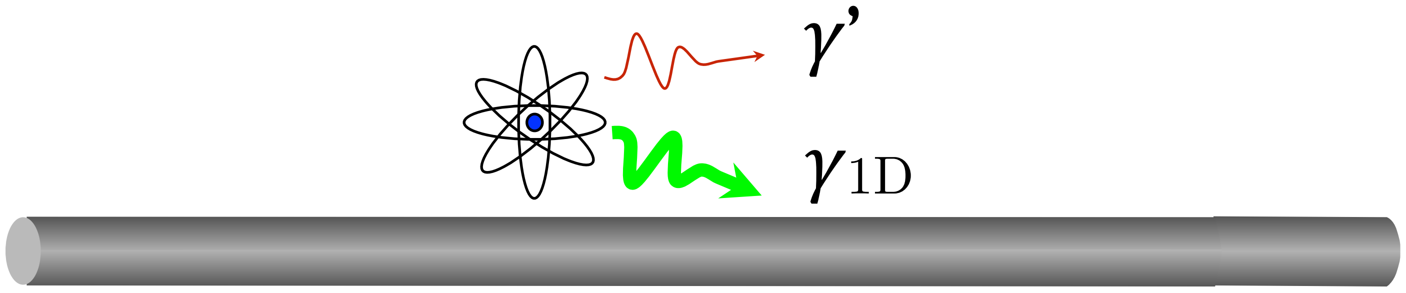

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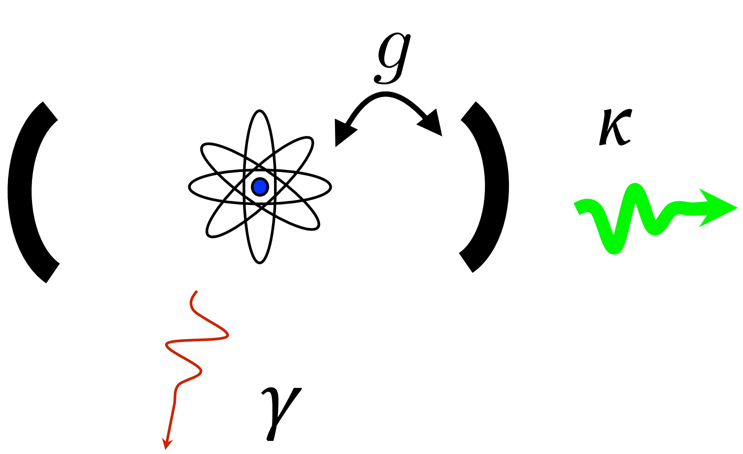

Limit $\kappa \rightarrow \infty$, $C = \dfrac{g^2}{\kappa\gamma}$ and γ fixed

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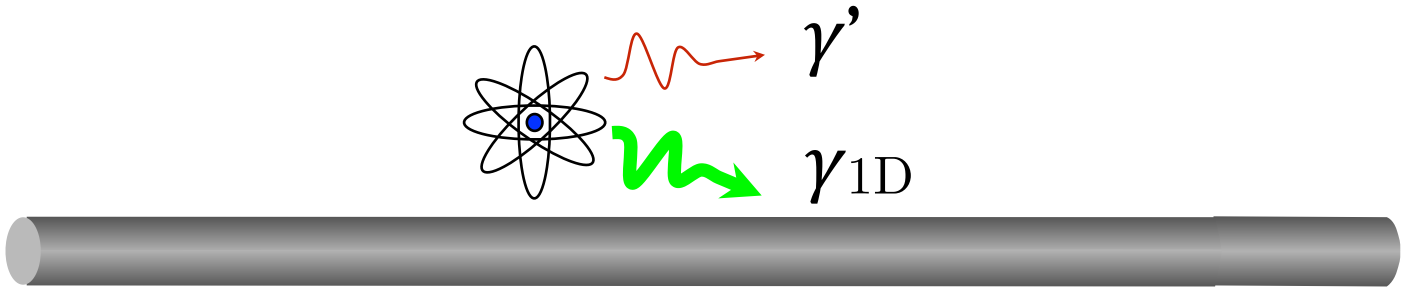

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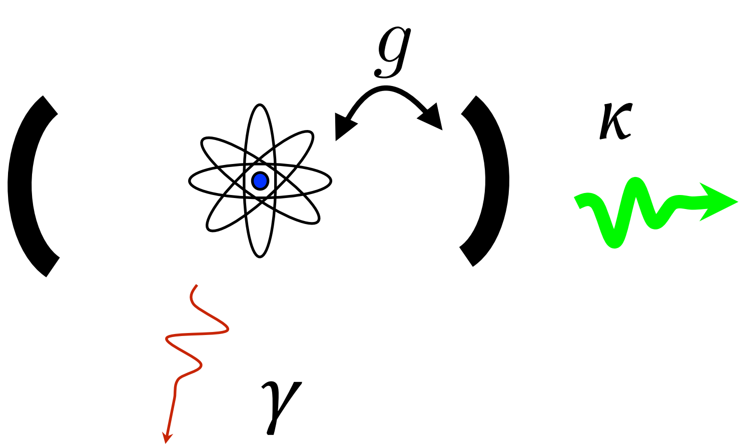

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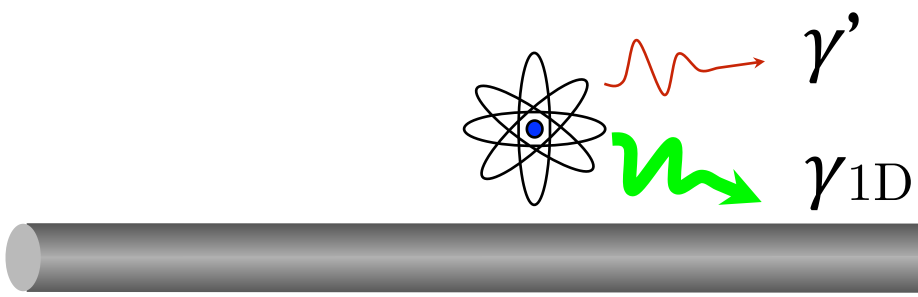

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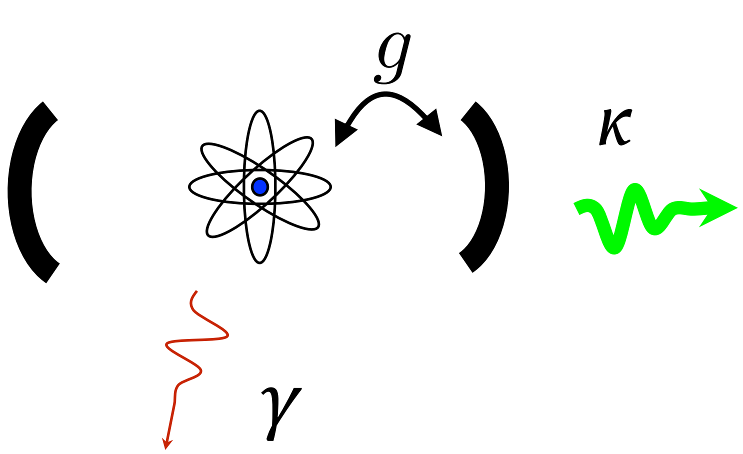

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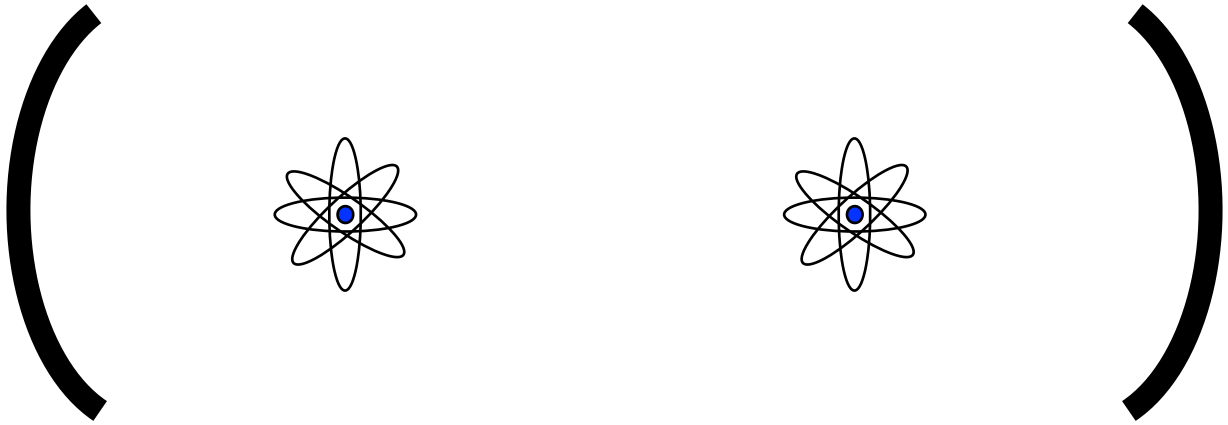
Good rate: $\gamma_{\text{good}} = 4\dfrac{g^2}{\kappa}$

Equivalent to: $\beta = 1 - \dfrac{1}{4C}$

Quantum information processing

Challenge: make gates between atoms

Cavity:



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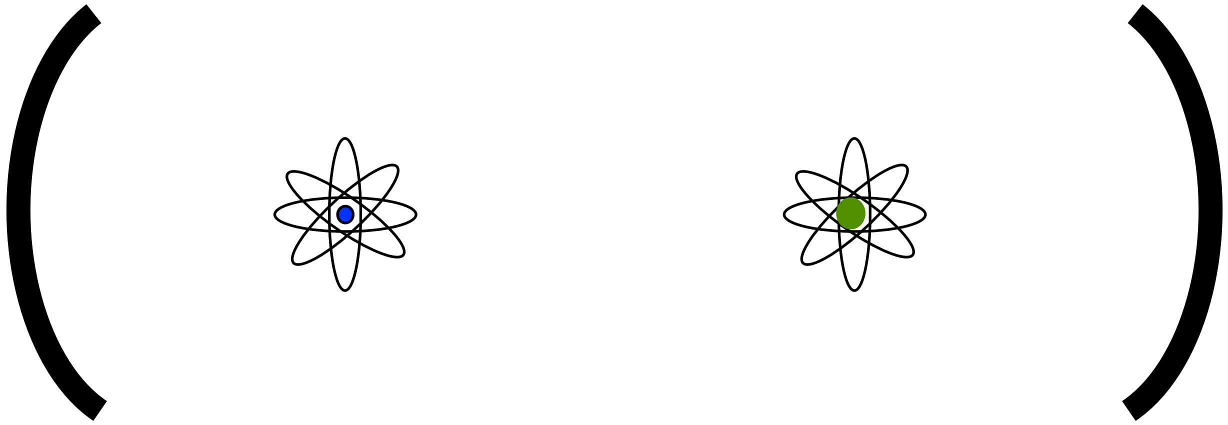

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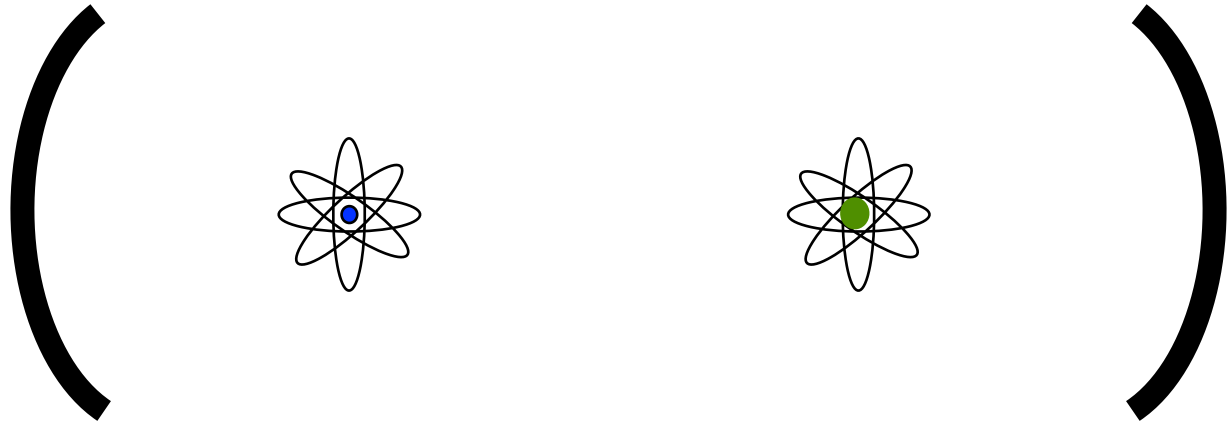

Works in principle

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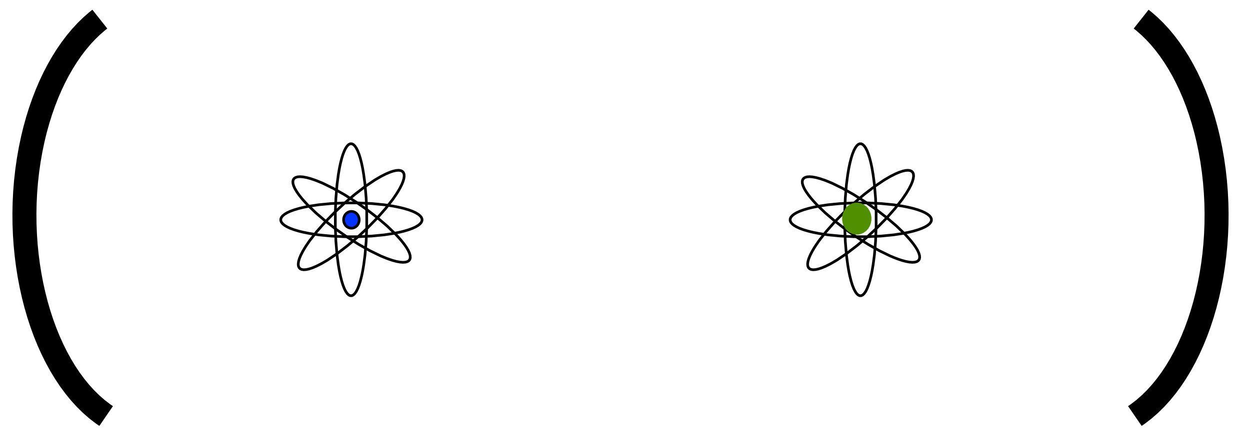

Works in principle

Fidelity limited $1 - F \propto \frac{1}{\sqrt{C}}$

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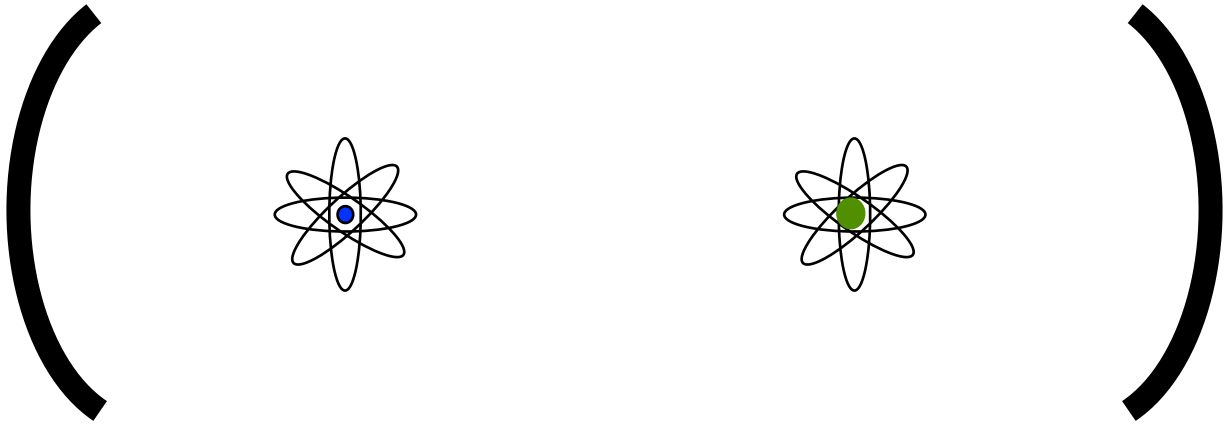

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Waveguide:

Quantum information processing

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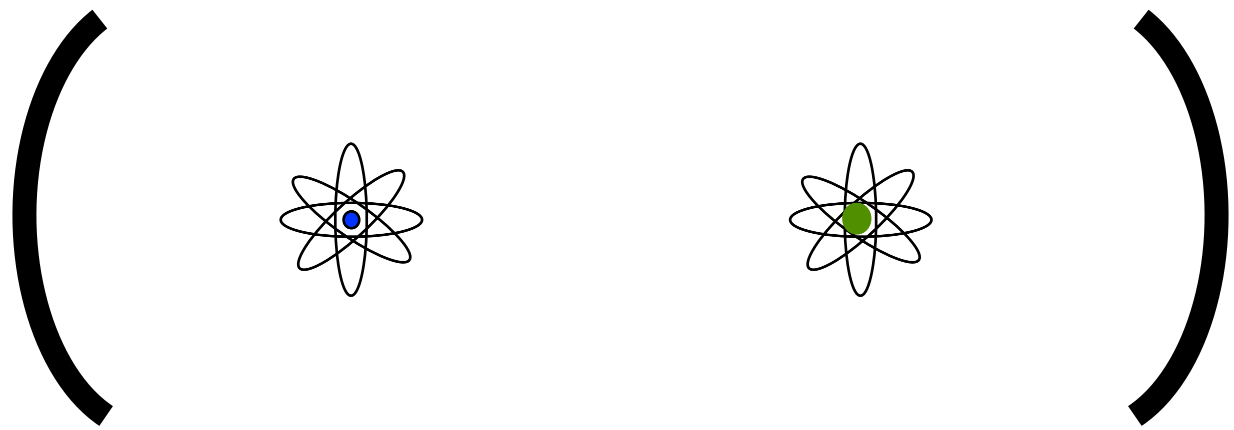

Works in principle

Fidelity limited $1 - F \propto \frac{1}{\sqrt{C}}$

Waveguide:

Limited fidelity[*]: $1 - F \propto \sqrt{1-\beta}$

[*]D. Dzsotjan, A. S. Sørensen, and M. Fleischhauer, Phys. Rev. B **82**, 075427 (2010)

Making use of imperfect coupling

Bad scaling can be overcome

Possible solutions:

- Probabilistic generation of entanglement[1]

$$F \approx 1, \quad P < 1$$

- Measurement and feedback[2]

$$1 - F \propto \frac{1}{\eta C}$$

- Dissipative generation of entanglement[3]

$$1 - F \propto \frac{1}{C}$$

- Heralded quantum gates[4]

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[1] C. Cabrillo, J. I. Cirac, P. García-Fernández, and P. Zoller, Phys. Rev. A **59**, 1025 (1999).
[2] AS. and Klaus Mølmer, Phys. Rev. Lett. **91**, 097905 (2003).
[3] M. J. Kastoryano, F. Reiter, and AS., Phys. Rev. Lett. 106, 090502 (2011).
[4] L.-M. Duan, B. Wang, and H. J. Kimble, Phys. Rev. A **72**, 032333 (2005), J. Borregaard, P. Komar, E. Kessler, AS, and M. D. Lukin, arXiv: 1501.00956, PRL in press

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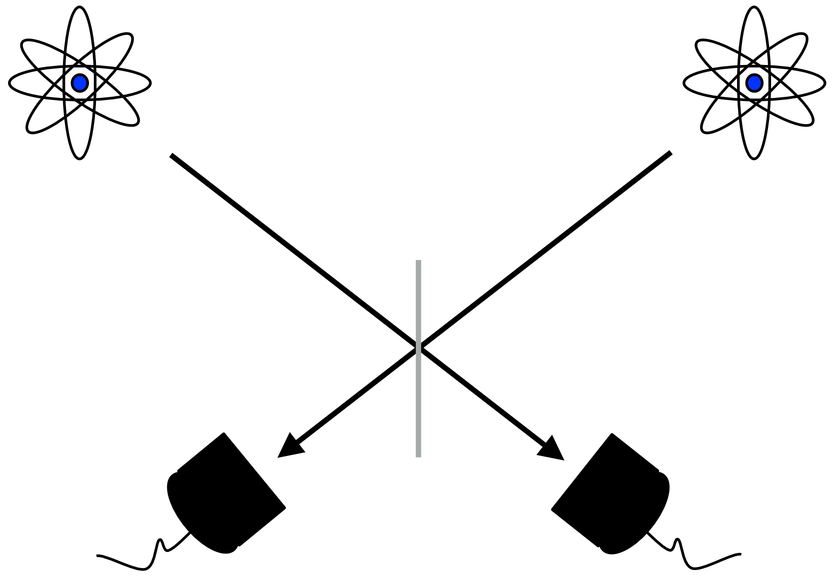
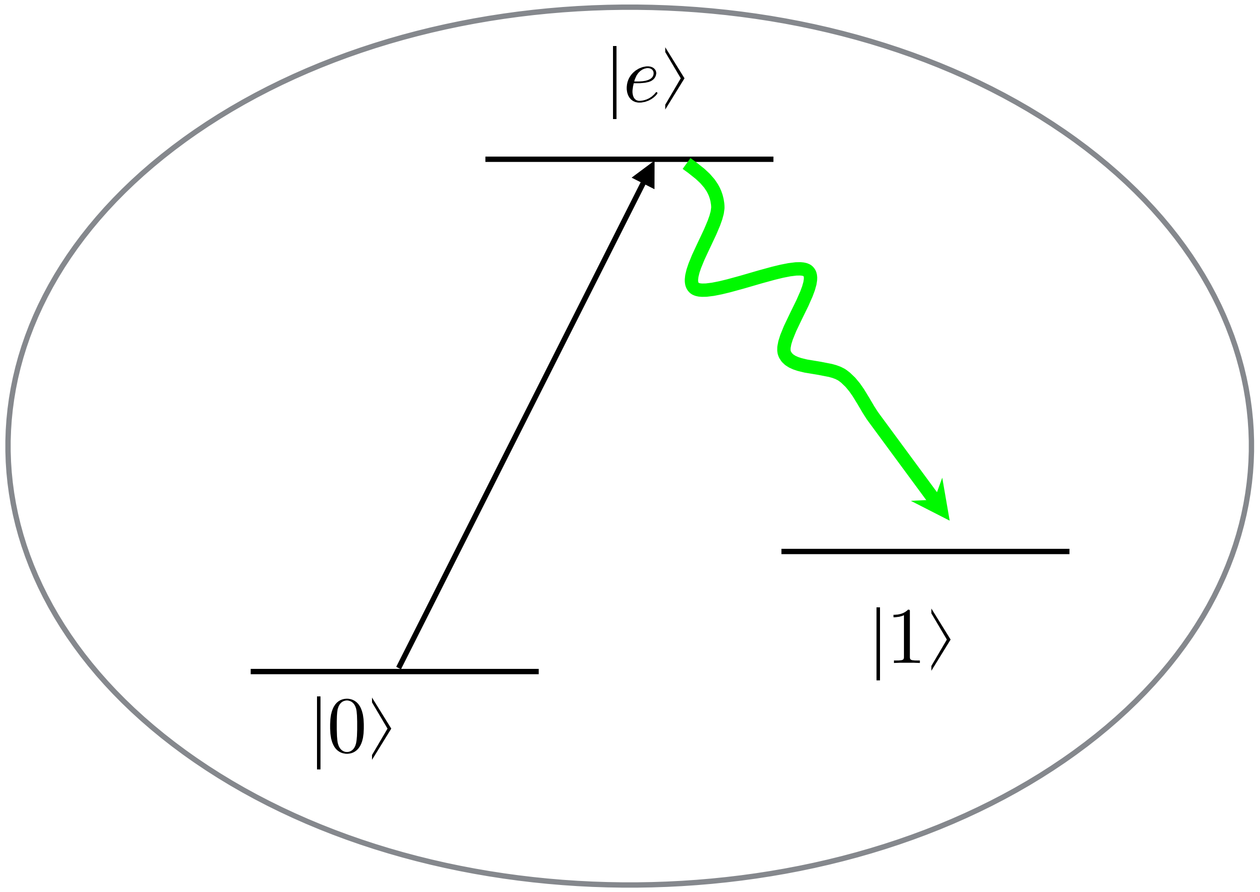
Entangling superconducting qubits coupled to molecules in waveguides

Preliminary work

Probabilistic entanglement

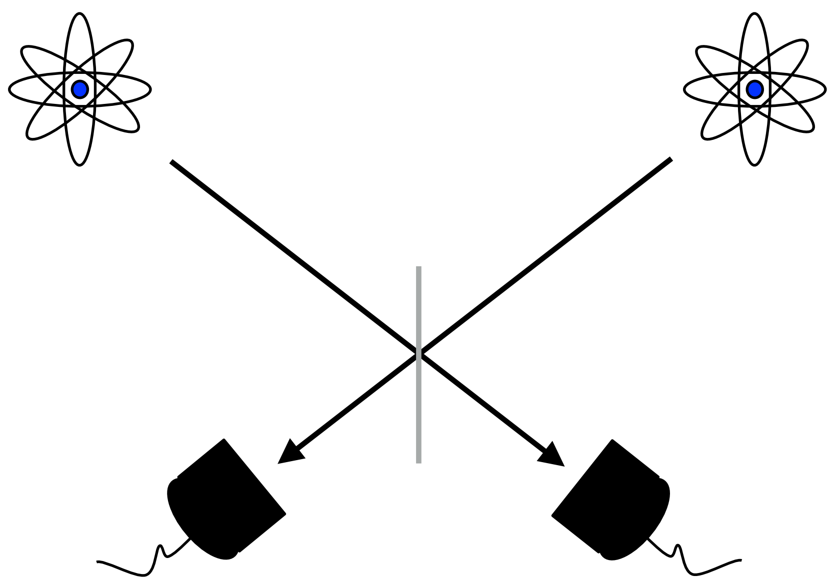


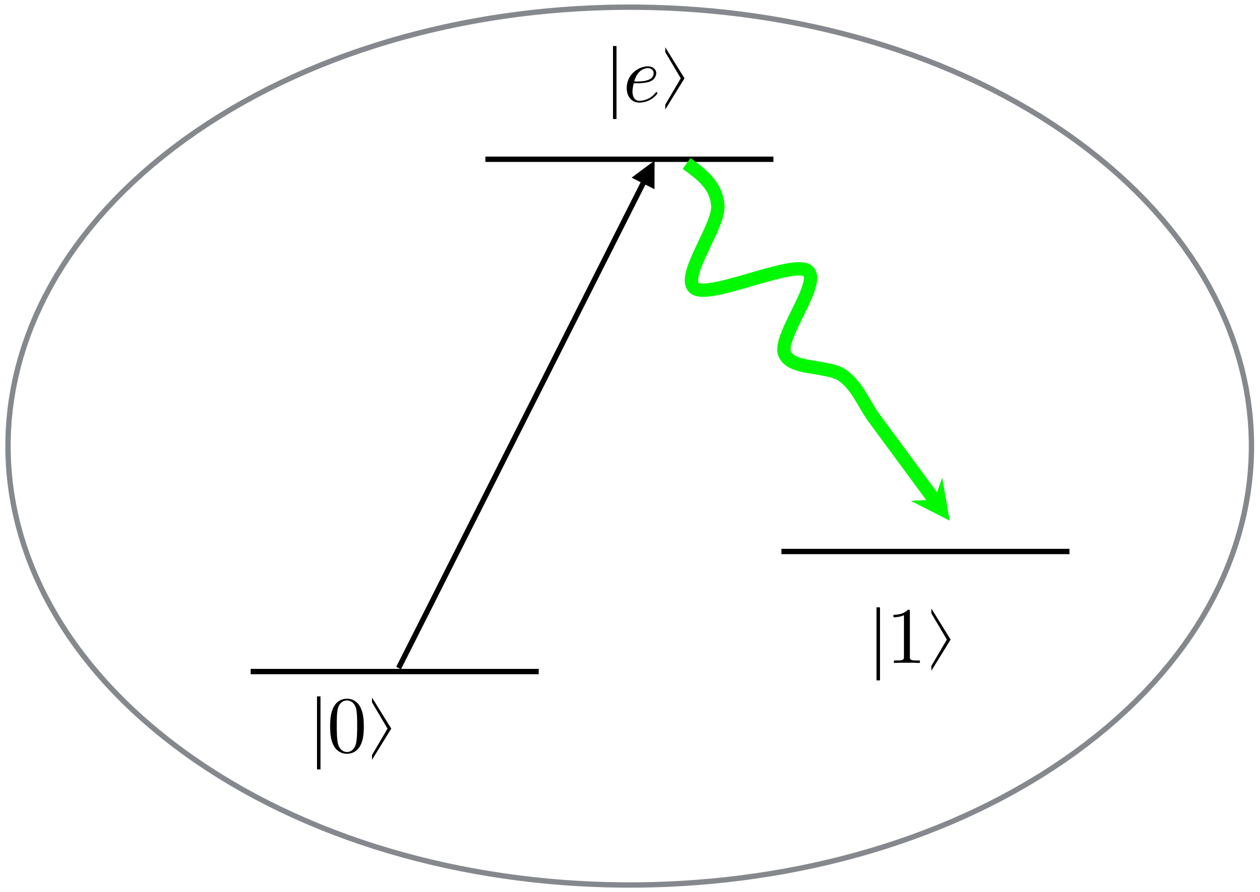


Start $|00\rangle$

Photon click => $\frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$

Probabilistic entanglement





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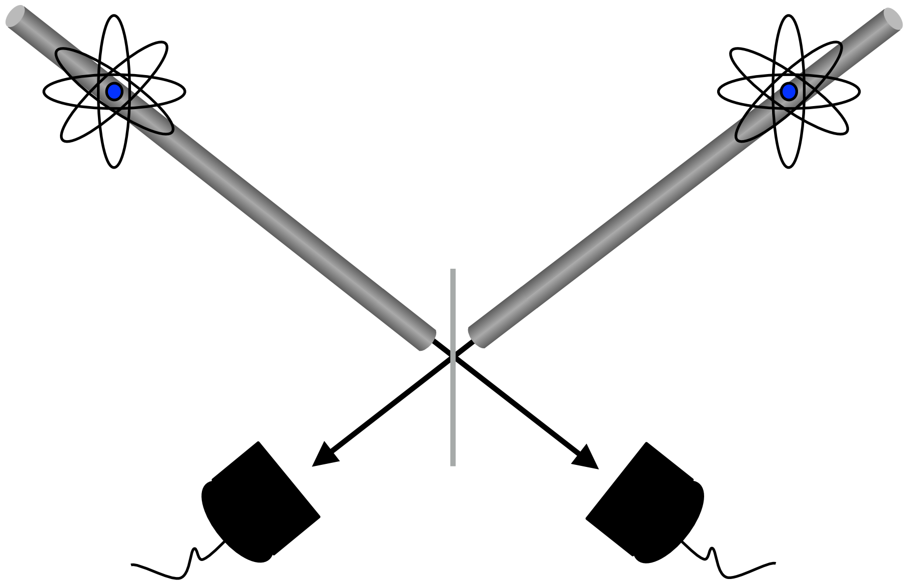
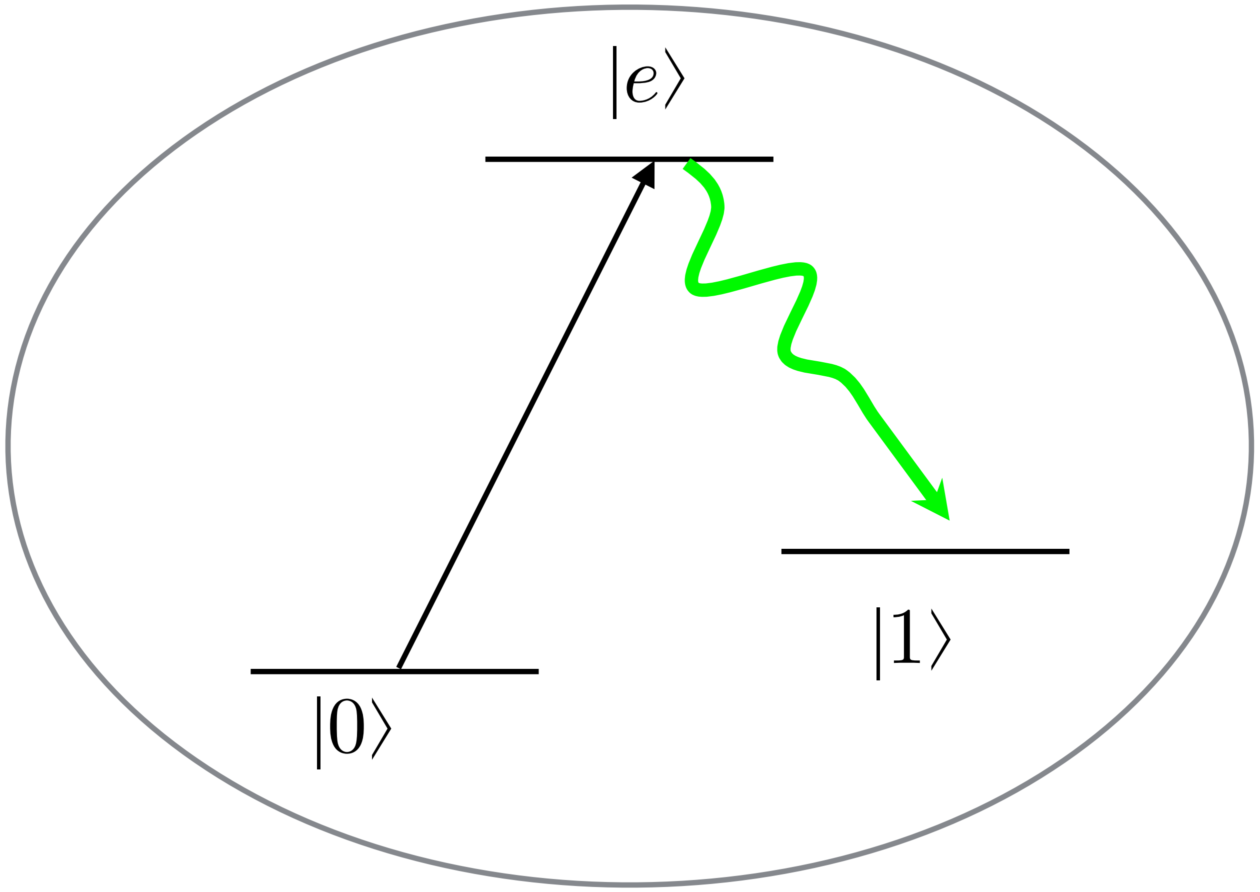
Non-local entanglement generation

Highly important for quantum communication

Probabilistic entanglement





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Non-local entanglement generation

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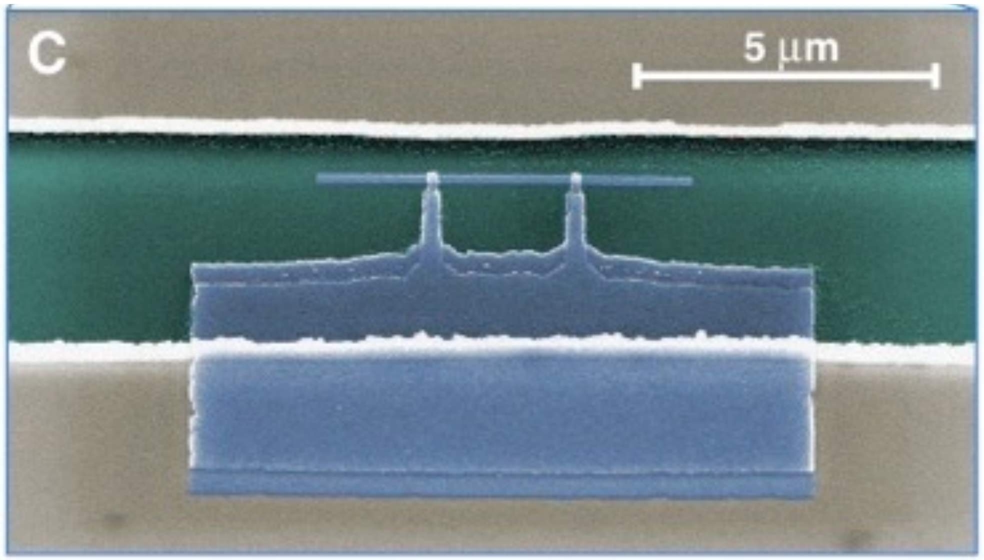
Waveguides: increase efficiency

Superconducting qubit

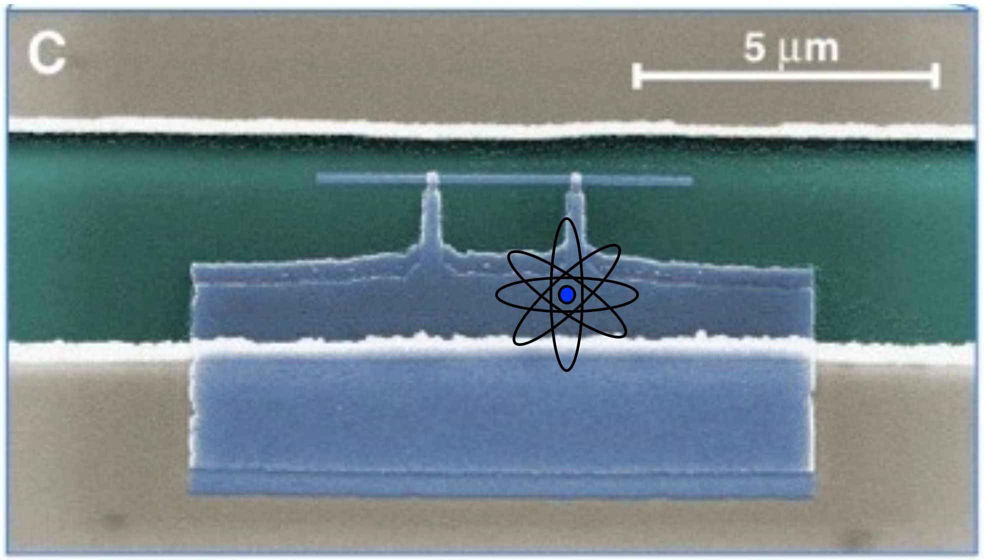


Picture: Schoelkopf group

Highly advanced system for quantum computation

Can’t couple to light => not useful for communication

Superconducting qubit



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Proposals: Put atom nearby => mediate coupling to light

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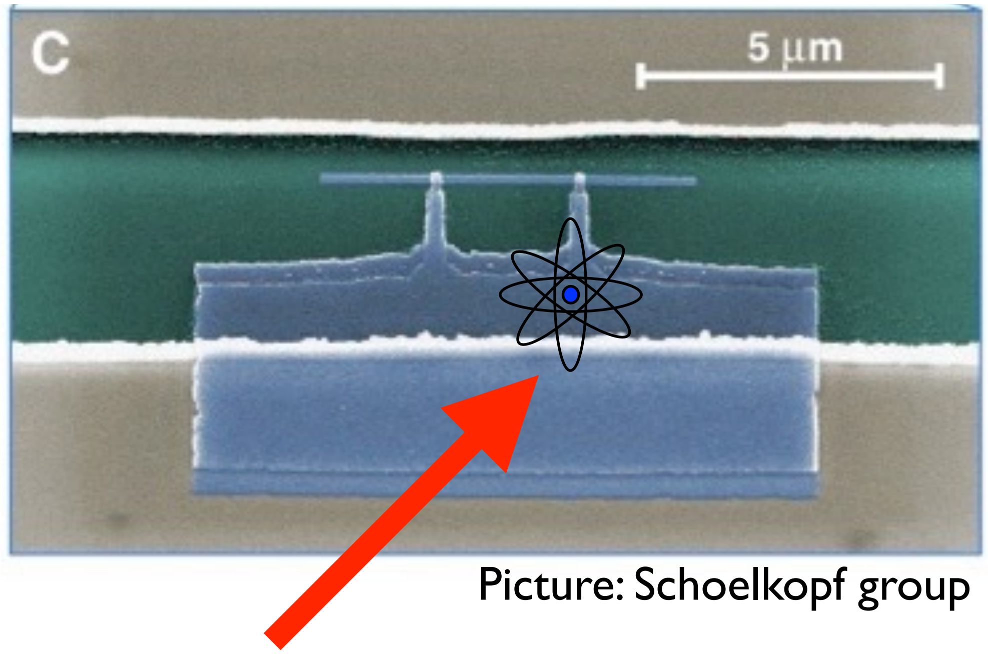

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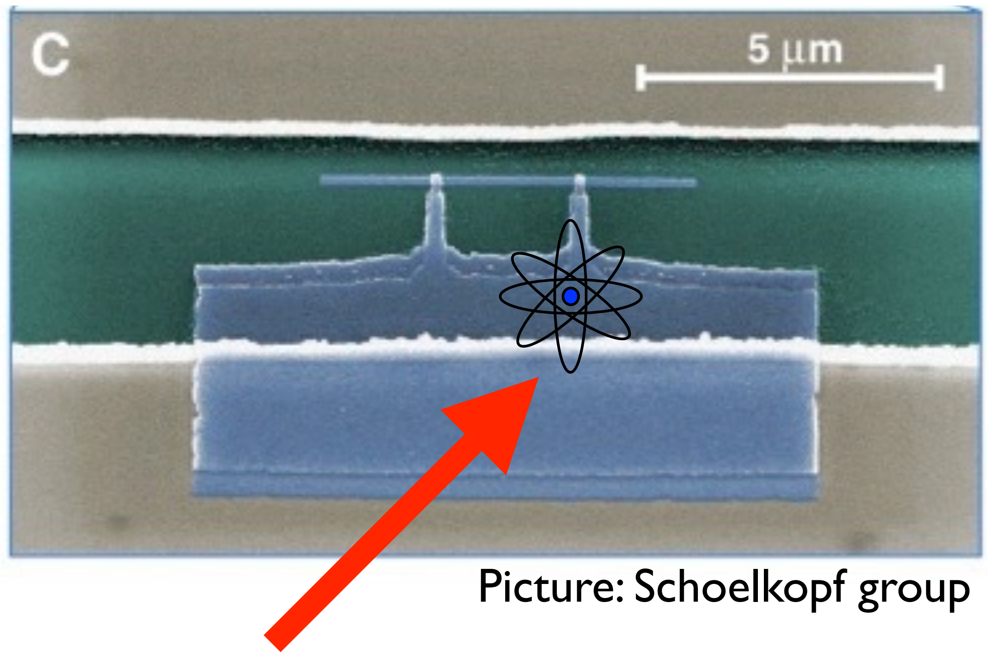

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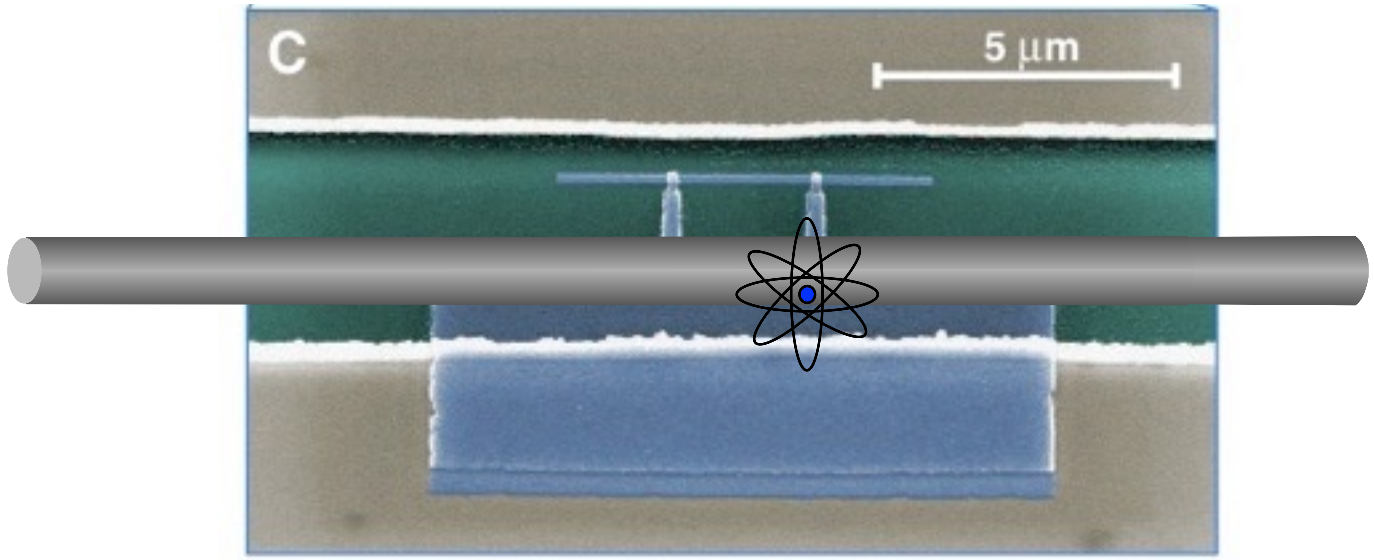

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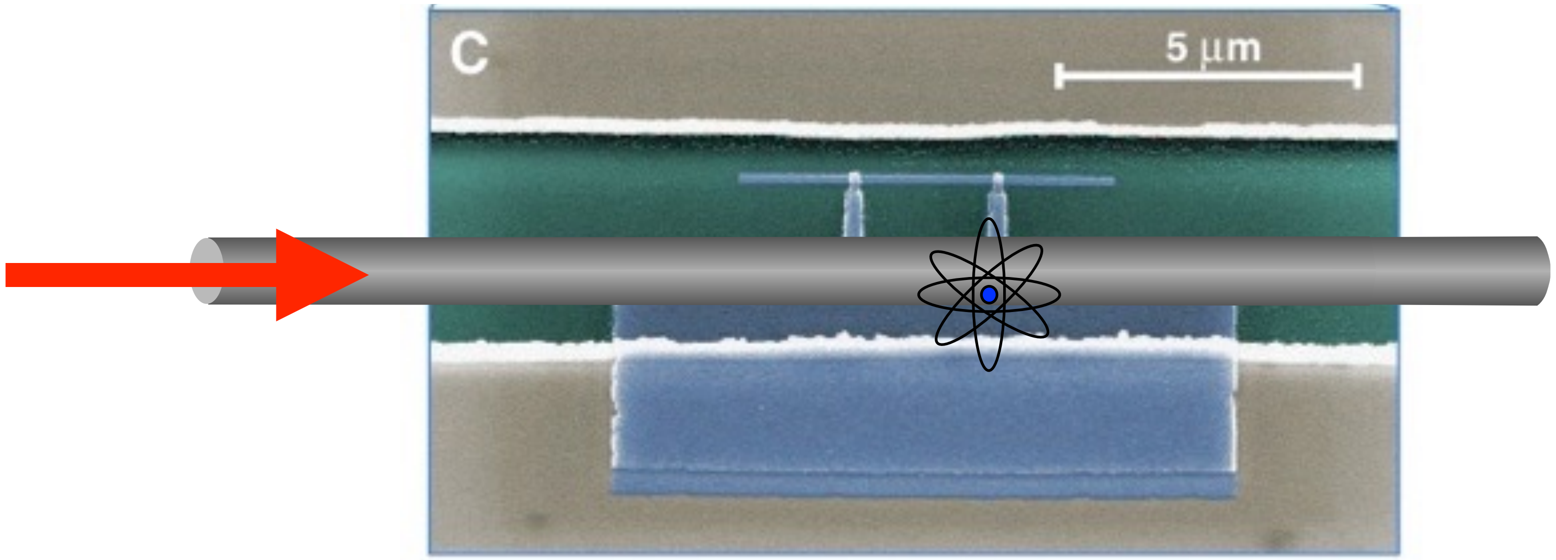

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Problem: superconductors don't like light

Send in light through waveguide => need very little light (one photon)

Molecules in waveguides

Experiments S. Faez, V. Sandoghdar: molecules in hollow core fiber

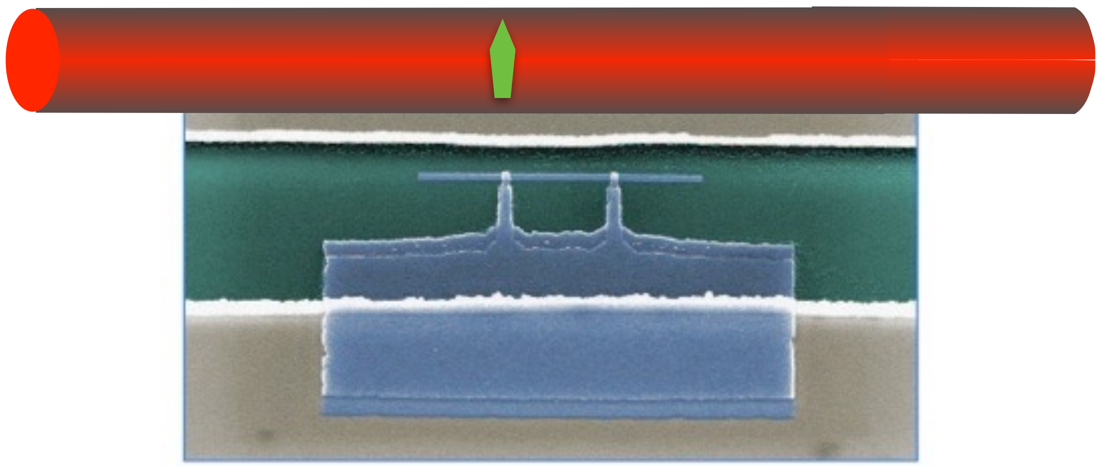
Can have good coupling* $\beta \approx 10\%$

Low temperatures: transitions nearly radiatively limited

Only a single ground state => not useful as a qubit

*S. Faez, P. Türschmann, H. R. Haakh, S. Götzinger, and V. Sandoghdar, Phys. Rev. Lett. **113**, 213601 (2014)

Coupling molecules and qubits



Transitions can have linear AC-Stark shift => couple to (charge) qubits

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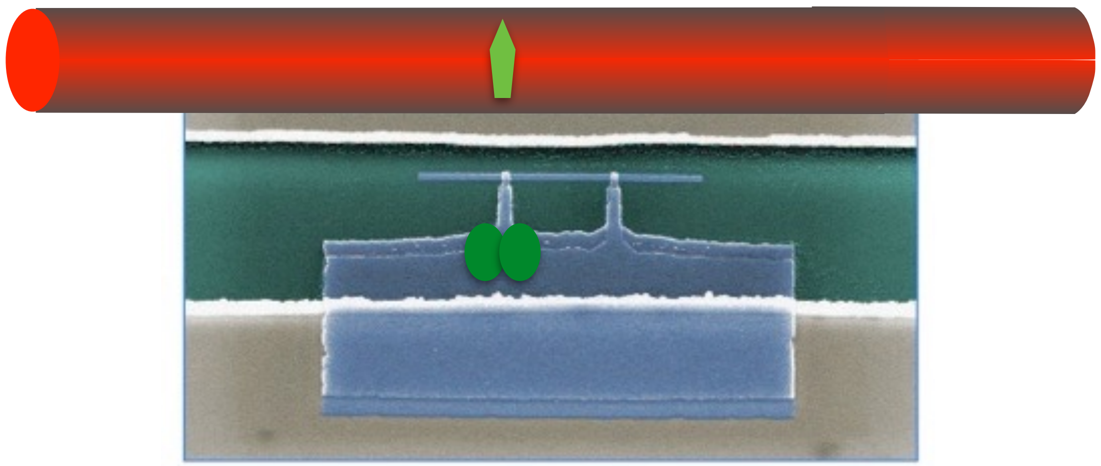

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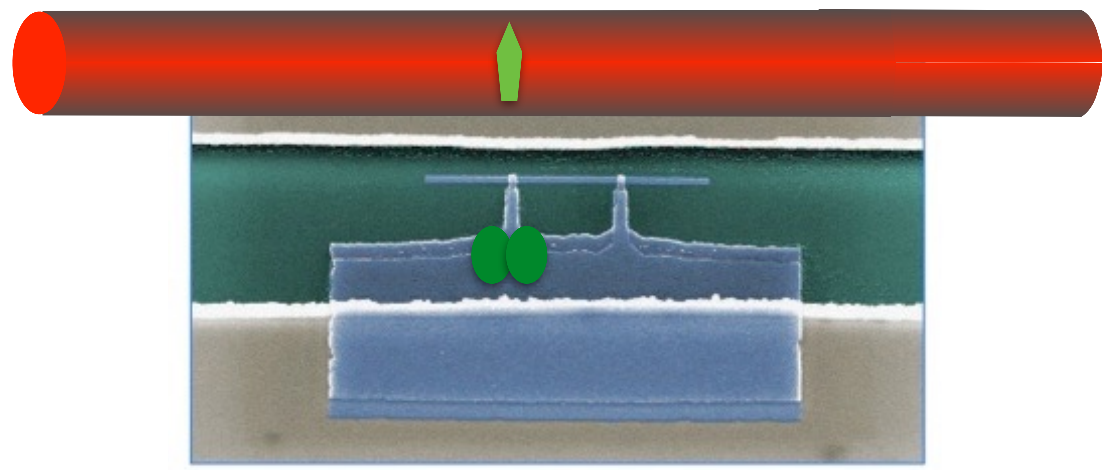

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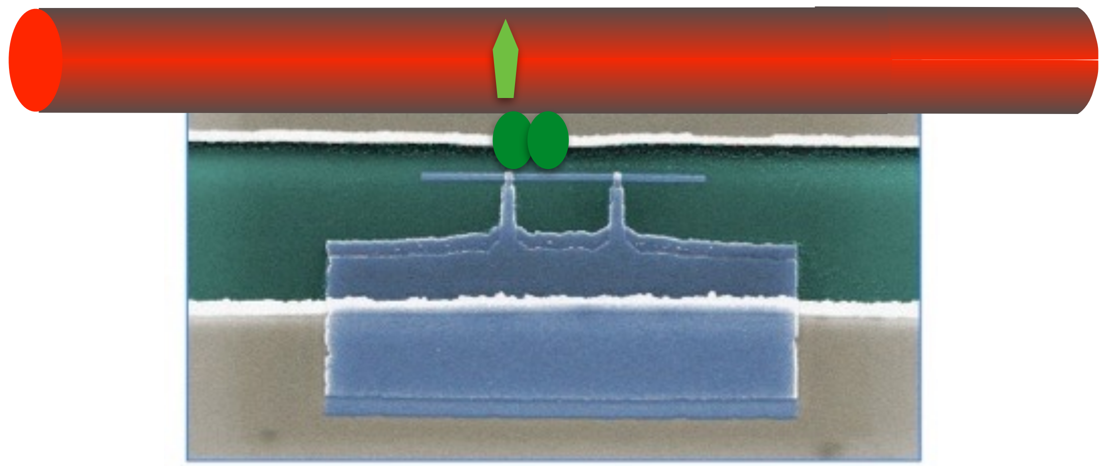

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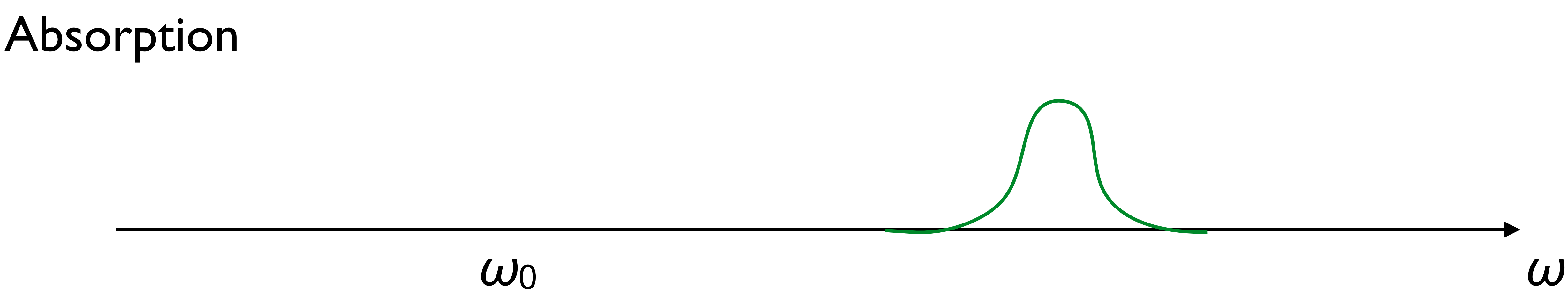

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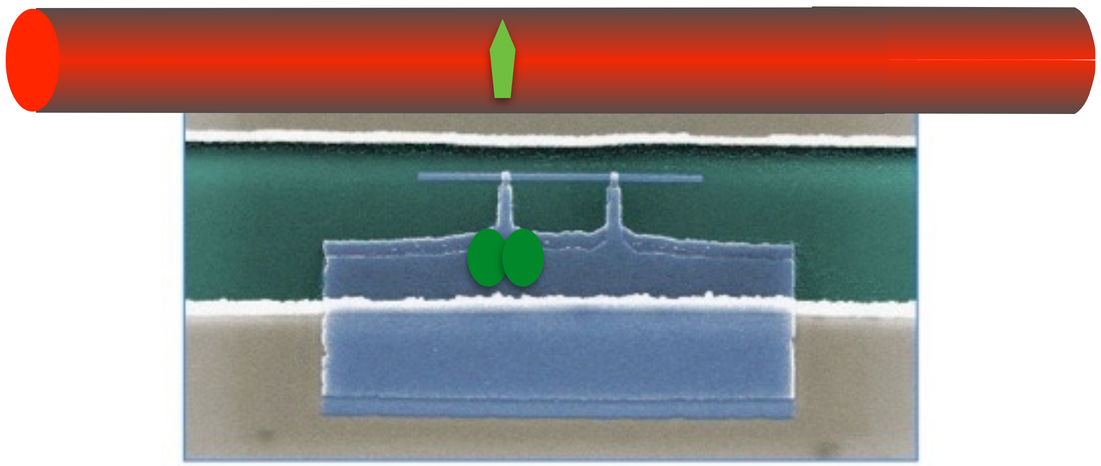

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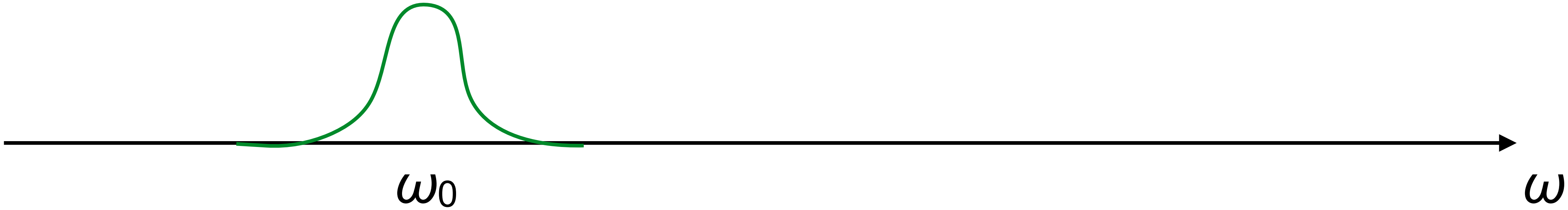

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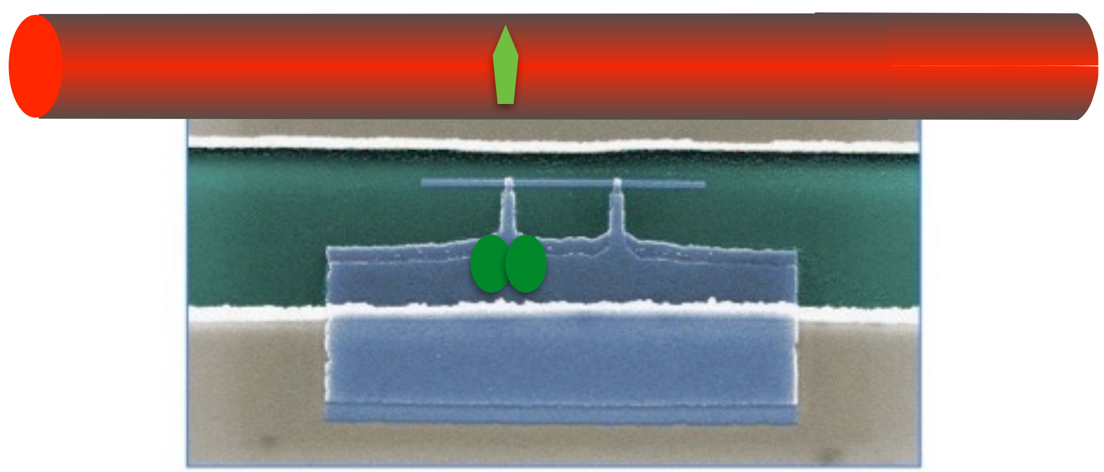
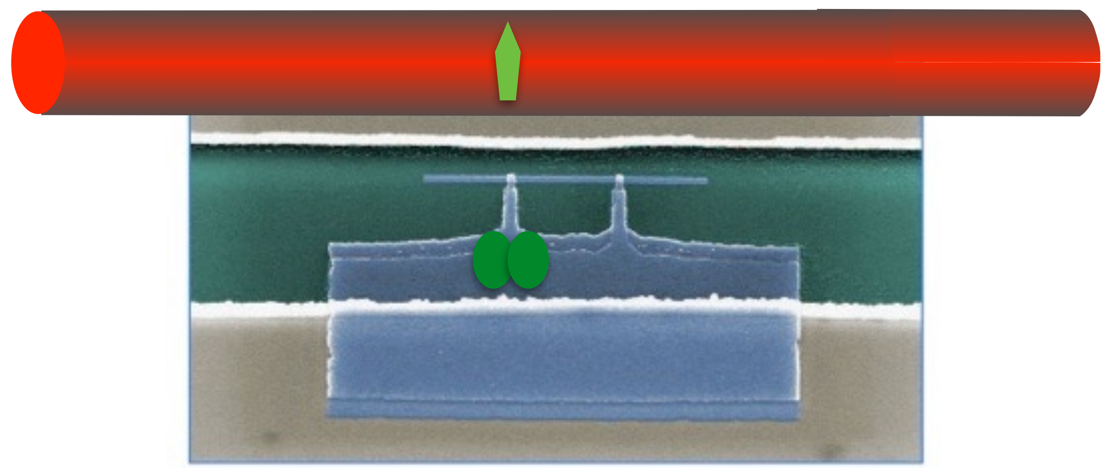


Transitions can have linear AC-Stark shift => couple to (charge) qubits

Absorption

Estimate: Dipole 1D, distance 500 nm, Shift: 45 MHz

Coupling molecules and qubits



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Absorption

Estimate: Dipole 1D, distance 500 nm, Shift: 45 MHz >linewidth ~20MHz

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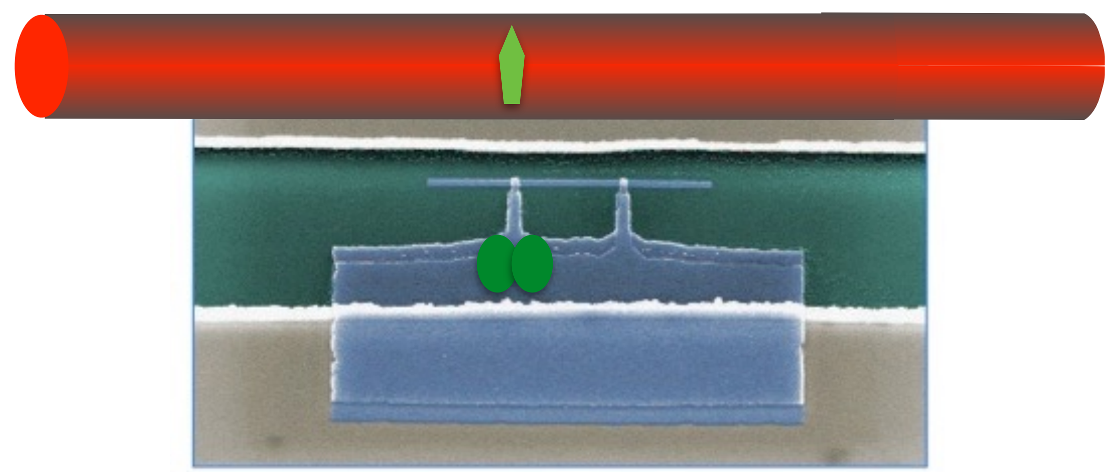

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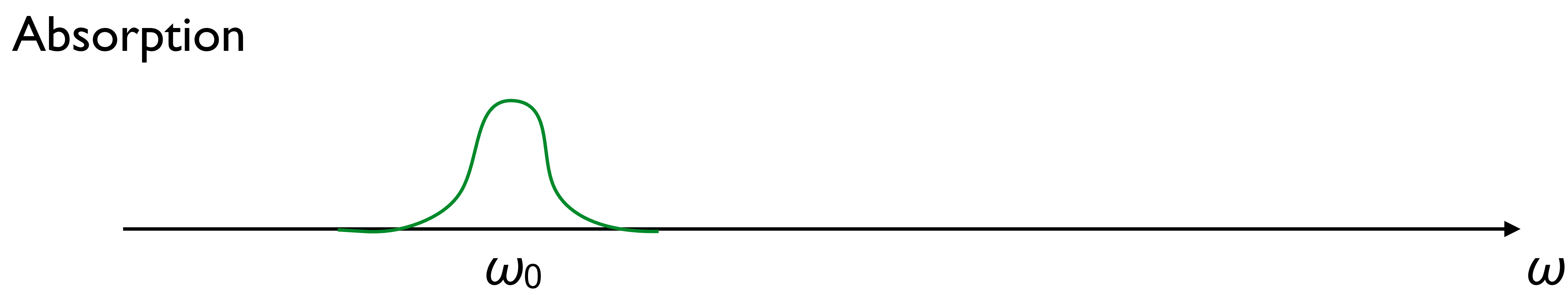

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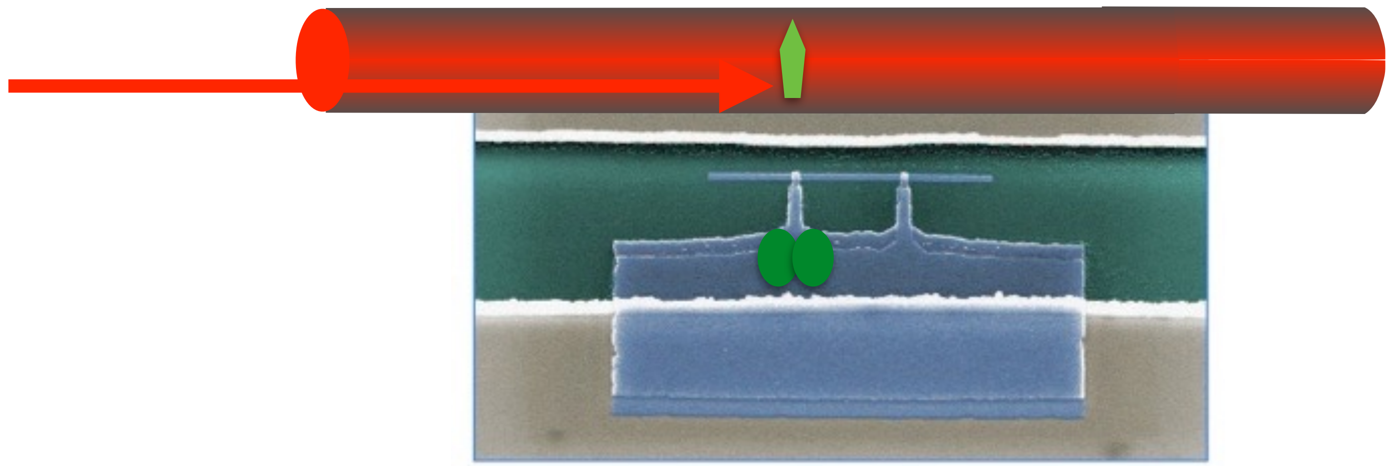
Can in principle give "strong coupling"

Coupling molecules and qubits



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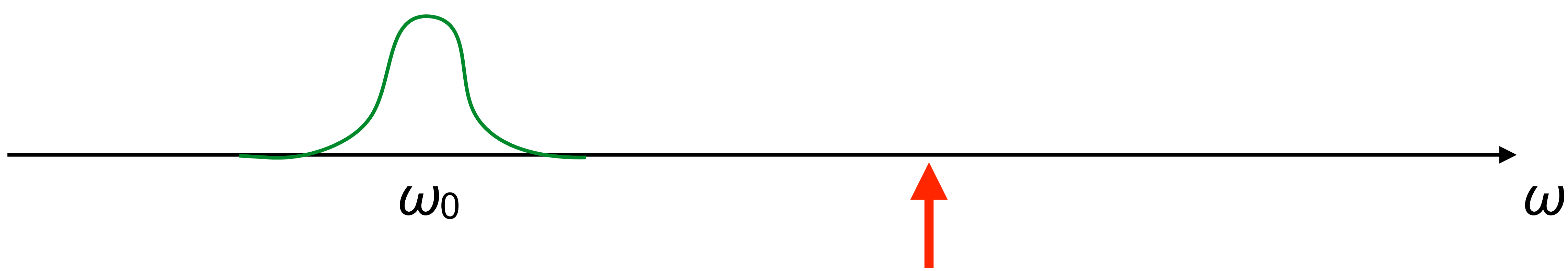

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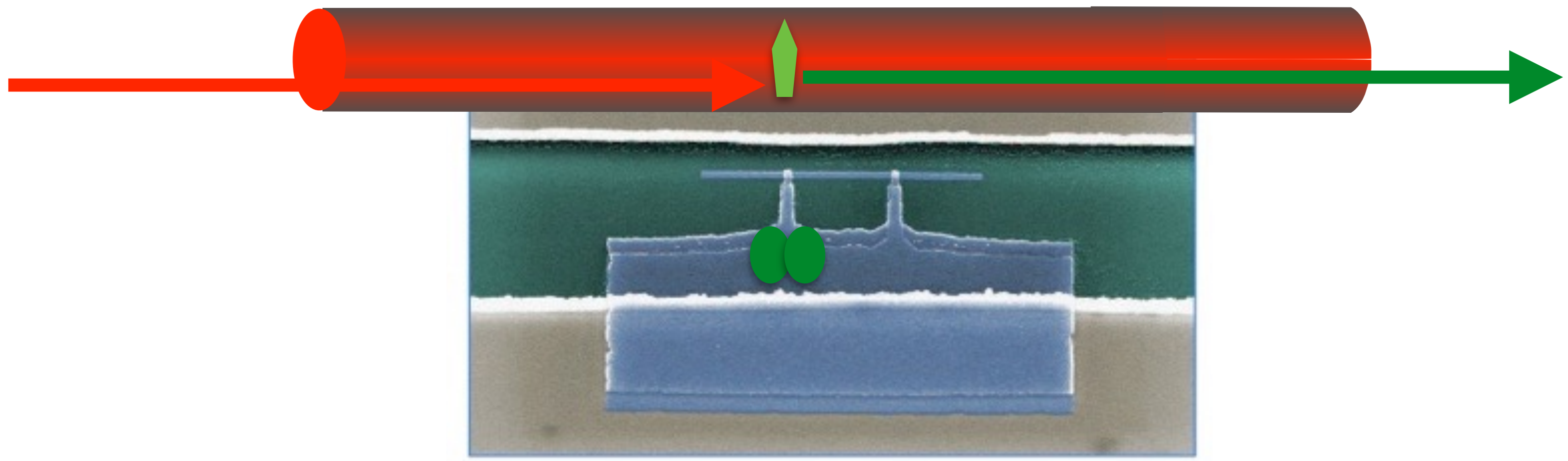

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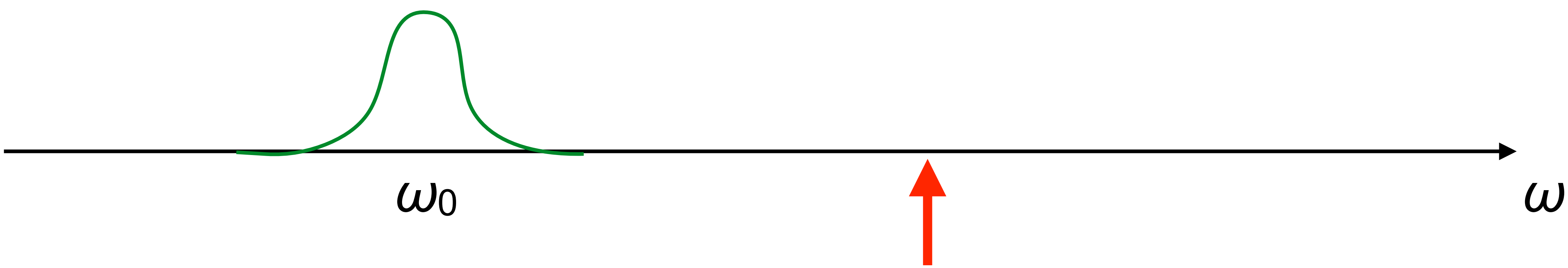

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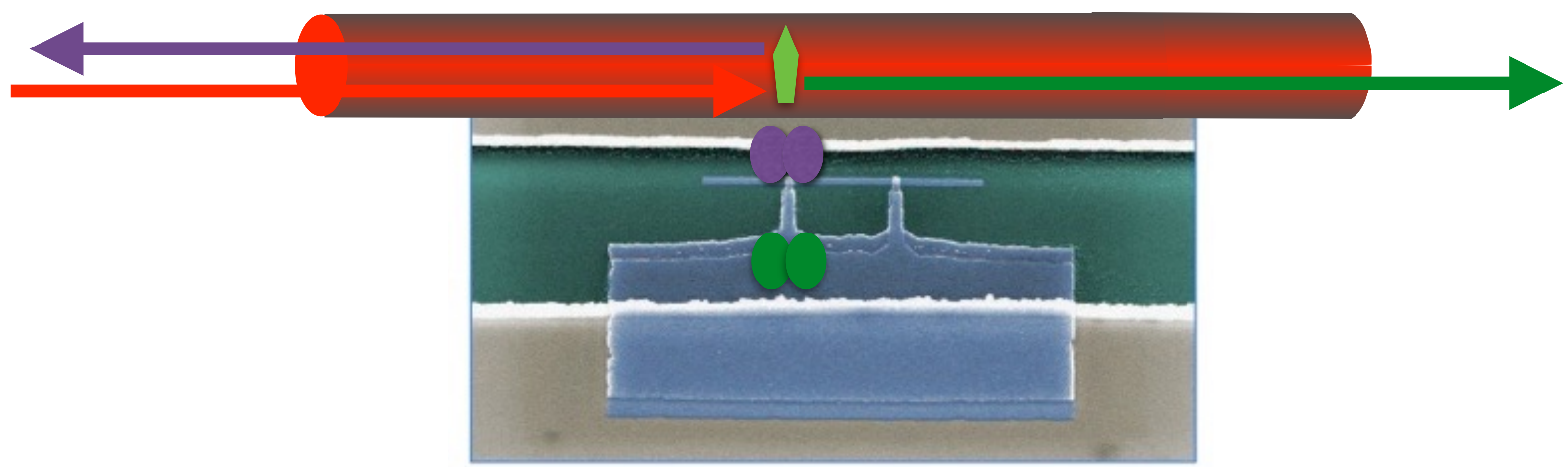

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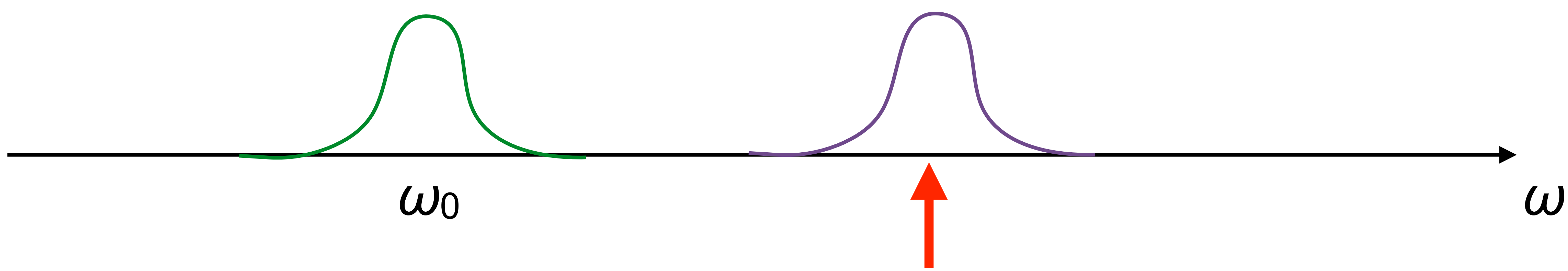

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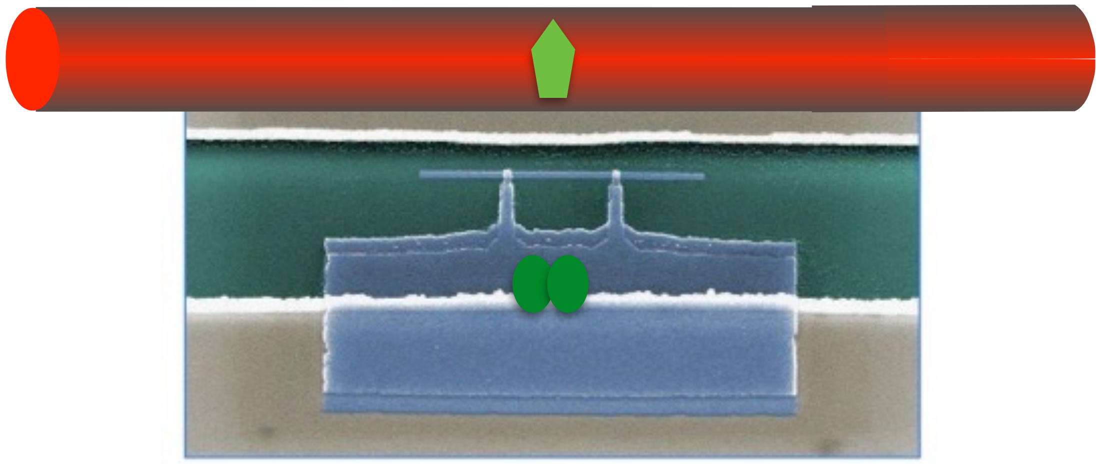
Problem



$|1\rangle$ Cooper pair on island

$|0\rangle$ No Cooper pair on island

=> Charge qubit

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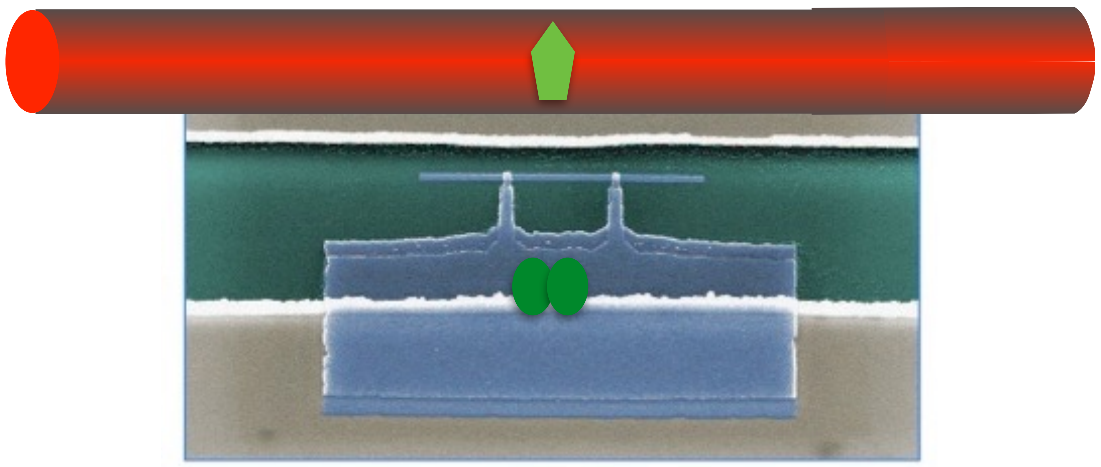

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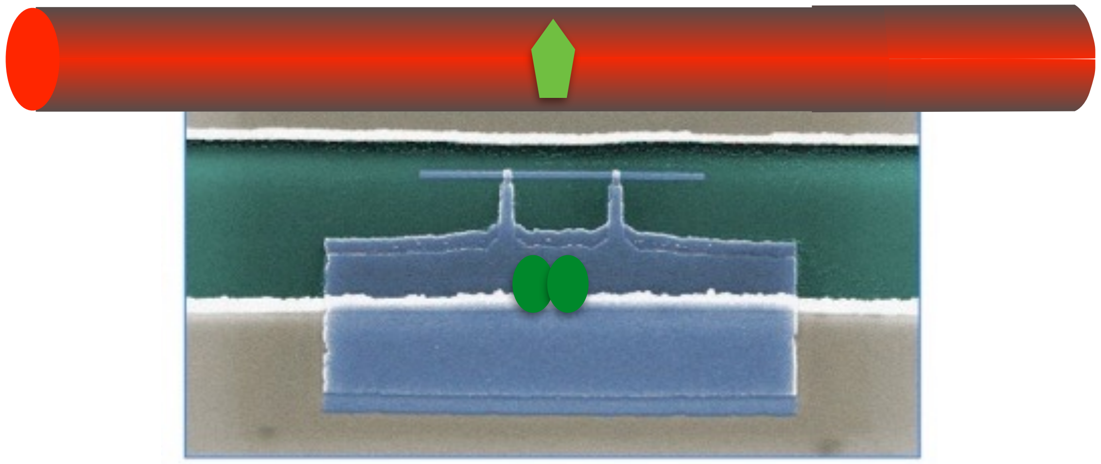
=> Charge qubit

Qubit couple to molecular dipole

Problem



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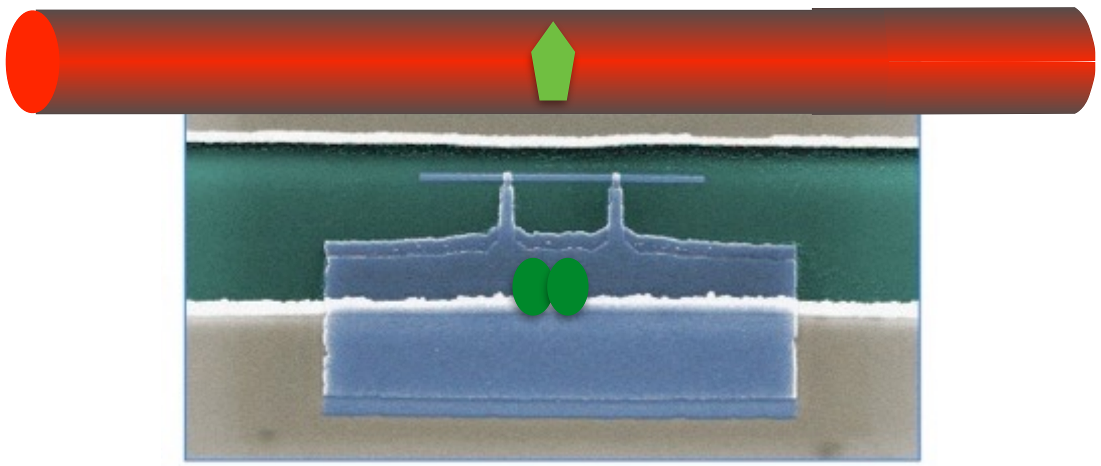
=> Charge qubit

Qubit couple to molecular dipole and all other dipoles

Problem



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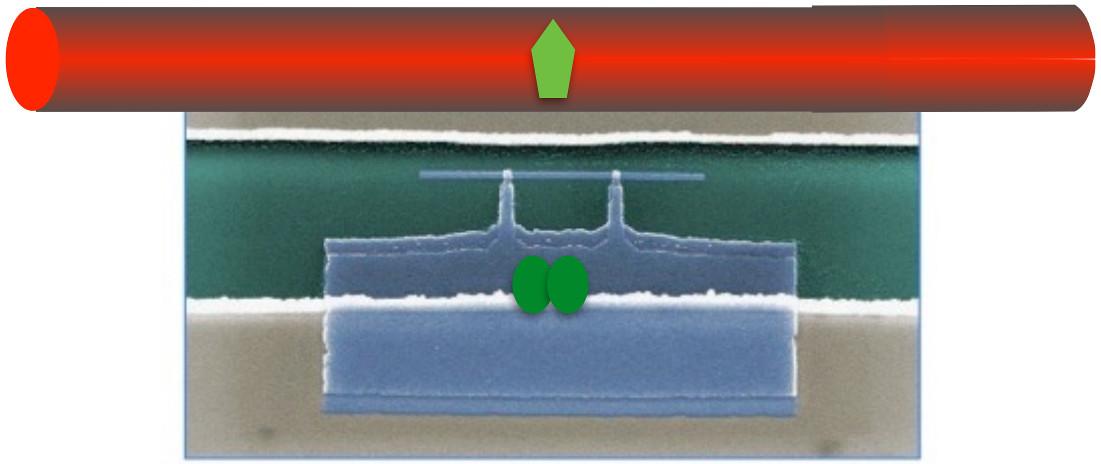
=> Charge qubit

Qubit couple to molecular dipole and all other dipoles = charge noise

Problem



$|1\rangle$ Cooper pair on island

$|0\rangle$ No Cooper pair on island

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Noise suppressed by going to degeneracy $E_0 = E_1$

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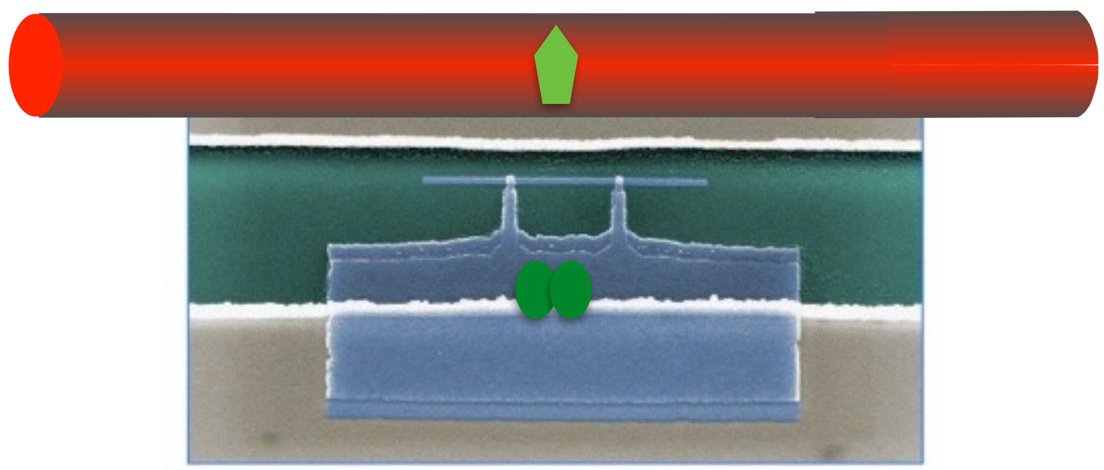

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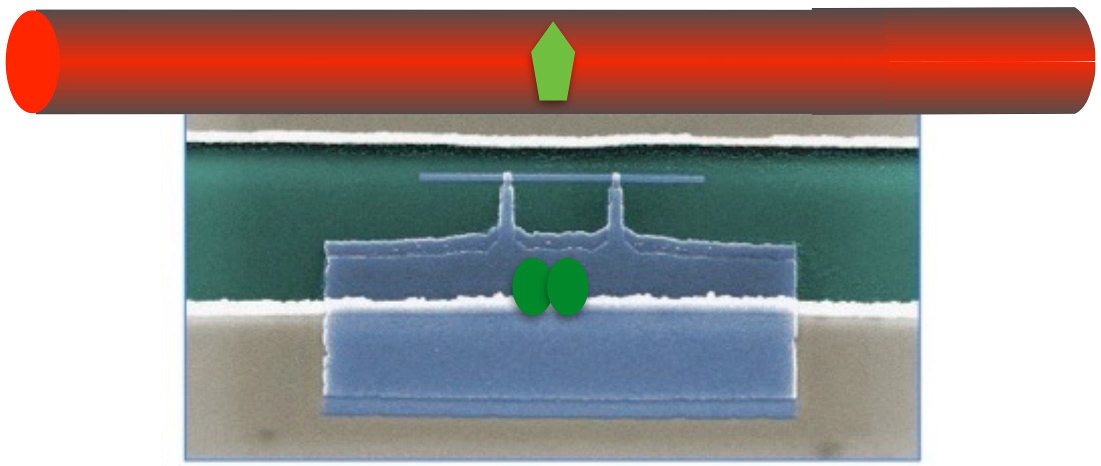

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Tunnelling average out noise

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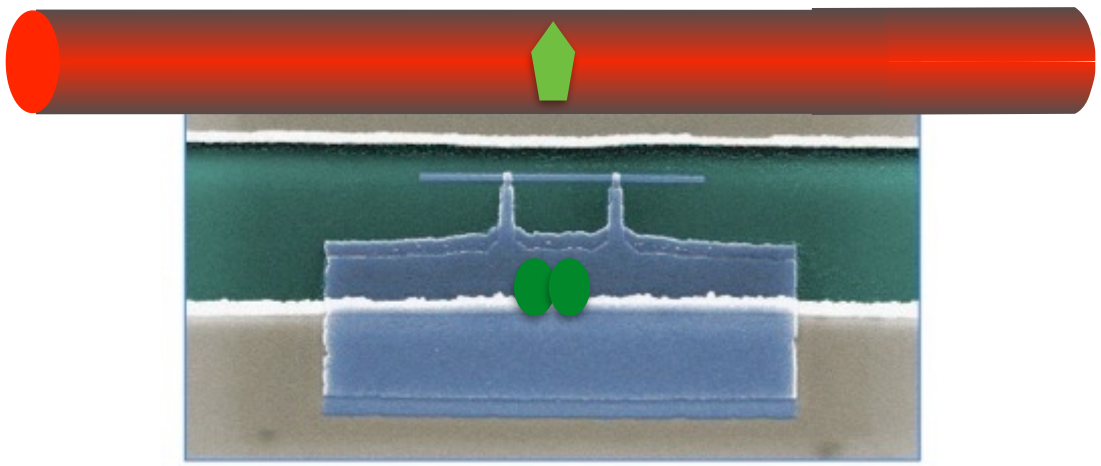

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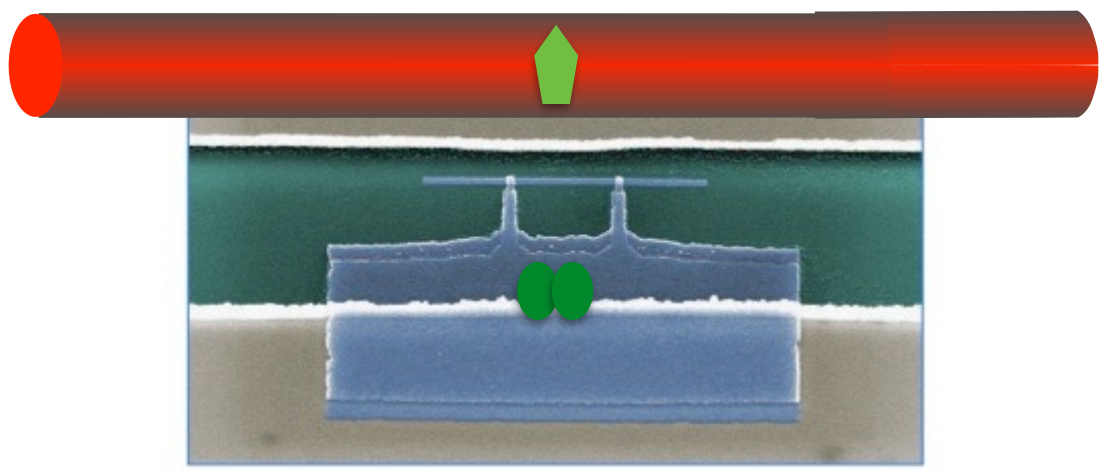

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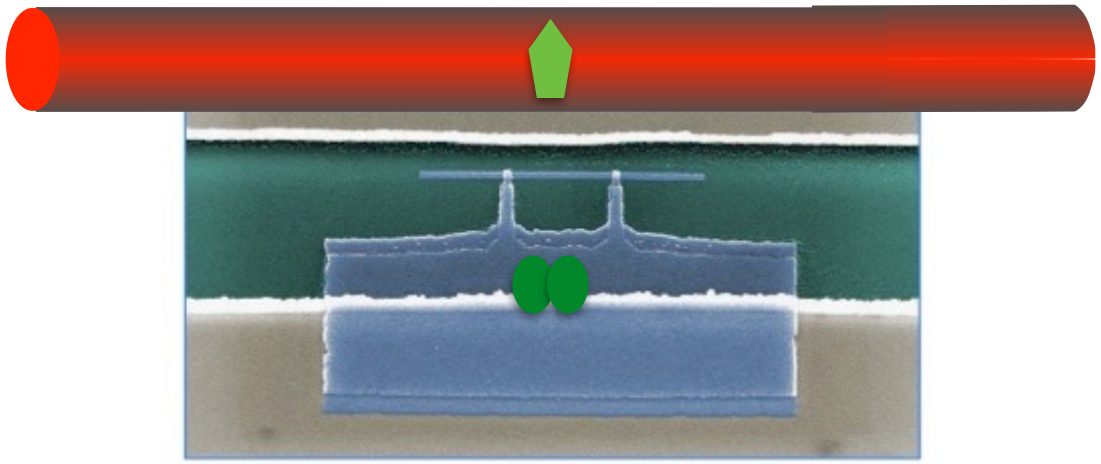
Tunnelling average out noise => coupling to dipole average out

Solution



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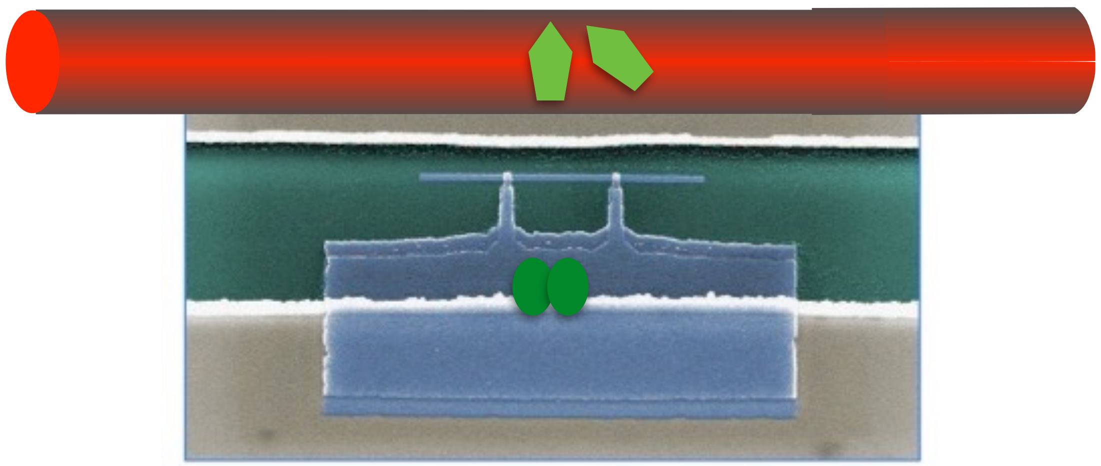

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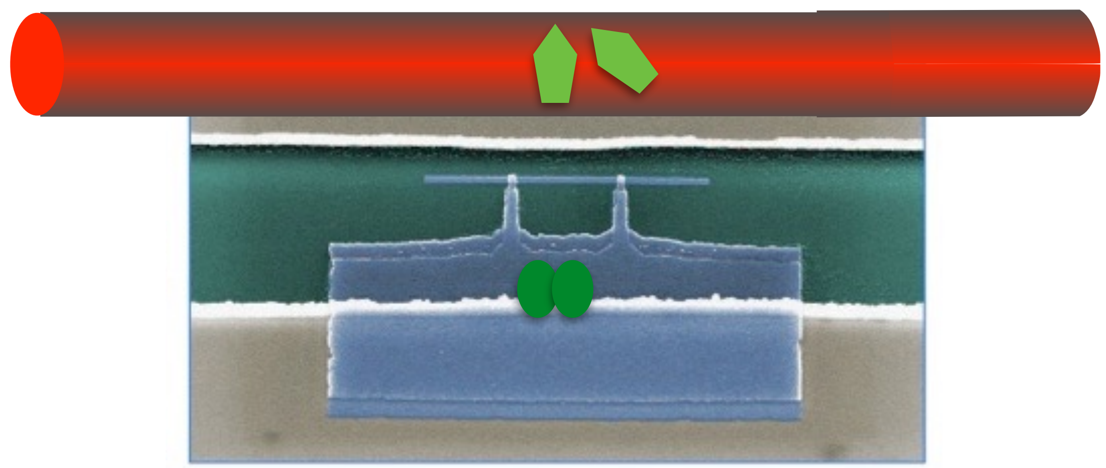

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Nearby molecules: strong (optical) dipole-dipole interaction*

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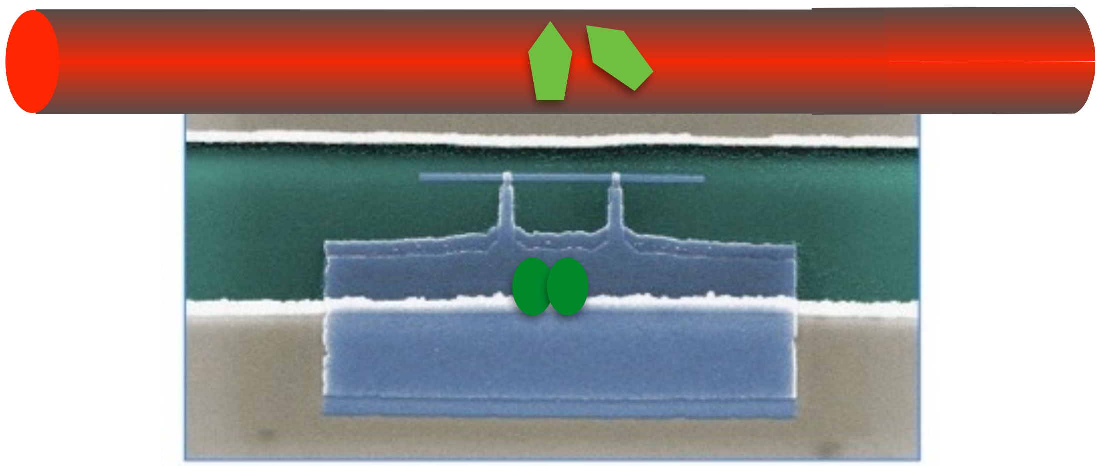

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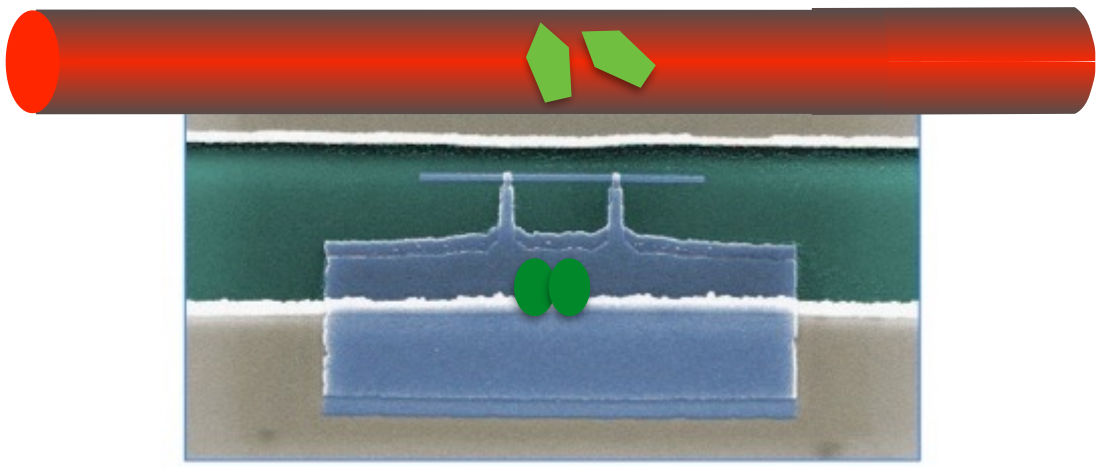

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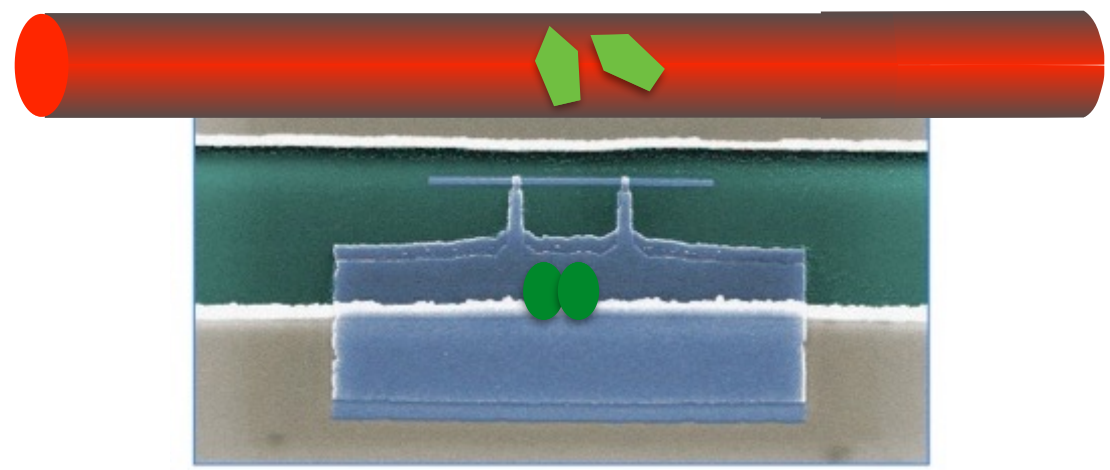

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Raman transition of coupled system

Molecule

Qubit

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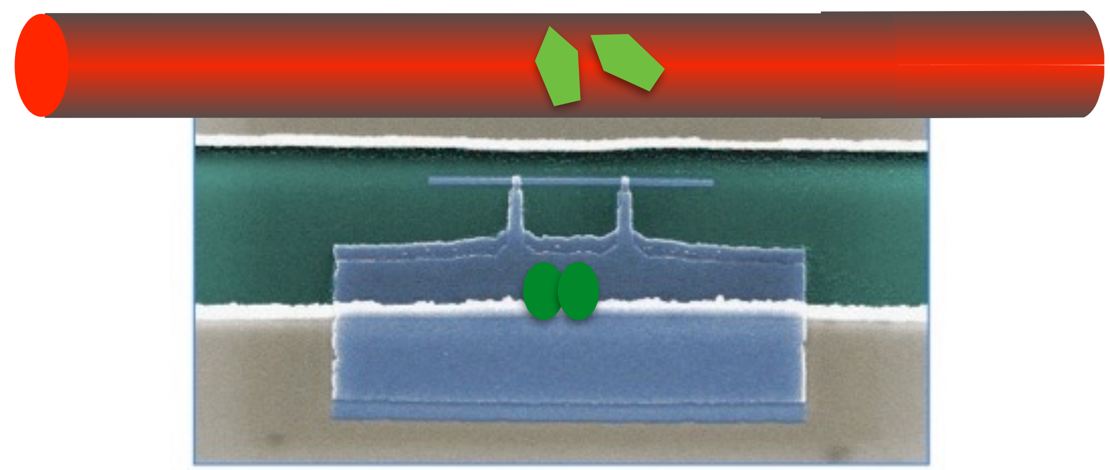

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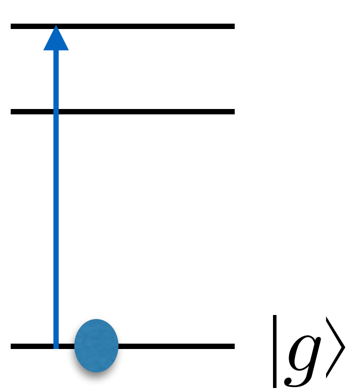

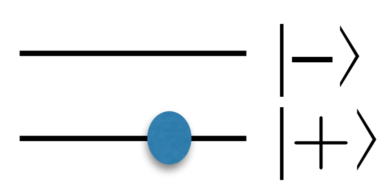

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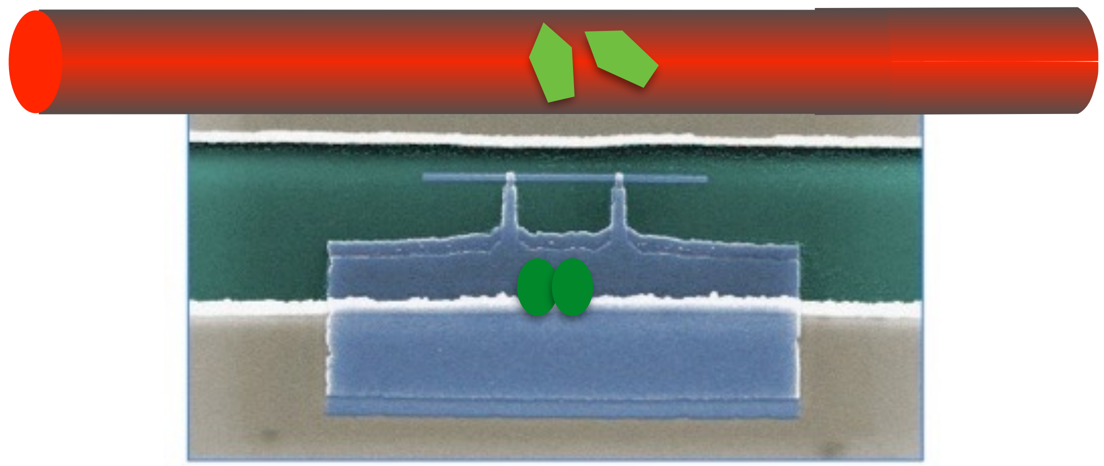

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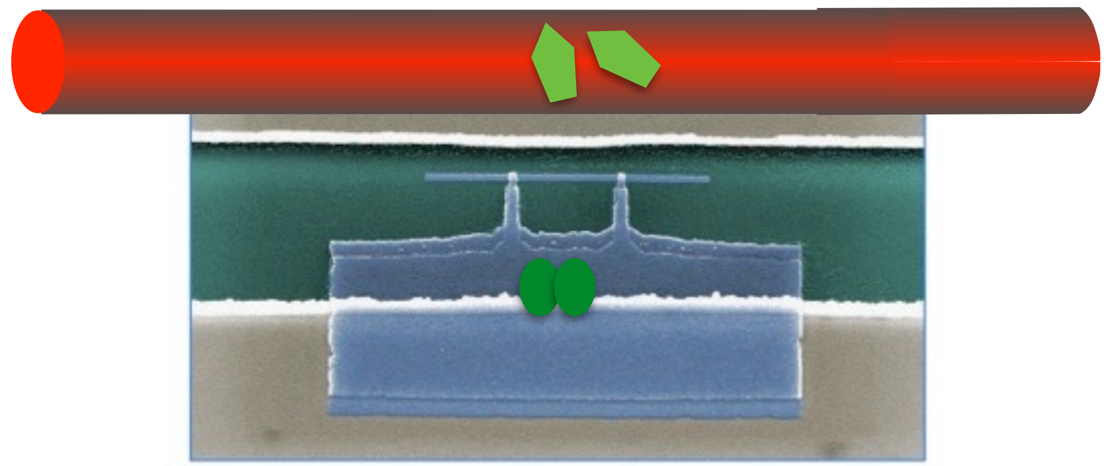

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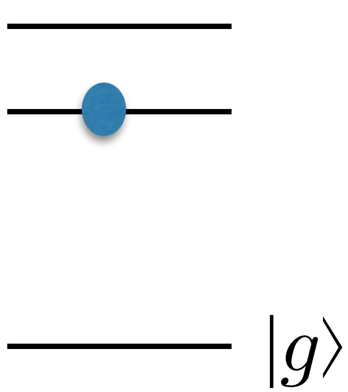
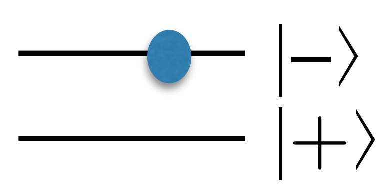
Molecule 



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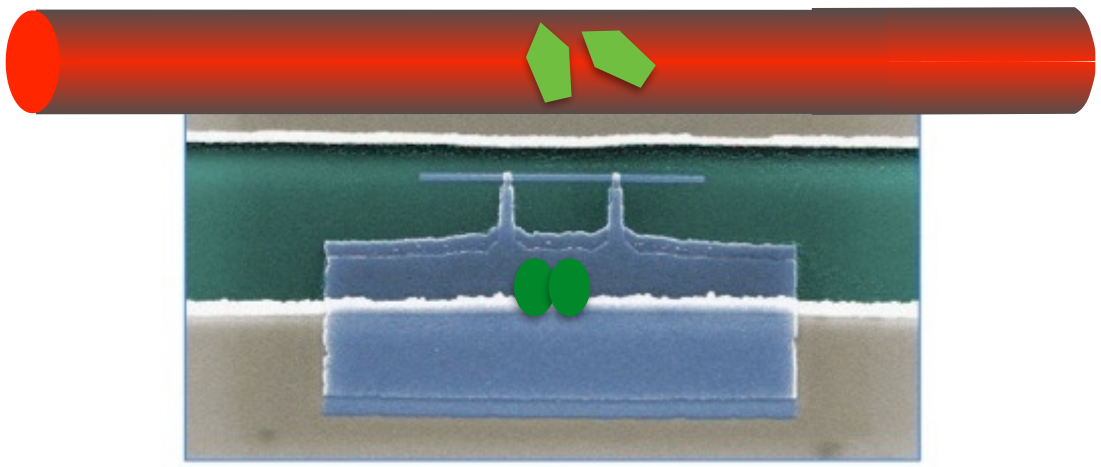

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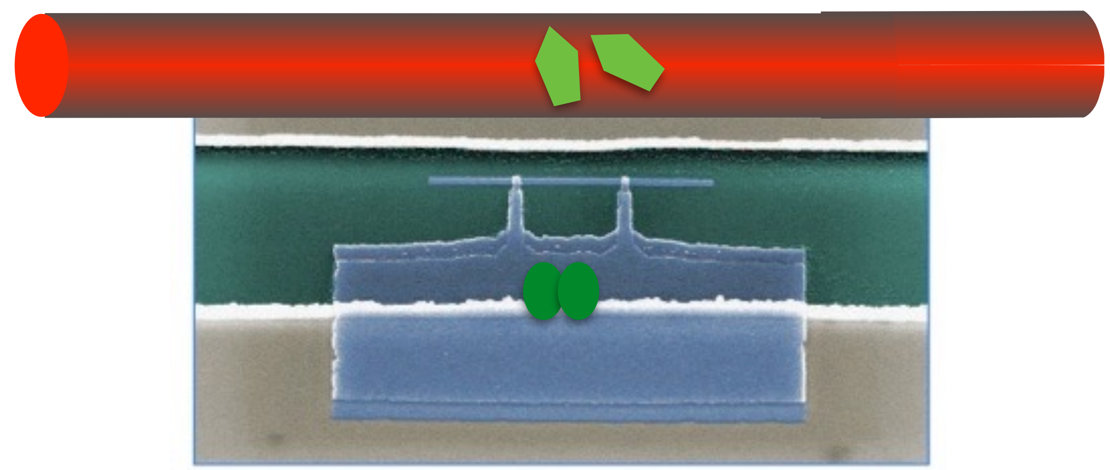

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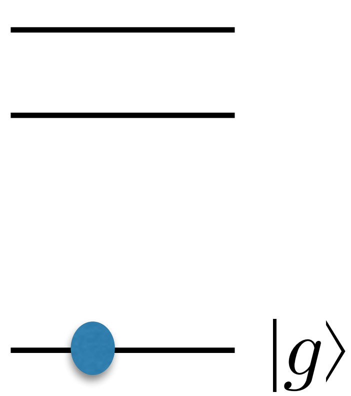

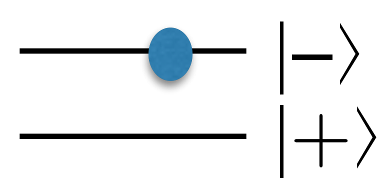

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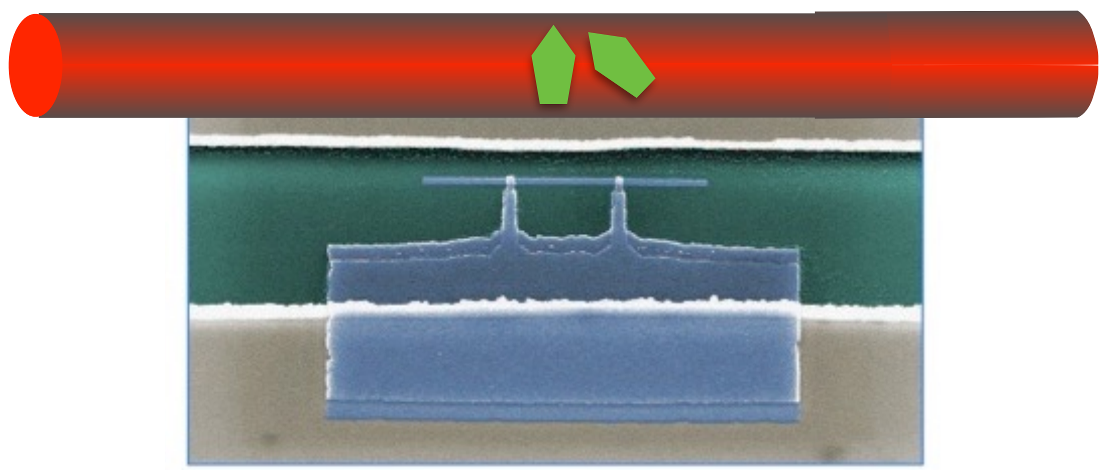
Entangling two qubits



* S. Das, S. Faez, ad AS in preparation

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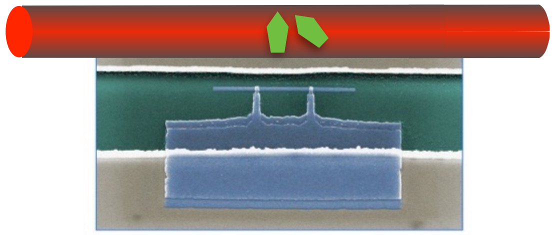

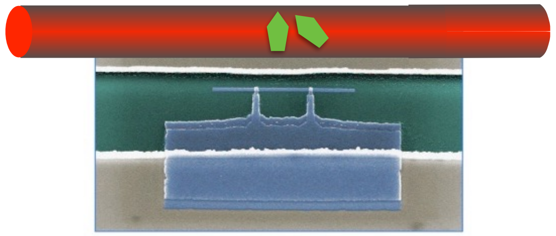

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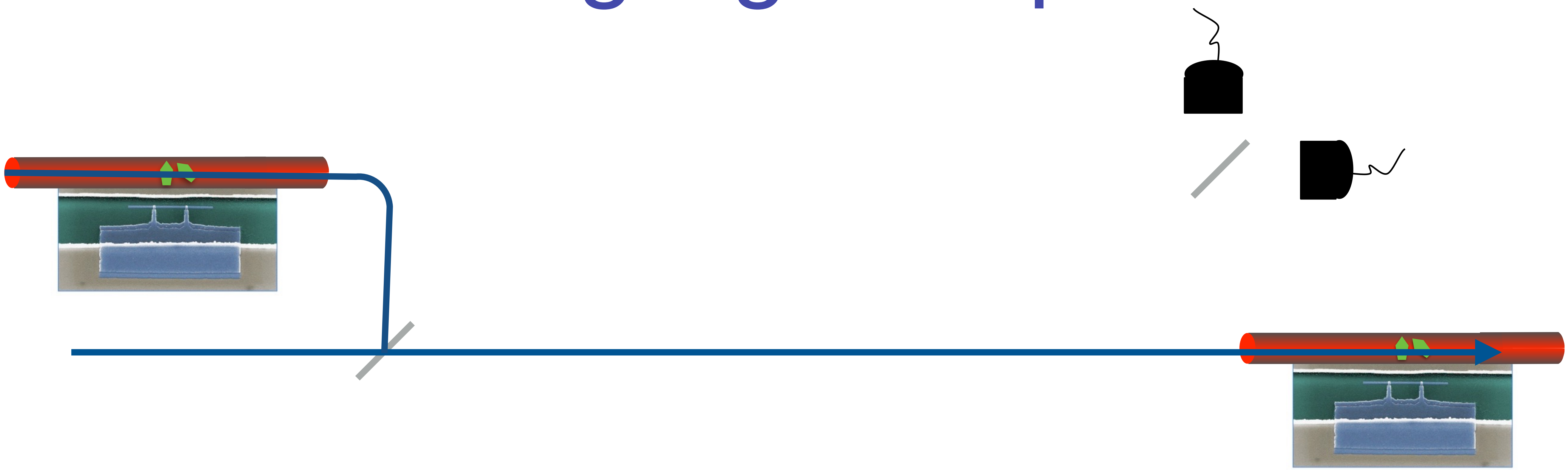

Send in blue

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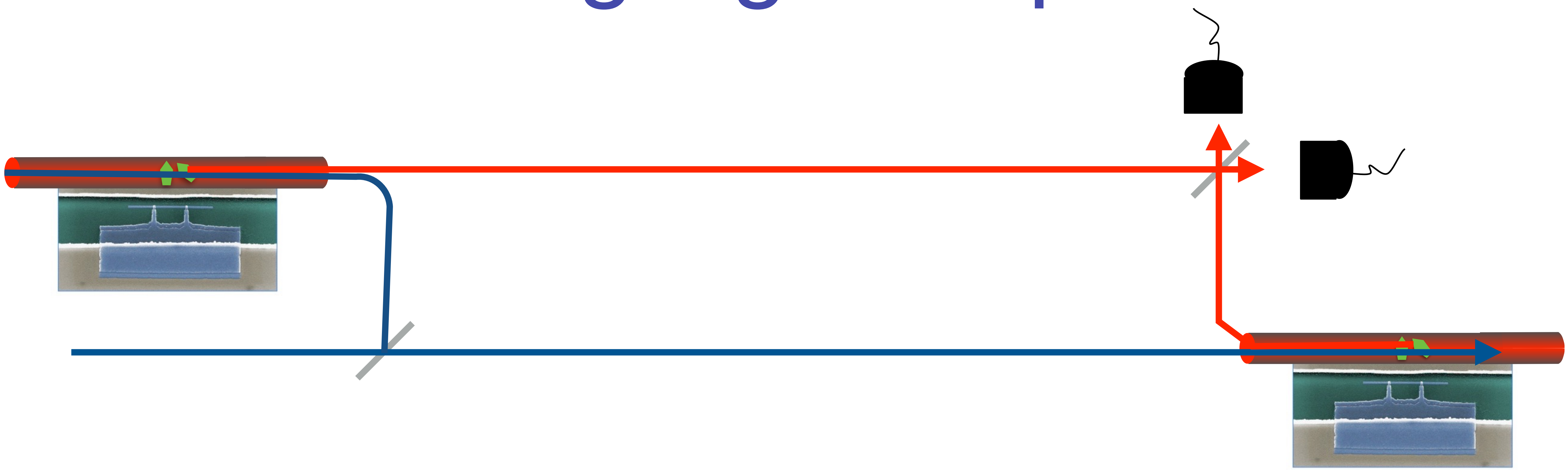

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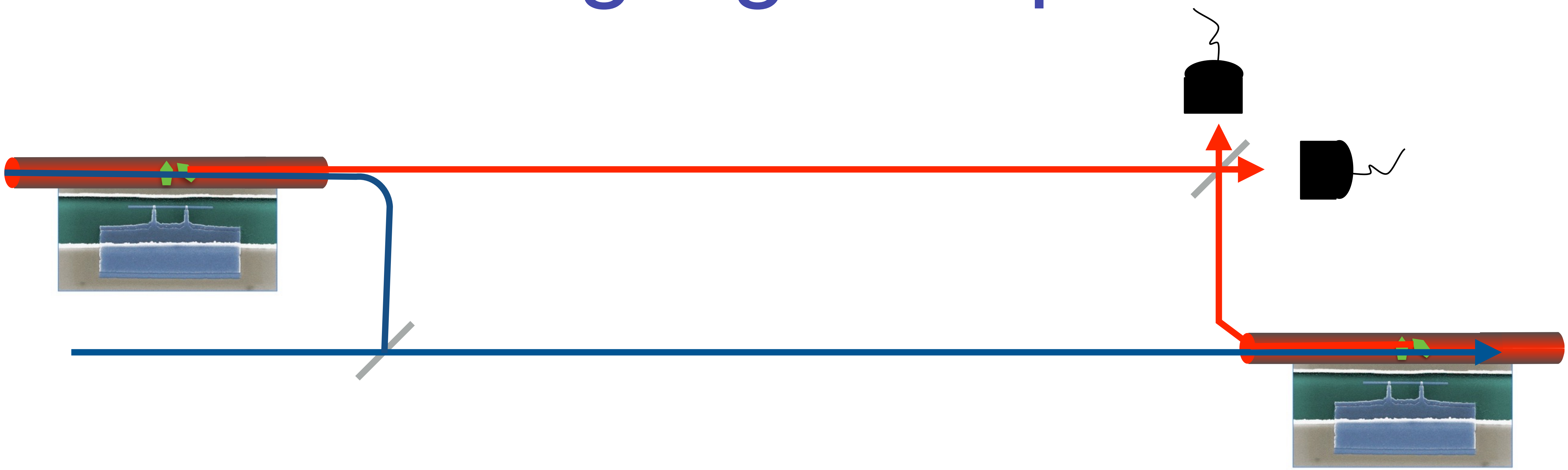

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Detect red photon => $\frac{1}{\sqrt{2}}(|+-\rangle \pm |-+\rangle)$

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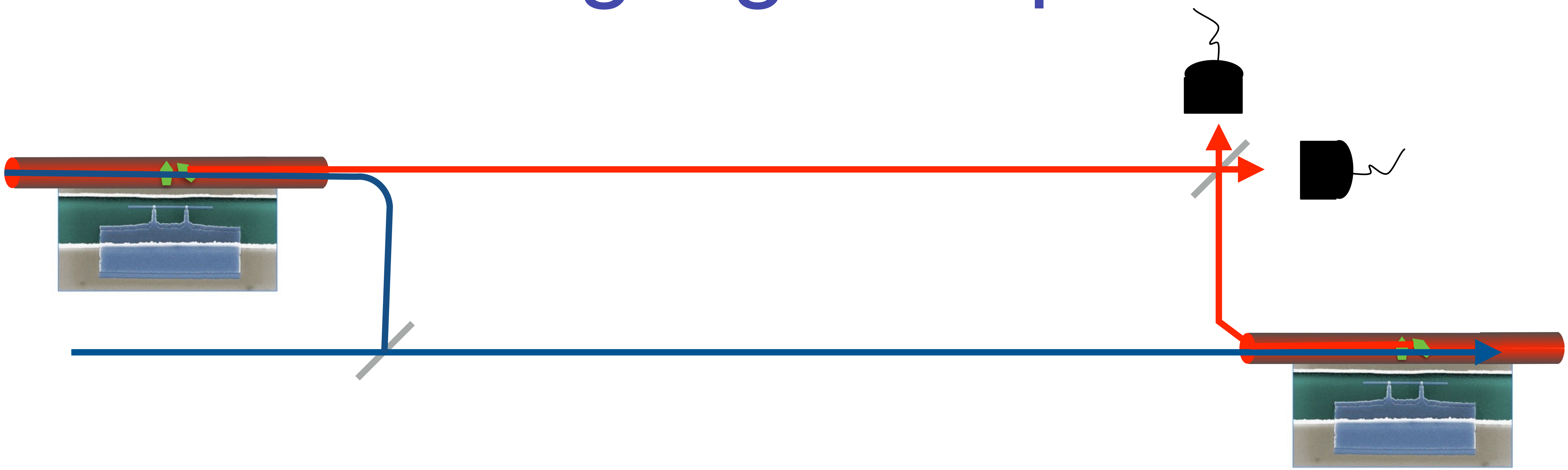

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Good coupling $\beta \gtrsim 10\%$

Qubits can be entangled by pulses containing 1-10 photons

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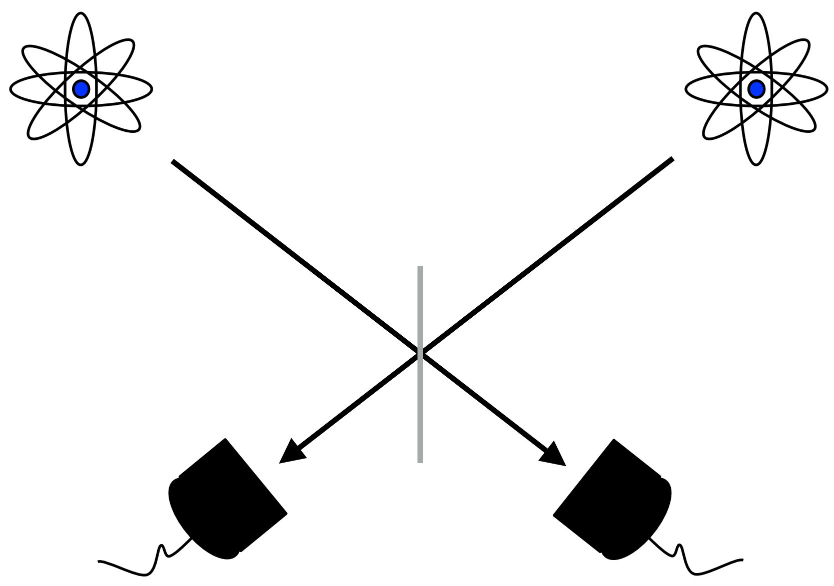
Heralded gates in optical cavities

Heralded gates

Probabilistic generation of entanglement



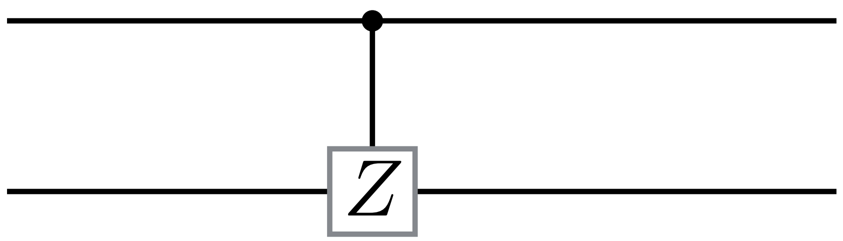
Click generate entangled state

$$\frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

$$F \approx 1, P << 1$$

Insensitive to losses

Quantum gates



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Deterministic, limited fidelity

$$1 - F \propto \frac{1}{\sqrt{C}}$$

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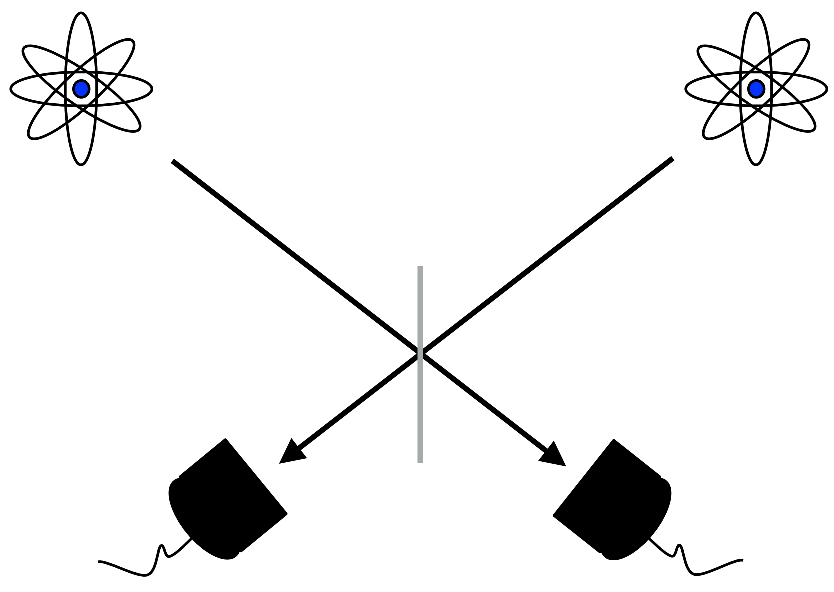

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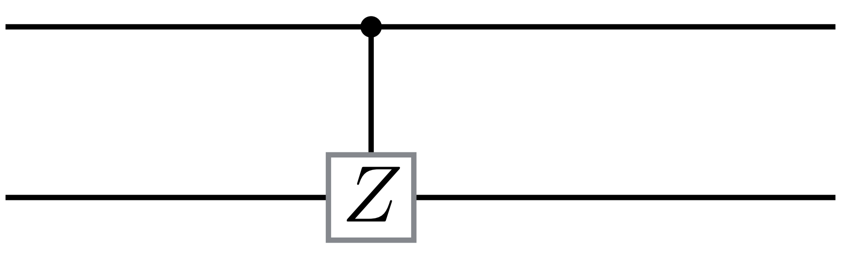

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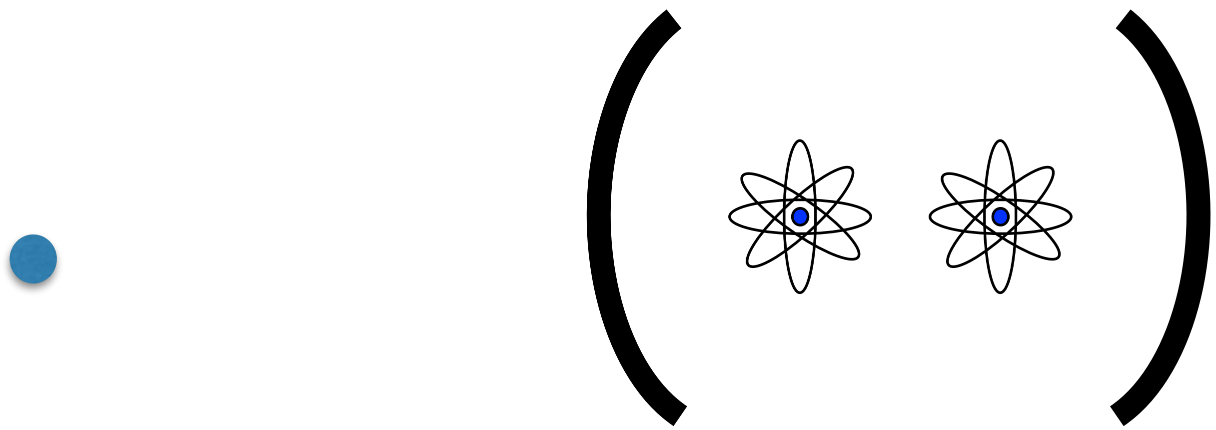
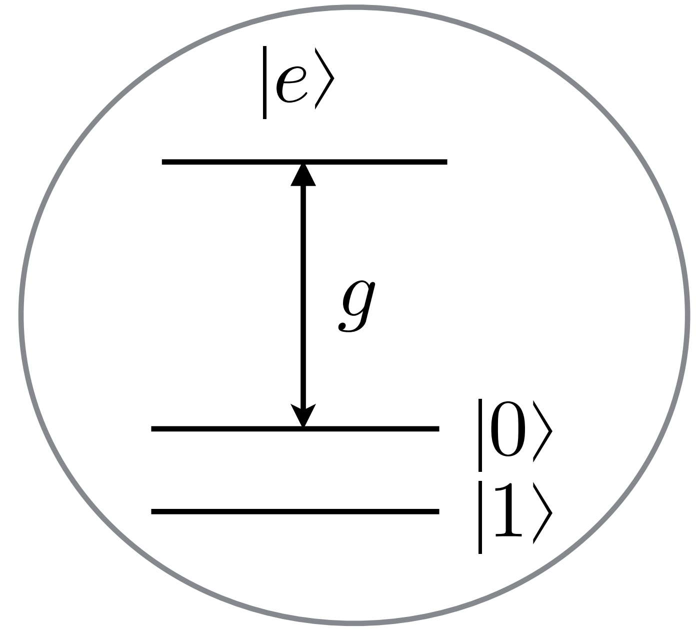
$\boxed{\text{Heralded gates: } F \approx 1, P < 1 \text{ ?}}$

Scattering gates

One sided cavity:





Scatter resonant photon off cavity

Atoms in $|0\rangle$ block cavity

Photon only enters cavity if atoms are $|11\rangle$

* L.-M. Duan, B. Wang, and H. J. Kimble, Phys. Rev. A **72**, 032333 (2005)

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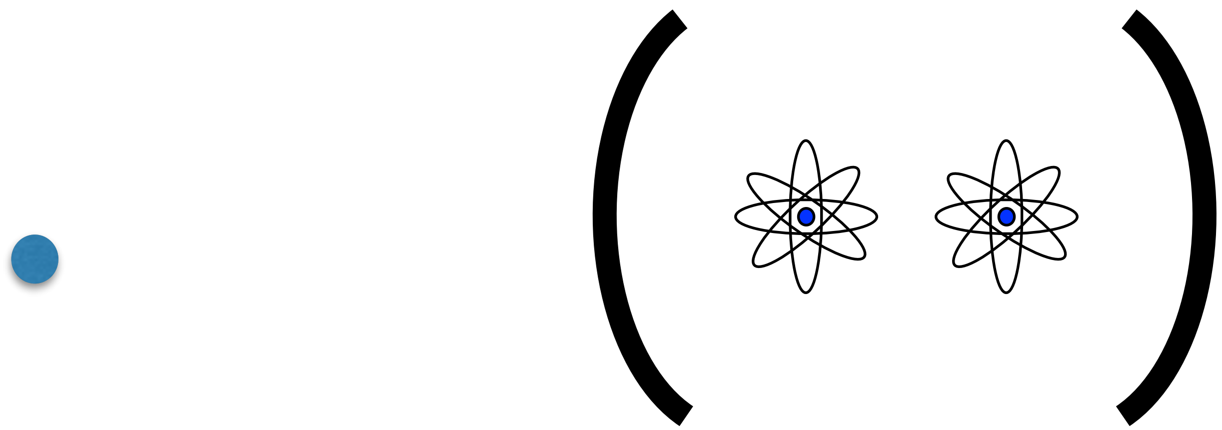

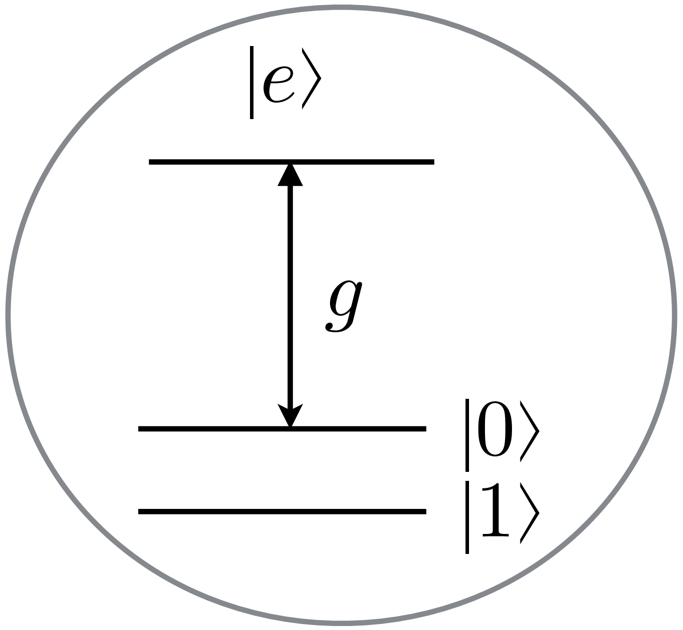

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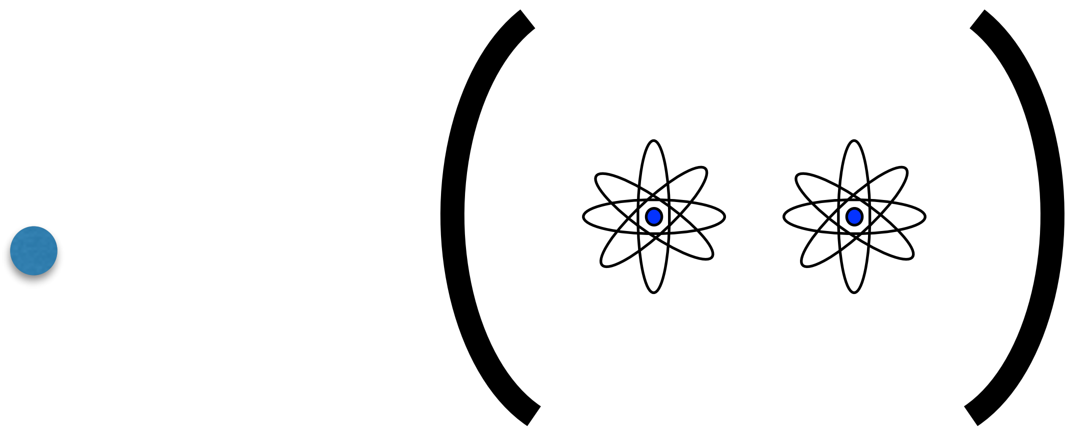

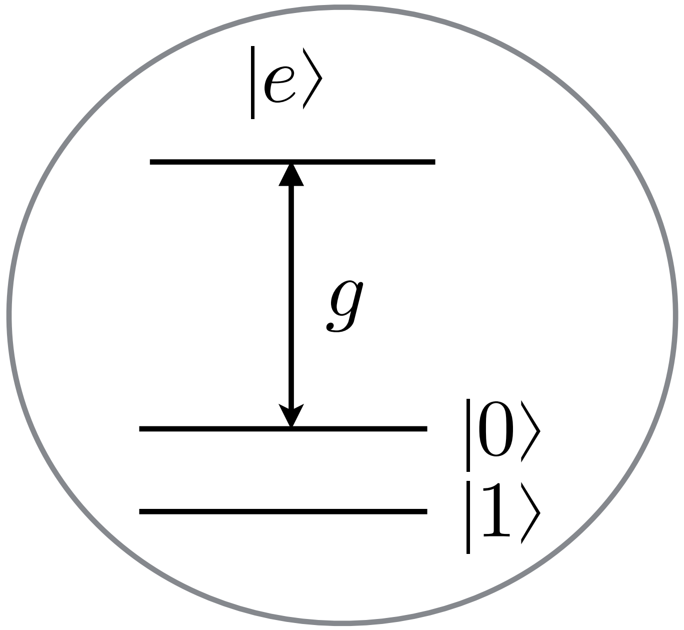

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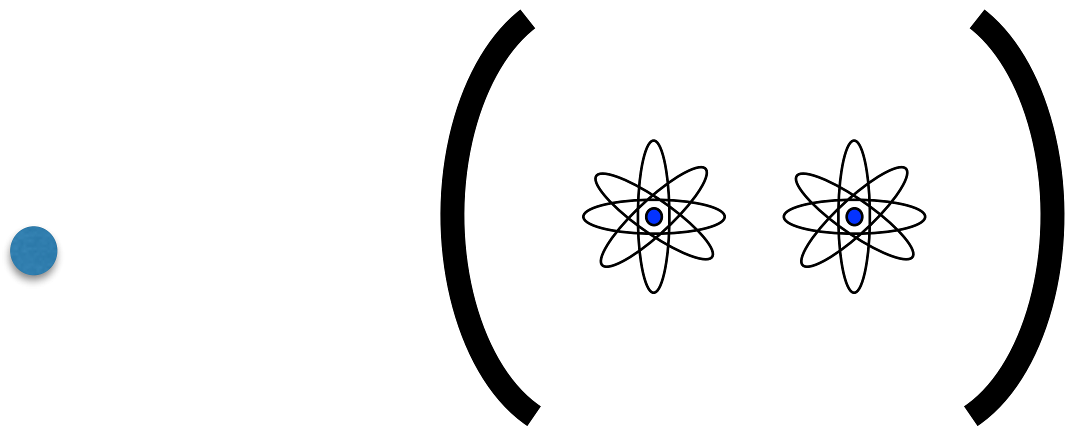

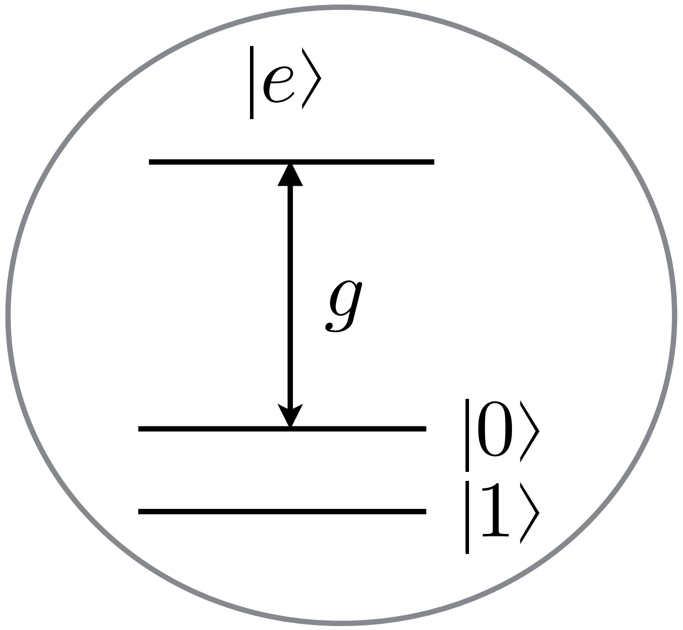

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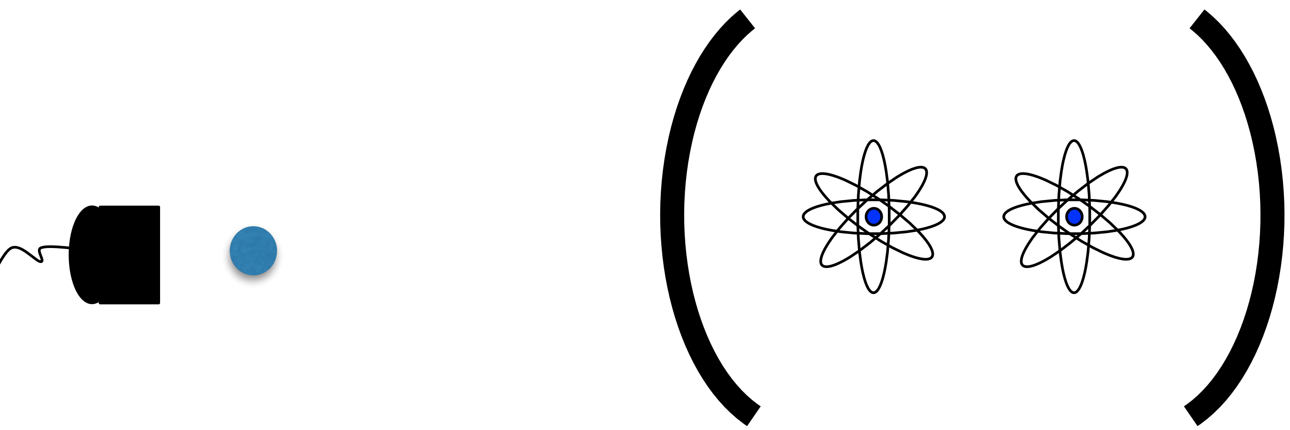

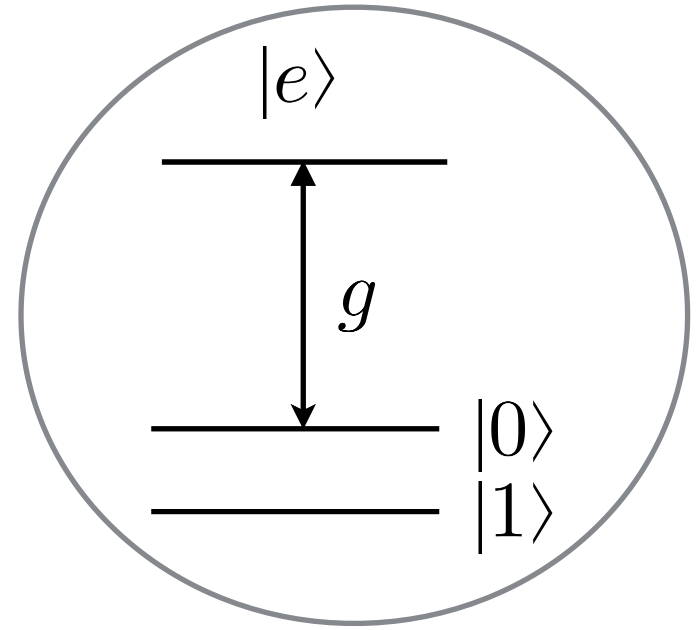

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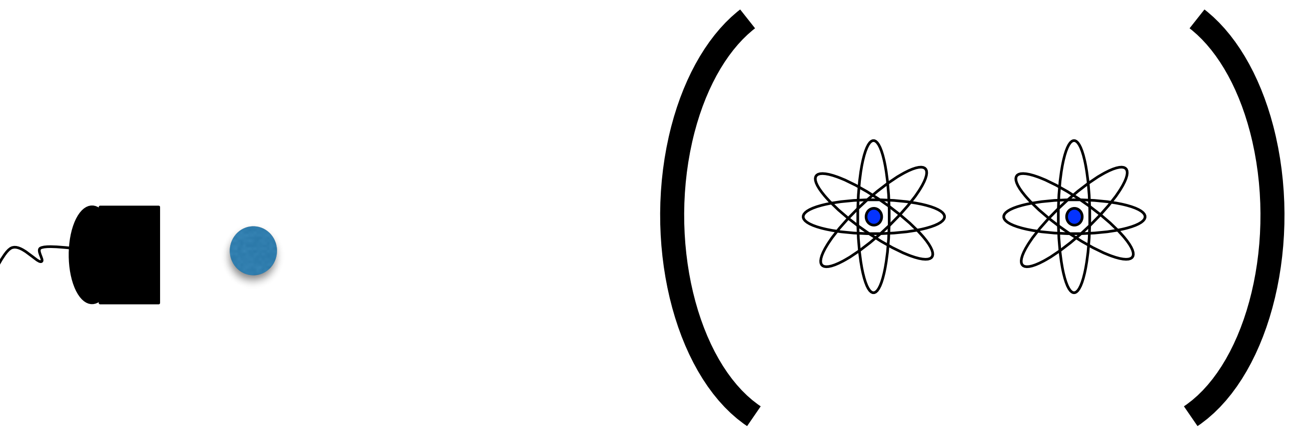

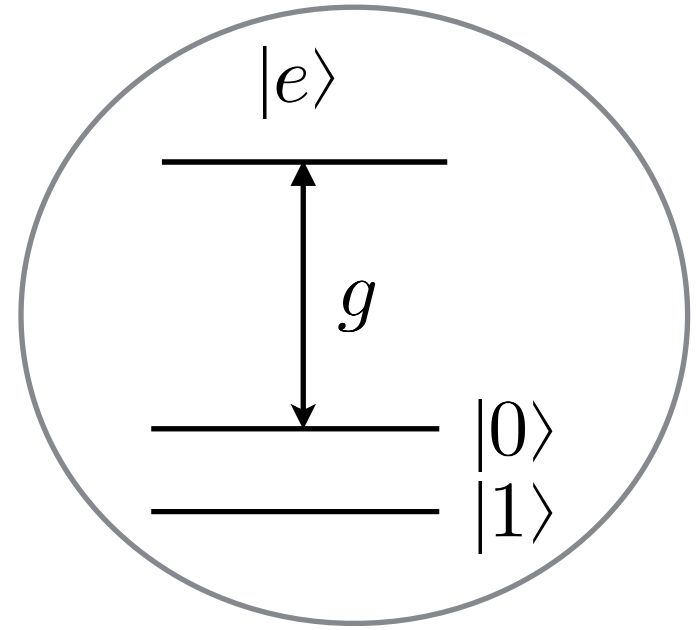

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Detect photon leaving cavity => high fidelity when detector clicks

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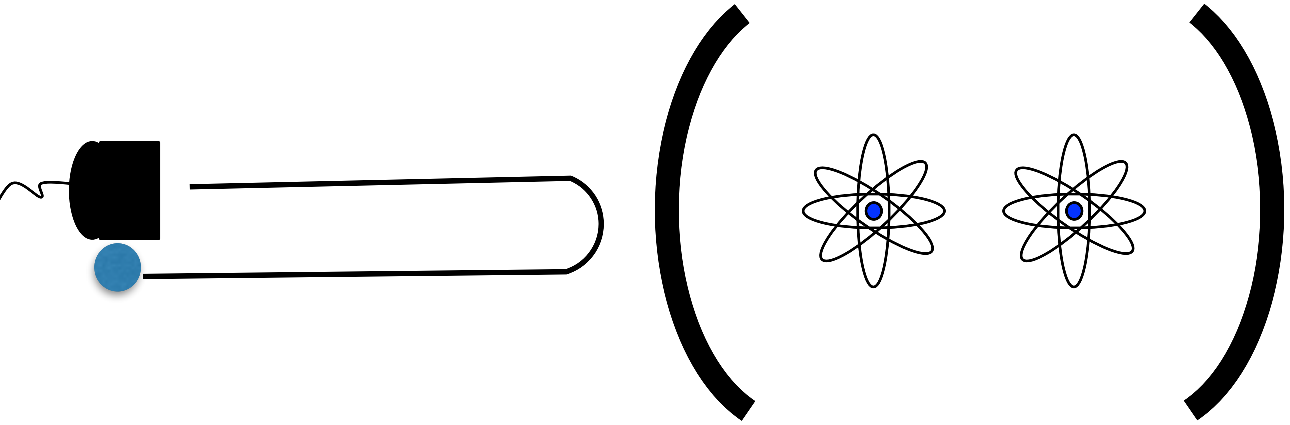
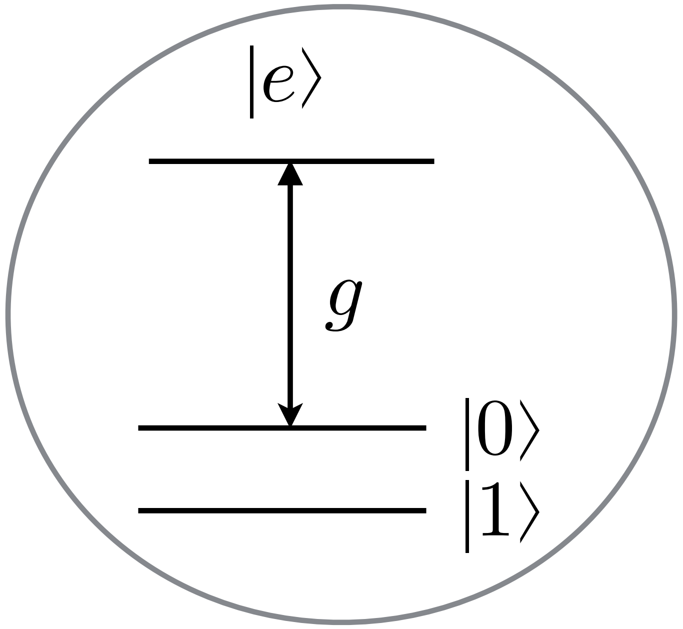
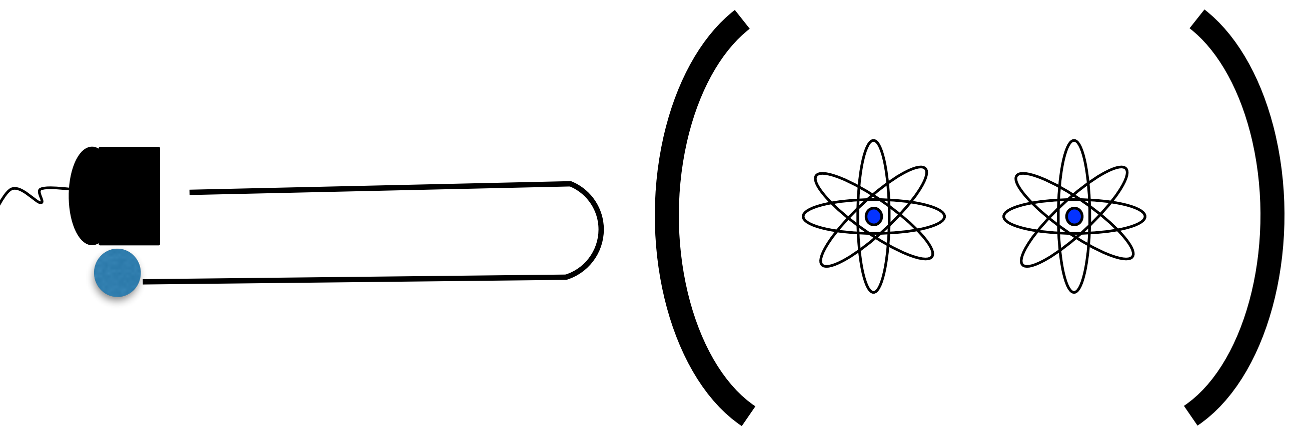
Auxiliary atom

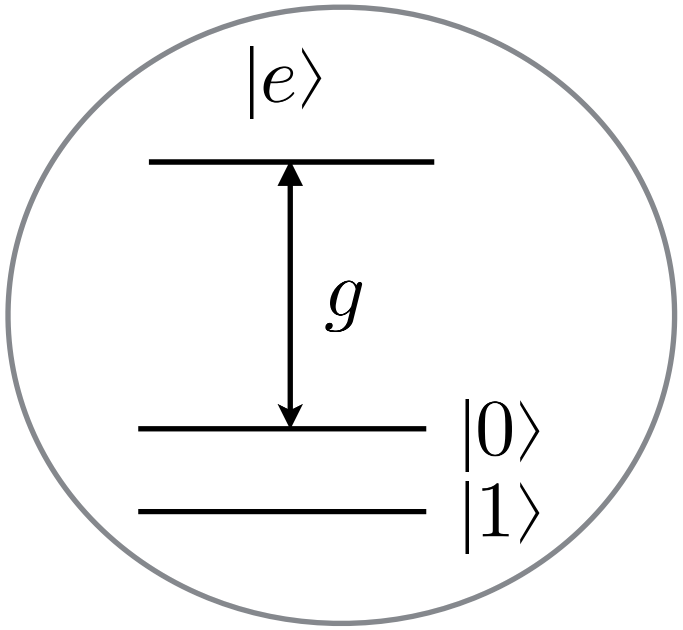




Requires: single photon source and efficient in/output, detection

Auxiliary atom





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Solution: add auxiliary atom as source and detector

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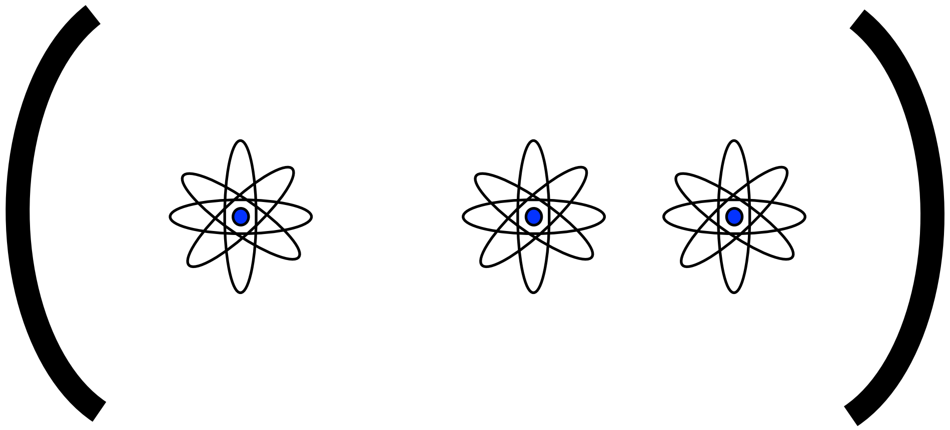

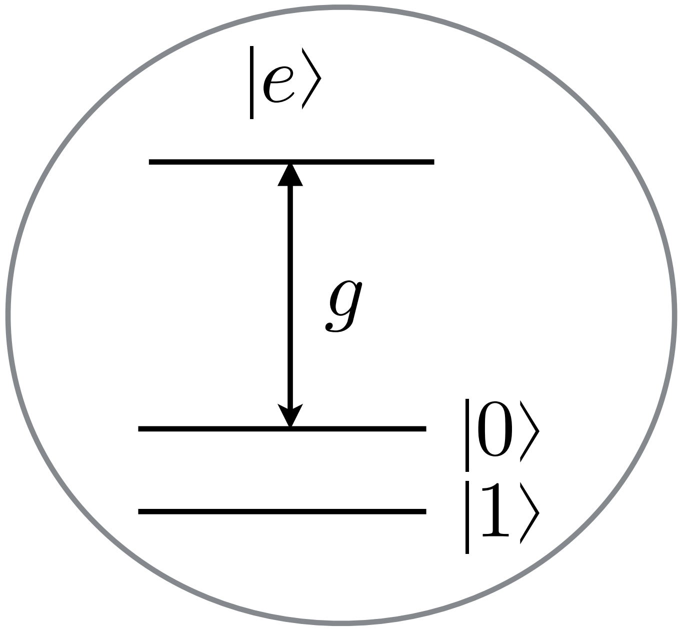

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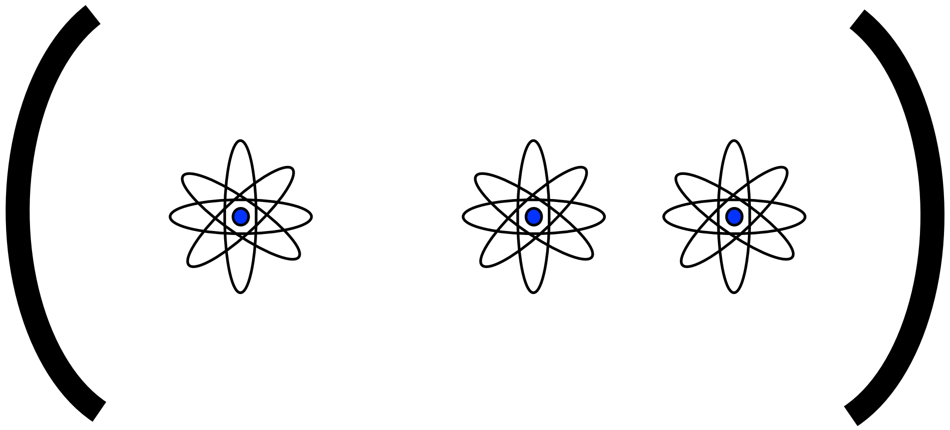

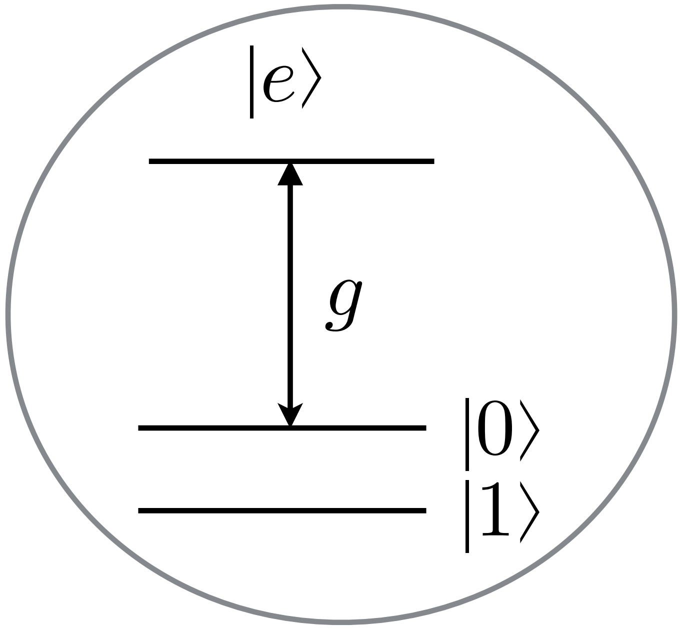

Requires: single photon source and efficient in/output, detection

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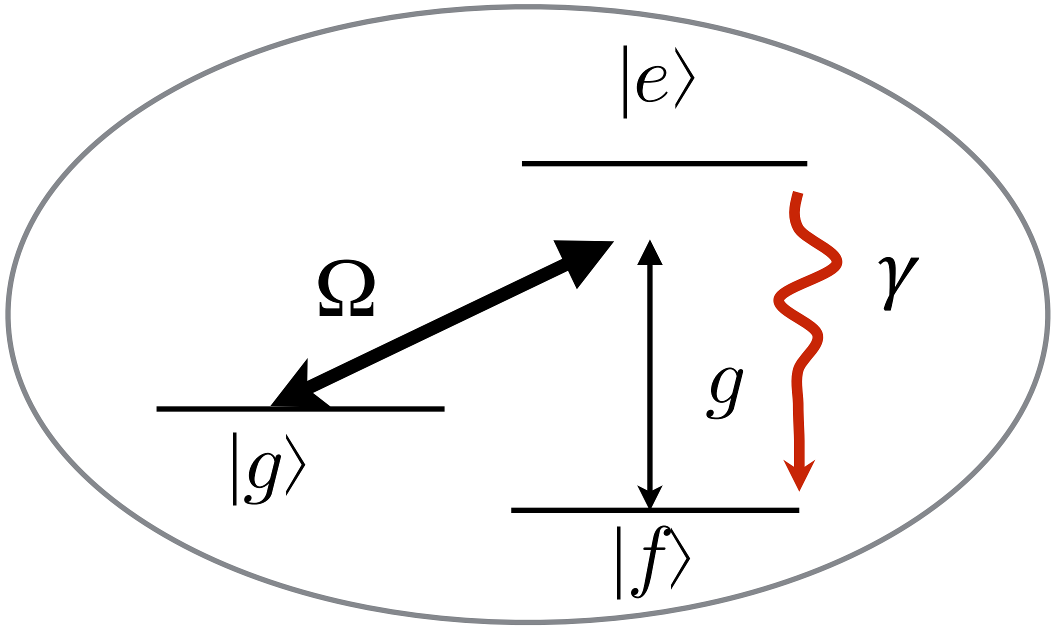

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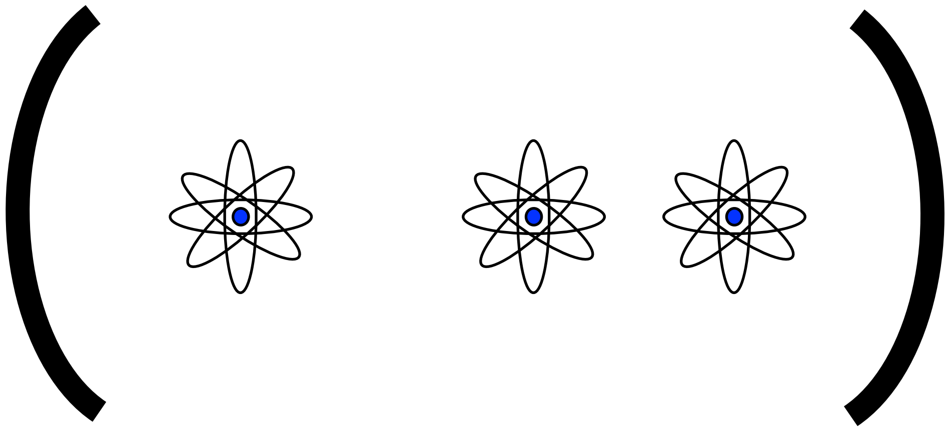

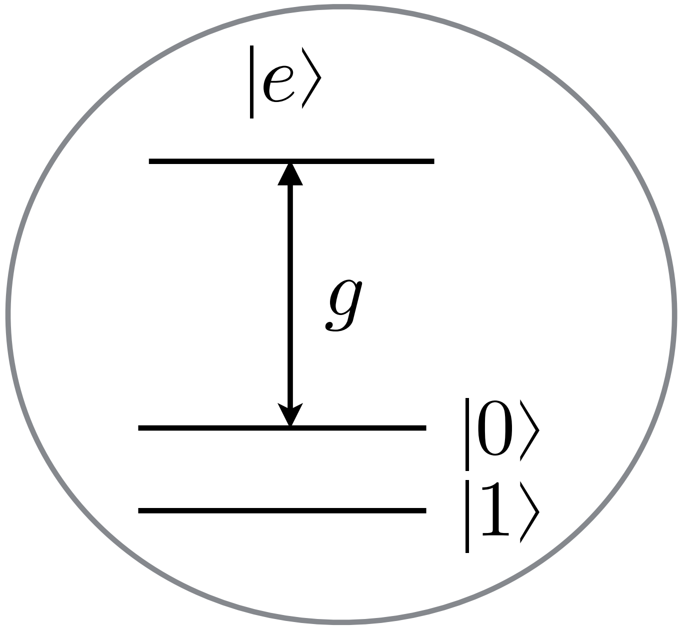

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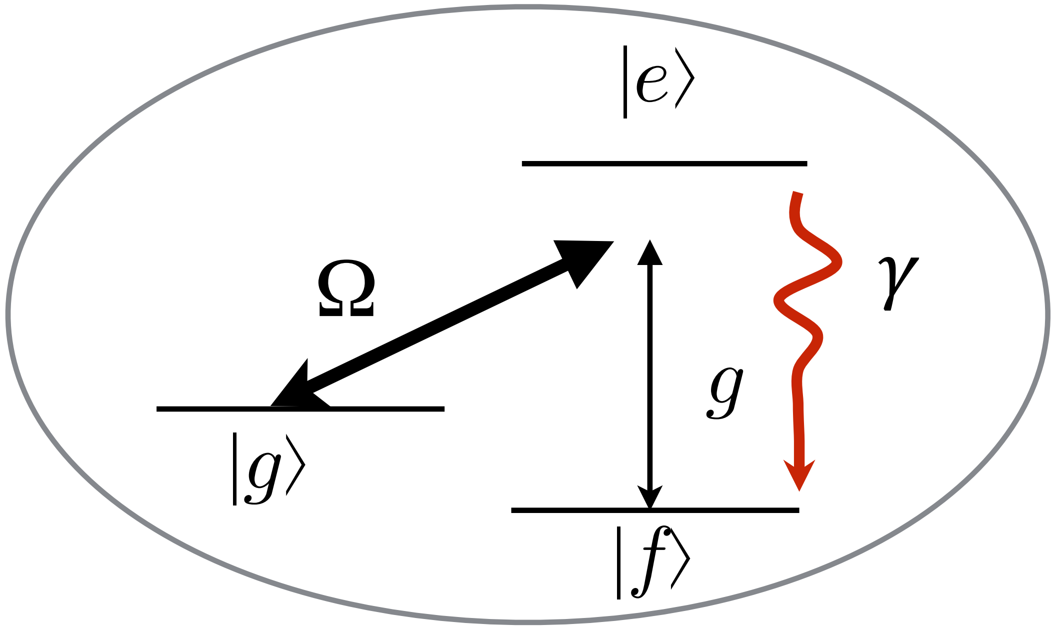

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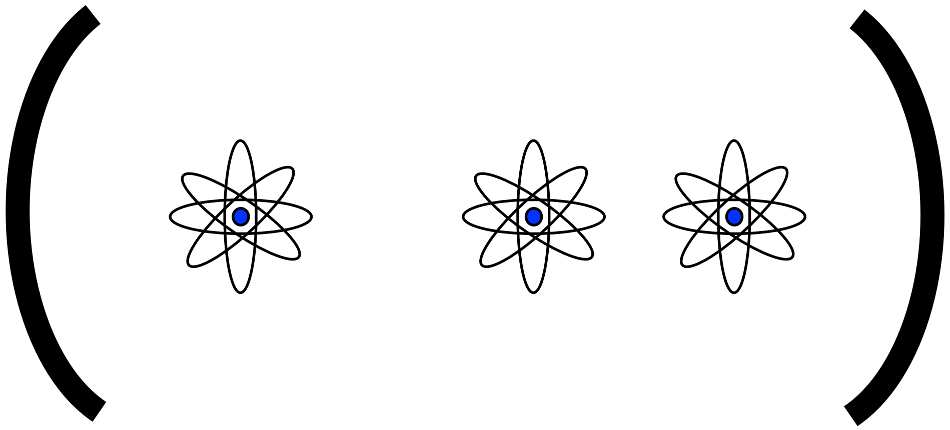

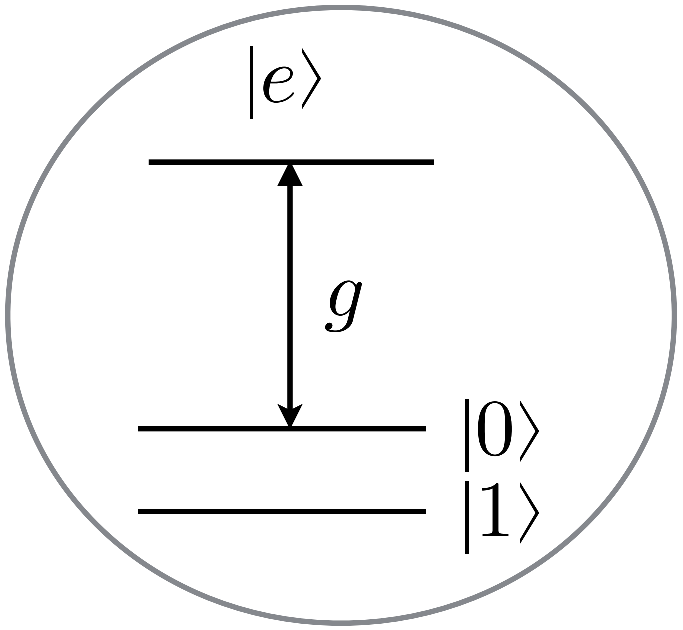

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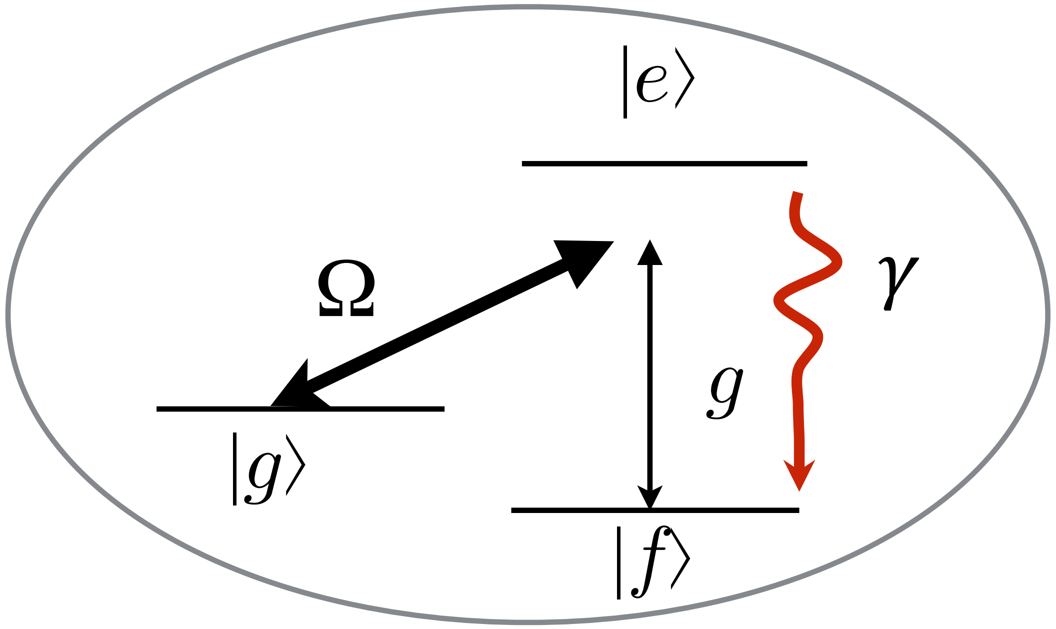

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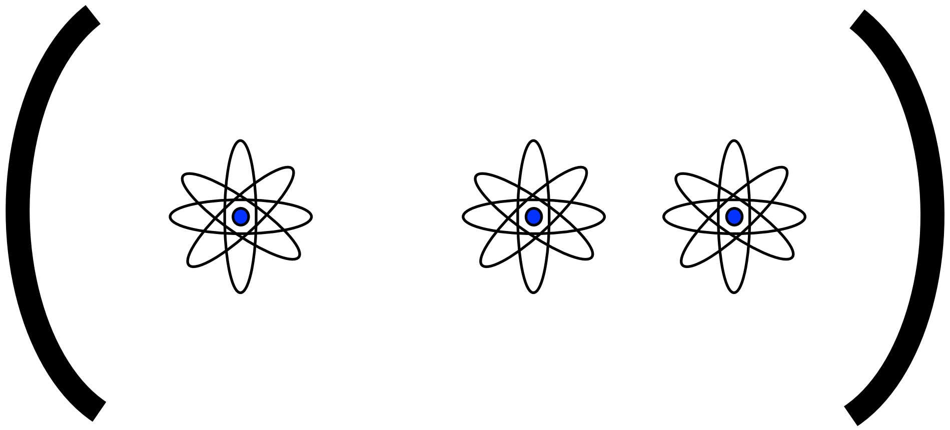

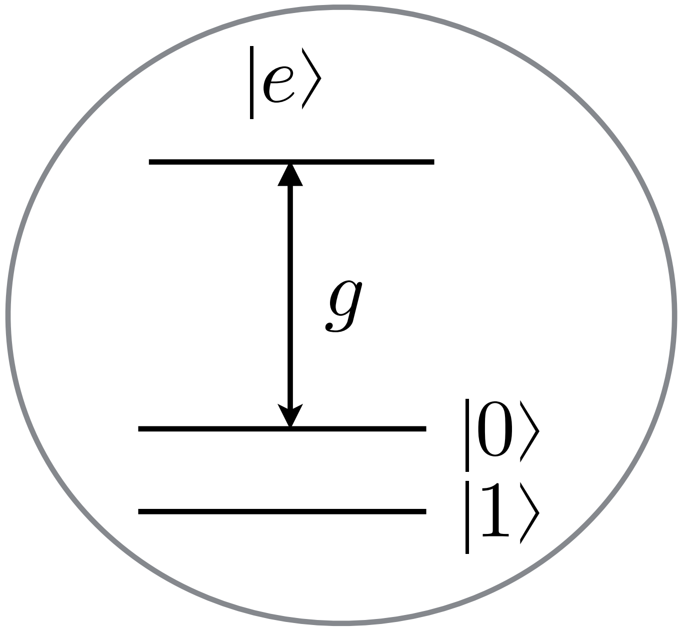

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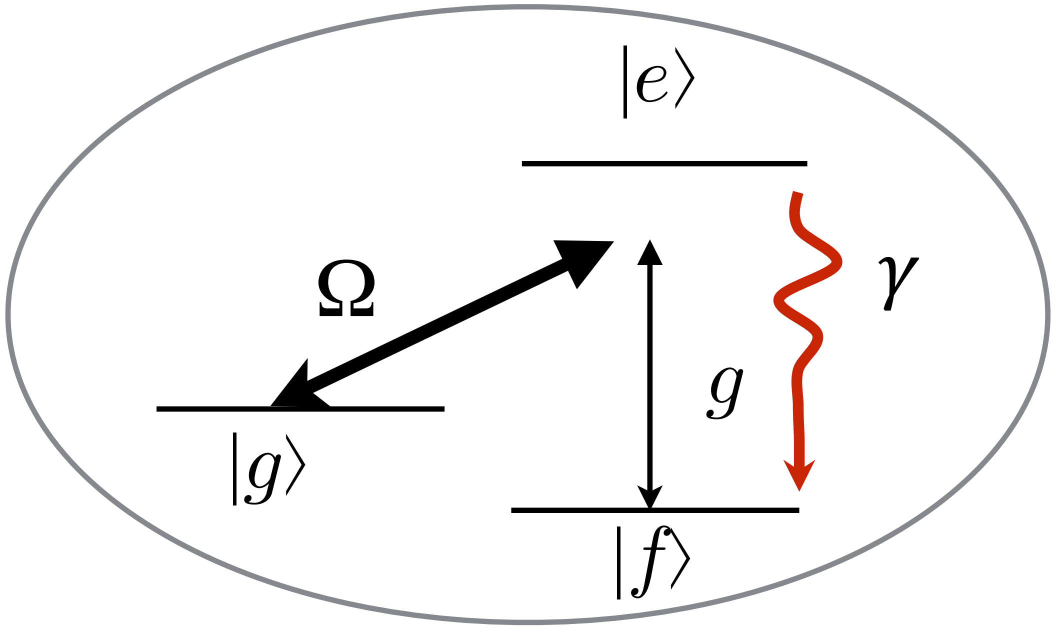
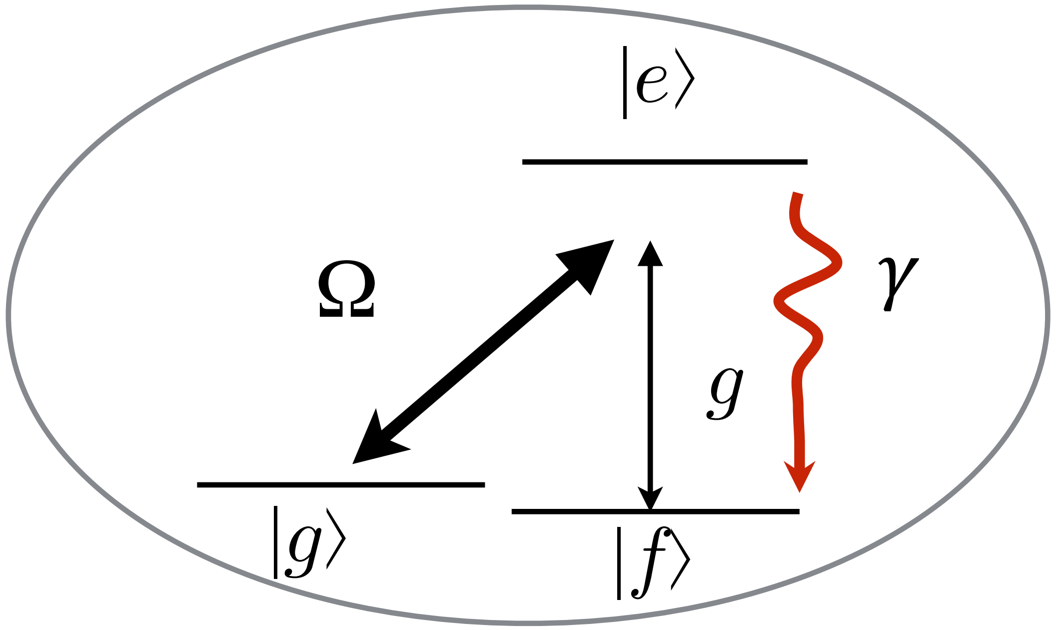
Atom heralds succesful gate

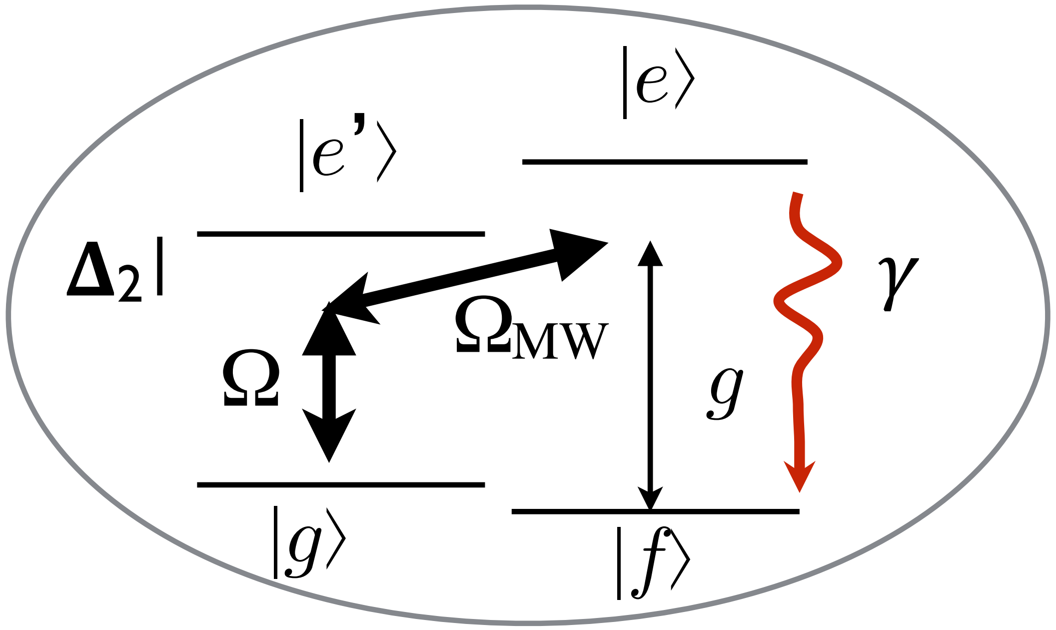


Two photon driving



* J. Borregaard, P. Komar, E. Kessler, AS, and M. D. Lukin, arXiv:1501.00956, Phys. Rev. Lett. in press

Two photon driving



Drive closed transition with two photon driving

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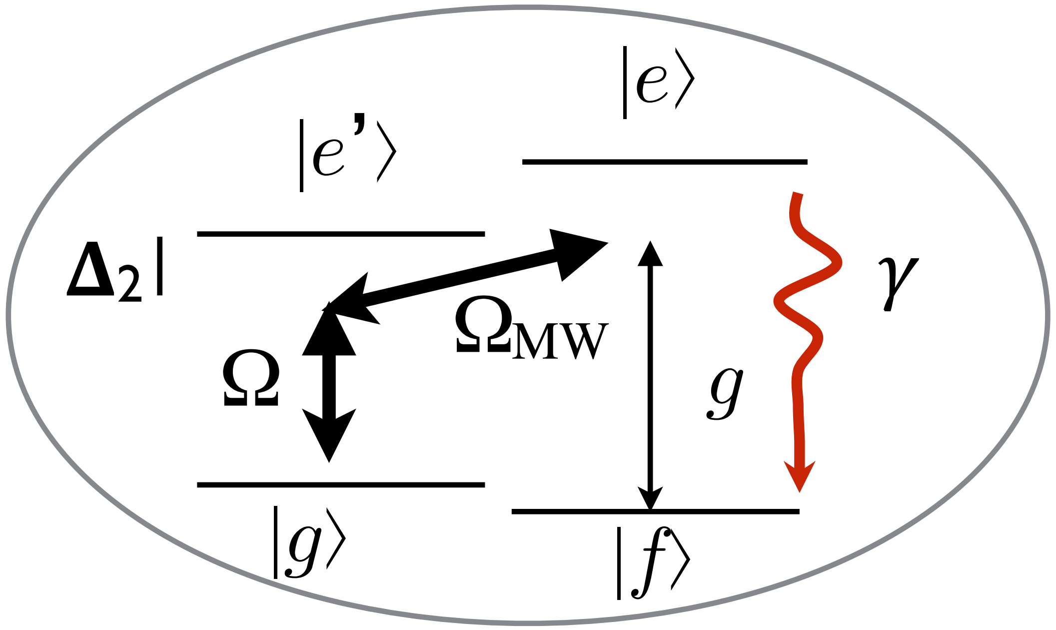

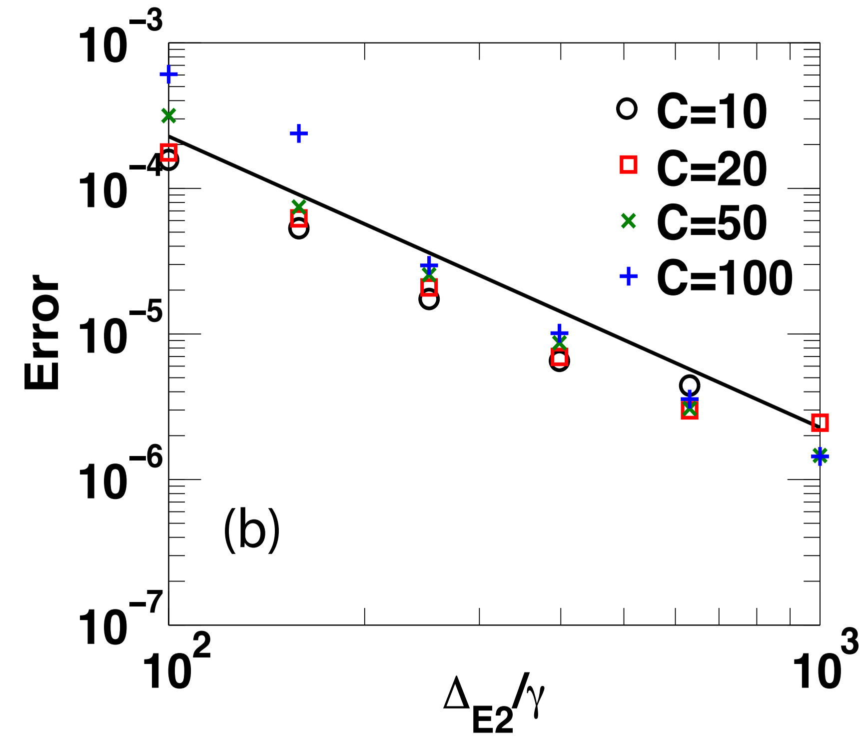

Drive closed transition with two photon driving => It works

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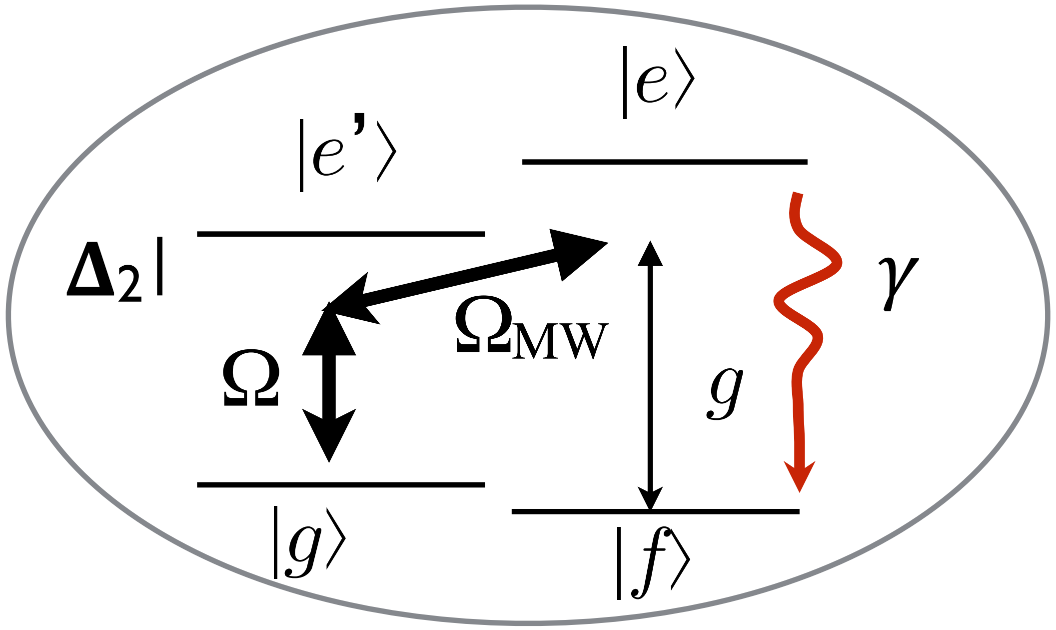

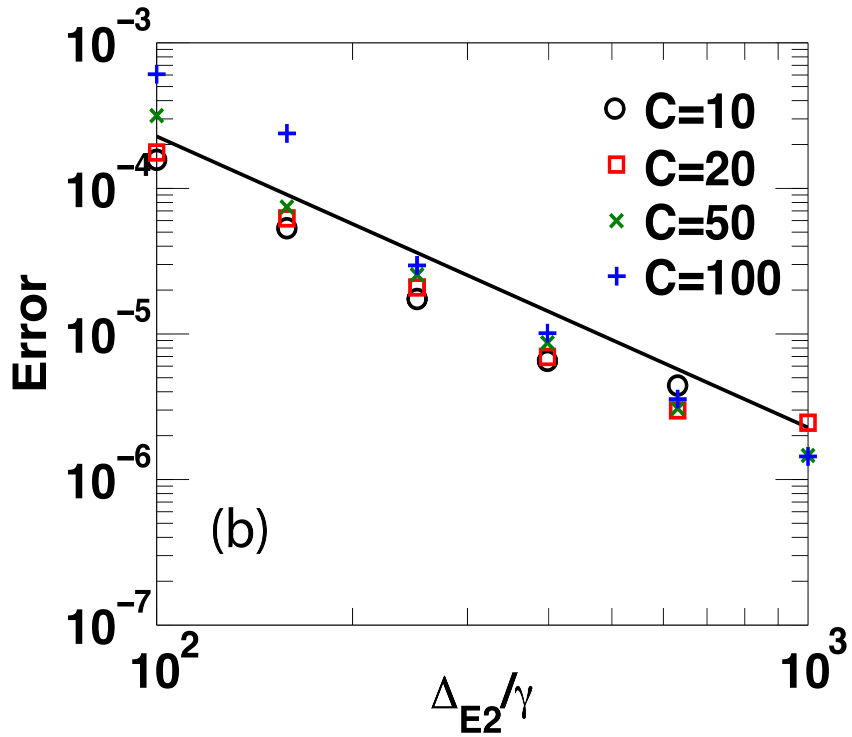

Drive closed transition with two photon driving => It works

Can make gate with $F \approx 1$ for ANY cavity

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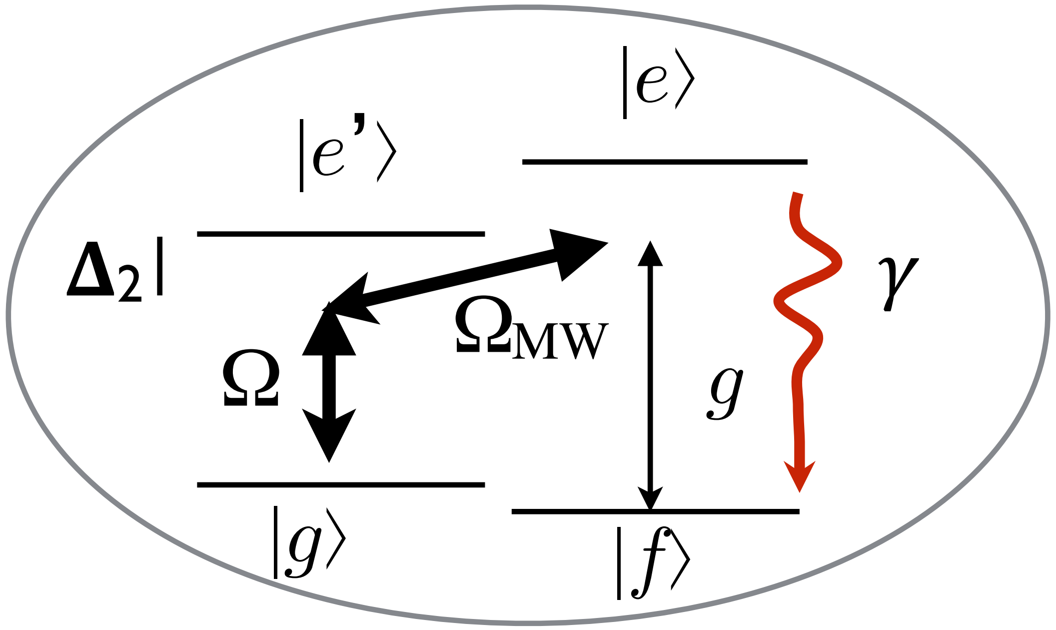

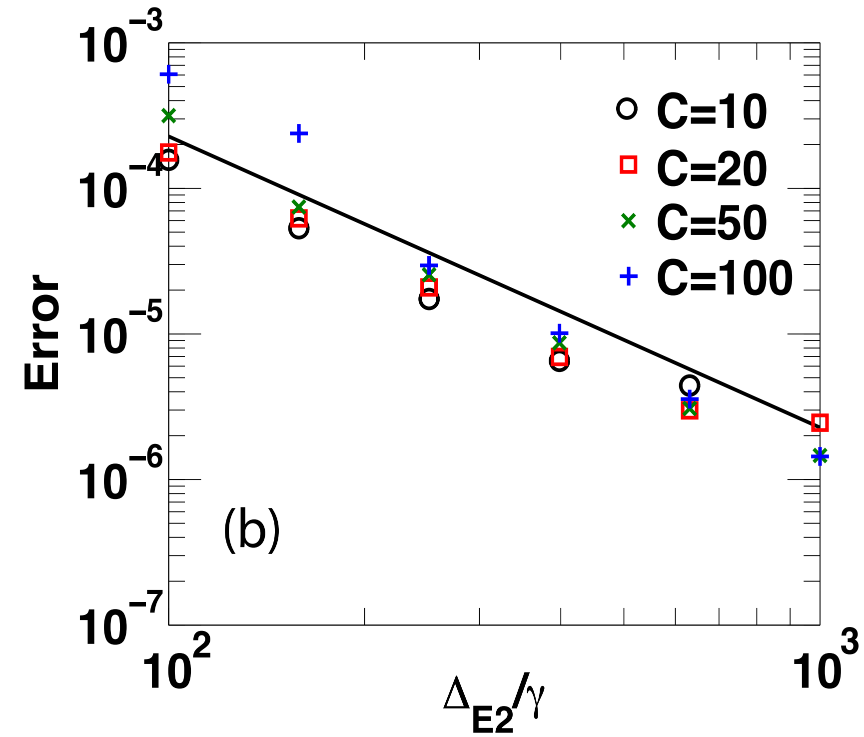

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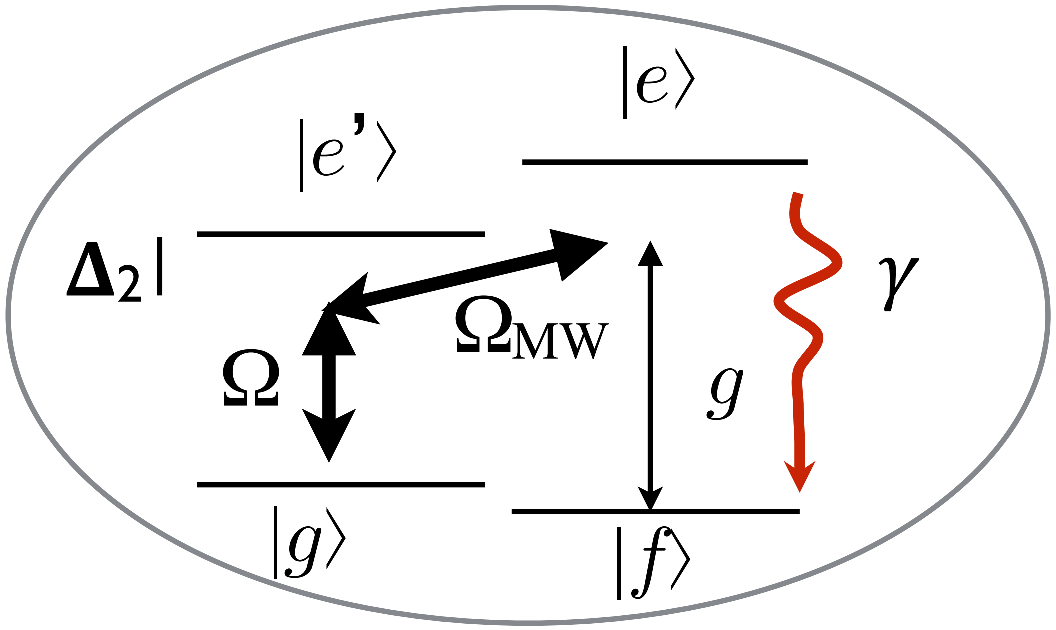
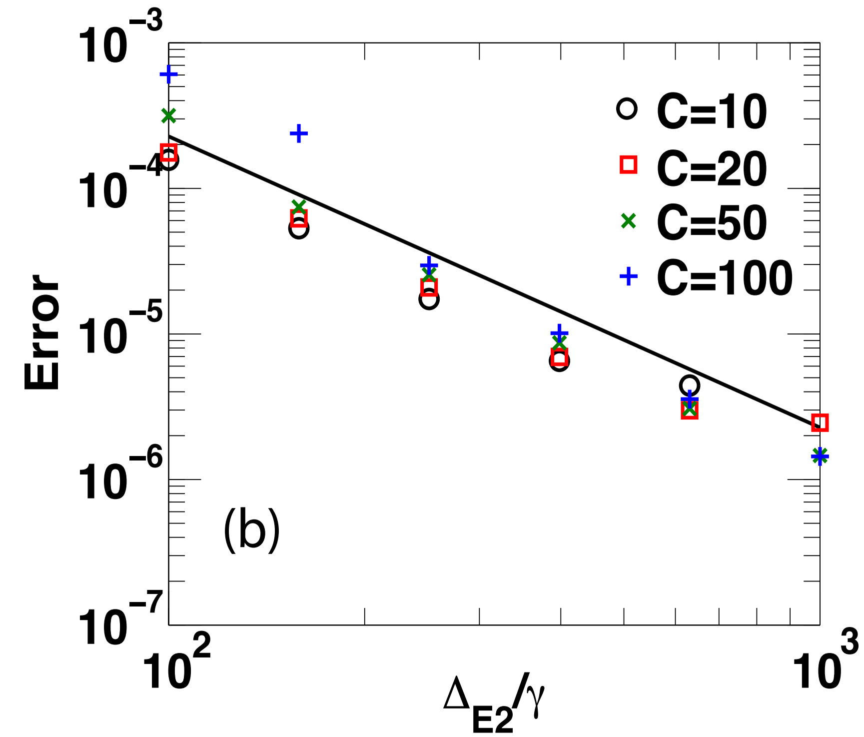




Drive closed transition with two photon driving => It works

Can make gate with $F \approx 1$ for ANY cavity

Probabilistic $1 - P \propto \frac{1}{\sqrt{C}}$

Realistic Ex: ^{87}Rb, C = 100

F = 1-10^{-3}

P = 67%

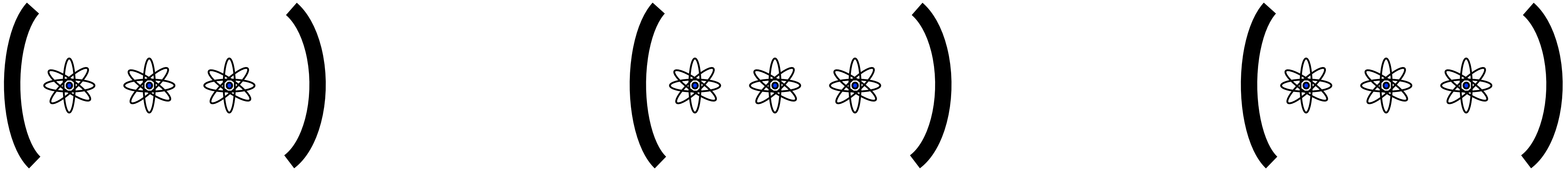
τ = 10 μs

* J. Borregaard, P. Komar, E. Kessler, AS, and M. D. Lukin, arXiv:1501.00956, Phys. Rev. Lett. in press

Application: quantum repeaters

Loss in optical fibers: exponential damping

Long distance communication requires repeaters



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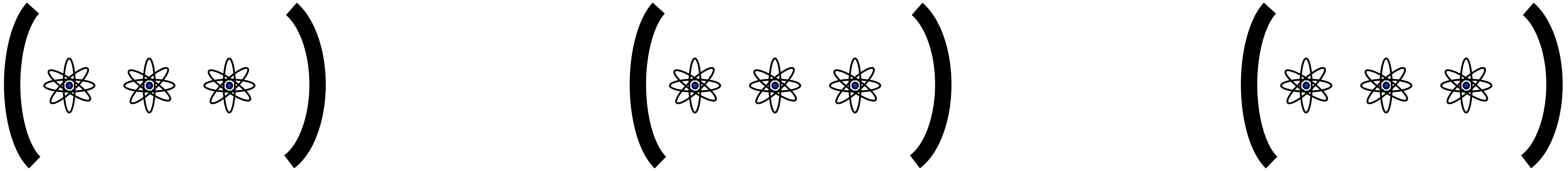

Generate entanglement over short distance

Application: quantum repeaters

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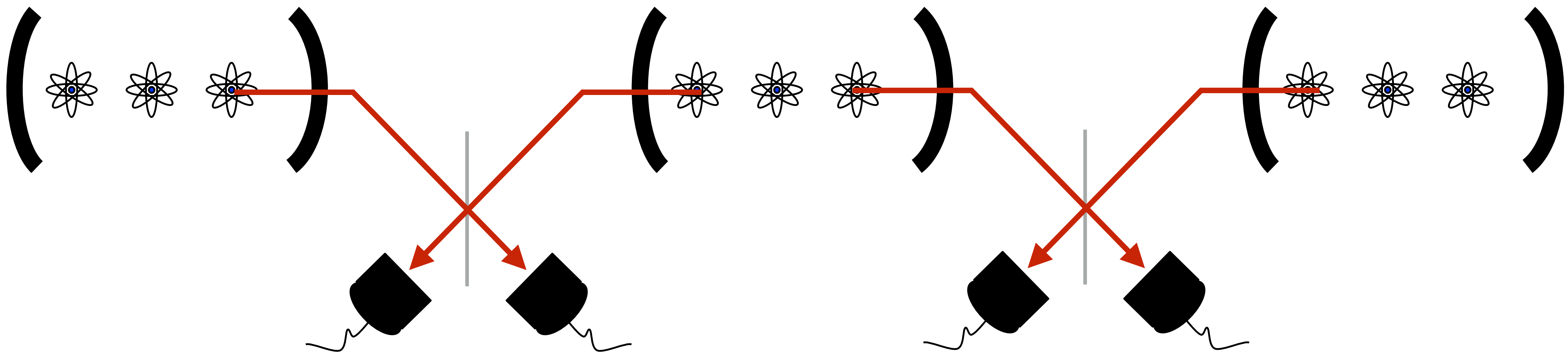

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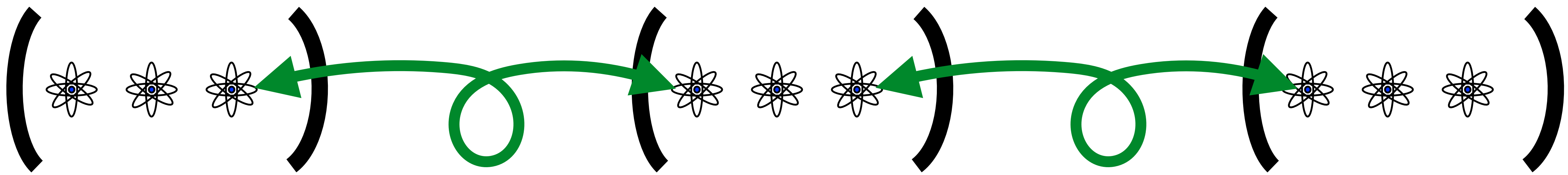

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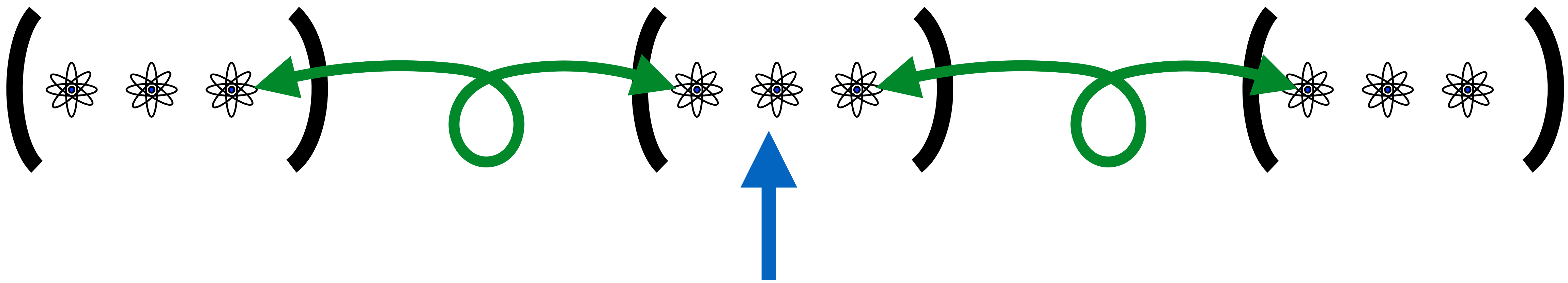

Generate entanglement over short distance

Gates=> swap entanglement get swapped to long distance

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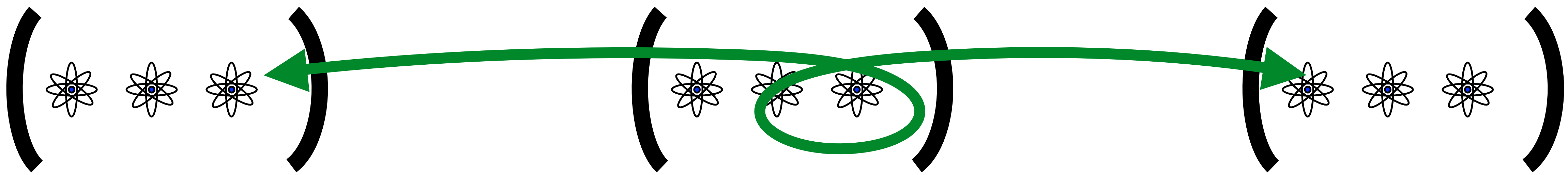

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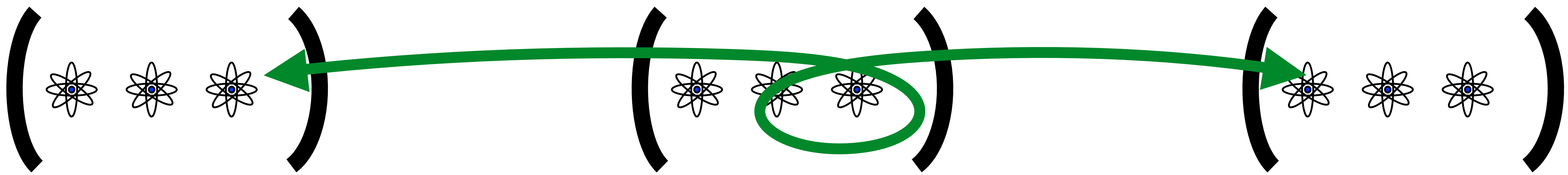


Generate entanglement over short distance

Gates=> swap entanglement get swapped to long distance

Still works for probabilistic gates (scaling polynomial, not exponential)

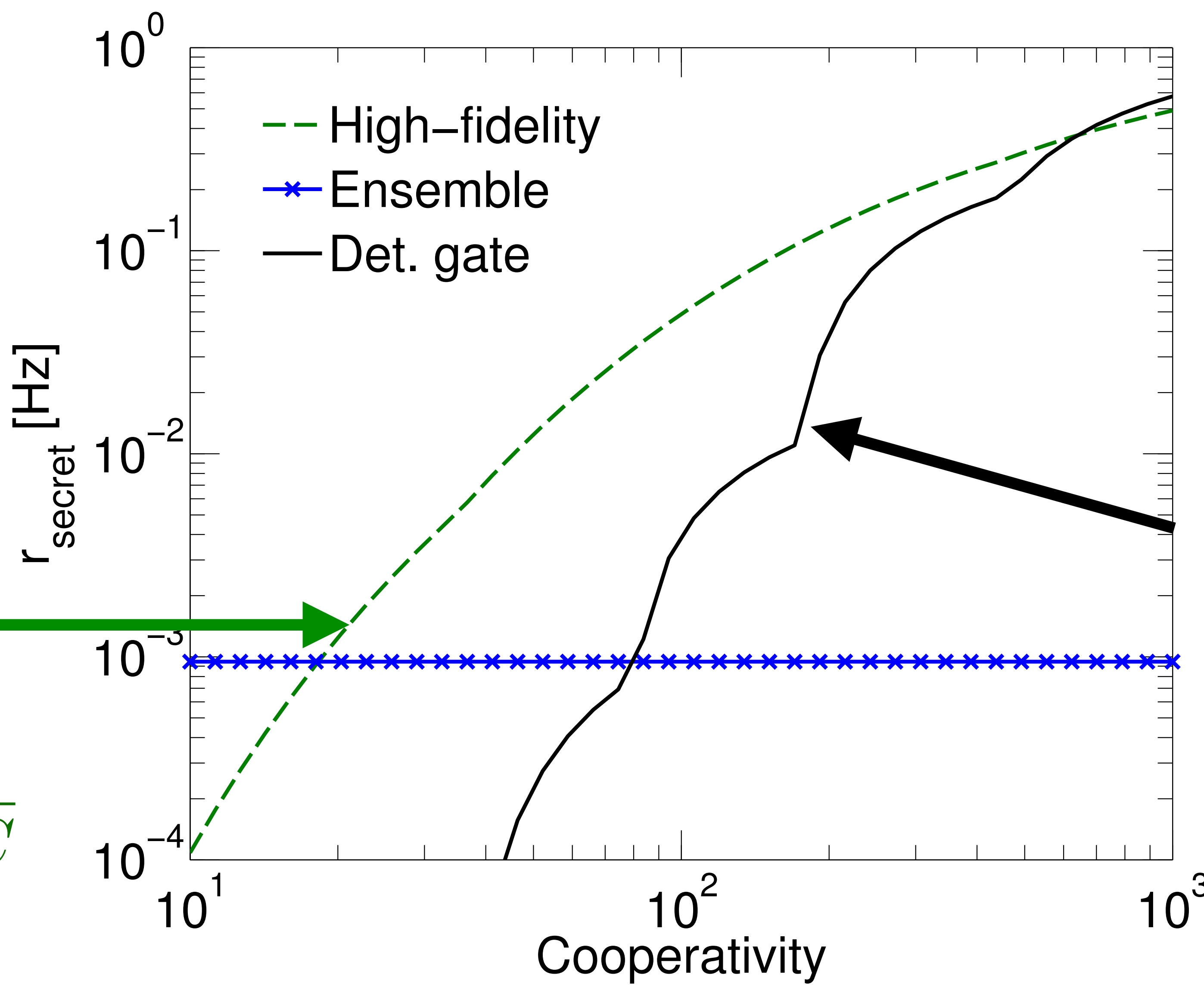
Application: quantum repeaters

Distance 1000 km, optimize over "all" parameters

This gate

$F \approx 1$

$1 - P \sim 1/\sqrt{C}$



Deterministic gate

1-F ~$1/C$

[*] J. Borregaard, P. Komar, E. Kessler, AS, and M. D. Lukin, in preparation

Application: quantum repeaters

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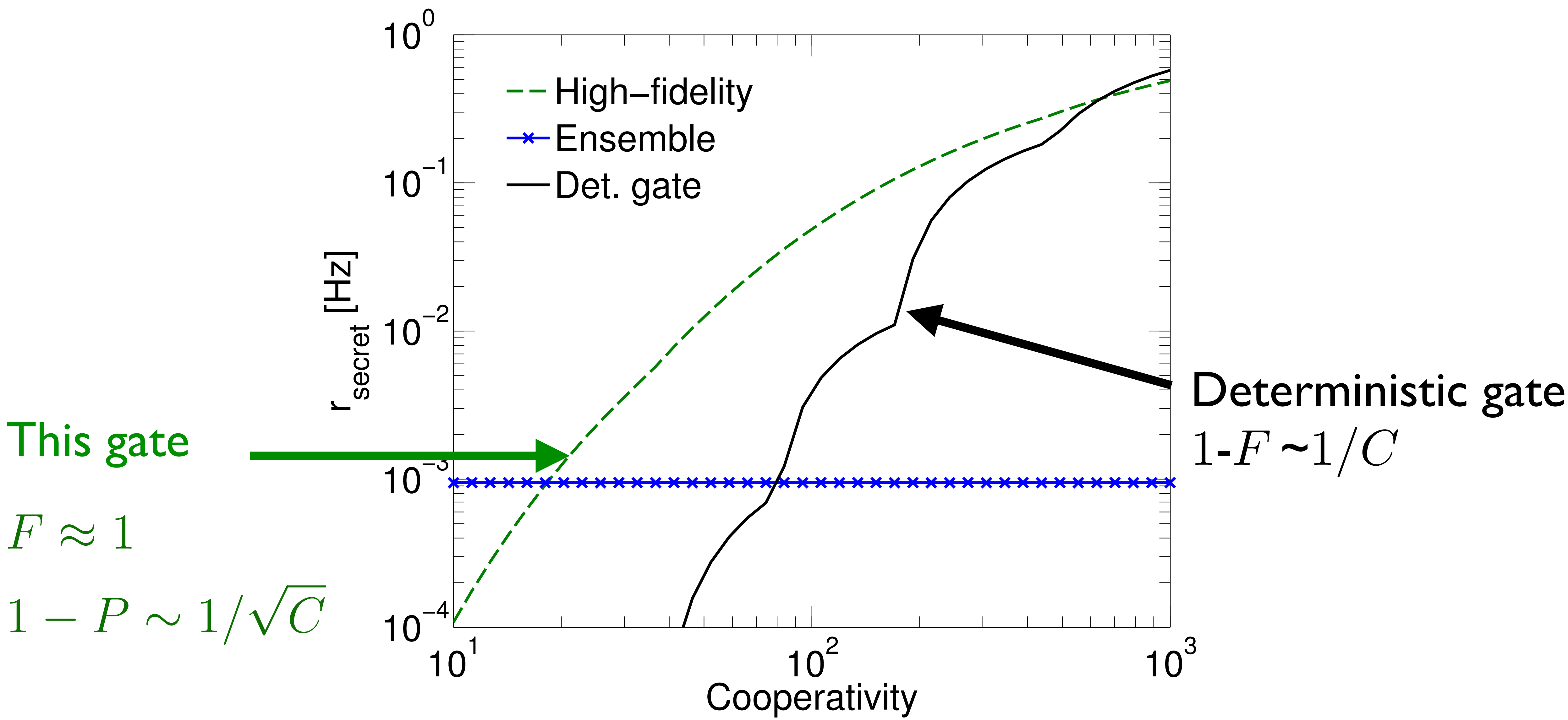

It is better to admit you don't know what to do than to do something wrong

* J. Borregaard, P. Komar, E. Kessler, AS, and M. D. Lukin, in preparation

Conclusion

Light matter interaction essential for quantum communication

Direct connections with light have a bad scaling

Bad scaling can be overcome

Examples:

Entangling superconducting qubits through nearby molecules in waveguides

Heralded gates in optical cavities $F \approx 1$

$$1 - P \sim 1/\sqrt{C}$$

Thanks to

<u>Copenhagen:</u>
Malte Dueholm Darling
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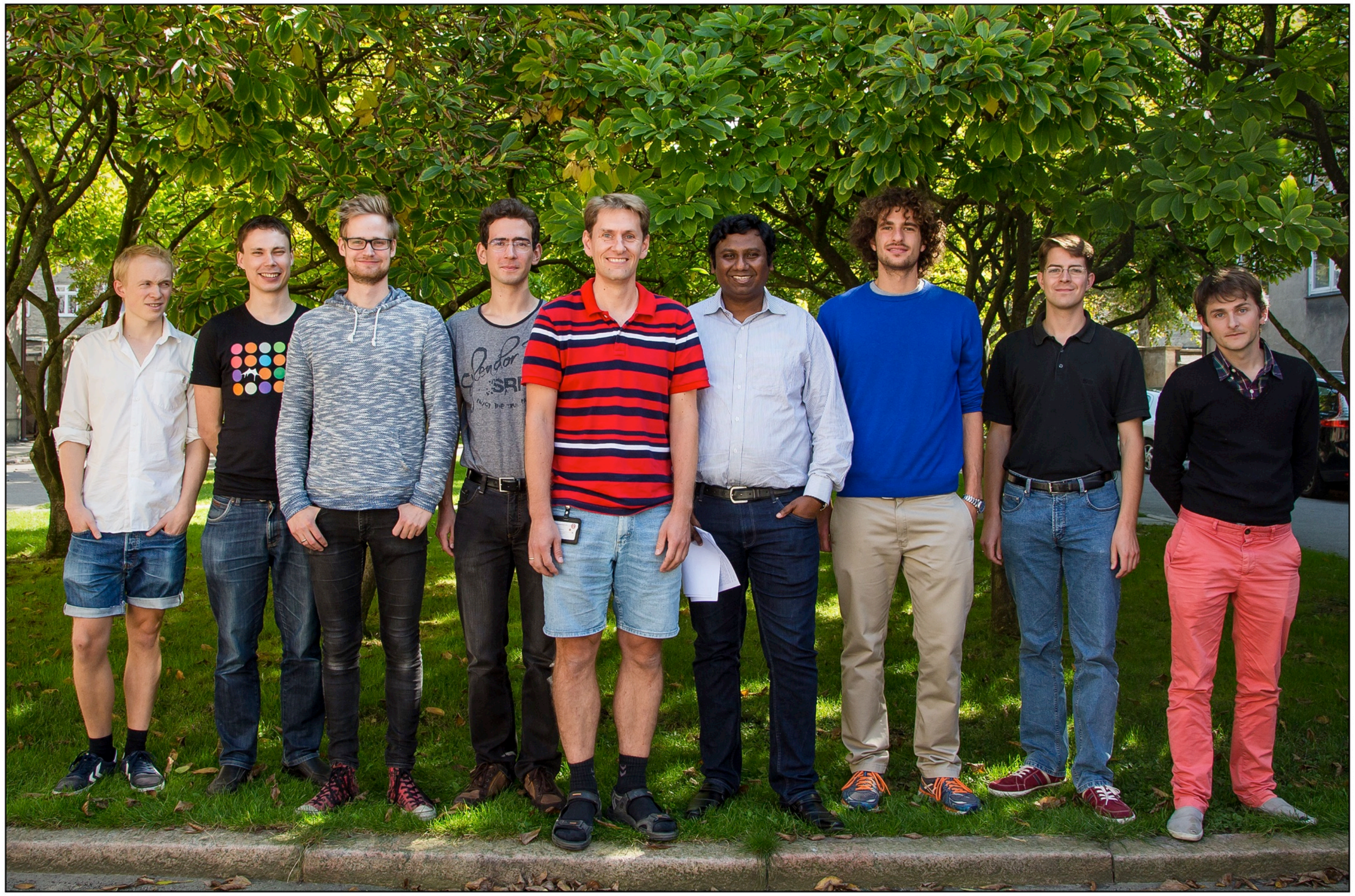
Florentin Reiter
Sumanta Das
Johan Ott
Oleksandr Kyriienko



Collaborators:

<u>Leiden:</u>
Sanli Faez

<u>Harvard:</u>
Peter Kómár
Eric Kessler
Mikhail Lukin