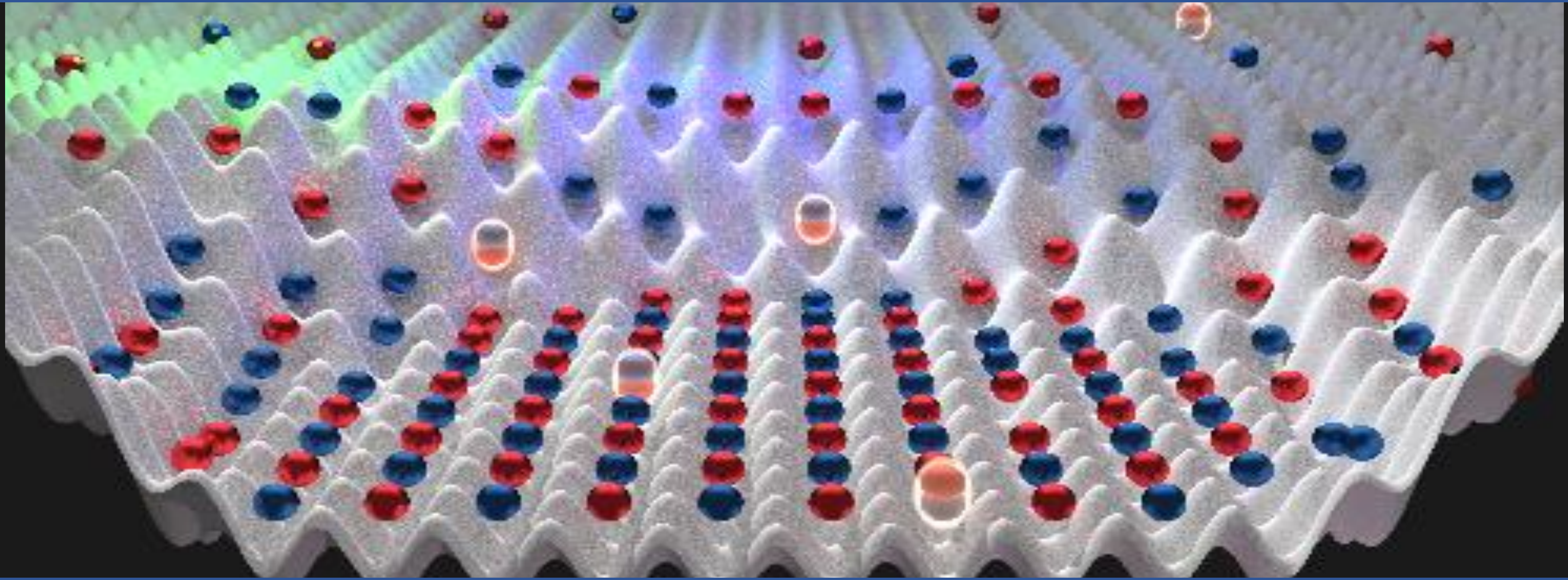


Quantum nonlinear optics based on 2D Rydberg atom arrays

Daniel Goncalves Romeu

ICFO, April 2021

Image from: *Physics* 12, 76 (2019)

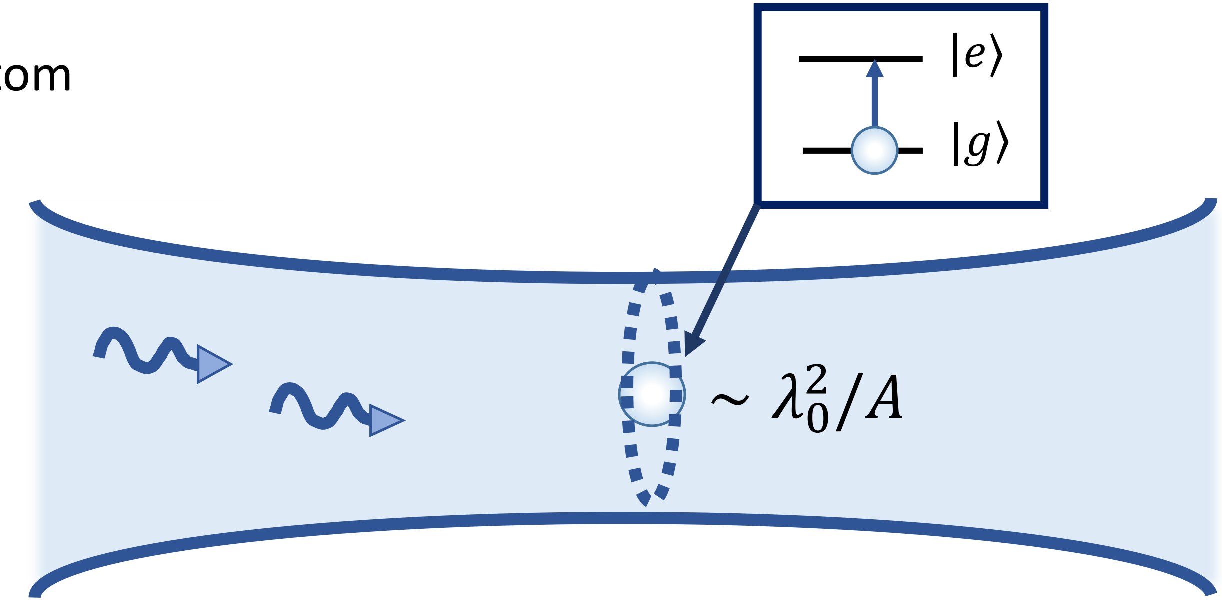
ArXiv: 2101.01936 (2021)

Dr. Mariona Moreno-Cardoner (UIBK, UB)

Prof. Darrick Chang (ICFO)

1. Motivation

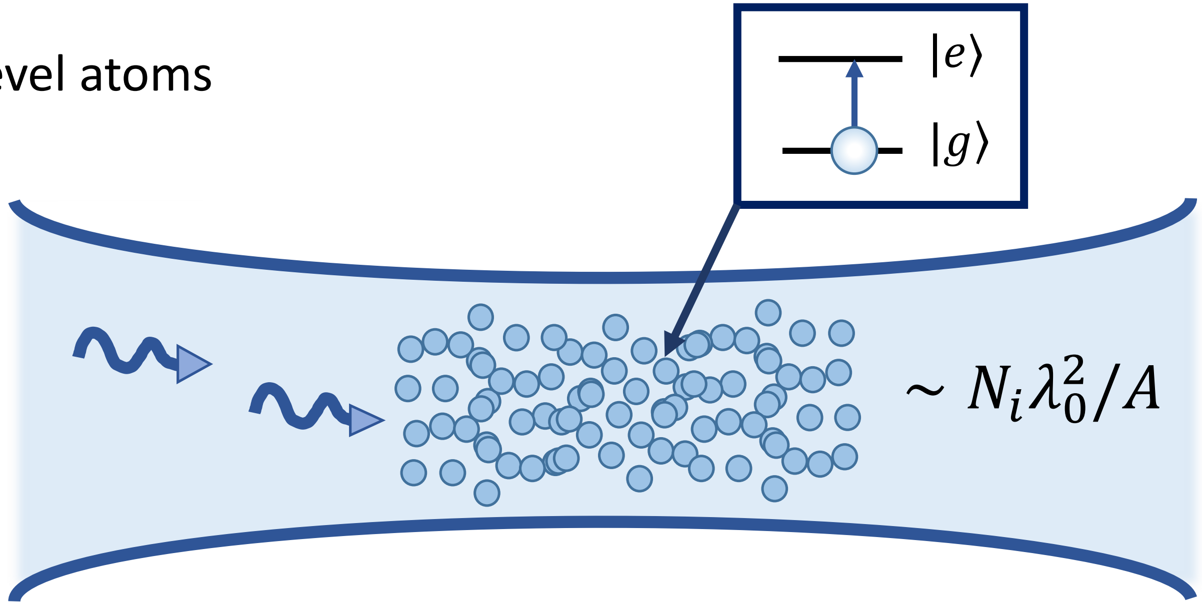
- **Single** 2-level atom



Very nonlinear, but low atom-light coupling

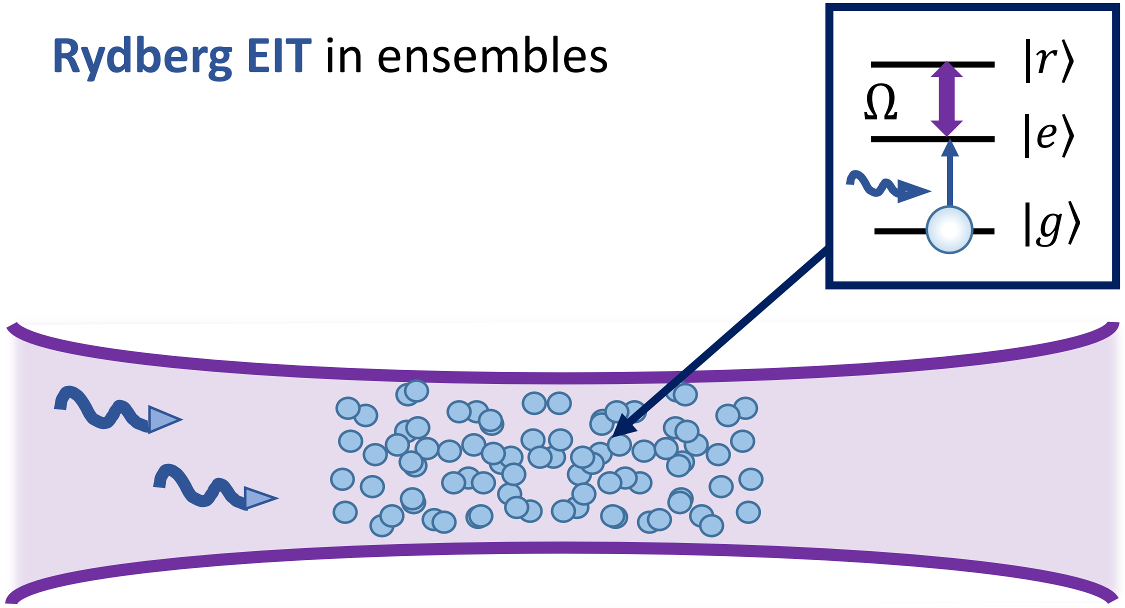
1. Motivation

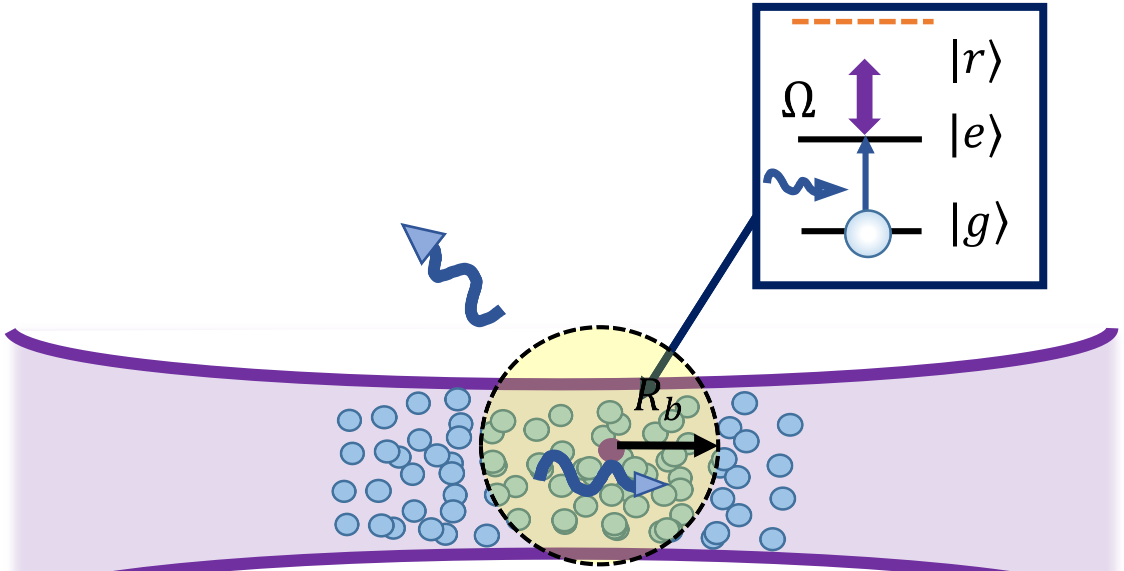
- **Ensemble** of 2-level atoms



Increased coupling, but low nonlinearity

- **Rydberg EIT** in ensembles





Blockade effect

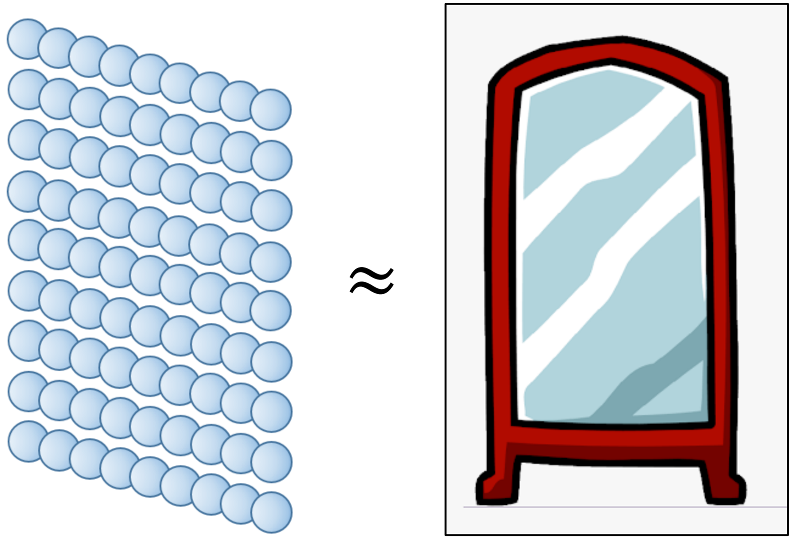
- **Strong nonlinearity**, but system is **dissipative**. Reduces efficiency of implementations such as photon gates ($\sim R_b^{-3/2}$). Typical values for photon-pair loss $\gtrsim 90\%$.

Nature **542**, 206 (2017)

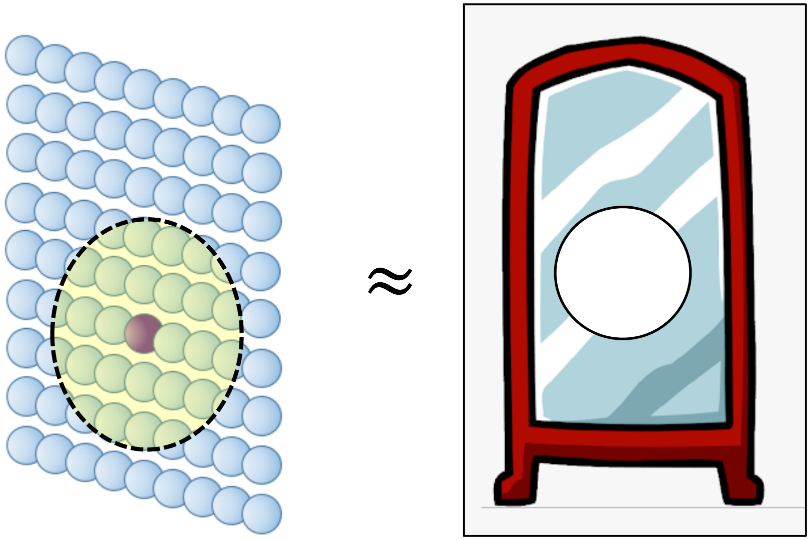
Nat. Phys. **15**, 124–126 (2019)

2. Ingredients for our photon gate

- 2D Array ≈ perfect **mirror**

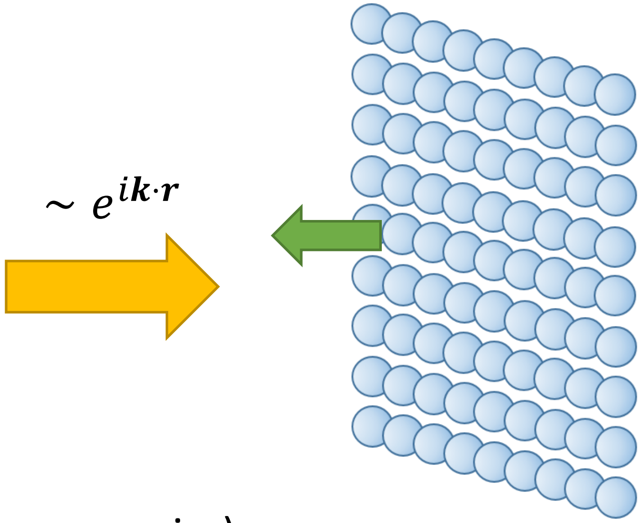


- Rydberg excitation ≈ **Aperture** in the mirror

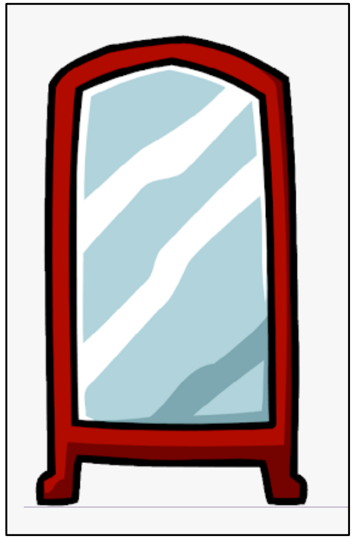


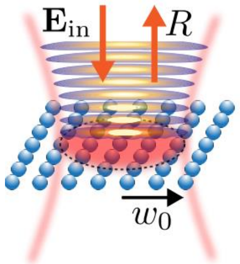
2.1. 2D arrays as perfect mirrors

- Consider an **incident plane wave**
- Spatial periodicity defines diffraction orders
- For sub-λ lattice constant, most become **evanescent**
- On resonance, there is **only one possible mode**
- The **Perfect reflection**: $R = 1$, 100% **lossless** interaction
- Still a good approximation **for realistic system** ($R > 95\%$, numerics)

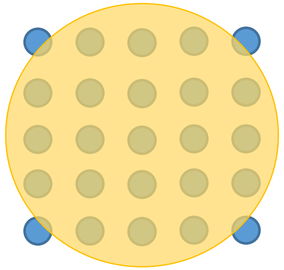


$\approx$

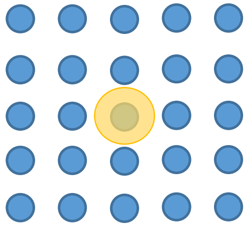




Optimal beam waist w_0



vs.



Theory: *PRL* **118**, 113601 (2017)
PRL **116**, 103602 (2016)
Comms. Phys. **3**, 141 (2020)

Experiment: *Nature* **583**, 369–374 (2020)

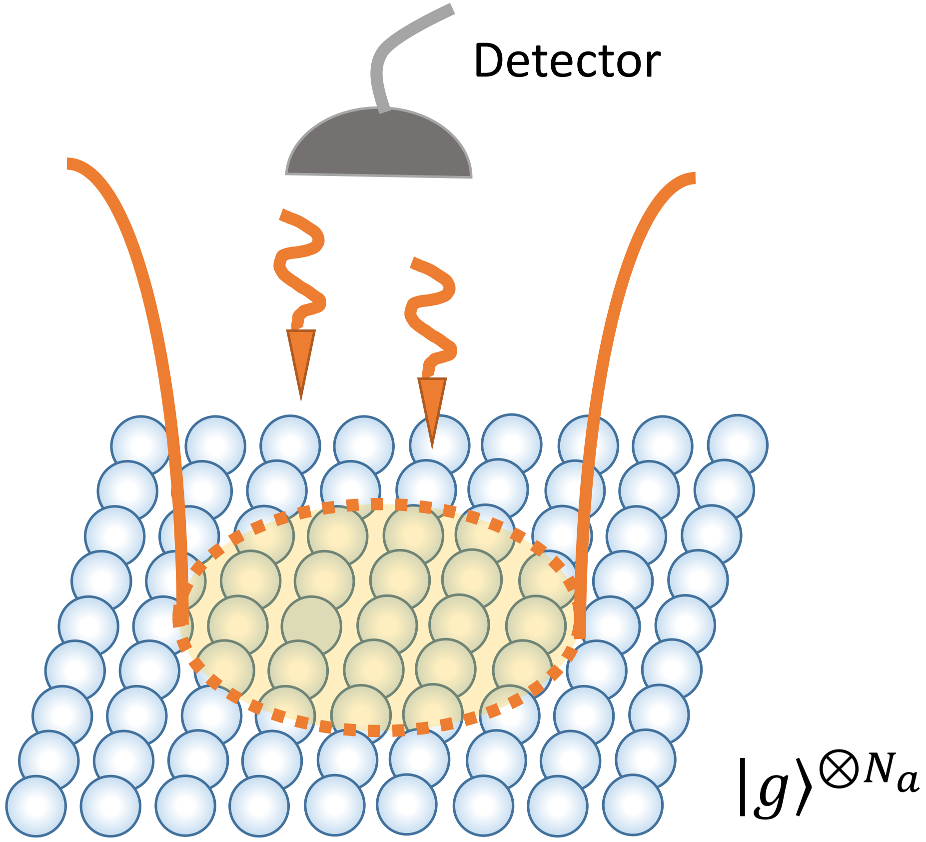
2.2. Nonlinearities in the mirror

- How much **nonlinear** is this mirror?

We use $g^{(2)}$, quantifies "effect" of reflecting one photon in the reflection of a 2nd photon

If $g^{(2)} = 1$ → Linear

If $g^{(2)} < 1$ → nonlinear



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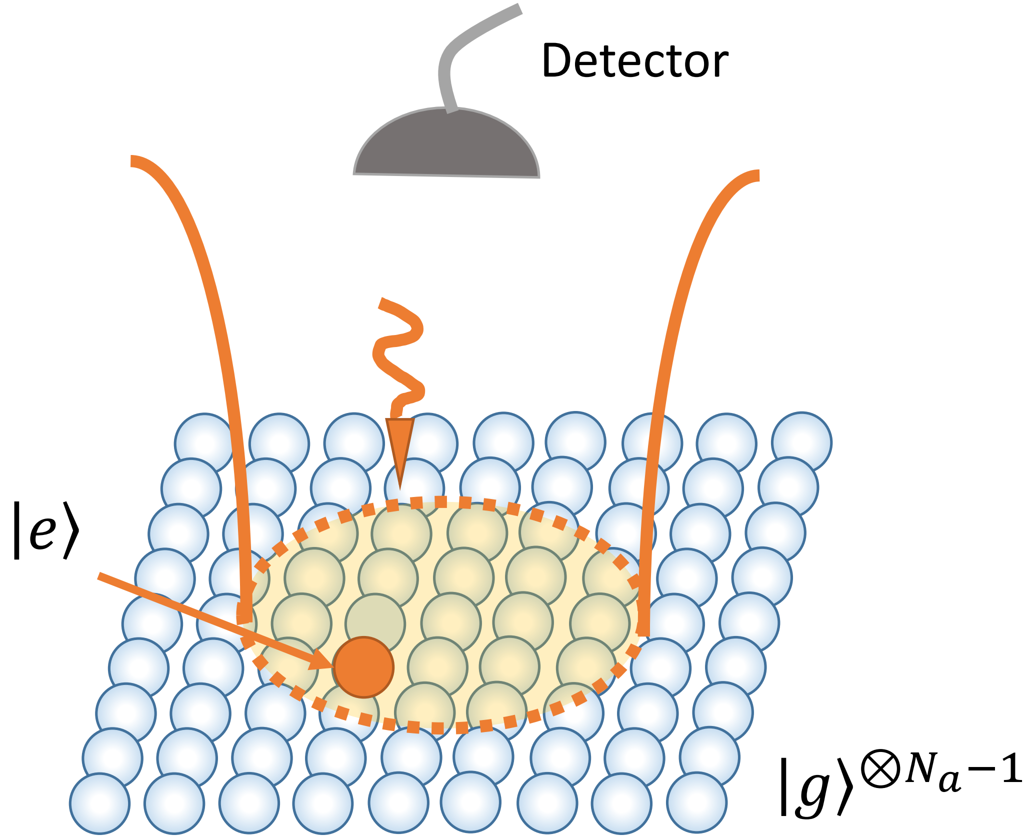

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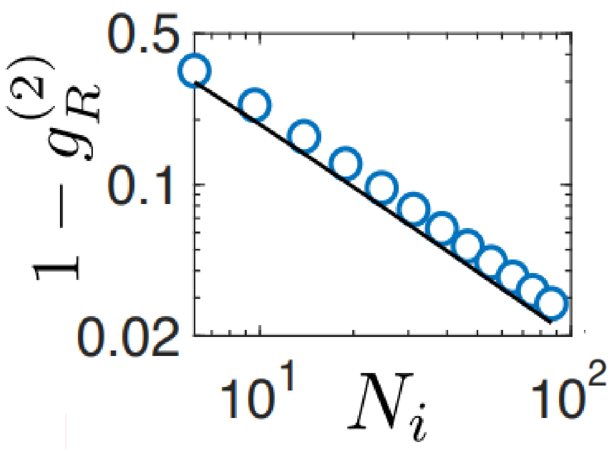
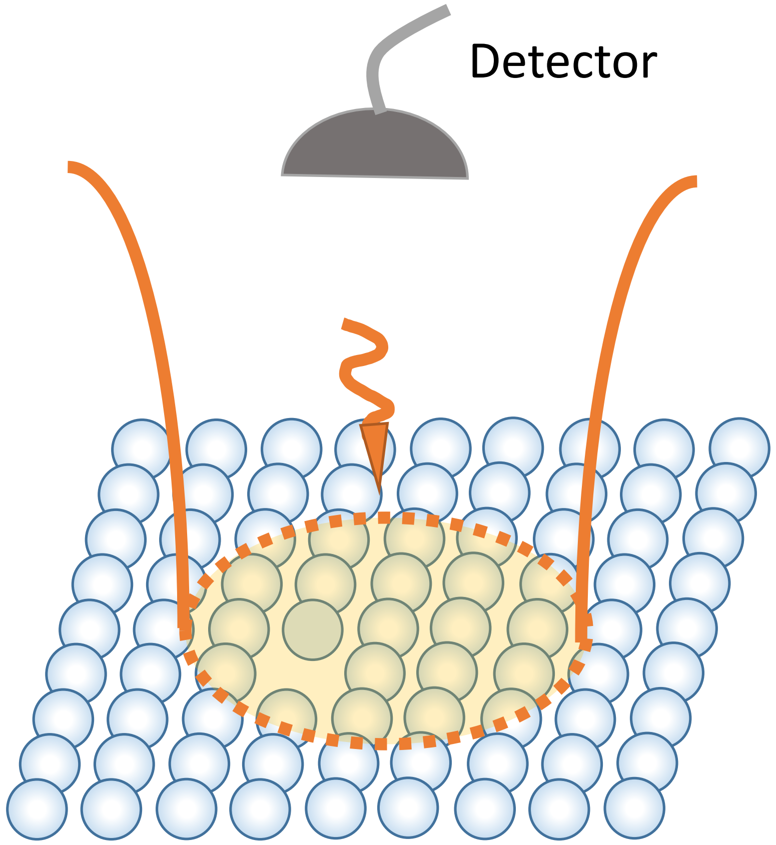


Single-atom hole in a mirror with N_i illuminated atoms

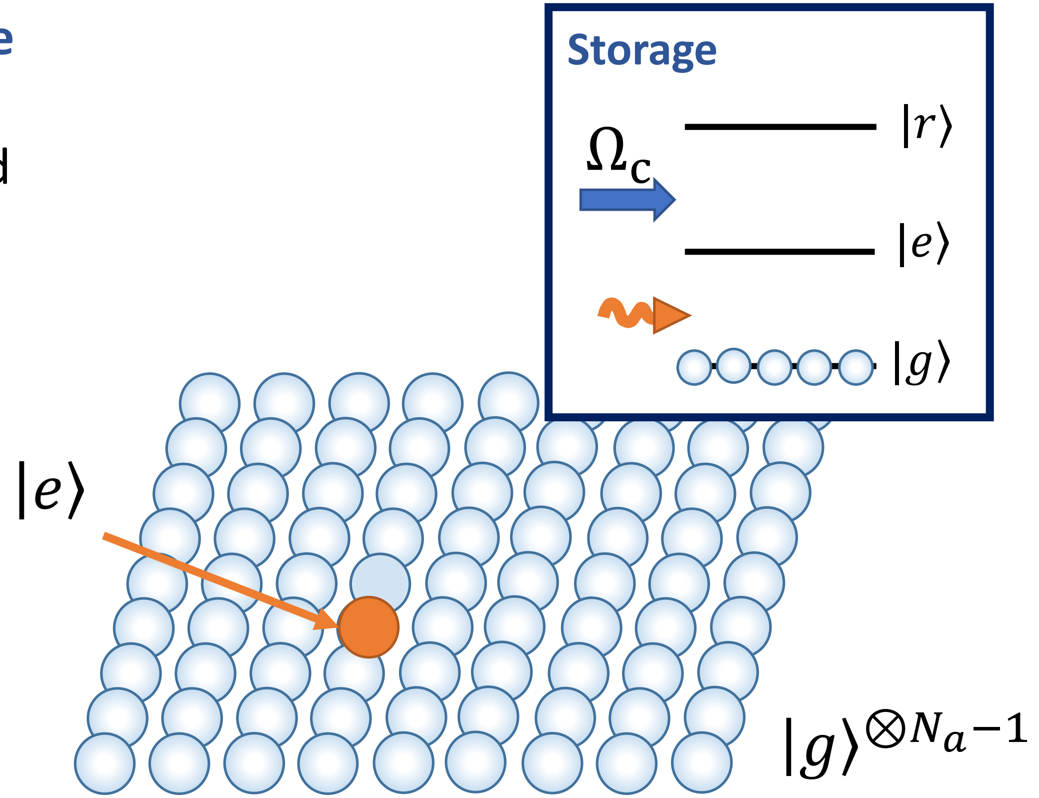
$$g^{(2)} \sim \left(1 - \frac{1}{N_i}\right)^2$$

Nonlinearity is negligible in practice ($g^{(2)} \approx 1$)



2.3. Rydberg dressing and apertures in the mirror

- We would like to **increase non-linearity** → **increase hole size**
- First, **store one photon** in a Rydberg state with a control field



PRA **89**, 011402 (2014)

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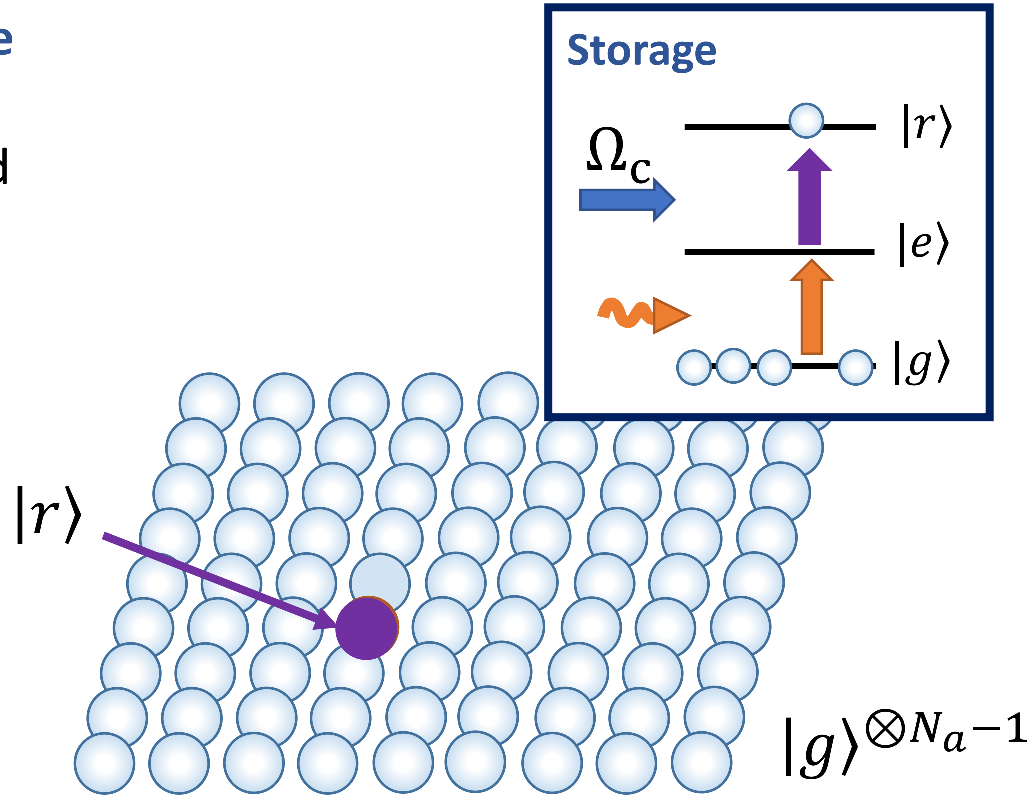

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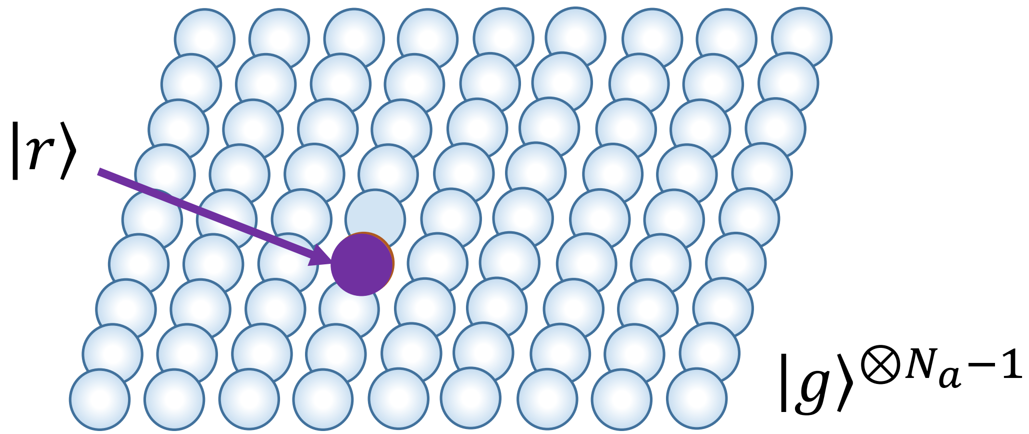

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- We would like to **increase non-linearity** → **increase hole size**
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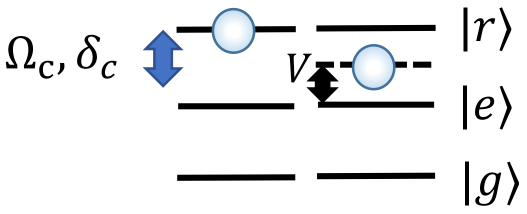
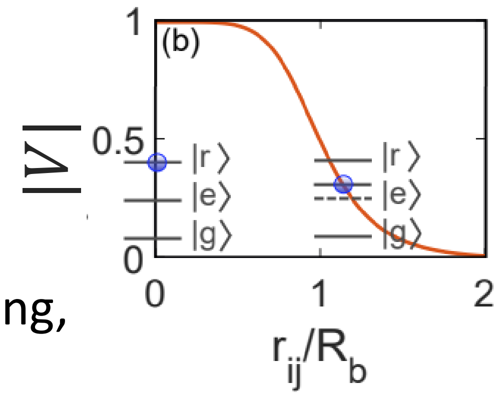
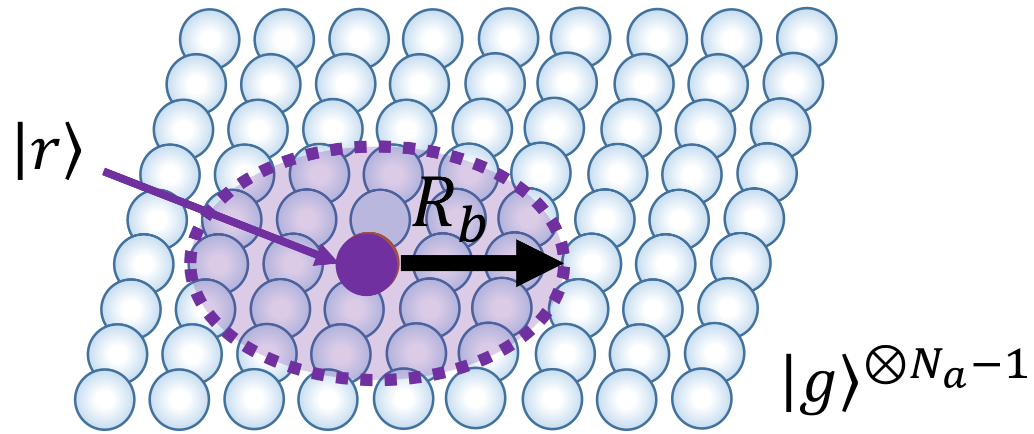
- Second, **detune** control field → Rydberg dressing. **Blockade mechanism** is communicated to the **$|e\rangle$ levels**



Presence of $|r\rangle$ disrupts dressing, yielding a **dressing-induced** interaction potential $|V(r_{ij})|$





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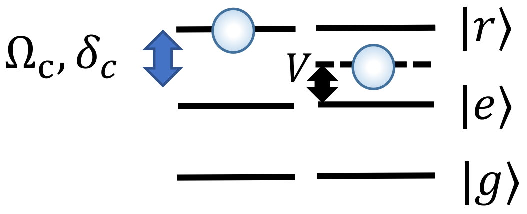

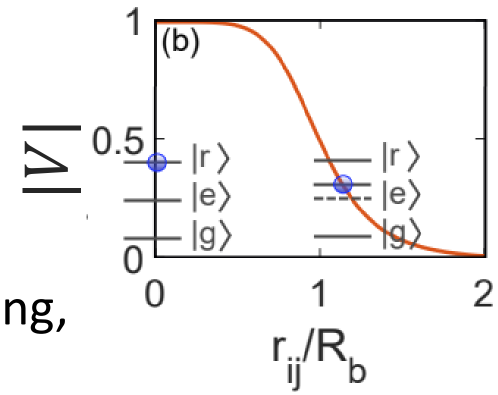

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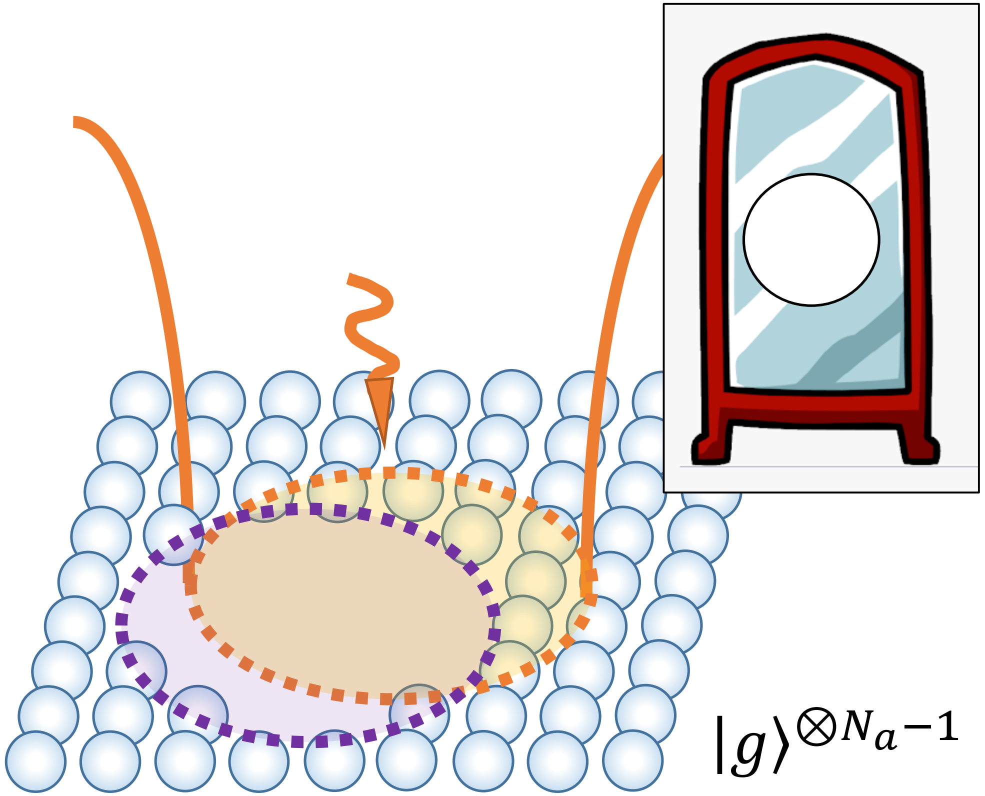
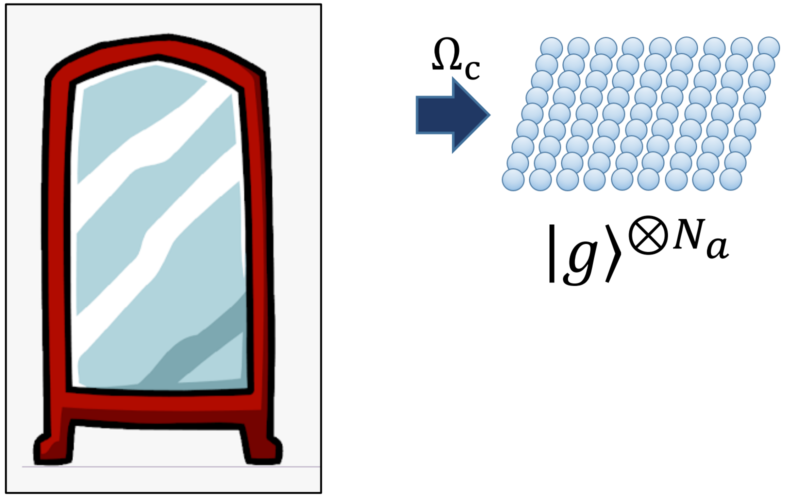


PRA **89**, 011402 (2014)

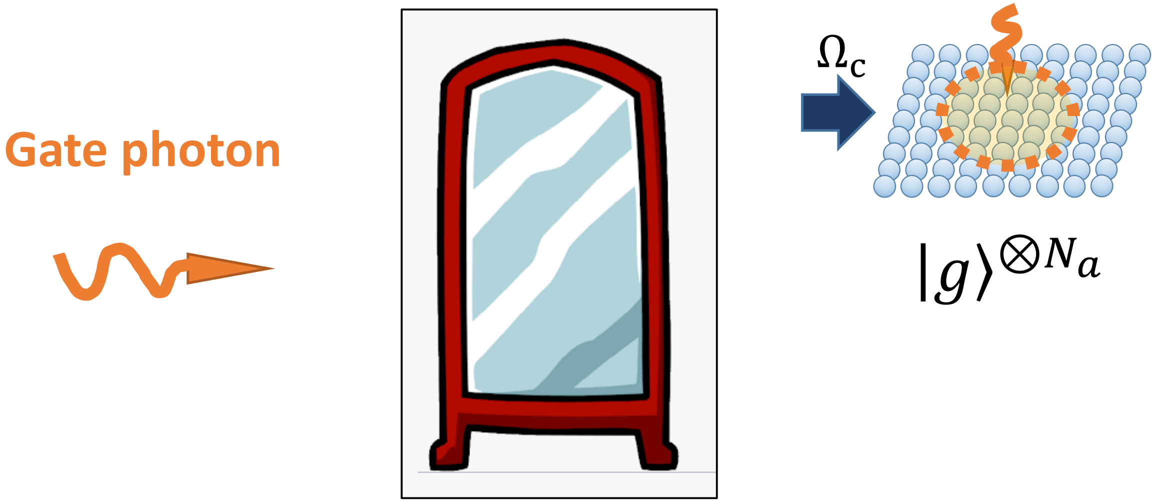
3. Single photon switch

Step 1: Gate photon

Reflecting scenario (0)



Transmitting scenario (1)



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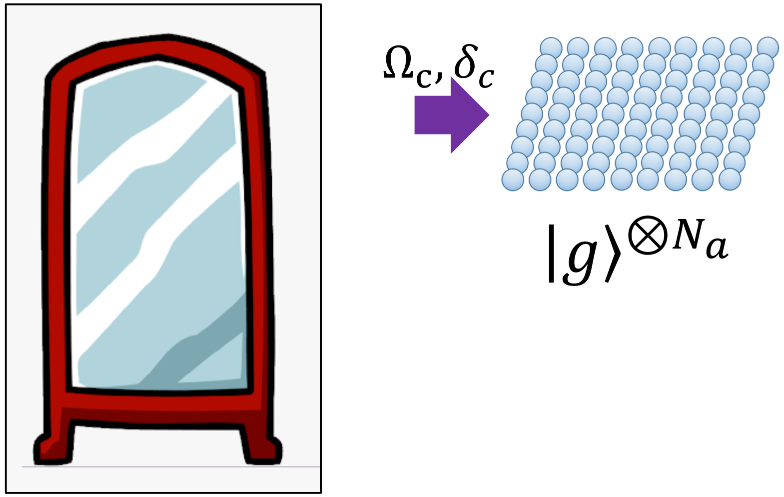

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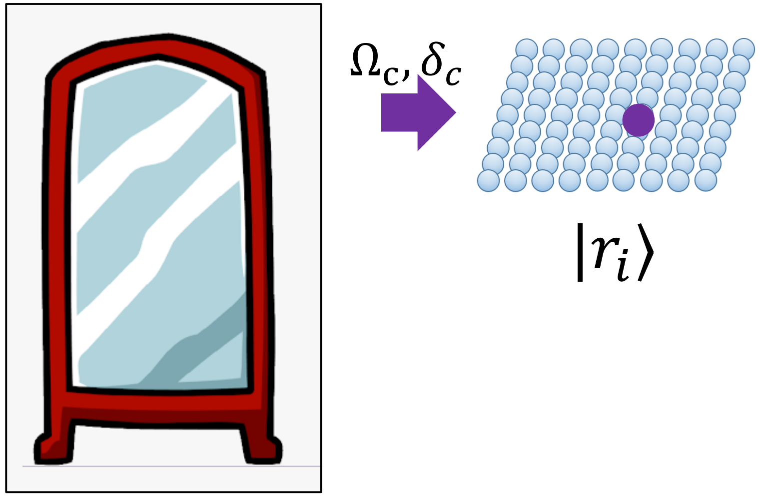

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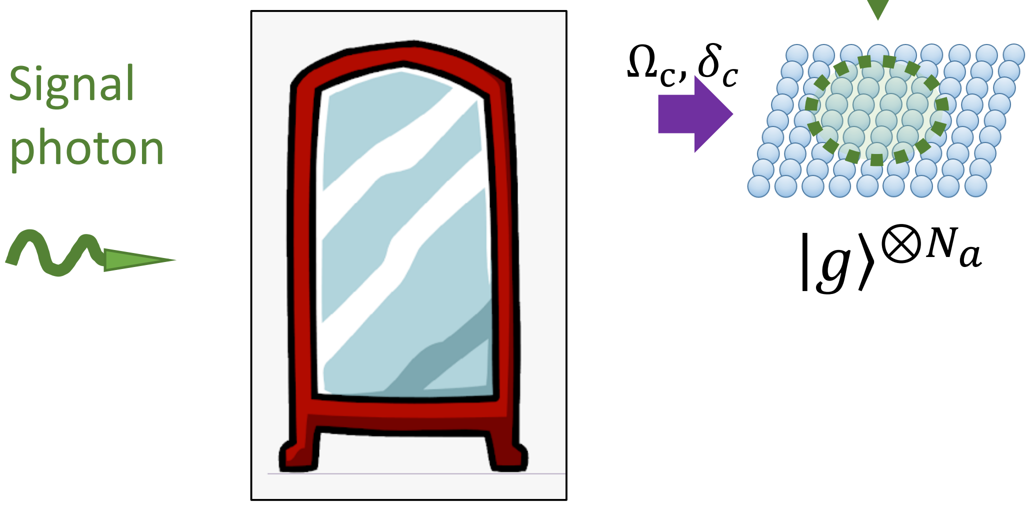
Step 2: Signal photon

Reflecting scenario (0)



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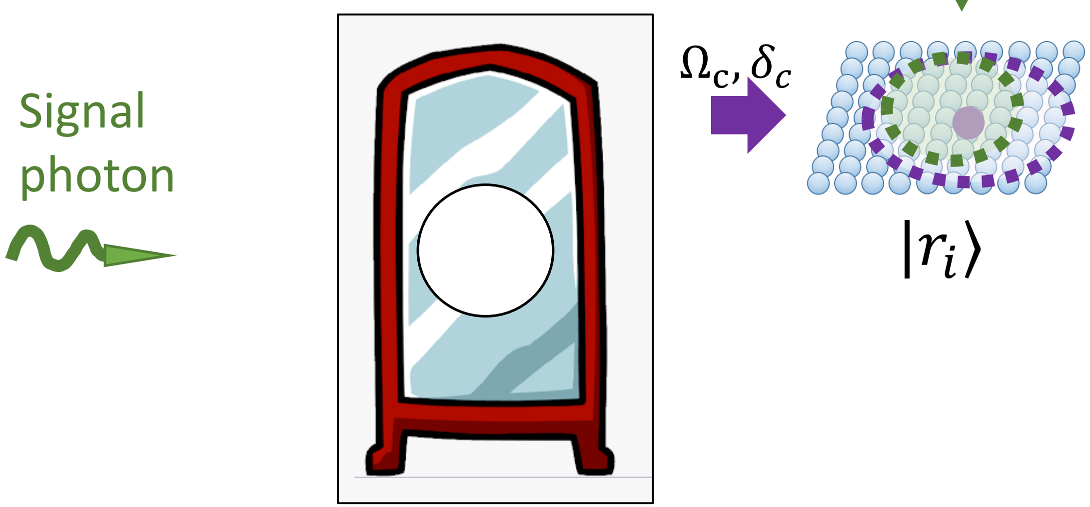

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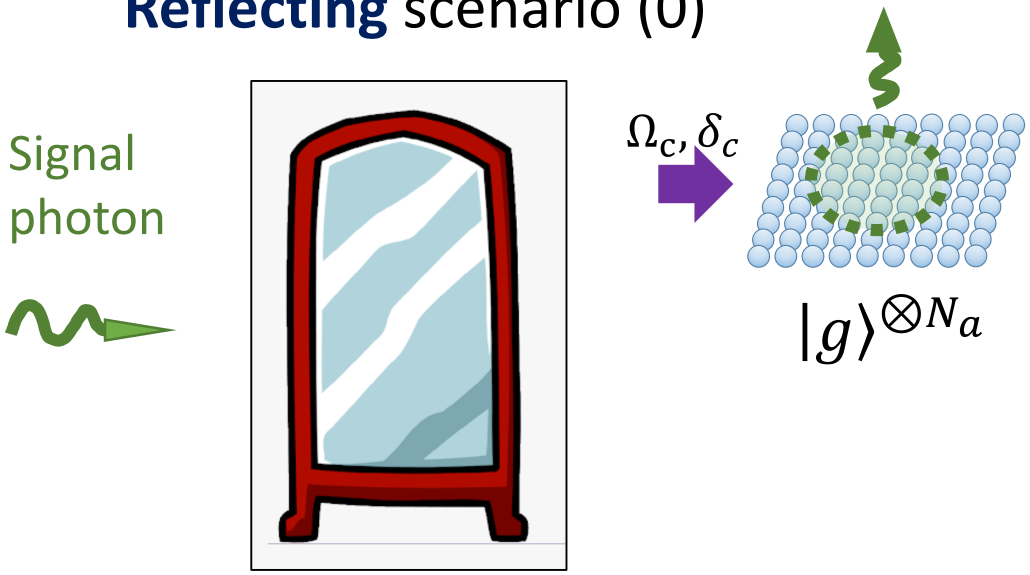

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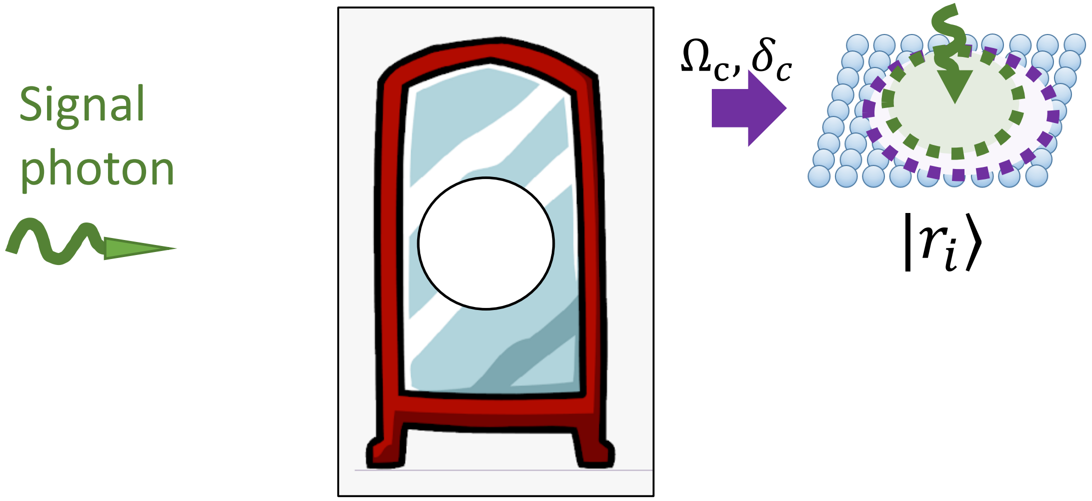
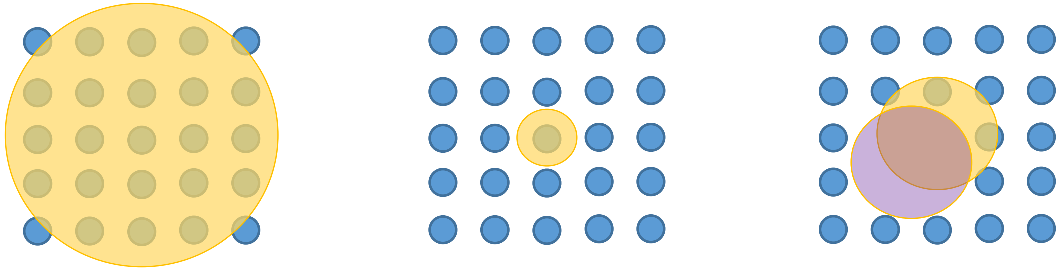
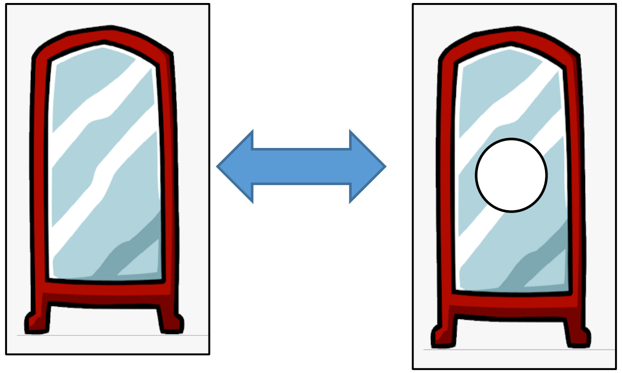


3.1. Photon switch optimization and conclusions

- **Switch:** Transmission/Reflection of signal photon is conditioned to the storage of a gate photon. For a given blockade radius:

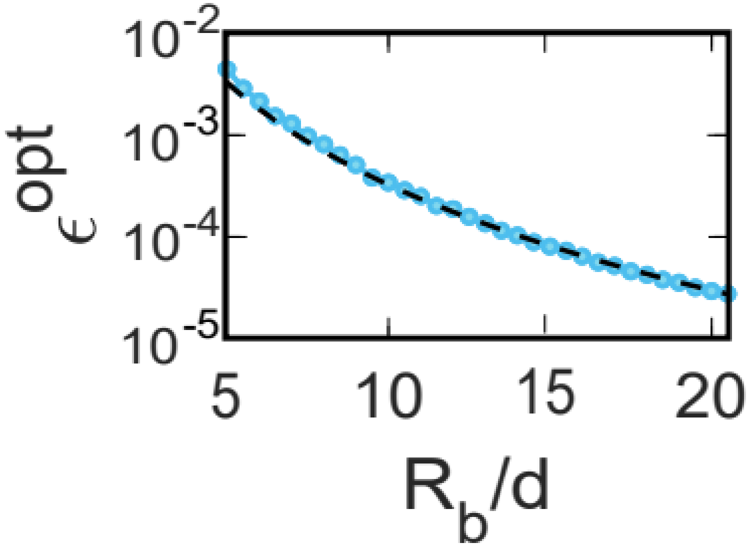
Optimal beam waist w_0





- **Switch error:** Maximal error between transmission and reflection

$$\epsilon^{opt} \approx C(d)\frac{\log^2(R_b/d)}{R_b^4} \sim R_b^{-4}$$, which beats $R_b^{-3/2}$



Simulations for finite array and realistic Rydberg dressing yield a **photon loss below 5%.** We can achieve **strong, nonlinear photon-photon interactions with low dissipation**.

Thank you for you attention!

Questions