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Rydberg Single Photon Source at Room Temperature (arXiv:1212.2811)

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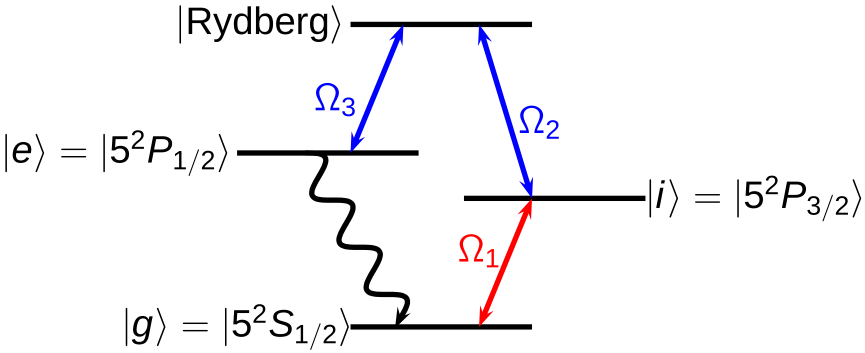
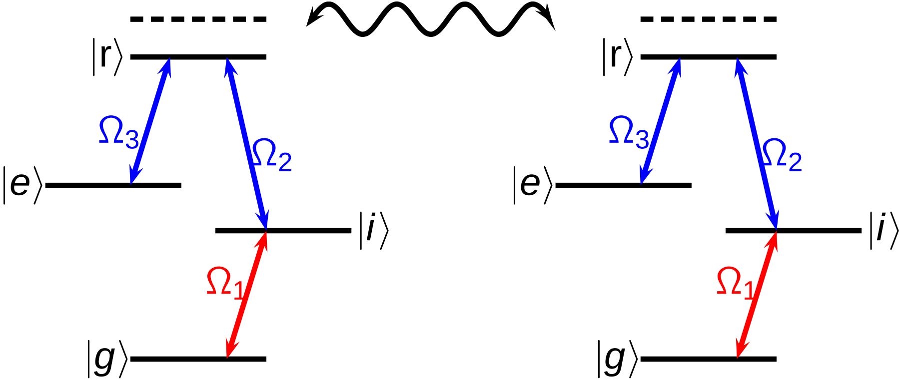
CO.CO.MAT
Control of Quantum Correlations in Tailored Matter
SFB/TRR 21 - Stuttgart, Ulm, Tübingen

Level Structure and Interaction – Rydberg Blockade

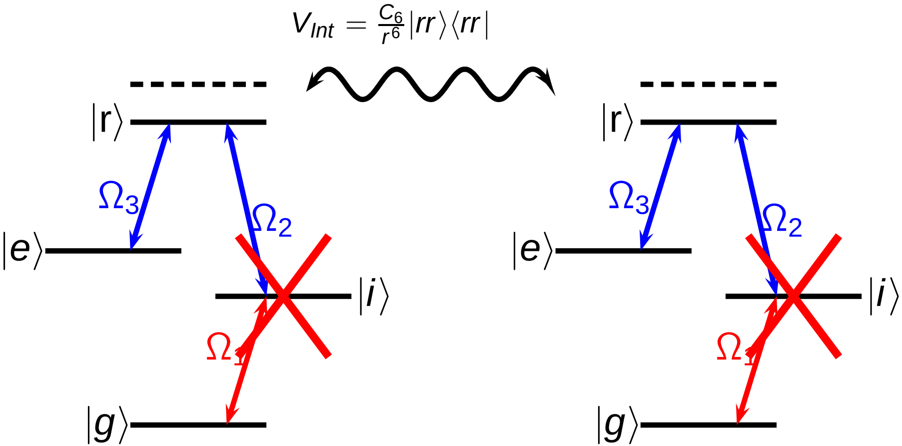


Level Structure and Interaction – Rydberg Blockade

$$V_{Int} = \frac{C_6}{r^6} |rr\rangle\langle rr|$$



Elimination of Intermediate State in Simulation



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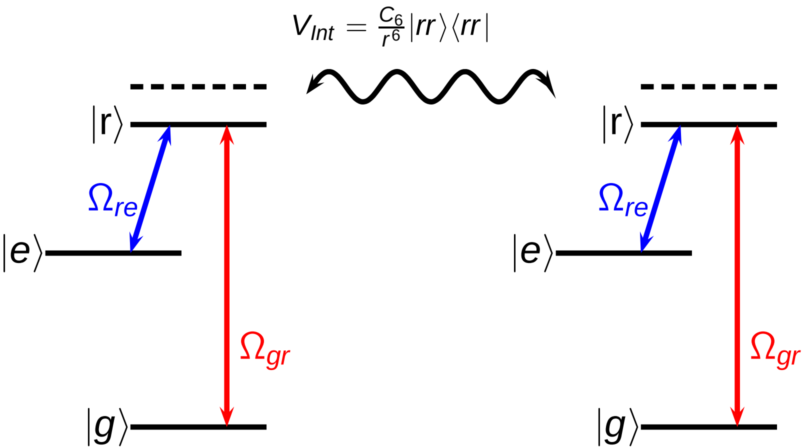


Concept of Single Photon Source

prepare W-state:

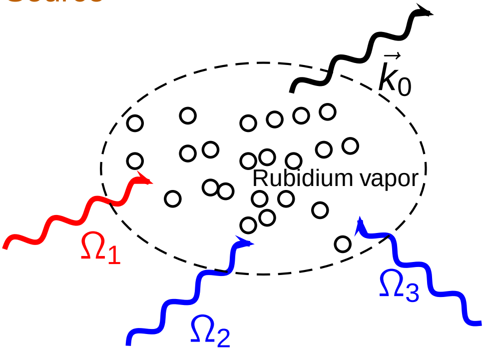
$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{\imath k_0 r_i} |e\rangle_i$$

phase matching

$$\vec{k}_0 = \vec{k}_1 + \vec{k}_2 - \vec{k}_3$$

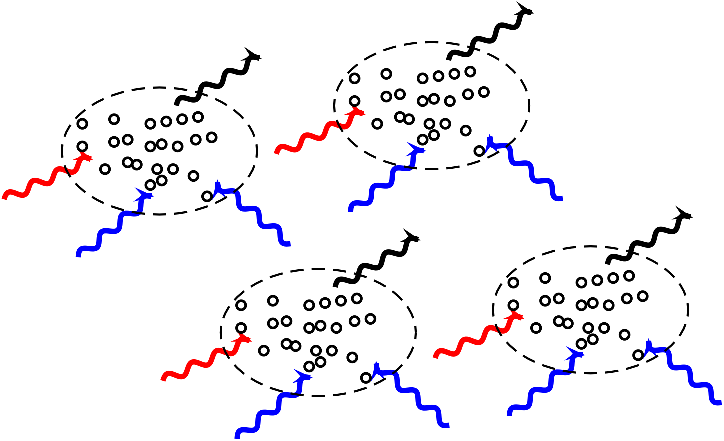
yields directionality:

$$P(k) \propto \frac{1}{N} \left| \sum_{i=1}^{N} e^{\imath (k - k_0) r_i} |e\rangle_i \right|^2$$



M. Saffman, T.G. Walker. PRA 66, 065403 (2002)

This Photon Source is Scalable



Preparation of W-state via Optimal Control

- prepare W-state $|W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \mathrm{e}^{\imath k_0 r_i} |e\rangle_i$ from ground state
- Simulating time dynamics by MPS code with long-range interactions
- CRAB Optimization method to shape pulses
- Hamiltonian for System is

$$H_{loc} = \frac{\Omega_{gr}}{2} |r\rangle\langle g| + \Delta_r |r\rangle\langle r| + \frac{\Omega_{re}}{2} |e\rangle\langle r| + \Delta_e |e\rangle\langle e|$$

$$H_{int} = \sum_{i \neq j} \frac{C_6}{r_{ij}^6} |r_i r_j\rangle\langle r_i r_j|$$

- Control $\Omega_{gr}(t)$ and $\Omega_{re}(t)$

CRAB Optimization Method

Chopped RAndom Basis:

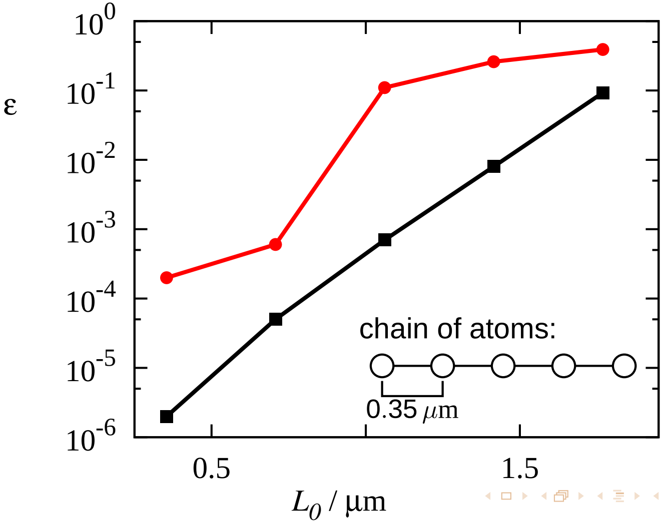
- Expand the Control Pulse into a truncated (chopped) basis
- $\Omega(t) = \sum_{i=1}^{N_{func}} c_i f_i(t)$, e.g. $f_i(t) = \sin(\omega_i t)$
- Search space reduced from L^2, $\Omega(t)$ to $\mathbb{R}^{N_{func}}$, $\vec{c}$
- Randomly chosen, but fixed ω_i
- Minimize $\varepsilon = 1 - |\langle W|\psi(T)\rangle|^2$

T. Caneva et al. Chopped random-basis quantum optimization
PRA 84, 022326 (2011)

Control of state preparation in 3 steps

- Optimization of Linear Chain of atoms (1D)
- Optimization of Square Grid of atoms (2D)
- Apply to Cloud of thermal atoms (3D)

Linear Chain of Atoms



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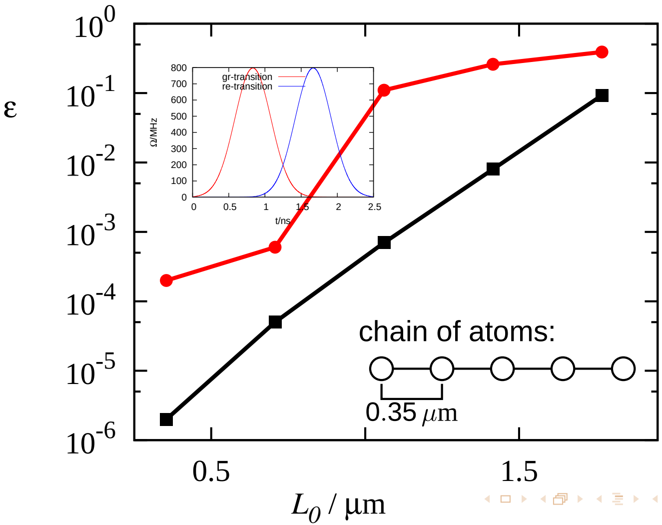

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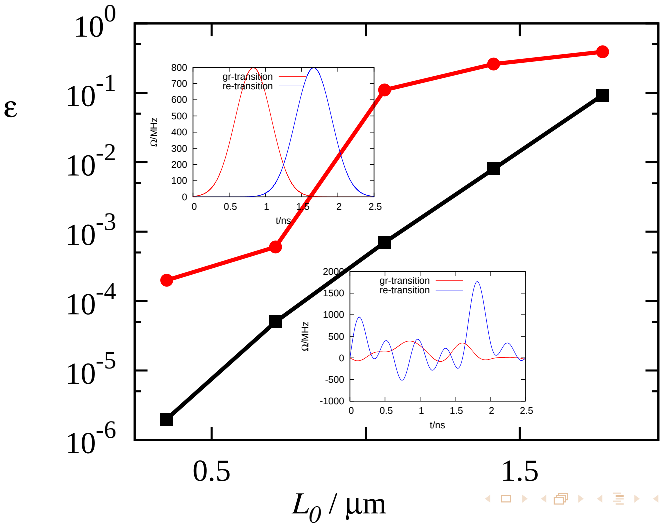

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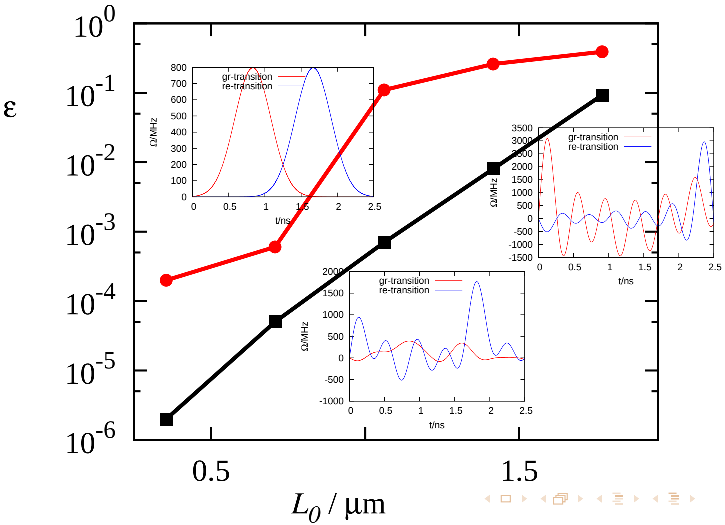

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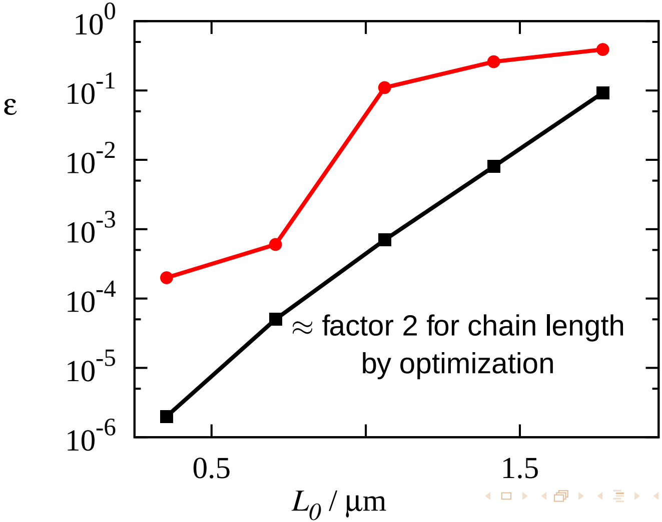
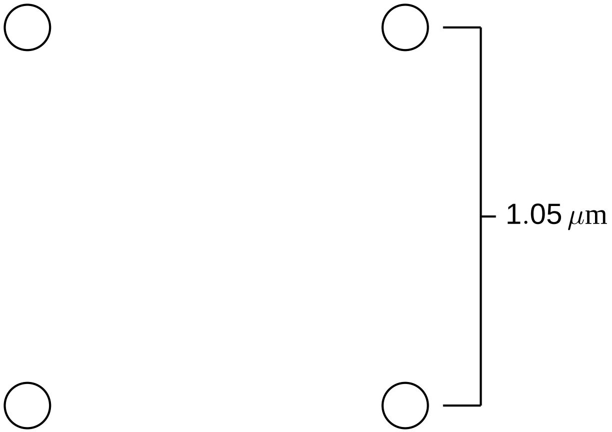
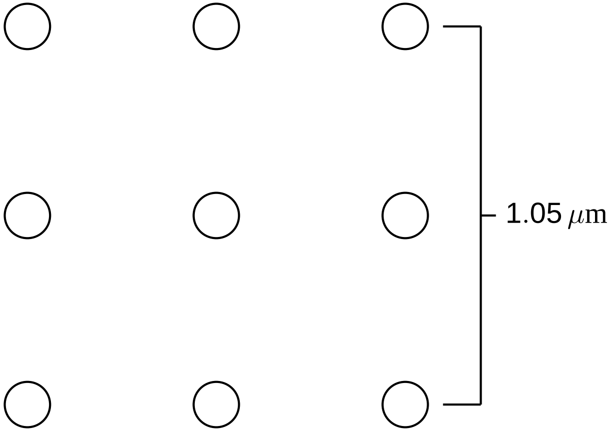


Square Grid of Atoms



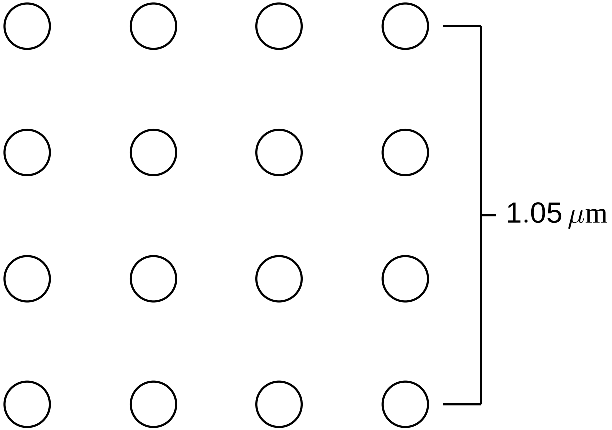
4 atoms

Square Grid of Atoms



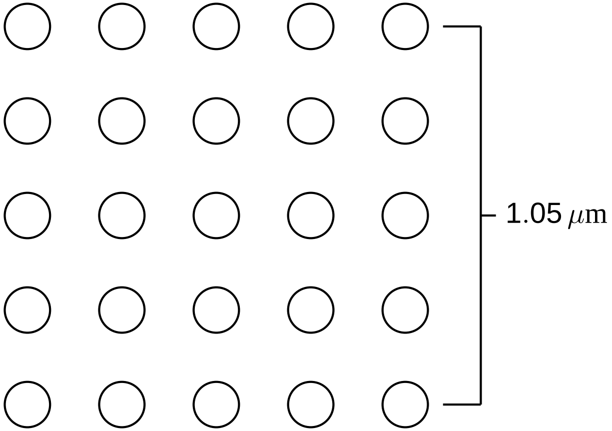
9 atoms

Square Grid of Atoms



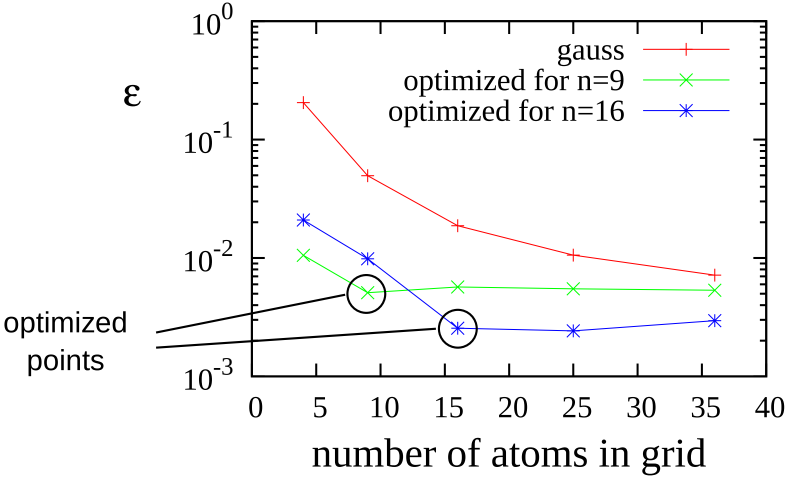
16 atoms

Square Grid of Atoms



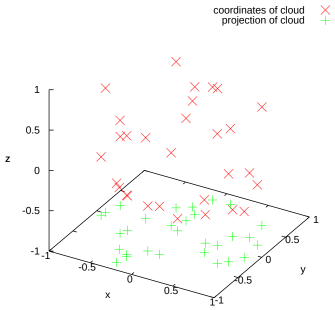
25 atoms,...

Square Grid of Atoms



Clouds of Atoms in 3D Space

- already 10-30 atoms allow to represent a 3D structure
- distribute atoms randomly



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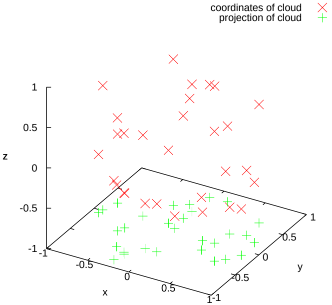
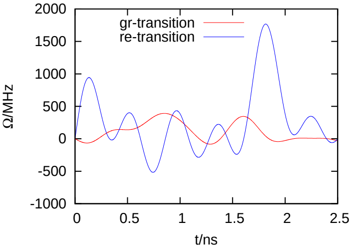


- extract relevant features from 1D and 2D optimized pulses
- scale $\Omega_{gr,N} = \Omega_{gr,1}/\sqrt{N}$ for N atoms (Rydberg enhancement)



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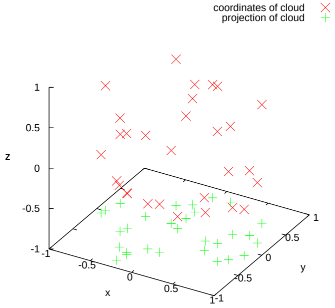

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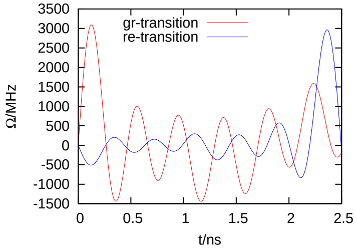

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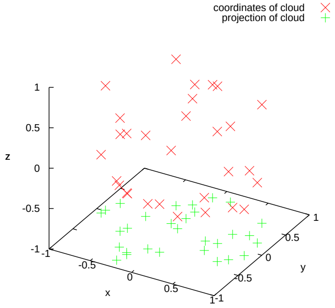

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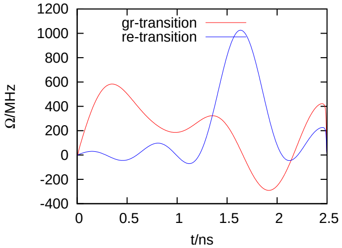

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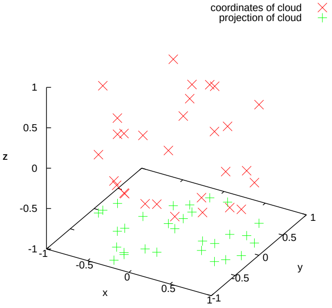

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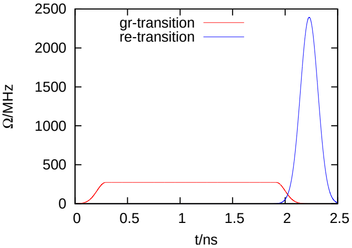
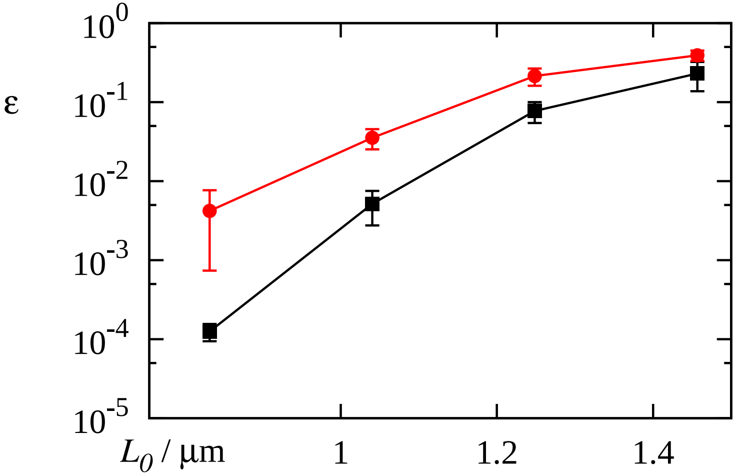


Results for 3D Clouds (10 atoms)



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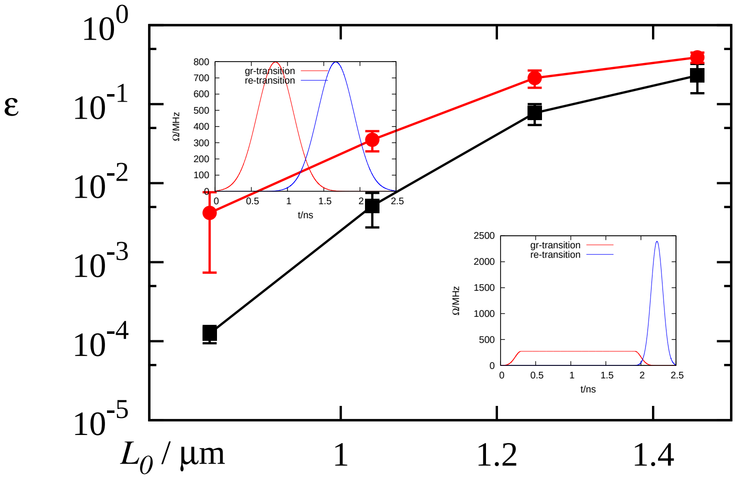

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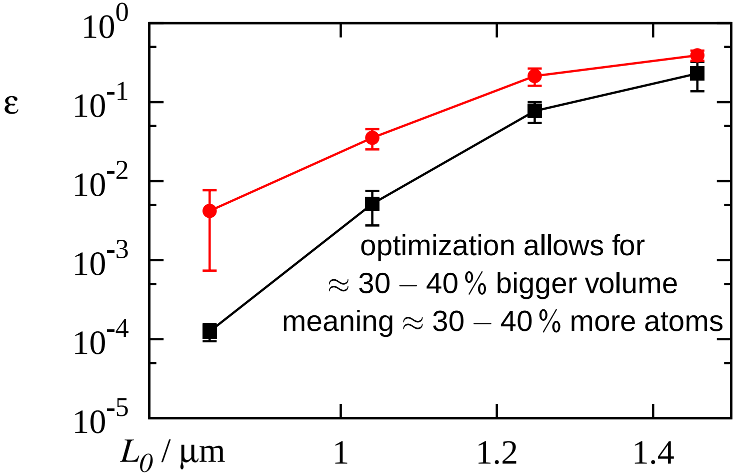
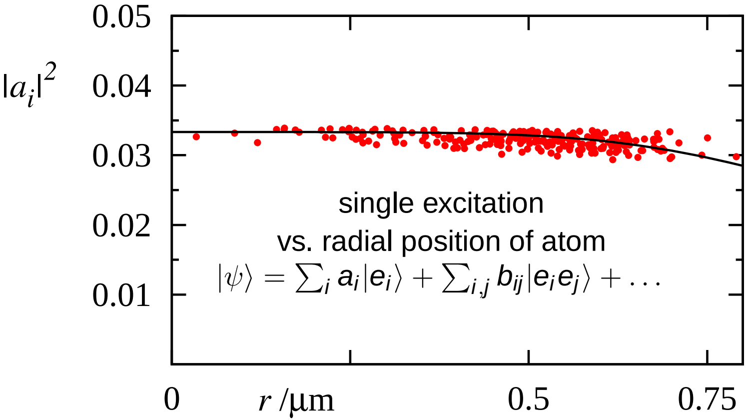
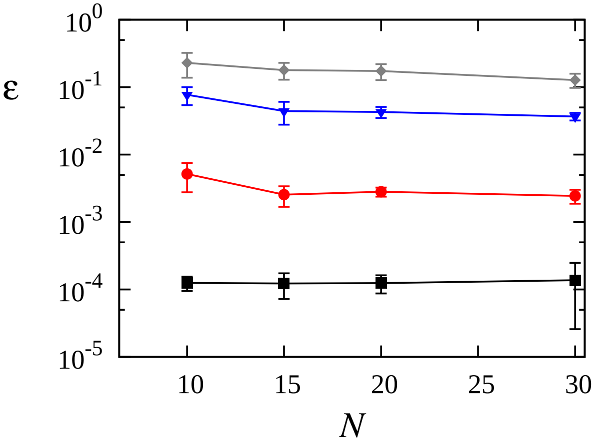


Corrections to perfect state preparation



MPS simulation for 30 atoms (red dots) vs.
high density semi-analytic model (black line)

Dependance on number of atoms



$L_0 = 0.83 \ldots 1.46\,\mu\text{m}$ (from lower to upper curve)

Collective Spontaneous Emission of the Photon

$$|\psi(0)\rangle = |W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \mathrm{e}^{\imath \vec{k}_0 \vec{r}_i} |e\rangle_i$$

$$|\psi(t)\rangle = \sum_{j=1}^{N} a_j(t) \mathrm{e}^{-\imath \omega_0 t} |e\rangle_j + \int d^3k b_k(t) \mathrm{e}^{-\imath ckt} |G\rangle |k\rangle$$

local Hamiltonian: $H_0 = \sum_{j=1}^{N} \hbar\omega_0 |e\rangle_j \langle e|_j + \int d^3k \, \hbar c k a_k^\dagger a_k$

interaction: $V_I = \sum_{j=1}^{N} \int d^3k \, \hbar g_k \mathrm{e}^{-\imath \vec{k} \vec{r}_j} a_k^\dagger |G\rangle \langle e|_j + h.c.$

with Wigner-Weißkopf approximation:

$$\dot{a}_i = \imath\gamma \sum_{j=1}^{N} \frac{\mathrm{e}^{\imath k_0 |\vec{r}_i - \vec{r}_j|}}{k_0 |\vec{r}_i - \vec{r}_j|} a_j \quad \text{remaining excitation}$$

$$\dot{b}_k = -\imath g_k \sum_{j=1}^{N} \mathrm{e}^{-\imath \vec{k} \vec{r}_j} \mathrm{e}^{\imath (ck - \omega_0) t} a_j \quad \text{mode occupation}$$

L. Pedersen, K. Mølmer. PRA 79, 012320 (2009)

Imperfect initial state

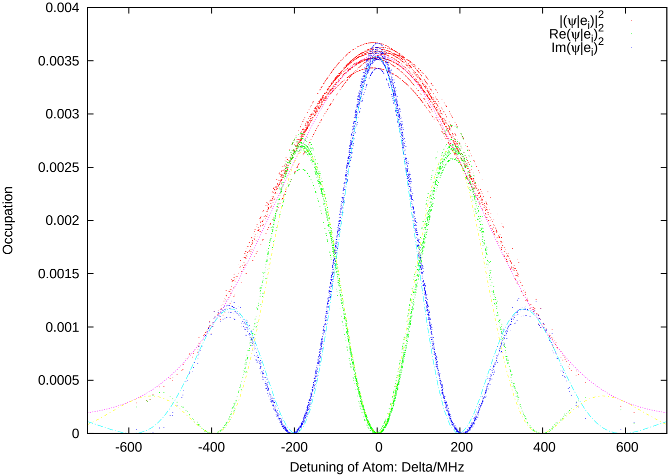
$|\psi(0)\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \alpha_i |e\rangle_i \neq |W\rangle$
Evaluate α_i

- assume perfect blockade: $N-1$-dim. space: $|G\rangle$, $|r_1\rangle, \ldots |r_N\rangle$
- excited state $|r_i\rangle$ Doppler shifted by $\Delta_i = (\vec{k}_1 \pm \vec{k}_2) \cdot \vec{v}_i$
- Velocity of atoms follows a thermal distribution

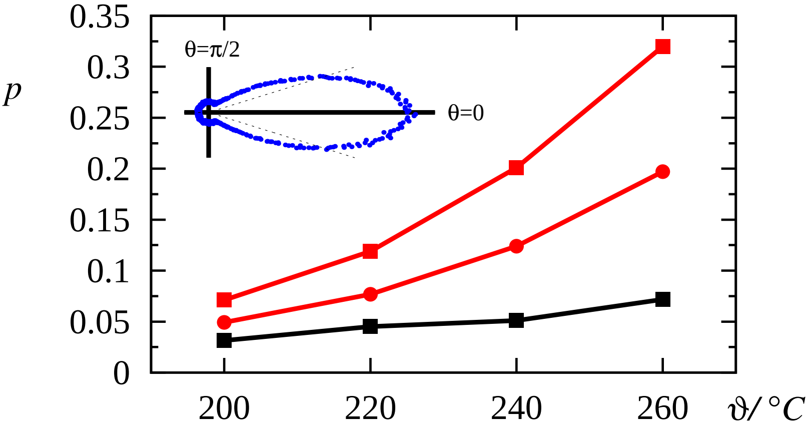
$$f(v_i) = \frac{1}{\sqrt{2\pi}\sigma_{v_i}} \exp\left(-\frac{mv_i^2}{2\sigma_{v_i}^2}\right)$$

- do a simulation for the realistic case of $N = 200 - 1200$ atoms, $r = 0.5\,\mu\mathrm{m}$, $T = 2.5\,\mathrm{ns}$

Imperfect initial state - Distribution of $|e_i\rangle$ excitation



Temperature and Directionality of Photon



black: parallel lasers, red: antiparallel lasers
squares: optimized pulse, circles: guess

Conclusions and Outlook

- Concept of Scalable Single Photon Source at Room Temperature has been examined
- Optimized State Preparation via simulation by MPS code with long-range interaction and CRAB
- Robust against considered realistic thermal noise
- Directionality of emission also at room temperature
- See what happens in the Experiment

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Thank you for your attention!